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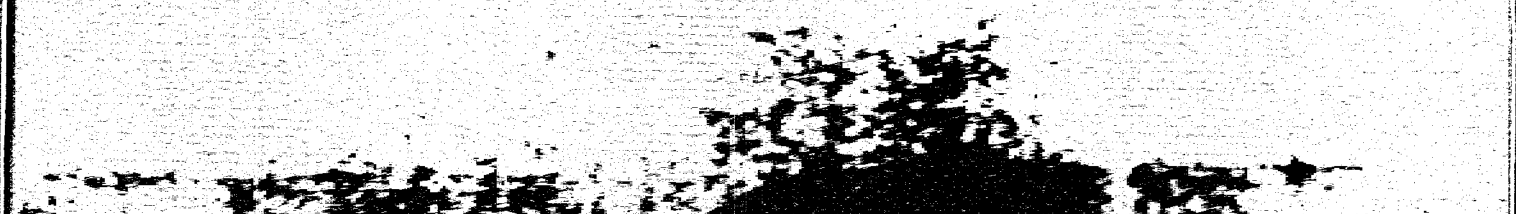
GEOTHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT PROGRAM QUARTERLY PROGRESS REPORT APRIL - JUNE 1980

SAMUEL G. VARNADO

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87185 and Livermore, California 94550 for the United States Department of Energy under Contract DE-AC04-76DP00789.

JULY 1980



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GEOTHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT PROGRAM QUARTERLY PROGRESS REPORT

April-June 1980

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Drilling Technology Division 4741
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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. Advanced drilling systems are also under development. The goals of the program are to develop the technology required to reduce well costs by 25% by 1983 and by 50% by 1987.

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GEOTHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT PROGRAM QUARTERLY PROGRESS REPORT

April-June 1980

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 costs, cost reduction goals have been set for the program. These are to develop the technology required to reduce well costs by 25% by 1983 and by 50% by 1987.

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 emphasizing activities directed at the near-term cost reduction goal, but increased emphasis on advanced system development is anticipated as time progresses.

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 primarily through contracts with private industries and universities. Some projects are conducted internally by Sandia.

This report describes the program, status, and results of ongoing R&D within the program for the quarter April-June 1980.

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2. HIGHLIGHTS

- Management -- The semi-annual meeting of the Geothermal Drilling and Completion Advisory Panel was held 19-20 June 1980 at Texas Tech University, Lubbock, Texas. The minutes of the meeting are being published separately.

- Lost Circulation Mapping Tools and Techniques -- A project to assess the state of the art of mapping lost circulation zones in geothermal wells was initiated this quarter.

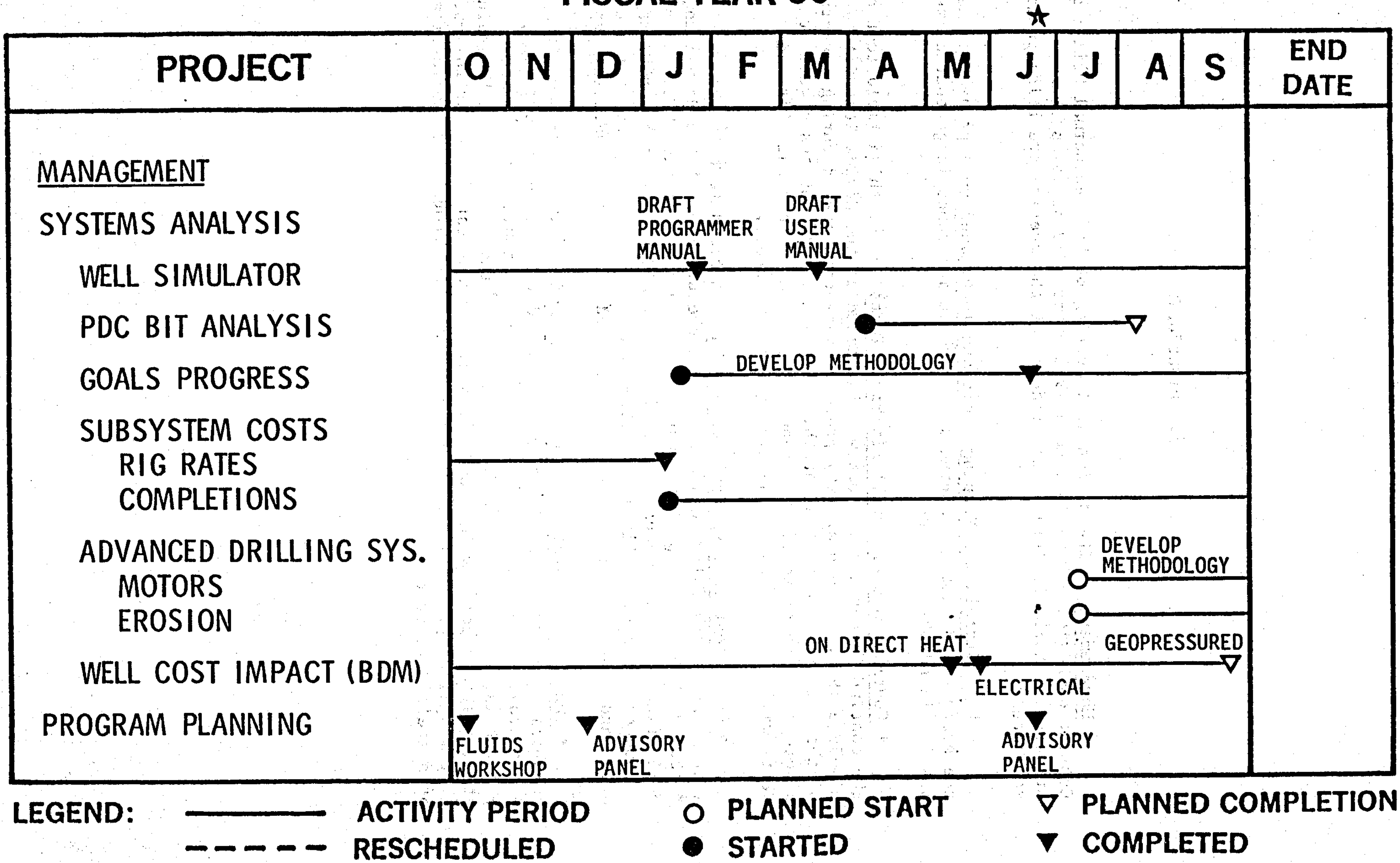
- Continuous Chain Drill Bit Field Tests -- The third field test of the continuous chain drill bit was initiated at the Nevada Test Site in mid-June 1980. Hole stability problems were encountered during preparation of the hole for the testing of the chain drill, and the tests were still in progress at the close of this reporting period. The results of the field tests will be included in the next quarterly report.

- Field Test of the HTM-1 Mud System -- A field test of the HTM-1 mud system was successfully conducted during the drilling of the McCulloch, Mercer 2-28 well in Imperial County, California, during May 1980. No mud solidification, no serious lost circulation, and no corrosion problems were encountered during drilling with HTM-1 mud. The test data are being evaluated, and a detailed report will be included in the next quarterly report.

- Inert Gas Generation from Diesel Exhaust -- Two, 100-hour catalyst durability tests, the first at full load and the second at part load, were successfully completed during this reporting period. A final report on the project is nearing completion. The data from the project will be evaluated, system specifications established, and cost estimates for full-scale system options prepared and compared before proceeding with the fabrication of a field-size system.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80



3. MANAGEMENT

Systems Analysis

Sandia has completed the definition of the approach to be taken in analyzing the progress that the program is making toward achieving its goals. In addition, new support contracts have been awarded for (1) the development of generic geothermal well plans and characterization of drilling problems, (2) the development of cost algorithms for drilling operations, and (3) a survey of future drilling requirements.

A paper recently submitted to the Geothermal Resources Council (GRC) contained the preliminary results of the cost impact of specific new technologies and the sensitivity of well costs to various drilling parameters.

The project to develop a method and an algorithm for computing charges and rates for drilling rigs has been completed. The analysis of the importance of cementing costs to total well cost was also completed. The case study of cementing costs examined the potential impact of technology on the reduction of total well cost. The study results indicated that technologies to improve the cementing and to avoid or reduce lost circulation would significantly reduce total well cost. In the study, the Raft River and Cove Fort wells were considered representative of "trouble" wells and The Geysers/Baca wells as representative of "trouble-free" wells. The break-even cost for a "perfect technology" that converts a trouble well to a trouble-free well is approximately 65% of the original total cementing cost. In the case of "less than perfect technology" that reduces cementing and lost circulation problems to those of the Baca-like well, the break-even point is about 20% of the original total cementing cost. A "less than perfect technology" that increases cement costs to 15% of their original value would give a 10% cost reduction in the total well costs. The comparison of the economics and effectiveness of different methods of descaling wells and the computing of the sensitivity of energy costs to well costs for both direct use and electricity generation were in the final stages as this reporting period came to a close.

The programmer's and user's manuals for IOSYM, an input-oriented simulation language for continuous systems, have been written and are undergoing final modification. IOSYM is an extension of the GASP IV simulation language. It permits systems which are sequences of continuous processes to be modeled graphically. Normally, the system can be described by data input only. The language permits scholastic sequencing and termination criteria for processes and allows crossing conditions for ending operations that are more general than GASP IV. Extensive capability exists for conditional branching and logical modification of the network. IOSYM has been used to model the cost of geothermal drilling where the various costly processes of drilling are represented by IOSYM operations. The language is much more general, however, since it retains most of GASP IV's discrete event capabilities and permits easy modeling of continuous processes.

S. Sarem, Union Oil Company of California, visited Sandia on 15 May 1980 to discuss Union's use of the GEOTEMP wellbore thermal simulation code. Union has installed this code on its computer and is using GEOTEMP to calculate temperature profiles both in muds and cements used in geothermal wells. Union requested Sandia's assistance in debugging the code. Union also indicated an interest in pursuing joint research programs with Sandia. The first of these activities will involve Union supplying some field data for Sandia to use in code verification runs. Since there are very few sources of such data, this interchange of information is expected to be of mutual benefit to Sandia and Union.

Drilling Hardware

Sandia is assisting Los Alamos National Scientific Laboratory (LANSL) in obtaining workable geothermal turbodrills for the hot dry rock (HDR) project. As part of this effort, two 13.7-cm (5.375-in.) diameter turbodrills manufactured by Maurer Engineering were tested at the Drilling Research Laboratory (DRL), Salt Lake City, Utah, during the week of 14 April 1980. The tools will be used for drilling part of the 22.2-cm (8.75-in.) segments of Wells EE-2 and EE-3 at LANSL's Fenton Hill site. The drills were tested with tricone bits of the size used in drilling in Texas pink granite. Although similar tools had previously given substantial problems with speed control, these turbines demonstrated stable operation at moderate speed, 350 to 400 rpm, and good penetration rate, 9.1 to 12.2 m/h (30 to 40 ft/h). The reasons for improved operation appeared to be the use of a different bit and a sealed, lubricated bearing assembly.

A meeting was held on 24 June 1980 between representatives from SNL and LANSL to discuss Sandia's further participation in the HDR project. A decision was made that Sandia would try to obtain two of the new 17.8-cm (7-in.) geothermal turbodrills that have been fabricated and tested by Dyna-Drill. These turbines would be evaluated in the HDR experiment for comparison with the Maurer turbodrill.

Completion Technology

A meeting was held with T. Muecke, Supervisor of Completions Research, at Exxon Production Research Company in Houston. The facility that Exxon has built for determining the effectiveness of mud displacement by cement during oil well completion operations was described. Exxon has also developed a proprietary computer code that models the non-Newtonian flow characteristics of these fluids. The facility simulates a wellbore, and cement and mud can be pumped through it. Once the cement sets up, the casing and the core that surrounds it can be sectioned to permit investigation of the displacement phenomenon. This test facility has been constructed at the Halliburton research headquarters in Duncan, Oklahoma. Halliburton conducts the tests for Exxon and supplies the data to Exxon for comparison with calculated values from their proprietary code. Since casing design and cementing techniques are extremely important to geothermal operations, a facility of a similar type would be extremely valuable to Sandia's completions technology program. The upper temperature limit on the existing facility is 121°C (250°F). The facility is reserved for use for the next two years by Exxon. Sandia is conducting a series of discussions with Exxon and Halliburton to determine the feasibility of constructing a larger diameter, higher temperature facility to do similar work for geothermal applications. Sandia's proposal for a facility for cementing and lost circulation material testing was presented to the Geothermal Drilling and Completion Advisory Panel, and the proposal was enthusiastically endorsed. Plans for constructing the facility are in progress.

T. Strickland of Republic Geothermal visited Sandia to discuss formation damage tests with Sandia and Terra Tek personnel. Republic's application for federal loan guarantees has been delayed pending a satisfactory solution to the apparent formation damage, i.e., reduction in permeability and thus production, that is occurring in the geothermal wells drilled in the East Mesa of the Imperial Valley. A Sandia-sponsored test at Terra Tek has been devised that will hopefully lead to a solution to this problem.

Lost Circulation Control Methods

W. Holman and D. Reynolds of Milchem, Inc., expressed an interest in the Geothermal Drilling and Completion Technology Program and a willingness to work with Sandia in the program. Two specific items in their product line may be of interest: Mil-Temp, a fluid additive to reduce high-temperature viscosity, and Mil-Squeeze, a silicate-based clay that is used for lost circulation control. Arrangements were made for a demonstration of Mil-Squeeze at Sandia.

Venture Chemicals, Inc., and Poly Plug, Inc., visited Sandia and presented ideas for sealing lost circulation zones in geothermal wells. Venture Chemicals has developed a dehydrated, pelletized, cellulose material that expands approximately 10 times when mixed with water. Sandia will perform some laboratory tests to quantify the material properties and its capability to plug formations under geothermal conditions.

Poly Plug, Inc., has developed a two-part mix, polyurethane foam that has been successfully used to stop water flows in water wells. Sandia will furnish Poly Plug with data on the geothermal environment and critique the Poly Plug tests conducted under the conditions presented in the data. Loffland Brothers Drilling Company has agreed to perform a mechanical design of a placement device for this material.

Supporting Technology

A meeting was held at the Amoco Production Research Center, Tulsa, Oklahoma, between representatives from Sandia and Amoco. Discussions were concerned with drill string dynamics and wellbore temperature prediction capabilities. Amoco is interested in Sandia's activities in these areas and requested a copy of the wellbore temperature prediction code, GEOTEMP.

The code will be supplied. Amoco is an industry leader in drilling research, and their participation and support should be valuable assets to the geothermal drilling program. Amoco also agreed to critique Sandia's plans for the drill string dynamics study.

A presentation on material needs for geothermal drilling and completions was made to the National Research Council Materials Advisory Board in Washington, DC. This committee is tasked to identify materials problems presently limiting geothermal development and to formulate recommendations aimed at finding solutions.

Geothermal Information Exchange with New Zealand

S. Varnado visited New Zealand in support of a recently signed International Cooperative Agreement between the U.S. Department of Energy and the New Zealand government. The Wairakei Geothermal Project in Wairakei, New Zealand, was visited on 14-16 April 1980 for discussions with personnel from the New Zealand Ministry of Works. In addition, technical discussions were held on 18 April 1980 with the geothermal staff of Kingston, Reynolds, Thom, and Allardice (KRTA), geothermal consultants in the Philippines. KRTA is located in Auckland, New Zealand. Key personnel at the Wairakei project were B. Denton, Geothermal Project Engineer, and L. Fooks, Investigations Engineer. At KRTA, the primary contact was T. Dobbie, Associate for Chemical Engineering.

The purpose of this trip was to discuss geothermal drilling and completion practices that are currently being used in New Zealand and in the Philippines and to present an overview of the DOE/DGE program in geothermal drilling and completion technology development. A summary of the discussions and observations concerning geothermal projects in New Zealand and the Philippines follows.

New Zealand -- The problems experienced in New Zealand are different from those encountered in The Geysers and other U.S. resources. The New Zealand Ministry of Works is willing to test new bit designs in their holes. Because they have a significant amount of experience in these formations, it would be in the interest of the U.S. to participate in such a joint program. They are also interested in testing some of the new high-temperature logging tools recently developed by Sandia.

The possibility of one of the engineers from the Wairakei project visiting the U.S. and working directly with Sandia for a period of 2 to 3 months in the design and setup of some new experimental testing facilities for studying mud displacement by cement was discussed. This would be beneficial in that this engineer could bring a great deal of practical experience to the ongoing technology development program.

In addition to the improved bit technology, interest was expressed in two other downhole tools. First, the need for a high-temperature, openhole packer for staged cementing was clearly expressed by the New Zealanders. In this application, the packer would have to tolerate a high temperature for about 2 hours. Second, there exists a need for a casing inspection tool that could be used in old wells to evaluate the effects of corrosion on the casing. This tool is needed to answer the question of the integrity of the casing after the well has been in operation for a period of 20 or more years.

The Philippines — The basic problems encountered in drilling geothermal wells in the Philippines are lost circulation control and drill string dynamics. Materials for controlling lost circulation under high-temperature conditions are needed. In addition, the development of an understanding of drill string dynamics and of the design of shock subs to mitigate the vibrations induced in drilling fractured formations is needed. This same technology would be useful in designing the bottomhole assembly to provide a straight-hole trajectory.

KRTA expressed a willingness to approach the government of the Philippines for permission to field test some of the new PDC bits being developed under the DOE/DGE Geothermal Drilling and Completion Technology Program. They felt there was a high probability of obtaining permission. Participation in such testing would provide valuable field data for comparative purposes.

Currently used completion procedures have proven to be reasonably successful in field operations; however, it is clear that there is a significant lack of understanding of the displacement of mud by cement and of the flow of cement in highly fractured formations. Experimental work to enhance the level of understanding of the cementing process would be beneficial to the U.S. geothermal operators as well as overseas operators.

Reports and Presentations

A list of significant presentations made and reports published during this reporting period is compiled in Appendix A.

4. DRILLING HARDWARE

Drilling hardware, such as bits and reamers, with improved penetration rates and life are required to reduce well drilling costs. The approach to achieving these performance goals includes the development and demonstration of a new drill bit concept, the improvement of existing hardware systems and sub-systems, and research into new materials and on rock-fracture/cutter wear mechanisms. Projects are presently underway to design and develop high-temperature seals and lubricants for sealed bits; 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 third-generation (MK-III) bits were evaluated in a geothermal well at The Geysers along with seven conventional bits. The material improvements allowed the MK-III 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, the MK-III bits are projected to save a minimum of 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 versions 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 metres (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 metres (41.6 feet); (2) weight on bit, 28 kN (6400 pounds); and (3) rate of penetration, 1.2 m/h (4.0 ft/h). A second field test was conducted in September 1979, but internal hydraulic leakage occurred. This problem was corrected, and a third field test at NTS was initiated in June 1980 and was continuing at the close of this reporting period. A parallel effort to develop an all-PDC chain link for the drill has also been initiated.

Full-scale drag bits, modified to use PDC cutters, have been successfully demonstrated in field tests. Both the Christensen (C-1) hard-matrix and the Smith (S-1, modified), steel-bodied, PDC bits were tested 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 1676 to 1707 metres (5500 to 5600 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 metres (50 feet) each, bit lifetime could not be established. Additional field testing is planned.

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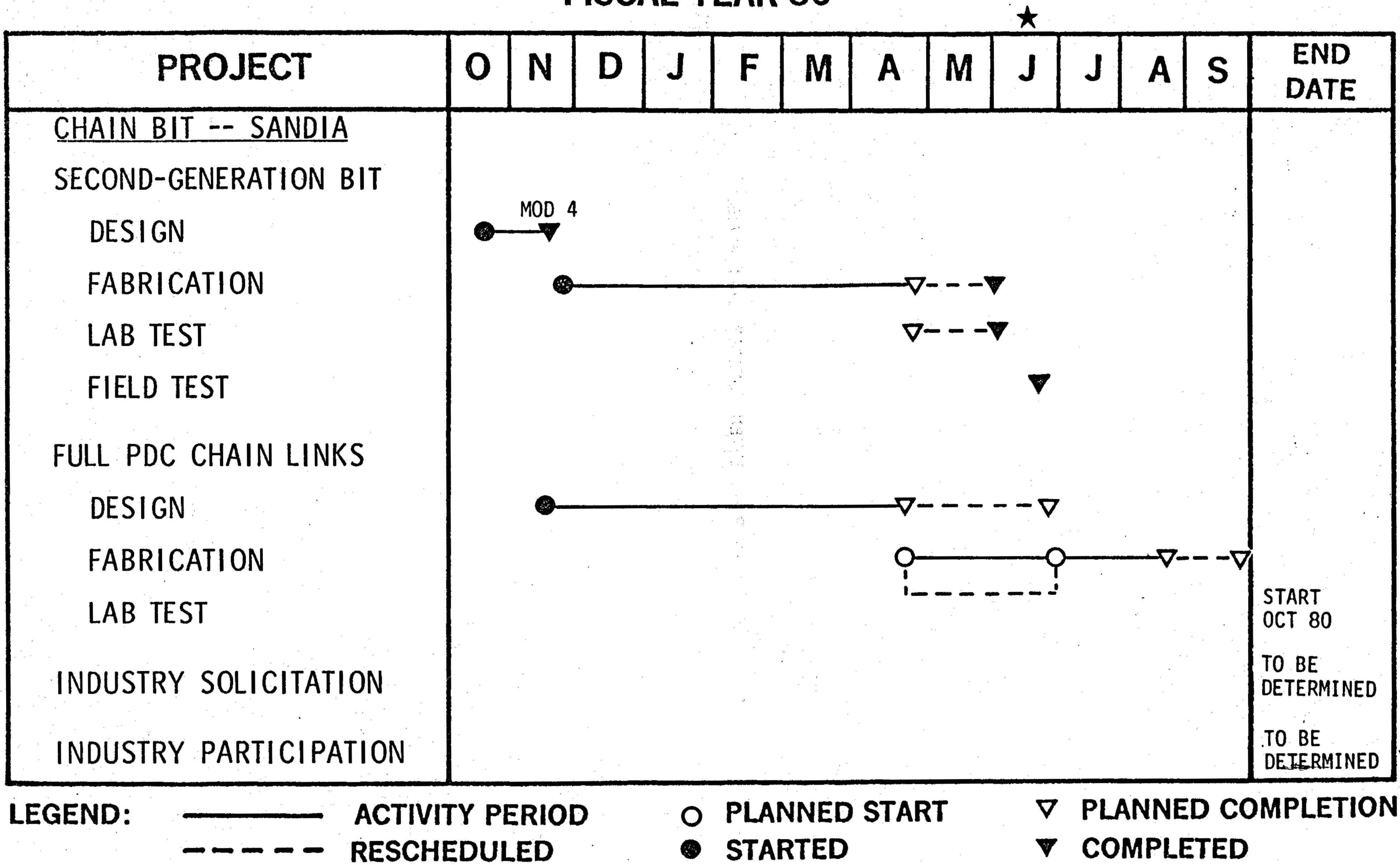
GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80



4.1 Continuous Chain Bit

Sandia National Laboratories
Technical Consultant: J. St. Clair (505) 844-7678

Project Objective

The objective of this project is to design, fabricate, and test a prototype downhole replaceable drill bit.

Project Status

The Prototype II, Mod 2, continuous chain drill bit field tests were conducted at NTS during the period 5-20 June 1979. The results were included in the April-September 1979 Semi-Annual Report. A follow-up field test at NTS was initiated in mid-September 1979. Unexpectedly rapid wear of the chain link cutting surfaces was experienced, and the tests were terminated after determination that field repair of the drills could not be made. 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 pre-drilling, surface, cycling tests.

Redesign and fabrication of two Mod 4 chain drills were completed, and a third field test was initiated in June 1980. A parallel effort to develop an all-PDC chain link is continuing.

Quarterly Progress

All-PDC Chain Link Design — The design of the full Stratapax™ chain link is progressing. A computer optimization code is being used to locate each Stratapax™ cutter as part of a computerized graphic drafting program. The final chain link design is expected to provide two options: (1) the chain links will have a tungsten carbide pad for holding the Stratapax™ cutters, a pad which will be brazed to an investment-cast base link, or (2) the chain link will be a one-piece investment casting.

Current plans include having Christensen, Inc., evaluate the effect on drilling when the diamond-set chain is misaligned. This evaluation will involve the use of Christensen's proprietary computer program and a special computer program developed previously for Sandia under another project. Sandia has developed a computer program for obtaining new diamond coordinates when the chain is displaced off-center with respect to the bit body. Christensen will use information from the computer program in their analysis. Completion of the analysis is expected early in the next reporting period.

Field Test — Preparations were completed for the third field test of the continuous chain drill bit to include (1) rebuilding and static-pressure testing the two chain drill units that failed in the September

1979 field tests, (2) manufacturing and assembling new chain links, (3) training a new drilling crew to permit 24-hour drilling, and (4) designing the instrumentation system to record and display the drilling conditions and results. The field test began on 12 June 1980. Hole stability problems were encountered during preparation of the hole for the tests, and completion of the field test was in process at the close of the quarter.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

PROJECT	O	N	D	J	F	M	A	M	J ★	J	A	S	END DATE
<u>GEOTHERMAL ROCK BIT SEALS AND LUBRICANTS TERRA TEK</u>													
SEAL DESIGN AND TESTING	—	—	—	—	—	—	—	▼					
LUBRICANT TESTING	—	—	—	—	—	—	—	▼					

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

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

PROJECT	O	N	D	J	F	M	A	M	★ J	J	A	S	END DATE
<u>GEOTHERMAL ROCK BIT SEALS AND LUBRICANTS TERRA TEK</u>													
SEAL DESIGN AND TESTING	—	—	—	—	—	—	—	—▼					
LUBRICANT TESTING	—	—	—	—	—	—	—	—▼					

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

4.2 Seal and Lubricant Development for Geothermal Rock Bits

Contractor:	Terra Tek, Inc.
Principal Investigator:	R. R. Hendrickson (801) 582-2220
Contract Period:	10 July 1979 to 10 May 1980
Contract Number:	13-8783 (Sandia)
Technical Consultant:	D. Wesenberg (505) 844-0129

Project Objective

The objective of this project is to design and develop improved tri-cone roller bits for geothermal applications. The project has two thrusts: (1) to substitute high-temperature steels in unlubricated bearings and (2) to develop high-temperature seals and lubricants for lubricated bearings.

Project Status

Research bits incorporating steels with higher hardness at high temperatures have demonstrated less wear than production bits in the simulated downhole environment. Third-generation unsealed bits have been field tested successfully, and this new technology is being considered for commercialization by a leading bit manufacturer.

A seal tester and a lubricant tester have been fabricated to simulate in-use conditions: 300°C (572°F), 34.5 MPa (5000 psi), translation, rotation, and eccentricity. Nonelastomeric seals and coated-elastomer seals were designed and tested. Life tests were run on coated-elastomer seals, and results compare favorably with previous, successful, Viton seal tests. Spring-loaded face seals have undergone preliminary tests, and the elastomeric side-seal system has been perfected.

Lubricant screening tests, while eliminating several products from further consideration, have established the exceptional high-temperature performance of Pacer PLX-014 oil. A grease based on this oil has also been compounded and is ready for field evaluation. An oil (PLX-022), not compatible with elastomers, has been developed for use with all-metal seals.

A follow-on program of seal and lubricant tests was initiated in July 1979 under a new contract. Elastomeric seals of EPDM compounds and Utex Industries proprietary elastomeric seals have been tested. Only the EPDM seal, 267-II-35, supplied by L'Garde, Inc., and the Utex HTCR seal did well. The testing of new candidate seals and lubricants has been completed, and the preparation of the final report on the project was nearing completion at the close of this reporting period.

Quarterly Progress

Elastomeric Seals — Trip-in-simulation seal tests were run on seals made of a proprietary compound from Utex Industries, Inc., known as HTCR. One seal survived a 2-hour soak at 288°C (550°F), followed by 120 hours of rotation at 90 rpm at 150°C (302°F) with abrasives and mechanical eccentricities present. The soak temperature was increased to 302°C (575°F) for the second test, and the seal failed after 5 hours of rotation. The soak temperature limit therefore lies between 288° and 302°C (550° and 575°F). The performance of HTCR is equivalent to the L'Garde, Inc., 267-II-35 EPDM, the Utex Industries, Inc., RD-227 and RD-231, and the Sandia Teflon-coated Viton seals.

L'Garde, Inc., supplied a new batch of EPDM seals that differed in composition from the original batch known as 267-II-35. The designation of the new batch was changed to Z-267. The first test attempted with this seal was terminated due to equipment malfunction. Subsequently, a trip-in-simulation seal test was run using a 288°C (550°F), 2-hour soak, followed by rotation at 150°C (302°F). Failure occurred after 33 hours of rotation; this performance compared unfavorably with the previous L'Garde 267-II-35 seal, which ran for 104 hours. The Z-267 was essentially unaffected by the temperature, pressure, or lubricant. The durometer dropped only 3 points, 95 to 92, Shore A, and the surface was free of cracks and discoloration. The seal failed due to abrasive wear on the inside diameter (i.d.) and also seized to the shaft, causing abrasive damage to the top.

Radial Lip Seal — Three tests were run on the Fluorocarbon, Inc., radial lip seal using soak temperatures of 250° to 288°C (482° to 550°F). In all tests, the seals held pressure at ambient temperature but not at test temperature. Upon examination, it was observed that the two seals that soaked at 288°C (550°F) had lost nearly all compression; the one seal soaked at 250°C (482°F) retained 70% of its original compression. Two of the tests were continued for approximately 10 hours in order to evaluate cuttings damage; none was observed. No further development is recommended for this seal. Although the exact failure mode has not been determined for all cases, the dimensional stability of the plastic seal body limits the maximum soak temperature to less than 250°C (482°F).

Metal Bellows Face Seal — Four tests were run to determine the wear and leakage rates for the primary seal surfaces. Leakage rates tended to increase with temperature and became excessive above 200°C (392°F). Two life tests were run at temperature, using The Geysers abrasives. The first test was run at 200°C (392°F) for 82 hours; the second test was run for 99 hours at 250°C (482°F). Both tests caused excessive wearing of the CBS-600 carburized steel "lug" surface: approximately 0.5 mm (0.019 in.) and 0.9 mm (0.035 in.), respectively. In both cases, the chrome oxide plasma coating on the seal rings was undamaged. A more wear-resistant surface material is required to protect the "lug" sealing surface. The 99-hour test utilized an initial 2-hour soak at 350°C (660°F). No damage to the springs, bellows, or seal ring was observed.

Lubricant Development — The Pacer Lubricants, Inc., PLX-40 Series was designed to evaluate the effects of molecular weight and suspended solids on the load-bearing ability of very-high-viscosity, synthetic, hydrocarbon oils. Four of the five grades were evaluated and are compared with the best lubricant previously tested, Pacer Geobond, in Table 1.

Table 1

Load-Carrying Capacity of Five Elastomer-Compatible Oils for Geothermal Journal-Type Rock Bits, at 316°C (600°F)

Designation	Viscosity* SUS	(CST)	Solids	Load Capacity MPa	(ksi)
Geobond Oil	190	(40.4)	Yes	73	(10.6)
PLX-042	180	(38.3)	Yes	64	(9.3)
PLX-043	290	(62.1)	No	63	(9.1)
PLX-044	280	(60.0)	No	66	(9.5)
PLX-045	313	(67.5)	No	69	(10.0)
PLX-046	466	(100)	No	21	(3.0)

*Saybolt universal seconds (SUS) at 99°C (210°F), or centistokes (CST) at 100°C (212°F).

The following observations can be made from these tests and the results shown in Table 1:

1. Suspended solids are not necessary,
2. Higher molecular weight has a slight beneficial effect,
3. Performance of the 40 series, except for PLX-046, exceeds the design requirement of 30 MPa (4.3 ksi) by more than 100%, and
4. Full-scale geothermal drilling tests should be run on at least two of the high-viscosity oils, as well as on Geobond oil and Geobond grease.

Note: PLX-046 was formulated with a very-high-viscosity, high-molecular-weight base oil.

The most successful lubricants developed by Pacer during this project are listed in Table 2, along with the performance criteria established by tests on a conventional bit lubricant. Full-scale drilling tests are recommended for any of the six Pacer products in Table 2.

Table 2

Lubricants Recommended for Field Testing

Designation	Type	Viscosity** SUS (CST) or Weight	Elastomer Compatibility at Temperature	Suspended Solids	Test Temperature °C	(°F)	Load Capacity MPa	(ksi)	Number of Tests
Conventional bit lubricant	Grease	NLGI No. 1	No	Yes	30	(86)	30	(4.3)	4
PLX - 014	Oil	190 (40.4)	Yes	Yes	316	(600)	73	(10.6)	15
PLX - 014	Grease*	NLGI No. 2	Yes	Yes	316	(600)	62	(9.0)	10
PLX - 022	Oil	180 (38.3)	No	Yes	316	(600)	81	(11.7)	12
PLX - 024	Oil	286 (61.4)	Yes	Yes	316	(600)	69	(10.0)	3
PLX - 043	Oil	290 (62.1)	Yes	No	316	(600)	63	(9.1)	2
PLX - 045	Oil	313 (67.5)	Yes	No	316	(600)	69	(10.0)	2

* Available commercially as Geobond grease.
** Saybolt universal seconds at 99°C (210°F), or centistrokes at 100°C (212°F).

This phase of the project was completed during this quarter, and preparation of a final report was nearing completion at the close of this reporting period. The final report will be published separately. A follow-on effort to test the successful lubricants and seals in full-scale, journal-type rock bits is under consideration.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

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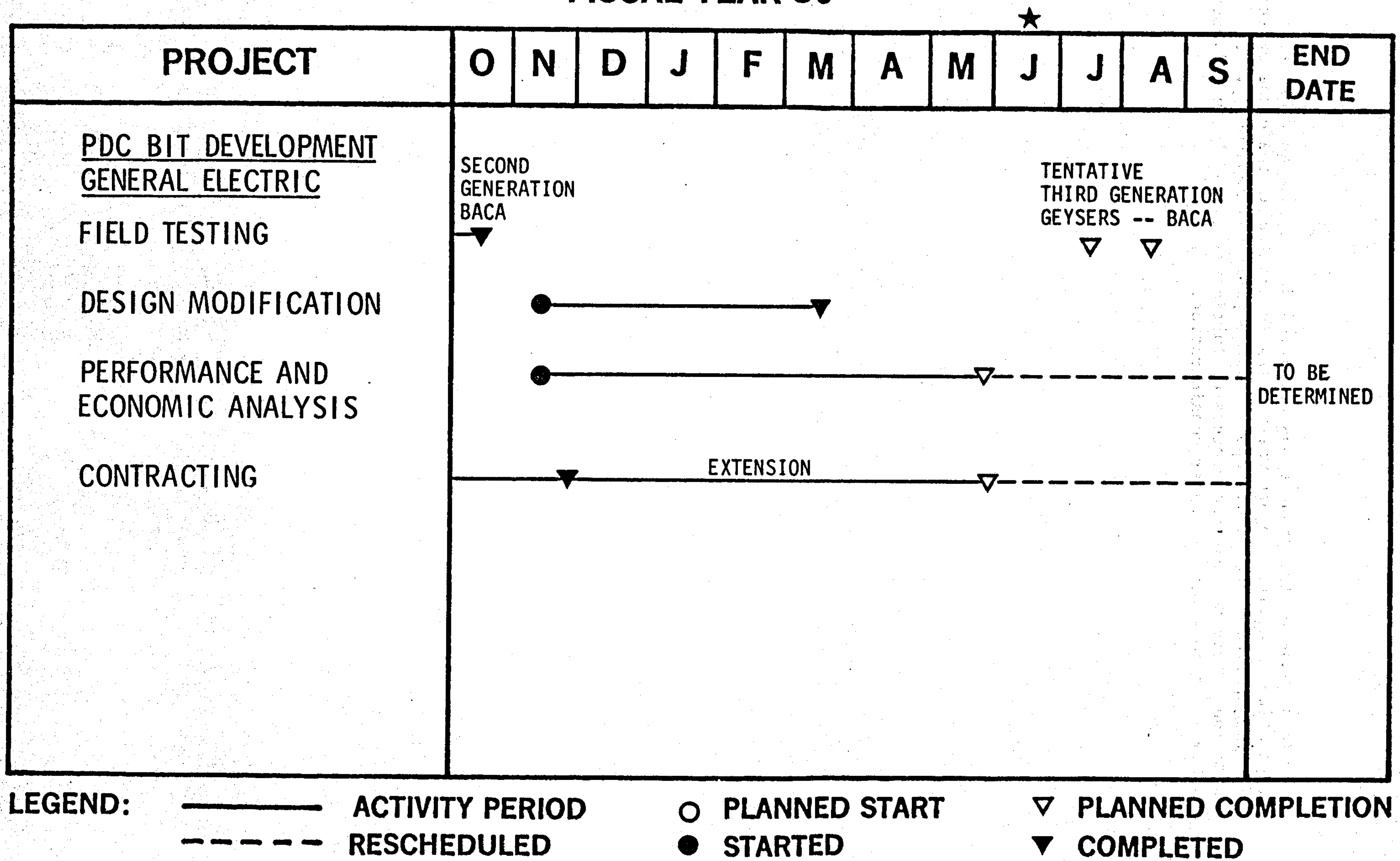

4.3 Geothermal Polycrystalline Diamond Compact Drill-Bit Development

Contractor:	General Electric Company, Corporate Research and Development (CRD)
Principal Investigator:	L. E. Hibbs, Jr. (518) 385-8330
Contract Period:	30 June 1976 to 31 May 1980
Contract Number:	DE-AC04-76ET27142
Technical Consultant:	D. Wesenberg (505) 844-0129

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, 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 predictive capability has been established for the performance of full-scale bits. This capability has been demonstrated with laboratory testing of full bits. Single-cutter tests have been run at simulated downhole conditions, and the data have been analyzed. The redesign and fabrication of the S-1, modified, bit, necessitated by the catastrophic failure during the November 1978 field test, has been completed. 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. Work is progressing in preparation for the field testing of the third-generation bits which is tentatively scheduled for the period July-August 1980. Preparation of a draft final report has been initiated.

Quarterly Progress

Final agreement was reached and purchase orders have been placed with SII Smith Tool, Irvine, California, for four steel-body, stud-type, geothermal, Stratapax™* bits to be utilized for the field tests required for the final phase of this program. The four steel-body, stud-type, Stratapax™ bits will incorporate eight changes to the S-1, modified, design, aimed at reducing cutter and gage wear but retaining the basic

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

cutting structure which performed well in the Baca field test in October 1979. The eight changes will be as follows:

1. Twenty-six cutters, Nos. 13 through 38, will be attached to -25°-back-rake, 25°-end-clearance, cemented, tungsten carbide studs, replacing the -20°-back-rake, 5°-end-clearance studs used previously. Figure 1 identifies cutter locations and Figures 2 and 3 give the stud specifications.

2. The positions of cutters Nos. 31 through 34 will be moved slightly, both radially and vertically, to obtain better bottom-hole coverage and eliminate the tracking configuration used originally. Figure 4 shows the original cutter profile.

3. The eight No. 2399 Stratapax™ blanks that were mounted flush with the bit side-ribs to serve as wear pads will be increased to 16 blanks per bit, mounted in groups of four. In addition, four No. 2399 Stratapax™ blanks per bit will be pressed into the junk slot walls so that the diamond layers extend past the bit body outside surface. These will be ground flush with the bit body to act as trimmers to maintain the hole gage.

4. Four larger, No. 2532, stud-mounted Stratapax™ gage trimmers, shown in Figure 5, will be press-fitted into the sides of each bit. If necessary, these trimmers will be ground after assembly to assure that they are accurately on gage.

5. The bit body corners behind cutters Nos. 35 through 38 will be relieved, and additional junk slots will be provided to improve the cooling of these diamond compact cutters.

6. The maximum cutter stand-off, i.e., the height above the bit body, will be reduced from 13.20 mm to 8.89 mm (0.520 in. to 0.350 in.), using Smith Tool's eccentric counter-bore technique.* This change will increase the stud support and reduce the chance of stud breakage without significantly reducing the maximum theoretical bit penetration rate.

7. Nozzle attachment will be improved to assure that no nozzles can become detached during drilling.

8. For two of the four bits, cutters Nos. 35 through 38 will be located so that the edge of the Stratapax™ diamond layer is tangent to the outside diameter of the bit. These bits will be designated Type No. S-2, modification A. On the remaining two bits, cutters Nos. 35 through 38 will be located so that the edge of the Stratapax™ diamond layer extends at least 1.27 mm (0.050 in.) beyond the outside diameter cutter press fitting. These cutters will then be ground so that the flat edge that is generated will be on gage. These bits will be designated Type No. S-2, modification B.

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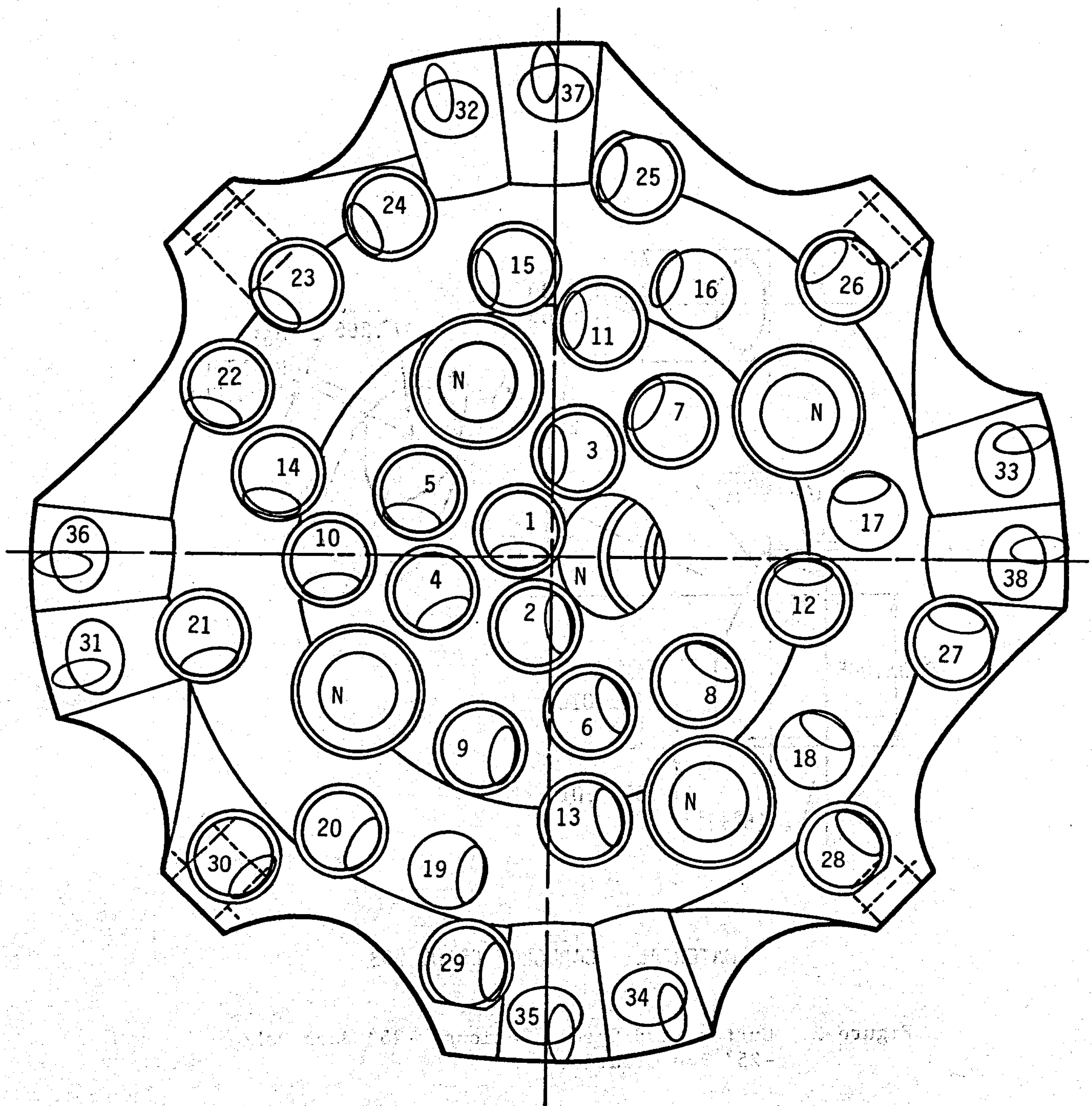
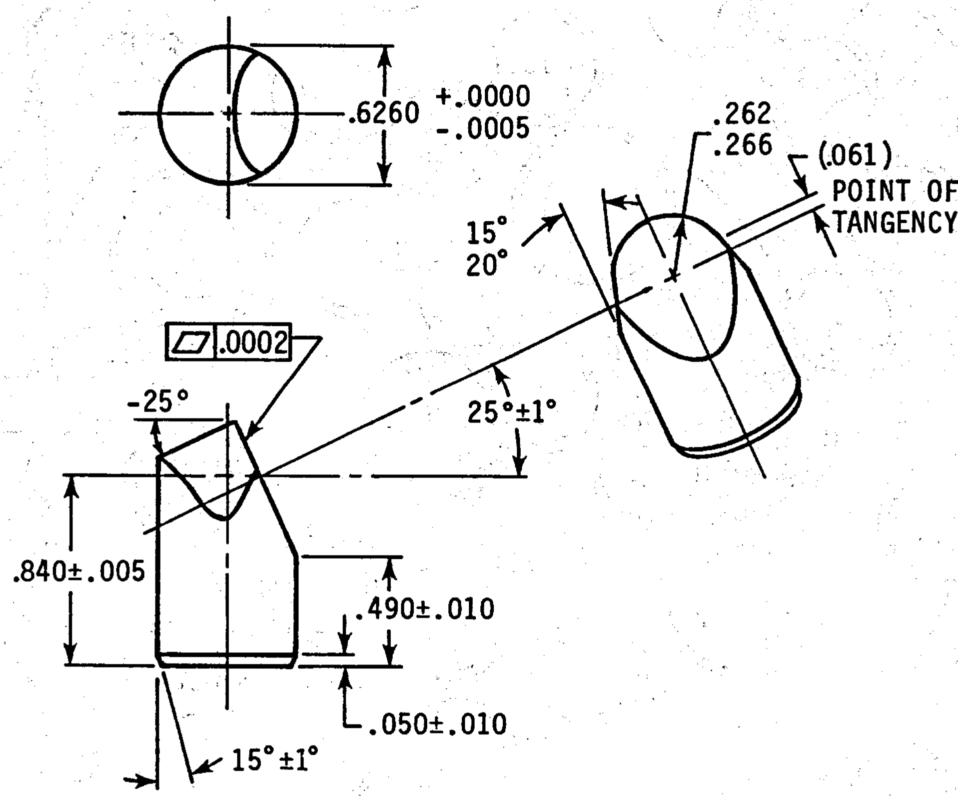
*William Baker, "Design Considerations for Stud-Type Stratapax™ Blank Bits," SII Smith Tool, Irvine, CA, presented at the Energy-Sources Technology Conference and Exhibition, 3-7 February 1980, New Orleans, LA.



CUTTERS No. 1-12 : -20° BACK RAKE, 5° END CLEARANCE
CUTTERS No. 13-38: -25° BACK RAKE, -25° END CLEARANCE

Figure 1. New Type No. S-2, Modification B, Stratapax™ Bit Design



MATERIAL: CARBOLOY GRADE 55B

Figure 2. Cutter Stud Specifications; -25° Back Rake, -25° End Clearance

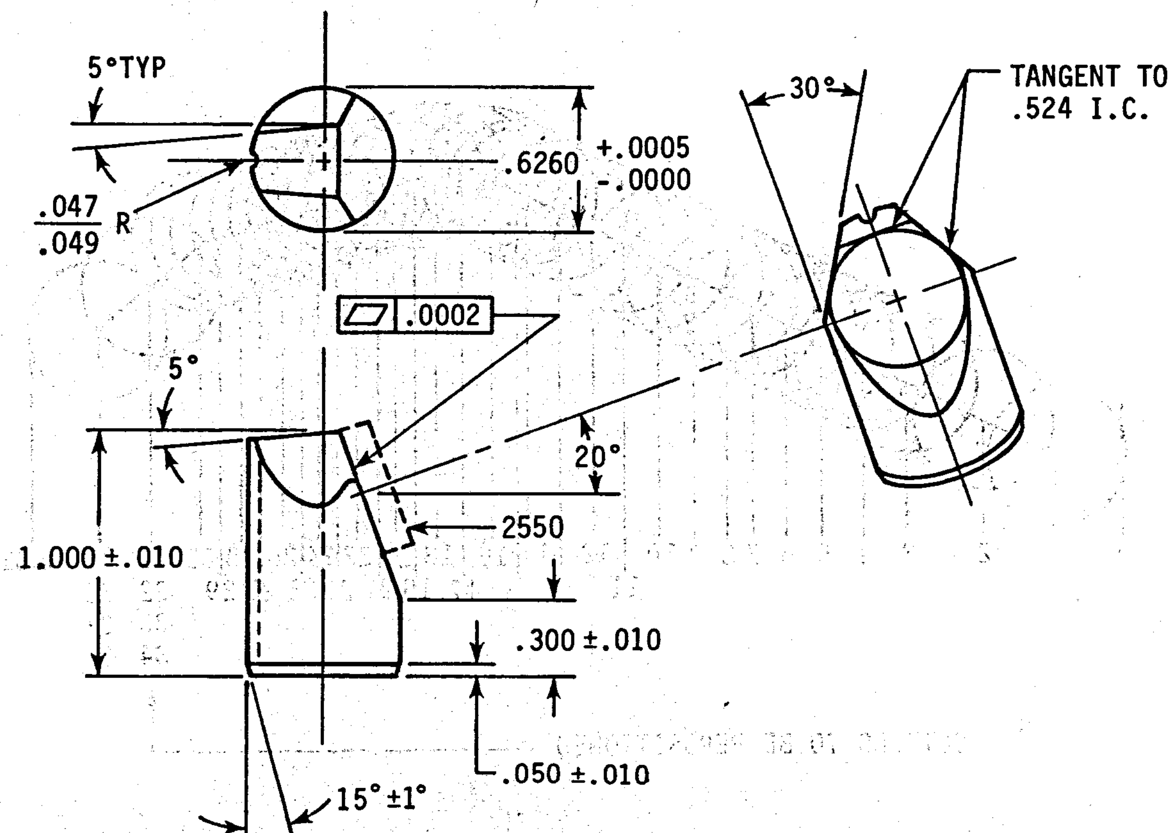


Figure 3. Cutter Stud Specification; -20° Back Rake, 5° End Clearance

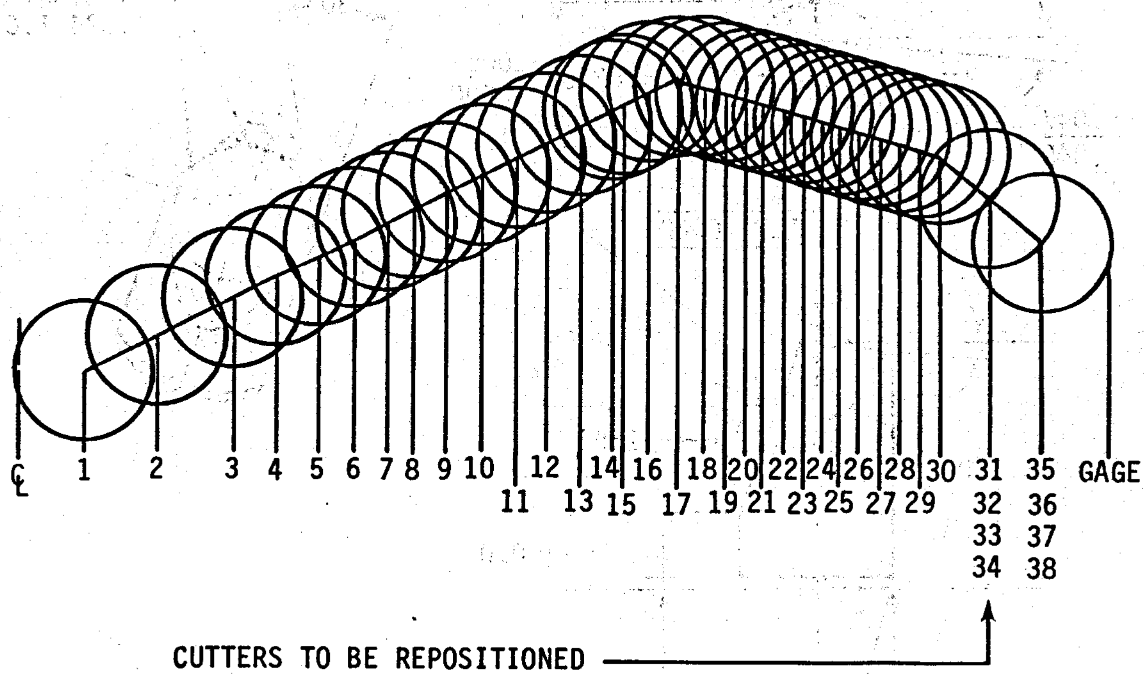


Figure 4. Cross Section of Half of Bit S-1 Showing Original Profile of Cutter Envelope. Four cutters, 31 through 34, will be repositioned in the S-2 design to obtain improved coverage and eliminate "tracking."

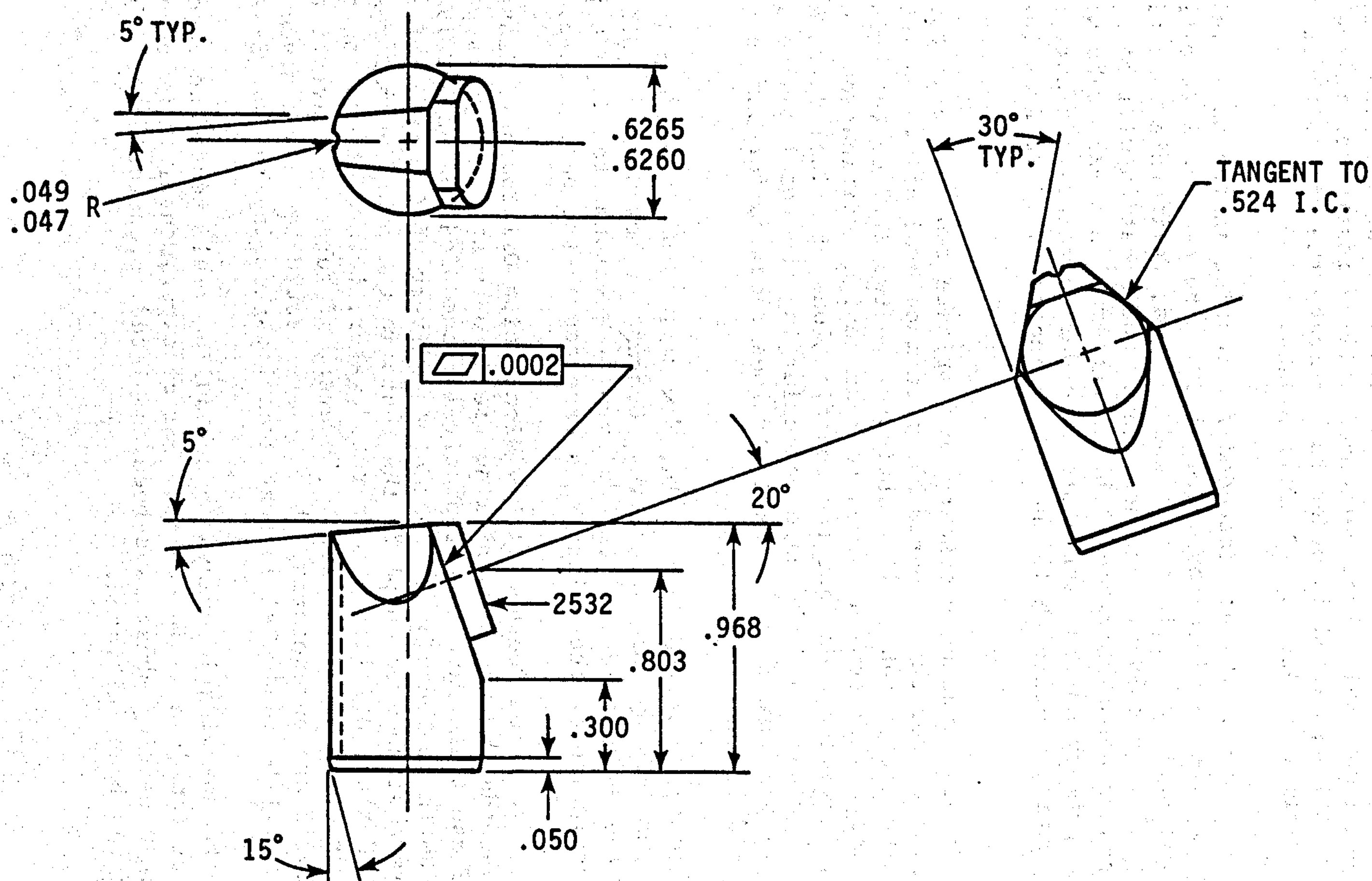


Figure 5. No. 2532 Stratapax™ Blank Trimmer and Stud

An adequate supply of the -25°-back-rake studs has been assured. One hundred studs purchased from Security Division, Dresser Industries, have been received, and an additional 20 will be supplied by Sandia.

The Drilling Technology Division, Sandia National Laboratories, has perfected the tooling and technique for press-fitting the -25°-back-rake carbide studs into steel-bit bodies. This operation is somewhat more difficult than pressing the conventional -20°-back-rake, 5°-end-clearance stud. If necessary, Smith Tool personnel will be instructed in the Sandia interference fitting method in order to fabricate the bits without damaging the studs and attached Stratapax™ drill blanks.

The two No. S-2A bits are intended for testing in the Baca field, New Mexico, and will be completed by 1 July 1980. The two No. S-2B bits are designated for field tests in air at The Geysers, California, and will be delivered by 15 August 1980. One additional modification will be made to both bit types; one more Stratapax™ blank cutter with a -25° rake will be added to the primary cutting structure in order to maintain a uniform bottomhole cutting profile while the bit is increased to 22.2 cm (8.75 in.) diameter.

The additional funding necessary to fabricate two more bits than were originally planned for this program has been made available. Christensen, Inc., Salt Lake City, Utah , will fabricate the two 22.2-cm (8.75-in.) Stratapax™ bits. Christensen agreed to make design modifications to their basic JD-26, 10-wing-bit design; the modifications will include extending the Stratapax™ blanks down the gage and enlarging the total nozzle area to reduce the bit pressure drop to the low values required for air and aerated-water drilling.

The field tests in the Baca field, New Mexico, have been tentatively rescheduled for July by Union Geothermal Company of New Mexico. Drilling activity in the Baca field has been delayed by environmental impact problems, but resolution of these issues is expected in the near future.

According to Union Geothermal Division, Union Oil Company, Santa Rosa, California, scheduling the air-drilling field tests at The Geysers poses no problems. These tests have been tentatively scheduled for August 1980 because (1) Smith Tool could not guarantee delivery of the bits before then and (2) it is desirable to complete the tests in the hydrothermal resource field in New Mexico, drilling with aerated water, before attempting the field tests drilling with air alone. However, if further delays of the Baca field tests are encountered, The Geysers test date may be moved up, and drilling will be conducted in that area first, using the No. S-2A bits.

Due to the unavoidable delays in scheduling field tests, an extension of the project schedule is in process. Since experimental tasks other than the final field testing phase have been completed, preparation of a draft final report has been initiated.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

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PROJECT	O	N	D	J	F	M	A	M	★ J	J	A	S	END DATE
PDC WEAR MECHANISMS TEST SUPPORT GENERAL ELECTRIC													
EFFECTS OF DRILLING FLUIDS		● —	—	—	—	—	—	—	—	—	—	—	
ROCK FRACTURE/CUTTER WEAR CONSULTATION		● —	—	—	—	—	—	—	—	—	—	—	
FINAL REPORT													JAN 81

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

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

Contractor: General Electric Company, CRD
Principal Investigator: L. E. Hibbs, Jr. (518) 385-8330
Contract Period: 16 November 1979 to 6 December 1980
Contract Number: 13-9406 (Sandia)
Technical Consultant: D. Wesenberg (505) 844-0129

Project Objective

The objective of this project is to provide technical assistance during Sandia's evaluation of the performance of PDCs in drill bits 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

Coordination of the project activities with related work and participating organizations has been completed. Preparation of the test facilities and equipment was nearing completion, and initiation of single-cutter experiments was anticipated near the end of this reporting period. Procurement of three rock types for use in the PDC cutter tests has been completed.

Quarterly Progress

Air Drilling Experiments -- Full-scale drilling tests using preheated air as the drilling fluid to simulate The Geysers, California, conditions were conducted in February 1980 at the Drilling Research Laboratory (DRL), Terra Tek, Inc., Salt Lake City, Utah. A brief summary of these tests was included in the last quarterly report. During this reporting period, the test data were analyzed, wear characteristics studied, and recommendations developed for improving Stratapax™ geothermal bit design. Detailed test information and results of the analysis follow.

Two 21.6-cm (8.5-in.) diameter Stratapax™ bits were tested. The first was a hard-matrix bit provided by the Diamond Technology Center, Christensen, Inc., Salt Lake City, Utah. The bit was a five-wing Christensen, type JD 23-P, that is designed for use with a downhole motor to drill relatively soft, plastic formations such as shale. The back rake for the diamond compact cutters was -7°. Natural diamond stones, 2 stones/carat, were mounted on the gage. The bit face had nine fluid ports with a total nozzle area of 6.5×10^{-4} m^2 (1 $in.^2$).

The second bit tested was the S-1, modified, steel-body, stud-type, Stratapax™ bit fabricated by Smith Tool, Irvine, California, and successfully tested in October 1979 in the Baca field, New Mexico. This bit was rebuilt at SNL. Seven worn Stratapax™ cutters were removed and replaced with new Stratapax™/stud assemblies, which included two -25°-back-rake steel studs with diffusion-bonded cutters. The assemblies included three -25°-back-rake tungsten carbide studs with LS* (brazed) bonded cutters and two of the older style -20°-back-rake tungsten carbide studs with LS* (brazed) bonded cutters. This latter stud design and cutter attachment was the one used initially for this bit; hence, the cutting structure of the rebuilt bit consisted of 33 -20°-back-rake brazed cutters, 3 -25°-back-rake brazed cutters, and 2 -25°-back-rake diffusion-bonded cutters. Figure 6 shows the cutting structure of the bit with the locations of the cutters installed by Sandia. Figures 2 and 3 in Section 4.3 illustrate the stud designs used.

The air for the drilling experiments was obtained from a compressor provided by the Western Air Drilling Service Co., Grand Junction, Colorado. An air flow of 0.94 m^3/s (2000 ft^3/min) was desired to fully simulate The Geysers drilling conditions. However, the pressure in the system had to be kept at 1.7 MPa (250 psi) or less in order to avoid damaging the gas heat exchanger and the drilling swivel. Therefore, the air flow was a maximum of 0.46 m^3/s (983 ft^3/min), with most tests being run at 0.43 m^3/s (916 $ft^3/min.$). A maximum input air temperature of 263°C (505°F) was obtained, which is well above The Geysers' bottomhole temperature.

Three rock types were used: Carthage marble, Nugget sandstone, and Sierra white granite. The principal rock of interest was the sandstone, because of its abrasiveness and its moderately high strength and ultimate compressive strength of approximately 124 MPa (18 000 psi). The granite was used to test the stud-type bit to destruction after the sandstone experiments had been completed.

• Christensen JD 23-P Bit Tests

The JD 23-P bit was tested in marble first and, subsequently, in Nugget sandstone. Three levels of speed and weight on bit were used. The results of these experiments are summarized in Table 3. The penetration rate-weight on bit relationships are shown in Figure 7. The bit performed well in both rocks and, in the sandstone, attained a maximum drilling rate of 26.1 m/h (85.7 ft/h) at 50 rpm and a weight on bit of 44.5 kN (10 000 lb). However, severe damage was done to the five gage Stratapax™ cutters after the drilling of a single hole approximately 0.9 metre (3 feet) deep in the sandstone. These cutters were badly spalled in the diamond layer and markedly worn. No other diamond compact cutters in this bit exhibited any damage. The spalling damage was apparently due to insufficient negative rake, which failed to keep the brittle diamond layer in compression.

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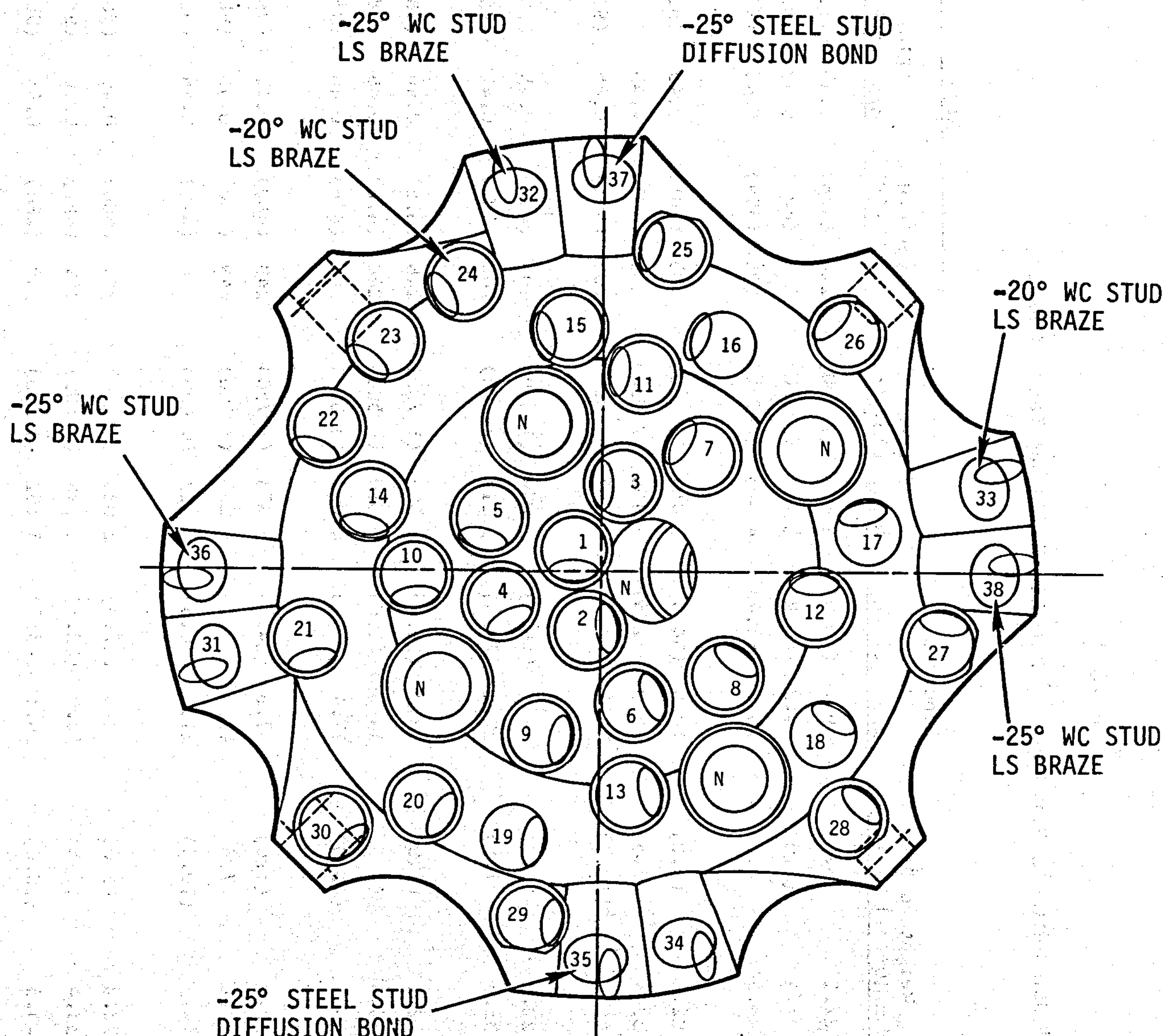
*LS bonding is a brazing process that incorporates cooling of the Stratapax™ compacts as the compacts are induction-brazed to the tungsten carbide studs.



WC = TUNGSTEN CARBIDE

LS BRAZE = SEE FOOTNOTE PAGE 48

Figure 6. S-1, Modified, Stratapax™ Bit Showing Cutter and Nozzle Locations and Identifying the Cutters and Studs Replaced prior to Hot Air Drilling Tests

Table 3

JD 23-P Hard-Matrix Stratapax™ Bit Air Drilling Test Results

Test No.	Rock Type	Hole No.	Speed rpm	Weight on Bit N x 10³	Weight on Bit (lb x 10³)	Penetration Rate m/h	Penetration Rate (ft/h)	Torque N·m	Torque (lbf·ft)	Air Temperature °C	Air Temperature (°F)	Air Flow m/s	Air Flow (ft³/min)
1	Carthage marble	1	25	22.2	(5.0)	9.1	(30.0)	2 034	(1 500)	220	(428)	0.45	(950)
			25	33.4	(7.5)	12.3	(40.2)	3 051	(2 250)	207	(405)	0.45	(950)
			25	44.5	(10.0)	13.8	(45.4)	4 406	(3 250)	204	(399)	0.45	(950)
1	Carthage marble	1	38	22.2	(5.0)	10.5	(34.5)	2 102	(1 550)	205	(401)	0.45	(950)
			38	33.4	(7.5)	16.0	(52.5)	3 186	(2 350)	205	(401)	0.45	(950)
			38	44.5	(10.0)	20.1	(66.0)	4 067	(3 000)	205	(401)	0.45	(950)
1	Carthage marble	1	49	22.2	(5.0)	14.1	(46.3)	2 034	(1 500)	206	(403)	0.45	(950)
			49	33.4	(7.5)	22.2	(72.8)	3 118	(2 300)	206	(403)	0.45	(950)
2	Nugget sandstone	1	25	22.2	(5.0)	8.8	(29.0)	2 305	(1 700)	248	(478)	0.46	(983)
			25	33.4	(7.5)	14.6	(48.0)	3 390	(2 500)	248	(478)	0.46	(983)
			25	44.5	(10.0)	17.4	(57.1)	4 067	(3 000)	248	(478)	0.46	(983)
2	Nugget sandstone	1	38	22.2	(5.0)	7.6	(24.8)	2 373	(1 750)	249	(480)	0.46	(983)
			38	33.4	(7.5)	15.9	(52.2)	4 203	(3 100)	249	(480)	0.46	(983)
			38	44.5	(10.0)	21.5	(70.6)	5 423	(4 000)	248	(478)	0.46	(983)
2	Nugget sandstone	1	50	22.2	(5.0)	8.3	(27.3)	2 034	(1 500)	249	(480)	0.46	(983)
			50	33.4	(7.5)	18.9	(62.1)	3 796	(2 800)	249	(480)	0.46	(983)
			50	44.5	(10.0)	26.1	(85.7)	5 152	(3 800)	249	(480)	0.46	(983)

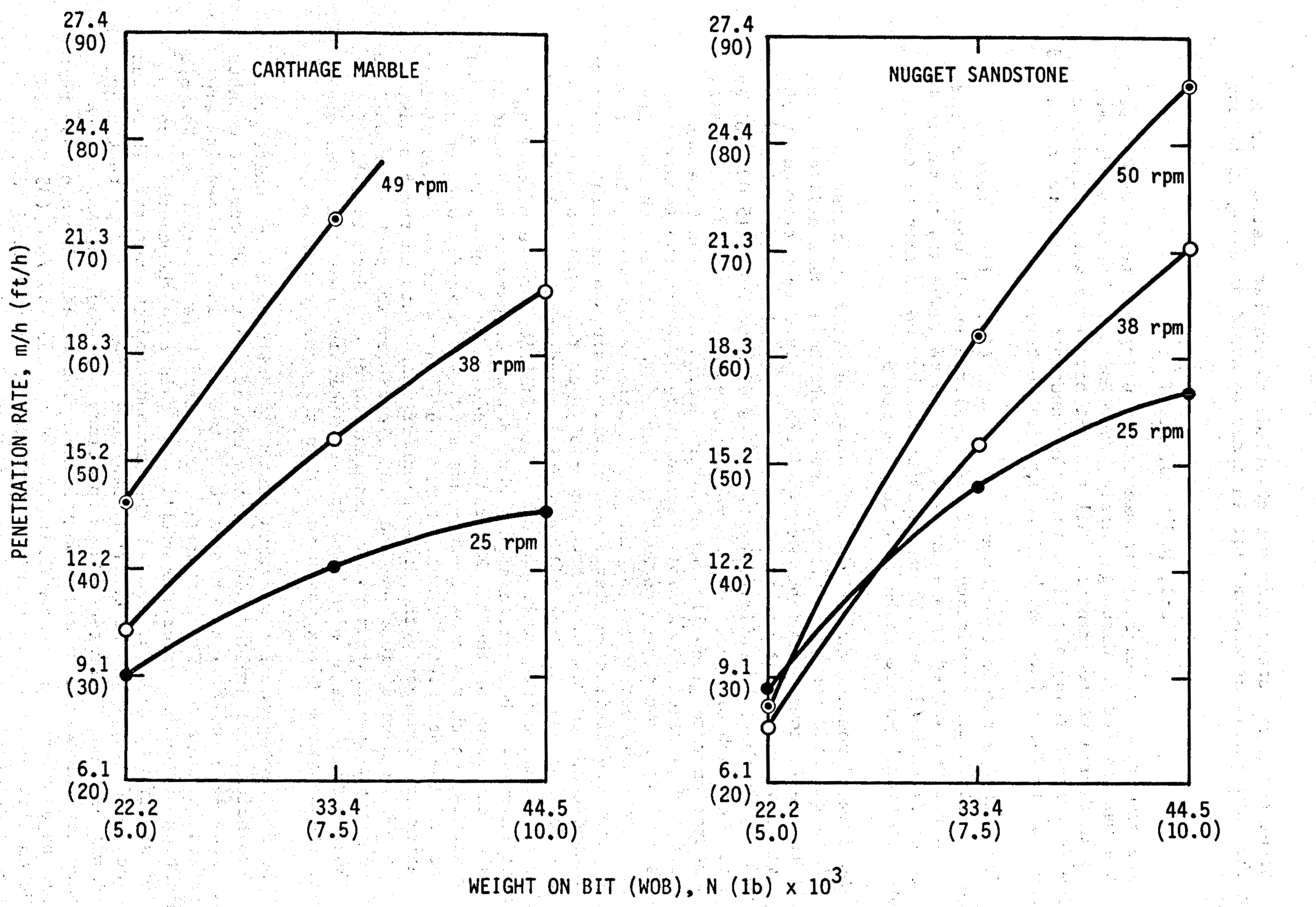


Figure 7. Penetration Rate versus Weight on Bit Test Results for Christensen JD 23-P Bit Drilling Carthage Marble and Nugget Sandstone

After the gage cutter wear was observed, no further testing was done with the hard-matrix Stratapax™ bit in order to avoid damaging it beyond repair.

• S-1, Modified, Bit Tests

The stud-type, steel-body bit was tested using all three rock types. One hole was drilled in Carthage marble, four holes in Nugget sandstone, and two in Sierra white granite. All the S-1 bit tests were run with a 0.43-m^3/s (916-ft^3/min) air flow, with the input air temperature maintained in the 240° to 263°C (464° to 505°F) range in most cases.

The Carthage marble results and the results of the first test in Nugget sandstone are summarized in Table 4. Three speeds were used, and weight on bit was varied from a minimum of 17.8 kN (4000 lb) in marble to a maximum of 77.8 kN (17 500 lb) in sandstone. The penetration rate-weight on bit relationships are shown in Figures 8 and 9.

No diamond compact cutter wear was observed after the first hole was drilled in the sandstone. Therefore, three more holes were drilled in an effort to create some measurable wear. These tests were performed at 50 rpm, with constant weight on bit. One hole was drilled with 44.5 kN (10 000 lb) on the bit, followed by two holes with 66.7 kN (15 000 lb) on the bit. For each of these constant-speed, constant-weight-on-bit tests, the penetration rate gradually and steadily decreased as the hole depth increased. This result is illustrated in Table 5, where the penetration rate is given for the first and last 10.2 cm (4 in.) drilled in each instance. After the completion of the fourth hole in sandstone, the bit was removed from the drill stand for examination. Again, no measurable wear of the diamond compacts was apparent. The -25°-back-rake cutters on the gage (cutters Nos. 35, 36, 37, and 38) were still sharp and in essentially new condition. Thus, cutter dulling was not responsible for the decreasing penetration rates. However, a significant degree of carbide-stud wear for cutters on the crown of the bit had taken place. For example, the stud for cutter No. 24, which was a new, -20°-rake stud, was markedly worn on one side, behind the Stratapax™ blank. Other studs on the crown showed similar wear patterns. Apparently the development of wear flats on these studs, which do not have sufficient end and side clearance, was partly responsible for reducing the penetration rate. Examination of the data in Table 5, tests Nos. 6 and 7, might also lead to the conclusion that the lower section of the sandstone block was harder than the upper portion.

The S-1, modified, bit was then tested by drilling Sierra white granite. Two holes were drilled, each at two speeds (25 and 50 rpm) at weights on bit from 44.5 to 155.7 kN (10 000 to 35 000 lb). The test results are summarized in Table 6. The bit drilled the first hole slowly (Test No. 8). Examination of the bit after the drilling of this hole showed the development of significant wear of some of the diamond compact cutters. There was some localized bluing of the bit body near the gage, indicating that high frictional heat was generated. The conditions used for Test No. 8 were repeated for the second hole in the granite. The data in Table 6 show that the bit began to fail catastrophically at 50 rpm and 155.7 kN (35 000 lb) weight on bit. Examination of the bit after Test No. 9 showed that 12 Stratapax™ drill blanks had become detached. Eleven of these cutters were

Table 4

S-1, Modified, Stratapax™ Bit Air Drilling Test Results for Variable Speeds and Weights on Bit

Test No.	Rock Type	Hole No.	Speed rpm	Weight on Bit N x 10^3	Weight on Bit (lb x 10^3)	Penetration Rate m/h	Penetration Rate (ft/h)	Torque N•m	Torque (lbf•ft)	Air Temperature °C	Air Temperature (°F)	Air Flow m^3/s	Air Flow (ft^3/min)
3	Carthage marble	2	25	17.8	(4.0)	2.7	(8.7)	1 152	(850)	249	(480)	0.43	(916)
			25	26.7	(6.0)	4.1	(13.4)	1 491	(1 100)	249	(480)	0.43	(916)
			25	35.6	(8.0)	5.0	(16.5)	1 898	(1 400)	249	(480)	0.43	(916)
			25	44.5	(10.0)	6.0	(19.7)	2 441	(1 800)	249	(480)	0.43	(916)
			25	53.4	(12.0)	7.2	(23.7)	2 847	(2 100)	249	(480)	0.43	(916)
3	Carthage marble	2	38	17.8	(4.0)	2.7	(8.8)	881	(650)	252	(486)	0.43	(916)
			38	26.7	(6.0)	3.5	(11.5)	1 152	(850)	252	(486)	0.43	(916)
			38	35.6	(8.0)	5.1	(16.7)	1 559	(1 150)	252	(486)	0.43	(916)
			38	44.5	(10.0)	6.9	(22.5)	2 034	(1 500)	252	(486)	0.43	(916)
			38	53.4	(12.0)	8.8	(28.8)	2 576	(1 900)	252	(486)	0.43	(916)
3	Carthage marble	2	50	17.8	(4.0)	3.9	(12.8)	814	(600)	257	(495)	0.43	(916)
			50	26.7	(6.0)	4.7	(15.3)	1 085	(800)	257	(495)	0.43	(916)
			50	35.6	(8.0)	6.3	(20.6)	1 491	(1 100)	257	(495)	0.43	(916)
			50	4.5	(10.0)	8.5	(27.9)	1 898	(1 400)	257	(495)	0.43	(916)
			50	53.4	(12.0)	12.5	(41.1)	2 576	(1 900)	257	(495)	0.43	(916)
			50	62.3	(14.0)	13.7	(45.0)	2 983	(2 200)	257	(495)	0.43	(916)
4	Nugget sandstone	2	25	26.7	(6.0)	1.6	(5.3)	1 288	(950)	258	(496)	0.43	(916)
			25	44.5	(10.0)	5.8	(18.9)	2 712	(2 000)	258	(496)	0.43	(916)
			25	55.6	(12.5)	8.6	(28.1)	3 457	(2 550)	258	(496)	0.43	(916)
			25	66.7	(15.0)	10.7	(35.0)	4 203	(3 100)	258	(496)	0.43	(916)
4	Nugget sandstone	2	38	26.7	(6.0)	4.1	(13.6)	1 356	(1 000)	260	(500)	0.43	(916)
			38	44.5	(10.0)	7.9	(25.9)	2 305	(1 700)	260	(500)	0.43	(916)
			38	55.6	(12.5)	11.9	(39.1)	3 118	(2 300)	260	(500)	0.43	(916)
			38	66.7	(15.0)	16.1	(52.9)	3 864	(2 850)	260	(500)	0.43	(916)
4	Nugget sandstone	2	50	26.7	(6.0)	4.4	(14.4)	1 356	(1 000)	260	(500)	0.43	(916)
			50	44.5	(10.0)	8.2	(26.9)	2 102	(1 550)	260	(500)	0.43	(916)
			50	55.6	(12.5)	15.0	(49.3)	2 983	(2 200)	260	(500)	0.43	(916)
			50	66.7	(15.0)	18.6	(61.0)	3 661	(2 700)	260	(500)	0.43	(916)
			50	77.8	(17.5)	22.9	(75.0)	4 474	(3 300)	260	(500)	0.43	(916)

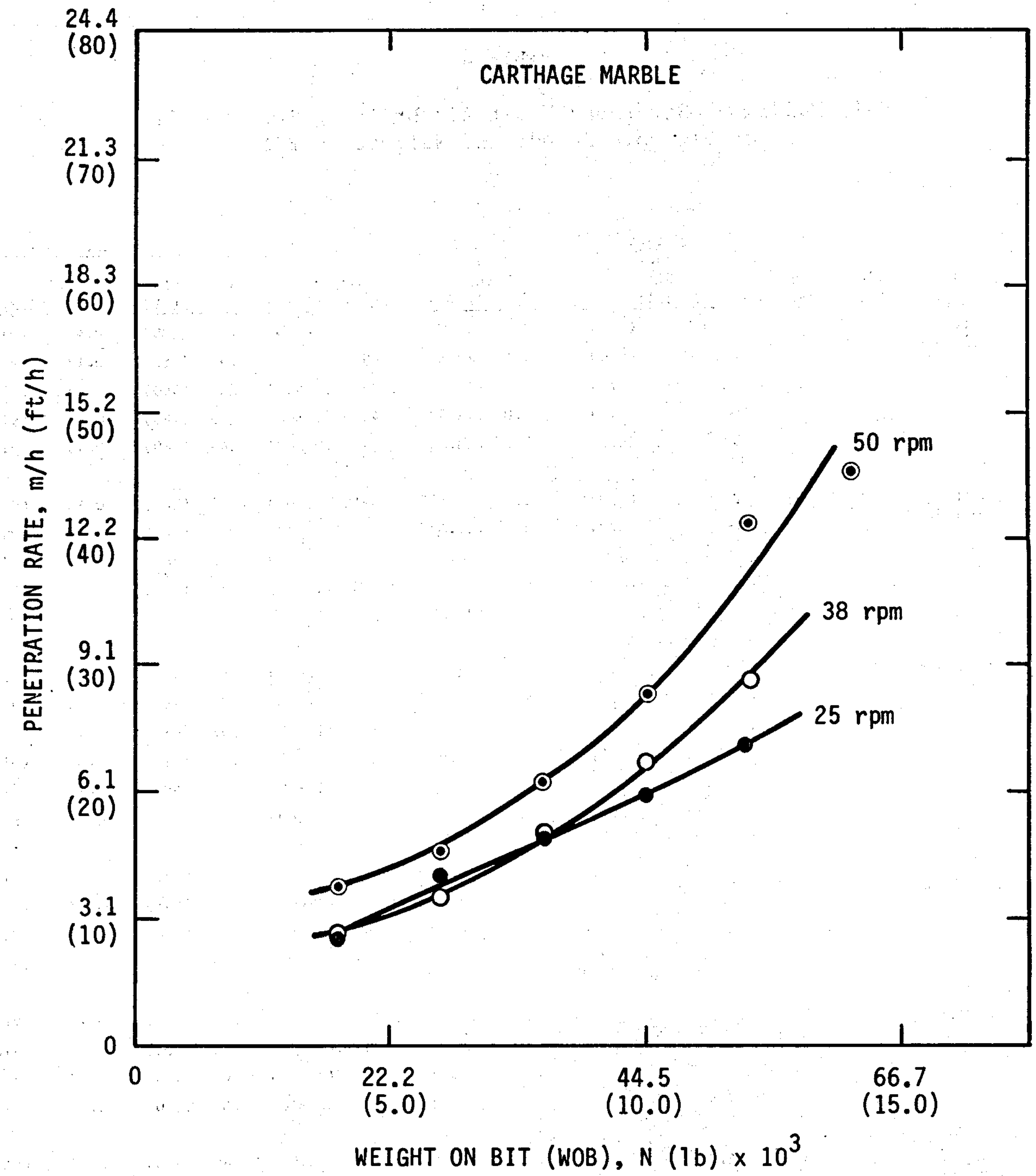


Figure 8. Penetration Rate versus Weight on Bit Test Results for S-1, Modified, Bit Drilling Carthage Marble

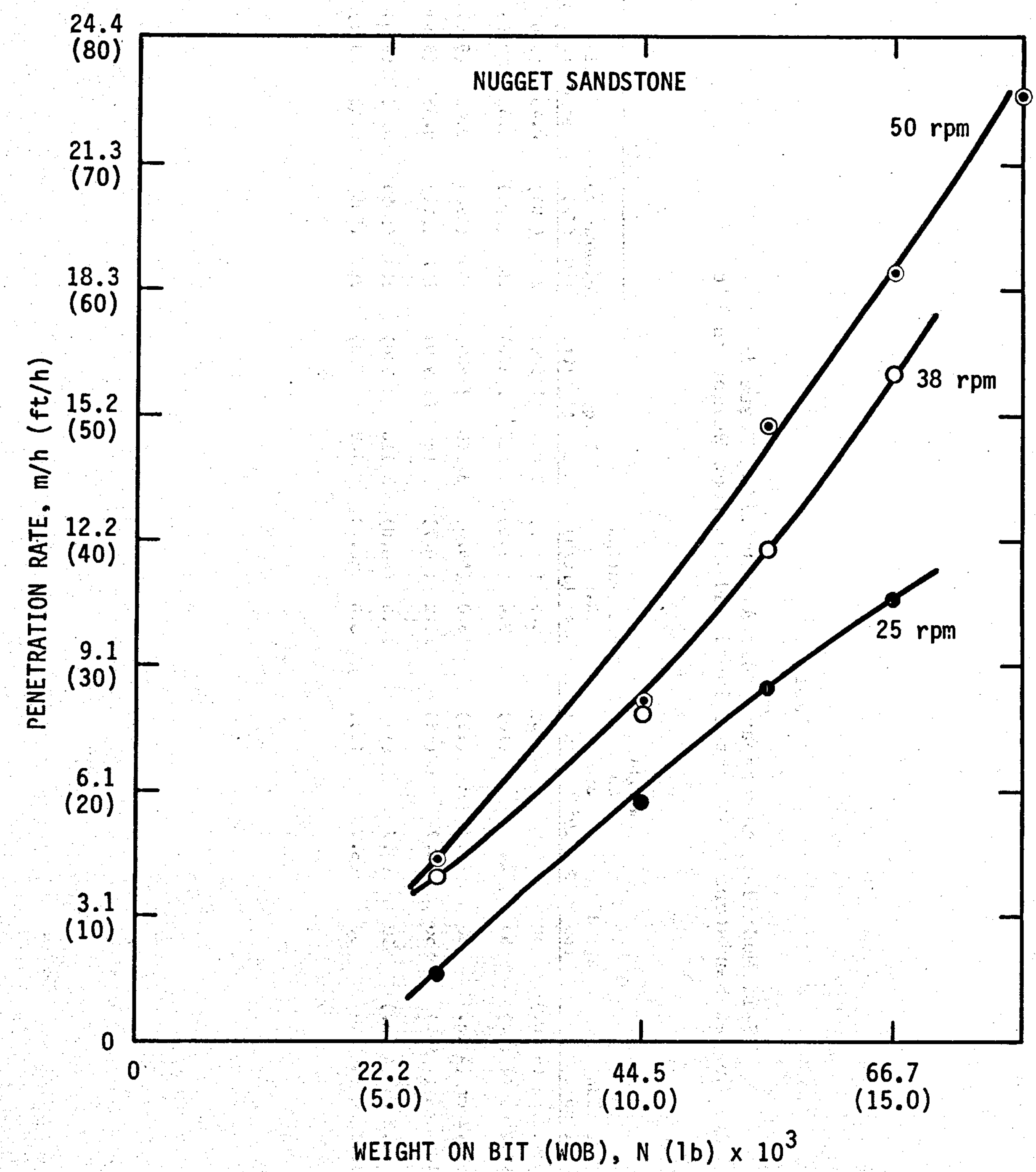


Figure 9. Penetration Rate versus Weight on Bit Test Results for S-1, Modified, Bit Drilling Nugget Sandstone

Table 5

S-1, Modified, Stratapax™ Bit Air Drilling Tests in Nugget Sandstone at Constant Speed and Constant Weight on Bit

Test No.	Hole No.	Section of Hole	Speed rpm	Weight on Bit N x 10^3	Weight on Bit (lb x 10^3)	Penetration Rate m/h	Penetration Rate (ft/h)	Torque N•m	Torque (lbf•ft)	Air Temperature °C	Air Temperature (°F)	Air Flow m^3/s	Air Flow (ft^3/min)
5	3	First 10.2 cm (4 in.)	50	44.5	(10)	8.6	(28.1)	2 034	(1 500)	262	(504)	0.43	(916)
5	3	Last 10.2 cm (4 in.)	50	44.5	(10)	5.4	(17.8)	1 627	(1 200)	262	(504)	0.43	(916)
6	4	First 10.2 cm (4 in.)	50	66.7	(15)	18.0	(59.0)	3 390	(2 500)	259	(498)	0.43	(916)
6	4	Last 10.2 cm (4 in.)	50	66.7	(15)	11.2	(36.7)	2 644	(1 950)	261	(502)	0.43	(916)
7	5	First 10.2 cm (4 in.)	50	66.7	(15)	14.6	(48.0)	3 118	(2 300)	263	(505)	0.43	(916)
7	5	Last 10.2 cm (4 in.)	50	66.7	(15)	8.8	(28.8)	2 169	(1 600)	263	(505)	0.43	(916)

Table 6

S-1, Modified, Stratapax™ Bit Air Drilling Tests
in Sierra White Granite

Test No.	Rock Type	Hole No.	Speed rpm	Weight on Bit N x 10^3	Weight on Bit (lb x 10^3)	Penetration Rate m/h	Penetration Rate (ft/h)	Torque N•m	Torque (lbf•ft)	Air Temperature °C	Air Temperature (°F)	Air Flow m^3/s	Air Flow (ft^3/min)
8	Sierra white granite	1	25	44.5	(10)	1.3	(4.2)	1 763	(1 300)	251	(484)	0.43	(916)
			25	66.7	(15)	2.0	(6.4)	2 508	(1 850)	164**	(327)	0.43	(916)
			25	89.0	(15)	2.5	(8.3)	3 254 to 3 279	(2 400) to (2 750)*	220	(428)	0.43	(916)
			25	111.2	(25)	3.2	(10.6)	4 610	(3 400)	231	(448)	0.43	(916)
8	Sierra white granite	1	50	66.7	(15)	2.2	(7.3)	1 966	(1 450)	246	(475)	0.43	(916)
			50	89.0	(20)	2.9	(9.6)	2 644	(1 950)	250	(482)	0.43	(916)
			50	111.2	(25)	3.6	(11.8)	3 186	(2 350)	250	(482)	0.43	(916)
			50	133.5	(30)	4.5	(14.6)	3 729	(2 750)	253	(487)	0.43	(916)
9	Sierra white granite	2	25	44.5	(10)	0.4	(1.4)	1 763	(1 300)	237	(459)	0.43	(916)
			25	66.7	(15)	0.5	(1.7)	2 983	(2 200)	240	(464)	0.43	(916)
			25	89.0	(20)	1.2	(4.1)	3 864	(2 850)	243	(469)	0.43	(916)
			25	111.2	(25)	1.7	(5.6)	4 610	(3 400)	237	(459)	0.43	(916)
9	Sierra white granite	2	50	89.0	(20)	1.7	(5.5)	2 847	(2 100)	246	(475)	0.43	(916)
			50	111.2	(25)	2.0	(6.5)	3 932 to 4 203	(2 900) to (3 100)*	246	(475)	0.43	(916)
			50	133.5	(30)	2.1	(6.8)	4 406	(3 250)	240	(464)	0.43	(916)
			50	155.7	(35)	1.9	(6.3)	4 610 to 4 745	(3 400) to (3 500)*	240	(464)	0.43	(916)
			50	133.5	(30)	0.7	(2.2)	4 068 to 4 406	(3 000) to (3 250)*	240	(464)	0.43	(916)
			50	155.7	(35)	0.7	(2.3)	4 406	(3 250)	240	(464)	0.43	(916)

*Torque was erratic at these operating conditions.
**Flame-out in gas fired heat exchanger.

recovered intact from a parking lot adjacent to the test site, where the hot air exhaust had ejected them.

The condition of the four gage cutters, Nos. 35, 36, 37, and 38, indicated that the bit may not have been running true. Both Stratapax™ cutters that were diffusion-bonded to the -25°-rake steel studs were still attached. However, diamond compact No. 37 was approximately one-third worn away, while the corresponding cutter (No. 35), 180° removed from it, was no more worn than it was following the Nugget sandstone tests. In addition, this cutter was still "on-gage." The two -25°-gage cutters brazed to tungsten carbide studs (Nos. 36 and 38) were similarly worn. Cutter No. 36 was missing, and the stud was badly worn. The opposite cutter (No. 38) was still attached and showed a relatively small wear flat. Figure 10 shows the locations of the cutters that became detached. Note that 7 of the 12 lost cutters were located between Nos. 34 and 36 inclusive, only slightly more than a 90° sector of the bit circumference. This portion of the bit showed the maximum discoloration due to overheating.

Examination of the recovered Stratapax™ drill blanks and the studs without cutters showed residual braze material on both the compact substrates and the studs. Apparently the bonds failed primarily within the braze line. The 11 Stratapax™ drill blanks which were detached were inspected ultrasonically for thermal degradation of the sintered diamond layer. No bulk thermal damage was detected--a promising and necessary condition for the successful application of diamond compacts to air drilling systems.

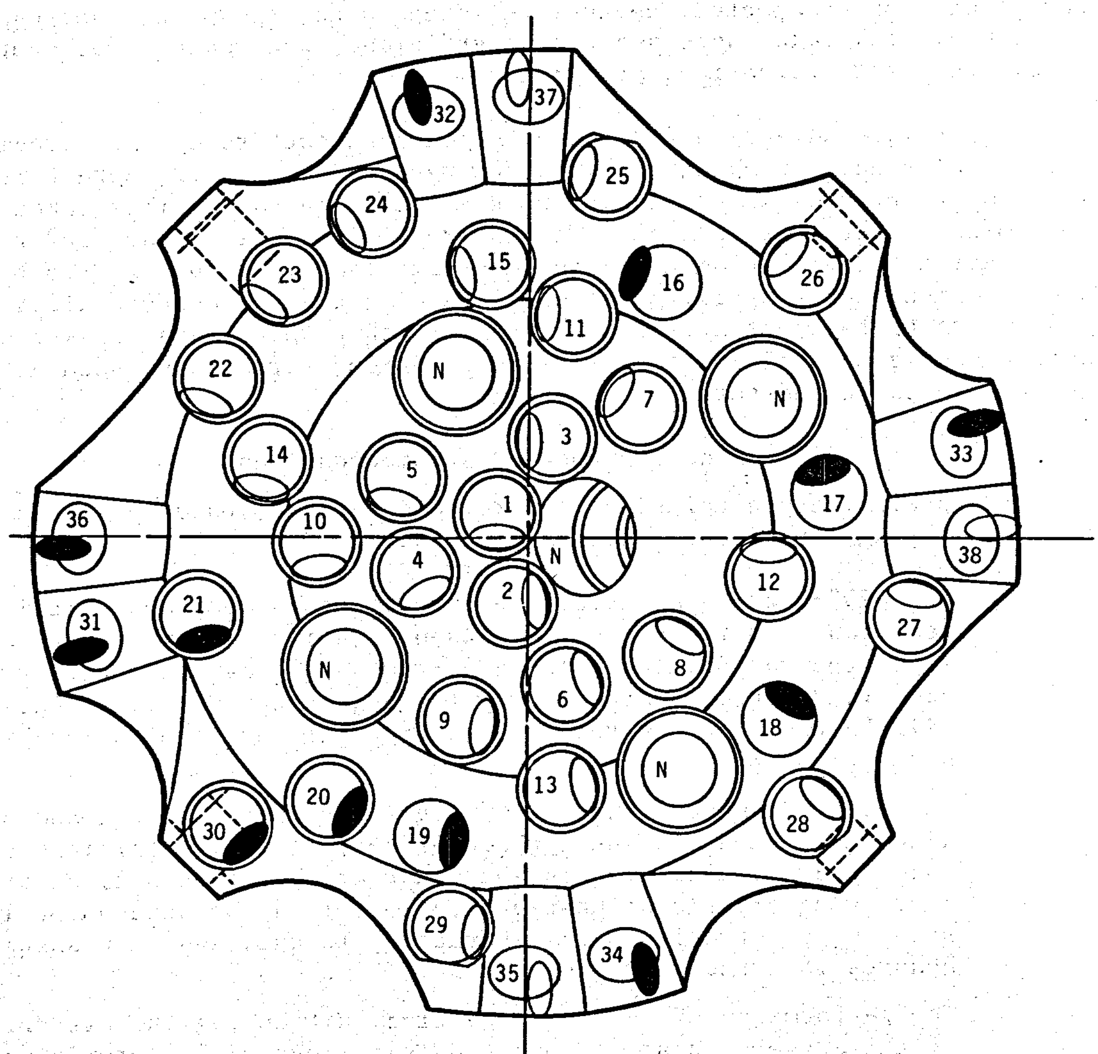
Most of the studs which lost their cutters had large wear flats on the ends. This condition was most pronounced for studs Nos. 17 through 21 on the crown of the bit and Nos. 30 through 34 nearer the gage. In contrast to similar cases of stud wear developed under drilling conditions using water or mud, there were no thermally generated heat check cracks in the studs. In addition, there were no cases of stud fracture and carbide spalling. Apparently the bulk temperature of the studs was high enough to prevent the difference between the surface and bulk temperature from becoming great enough to cause surface tensile failure.

Several of the diamond compacts were examined using scanning electron microscopy, and failure by shear in the braze alloy was confirmed. No evidence of failure by oxidation or fatigue was observed, and no visible evidence that failure occurred within the cemented tungsten carbide studs or drill blank substrates was detected.

The Stratapax™ drill blanks which became detached while drilling the Sierra white granite were ejected from the drilling system so rapidly that the fine structure of the braze attached to the cutters was not damaged by the accompanying rock particles. Further study of these specimens may provide additional useful information for improving the brazing attachment technology for diamond compacts.

• Torque Measurements

Although the principal objectives of the air drilling tests were to determine the wear characteristics and the potential failure mechanisms of



CUTTERS DETACHED

-20° WC STUDS LS BRAZE		-25° WC STUDS LS BRAZE
16	21	32
17	30	36
18	31	
19	33	
20	34	

Figure 10. Location of 12 Stratapax™ Cutters Detached from S-1, Modified, Bit during Test No. 9

Stratapax™ drag bits under very harsh conditions, the torques generated by the two bits provide some interesting comparisons.

The torque values for the JD 23-P hard-matrix bit drilling the relatively soft Carthage marble were significantly lower than those generated by the stud-type bit. This is shown by graph in Figures 11 and 12. This result was not unexpected, because Christensen has shown that decreasing the cutter back rake increases cutter efficiency and reduces rock-cutting forces when soft formations are drilled.

The torque advantage for the -7°-back-rake cutters on the hard-matrix bit was eliminated when the rock was changed to the harder, more brittle sandstone. Figures 13 and 14 are plots of all the data points taken for both bits at rotary speeds of 38 and 50 rpm. At these speeds, the torque-penetration rate relationship is essentially identical for the two bits. Since diamond layer spalling was obtained with the -7° cutters after only 0.91 metre (3 feet) of drilling, it appears that the greater back-rake cutter should be utilized for drilling sandstone formations, such as the graywackie in The Geysers.

• Conclusions and Recommendations

The preliminary conclusions and recommendations, based on these limited air drilling experiments, are as follows:

1. The -25°-back-rake cutters were superior in wear and chipping resistance to the -7° cutters when abrasive, relatively hard sandstone was drilled. The -25°-rake angle may be superior to the -20°-rake cutter, particularly for gage cutter application, and will be used for the third-generation geothermal bits in the bit development program.
2. The Sandia stud design, with the greatly increased end and side clearance, should be used wherever possible. Insufficient clearance leads to early rubbing and wear of the studs against rock, increasing frictional heat generation, reducing attachment life, reducing penetration rate, increasing torque, and increasing the chances for stud fracture.
3. The performance of the S-1, modified, bit during the air drilling of the Nugget sandstone, was promising; especially promising was the apparent high wear resistance of the diamond compacts under very hot conditions. The test results indicate that a stud-type Stratapax™ bit has a good chance of performing well in The Geysers, providing that the bit design includes the high-clearance-type studs to permit reasonable cutter wear without the development of large tungsten carbide wear surfaces.
4. The hot air drilling experiment in the granite took place in a severe test environment. There are currently no applications for deep-hole drilling with diamond compact bits using only air. The objective of the granite test was to wear the bit rapidly so that the effect of wear on bit performance and bit integrity could be evaluated in a reasonable rock, such as the sandstone. Drilling granite with hot air caused catastrophic failure and termination of the experiments. If this kind of testing is done again,

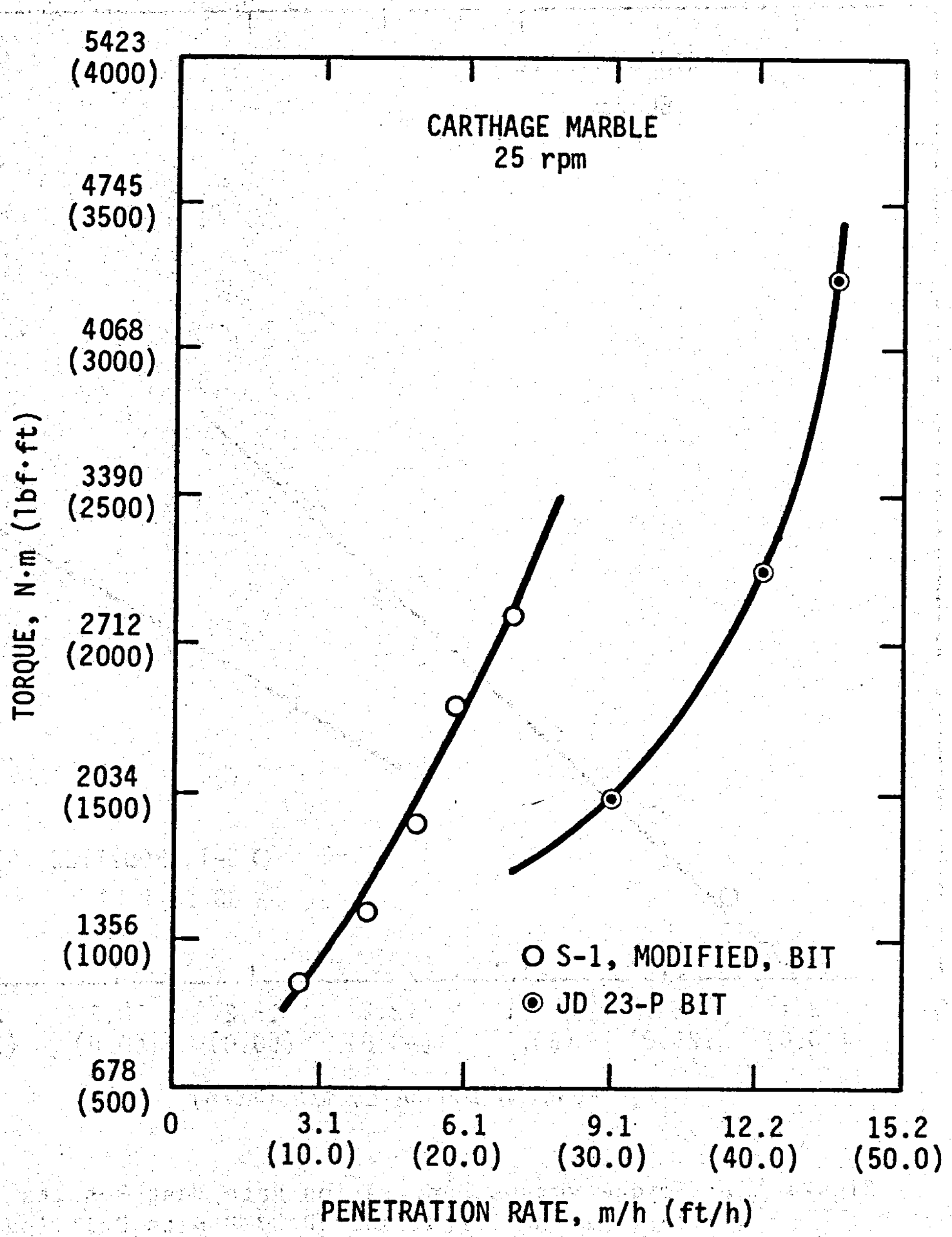


Figure 11. Torque versus Penetration Rate Test Results for S-1, Modified, and JD 23-P Bits Drilling Carthage Marble; 25 rpm

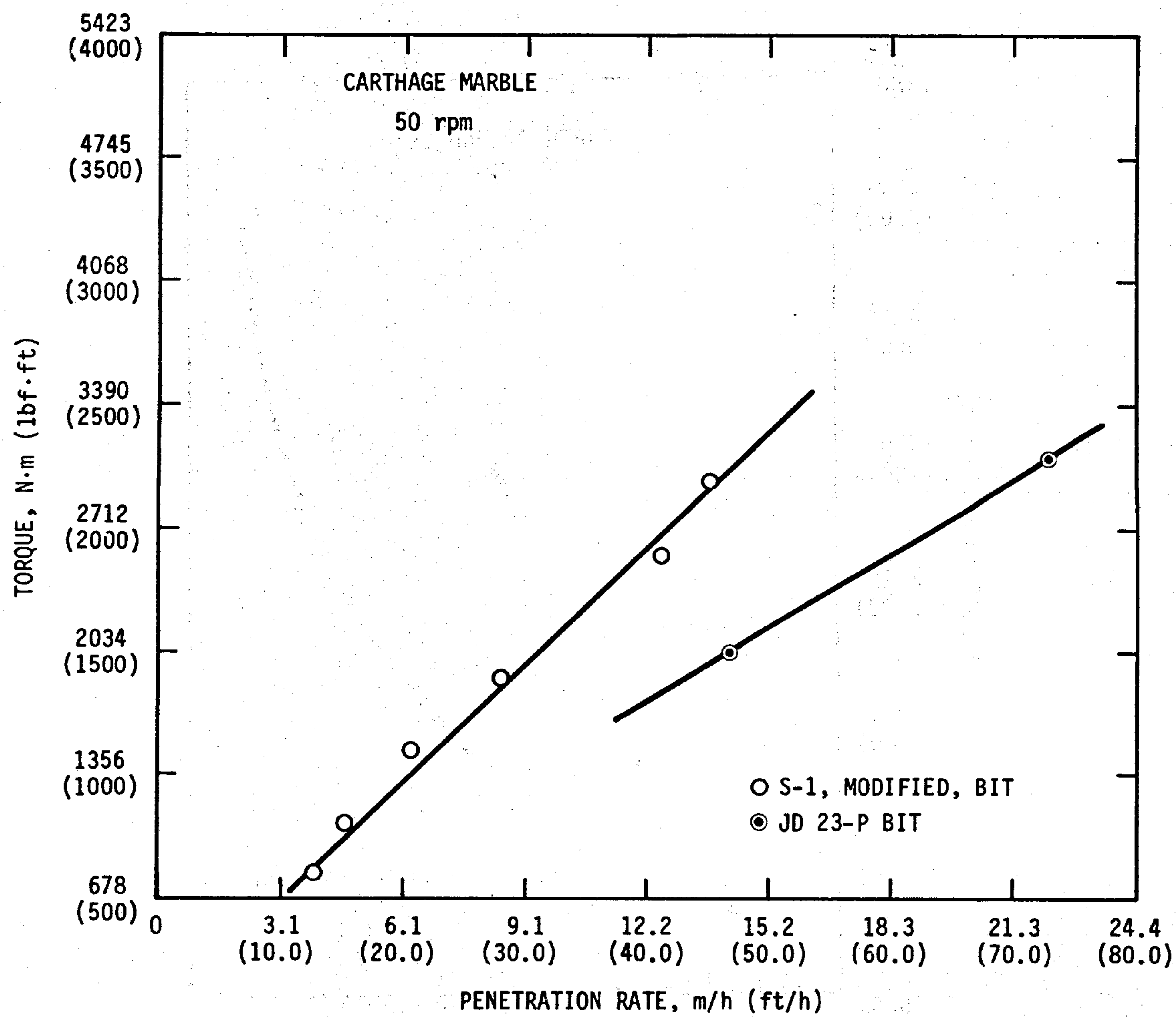


Figure 12. Torque versus Penetration Rate Test Results for S-1, Modified, and JD 23-P Bits Drilling Carthage Marble; 50 rpm

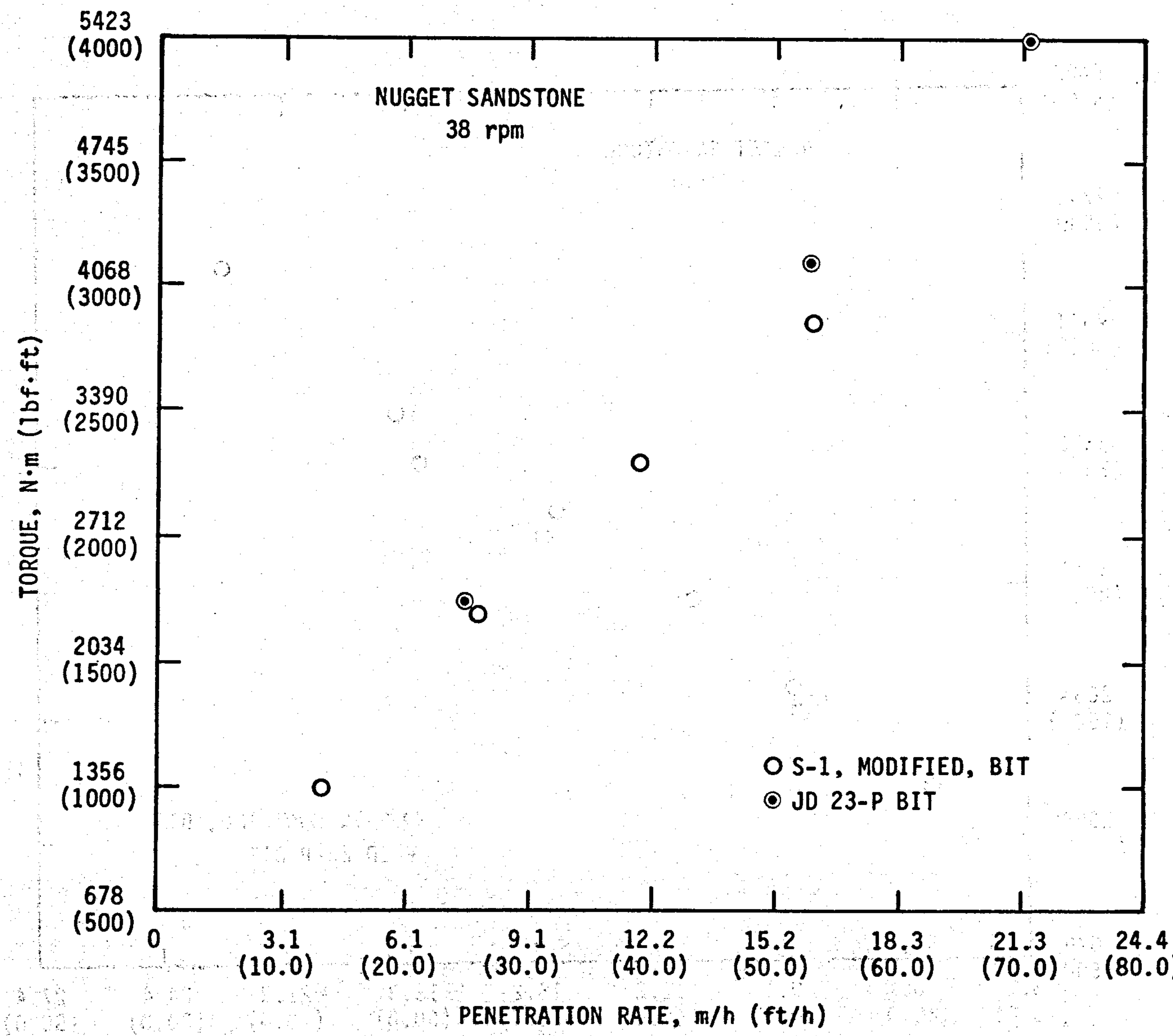


Figure 13. Torque versus Penetration Rate Test Results for S-1, Modified, and JD 23-P Bits Drilling Nugget Sandstone; 38 rpm

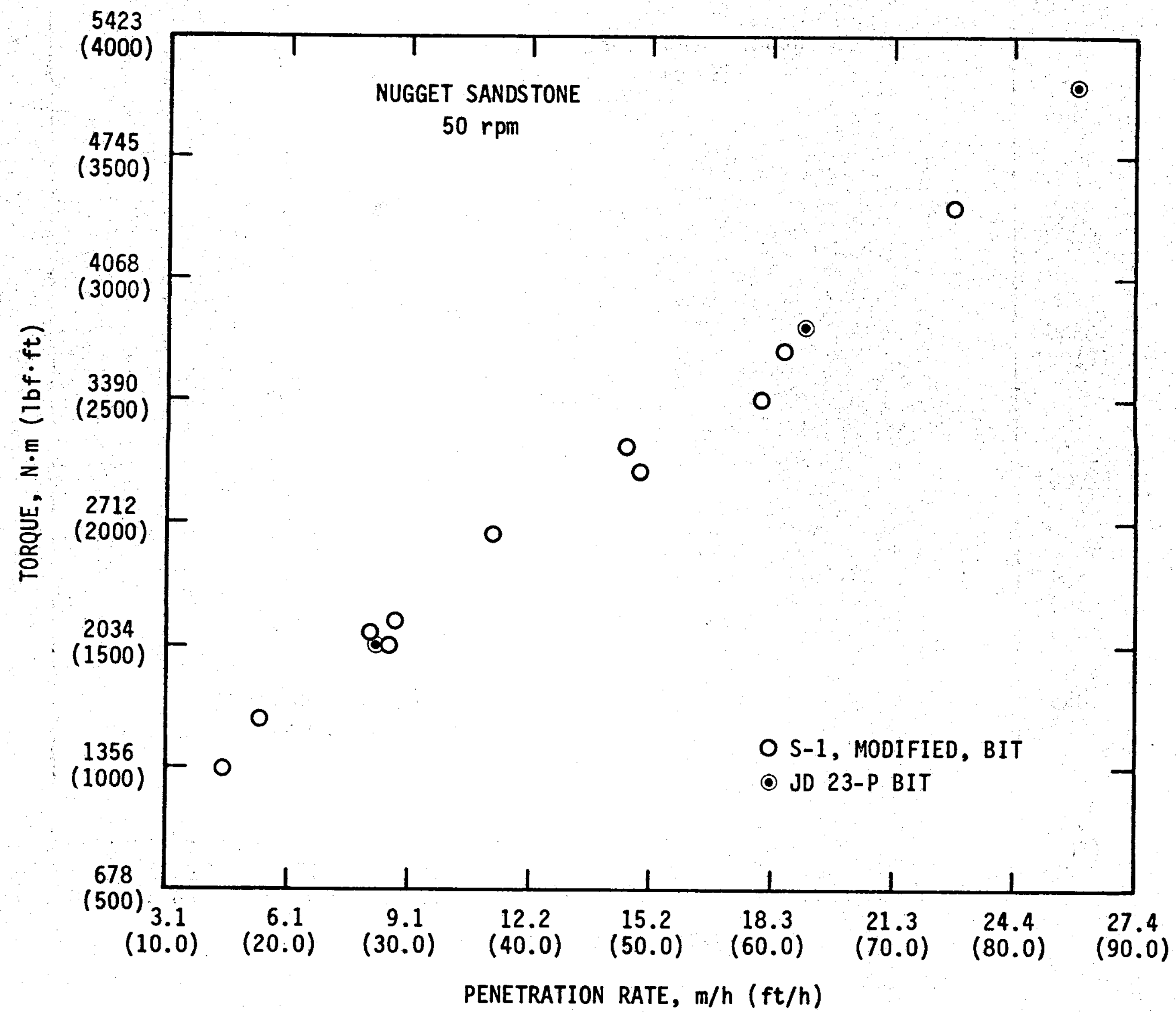


Figure 14. Torque versus Penetration Rate Test Results for S-1, Modified, and JD 23-P Bits Drilling Nugget Sandstone; 50 rpm

drilling in granite should be carried out using water, followed by hot air testing in sandstone.

5. The performance of the steel studs with the diffusion-bonded cutters was promising but not conclusive, because only two steel-stud-supported cutters were used. Testing should be continued using a bit constructed entirely with steel studs, with both diffusion- and braze-bonded cutters. Steel studs are attractive from the point of view of ease of manufacture, economy, and the ease of replacement in the bit body. However, application areas should be chosen with care. Erosive drilling conditions will destroy steel studs far faster than they will destroy cemented tungsten carbide studs.

6. The "LS"-type braze attachment failures apparently occurred within the bond line. The exact failure mechanism is not clear and should be identified, if possible. Appropriate research will be undertaken as part of this program.

Laboratory Rock Cutting Studies -- Installation of the equipment needed to perform the laboratory cutting tests is proceeding on schedule. The wiring of the 54-inch, vertical-turret lathe is completed, and the machine is operational. The designing of rock-cutting tooling for the lathe, including tooling necessary for force measurements as well as rock fixturing and rock handling, was completed, and fabrication of the tooling is underway. All worn lathe parts have been replaced. The lathe has been evaluated in dry-cutting Nugget sandstone and is operating satisfactorily. All the special tooling necessary to utilize Stratapax™ PDC cutters on this machine has been finished.

The mud circulation system to effect accurate control of the fluid flow rate and direction for mud circulation for the 54-inch, vertical-turret lathe was designed, fabricated, and installed. The 100-gallon-capacity tanks and the pumps are in place, and the special enclosure mounted on the machine to confine the fluid and return it to the tanks has been installed. The wiring for the pumps remains to be completed.

All the materials for suitable sepiolite- and bentonite-base mud compositions have been obtained. The materials for a polymer-base fluid based on hydroxyethyl cellulose will be ordered soon.

Controlling the flow rate and direction of the fluid in the mud circulation system is particularly important for the experiments aimed at determining diamond compact cutter heat generation. The design concepts for the mud circulation system were reviewed by Sandia before the system was fabricated in order to assure that these experiments will provide usable information for Sandia's diamond compact cutter temperature modeling studies.

The Stratapax™ drill blanks, including some smaller blanks for friction measurements, the accompanying studs, and all the necessary rock materials have been received. In order to reduce costs, as well as improve the efficiency of diamond compact utilization, the attachment of the cutters to the studs will be accomplished at the test facility. In this way, slightly worn cutters can be detached, rotated, and reattached, thus using all the available cutting edges and reducing the total number of drill blanks required.

With the 12-inch Pratt and Whitney lathe used to turn Jack Fork sandstone, preliminary rock-cutting experiments were carried out to establish the feasibility of utilizing small thermocouples inserted into the Stratapax™ cutter substrate and supporting stud to monitor tool temperature. Both dry and liquid-cooled tests were carried out successfully. Temperature data from four thermocouple locations were sampled continuously, using a Fluke 2240A data logger in conjunction with a Texas Instruments (T.I.) Silent 700 terminal equipped with magnetic tape. The data were recorded sequentially at a rate of five data points per second, stored on tape, and subsequently printed out using the T.I. terminal.

Because it will be necessary to obtain cutting-force measurements as well as temperature data, a special integrating circuit has been designed to accept the piezoelectric dynamometer charge amplifier output, which is comprised of three force-component channels, and to then modify the signals so that they can also be recorded by the data logger/tape/terminal system. A prototype circuit has been built and tested cutting rock. The performance was excellent, and the final three-channel device has been constructed in the CRD model shop.

The details of the Stratapax™ cutter-stud design to be used, together with the preliminary specifications for "worn" cutters, were forwarded to Sandia for review and suggestions, particularly with regard to the precise locations of the thermocouples.

The planned single-cutter experiments were nearing initiation at the close of this reporting period.

Hard-Matrix Stratapax™ Geothermal Bits -- Design consultation on the two, 22.2-cm (8.75-in.) diameter, hard-matrix, Stratapax™ geothermal bits being fabricated for field testing in aerated water and for air drilling applications was completed this quarter. The bits will be tested under the project described in Section 4.3, and the specific bit design changes are reported in that section.

5. DRILLING FLUIDS

Improved drilling fluids are required 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 are not currently well understood; thus, basic investigations are required 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 the 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. Demonstration of a technique of N_2 generation from diesel engine exhaust using a catalyst and field testing a high-temperature drilling mud, HTM-1, were successfully completed this quarter. The status and progress of these activities are described within this section.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

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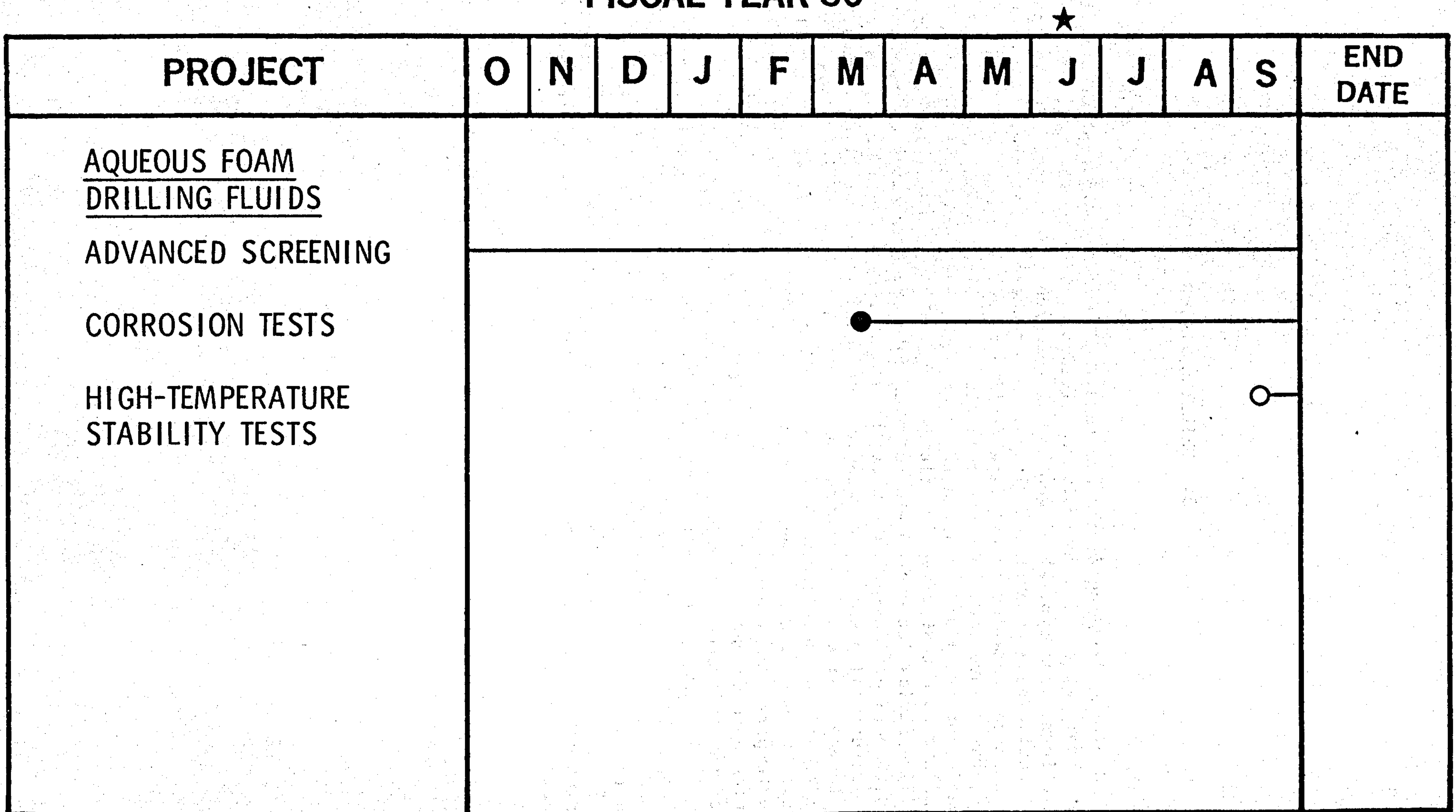

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5.1 Aqueous Foam Drilling Fluids for Geothermal Applications

Sandia National Laboratories
Technical Consultant: P. Rand (505) 844-7953

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 has been issued defining the basic problems to be encountered, the various solutions thought to be obtainable, and a project procedure. Initial surfactant screening has been completed. Fifty-six surfactants have been evaluated before and after exposure to a temperature cycle reaching 260°C (500°F). Twelve surfactants were selected for further testing. The evaluation of these surfactants in various chemical environments at 260°C (500°F) has been completed. Six surfactants, selected because of their good performance in the chemical environment tests, have been evaluated after exposure to 310°C (590°F) in deionized water. Four of these surfactants showed good to excellent performance and are now being evaluated in various chemical environments at 310°C (590°F). Surfactant evaluation at 260°C (500°F) is continuing on new surfactants that have been recommended.

Quarterly Progress

A number of new surfactants were obtained from industries supplying the drilling companies. These and other candidate surfactants are being evaluated after exposure to 260°C (500°F) and 310°C (590°F) temperatures in various aqueous environments.

An aqueous foam generator that provides uniform, fine-celled, aqueous foams with controlled density has been used in the evaluation of the effects of high-temperature cycles on surfactant solutions. A description of the generator and apparatus used to generate foams follows. The basic setup is depicted by the schematic, Figure 15.

The aqueous foam generator (static mixer) consists of an 11.7-cm (4.6-in.) long, 4.6-mm (0.18-in.) i.d., stainless-steel tube packed with 1.5 g (0.05 oz) of coarse stainless-steel wool, 0.051 mm thick by 0.635 mm wide (0.002 in. thick by 0.025 in. wide). The steel wool is packed into a 9.7-cm (3.8-in.) section of the tube.

The setup includes an air or nitrogen gas supply at 0.35 MPa (50.0 psig) for gas flow and solution overpressure. Flow rates of 10 to 12 g/min

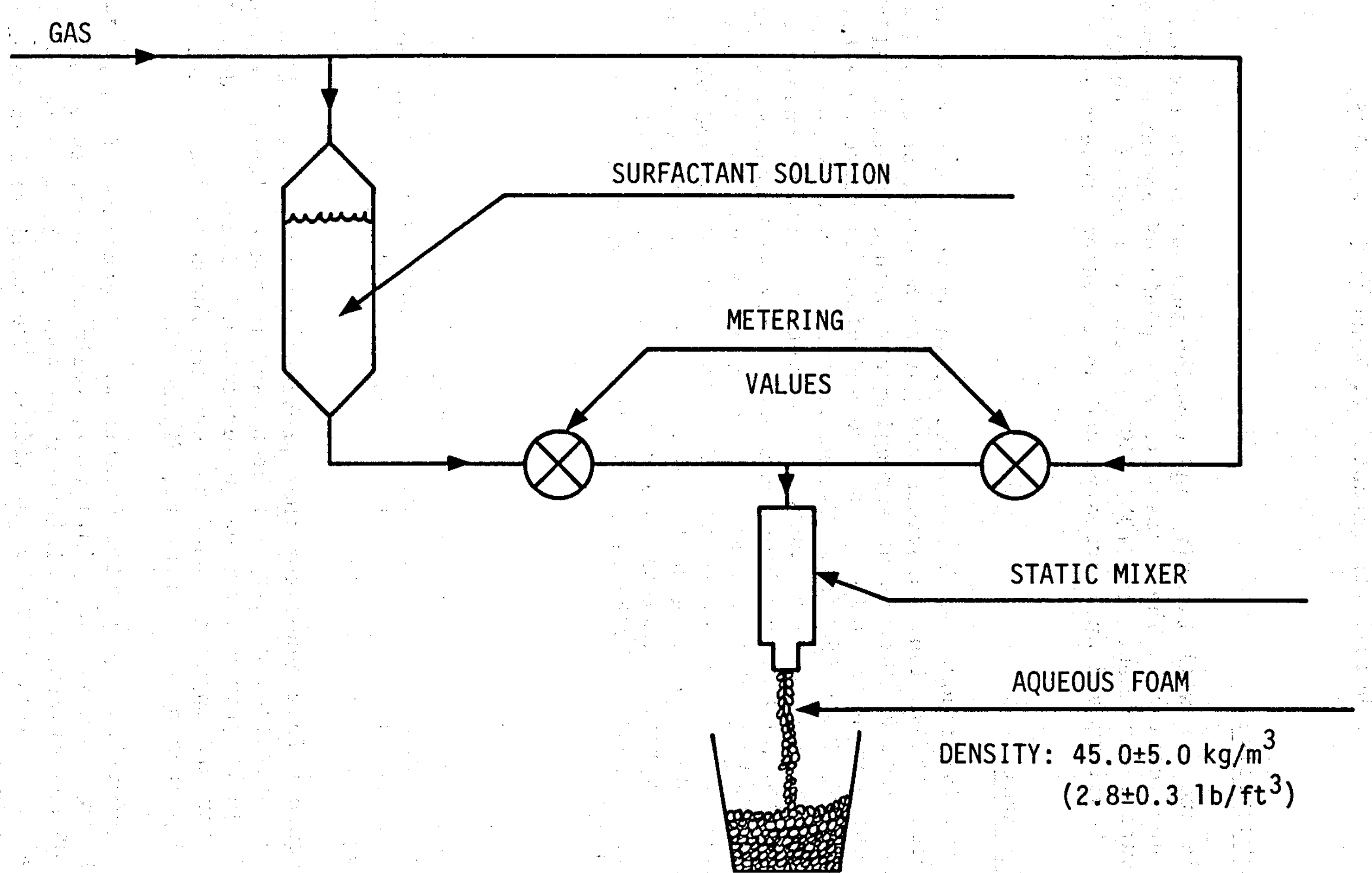

Figure 15. Aqueous Foam Generator

(0.02 to 0.03 lb/min) for the liquid and 200 to 250 cm^3/min (0.007 to 0.009 ft^3/min) for the gas are possible. Metering valves with micrometer heads have been used to control gas and liquid flow rates. Shut-off valves are used in the gas and liquid lines to minimize wear on the metering valves.

Foams with a density of 45.0 ± 5.0 kg/m^3 (2.8 ± 0.3 lb/ft^3), ≈ 0.045 liquid volume fraction, have been used. If the foams generated are used to evaluate foam drainage or other foam properties, precise temperature control is necessary for repeatable results.

The surfactant evaluation program was interrupted during this reporting period by a problem with the temperature-controlled room in which the tests must be conducted. The problem was corrected, and testing was proceeding at the close of this reporting period. The results of the experiments will be reported in the next quarterly progress report.

Corrosion coupons to evaluate the corrosivity of selected surfactant solutions have been machined and will be exposed to surfactant solutions. Corrosion inhibitors, recommended by suppliers for high-temperature aqueous environments, are also being collected for evaluation.

A presentation, "Aqueous Foams for Geothermal Drilling Fluids," is being prepared for presentation at the Gordon Research Conference in August 1980.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

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PROJECT	O	N	D	J	F	M	A	M	★ J	J	A	S	END DATE
FLOW LOOP TESTER UNIV. OF OKLAHOMA													
TESTING	- - -	- - -	- - -	- - -	- - -	- - -	- - - ▼						
	EXTENSION												
FINAL REPORT							▼						

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

5.2 Determining Temperature Limits of Drilling Fluids (Flow Loop Tester)

Contractor: University of Oklahoma
Principal Investigator: E. F. Blick (405) 325-5011
Contract Period: 1 August 1978 to 15 April 1980
Contract Number: 13-0346 (Sandia)
Technical Consultant: A. Maish (505) 844-3601

Project Objective

The objective of this project is to evaluate the high-temperature properties of available drilling-fluid additives in a dynamic flow loop. This contract provides for the establishment of a mud test laboratory, for the design and fabrication of a 288°C (550°F) flow loop, and for a moderate amount of drilling-fluids testing.

Project Status

Sufficient testing has been accomplished using a modified flow loop at Magcobar to demonstrate the existence of a large discrepancy between ambient data as normally taken in mud laboratories and the actual characteristics of the fluid under dynamic, simulated downhole conditions. A new flow loop was fabricated at the University of Oklahoma, and testing of muds was started. Repetitive malfunctions of the test equipment delayed the test program; however, correction of all problem areas was accomplished in September 1979. The contract was extended to permit the completion of scheduled mud tests. The project was completed this quarter, and a final report has been prepared.

Quarterly Progress

The final report has been received and will be published separately. This project will be deleted from the next quarterly progress report.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

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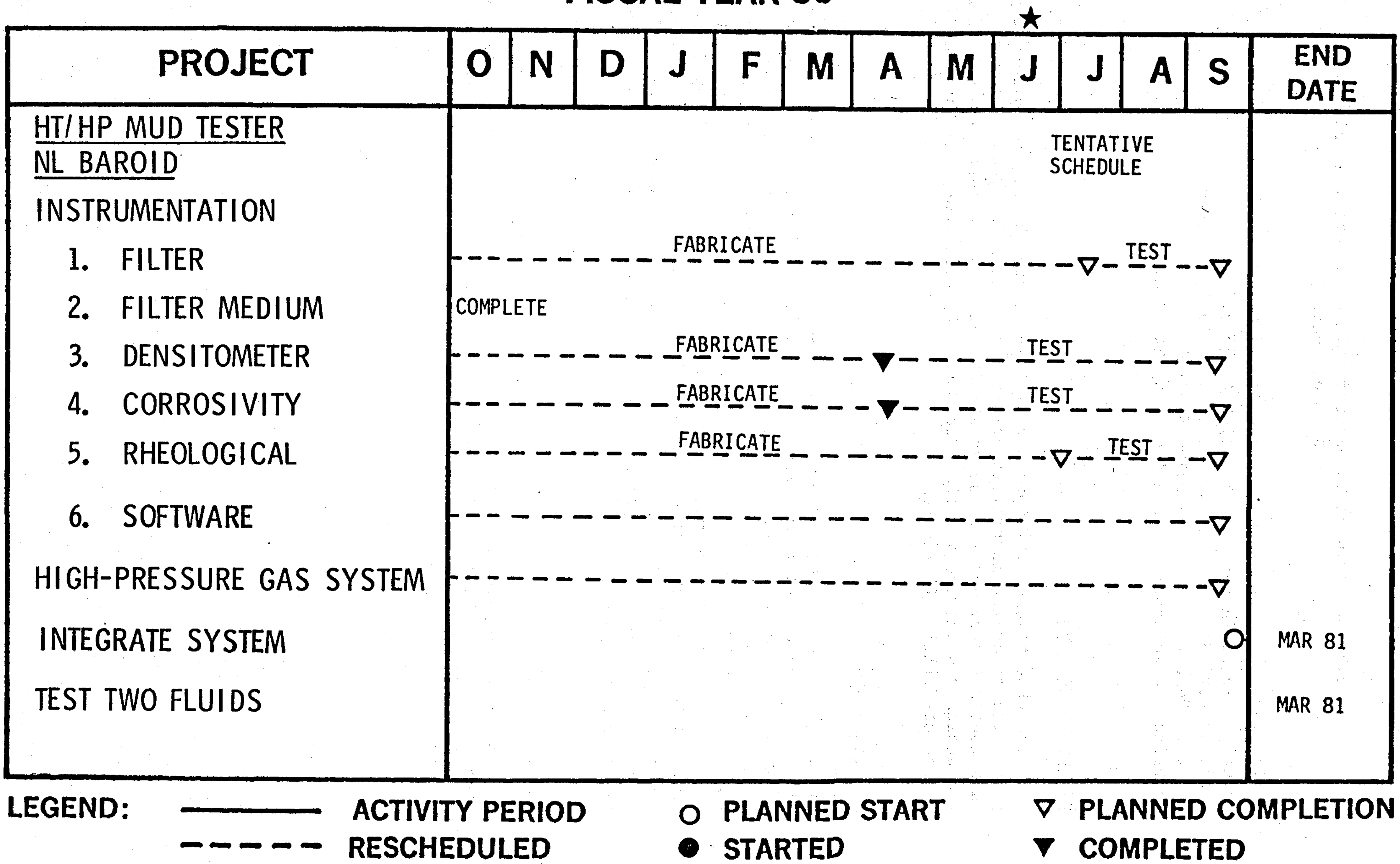

5.3 Development of High-Temperature/High-Pressure Drilling Mud Research Instrumentation

Contractor: NL Baroid
Principal Investigator: K. L. Walter (713) 527-1100
Contract Period: 1 April 1978 to 31 March 1981 (proposed)
Contract Number: DE-AC04-77ET27144
Technical Consultant: A. Maish (505) 844-3601

Project Objective

This project will result in the fabrication of a drilling-mud testing instrument capable of measuring fluid properties under dynamic flow conditions of up to 371°C (700°F) and 138 MPa (20 000 psi). This is an extension of the 288°C (550°F) capability provided by the University of Oklahoma project.

Project Status

State-of-the-art studies have been conducted. Three fabrication bids for the pressure vessel were received, and a design was chosen for testing. Design work on the system instrumentation is continuing. A time schedule has been determined for the Microcomputer System software development. The installation site for the geothermal drilling fluid test system has been tentatively selected. A contract extension is under consideration, and a new schedule is being developed.

Quarterly Progress

The water-cooled interface plate between the hot drilling fluid and instrumentation compartment was received from the machine shop. The stainless-steel plate was fabricated in two halves to allow machining of the water chase in one half. Following surface-smoothing of the rough water chase, the two halves were taken to another shop to be vacuum-brazed together. Two unsuccessful attempts were made to accomplish the procedure. Apparently furnace temperatures were not sufficiently high. The work was transferred from the only commercial heat treating shop in Houston with vacuum-brazing facilities to a shop in Ohio. The brazing together of the two halves of the plate at Wall Colmonoy in Ohio was only partially successful. The halves will have to be separated, the surfaces cleaned, and the brazing redone. When completed, this plate will be the foundation for mounting all of the instruments.

The larger diameter rheometer shaft and corrosion probes were also received. The larger shaft gives more stability to the torque transducer. Corrosion probes were plasma-spray-coated with ceramic insulation.

The proximity sensor has been received and attached to the torque transducer of the rheometer, and the assembly has been tested. The presence of a small amount of high-frequency vibration caused an increase in scatter of the electronically sensed torque data. The scatter was satisfactorily reduced by installing an electronic damping circuit between the proximity sensor and the digital readout. Similar circuitry may be used with other system sensors.

Most of the sheet metal parts have now been received. Using the coarse Tetko filter medium instead of the fine medium would reduce the cost of an order for this material by a factor of two. Technically this seems acceptable. Nevertheless, another manufacturer of similar material will be contacted.

The frequency synthesizer has been tested successfully as a means of supplying input signals to a stepper motor controller. As a result, two more frequency synthesizers were ordered. The malfunctioning of the controller has not yet been completely resolved, but two more of these were also ordered. Wiring sketches for transducer signal conditioners and hookups with their power supplies have been completed. Drawings have been started.

The new stepper motor controller ordered to replace a defective unit was received from the manufacturer and operates satisfactorily. Installation of about half of the electronic components into a blower-cooled rack has been completed. Interfacing problems between the stepper motor controller and the microcomputer were being caused by slow-speed relays. Their removal cured the problem. Two other controllers have been received.

Final details of the subcontract with Systran Corporation were resolved, and formal documentation is in process. Systran has nearly completed software for the command line interpreter, which gives the operator access to the microcomputer. Work on the cathode ray tube display software is also proceeding. A purchase order has been issued for a Millennium microsystem analyzer that will be needed for debugging and reprogramming the microcomputer.

The subcontract with National Forge Company incorporating modest price increases has been completed and sent to the firm. National Forge has resumed construction of the pressure vessel and internal cooling jacket. Approval of the National Forge subcontract and the subcontract with Systran Corporation will be needed from DOE. Regarding the contract with National Forge, the question was raised as to whether or not hardware purchased for the contract would be exempt from state and local sales taxes. The question is being investigated.

Authorization to construct the building to house the drilling-mud testing instrument is still pending. A firm project completion schedule is dependent on resolution of this issue.

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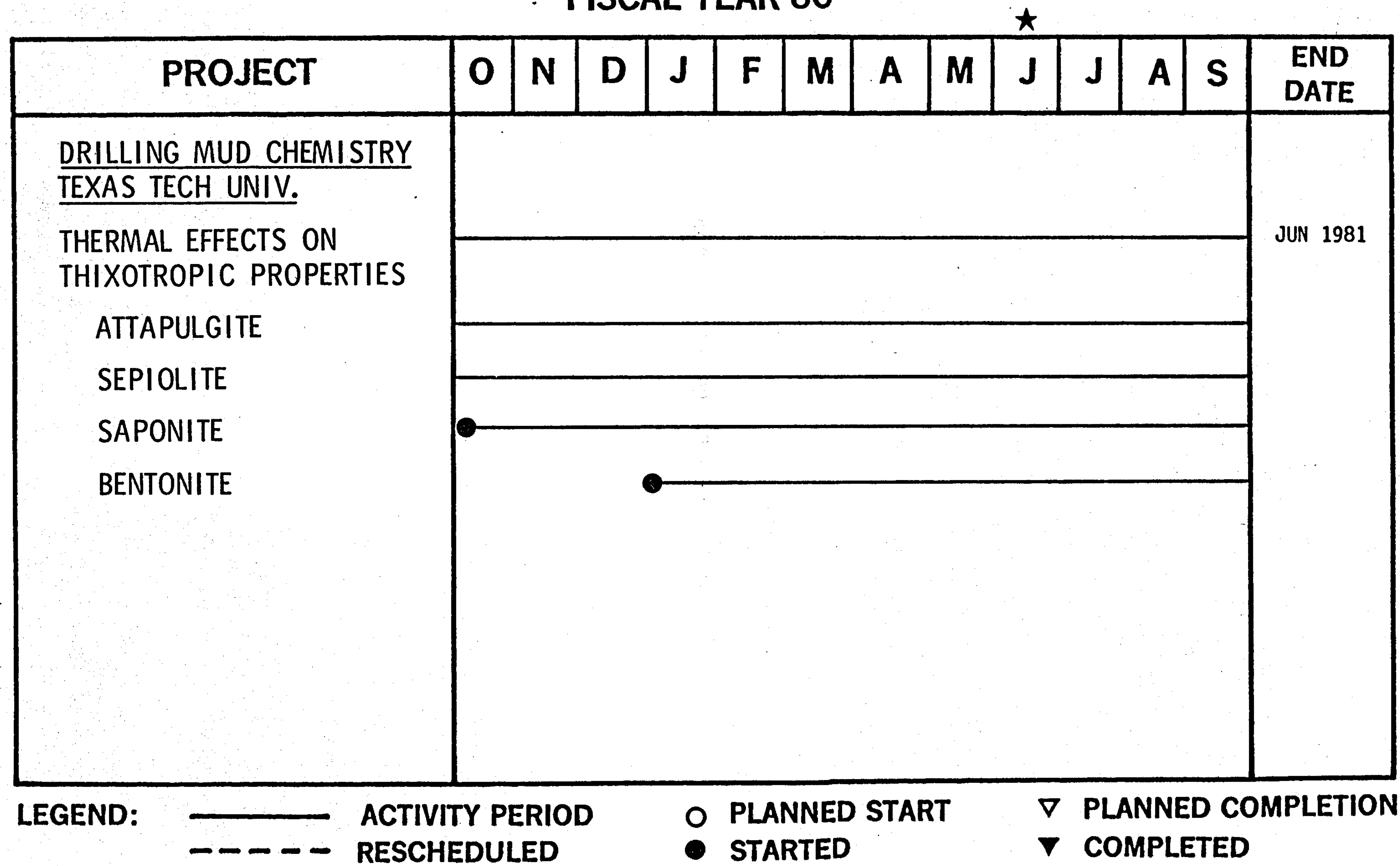

5.4 Basic Understanding of Chemical and Elevated Temperature Effects on Clay-Based Drilling Fluids

Contractor:	Texas Tech University
Principal Investigator:	N. Güven (806) 742-3110
Contract Period:	15 July 1979 to 15 July 1981
Contract Number:	13-5104 (Sandia)
Technical Consultant:	B. Kenna (505) 844-1565

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

Clay Morphology Studies — One original and 16 treated bentonite samples were examined by X-ray diffraction. The results of the diffraction examination for each sample are presented in Table 7.

The original bentonite sample is composed of smectite and a small amount of feldspar. The smectite has a 12-Å basal reflection which expands to 17 Å with glycolation. In the treated bentonite samples, smectite is abundant, but some samples contain illite, quartz, and feldspars. The X-ray data indicate that the bentonite/$CaCl_2$ samples have all three minerals, whereas the bentonite/KCl samples have only quartz. These properties of the samples may be source dependent.

After treatment of the bentonite sample with various salts, the following two characteristics were noticed in some of the samples:

1. Development of a 34-Å reflection: Samples from KCl and NaCl runs showed a weak reflection at 34 Å after glycolation. This reflection is exactly twice the original basal reflection at 17 Å. This phenomenon may be the result of a change in stacking sequence.

Table 7

X-Ray Diffraction Data on the Products of the Hydrothermal Runs in Bentonite Systems

Systems	Hydrothermal Conditions °C	(°F)	Run Time Hours	Bentonite before and after Glycolation: Before Å	After Å	Other Minerals Present in Bentonite Clay: Quartz Å	Feldspar Å	Illite Å
Bentonite and KCl	93	(200)[a]	24	12.2	17.0	+	+	+[b]
	149	(300)	24	15.2	33.7,17.1	+	-	-[c]
	149	(300)	72	15.2	33.2,17.1	+	-	-
	204	(400)		15.0	33.6,17.1	+	-	-
	260	(500)	24	15.1	34.0,17.4	+	-	-
	316	(600)	24	10.9	12.6	+	+	-
	371	(700)	24	11.0	12.3	+	+	-
Bentonite and $CaCl_2$	93	(200)[a]	24	15.0	34.0,17.5	+	-	-
	149	(300)	24	12.2	17.0	+	+	+
	149	(300)	72	11.8	17.1	+	+	+
	204	(400)	24	12.4	17.1	+	+	+
	260	(500)	24	12.3	16.5	+	+	+
Bentonite and NaCl	316	(600)	24	12.5	34.0,17.5	+	-	-
	371	(700)	24	12.6	33.0,17.0	+	-	-
Bentonite and gel	316	(600)	24	13.1	17.1	+	+	+
	371	(700)	24	13.0	17.3	+	+	+
Original bentonite sample B-1227-11				12.0	17.1	-	+	-

[a]The data on the bentonite/KCl 93°C (200°F) run may be in error because they do not agree well with the rest of the KCl runs. The same is true of the $CaCl_2$ runs at 93°C (200°F). Also, the Ca-saturated smectite does not show a (001) reflection at 15 Å, but at 12 Å, which should be the (001) reflection of a Na- or K-smectite. A mistake in labelling the samples is suspected.

[b]+ = presence

[c]– = absence

2. Decrease of the d-value of (001) reflection: The KCl runs at 316° and 371°C (600° and 700°F) showed a distinct decrease in (001) reflection from 15 Å to 11 Å, indicating little expansion after glycolation. This property may be the result of structure collapse.

The 17 bentonite samples were studied by electron microscopy to investigate the morphological changes and the reactions which may occur during the hydrothermal treatments. In those treatments, the 4% clay slurries were subjected to the conditions indicated in Table 7. A summary of observations follows.

The original material mainly consisted of fluffy smectite flakes, with few particles showing elongated, illite-like lath that extended out from the smectite flakes, as shown in Figure 16.

Most of the smectite particles retained their original morphology, as did the particles in the original starting material at 93°C (200°F) runs for 24 hours in the presence of KCl and NaCl. However, some of the flakes disintegrated into smaller flakes. As the temperature increased from 149° to 260°C (300° to 500°F), the fluffy smectite flakes turned into somewhat platy particles which were thinner than the original flakes (Figures 17 and 18). At the higher temperatures of 316° and 371°C (600° and 700°F), the platy particles replaced most of the fluffy smectite and formed aggregates (Figure 19). Similar results were obtained in the bentonite/$CaCl_2$ system, but the aggregates seemed to be more compact.

East Mesa Core Study -- Formation damage, apparently caused by sepiolite-based high-temperature drilling fluid, is being studied by Terra Tek, Inc., on cores from the East Mesa known geological resource area (KGRA) under a separate project. Three of these cores were provided by Terra Tek for further mineralogical examination. The results of X-ray diffraction studies on these cores follow.

The core sections received were 10.2 cm (4 in.) in length and 5.1 cm (2 in.) in diameter. The samples carried the designations East Mesa, 64, and East Mesa, 76. Since the cores were previously subjected to flow tests with sepiolite mud, each core was sampled at 2.5-cm (1-in.) intervals, and the mineralogy, especially the clay content, at each section was examined. These sections were labeled A, B, C, and D from the top to the bottom of the core. The bulk samples were first X-rayed in randomly selected powders. The clays in -2-micron fractions were separated by sedimentation within the suspensions which had been prepared from the lightly ground samples. Oriented clay films were prepared from -2-micron fractions after the suspensions were washed to a salt-free state, i.e., deflocculated.

The results of the X-ray diffraction analyses presented in Table 8 indicate that the amount of calcite in the core increases towards the bottom for Core 76, whereas no such trend was present in Core 64. The clay mineralogy in both cores was similar. Chlorite and illite/smectite mixed layers were the only clay minerals present. In Core 64, the chlorite content increased from the top to the bottom of the core. These clays are distinctly different from the clays in the mud, in which sepiolite and

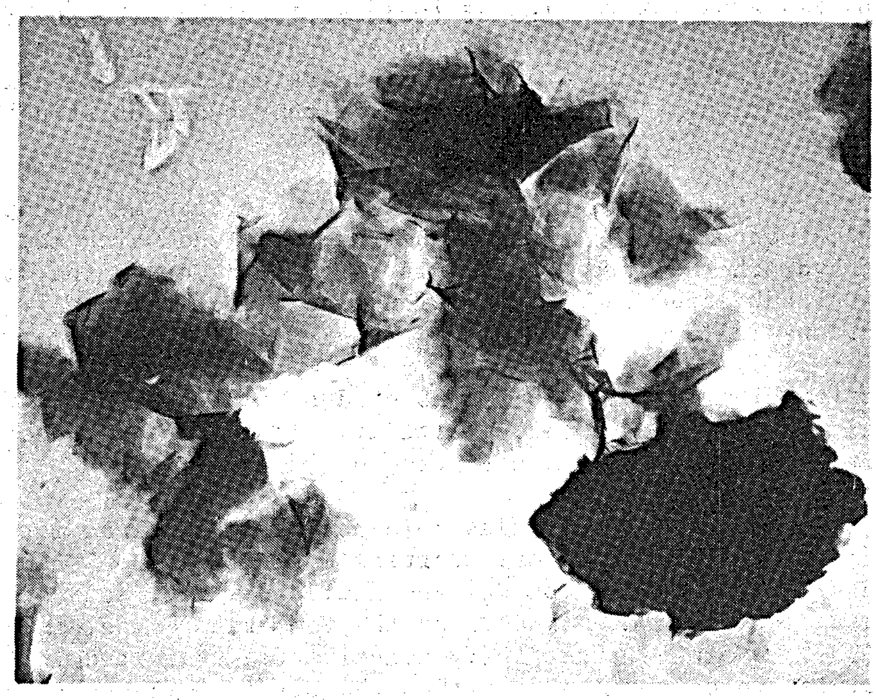

Figure 16. Original Bentonite Particles before the Hydrothermal Treatments

Figure 17. Typical Bentonite Particles after the Hydrothermal Treatment at 149°C (300°F) in the Presence of KCl

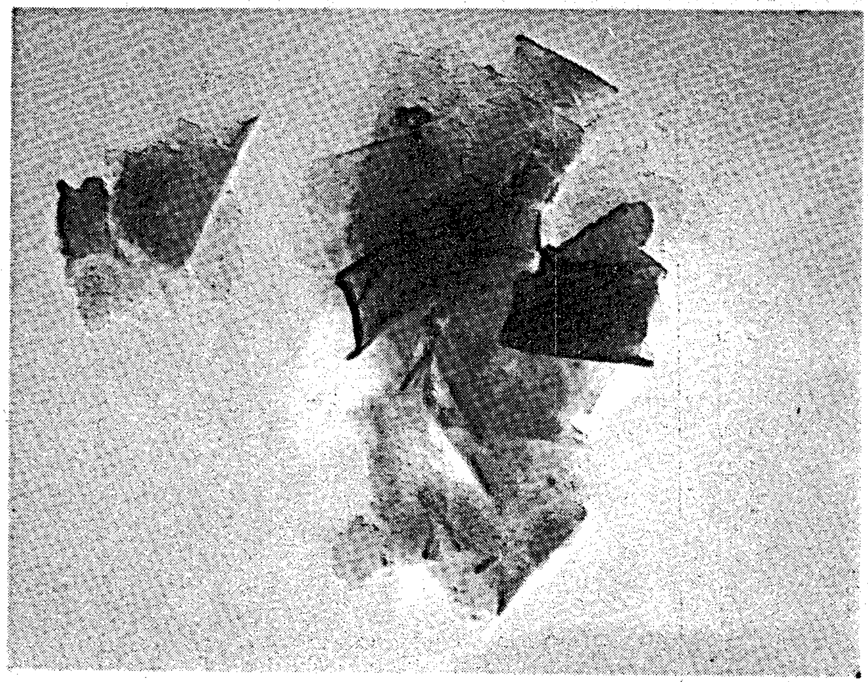

Figure 18. Development of Platy Smectite Morphology after the Hydrothermal Run at 260°C (500°F) in the Bentonite/KCl System

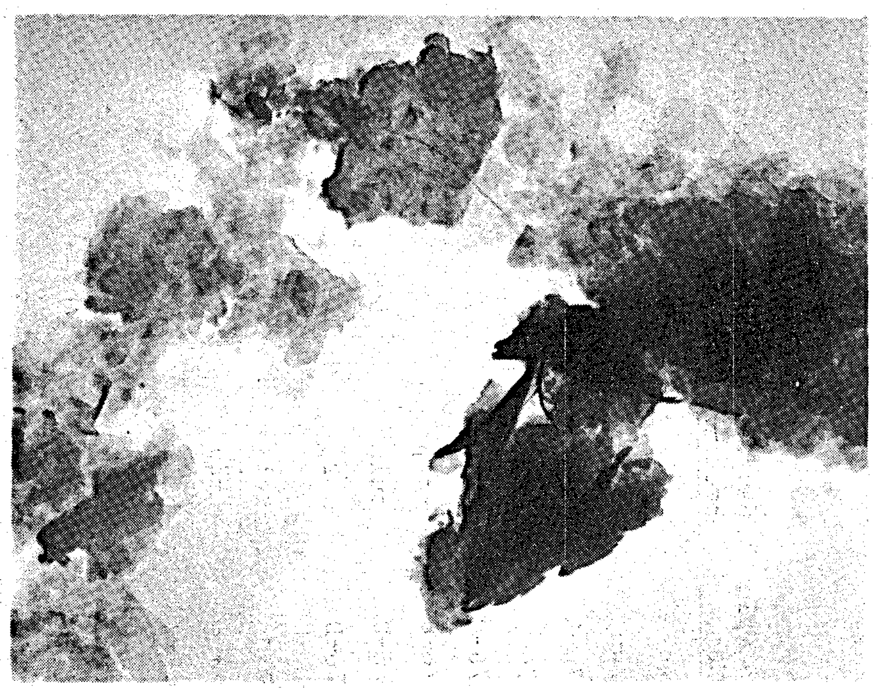

Figure 19. Platy Smectite Particles Which Are Probably Formed after Dissolution of the Original Bentonite during the Hydrothermal Run at 371°C (700°F) in the Presence of KCl

Table 8

X-Ray Diffraction Analyses of East Mesa Cores

Sample Number	Sample Fraction	Quartz %	Feldspars %	Calcite %	Chlorite %	Illite/Smectite Mixed Layer %	Kaolinite %
76-A	bulk	60	25	10	5	–	–
76-A	-2μ	–	+	–	50	50	–
76-B	bulk	60	25	10	5	–	–
76-B	-2μ	–	–	10	50	40	–
76-C	bulk	70	15	15	–	–	–
76-C	-2μ	–	–	10	40	50	–
76-D	bulk	50	20	25	5	–	–
76-D	-2μ	–	+	10	50	40	–
64-A	bulk	75	15	10	–	–	–
64-A	-2μ	–	–	5	50	40	–
64-B	bulk	75	25	+	–	–	–
64-B	-2μ	–	–	+	50	50	–
64-C	bulk	70	25	5	–	–	–
64-C	-2μ	–	+	+	60	40	–
64-D	bulk	75	20	5	–	–	–
64-D	-2μ	–	+	–	70	30	–

NOTE: + = presence
– = absence

bentonite are the predominant components, occurring in a ratio of 3 to 1. Hence, it should be easy to determine with the scanning electron microscope (SEM) whether or not the clays from the drilling mud are penetrating into the cores during the flow tests. These SEM studies are in progress.

Test Equipment -- A high-temperature FANN 50C viscometer was received and installed. Calibration tests have been completed, and the equipment is ready for use in future studies.

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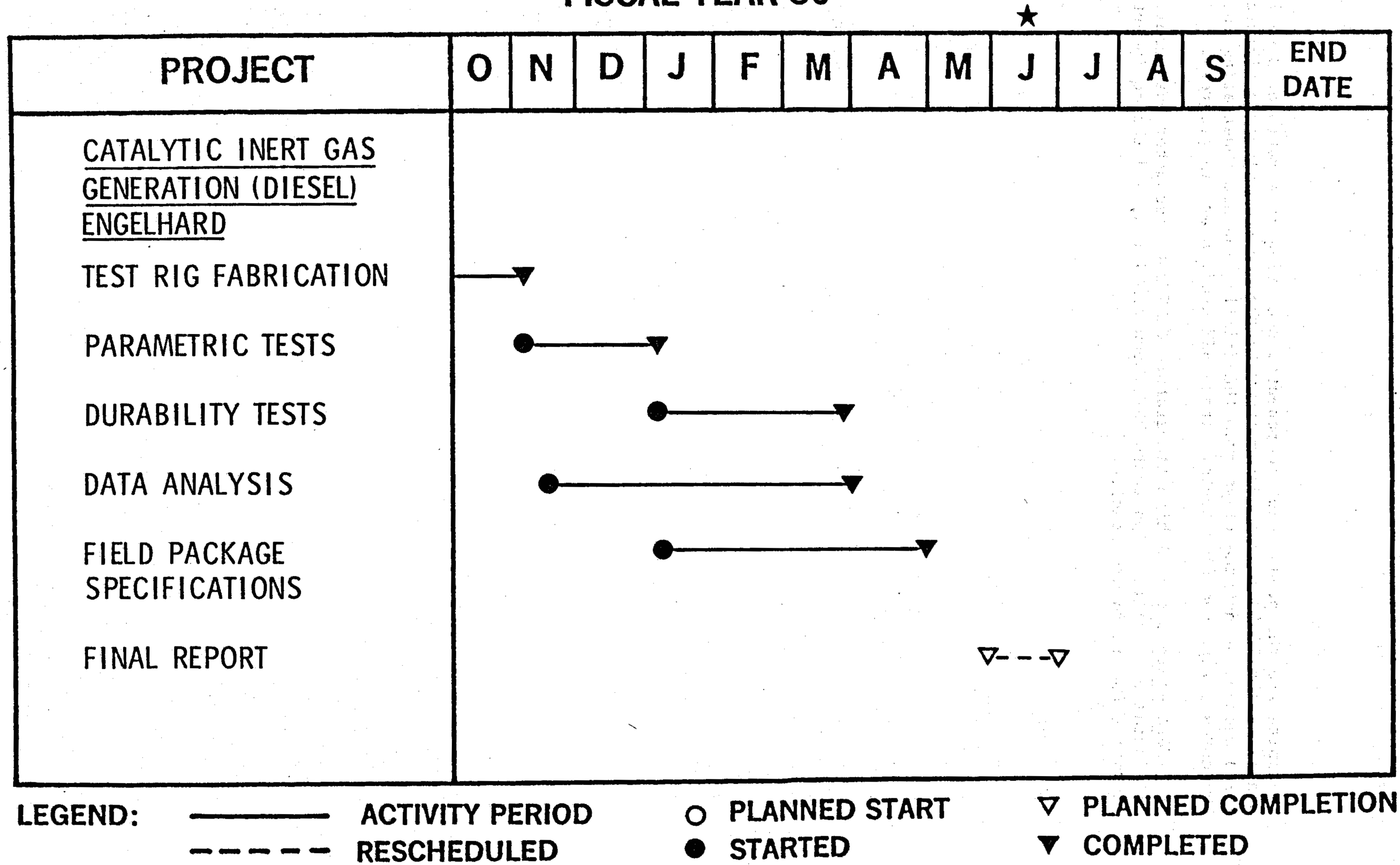

5.5 Inert Gas Generation from Diesel Exhaust - Catalyst System

Contractor: Englehard Minerals & Chemicals Corporation
Principal Investigator: I. T. Osgerby (201) 321-5230
Contract Period: 1 August 1979 to 30 April 1980
Contract Number: 13-5071 (Sandia)
Technical Consultant: B. Kenna (505) 844-1565

Project Objective

The objective of this project is to demonstrate catalytically supported thermal combustion as a means of generating an inert gas from the exhaust stream of a commercially available diesel engine. An existing, proprietary catalyst will be used with supplemental No. 2 fuel over the load range of the diesel engine to achieve this objective. This performance objective will be evaluated over an extended period of time to verify that the catalyst activity can be retained under operating conditions consistent with the intended field application.

Project Status

The test rig design and fabrication have been completed, the facility debugged, and the unit demonstrated. The parametric test program and the durability tests have been completed. Control of emissions in the catalytic generation of N_2 has been demonstrated. Additional experiments are planned subsequent to a period of independent research by the contractor.

Quarterly Progress

The 100-hour durability test at the maximum engine load condition of 60 kW (80.4 hp) was completed. Emissions from the diesel inert gas generator at the maximum load condition are shown in Table 9. Emission levels of NO_x and O_2 remained at less than 10 ppm. A CO level of less than 1% was achieved.

The catalyst durability tests at the engine load condition of 48 kW (64.3 hp) was also completed. Emissions from the diesel inert gas generator at the 48-kW load condition are shown in Table 10. Emission levels of NO_x and O_2 remained at less than 10 ppm.

Preparation of the final report on the project was nearing completion at the close of the reporting period.

Table 9

Emissions Data From Catalyst Durability Test at 60-kW (80.4-hp) Engine Load

Elapsed Time of Life Test hours	Emissions			
	HC[a] ppm[b]	CO[c] %	NO_x ppm	O_2[d] ppm
3.5	-	9.6	0.14	<10
10.5	270	7.6	0.30	<10
12.5	-	6.2	0.05	<10
20.5	105	5.2	0.25	<10
31.0	-	5.0	0.40	<10
38.0	350	6.8	0.17	<10
44.0	100	5.0	0.55	<10
51.5	200	5.0	0.31	<10
54.5	300	5.0	0.20	<10
64.0	-	5.4	0.50	<10
70.0	-	4.6	0.40	<10
76.5	-	3.0	0.15	<10
83.0	30	0.7	0.50	<10
89.0	30	0.6	0.35	<10
93.5	30	4.4	0.08	<10
97.0	38	0.8	0.05	<10
100.0	50	0.7	0.10	<10

[a]HC = hydrocarbons.

[b]ppm = parts per million.

[c]Variable emission levels caused by small variations in fuel flow under manual control operation.

[d]ppm over baseline reading.

Table 10

Emissions Data From Catalyst Durability Test at 48-kW (64.3-hp) Engine Load

Elapsed Time of Life Test hours	Emissions			
	HC[a] ppm[b]	CO[c] %	NO_x ppm	O_2[d] ppm
4.5	3250	7.7	<10	≤10
9.0	3500	7.7	<10	≤10
18.0	5000	10.0	8.9	≤10
22.5	5000	10.0	1.5	≤10
28.0	4750	9.2	1.2	≤10
32.0	2700	10.0	-	≤10
46.0	-	9.5	1.4	≤10
52.5	-	5.6	0.9	≤10
67.0	-	4.8	0.5	≤10

[a]HC = hydrocarbons.

[b]ppm = parts per million.

[c]Variable emission levels caused by small variations in fuel flow under manual control operation.

[d]ppm over baseline reading.

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PROJECT	O	N	D	J	F	M	A	M	J ★	J	A	S	END DATE
FIELD EVALUATION OF HTM-1 MUD SYSTEM MAURER ENGINEERING													
LABORATORY TESTS		●	——	——	AS REQUIRED	——	——	▽	- - -	- - -	▽		
FIELD TESTS						○ IMPERIAL VALLEY	▽	▼					

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

5.6 Field Evaluation of HTM-1 Mud System

Contractor: Maurer Engineering, Inc.
Principal Investigator: L. J. Remont (713) 683-8227
Contract Period: 15 November 1979 to 31 August 1980
Contract Number: 07-7068 (Sandia)
Technical Consultant: D. Wesenberg (505) 844-0129

Project Objective

The objective of this project is to determine the performance of the high-temperature mud system (HTM-1) under field conditions. Appropriate laboratory tests will also be conducted in order to monitor the field performance of HTM-1, which is an improved geothermal drilling fluid developed for drilling into hydrothermal reservoirs. HTM-1 can be prepared with conventional equipment, using commercially available materials.

Project Status

A suitable well for testing HTM-1 was identified, and a field test was completed this reporting period. Laboratory testing of sample formulations has been conducted, and tests of mud samples from the field tests are continuing.

2

Quarterly Progress

Laboratory Tests — HTM-1 mud samples were prepared for testing using the formulations shown in Table 11. The muds were stirred for 40 minutes at high speed, rolled at 66°C (150°F) for 18 hours, and static aged at 288°C and 3.5 MPa (550°F and 500 psi) for 24 hours and for 15 days. The mud properties after exposure to these conditions are shown in Table 12. The static-aged samples exhibited an increase in viscosity, gel strengths, and American Petroleum Institute (API) filtrates. Low shear strengths of 12.0 to 14.4 Pa (25 to 30 lb/100 ft^2) after static aging indicated very little tendency toward solidification at temperatures up to 288°C (550°F). The shear strength of the sample aged 15 days showed that the mud will not solidify under these conditions.

HTM-1 Sample V was used in salt and solid contaminant tests. The contaminant was added to the mud, stirred 10 minutes, and tested. Each sample was rolled at 66°C (150°F) for 16 hours and then tested again. The results of these tests are contained in Table 13. The mud tested with salt and solid contaminants demonstrated the ability to tolerate up to 42.5 kg/m^3 (15 lb/bbl) of salt and 283.5 kg/m^3 (100 lb/bbl) of low-specific-gravity solids.

Gypsum and cement are sometimes encountered in drilling operations. In order to determine the effects of these contaminants on HTM-1, tests were conducted with laboratory-prepared samples of HTM-1. Additions of

Table 11

HTM-1 Muds Formulated from Thermogel and Geogel

Sample No.	Formulation		
IV	Water	0.16 m^3	(1.0 bbl)
	Thermogel	6.8 kg	(15.0 lb)
	Aquagel	2.3 kg	(5.0 lb)
	Composite coal sample	9.1 kg	(20.0 lb)
	Sodium polyacrylate	1.1 kg	(2.5 lb)
	NaOH	0.91 kg	(2.0 lb)
Sample No.	**Formulation**		
V	Water	0.16 m^3	(1.0 bbl)
	Geogel	6.8 kg	(15.0 lb)
	Aquagel	2.3 kg	(5.0 lb)
	Composite coal sample	9.1 kg	(20.0 lb)
	Sodium polyacrylate	1.1 kg	(2.5 lb)
	NaOH	0.91 kg	(2.0 lb)

5.7 kg/m3 (2 lb/bbl) of each material were made to separate samples of HTM-1. Neither of the contaminants had much effect on the rheological or filtration control characteristics of the mud when tested initially or after rolling 16 hours at 66°C (150°F). Cement increased the pH of the mud from 9.6 to 11.0 and increased the filtrate at 177°C and 3.5 MPa (350°F and 500 psi) from 21.0 ml to 24.4 ml (1.28 in.3 to 1.49 in.3). Gypsum contamination had even less effect on the mud properties than did the cement. Mud pH was lowered slightly, but, when the pH was readjusted with caustic soda, the mud properties were almost identical to those of the uncontaminated mud. Properties of the mud are indicated in Table 14.

Field Test — Arrangements for field testing the HTM-1 mud system were completed early in this reporting period. The high-temperature mud was used to drill from 2316 metres to 3328 metres (7600 feet to 10 920 feet) on McCulloch's Mercer No. 228 well in Imperial County, California. The formation temperature was 232°C (450°F) at total depth. Brown coal used in the HTM-1 formulation was shipped from Sandia to the test site. Dresser Magcobar furnished all of the remaining mud additives used in the HTM-1 mud. Maurer Engineering supplied the equipment and personnel for testing, monitoring, and evaluating the performance of HTM-1. The drilling contractor was Republic Drilling.

Table 12

Mud Properties

Conditions/Properties	Sample Number IV	V	V
Rolled at 65.6°C (150°F), hours	18	18	18
Static aged at 287.7°C (550°F) 3.5 MPa (500 psi), hours	24	24	360
Plastic Viscosity, Pa•s (cp)	0.019 (19)	0.020 (20)	0.017 (17)
Yield point, Pa (lb/100 ft^2)	12.9 (27)	9.6 (20)	34.0 (71)
10-second gel, Pa (lb/100 ft^2)	6.7 (14)	3.4 (7)	20.1 (42)
10-minute gel, Pa (lb/100 ft^2)	37.3 (78)	12.5 (26)	23.0 (48)
pH	9.5	9.5	9.2
API filtrate, ml ($in.^3$)	15.8 (0.96)	18.2 (1.11)	24.5 (1.49)
Filtrate at 176.6°C (350°F), 3.5 MPa (500 psi), ml ($in.^3$)	38.4 (2.34)	47.5 (2.90)	69.2 (4.22)
Shear strength, Pa (lb/100 ft^2)	14.4 (30)	12.0 (25)	95.8 (200)

Table 13

Mud Contaminants Tests: Salt and Solids

Conditions/Properties	Sample Number V							
	Salt Contamination							
Salt, kg/m^3 (lb/bbl)	0 0	0 0	14.2 (5)	14.2 (5)	28.3 (10)	28.3 (10)	42.5 (15)	42.5 (15)
Rolled at 65.6°C (150°F), hours	0	16	0	16	0	16	0	16
Plastic viscosity, Pa•s (cp)	0.022 (22)	0.017 (17)	0.013 (13)	0.013 (13)	0.016 (16)	0.016 (16)	0.017 (17)	0.017 (17)
Yield point, Pa (lb/100 ft^2)	2.9 (6)	3.8 (8)	2.4 (5)	2.4 (5)	5.8 (12)	6.2 (13)	8.1 (17)	7.2 (15)
10-second gel, Pa (lb/100 ft^2)	1.4 (3)	1.0 (2)	1.0 (2)	1.0 (2)	1.0 (2)	1.0 (2)	1.9 (4)	1.4 (3)
10-minute gel, Pa (lb/100 ft^2)	1.9 (4)	1.9 (4)	4.8 (10)	1.9 (4)	12.0 (25)	5.8 (12)	23.9 (50)	11.0 (23)
pH	11.1	9.6	10.0	10.5	9.8	9.9	9.6	10.3
API* Filtrate, ml (in.^{3})	4.8 (0.29)	4.4 (0.27)	3.8 (0.23)	4.0 (0.24)	4.5 (0.25)	4.5 (0.25)	5.0 (0.31)	5.2 (0.32)
Filtrate at 176.6°C (350°F), 3.5 MPa (500 psi), ml (in.^{3})	- -	21 (1.28)	- -	24 (1.46)	- -	25 (1.53)	- -	25 (1.53)
	Solids Contamination							
Shale, kg/m^3 (lb/bbl)	0 0	0 0	141.8 (50)	141.8 (50)	212.6 (75)	212.6 (75)	283.5 (100)	283.5 (100)
Rolled at 65.6°C (150°F), hours	0	16	0	16	0	16	0	16
Plastic viscosity, Pa•s (cp)	0.022 (22)	0.017 (17)	0.023 (23)	0.027 (27)	0.028 (28)	0.036 (36)	0.035 (35)	0.049 (49)
Yield point, Pa (lb/100 ft^2)	2.9 (6)	3.8 (8)	3.8 (8)	6.7 (14)	5.8 (12)	12.5 (26)	7.2 (15)	14.4 (30)
10-second gel, Pa (lb/100 ft^2)	1.4 (3)	1.0 (2)	1.4 (3)	1.4 (3)	1.4 (3)	3.8 (8)	1.9 (4)	3.8 (8)
10-minute gel, Pa (lb/100 ft^2)	1.9 (4)	1.9 (4)	12.0 (25)	8.6 (18)	21.1 (44)	28.7 (60)	22.5 (47)	31.6 (66)
pH	11.1	9.6	9.5	9.5	9.5	9.7	9.5	9.7
API* filtrate, ml (in.^{3})	4.8 (0.29)	4.4 (0.27)	3.6 (0.22)	3.2 (0.20)	3.6 (0.22)	3.2 (0.20)	3.2 (0.20)	3.2 (0.20)
Filtrate at 176.6°C (350°F), 3.5 MPa (500 psi), ml (in.^{3})	- -	21 (1.28)	- -	16 (0.98)	- -	17 (1.04)	- -	18.8 (1.15)

*API = American Petroleum Institute

Table 14

Mud Contaminants Tests: Cement and Gypsum

Conditions/Properties	HTM-1 Sample			
	Cement Contamination			
Cement, kg/m³ (lb/bbl)	0 0	0 0	5.7 (2)	5.7 (2)
Rolled at 65.6°C (150°F), hours	0	16	0	16
Plastic viscosity, Pa•s (cp)	0.022 (22)	0.017 (17)	0.016 (16)	0.018 (18)
Yield point, Pa (lb/100 ft²)	2.9 (6)	3.8 (8)	1.9 (4)	2.4 (5)
10-second gel, Pa (lb/100 ft²)	1.4 (3)	1.0 (2)	1.0 (2)	1.4 (3)
10-minute gel, Pa (lb/100 ft²)	1.9 (4)	1.9 (4)	1.9 (4)	2.4 (5)
pH	11.4	9.6	11.3	11.0
API filtrate, ml (in.³)	4.8 (0.29)	4.4 (0.27)	4.8 (0.29)	4.8 (0.29)
Filtrate at 176.6°C (350°F), 3.5 MPa (500 psi), ml (in.³)	- -	21 (1.28)	- -	24.4 (1.49)
	Gypsum Contamination			
Gypsum, kg/m³ (lb/bbl)	0 0	0 0	5.7 (2)	5.7 (2)
Rolled at 65.6°C (150°F), hours	0	16	0	16
Plastic viscosity, Pa•s (cp)	0.022 (22)	0.017 (17)	0.016 (16)	0.018 (18)
Yield point, Pa (lb/100 ft²)	2.9 (6)	3.8 (8)	1.9 (4)	3.4 (7)
10-second gel, Pa (lb/100 ft²)	1.4 (3)	1.0 (2)	1.0 (2)	1.0 (2)
10-minute gel, Pa (lb/100 ft²)	1.9 (4)	1.9 (4)	2.4 (5)	1.9 (4)
pH	11.1	9.6	10.3	10.3
API filtrate, ml (in.³)	4.8 (0.29)	4.4 (0.27)	4.0 (0.24)	3.9 (0.24)
Filtrate at 176.6°C (350°F), 3.5 MPa (500 psi), ml (in.³)	- -	21.0 (1.28)	- -	21.4 (1.31)

McCulloch used HTM-1 to deepen its Mercer No. 228 well. The Mercer No. 228 well was being used as an injection well. Casing (34.0 cm [13.375 in.]) was set at 1219 metres (4000 feet). A drilling rig was moved on location during the last week of April, and rig-up operations were begun. Drilling began at 1219 metres (4000 feet). A conventional bentonite mud was used to drill from 1219 metres to 2316 metres (4000 feet to 7600 feet). The mud was converted to an HTM-1 mud after a trip to change bits. Water, sepiolite, brown coal, sodium polyacrylate, and caustic soda were added to the mud while drilling was being carried out with a new bit. The exact amount of water dilution was determined by pilot testing on location. Daily treatments were also based on daily tests and on pilot tests run on location.

HTM-1 was used to drill the interval from 2316 metres to 3328 metres (7600 feet to 10 920 feet). The formation temperature was 232°C (450°F) at the bottom of this interval. Under these conditions, the HTM-1 mud system performed well. There was no mud solidification, no corrosion problem, and no serious lost circulation.

The following mud tests were run daily:

<u>Physical Properties</u>

Mud density
Funnel viscosity
Plastic viscosity
Yield point
10-second gel
10-minute gel
API filtrate
Cake thickness
Filtrate at 177°C (350°F) and 3.5 MPa (500 psi)
Sand content
Water content
Oil content
Solids content

<u>Chemical Properties</u>

Bentonite
Calcium
Magnesium
Chloride
Carbonate
Bicarbonate
Hydroxide
API alkalinity

Each time a test was run, the sample was given an identifying number, the well depth at the time the sample was obtained was indicated, and the sample source was identified. Material additions were based on pilot tests run on location. Table 15 shows the anticipated consumption of brown coal as depth increased.

Other pertinent information obtained included a complete bit record and records on daily operations, casing and equipment, daily material additions, and pilot tests. Analysis of the test data was continuing at the close of this reporting period. A comprehensive review of the results of this field test will appear in the next quarterly report.

Table 15

Anticipated Cumulative Consumption of Brown Coal with Increase in Depth

Approximate Depth metres	(feet)	Planned Coal Consumption Sacks
2 438	(8 000)	200
2 743	(9 000)	350
3 048	(10 000)	500
3 200	(10 500)	680
3 353	(11 000)	850

*The actual consumption of brown coal will be included in the report of the test results.

6. COMPLETION TECHNOLOGY

Overall geothermal well costs can be reduced significantly by improvements in completion technology. 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 to extend well life and improve production. Projects are presently underway with the objectives of (1) designing a downhole perforator for use in geothermal well completions, (2) establishing needs and defining requirements for downhole primary cementing tools and for monitoring tools to detect critical failure modes of a geothermal well completion, and (3) designing and demonstrating a system using a controlled cavitation technique for downhole geothermal well cleaning and scale removal. 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 improvements in geothermal well completion technology and identification of needed technology development. Failure modes and reasons for geothermal well casing failures have been documented and published. 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.

Elastomeric failure at high temperatures limits the use of conventional open-hole packers in geothermal wells. A new design concept was prepared which utilizes a reinforced elastomeric element and the principle of mechanically supporting the elastomer to produce minimum stress on the element.

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 design of an operational downhole geothermal well cleaning and scale removal system were established. Development of this system is nearing completion, with a field demonstration planned for July 1980.

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

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

PROJECT	O	N	D	J	F	M	A	M	J ★	J	A	S	END DATE
<u>HIGH-TEMPERATURE PERFORATOR</u>													
STUDY OF OFF-THE-SHELF PERFORATORS				●	———	———	———	———	———	———	———	———	
HIGH-TEMPERATURE PERFORATOR DESIGN		START DEPENDENT ON STUDY FINDINGS											

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 a temperature of 250° to 300°C (482° to 572°F) for 45 minutes.

Project Status

A variety of conventional explosive perforators have been purchased from a commercial supplier. Diagnostic techniques for determining the performance of these perforators have been developed. A test chamber has been designed and constructed for the heating of perforators at elevated temperatures. After heating, the explosive charges will be fired into a target and the performance of the perforator evaluated from a study of the target. Trials with the chamber have been made to establish that it will function as designed. Findings of the ongoing study phase of the project will determine subsequent efforts to design a high-temperature perforator.

Quarterly Progress

An experimental chamber was designed and constructed for the testing of perforating explosive charges at elevated temperatures. The chamber is designed to bring the perforator up to a predetermined temperature rapidly and maintain that temperature. The temperature of the perforator can be monitored continuously during the heating process.

After a fixed time at temperature, the explosive will be detonated and allowed to perforate a composite target composed of a 9.5-mm (0.375-in.) thick steel plate securely attached to an aluminum block. The performance of the perforator will be evaluated by measuring (1) the diameter of the jet entrance hole, (2) the depth of the hole, and (3) the volume of the hole.

Trials without explosives were run with the chamber, and a few minor deficiencies were identified. Activities to correct these deficiencies are in process.

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PROJECT	O	N	D	J	F	M	A	M	J ★	J	A	S	END DATE
<u>COMPLETION TECHNOLOGY CONSULTATION COMPLETION TECHNOLOGY COMPANY</u>													
LONG-RANGE GEOTHERMAL WELL TECHNOLOGY PROGRAM FORMULATION/EXECUTION		●	—	—	—	—	—	—	—	—	—	▽	
CEMENTING TOOLS						●	—	—	—	—	—	▽	
MONITORING TOOLS					●	—	—	—	—	—	—	▽	

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

6.2 Completion Technology Consultation

Contractor:	Completion Technology Company
Principal Investigator:	R. E. Snyder (713) 961-5011
Contract Period:	16 November 1979 to 30 September 1980
Contract Number:	46-0173 (Sandia)
Technical Consultant:	T. Hinkebein (505) 844-5202

Project Objective

The project objective is to provide consulting and engineering services to the Geothermal Drilling and Completion Technology Development Program in the following areas: (1) establishing needs and defining requirements for downhole primary cementing tools; (2) establishing needs and defining requirements for monitoring tools to detect critical failure modes of a geothermal well completion; (3) defining, at a state-of-art level, geothermal well completion technology and transferring the technology to industry; and (4) formulating and implementing the long-range DOE/Sandia geothermal drilling and completion technology development program.

Project Status

The project was initiated in the latter part of the 1st quarter FY80 reporting period and continued the consulting services provided under a previous contract concerning other elements of completion technology development. Work on the state-of-the-art study of cementing and monitoring tools is continuing.

Quarterly Progress

Cementing Tools -- The activities essential for establishing the needs and defining the requirements for downhole primary cementing equipment in geothermal wells were planned and organized during this reporting period. A minimum of time will be spent on a literature review, because previous reports serve as a background to this study. The greatest amount of time will be spent in contacting operators, suppliers, and manufacturers for documentation of failures. Work was initiated on this task.

J. Rowley of the HDR project, LANSL, was interviewed concerning cementing equipment failures. Operators and service companies in The Geysers, California, were contacted by phone, and meetings were scheduled in Santa Rosa, California. Downhole cementing equipment and monitoring tool requirements for detection of geothermal well failures will be covered in the meeting.

Monitoring Tools -- Work continued on establishing the needs and defining the monitoring tool requirements for detecting geothermal well failures. All major wireline companies were contacted, and a list of casing inspection equipment available to the geothermal industry was compiled. Mechanical as well as electrical monitoring equipment was investigated. The emphasis was placed on the temperature limitations of existing equipment. Geothermal well designs were reviewed to determine the dimensional requirements of monitoring equipment. Mechanical casing inspection techniques, such as the use of impression packers and mechanical or slick line calipers, were also reviewed. The applicability of logging tools that have been developed by SNL was also assessed.

Additional contacts with logging companies were made in the Houston area, including a meeting with the Atlas Oilfield Services Group of Dresser Industries.

Technology Transfer — The technical paper "Geothermal Well Completion: A Critical Review of Downhole Problems and Specialized Technology Needs" was presented to about 200 petroleum engineers at the Society of Petroleum Engineers (SPE) Southwest Texas Spring Symposium in Corpus Christi, Texas, on 9 April 1980. Although this particular geographical area does not have hydrothermal geothermal wells, the area is on the fringes of the Gulf Coast geopressured geothermal area; therefore, the technology presented at the symposium is highly relevant to the portion of southwestern Texas which borders the Gulf. Interest in the technology was expressed by some operators who are investing in western U.S. hydrothermal sites.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

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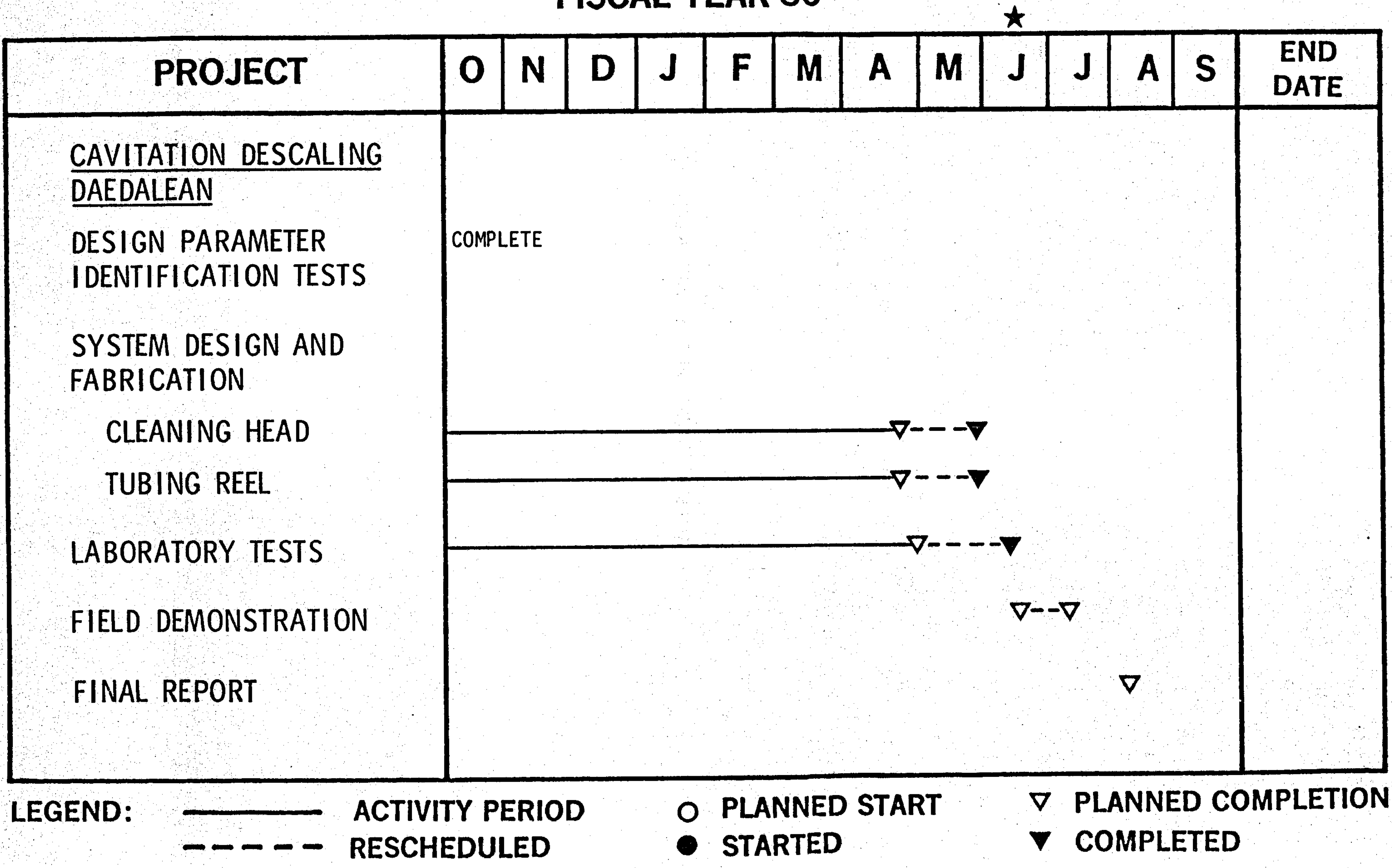

6.3 Cavitation Descaling Technique for Downhole Geothermal Well Cleaning

Contractor:	Daedalean Associates, Inc.
Principal Investigators:	Dr. A. P. Thiruvengadam (301) 442-2620 Dr. A. A. Hochrein, Jr.
Contract Duration:	14 February 1979 to 30 September 1980
Contract Number:	13-2361 (Sandia)
Technical Consultant:	T. Hinkebein (505) 844-5202

Project Objective

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

Work in this program is 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 (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 is based on the data obtained from this test. The water-powered, hydraulic, cleaning head motor was in the final design and fabrication stages at the close of this reporting period. The current target date for the completion of the field demonstration is 15 July 1980.

Quarterly Progress

All work required in preparation for the field demonstration currently scheduled for mid-July 1980 was nearing completion as this reporting period came to a close. Activities during the quarter which were associated with development of the demonstration system follow.

The modification of the hydraulic motor involved replacement of the existing metal-to-metal wear surfaces on which the ends of the rotor slide. Several candidate materials that exhibit good self-lubricating properties were considered. Among the materials evaluated were

Aluminum bronze,
P/M bronze,
Fluorosint 500,
Fluorosint 207,
TFE, and
Torlon 4301.

The aluminum-bronze material was suggested by the motor manufacturer as a substitute material for the end plates. This material contains approximately 11% aluminum. It possesses excellent wear resistance, corrosion resistance, and elevated-temperature properties.

The P/M bronze is an oil-filled, self-lubricating bronze with a chemical composition of 90% copper and 10% tin.

The remaining four materials are all thermoplastics. Three materials, Fluorosint 500, Fluorosint 207, and TFE, are polytetrafluroethylene-based materials. The TFE fluorocarbon is a standard, unmodified Teflon that possesses a low coefficient of friction and a 260°C (500°F) continuous-service temperatute. The fluorosint series are composed of TFE fluorocarbon filled with a synthetic mica. The Fluorosint 207 retains the low coefficient of friction of unfilled TFE, but the wear rate is much lower. Fluorosint 500 uses the same mica filler as 207 but at a higher fill level, which reduces the wear rate even more.

Finally, Torlon 4301 is a poly(amide-imide) which exhibits exceptional physical and chemical properties and has good wear resistance at elevated temperatures.

The cost quote has been received from Otis to hydrostatically fail-test 30.5 metres (100 feet) of the R-70, 2.1-mm (0.083-in.) wall tubing. The tube burst test was scheduled near the end of this quarter at the Otis Engineering Special Services Division in Dallas, Texas, and Otis has transferred several sections of the tubing to their Dallas facility. The test will consist of Otis personnel attaching the tubing to reel plumbing. The tubing will then be hung through the injector assembly with a load equivalent to 610 metres (2000 feet) of 1.2-kg/m (0.81-lb/ft) tubing attached. Then the internal pressure will be increased until the burst point is attained. This test is being conducted to produce information on the maximum operating pressure to which the tubing can be subjected during the actual field test. The calculated burst pressure of the R-70 tubing is 96.5 MPa (14 000 psi).

The final machining operation on the cleaning head rotator has begun. The top section of the rotator is being machined to incorporate a rotating seal utilizing two, polytetrafluoroethylene-lined, spherical bearings and a high-pressure/high-temperature, graphite-carbon-glass-teflon cartridge seal.

Design drawings are being sent from Otis on the coupling configuration that they recommend be utilized to connect the cleaning heat rotator to the Otis R-70 tubing. There are several coupling methods that can be used, such as threading the tubing with line pipe thread or using a swaged-type fitting. Otis is selecting the fitting design most suitable for this high-pressure application. When this information is received, the top of the tool will be machined to incorporate the specified connector.

Experiments to determine the threshold intensity of erosion of the calcium-based scale found in the East Mesa wells have been completed. It has been determined that the minimum intensity that must be produced at the scale surface is equal to 650 W/m^2 (0.42 $W/in.^2$). In the laboratory, this intensity was realized using a taper-jet-configuration nozzle, T-804, at a pressure of 68.9 MPa (10 000 psi) and at a distance from the nozzle of 6 inches. When the nozzle distance is decreased to the optimum distance of 1.9 cm (0.75 in.), the intensity delivered to the scale surface increases to 15 000 W/m^2 (9.7 $W/in.^2$).

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

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PROJECT	O	N	D	J	F	M	A	M	J ★	J	A	S	END DATE
DRILLING FLUID/ FORMATION INTERACTIONS TERRA TEK													
FILTRATE CHEMISTRY EFFECTS						●	—	—	—	▽			
PARTICLE SIZE EFFECTS							●	—	—	—	—	▽	
FRACTURED FORMATION SIMULATION									●	—	—	▽	
FINAL REPORT													OCT 80

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

6.4 Drilling Fluid/Formation Interactions

Contractor: Terra Tek, Inc.
Principal Investigator: D. Enniss (801) 582-2220
Contract Period: 10 March 1980 to 30 September 1980
Contract Number: 46-8747 (Sandia)
Technical Consultant: T. Hinkebein (505) 844-5202

Project Objective

The objective of this project is 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, and
3. The best method of simulating formation damage in a fractured formation under laboratory conditions.

Project Status

This project is the second phase of the study of formation damage associated with drilling fluids. Earlier work investigated drilling mud formation invasion effects upon permeability as a function of (1) varying stagnation times, mud types, and temperature and (2) backflow duration and mud types. The Phase I efforts were completed at the close of FY 79. The current phase of the investigation was initiated with laboratory tests to determine any effect in situ brines may have on drilling fluid/formation permeability. The tests were nearing completion at the close of this reporting period. Work on the effects of drilling-fluid-entrained particles on formation permeability and on simulation of formation damage in a fractured formation were initiated this quarter.

Quarterly Progress

East Mesa core material was selected, and test samples were prepared for the testing of filtrate chemistry effects. In this testing, the permeability to a synthetic brine is determined during simulation of in situ overburden stress, pore fluid pressure, and temperature. The brine is formulated to be similar to the in situ brine and is based on East Mesa water quality reports. Following this initial permeability measurement, a fluid formulated to represent a typical drilling fluid filtrate is passed through the core. Permeability is again determined over the same time period, and any effects attributable to the change in permeating fluid are noted.

Procedures were developed for this testing, and all modifications and calibrations to the test apparatus were performed. Debugging tests of the computer data acquisition system and discussions with technical and area representatives of the leading drilling fluid service companies were completed. Formulation of the drilling fluid filtrate solutions were based upon the most commonly used systems in the Imperial Valley, which specify 3 to 5% concentration of salt per barrel.

The tests to assess the effects of filtrate chemistry on geothermal formation permeability were completed in mid-June. Data reduction was initiated at the completion of testing, and the results were being analyzed at the close of this reporting period. Modifications to sample preparation for 275°C (527°F) test temperatures were not successful, and, in order to stay on schedule, this test parameter was lowered to 250°C (482°F).

A review of available sandstone materials was initiated in the testing of particle size effects to determine a suitable testing material. Materials are being evaluated according to the following criteria:

- Homogeneity
- Porosity
- Port size uniformity
- Minimal clay content
- Permeability
- Availability

The following progress has been made on the particle size distribution experiments:

- Material samples of 5, 20, and 50 microns have been received from the manufacturers. The study of these samples by SEM has been initiated to select samples most uniform in size and shape.

- A literature search for core material has tentatively identified the Nugget sandstone as fulfilling the criteria of uniform grain size, 15 to 20% porosity, less than 5% clay content, 1 to 200 mD permeability and local availability.

- The thin section analysis, determination of physical properties, and permeability testing are proceeding to accurately characterize the local outcrops. An alternative to the local material is also being sought as a backup.

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 or terminated cooling of the bit and removal of bottomhole chips. Also, most drilling fluids are expensive, and transportion of additional fluid additives to the drilling site results in costly time delays as well as an 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. Normal industry practice is to treat each lost circulation situation separately as it occurs. 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 (1) of determining the geological characteristics of lost circulation zones, (2) of collecting, collating, and analyzing industry experience concerning the causes, prevention, and remedy of lost circulation in geothermal environments and (3) of assessing the state of the art of mapping lost circulation zones in geothermal wells. The status and progress of these activities are described within this section.

5

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

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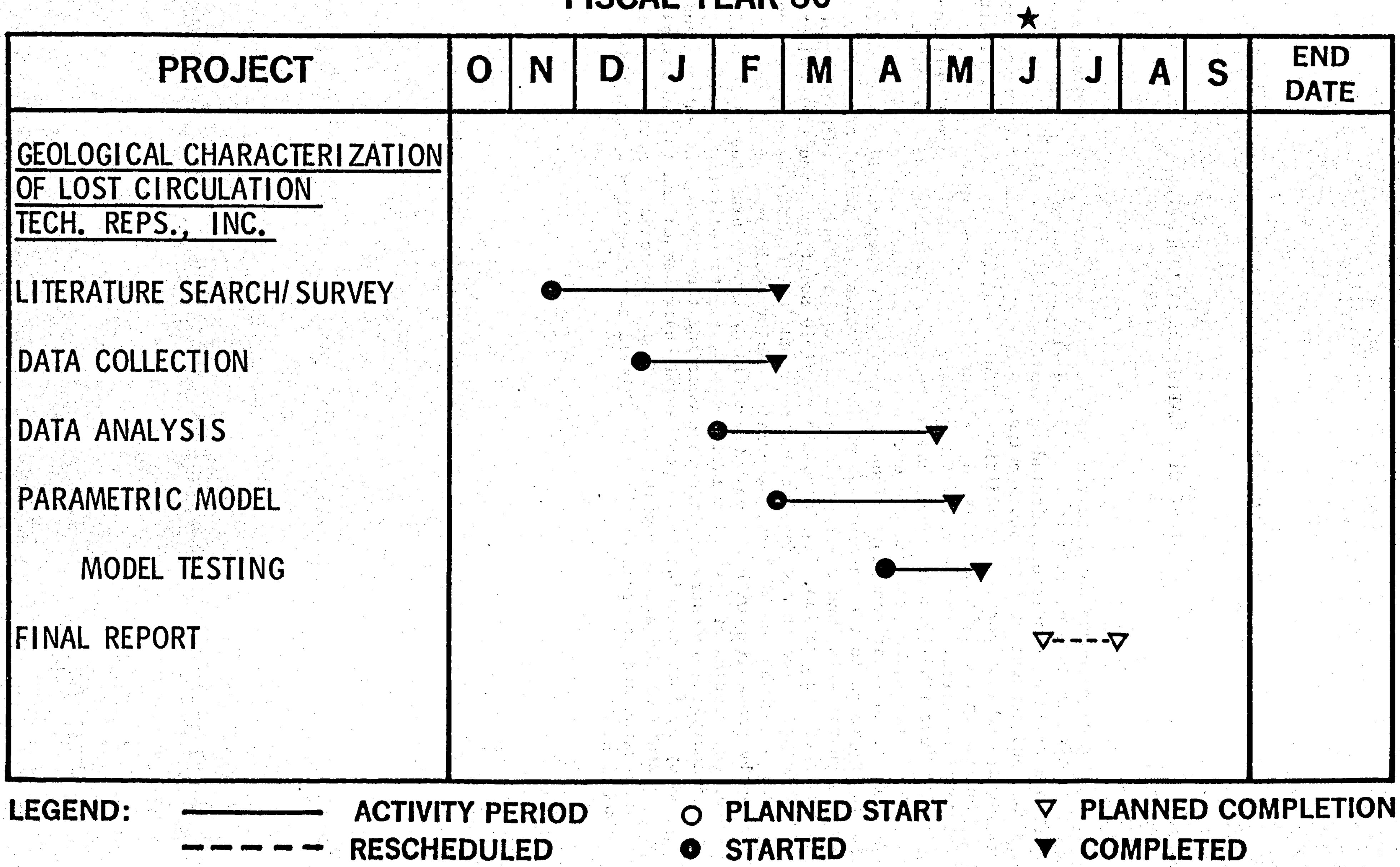

7.1 Geological Characterization of Lost Circulation Zones

Contractor: Tech. Reps., Inc.
Principal Investigator: R. V. Guzowksi (505) 262-2077
Contract Period: 10 December 1979 to 31 July 1980
Contract Number: 46-8886 (Sandia)
Technical Consultant: J. Kelsey (505) 844-6968

Project Objective

The objective of this project to determine the geological characteristics of lost circulation zones in the volcanic sequences encountered during the drilling of geothermal wells. These characteristics will be compared for consistency within each of several KGRAs. If specific lithologic properties are related to lost circulation in each area, the results for the various KGRAs will be compared to determine if the properties are of local or regional significance. In addition to rock properties, the effects of various drilling practices will be considered to determine whether lost circulation is naturally occurring or drilling induced.

Project Status

Information on lost circulation experience in geothermal well drilling in Cove Fort-Sulphurdale, Utah; Raft River, Idaho; and Valles Caldera, New Mexico; is included in the data collected. The literature search and data collection efforts have been completed. Analysis of the data and development of a parametric model have also been completed, and a final report is nearing completion.

Quarterly Progress

The search for data sufficiently detailed to be of use to this project was pursued through private industry, government agencies, and government contractors. To date, only one government agency has been able to provide usable data.

The National Reactor Testing Station (NRTS) located on the Eastern Snake River Plain (ESRP) of Idaho has lost circulation problems that are so severe that any new techniques which may be developed to solve these problems undoubtedly will be effective elsewhere. In addition, a substantially thicker sequence of basalts is found in the ESRP than in most volcanic areas associated with geothermal anomalies.

The Water Resources Division of the U.S. Geological Survey (USGS) at the NRTS office in Idaho provided a description of the geologic setting of the area, as well as the details of the local structural features and the stratigraphic sequence. The results of various liquid and gas injection well experiments and their relationship to the geological characteristics of the rocks were provided, along with several reports dealing with the various topics reviewed. Some of these reports contain data on the porosity and permeability of the rocks of the ESRP.

The core from one of the injection wells was examined. Except for providing a visual representation of the rocks described in the reports, the core gave no information regarding the size of fractures in lost circulation zones or the extent to which permeability is related to porosity for these rocks.

Excluding lava tubes because of their unpredictable and highly localized distribution, the most severe and commonly encountered lost circulation problems occur in the zones between overlapping lava flows. When an emplaced lava flow cools, extensive fracturing occurs at the surface. An overriding flow has a blocky cooling rind that forms at the surface and is incorporated into the base of the flow and overridden as the flow moves downslope. The combination of a highly fractured flow-top and a blocky basal portion of the overlying flow result in zones of extremely high permeability. These zones are not exposed in the NRTS area, but measurements were taken of some fracture zones in the top of a lava flow that is exposed.

According to the USGS in Denver, there are no data readily available on lost circulation problems. However, this office has been working with an acoustical televiewer that may yield results in this area. Fractures can be identified by use of the televiewer, although additional data on the size and amount of lost circulation material are required in order to determine the permeability of fracture zones. The problem with the televiewer is its inability to distinguish open and sealed fractures. A report has been completed by the USGS on this work, but the data will not be available until publication.

USGS open file reports containing the electric and lithologic logs for the Cove Fort-Sulphurdale KGRA were reviewed. Lost circulation zones are not indicated on the logs either directly or through interpretation. The drilling summary reports provided by the DOE office in Idaho Falls contain only references that lost circulation was encountered, with no indication of what was done to solve the problem.

Although the Nevada Test Site (NTS) is not a KGRA, the volcanic rocks at the site are similar in origin and composition to the volcanic rocks in many areas that do have geothermal potential. The fracture studies available from the drilling at NTS were expected to be detailed because of the concern by the federal government about possible leaks of radioactive gases from nuclear tests.

Fennix & Scisson, Inc. (F&S), is the government contractor that supplies the technical personnel for the drilling and mining at NTS. The F&S Geology Division supplied the drill hole lithologic logs. Electric logs and drilling histories were supplied by the F&S Engineering Division. Cores are stored at the USGS Core Library and are available for examination, provided that a specific drill hole number and depth interval are requested.

Because of all the drilling that has been completed at NTS, the geological personnel contacted could not remember the specific details of specific drill holes. The drilling histories and daily drilling sheets generally provided only the 8-hour intervals during which circulation was lost and the amounts of lost circulation material used during each time interval. When the specific depths of lost circulation zones were determined, the electric logs showed no anomalous values that correlated with these zones.

Outcrops of various rock types were examined in the NTS Rainier Mesa area, and the possible influence that the fractures might have on drilling was investigated. The relatively brittle vitrophyre, welded tuff, and zeolitized tuff are extensively fractured. Because the outcrops are exposed at the surface, those fractures with widths that could cause significant lost circulation probably are the result of frost wedging and are not typical of the rock type as a whole. Most of the fractures have widths of less than 5.0 mm (0.2 in.). The granular, weakly consolidated, waterlaid tuffs were able to dissipate imposed stresses by intergranular movement instead of by fracturing. This rock type has a porosity and permeability similar to that of a coarse-grained quartz sandstone and probably would cause some fluid loss if penetrated during drilling. Conventional lost circulation control techniques would stop the fluid loss.

In addition to their surface exposures, the zeolitized tuffs were examined in two of the tunnels into Rainier Mesa. Most of the fractures are closed. Those fractures that are open usually have a width in the range of 0.1 to 6.0 cm (0.04 to 2.36 in.). The lateral extent of the fractures could not be determined.

Lawrence Livermore Laboratory (LLL) showed movies, taken at NTS with a downhole camera, of several of the large-bore drill holes. If the hole diameter is known, the circumference can be established. On a single-frame picture from the movie, the ratio of the fracture width to the hole circumference also can be established. Determining this ratio would allow for the actual fracture width to be calculated. Each movie has a continuous readout of the depth being observed, so that the vertical extent of the lost circulation zone can be determined. A fracture permeability can be estimated based on the fracture data and on the amount and the size of the lost circulation material used. No measurements could be made from the movies because the projector could not be stopped for a single frame. Sandia has made arrangements to obtain copies of several films from LLL.

A review of the various reports collected at NTS indicates that the detailed data required for this project are not included. F&S stated that the data are not available from any source at any location of which they are aware.

Data collection from private companies continued to be unproductive. The drilling data and logs from Herkenhoff, Gordon, and Associates for the water wells located south of Los Alamos are not in sufficient detail to be of use in determining the characteristics of lost circulation zones. All knowledgeable personnel of Phillips Geothermal were overseas and therefore not available for interview during the project work period. Other than the reports on file with DOE, information on lost circulation zones from Union Geothermal is not available at this time.

Preparation of the final report was nearing completion at the close of this reporting period. The report will be published separately. The preliminary conclusions based on the findings in this project are

1. Detailed quantitative data on the geological characteristics of lost circulation zones do not exist,
2. Electronic logging methods are able to measure the physical properties of the rocks and interstitial fluids, but these methods do not measure the dimensions of voids that might cause loss of drilling fluids,
3. Other equipment, such as an acoustical televiewer and a downhole camera, may locate fractures and voids, but the lateral extent and permeability of these features cannot be determined by using these instruments, and
4. If new techniques to control lost circulation are to be developed, experiments must be conducted in drill holes to determine the physical parameters of those zones for which present techniques to control fluid loss are not adequate.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

PROJECT	O	N	D	J	F	M	A	M	J ★	J	A	S	END DATE
<u>DOWNHOLE TEMPERATURES--</u> <u>LOST CIRCULATION</u> <u>ENERTECH</u>													
									EXTENSION				
TEMPERATURE HISTORIES													
LOST CIRCULATION													
FINAL REPORT													

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

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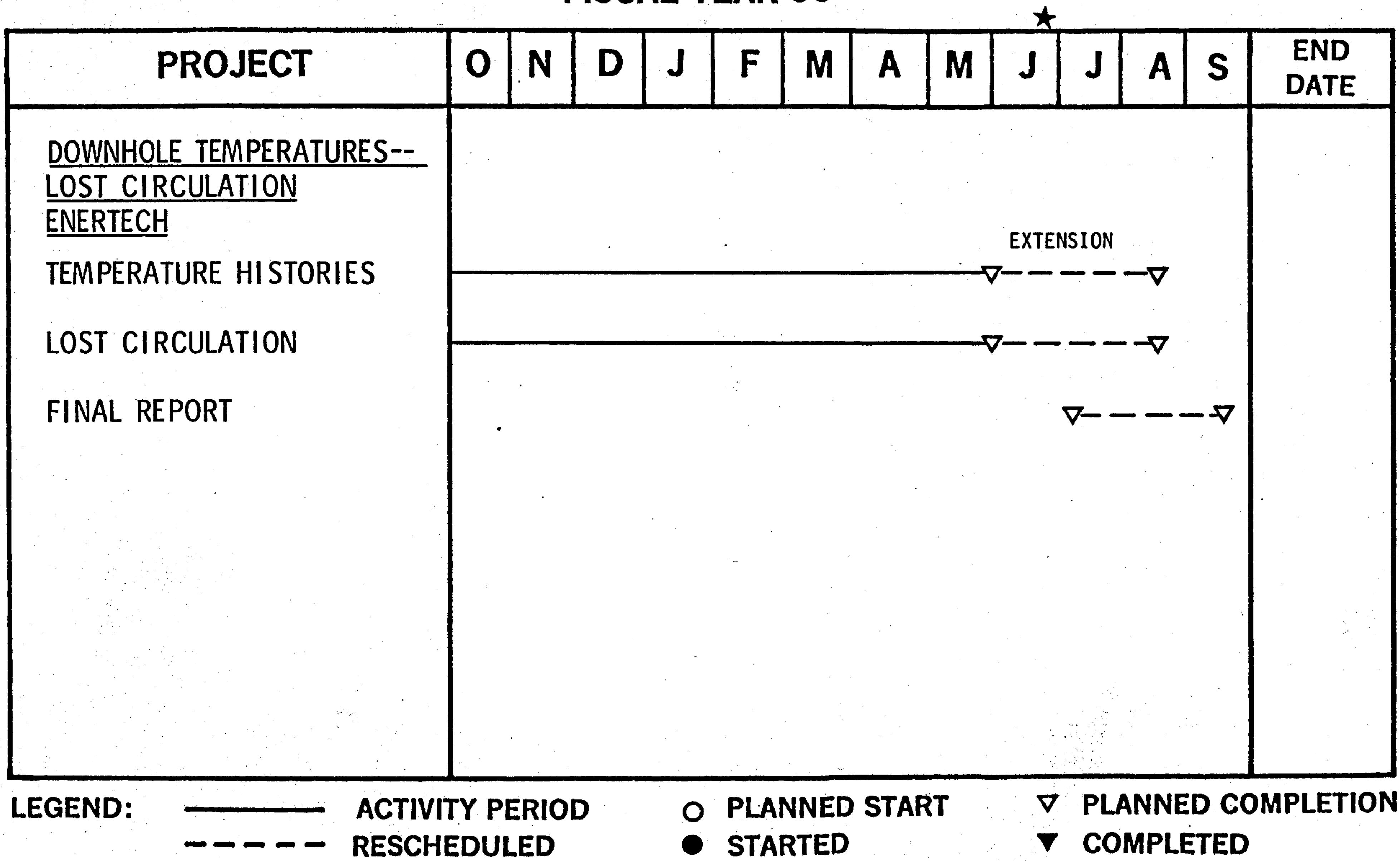
GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80



7.2 Temperature History and Lost Circulation Experience in Geothermal Wells

Contractor: Enertech Engineering and Research Co.
Principal Investigator: G. Wooley (713) 521-9294
Contract Period: 29 August 1979 to 31 May 1980
Contract Number: 13-8769 (Sandia)
Technical Consultant: T. Hinkebein (505) 844-5202

Project Objective

The objective of this project is to provide temperature histories required for geothermal well casing design and to provide a synopsis of causes and preventions of, and remedies to, lost circulation in geothermal environments. The data will be used for thermal simulation of wells during drilling, production, and injection, using the GEOTEMP code.

Project Status

An information survey plan was developed to acquire and organize the required well thermal history and lost circulation experience data. The data collection effort is nearing completion, and thermal simulations using the GEOTEMP code have been initiated. Extension of the project work period is in process.

Quarterly Progress

Temperature History — The literature search on thermal and mechanical properties of geothermal formations has identified 45 potential reference sources. These references are divided by year and key word, as shown in Table 16.

Table 16

Potential Reference Sources on Thermal and Mechanical Properties of Geothermal Formations

Key Word	Number of References by Year					
	1975	1976	1977	1978	1979 (thru Oct)	Total
Geothermal Property					1	1
Rock Property	7	3	7	2	8	27
Thermal Property			1	1		2
Rock Mechanics		3		2	2	7
Other			1	1	6	8
Total	7	6	9	6	17	45

Abstracts for these 45 references have been requested. Based on a review of the abstracts, appropriate papers are being selected as the final step in the search process. Selected papers will be reviewed for property data. Note that the key word "Rock Property" has provided more than half of the references.

Based on the 29 January 1980 interview with Los Alamos personnel, and from information obtained from Los Alamos publications, input data for thermal simulation of drilling of the Los Alamos GT-2 well have been compiled for application to GEOTEMP. Figure 20 shows the actual drilling schedule down to a depth of 1067 metres (3500 feet) in the GT-2 well. The total depth is 2932 metres (9619 feet), with a bottomhole temperature of 197°C (387°F). Additional data were requested from Los Alamos to complete the drilling schedule to total depth. For simulation purposes, the depth-time plot in Figure 20 has been approximated by the four straight-line segments shown in Figure 21.

The average mud circulation time per day is required by GEOTEMP because each day of drilling simulation is divided into a shut-in part (zero flow rate) and a circulating part. In Figure 22, the cumulative time as determined from the penetration rate for each 3.1-metre (10-foot) depth increment in the GT-2 well is plotted versus depth. Because depth penetration occurs only while drilling mud is circulating, the plot in Figure 22 represents the cumulative circulation time. For the depth interval shown in Figure 22, 37 to 488 metres (120 to 1600 feet), the circulating time is 2.25 days. As shown in Figure 20, the total time required to drill this depth interval is 6.75 days, indicating that the average circulating time per day is 8 hours. This average value will be assumed to occur throughout the drilling schedule.

The actual undisturbed geothermal temperature distribution is shown in Figure 23. A bilinear approximation of the geothermal gradient for use in GEOTEMP is presented in Figure 24.

Four drilling fluids were used in drilling the GT-2 well. Water-base mud, water, foam, and air were used for the depth intervals shown in Figure 20. In the GEOTEMP simulation, Figure 21, the different drilling fluids correspond to the four straight-line segments. Hence, the fluid properties can be changed in the simulation at the same time that the penetration rate is changed. The mud parameters follow:

Mud density	1108 kg/m^3	(9.25 lb/gal)
Plastic viscosity	0.01 Pa•s	(10.0 cp)
Yield point	1.4 Pa	(3.0 $lb/100\ ft^2$)
Flow rate	0.008 m^3/s	(3.0 bbl/min)

Although mud viscosity for the GT-2 well is reported in units of 40 seconds, corresponding to the Marsh funnel viscosity, GEOTEMP simulation requires values in terms of plastic viscosity and yield point. Since funnel viscosity cannot be converted directly to plastic viscosity and yield point, typical values of these parameters have been assumed for the water-base, low-solids mud used in drilling the GT-2 well.

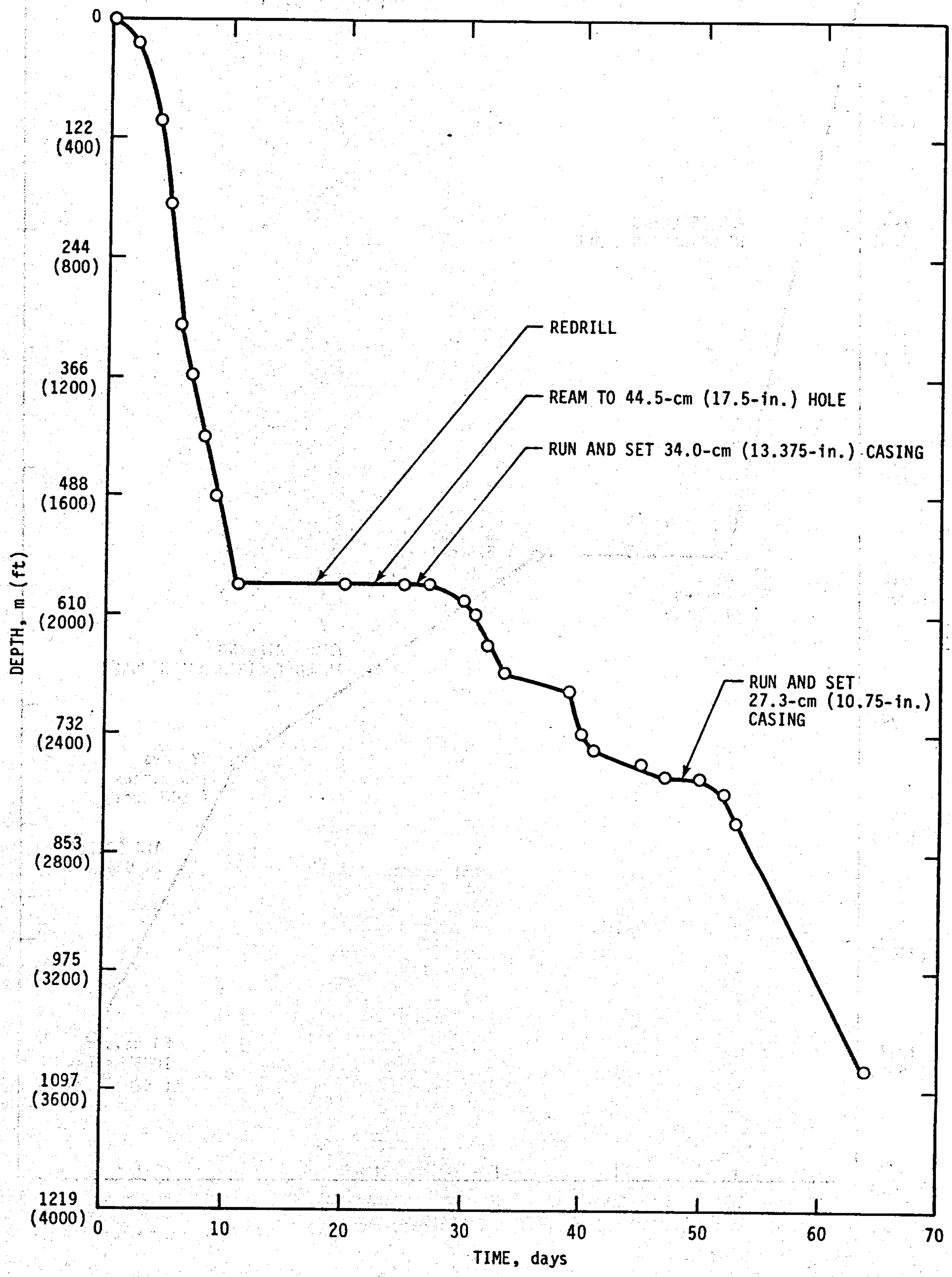


Figure 20. Drilling Schedule for Los Alamos GT-2 Well

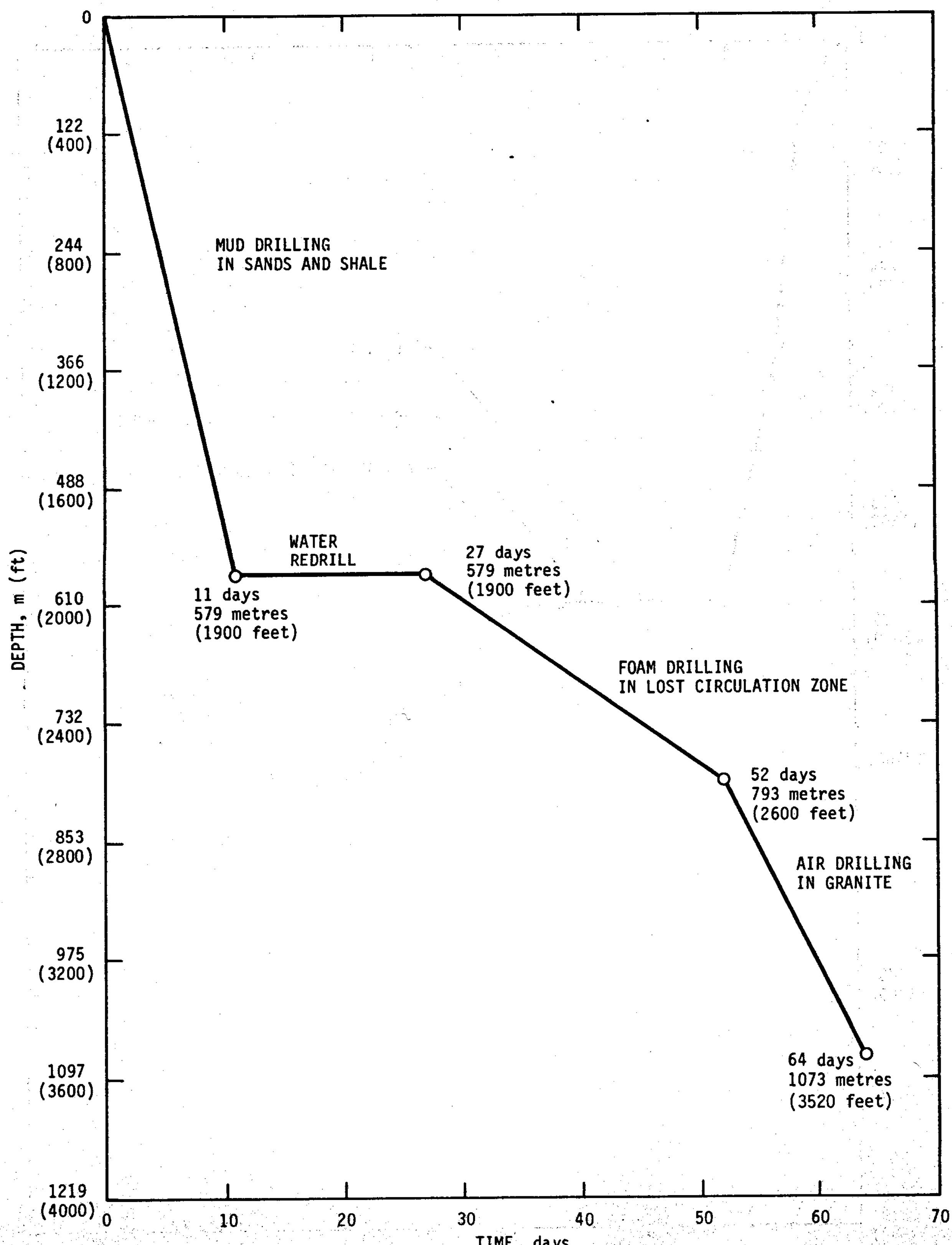


Figure 21. GT-2 Well Drilling Schedule Approximation for GEOTEMP Simulation

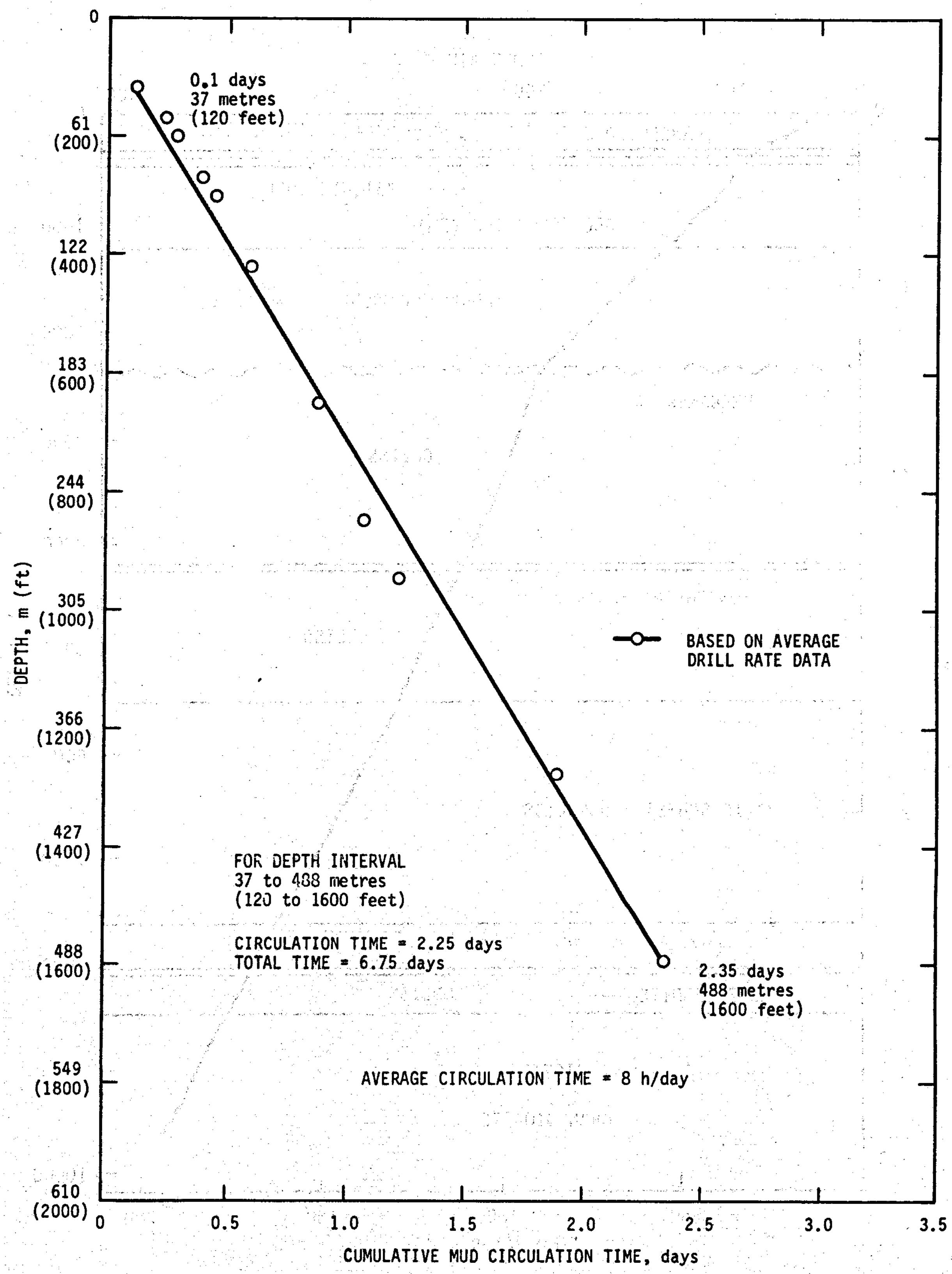


Figure 22. Mud Circulation Time for GEOTEMP Simulation of the Los Alamos GT-2 Well

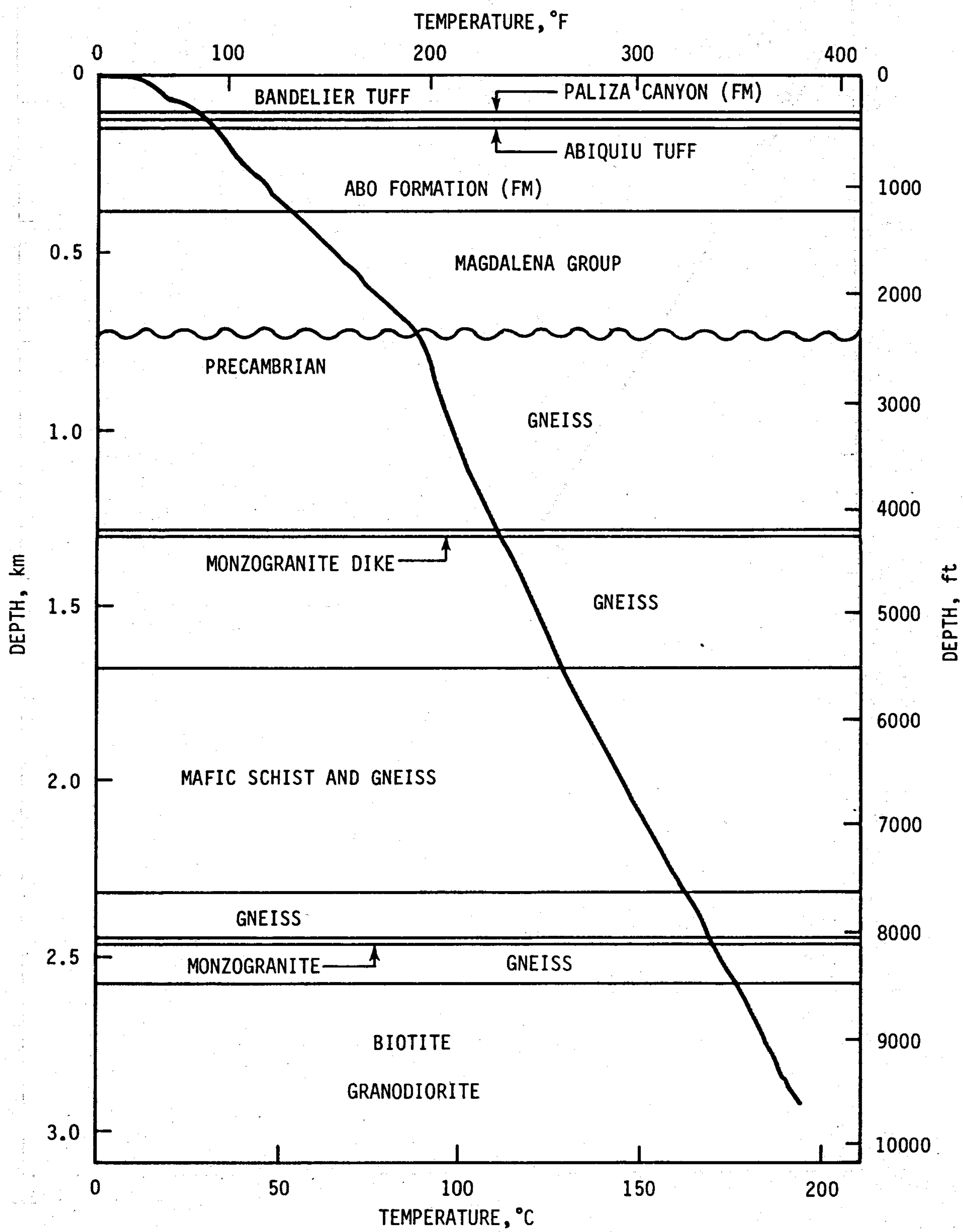


Figure 23. Geothermal Temperature Distribution for Los Alamos GT-2 Well

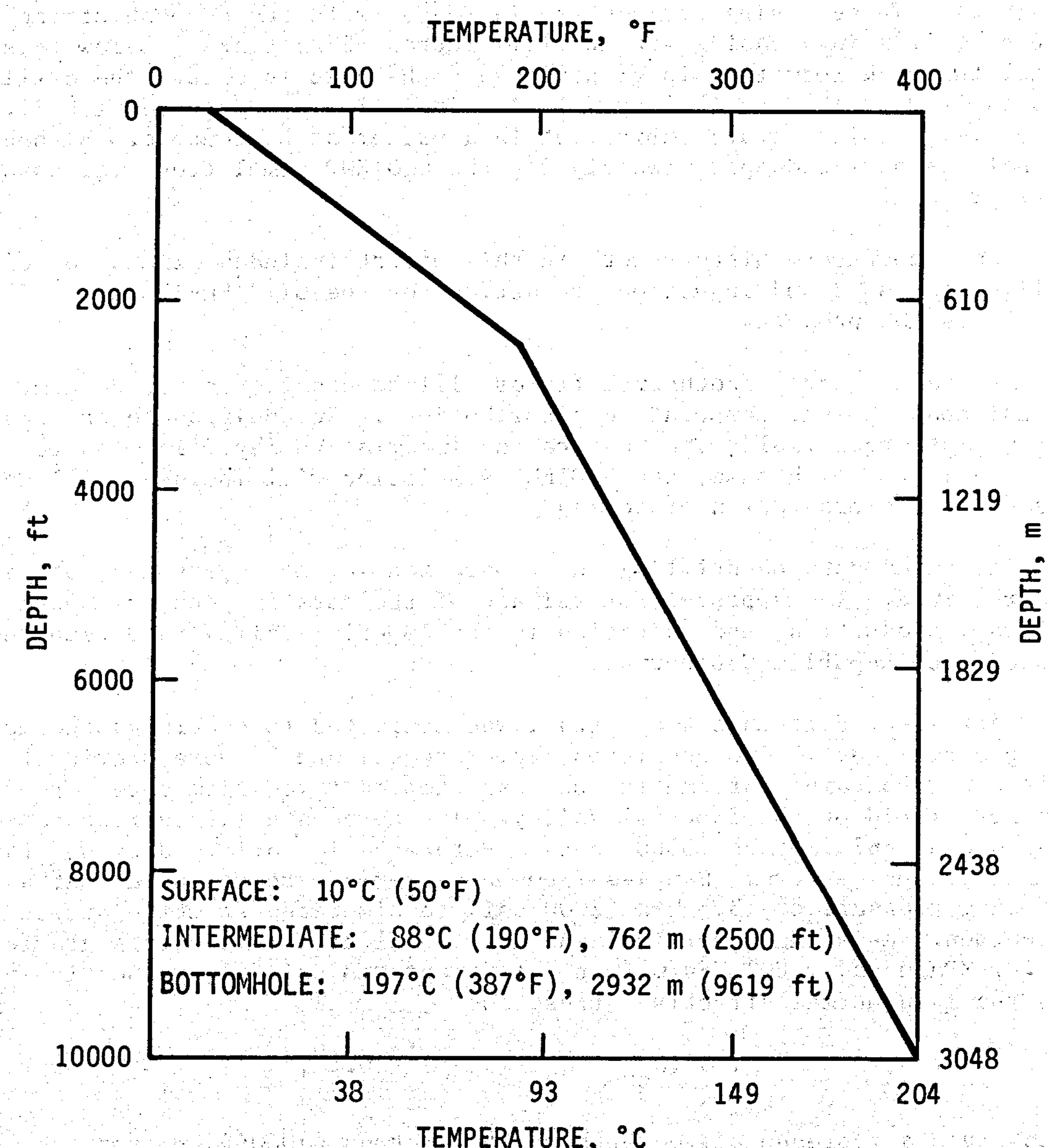


Figure 24. Los Alamos GT-2 Well Undisturbed Temperature Distribution for GEOTEMP Simulation

Water properties correspond to fresh water properties. Air and foam properties will be approximated in GEOTEMP with the assumption of low-density, low-heat-capacity fluids. Typical values for viscosity of air and foam will be used.

The GT-2 casing and cement program for GEOTEMP simulation is shown in Figure 25. Three casing strings are included, with the deepest string of 27.3-cm (10.75-in.) casing set at 772.7 metres (2535 feet). Below this depth, the rock formation is granitic, and the hole is open. The drill pipe is 14.0 by 10.2 cm (5.5 by 4 in.). The well is completed with 11.4-cm (4.5-in.^{2}) outside (o.d.) tubing set in a packer at bottomhole. Although the hole is deviated approximately 5°, the GEOTEMP simulation will assume a vertical well.

The temperature history work in this effort includes simulation of drilling for GT-2 and injection/production for the GT-2/EE-1 system of the Los Alamos HDR project.

A total of three geothermal fields will be considered for determining typical and atypical temperature distributions. In addition to the Los Alamos geothermal field, The Geysers and Imperial Valley will also be simulated. For each case, the GEOTEMP simulation will include drilling, injection, and production histories.

The Union data on drilling and production in The Geyers has not yet been received. The approval for release of the data is pending. Data on drilling, production, and injection in the Imperial Valley have been requested from Republic Geothermal.

Terra Tek, Salt Lake City, Utah, was contacted to obtain geothermal rock property data. Two documents, References 1 and 2, were provided. Reference 2 contains information on test samples taken from cores from the East Mesa field of the Imperial Valley. The core material represents a sandstone at 1676 metres (5500 feet). Reference 1 provides data on granite cores from The Geysers. Samples from these cores were tested dry at a confining pressure of 13.8 MPa (2000 psi) to simulate effective stress overburden. Assuming a vertical and horizontal effective stress gradient of 0.01 MPa/m and 0.007 MPa/m (0.6 psi/ft and 0.3 psi/ft), respectively, then the mean normal effective stress is

$$1/3\ (\sigma_{zz} + \sigma_{xx} + \sigma_{yy}) = 0.4\ ,$$

which gives a representative depth of 1524 metres (5000 feet) for the confining pressure of 13.8 MPa (2000 psi).

Mechanical properties laboratory test data for the granite are shown in Figures 26 and 27 and represent pure compression from the reference state of 13.8 MPa (2000 psi), i.e., strains during hydrostatic loading to the reference state are not included in the plots. The straight-line portions of the plotted data can be used to calculate elastic moduli for the simulated depth conditions. The right-hand-side of Figure 26 provides the Youngs modulus, and the left-hand-side gives the Poisson ratio. Figure 27

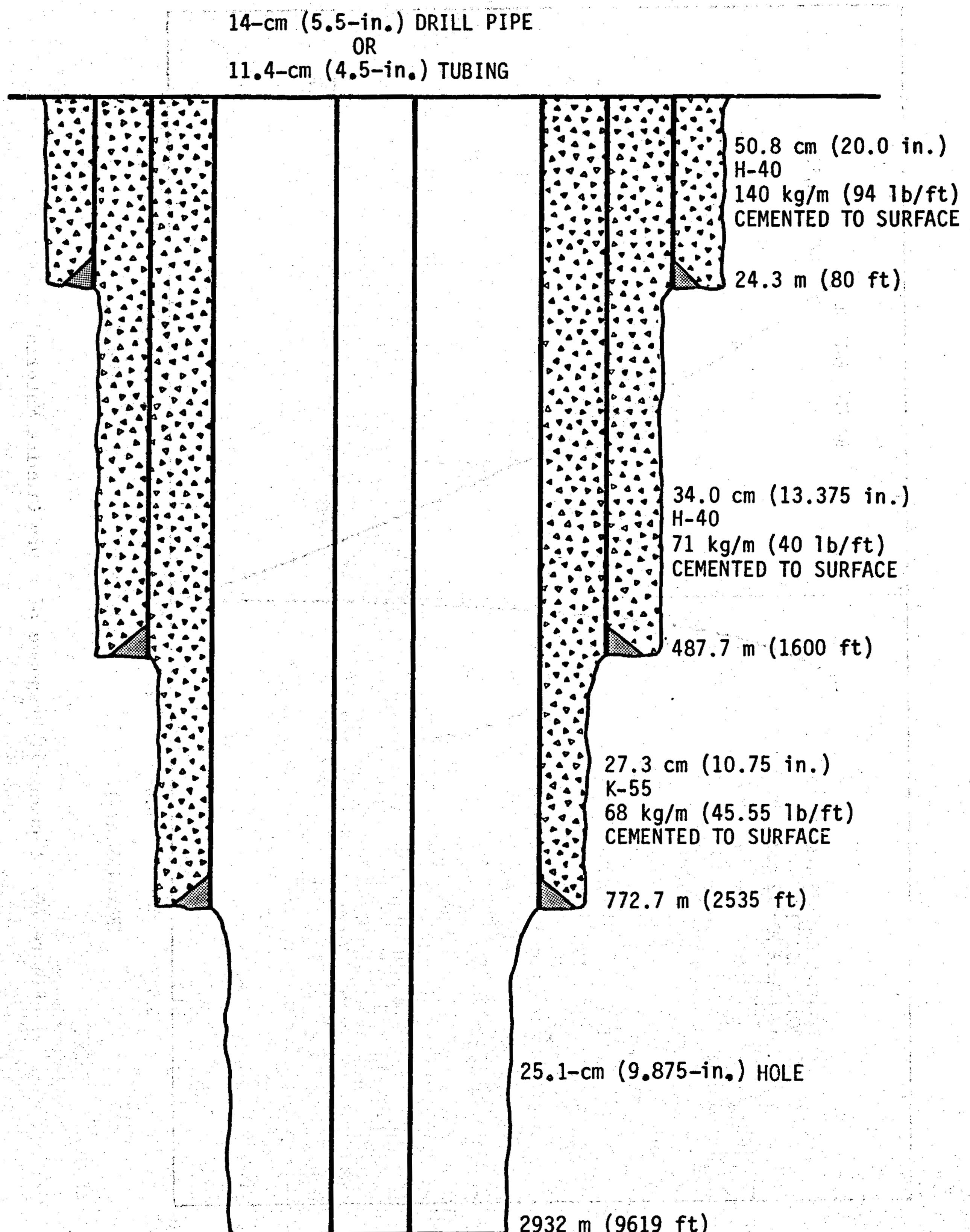


Figure 25. GT-2 Well Completion for GEOTEMP Simulation

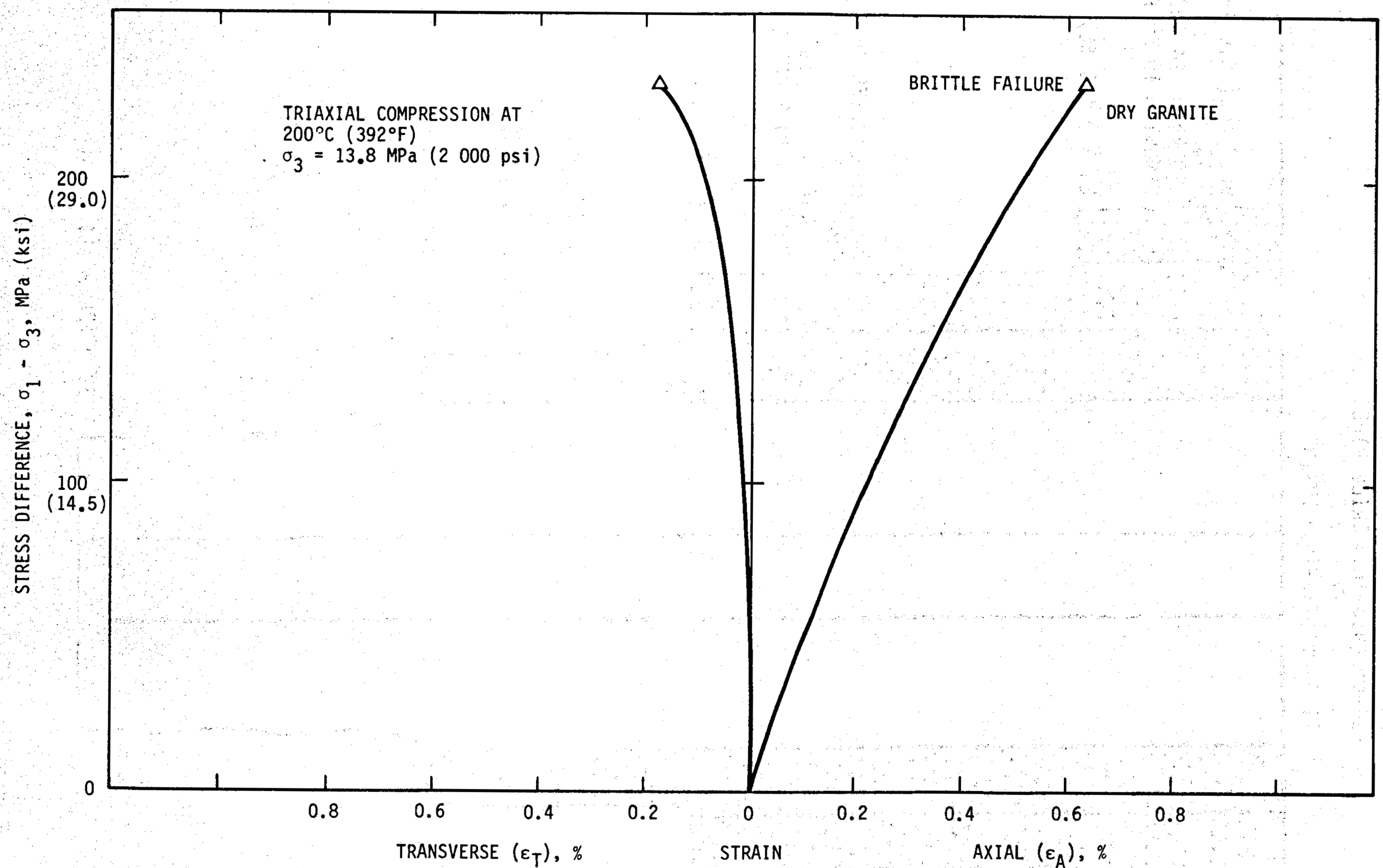


Figure 26. Mechanical Response of a Dry Granite Material

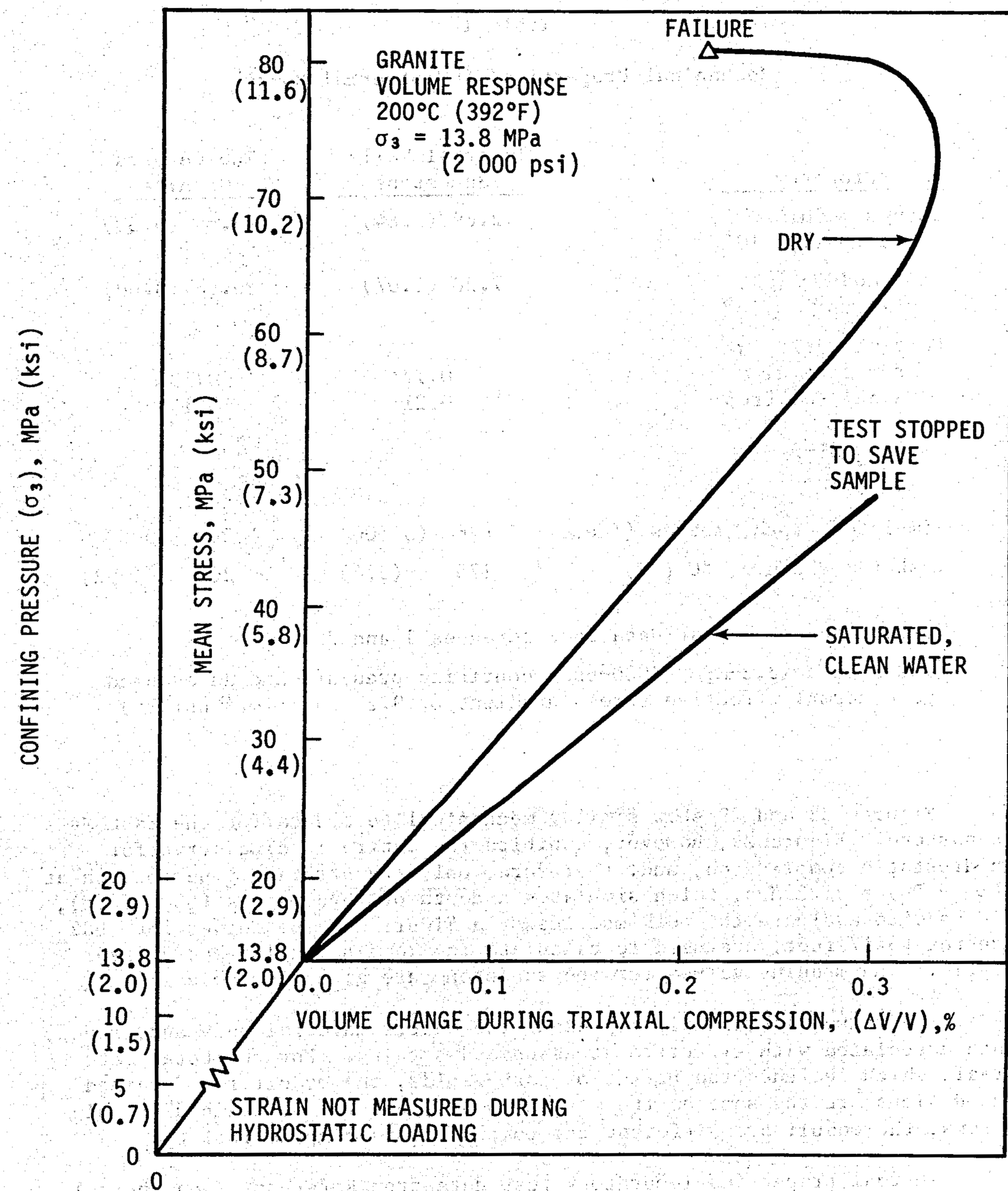


Figure 27. Volumetric Response of a Granite Material

gives the bulk modulus. Values of these properties are presented in Table 17. As a comparative test of the results, the Poisson ratio determined from the laboratory data shows reasonably close agreement with the value calculated from the other two moduli.

Table 17

Mechanical Properties of Geothermal Rocks[a]

Property	Imperial Valley Sandstone	The Geysers Granite
Youngs modulus, E, kPa (psi) x 10^6	12.69 (1.84)	43.64 (6.33)
Bulk modulus, K, kPa (psi) x 10^6	7.38 (1.07)	20.68 (3.00)
Poisson ratio, γ		
From test data	0.17	0.13
Calculated from $\gamma = \frac{3K-E}{6K}$	0.21	0.15
Simulated depth, metres (feet)	1 676 (5 500)	1 524 (5 000)[b]
Test temperature, °C (°F)	175 (374)	200 (392)

[a]Determined from test data in References 1 and 2

[b]Based on a 13.8-MPa (2000-psi) confining pressure and an assumed mean normal effective stress gradient of 9.2 kPa/m (0.4 psi/ft)

Figures 28 and 29 show similar mechanical test data for the East Mesa sandstone. Figure 29, however, exhibits the entire loading curve for hydrostatic compression, and, therefore, only the straight line portion at $(\sigma_3 - P_p) = 21.3$ MPa, which simulates a depth of 1676 metres (5500 feet), is used to evaluate the bulk modulus. In Figure 28, the curves for 1682 metres (5517 feet) are used to calculate the Youngs modulus and Poisson ratio. The modulus values for the sandstone are given in Table 17.

The values in Table 17 represent the matrix material only and, hence, are associated with effective stresses and strains. For the total material, which includes the effect of port fluids, the moduli for "drained" conditions are the same as the matrix moduli, but for "undrained" conditions, the moduli are different due to pore fluid compressibility.

Thermal properties laboratory test data from Reference 1 on thermal conductivity and thermal diffusivity for granite are shown in Figures 30 and 31. Heat capacity for a range of rock types is presented in Figure 32 and indicates that property values are governed mainly by temperature

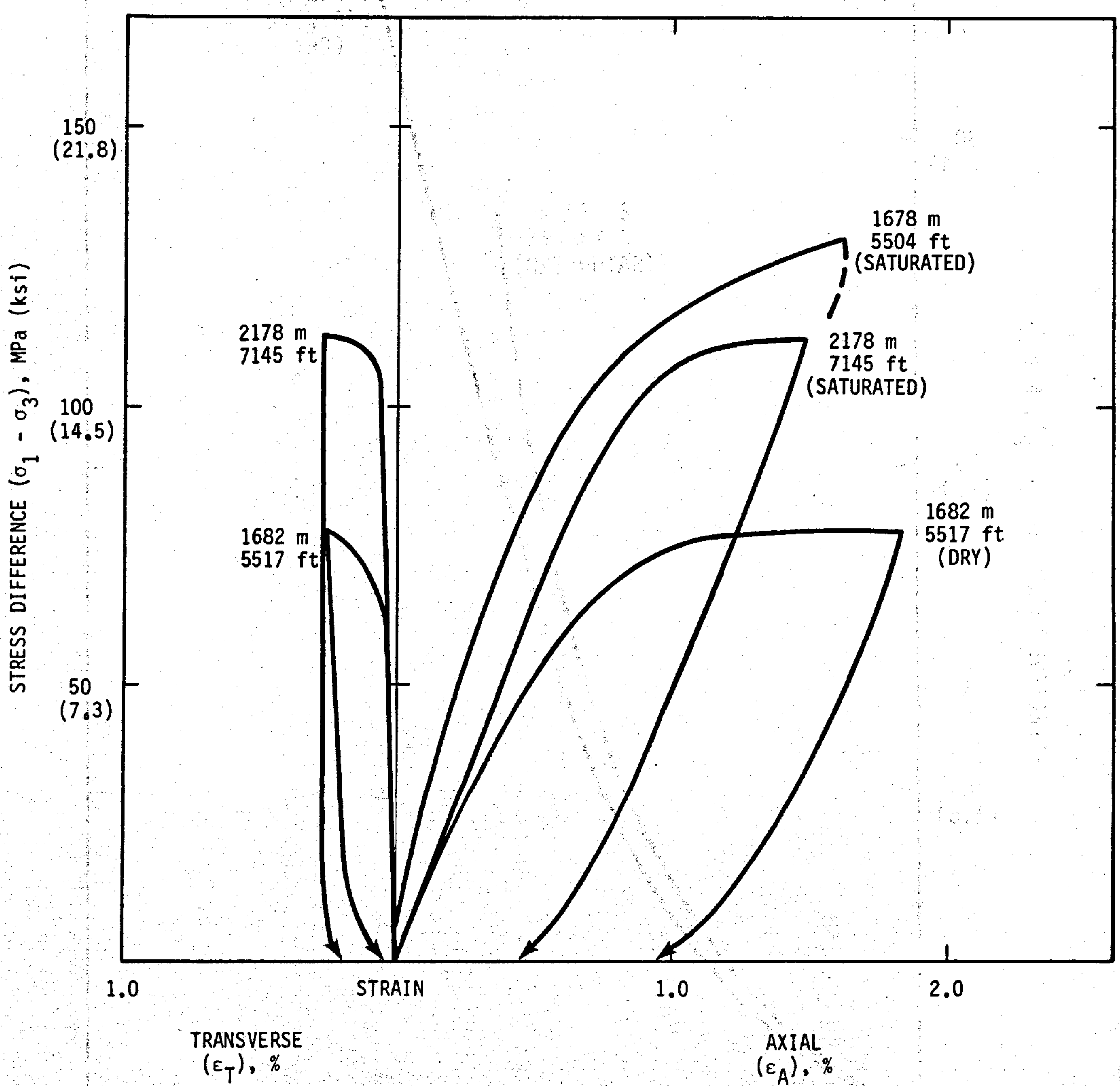


Figure 28. Axial and Transverse Strain Behavior in Triaxial Compression of East Mesa Sandstone

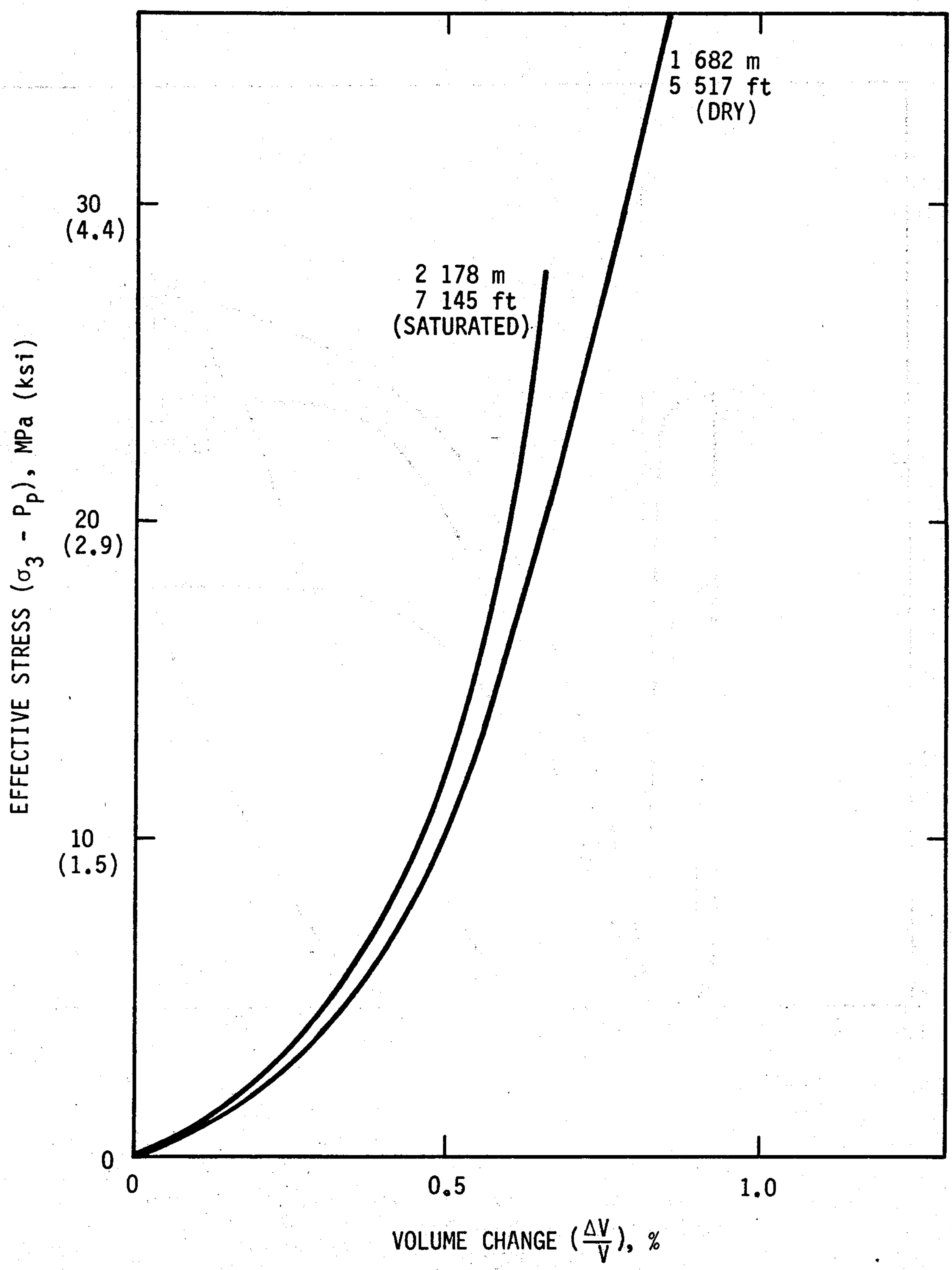


Figure 29. Volumetric Compression of East Mesa Sandstone

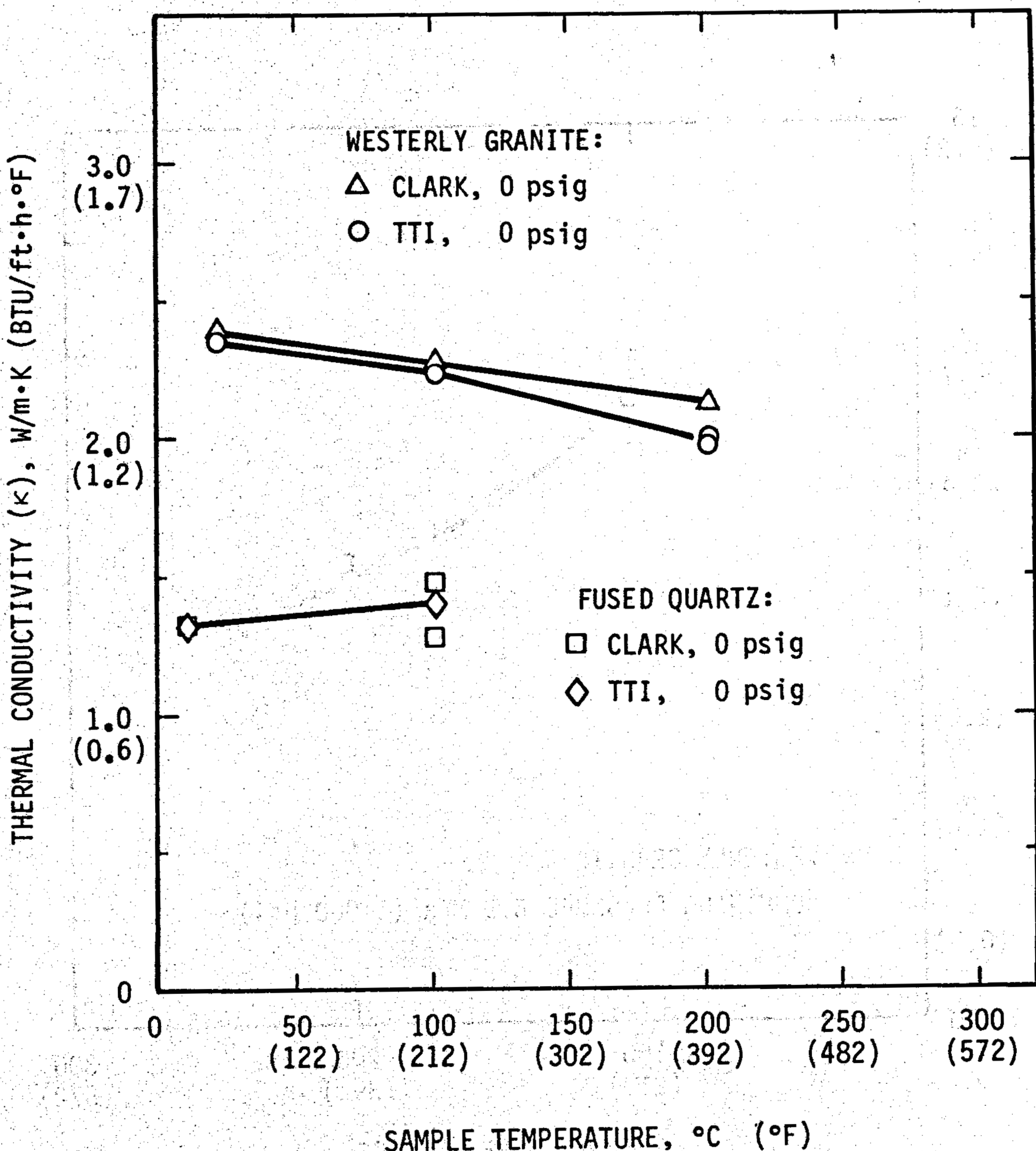


Figure 30. Thermal Conductivity Variation with Temperature

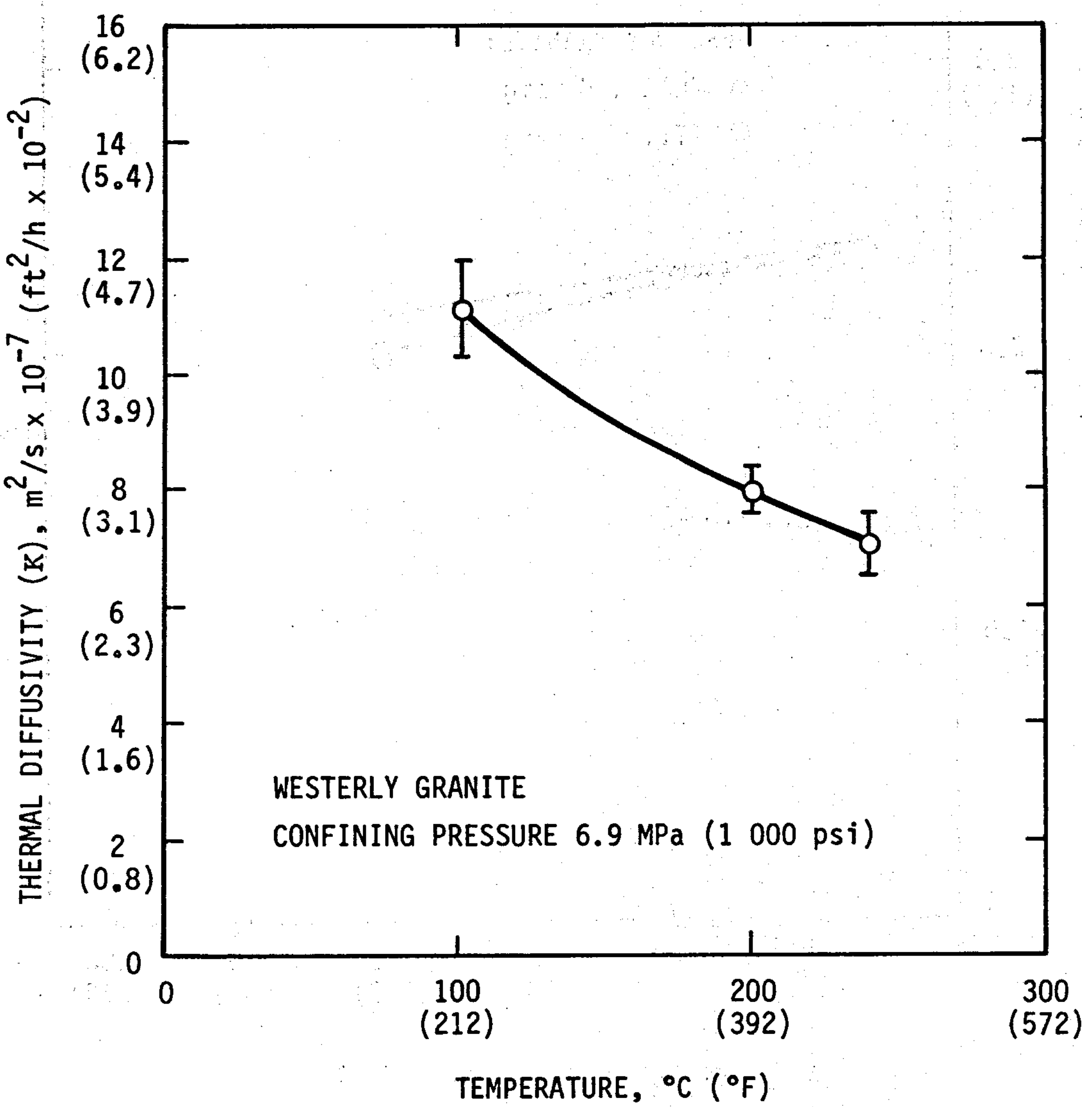


Figure 31. Thermal Diffusivity Response to Temperature of Westerly Granite

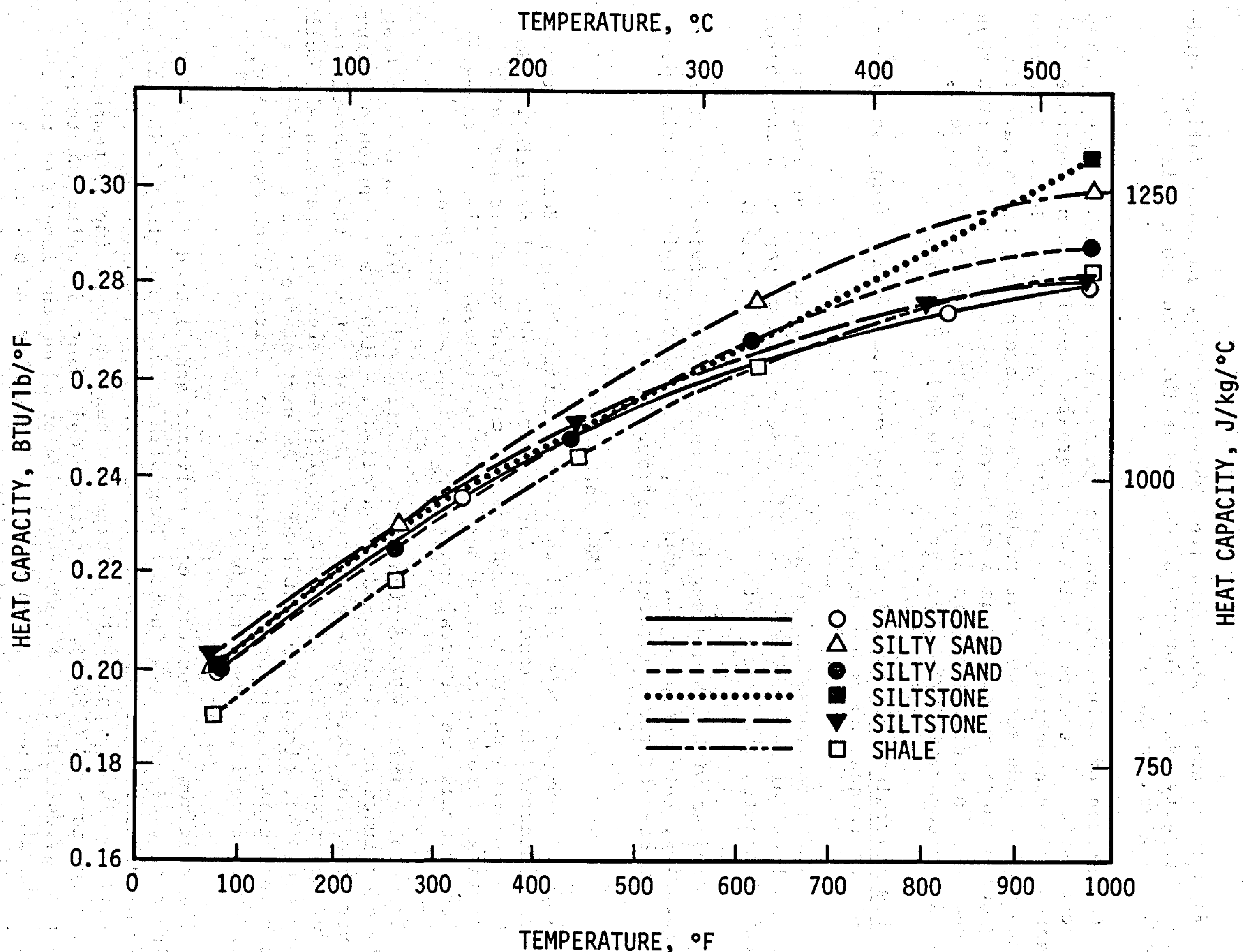


Figure 32. Experimental Heat Capacities of Different Rock Materials

rather than rock type. It is assumed that granite falls within the range shown in Figure 32. Table 18 lists data taken from Figures 30, 31, and 32 for two temperatures of interest, 100° and 200°C (212° and 392°F). Density is also presented.

Figures 33 and 34 show data from Reference 2 for Imperial Valley sandstone. Property values for the sandstone at 100° and 250°C (212° and 482°F) are given in Table 18.

Comparison of values for granite and sandstone indicate an interesting characteristic. Although granite has a greater density than sandstone, as expected, the conductivity of the granite is significantly less. Intuition suggests that a denser material would be more conductive, but apparently the granite matrix material has a much greater resistance to heat flow than has quartz. This difference is also supported by data in Reference 3, which lists conductivity values for granite and sandstone.

Lost Circulation -- The lost circulation literature search has uncovered 64 references, as shown in Table 19.

Abstracts for these references have been obtained, and an abstract review has been initiated. After the final selection of papers is made based on the abstracts, the papers will be retrieved and evaluated.

Interviews with two mud service companies, IMCO Services and NL Baroid Laboratories, were conducted in Houston, Texas, during this reporting period. Synopses of these interviews follow.

• IMCO Interview

IMCO in Houston recommended that their office in Long Beach, California, be contacted about lost circulation during geothermal drilling. The meeting in Houston concentrated on lost circulation materials and laboratory testing of lost circulation method effectiveness. A list of commercial lost circulation materials marketed by IMCO was provided.

In October 1979, IMCO designed and constructed a lost circulation test cell to evaluate an oil-base mud for a client. With the exception of testing performed for this one application, IMCO has not used the apparatus for any further testing. The IMCO cell is different from the standard API cell for testing lost circulation materials. As part of the task to provide a list of existing experimental equipment for lost circulation evaluation, the IMCO test cell is described below.

The aluminum cell consists of a cylinder and slotted insert. The cylinder is 0.61 metre (24 inches) long with a 10.2-cm (4-in.) i.d. and 12.7-mm (0.5-in.) wall thickness. It is rated for a pressure of 3.5 MPa (500 psi) and is equipped with an electric heat strap to impose temperatures of up to 66°C (150°F). The cylindrical insert is split lengthwise into two halves that form a wedge-shaped slot along the length of the insert. The slot size is 30.5 cm (12 in.) vertically and 6.4 cm (2.5 in.) horizontally, with a variable slot width depending on the insert halves used in a given test. Different insert halves can be combined to give slot

Table 18

Thermal Properties of Geothermal Rocks*

Property	Imperial Valley Sandstone		The Geysers Granite	
Temperature, °C	100	250	100	200
(°F)	(212)	(482)	(212)	(392)
Thermal conductivity, κ				
W/m•K	3.47	2.90	2.30	1.90
(BTU/ft•h•°F)	(2.01)	(1.68)	(1.33)	(1.10)
Heat capacity, c				
J/g•°C	0.900	1.075	0.900	1.050
BTU/lb•°F)	(0.215)	(0.256)	(0.215)	(0.251)
Thermal diffusivity, K				
cm^2/s	0.018	0.015	0.011	0.008
(ft^2/h)	(0.070)	(0.057)	(0.043)	(0.031)
Density, ρ**				
g/m^3	2.13	1.84	2.32	2.26
(lb/ft^3)	(133)	(115)	(144)	(141)
Simulated depth, metres	1 676	1 676	1 524	1 524
(feet)	(5 500)	(5 500)	(5 000)	(5 000)

*Determined from test data in References 1 and 2

**Calculated from $\rho = \kappa/Kc$

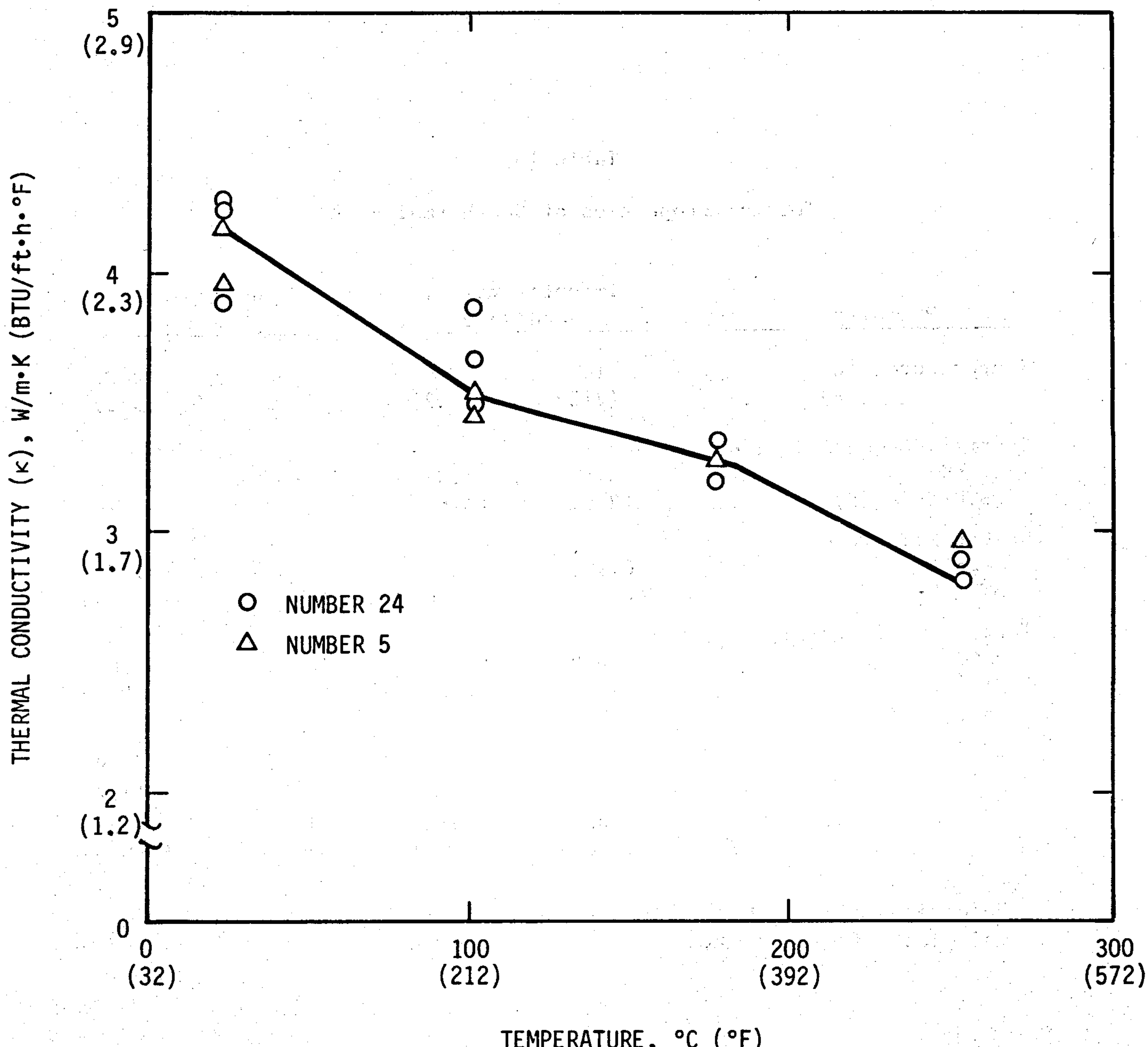


Figure 33. Thermal Conductivity Measurements on East Mesa Sandstone

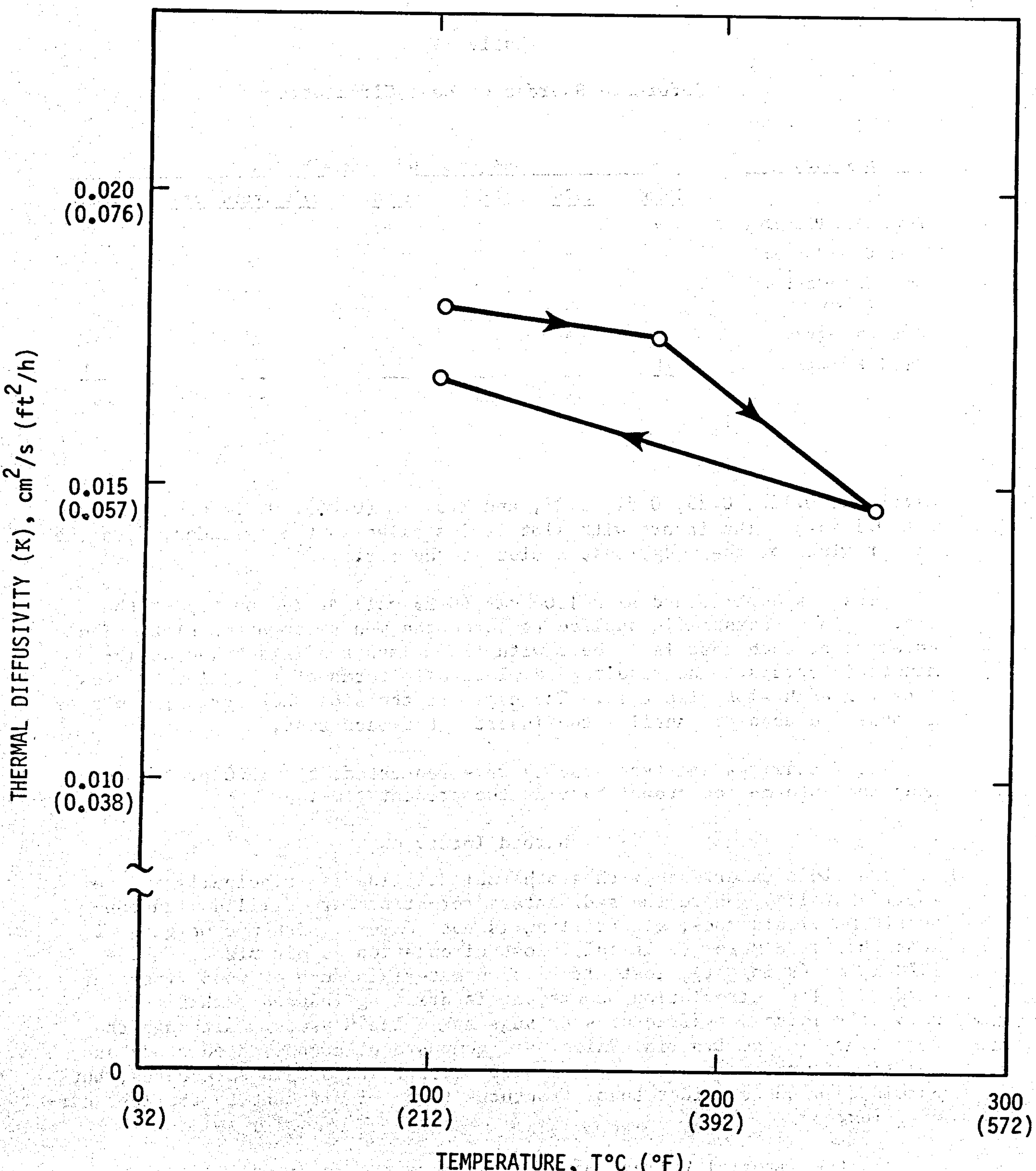


Figure 34. Thermal Diffusivity Measurement on East Mesa Sandstone

Table 19

Reference Sources on Lost Circulation

Key Word	Number of References by Year					
	1975	1976	1977	1978	1979 (thru Oct)	Total
Formation Plugging	9	5	5	4	4	27
Lost Circulation	6	4	3		2	15
Lost Circulation Additive			3		1	4
Plugging Agent	6	4	2	4	1	17
Thief Formation	1	—	—	—	—	1
	22	13	13	8	8	64

widths of 0.127, 0.25, 0.51, 1.27, and 2.54 mm (0.005, 0.01, 0.02, 0.05, and 0.1 in.). The insert with slot is installed in the cylinder, with the larger width of the wedge-shaped slot at the top.

Tests are performed with 1000 cm^3 (0.26 gal) of mud on top of the slot. Fluid pressure is applied to force the mud through the slot. The duration of each test is 1 hour, with fluid loss readings taken at 15-minute intervals. The results are plotted in terms of fluid loss versus time for each slot size used. The depth in the slot where bridging occurs is observed upon dismantling the insert after each test.

Cell drawings and test results were requested, but IMCO prefers to keep the information proprietary at the present time.

• Baroid Interview

Baroid's experience with geothermal drilling is principally in the Imperial Valley, where the sedimentary formations are drilled with conventional liquid muds; air drilling is not common. With mud weights of less than 1078 kg/m^3 (9 lb/gal), lost circulation is minimized. Above 1078 kg/m^3 (9 lb/gal), lost circulation materials such as wood fibers are used. If lost circulation occurs, it is drilling induced rather than naturally induced by fractures or vugs as in The Geysers. Although the formations in the Imperial Valley are composed of consolidated sands and shales, natural fractures have been observed by Baroid in some cores, but Baroid does not consider these fractures to be significant to the lost circulation.

In the Imperial Valley, Baroid considers the major drilling problem to be temperature, not lost circulation. Typical muds offered by Baroid for drilling in the 204° to 260°C (400° to 500°F) temperature range consist of lignite, clay, bentonite, and surfactant to reduce high-temperature gelation. In addition to the use of the surfactant, sepiolite is sometimes used as a substitute for a portion of the bentonite to minimize gelation and baking. Ratios of sepiolite to bentonite range from 25 to 50%. Cypan is also used as an additive for high-temperature filtrate control but is very sensitive to calcium in formation water. Evaporative-type cooling towers are used to maintain mud temperatures below 54°C (130°F) inlet and 82°C (180°F) outlet.

With regard to cementing in the Imperial Valley, Baroid is not aware of lost circulation problems, even though cement weights exceed 1078 kg/m^3 (9 lb/gal). It was mentioned that remedial cementing is often necessary because of cement fingering caused by underground water percolation. No well control problems due to high-pressure gas or hydrogen sulfide have been encountered.

Two types of casing problems in the Imperial Valley were noted. One is corrosion associated with underground water percolation. The other is thermal parting and/or buckling due to temperature changes during operations.

- Phillips Geothermal Drilling Experiences

Drilling experiences in six geothermal areas were discussed with Phillips Geothermal, Salt Lake City, Utah. The areas discussed were as follows:

Utah:	Roosevelt Hot Springs
Iowa:	Soda Lake/Mountain Home Site
Nevada:	Humboldt House Reservoir
Nevada:	Desert Peak
Nevada:	Steamboat Springs
California:	Plumas County

Most experience with lost circulation has occurred in the Roosevelt lease, where six wells have been drilled by Phillips and five wells by other operators, including Getty, McCulloch, and Amax Thermal Power. Depths to the top of the reservoir at Roosevelt vary across the field between 366 and 2286 metres (1200 and 7500 feet). Lost circulation occurs in the granite, which is covered by a mantle of sedimentary formations.

In Roosevelt Well No. 82-33 drilled by Phillips, lost circulation was particularly severe. The problem was aggravated in part by the fact that no formation fluids were encountered during drilling of the lost circulation zone and, hence, fluid pressure differential was highly overbalanced. Casing was finally set below 1829 metres (6000 feet). The well is presently used for reinjection of fluids produced during tests in nearby production wells. When first used as an injector, the well would not accept all fluid injected, and the casing was then perforated opposite the lost circulation zone. No injection problems have occurred since. Initially, after the casing was perforated, the well lost all injected fluid to the lost circulation zone, and no fluid remained standing in the casing. But after a number of injection periods, the well began holding fluid, indicating that the lost circulation zone became less permeable.

The lost circulation problem in Well No. 82-33 started at 504 metres (1655 feet), when the drill pipe dropped 0.61 metre (2 feet). Approximately 2 weeks were required to drill through the lost circulation zone from 504 to 610 metres (1655 to 2000 feet). The day-by-day experience, as recorded, is shown in Table 20. The list of lost circulation materials used in this well, including huge amounts of lumped coal, alfalfa cubes, and plastic bags filled with wood and barite, demonstrates the severity of the problem. The extra cost in rig time and materials represents a major part of the total well cost.

Table 20

Lost Circulation Experience Record, Roosevelt Lease, Utah

DATE	Lost Circulation Control Activity
11-19-75	Lost returns at 1655 to 1657 ft; fractured formation. Mixed pit with 30% lost circulation materials (LCM); drilled to 1678; no returns.
11-20-75	Lost 1400 bbl mud. Pumped 300 bbl mud, 35% LCM; hole filled to 50 ft. Pumped 300 bbl mud, 35% LCM. Pumped 100 bbl mud in drill pipe, 25 bbl; mud in annulus; no returns. Pumped high-water-loss pill; no returns. Mixed 1 pit mud, 35% LCM; pumped in hole. Mixed and pumped 50 sacks Class B cement; tagged top of cement.
11-21-75	Mixed and pumped 50 sacks Class B cement; tagged cement. Mixed and pumped 50 sacks Class B cement; tagged top of cement at 1647 ft. Dropped 2 tons alfalfa cubes plus 300 bbl of water; no fill in hole. Dropped 1-1/2 tons alfalfa cubes plus 200 bbl water; no fill. Dropped 200 gal soaked burlap sacks. Dropped 1-1/2 tons alfalfa cubes plus 200 bbl of mud, 35% LCM.
11-22-75	Bit in hole; no fill. Pumped 200 gelled burlap sacks. Pumped 3 tons lumped coal, 6 to 9 in. Pumped 2 tons alfalfa cubes. Hole filled up. Drilled bridges to 1650 ft; lost returns.
11-23-75	Dropped 180 burlap sacks in hole. Dropped 1 ton lumped coal, 6 to 9 in. Dropped 2-1/2 tons alfalfa cubes in hole. Dropped 2 tons lumped coal in hole.

Table 20 (Continued)

Lost Circulation Experience Record, Roosevelt Lease, Utah

DATE	Lost Circulation Control Activity
11-24-75	Bit drilled bridges to 750 ft; lost returns. Bit to 1650 ft; hole clear. Dropped 7 plastic bags filled with mud (10-in. o.d. by 15 ft long) followed with gelled mud. Hole clear to 1658 ft.
11-25-75	Dropped 2 tons lumped coal in hole. Pumped 1 pit mud, 35% LCM; drilled bridges 1675 ft. Spot 150 sacks barite plug; no fill. Spot 150 sacks barite plug; no fill. Pumped 1 pit mud, 35% LCM.
11-26-75	Dropped 400 plastic bags filled with wood chips and barite in hole; flushed with 400 bbl mud; no fill.
11-28-75	Flushed 420 gal diesel oil. Flushed 840 gal diesel oil mixed with 6 gal DOC No. 12. Flushed with 200 sacks Class B cement.
11-30-75	Drilled 12 hours; no returns. Drilled 15 hours to 2004 ft; tried to run logs.
12-2-75	Ran 9-5/8 in., 40-ppf casing; set at 2001 ft. Pumped 200 sacks Class B cement plus silica flour. Pumped 600 sacks Class B cement plus silica flour. Drilled to 2160 ft; lost returns. Pumped mud with coarse mica flakes, Fibertex, Plug-It, cotton seed hulls. Pumped mud containing high seal paper. Drilled to 2240 ft; full returns. Carrying 12% LCM in mud.
12-4-75	Full returns.

No casing problems such as buckling or thread jump have occurred at Roosevelt, even though 10 to 12 cycles of on-off production have taken place.

Concentric drill string was considered and was inquired about for drilling lost circulation zones but has not been used. Phillips has not used any sensing devices or detection methods in lost circulation zones. However, it was reported that Amax Thermal Power has run the borehole televiewer in wells after drilling to inspect fractures.

In 1978, Phillips drilled wells in Idaho in two sites, Soda Lake and Mountain Home. All wells were nonproductive. Lost circulation was encountered in metamorphic formations but was controlled with commercially available lost circulation materials.

During 1976 through 1979, three sites in western Nevada were drilled by Phillips. In the Humboldt House reservoir, three wells were completed--two productive hot water wells and one dry well. No lost circulation problems were encountered. In the Desert Peak reservoir, three commercial wells were drilled without lost circulation. In the Steamboat Springs site, lost circulation was experienced at shallow depth down to 107 metres (350 feet). Near the surface in an interval of 17 to 21 metres (55 to 70 feet), a lost circulation zone consisting of rocks and boulders was plugged by using Class G cement. Cement plugs were also used between 58 and 61 metres (190 and 200 feet). Below 85 metres (279 feet), the hole was drilled without returns to 107 metres (350 feet), where a 50.8-cm (20-in.) casing was run and set with cement/perlite by dropping the mixture in the annulus. Between 914 metres (3000 feet) and a total depth of 937 metres (3073 feet), drilling was done by adding 143 m^3 (900 bbl) of water or aerated water per day, but no lost circulation material was used.

In 1978, a well in Plumas County, California, was reentered for deeper drilling in metamorphic rock. Lost circulation was controlled with lost circulation material.

References

1. D. O. Enniss, S. W. Butters, R. Lingle, R. G. Van Buskirk and F. R. Prater, "Capabilities to Measure Geothermal Material Properties at Simulated In Situ Conditions," Terra Tek Report TR 79-49, submitted to Department of Energy, Division of Geothermal Energy, July 1979.

2. "Rock Properties Source Book," Terra Tek Report TR 80-13, submitted to Department of Energy, Division of Geothermal Energy, March 1980.

3. <u>CRC Handbook of Chemistry and Physics</u> (Boca Raton, FL: CRC Press, Inc., 1979) p E-16.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

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PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
LOST CIRCULATION MAPPING TOOLS													
MAURER ENGINEERING													
COMPILE TOOL LIST								●—▼					
INDUSTRY SURVEY								●—	—	▽			
EVALUATION OF TOOLS AND TECHNIQUES									○—	—	—	▽	
FINAL REPORT													OCT 80

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

7.3 Lost Circulation Mapping Tools and Techniques

Contractor:	Maurer Engineering, Inc.
Principal Investigator:	W. McDonald (713) 683-8287
Contract Period:	1 May 1980 to 31 October 1980
Contract Number:	49-1458 (Sandia)
Technical Consultant:	J. Kelsey (505) 844-6968

Project Objective

The objective of this project is to assess the state of the art of mapping lost circulation zones in geothermal wells. Tools and techniques will be identified, described, and evaluated concerning their capabilities to map lost circulation zones. Cost, effectiveness, accuracy, and limiting factors such as high temperatures will be considered in the assessment.

Project Status

The project was initiated during this reporting period. An initial list of tools and techniques that can be used to map lost circulation zones has been compiled. The list includes mechanical and electrical devices as well as drilling-fluid-monitoring techniques. The survey of industry for additional information on lost circulation mapping tools and techniques has been initiated and is continuing.

Quarterly Progress

A comprehensive list of tools has been prepared. New tools added to the list include downhole cameras, televisions, and straddle packers.

To date, several technical reports and brochures have been collected for the tools in the master tool list. Work is well underway concerning an explanation of how the various tools operate and the techniques necessary for effective use and interpretation of such tools in relationship to contract requirements. Several people knowledgeable in the use and capabilities of the tools have been located and have agreed to assist Maurer Engineering in this endeavor. Interviews are being planned and will begin in the next quarter.

The collected data are being classified into three major files which are appropriately coded for cross-referencing. These files are

- Manufacturer File -- Includes all manufacturers that have been located to date who provide services and tools found in the master tool list.

- Customer File -- Will include all contacted companies that use the services and products outlined in this program. These companies will be asked to give their evaluation of tool performance and their view on the cost effectiveness of the provided services.

- Tool File -- The tool file has been divided into five major categories by the type of sensing element utilized. The categories are acoustic, chemical, electrical, mechanical, and radioactive.

Work has been started on defining the parameters that the tools must provide to completely quantify fracture size and to locate lost circulation zones. Several tentative schemes are now being discussed, and a draft plan will be provided for Sandia's review. When completed, the plan will provide a firm foundation for numerically rating the tools' capabilities with respect to performance, risk, schedule, and cost.

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 underway to expand capabilities to predict transient wellbore temperatures during drilling, circulating, injection, and production in geothermal wells; to determine optimal number, size, and placement of nozzles used for bit cooling and cleaning; to optimize the design of PDC geothermal bits by study of the stress buildup and chip formation processes of rock-cutting tools utilizing PDC cutters; 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; to evaluate elastomers for use in geothermal applications; and to extend 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. Validation of the model involved comparison of computer predictions with actual field measurements of temperature in oil and gas and geothermal wells. The model is being modified to predict single-phase, compressible flow, transient wellbore temperatures.

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 use of the model.

A laboratory facility for use in optimizing drill bit hydraulics has been designed and fabricated.

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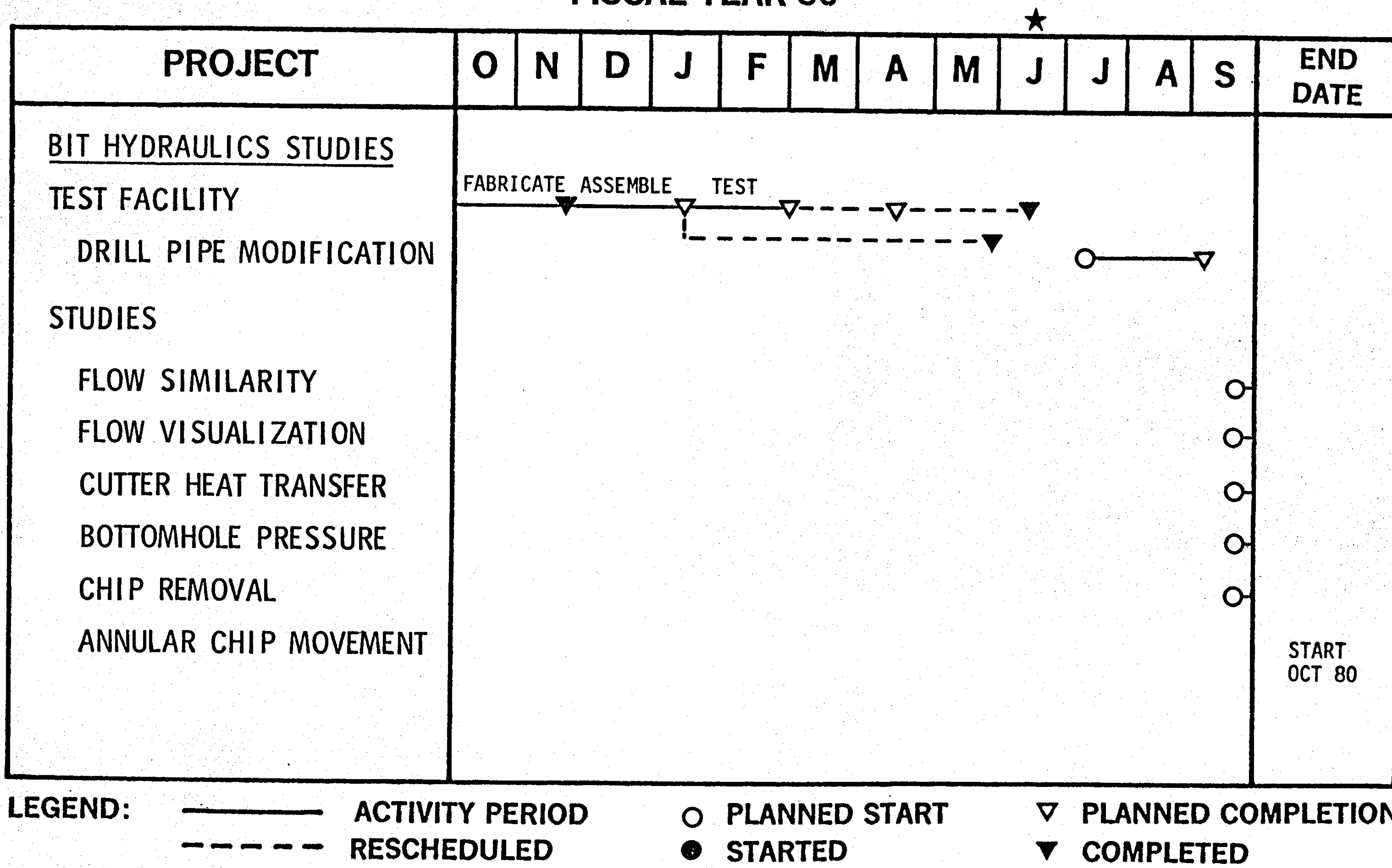

8.1 Bit Hydraulics Studies

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 will be conducted to determine optimal position, size, and placement of nozzles used for cooling and cleaning purposes. A bit hydraulics laboratory will be built in order to visualize the flow field along the bit face.

Project Status

The design and assembly of the test facility have been completed. A technical investigation procedure for the study has been updated. The fabrication of the test stand has been completed. The proof testing of the test stand resulted in a damaged drill pipe, potentially delaying the bit hydraulics studies until September 1980.

Quarterly Progress

The assembly of the bit hydraulics test facility was completed this reporting period. The Safe Operating Procedures manual was approved within Sandia, and the facility was successfully pressure tested. However, a problem with rotation of the bit was encountered.

The facility is designed to provide bit rotation by rotating the drill pipe that supplies hydraulic fluid to the bit. This drill pipe is supported by two bearing assemblies. Fluid is sealed by rotary O-rings at four points along the drill pipe. Because these seals require a smooth rubbing surface, the pipe was plated along its entire length.

To begin the testing, the drill pipe drive motor was engaged to test the bit rotation capability. Initially, the system worked well, and rotation to approximately 400 rpm was achieved without the supplying of full power to the motor. After approximately 1 minute of operation, however, the torque required to rotate the drill pipe increased significantly, eventually reaching the point at which the motor could no longer rotate the drill pipe. The motor was disengaged, and the test stand was disassembled so that the components could be examined. It was found that the drill pipe plating had begun to flake due to a poor plating job. Although flaking was widespread over the surface, localized flaking at the seal interfaces had caused the problem. The resultant surface roughness had torn the elastomeric seal surfaces, thereby increasing interface friction and torque.

The drill pipe is currently being inspected to determine the feasibility of replating. If the pipe cannot be replated, a new pipe will be machined to the required dimensions. It is believed that either of these solutions will delay testing until September. The project schedule has been revised accordingly.

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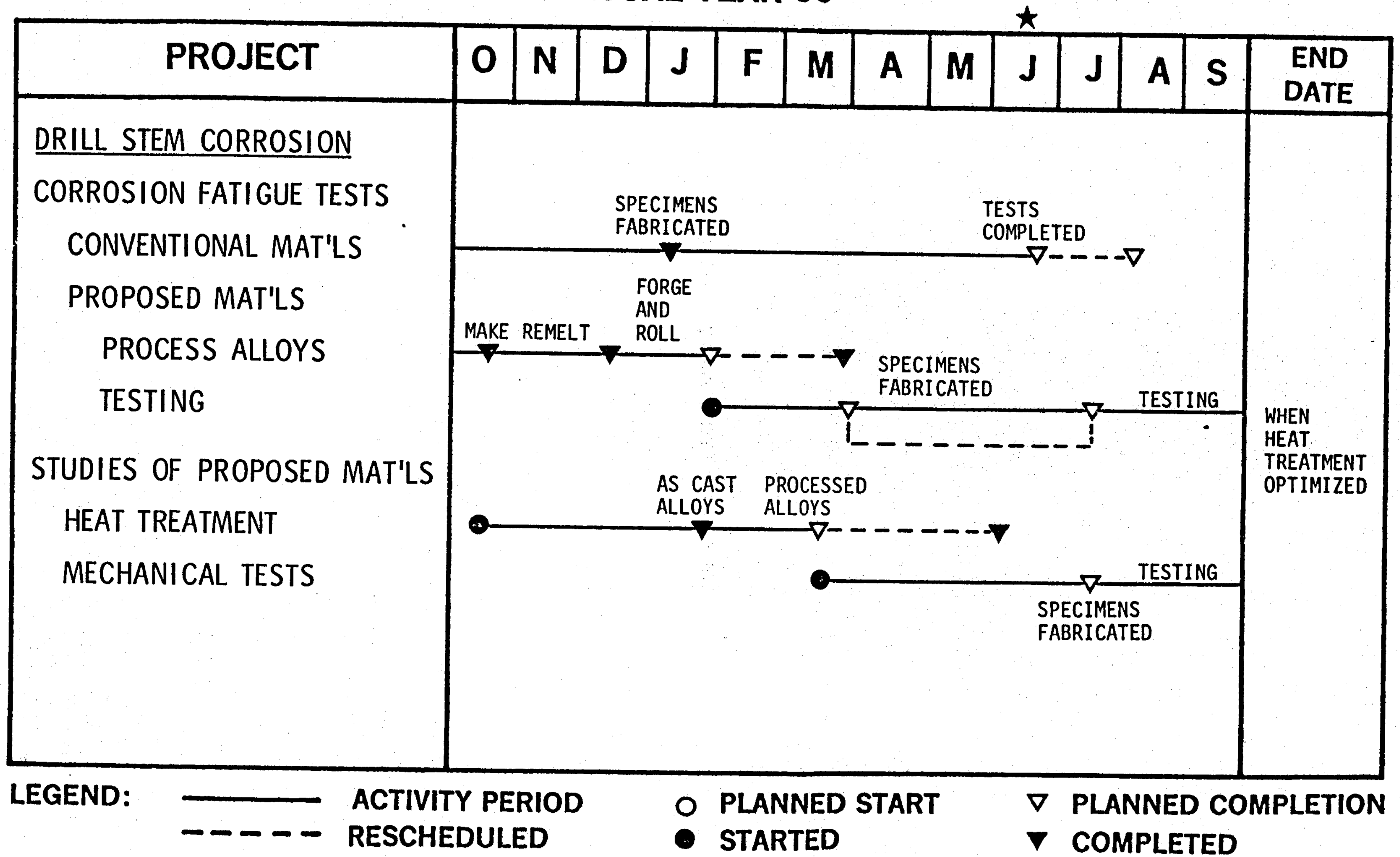

8.2 Drill Stem Corrosion

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 H_2S environment without large sacrifices to its mechanical properties or cost.

Project Status

An Internal R&D research report has been issued. The test facility design has been completed, and the facility will be built by the time test specimens are ready for testing. Compositional changes to the drill stem material have been defined, and conventional drill stem material suitable for the corrosion fatigue study has been identified. Unavoidable delays in the delivery of the steel for test specimens delayed the inception of the test program. However, the dual-phase steel alloys have now been made and the conventional drill stem material delivered. General corrosion tests have been initiated. Processing of the dual-phase alloys has been completed, and fabrication of specimens for the heat treatment experiments is proceeding.

Quarterly Progress

The low-alloy, dual-phase steels designed for resisting corrosion fatigue in an H_2-containing environment were sent to the Rocky Flats Plant for fabrication. These steels contain 2.0 weight percent silicon, 0.1 weight percent carbon, and 0 to 1.0 weight percent vanadium as the main alloying additions; the design considerations for these steels have been discussed in previous progress reports on this project. The arc-remelted ingots, 19.05 cm in diameter by 20.32 to 40.64 cm long (7.5 in. in diameter by 8 to 16 in. long) were homogenized at 1150°C (2102°F) in argon for 16 hours prior to shipment to Rocky Flats at the end of March.

At the Rocky Flats Plant, the ingots were double hot-forged. First, each ingot was heated to 1050°C (1922°F), laid on its side, and steam hammered to about 8.26 cm (3.25 in.) in thickness. The resulting slabs were then reheated and positioned to deform the material in a direction perpendicular to the first forging operation. The final forging thickness for each steel was about 7.6 cm (3.0 in.); the steels were air-cooled to room temperature from their hot-forging temperature.

During the hot-rolling operation, the forged slabs were preheated to 955°C (1751°F) for 2 hours and were then rolled to plate in approximately eight passes. The temperature of the final pass on each steel was in the

800° to 850°C (1472° to 1562°F) range, and the deformation induced by the final pass was about 40%. This amount of deformation at temperatures in the 800° to 850°C (1472° to 1562°F) range should produce steel plate with a very fine grain size, particularly for those steels that contain vanadium additions. A fine grain size in these steels should enhance the resistance to corrosion fatigue in H_2S and, additionally, improve mechanical properties such as strength and toughness. The final thickness of the as-rolled plates was 1.334 cm (0.525 in.). The as-rolled material was cleaned and shipped to Sandia. Heat treating studies and mechanical test specimen preparation are proceeding.

Discussions were held with G. Krauss of the Colorado School of Mines on the development of dual-phase steels. Krauss is currently involved in a research project dealing with the microstructures of dual-phase steels. The drill stem corrosion program was generally outlined to him, and a detailed discussion was held on the possible application of particular dual-phase steels for drill stem applications.

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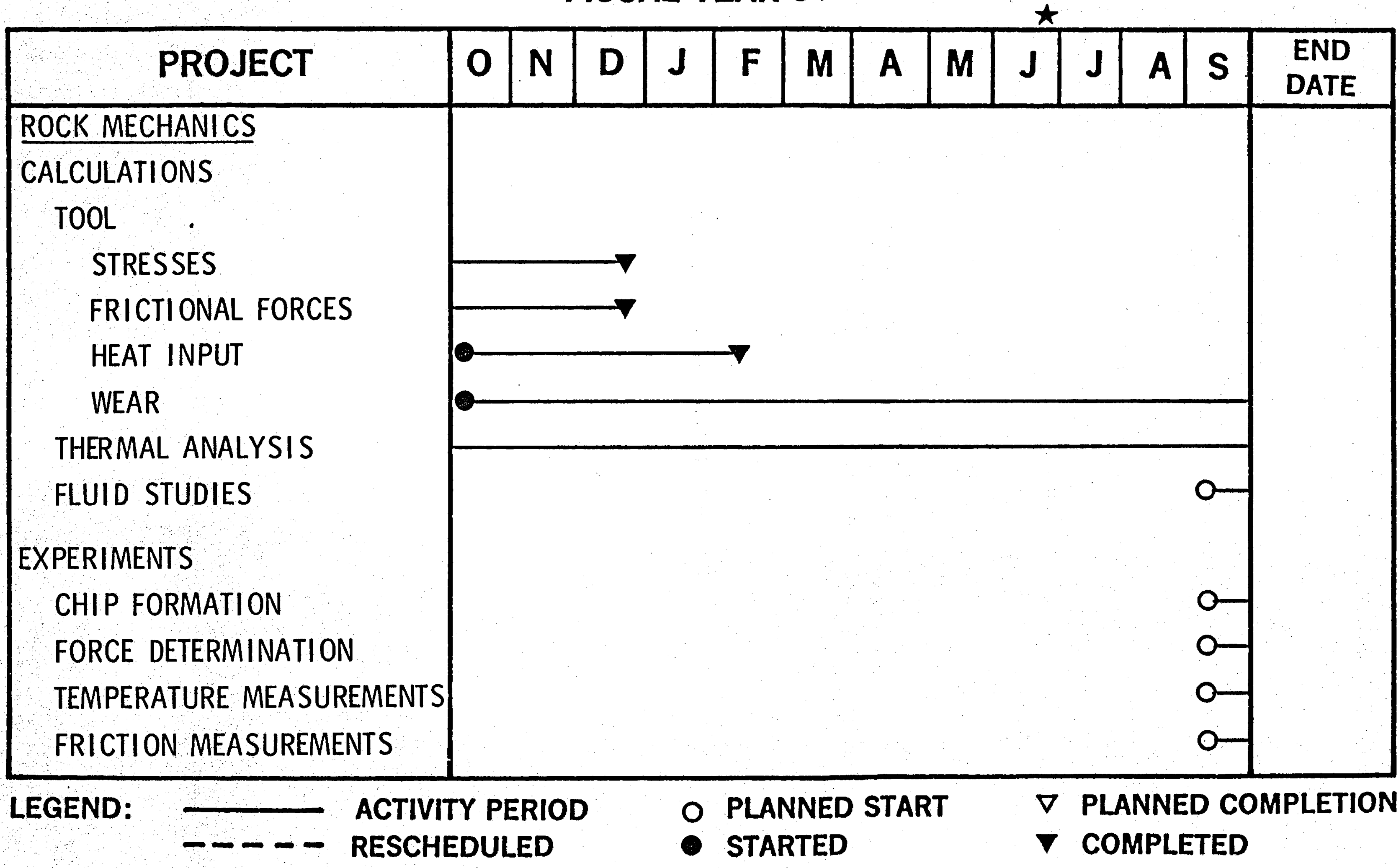

8.3 Rock Mechanics for Polycrystalline Diamond Compact Cutters

Sandia National Laboratories
Technical Consultant: D. Wesenberg (505) 844-0129

Project Objective

The project objective is to conduct research on and testing of the chip formation process of rock cutting tools utilizing 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 has been initiated. Modeling of the rock/tool interface has begun. Calculations of tool stresses and frictional forces have been completed. Calculations of heat input have been completed, and wear calculations are continuing. A thermal analysis is being conducted.

Quarterly Progress

A preliminary study of the interaction between the Stratapax™ drag bit and rock has been completed. It has been determined that rock fracturing occurs in roughly four identifiable steps. Each step influences the tool forces. In the first step, little or no cracking of the rock occurs. The rock is being deformed elastically, and the tool forces are increasing at approximately a constant rate.

In the second step, there is little or no cracking of the rock ahead of the bit. However, a crack forms and runs from the bottom of the drag bit down into the rock. The rock corner at the front of the bit causes a stress concentration which leads to the tensile fracture. The bit corner at the back of the rock/bit interface causes a stress concentration which also leads to tensile failure. These two cracks tend to coalesce and form one vertical tensile crack. The tool cutting force changes little during the first 30 μs of this phase. After this period of time, the tool cutting force increases. The tool thrust force continues to increase at the same rate as in the first step.

In the third step, the crack propagating from the bottom of the bit terminates, and another crack initiates in front of the bit. The gap or V-groove between the rock and bit in front of the bit causes the formation of a tensile-stress region inside the rock in front of the gap. As the loads increase, the tensile stresses increase, resulting in a tensile fracture in front of the bit. In one calculation the gap was eliminated. The tensile region still formed in front of the bit below the surface of the rock. The tool cutting force increases during this step, and the thrust force continues to increase at the same rate as in earlier steps.

In the last step, all of the rock in front of the bit is fractured. The fracture region continues to grow in the neighborhood of the tool/rock interface. The tool forces drop very quickly because the fractured rock has little strength. These observations on tool forces are in qualitative agreement with the experimental results.

Table 21 shows the times at which each of the four previously described steps occurs. In one case, the vertical crack continues to grow throughout the entire problem. However, its late-stage growth is very slow. The time chosen when the crack "ends" is when the crack dramatically slows down. All four of the runs were stopped because of severe mesh distortion.

All four of these runs use the same drag bit with a -20° rake angle, an initial velocity of 0.5 m/s (1.6 ft/s) and a depth of cut of 5 mm (0.2 in.). The coefficient of friction between the rock and bit was 0.5 in all runs, except for one that was set to 0. In the first run, the rock in the problem was approximately 7 by 7 cm. In the rest of the runs, the rock was approximately 9 by 9 cm. The second run was identical to the first except for the size of the rock. The geometry of the third run was identical to the second, but the coefficient of friction between the rock and bit was decreased from 0.5 to 0.0. In the fourth run, the small gap between the front of the drag bit and the rock was eliminated. An earlier analysis indicated that the tool forces will increase dramatically when this gap is eliminated. This implication is confirmed by Run No. 4.

As shown in Table 21, the vertical crack begins at the same time in all four runs. The crack continues throughout the 9 by 9 cm/0 friction problem but is essentially formed at 120 μs. The times for the 9 by 9 cm/0.5 friction and 9 by 9 cm/0 friction runs are almost identical. However, the times for the 9 by 9 cm/0.5 friction runs are different from those for the 7 by 7 cm/0.5 friction or the 9 by 9 cm/no-gap runs. These observations imply that the rock failure process is relatively insensitive to the coefficient of friction but is sensitive to the geometry of the rock.

Figures 35 through 40 are a set of plots comparing the tool forces of four runs. Figures 35, 37, and 39 are comparisons of thrust forces for the four runs. The thrust force is directed downward into the rock perpendicular to the motion of the bit. The thrust forces are very similar for all four runs and begin to decrease only after the rock has failed in front of the tool. Figures 36, 38, and 40 are comparisons of the cutting force of all four runs. The cutting force is in the same direction as the motion of the bit. Figure 36 compares the 9 by 9 cm/0 friction and 9 by 9 cm/0.5 friction runs. The cutting forces are identical up to 120 μs. There is some deviation after 120 μs, when the cutting force associated with the 0 friction run continues to increase. Figure 38 compares the 9 by 9 and 7 by 7 cm runs in which the coefficient of friction was 0.5. The results are practically identical up to 100 μs. After this time, the forces associated with the 7 by 7 cm run continue to grow. This result is consistent with the data presented in Table 21. At 125 μs, the rock in front of the bit in the 9 by 9 cm calculation has completely failed, and the forces begin to drop. However, in the 7 by 7 cm run, some of the rock in front of the bit remains competent until 180 μs. This competent rock continues to support an increasing cutting force. The cutting forces of the 9 by 9 cm gap and no-gap runs (Figure 40) are very close until approximately 90 μs. The cutting forces of the no-gap problem continue to grow for much longer. This condition results from the delayed failure of the rock in front of the bit. Once the rock in front of the bit begins to fail, the tool forces drop rapidly.

Table 21

Crack Growth Times for Four Calculation Runs

Run	Vertical Crack Begins	Vertical Crack "Ends"	Horizontal Crack Begins	Failed Rock in Front of Bit
7 by 7 cm/0.5 friction	35 μs	85 μs	95 μs	180 μs
9 by 9 cm/0.5 friction	35 μs	110 μs	90 μs	125 μs
9 by 9 cm/0 friction	35 μs	120 μs	90 μs	130 μs
9 by 9 cm/no gap	35 μs	205 μs	230 μs	245 μs

These calculations are an improvement over earlier calculations because modifications were made which led to the incorporation of finer zoning, larger rock, and longer run time into the study. Some of the earlier runs used smaller, more coarsely zoned rocks whose stress-free boundaries strongly influenced the stress fields. If larger rocks were used, the details would change, but the four steps identified in this report would remain. The zoning used in these calculations is quite fine, as shown in Figure 41, but, due to the unstable nature of tensile fractures, changes in zoning will change the tool loads and details of the fracture. The delayed failure of a few cells can strongly influence the cutting force. These calculations were terminated because of extreme distortion of some of the cells. Some of the earlier runs were terminated on a different criterion before the rock had completely failed.

These calculations resulted in the following findings: (1) rock failure occurs in four steps; (2) the thrust forces increase at a steady rate throughout the fracturing process and begin declining in the fourth step; and (3) the cutting force goes through several phases which are strongly dependent on the rock failure.

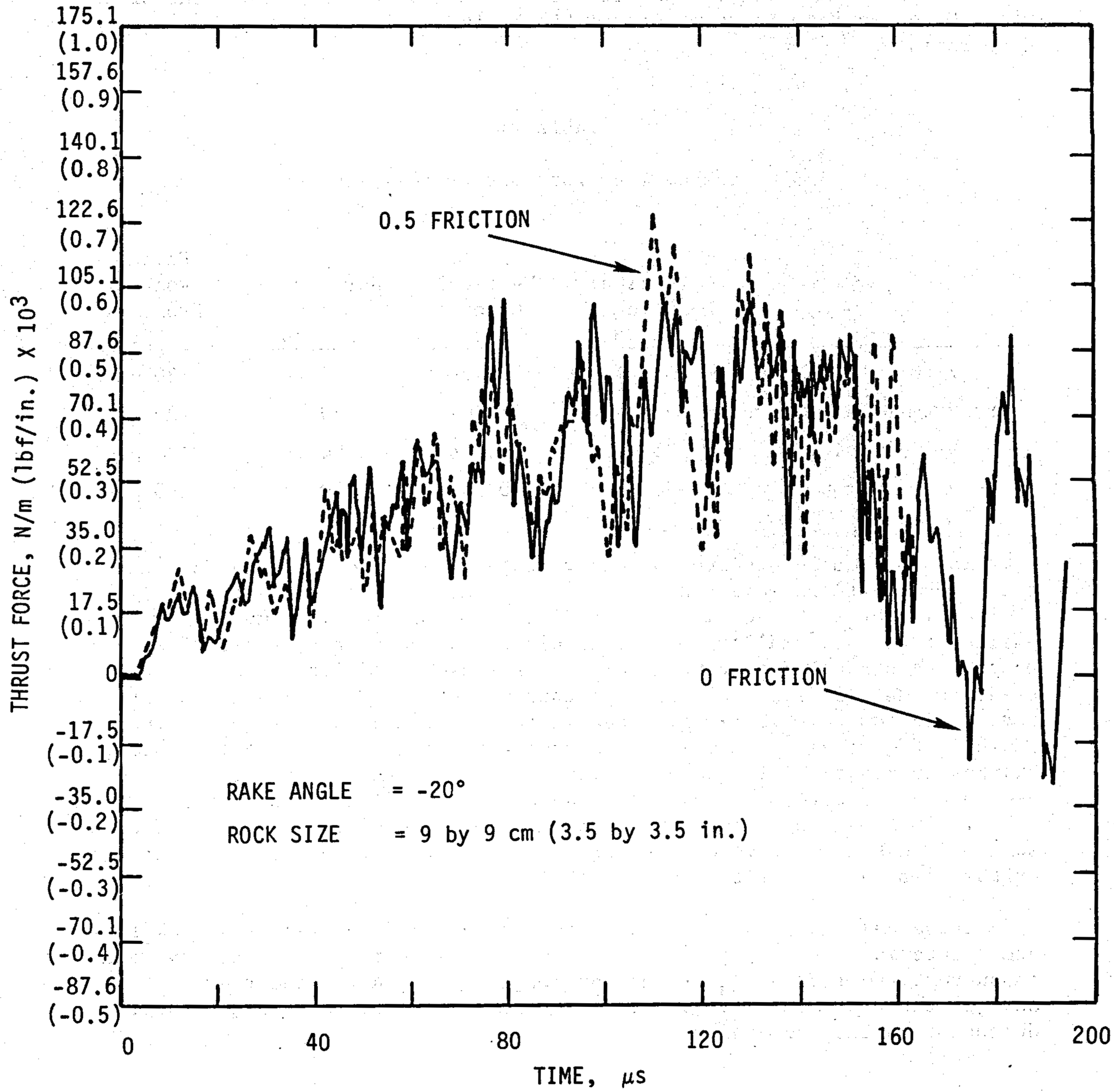

Figure 35. Comparison of Drag Tool Force Histories; Thrust Force

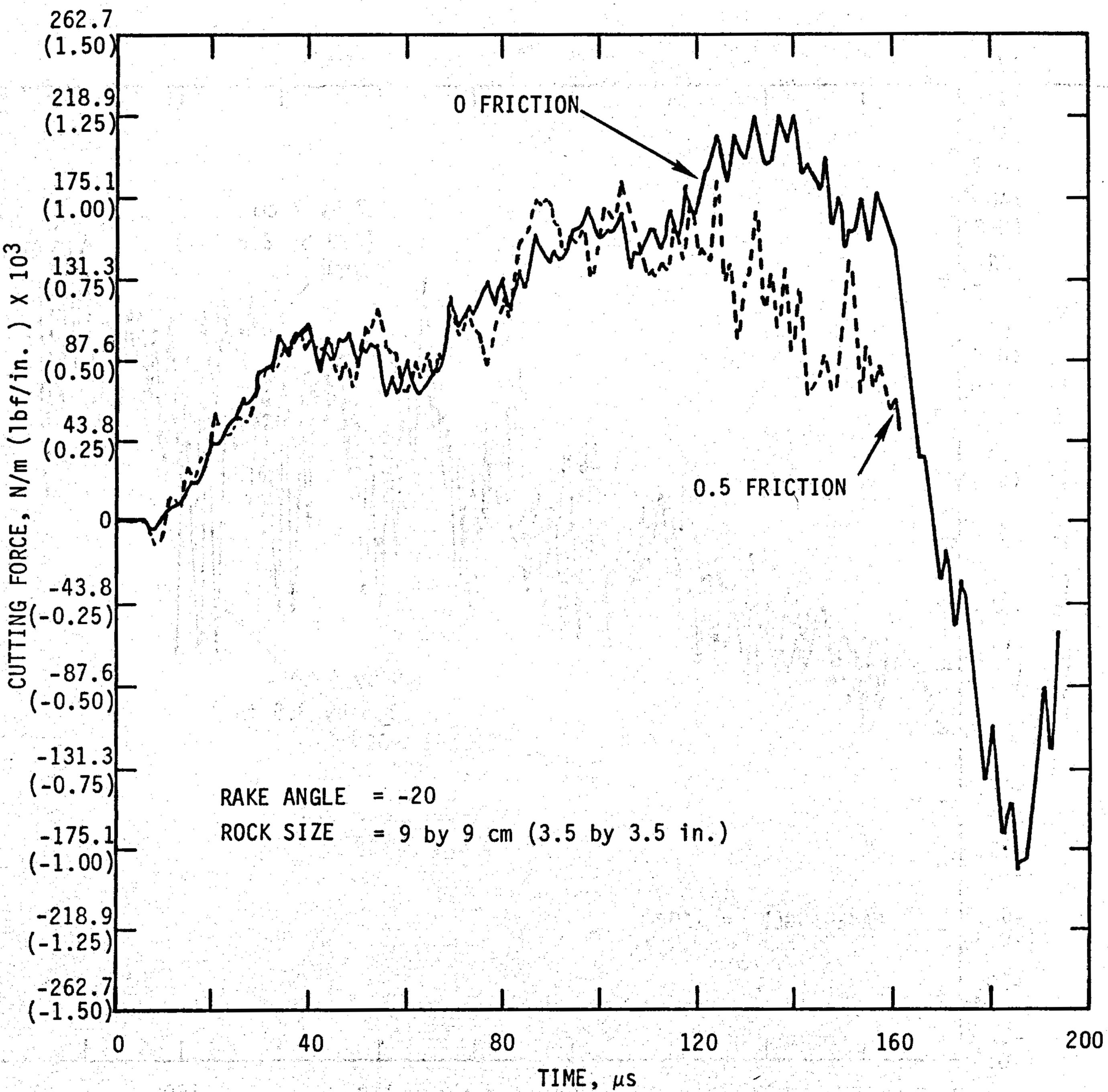

Figure 36. Comparison of Drag Tool Force Histories; Cutting Force

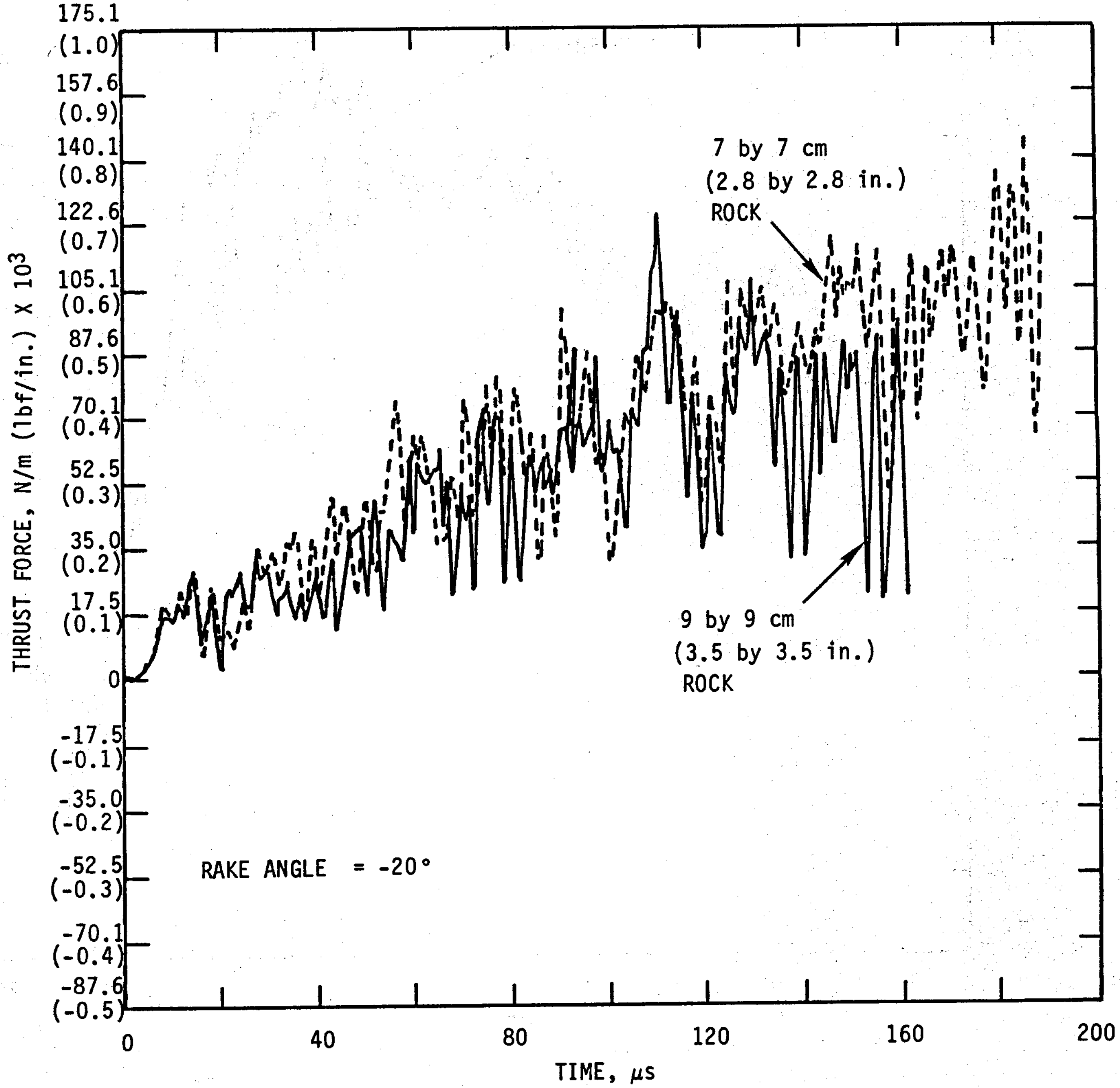

Figure 37. Comparison of Drag Tool Force Histories; Thrust Force

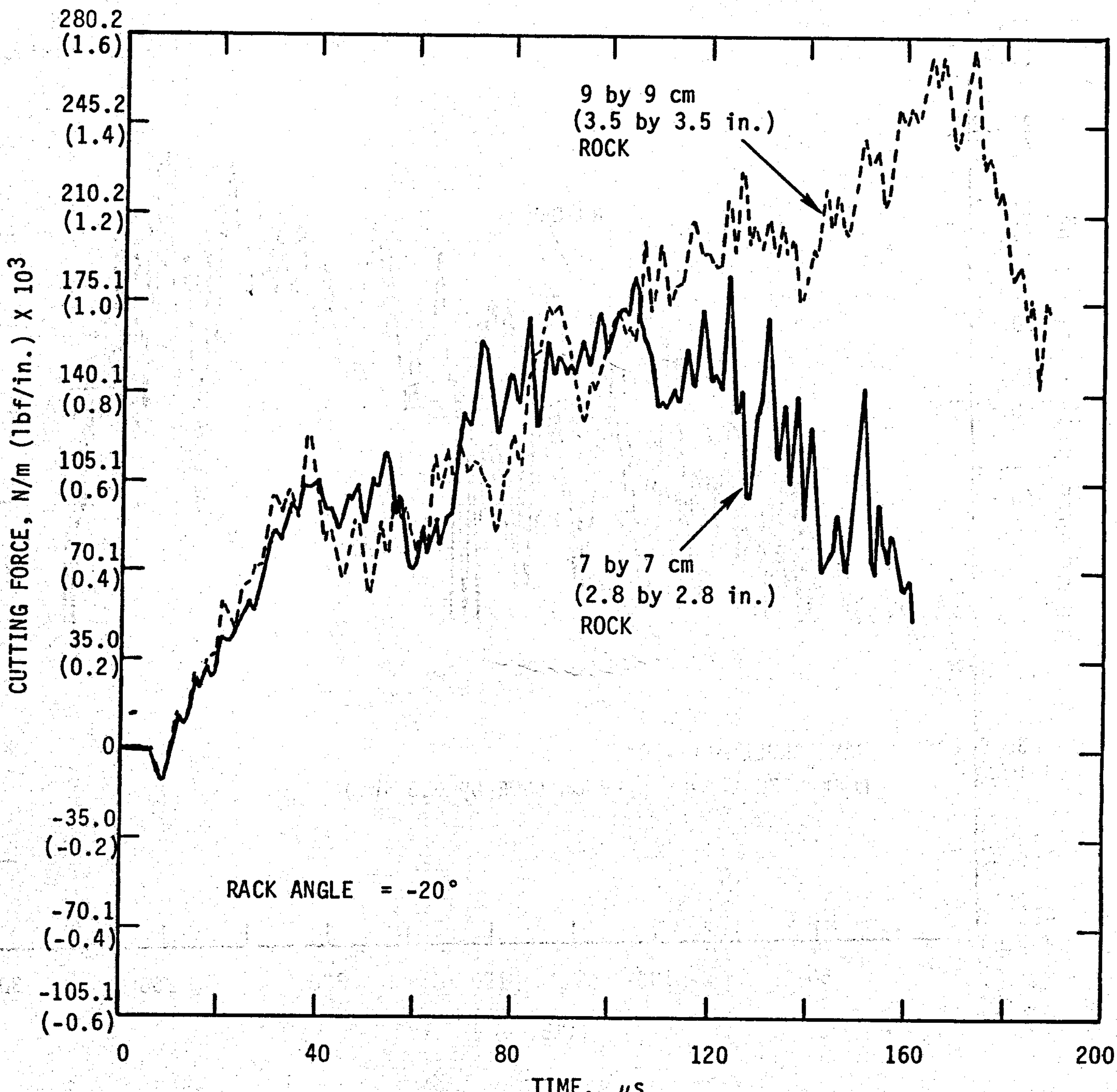

Figure 38. Comparison of Drag Tool Force Histories; Cutting Force

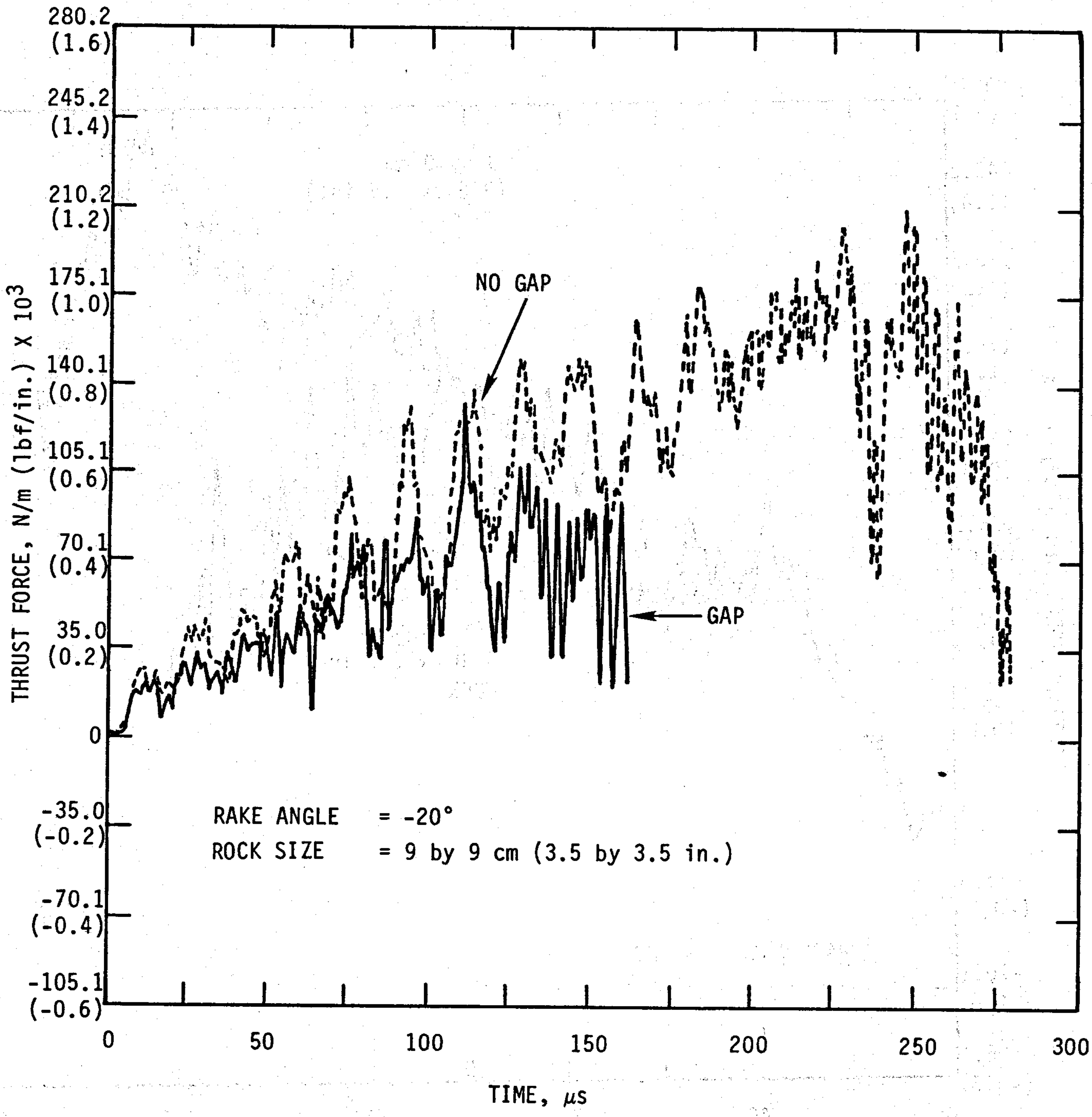

Figure 39. Comparison of Drag Tool Force Histories; Thrust Force

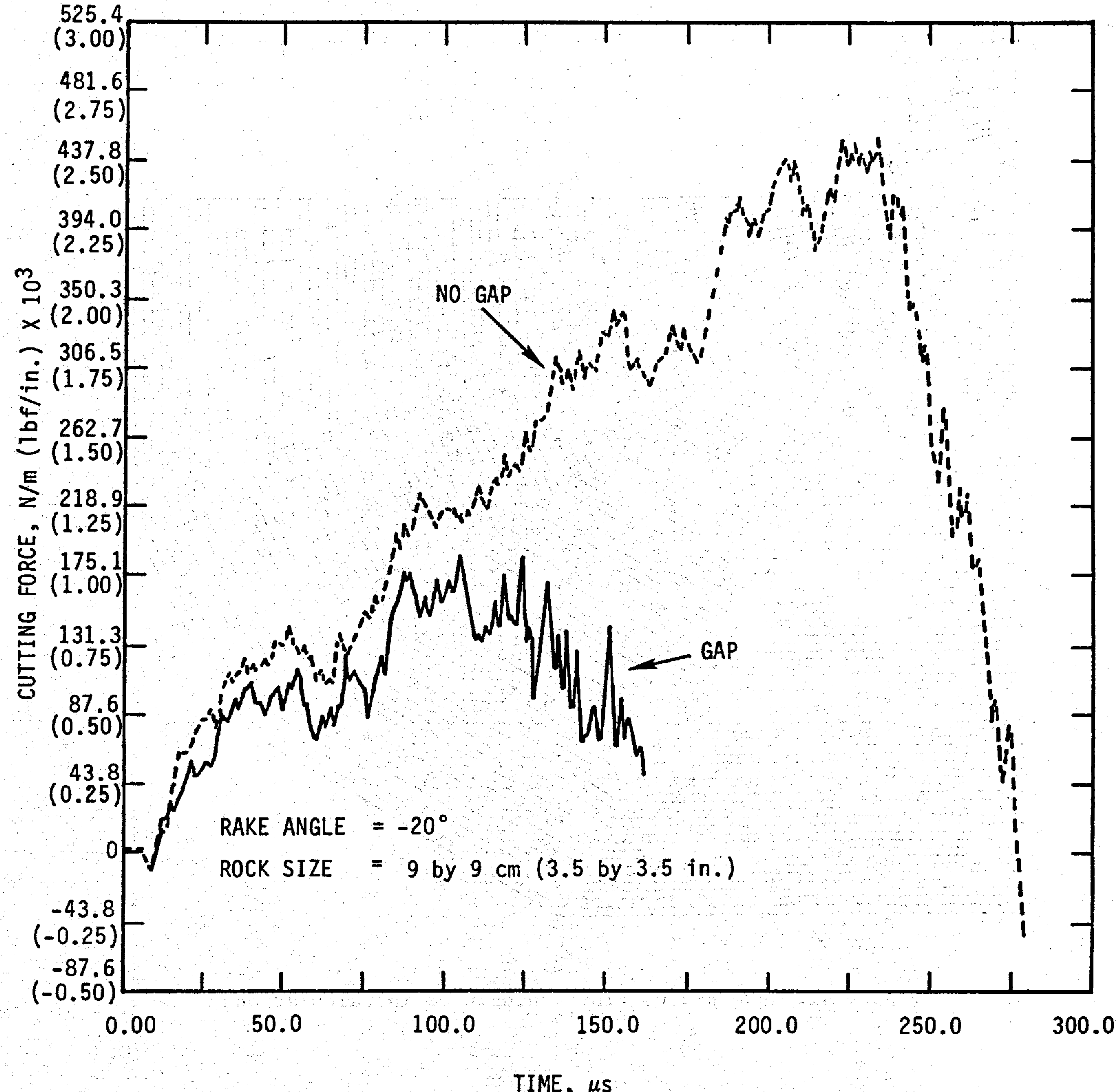

Figure 40. Comparison of Drag Tool Force Histories; Cutting Force

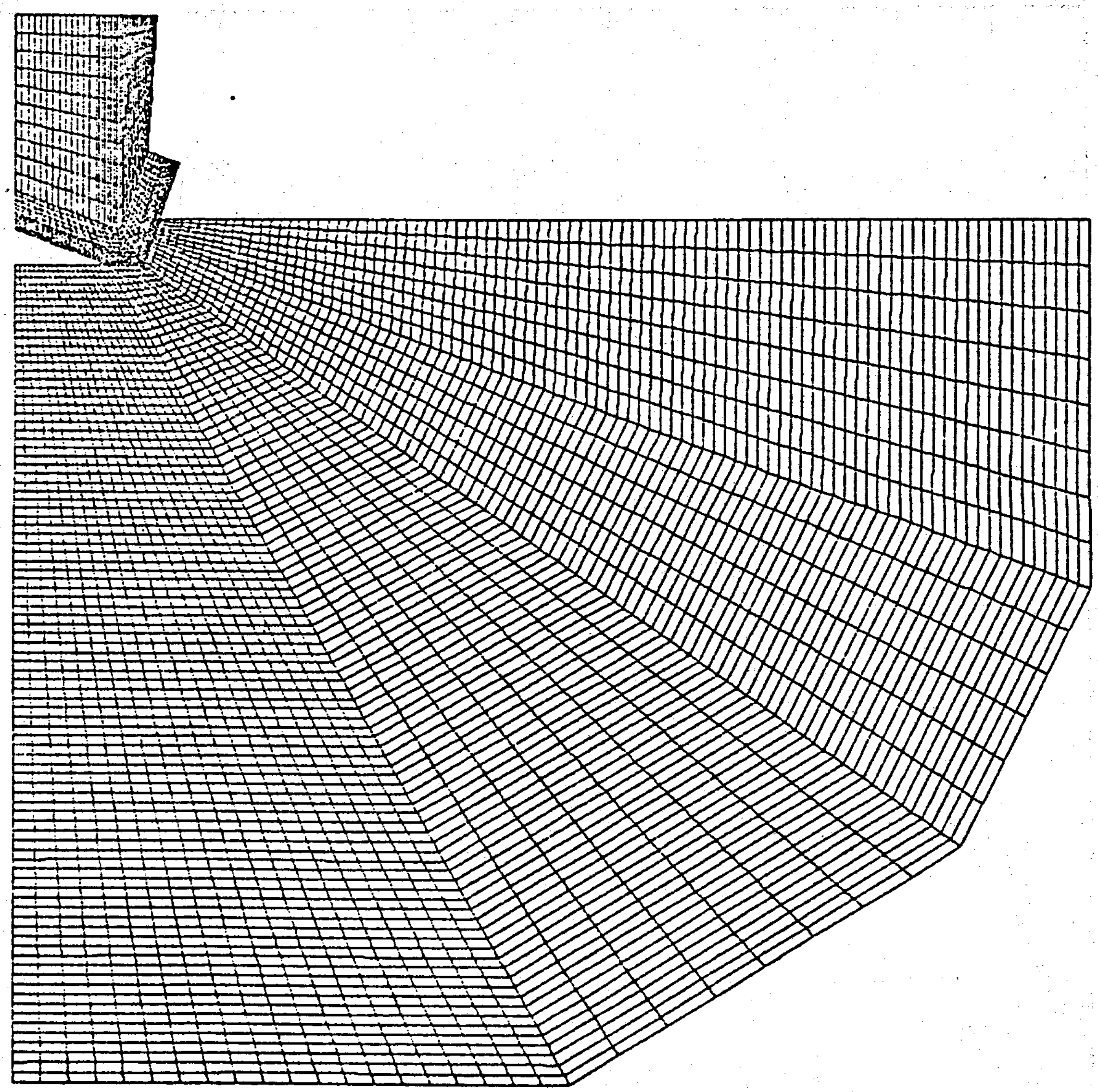

Figure 41. Example of Fine Zoning Used in Calculations

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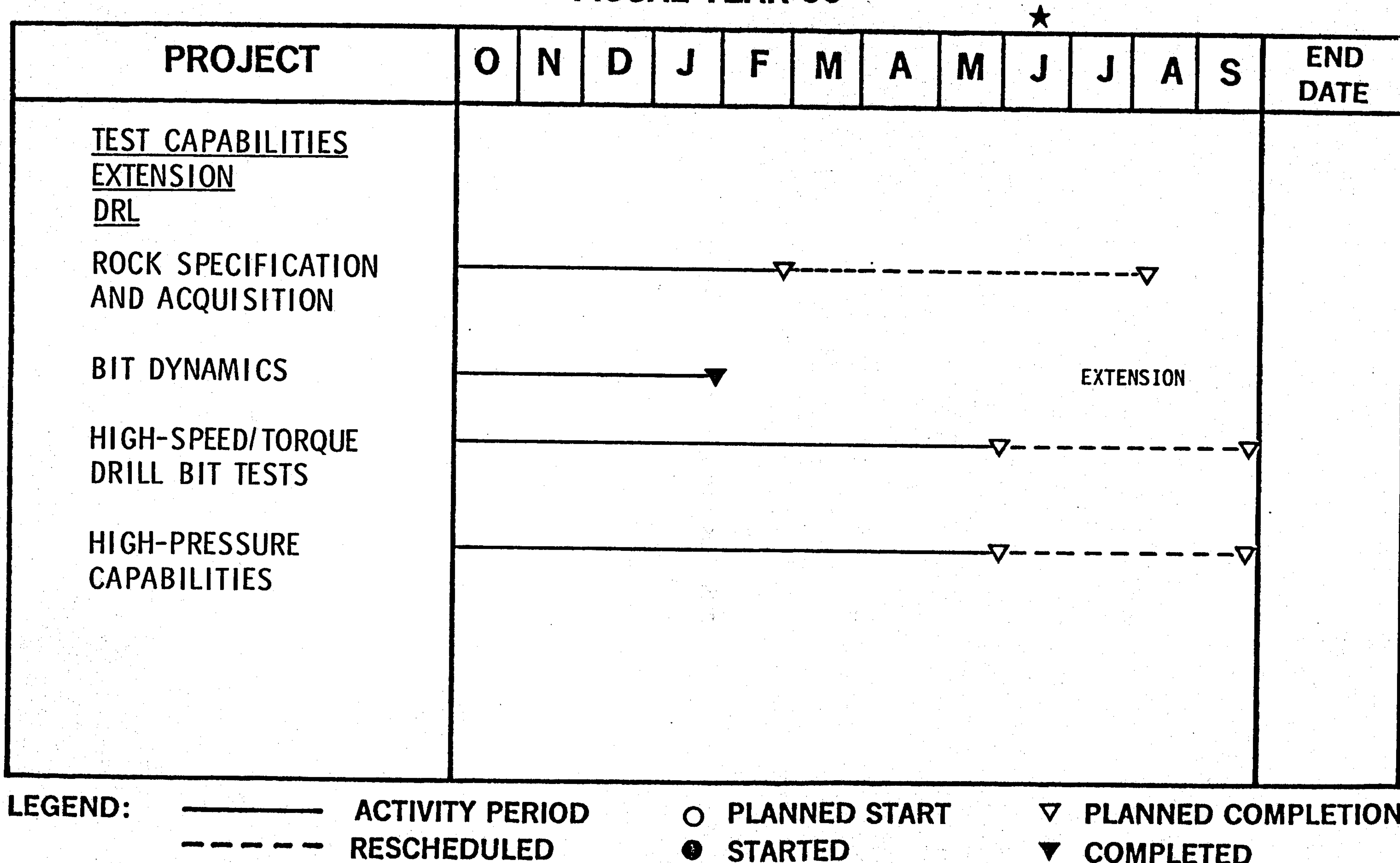

8.4 Modification and Extension of Testing Capabilities

Contractor:	Drilling Research Laboratory, Inc.
Principal Investigator:	A. D. Black (801) 582-2220
Contract Period:	12 September 1979 to 30 September 1980
Contract Number:	13-8785 (Sandia)
Technical Consultant:	D. Wesenberg (505) 844-0129

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 availability for testing high-speed/high-torque bits,
3. Bit dynamic data acquistion, and
4. High-pressure/jet-drilling testing capability.

Project Status

All project tasks have been initiated. Rock specification data are being compiled, and potential sources of rock specimens have been identified. Design of the high-speed/high-torque facility has been completed, and assembly is virtually complete. A high-rate, data acquisition, computer program has been completed. Conceptual ideas for the high-pressure facility were evaluated, and design and fabrications of the facility is continuing.

Quarterly Progress

Rock Selection and Acquisition -- Several hand samples of a hard, abrasive sandstone known as Crab Orchard were obtained from a quarry in Tennessee. Physical property tests indicated one of the rocks has an unconfirmed strength of 257.2 MPa (37 000 psi), a density of 2.490 g/cm^3 (155.5 lb/ft^3), and a porosity of 9.7%. Two other samples had densities of 2.515 g/cm^3(157.0 lb/ft^3) and 2.450 g/cm^3(153.0 lb/ft^3) and porosities of 6.2% and 6.7%, respectively. The first rock is available in a block 0.91 metre (3 feet) thick and may be a candidate to simulate the hard, abrasive sandstones at The Geysers. The other two sandstones are not available at this time in blocks thick enough for full-scale laboratory drilling tests.

High-Speed/High-Torque Capabilities -- The assembly of the new transmission and drive system was completed; however, the installation of the high-speed/high-torque system on the drill rig has been delayed until July

1980 due to the heavy testing schedule at the DRL. A cost estimate is being prepared to provide a 500- to 1000-rpm, high-speed, all-hydraulic drive system. The receipt of quotations on the hydraulic system is expected in the next reporting period.

High-Pressure Capabilities — A piping manifold skid and a lifting device were designed to minimize the time required to change over from the mud pump standard fluid ends to the high-pressure fluid ends. All modifications to the system for reducing the changeover time from standard to high-pressure fluids ends have now been completed. Some of the final modifications were completed during the setting up for the Hydronautic/Hycalog high-pressure Cavijet® test program in April. The fluid end changeover took between 2-1/2 and 3 days. With all modifications now complete, the changeover time for the next high-pressure program is estimated at 1-1/2 to 2 days. Some of the high-pressure hammer unions and swivel-joint fittings to be used in the high-pressure pulsation dampening and pressure drop systems have been received.

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PROJECT	O	N	D	J	F	M	A	M	★ J	J	A	S	END DATE
ADVANCED WELLBORE THERMAL CODE ENERTECH													
MODIFICATION EXISTING CODE				●	—	—	—	▼					
ADVANCED CODE DEVELOPMENT													
SINGLE-PHASE, COMPRESSIBLE FLOW						●	—	—	—	—	—	▽	
TWO-COMPONENT, COMPRESSIBLE FLOW												○	April 1981
USERS' MANUAL													May 1981
FINAL REPORT													May 1981

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

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 30 April 1981
Contract Number: 46-5670 (Sandia)
Technical Consultant: D. Wesenberg (505) 844-0129

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. Modification of the existing, single-phase fluid code to allow

    a. A variable-tubing flow area,
    b. Separated, multiple fluids in the wellbore,
    c. Provision for a deviated wellbore, and

2. Advanced code development providing for

    a. Formulation of single-component, compressible flow in a wellbore,
    b. Formulation of multicomponent, compressible flow in a wellbore, and
    c. Reconstruction of the existing code to include compressible, multicomponent flow.

Project Status

The project was initiated in January 1980. The effort to modify the existing GEOTEMP code to handle deviated holes has been completed, and work has been started on the compressible flow model and on two-component flow. The code modifications to accommodate variable tubing areas and multiple fluids have also been completed and checked out.

Quarterly Progress

The modifications to GEOTEMP have been completed. These modifications consist of the following additional capabilities:

1. Variable tubing flow areas,
2. Multiple fluids, separated by interfaces in the wellbore, and
3. Deviated wellbores.

The modified code was tested by rerunning previous GEOTEMP test cases and by running special problems that use the new capabilities. The modified code performed well for all these cases. A case copy and a magnetic tape copy of the modified program were delivered on 28 May 1980, and the new capabilities were discussed with Sandia. Details of the modified code and the test cases are presented in the report, Appendix B.

The mixture theory studies have been temporarily set aside. Early in the studies, it became apparent that a compressible flow wellbore model was a necessary part of the mixture theory formulation. Thus, a decision was made to begin formulating the compressible flow model for GEOTEMP, a model which could also serve as a major component of the two-component flow analysis.

Figure 42 illustrates a control volume for deriving the one-dimensional balance laws for compressible fluid flow. The fluid enters the volume with a given density, velocity, enthalpy, pressure, and temperature through area A_1 and exits with different values of these variables through area A_2. Forces F_W are exerted on the fluid by the walls of the control volume, and heat Q is conducted into the volume. The balance laws for this volume will be written for steady-state flow, although transient heat flow will still be considered. Conservation of mass requires

$$\rho_1 A_1 \nu_1 = \rho_2 A_2 \nu_2 = \dot{m} = \text{mass flow rate} \; .$$

Conservation of momentum requires

$$A_2 \, (p_2 + \rho_2 \nu_2^2) - A_1 \, (p_1 + \rho_1 \nu_1^2) = F_B + F_F + F_W \; .$$

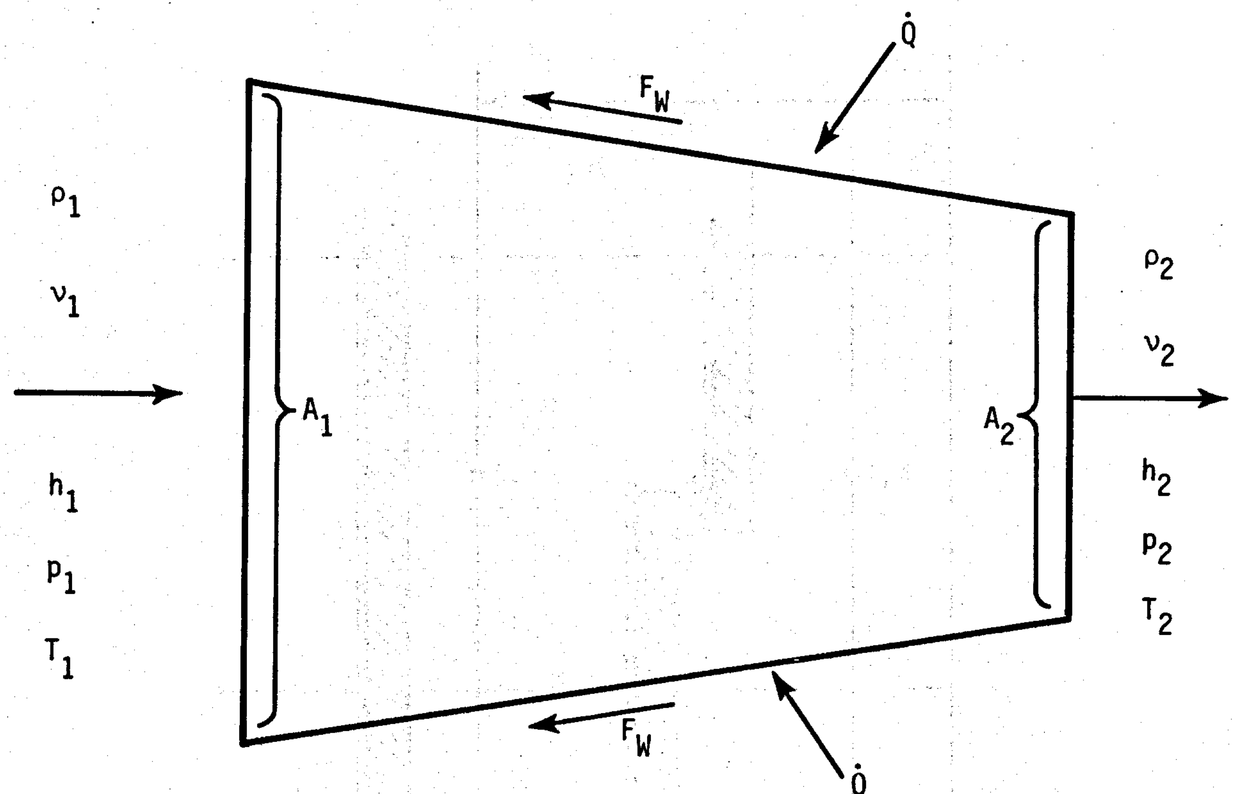
Where F_B is the gravity force, F_F is the viscous force, and F_W is the wall force. Conservation of energy requires

$$\dot{Q} = \dot{m} \, [h_2 - h_1 + 1/2 \, (\nu_2^2 - \nu_1^2)] \; .$$

Solution of these equations requires equations of state for pressure and enthalpy and a constitutive equation for the viscous force.

The details of the compressible flow formulation proposed for GEOTEMP were presented to Sandia in late May 1980. The information is contained in Appendix C. The consensus at the Sandia briefing was that the compressible flow model was somewhat unconventional although promising, and that suitable testing against analytical solutions was called for.

The two modifications of GEOTEMP, variable tubing areas and multiple fluids in the wellbore, were initiated in late March. The necessary changes in the input variables have been coded: 10 different tubing sizes and 5 different primary fluids can now be specified. The effect of variable tubing size on grid formulation, as illustrated in Figure 43, was fairly straightforward, with the radius of the inner-most grid points determined by the smallest tubing size and the radius of the next layer of grid points governed by the largest tubing size. The variation in tubing size results in variable cell size, and further modifications were necessary to account for variable cell conductivities and changes in the



F_W = FORCES EXERTED BY WALLS
$\dot{Q}$ = HEAT
ρ = DENSITY
ν = VELOCITY
h = ENTHALPY
p = PRESSURE
T = TEMPERATURE
A = FLOW AREA

Figure 42. 1-D Balance Laws for Use with Compressible Flow

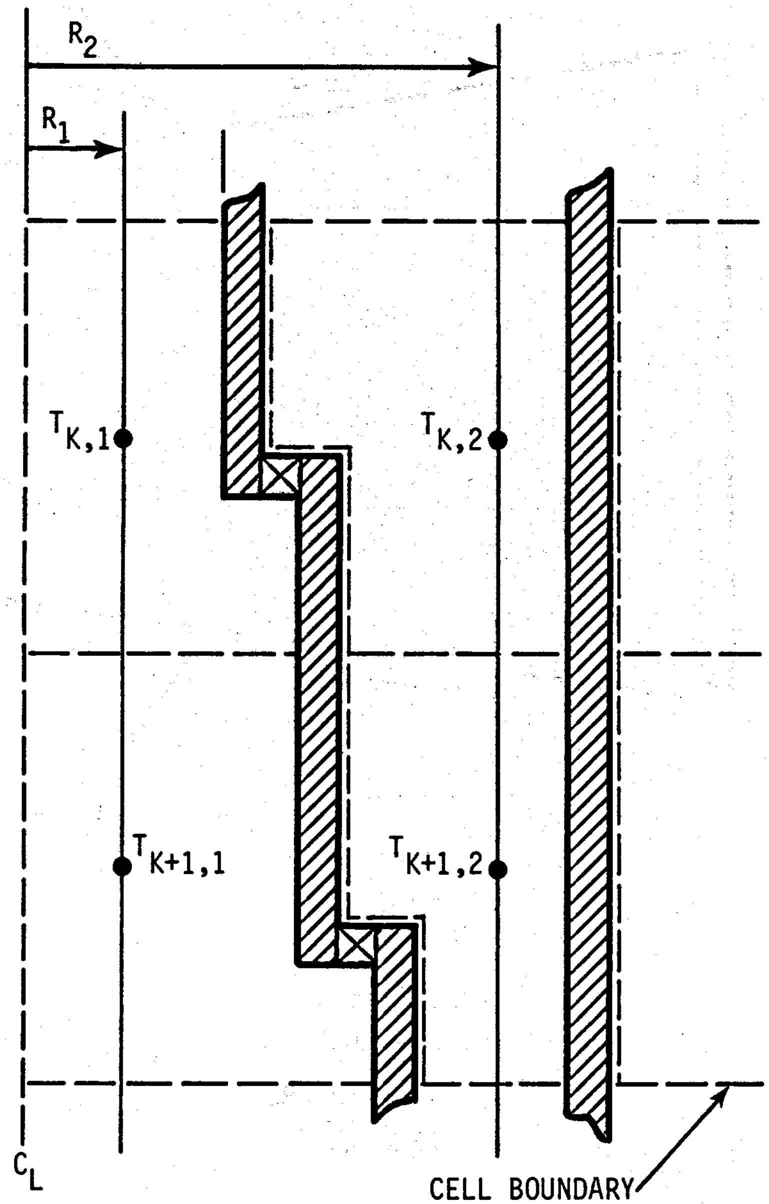


Figure 43. Variable Tubing Sizes--Mathematical Cells in Wellbore

flowing stream energy balance due to variable cross sections and multiple fluids.

Modifications to allow multiple tubing areas were completed, and preliminary testing determined that the code is operating properly. Three principal changes were necessary to allow variable tubing areas: (1) changes to the input routines to allow multiple tubing sizes, (2) changes to the subroutine COND to compute the correct conductivity with multiple tubing, and (3) changes to subroutine COEF to account for the changes in fluid velocity due to tubing area changes. The input routine READ was modified so that no changes were necessary to the mesh generator GRID. The revised GEOTEMP code input data format corresponding to the changes made in the main program and subroutine READ is contained in Appendix D.

A sample calculation with variable tubing size is illustrated in Figure 44. Two problems were calculated. Case I is the same sample injection problem included in the GEOTEMP user's manual and gives identical results. Case II uses smaller tubing below 610 metres (2000 feet). The temperatures predicted by Case II below 610 metres (2000 feet) are lower than those predicted by Case I below the same level, because the faster moving fluid in the smaller tubing receives less heat from the surroundings. Above 610 metres (2000 feet), the two cases are essentially identical and predict the same temperatures.

Modifications to allow multiple fluids in the wellbore were also completed. The main addition necessary was a subroutine to calculate the positions of the interfaces between the different fluids in the wellbore based on the injection, production, and circulation histories of the well. This subroutine was tested before being incorporated into GEOTEMP.

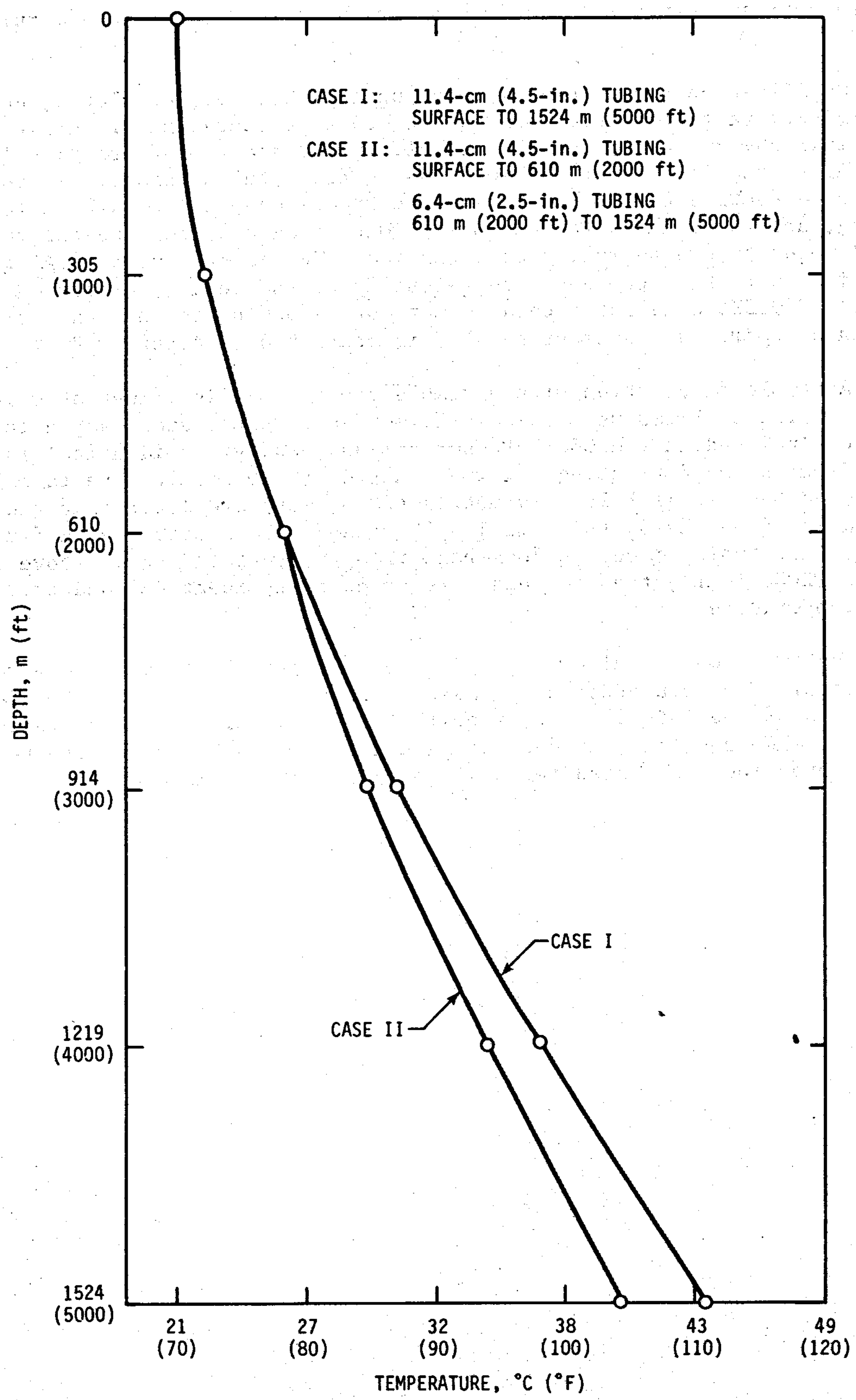


Figure 44. Variable Tubing--Injection Sample Calculation

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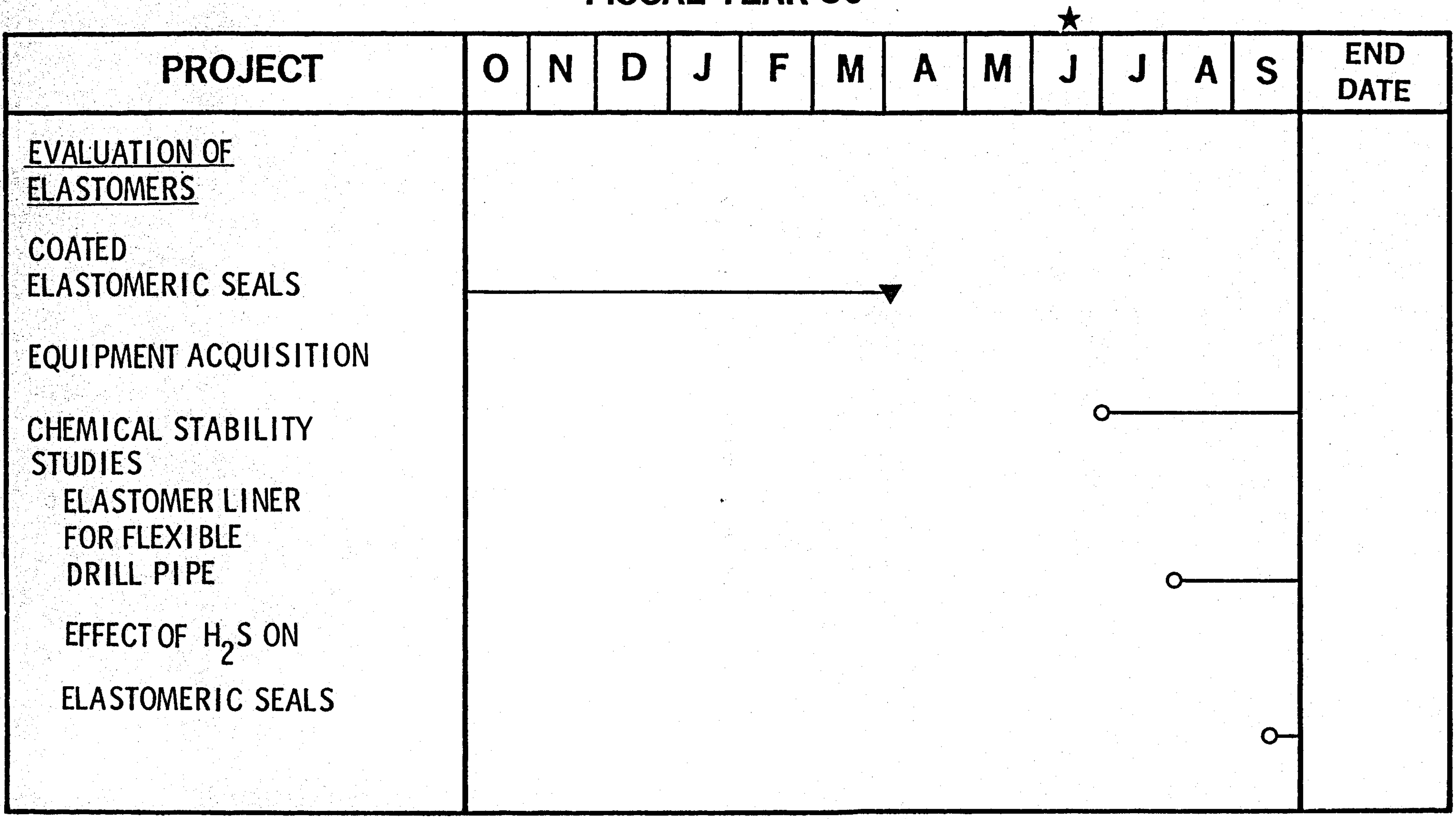

LEGEND: ——— ACTIVITY PERIOD ○ PLANNED START ▽ PLANNED COMPLETION
– – – – RESCHEDULED ● STARTED ▼ COMPLETED

8.6 Evaluation of Elastomers

Sandia National Laboratories
Technical Consultant: C. Arnold (505) 844-8728

Project Objective

The project objectives are to determine (1) the effect on the life of elastomeric seals of coating the seals with Parylene C, a polymer, or with tetrafluorethylene (TFE), (2) the chemical stability of various elastomer liner candidates for flexible drill pipe, and (3) the effect of H_2S on elastomeric seals.

Project Status

The experiments on coated elastomeric seals have been 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 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 drilling 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 non-coated rings, and exhibited improved abrasion resistance. Chemical stability studies of elastomer liners for flexible drill pipe and the investigation of the effects of H_2S on elastomeric seals will be initiated in the next quarter.

Quarterly Progress

The study of the coating of elastomeric seals was completed early in this reporting period with an analysis of the effect of coatings on the coefficient of friction. Certain types of abrasive wear can be minimized by encapsulating the elastomers with a low-coefficient-of-friction coating such as Teflon. Teflon-coated seals are commercially available. However, when these seals were evaluated under simulated geothermal conditions, the Teflon took a set and leaked after a few hours of service. In addition, the hoop stresses inherent in this nonhomogeneous seal could not be adequately relieved as the drilling cone rotated, and, as a result, the coating buckled.

In contrast, enhanced service-life was realized with seals on which plasma-polymerized tetrafluoroethylene (TFE) had been deposited. For example, uncoated Parker EPR seals failed after 9 hours at 150°C (302°F)

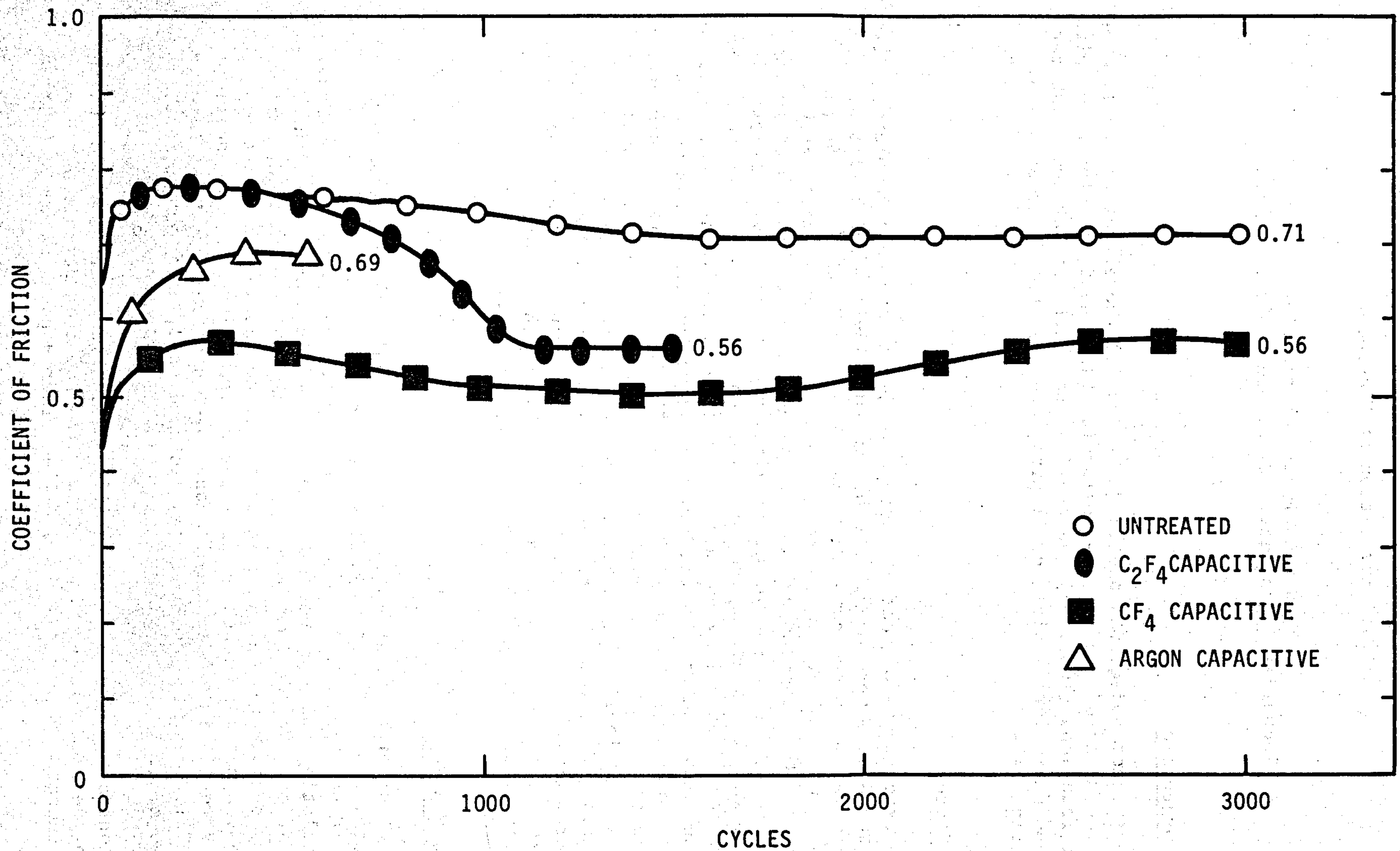

Figure 45. Effect of Plasma Treatments on the Frictional Coefficients of Buna N

following a 2-hour presoak at 288°C (550°F). The presoak simulated tripping-in, when there is no circulation. In contrast, the TFE, plasma-coated seal lasted 34 hours. Similar results were obtained with TFE, plasma-coated, Parker Viton seals. Studies of friction affirmed that plasma-coated TFE did, on a short term basis, reduce the coefficient of friction (see Figure 45).

Planning for the evaluation of elastomer liners for flexible drill pipe and for the investigation of the effect of H_2S on elastomeric seals was completed this quarter. The acquisition of equipment for conducting the studies is underway.

9. ADVANCED DRILLING SYSTEMS

Advanced and innovative drilling systems are required in order to meet the 1987 well cost reduction goal of 50%. The approach to the development of advanced systems involves investigations of high-pressure water-jet erosion drilling systems, cavitating jets, improved downhole motors, and percussion drills. The investigations include laboratory testing and field demonstration of full-scale devices. Projects are presently underway to design, fabricate, and laboratory test a pressure-pulsing device for use with cavitating jets and to improve downhole motor bearings and seals. Projects to evaluate the potential of percussion drilling devices for use in the geothermal environment and to assess the performance potential and economics of erosion drilling systems are also proceeding. The objective of these projects is to develop and demonstrate hardware incorporating these concepts so that increased rates of penetration and longer downhole drilling periods may be achieved. The project to design, fabricate, and demonstrate a water-jet erosion drilling under-reamer has been completed, and a report is being prepared. The status and progress of these 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-inch) 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.

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 are being used in an attempt to correlate rock response to cavitation/water-jet action. The experiments are being evaluated and a final report prepared.

Laboratory tests were completed to establish the design parameters for a cavitating-type jet nozzle using drilling mud as a 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 which increases as the third power of borehole pressure, and 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 underway.

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 (5000 psi). Design parameters include a differential pressure across the bearing/seal package of 0 to 13.8 MPa (0 to 2000 psi), a flow rate of 0.006 to 0.013 m^3/s (100 to 200 gpm), a rotational speed of 100 to 1000 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.

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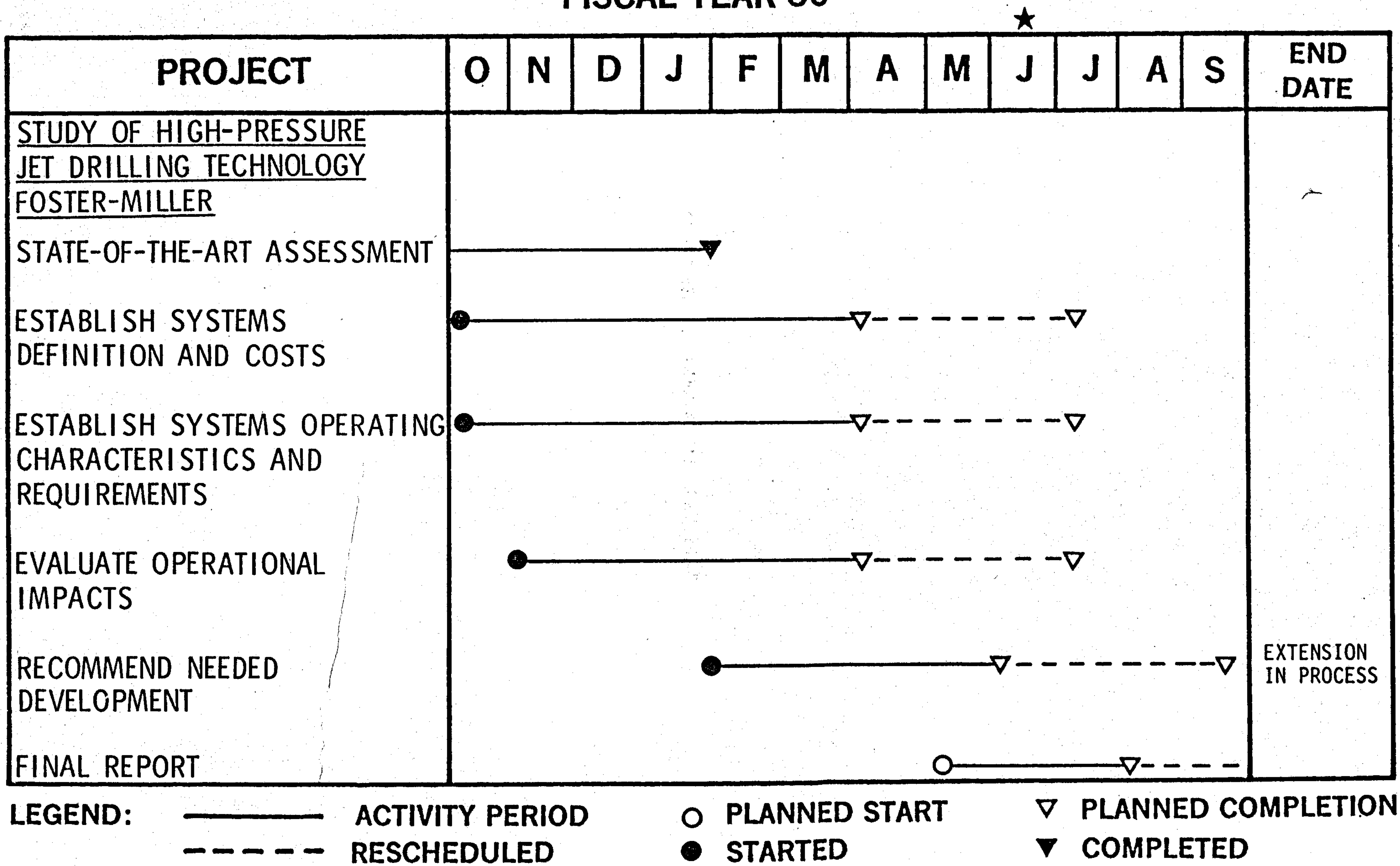

9.1 Characterization of High-Pressure Jet Drilling Systems

Contractor: Foster-Miller Associates, Inc.
Principal Investigator: A. Guzdar (617) 890-3200
Contract Period: 1 August 1979 to 31 July 1980
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 has been completed. Coordination has been made to assure a proper interface between the study output and the Sandia Well Cost Simulation Model. An erosion drilling information computer search has been made and data on the Gulf Oil Company abrasive-jet drilling program obtained. The assessment of the Gulf data is progressing, and cost estimates based on the data are being generated. Arrangements to obtain jet-drilling data from Exxon were being completed at the close of this reporting period. An assessment of the Exxon data will be conducted during the next quarterly reporting period.

Quarterly Progress

During this quarterly reporting period, efforts continued to acquire data on industry jet-drilling experience and to develop cost estimates based on the information obtained and analyzed to this point in the project.

Included in the data collecting efforts were the following:

1. Three operating oil rigs were observed in Oklahoma. Two of these rigs were located near Chickasha and the third near Duncan. Tripping operations were observed, and photographs were taken.
2. Halliburton, Inc. was visited. Halliburton is a major supplier of high-pressure intensifiers. These intensifiers are considered critical components of the Gulf abrasive-jet drilling system. Halliburton will assist in the development of costing estimates on their own equipment.
3. Gulf was requested to provide additional data on their abrasive-jet drilling system. The data are required in the evaluation of the system.
4. An agreement to obtain Exxon's jet-drilling data was processed, and selected data were obtained for evaluation.
5. Equipment costs were discussed with drilling consultant, R. Rinaldi.

The development of cost estimates included the following activities:

1. Cost estimates of the low-pressure system of the Gulf abrasive-jet drilling system were completed.
2. Costing of the high-pressure system of the Gulf project was initiated.
3. A report on the costs of three of the five Gulf abrasive-jet drilling subsystems was completed.
4. Cost estimates for the downhole equipment used in the Gulf abrasive-jet drilling system were completed.
5. Cost estimation for expendable materials, e.g., mud and abrasive, used in the Gulf abrasive-jet drilling system was completed.
6. A preliminary report on costs of the low-pressure system, downhole equipment, and expendable materials needed for abrasive-jet drilling was prepared.
7. Costing of rig equipment required for abrasive-jet drilling was started.

Following a presentation by Exxon on their high-pressure drilling program, the available reference material was reviewed, and material was selected for subsequent evaluation. Copies of this material were provided in two note books entitled

1. "Information Previously Given to Technical Members from Participating Companies - High Pressure Drilling Industry Program."
2. "High Pressure Drilling - Joint Industry Program Summary."

Evaluation of this material is underway.

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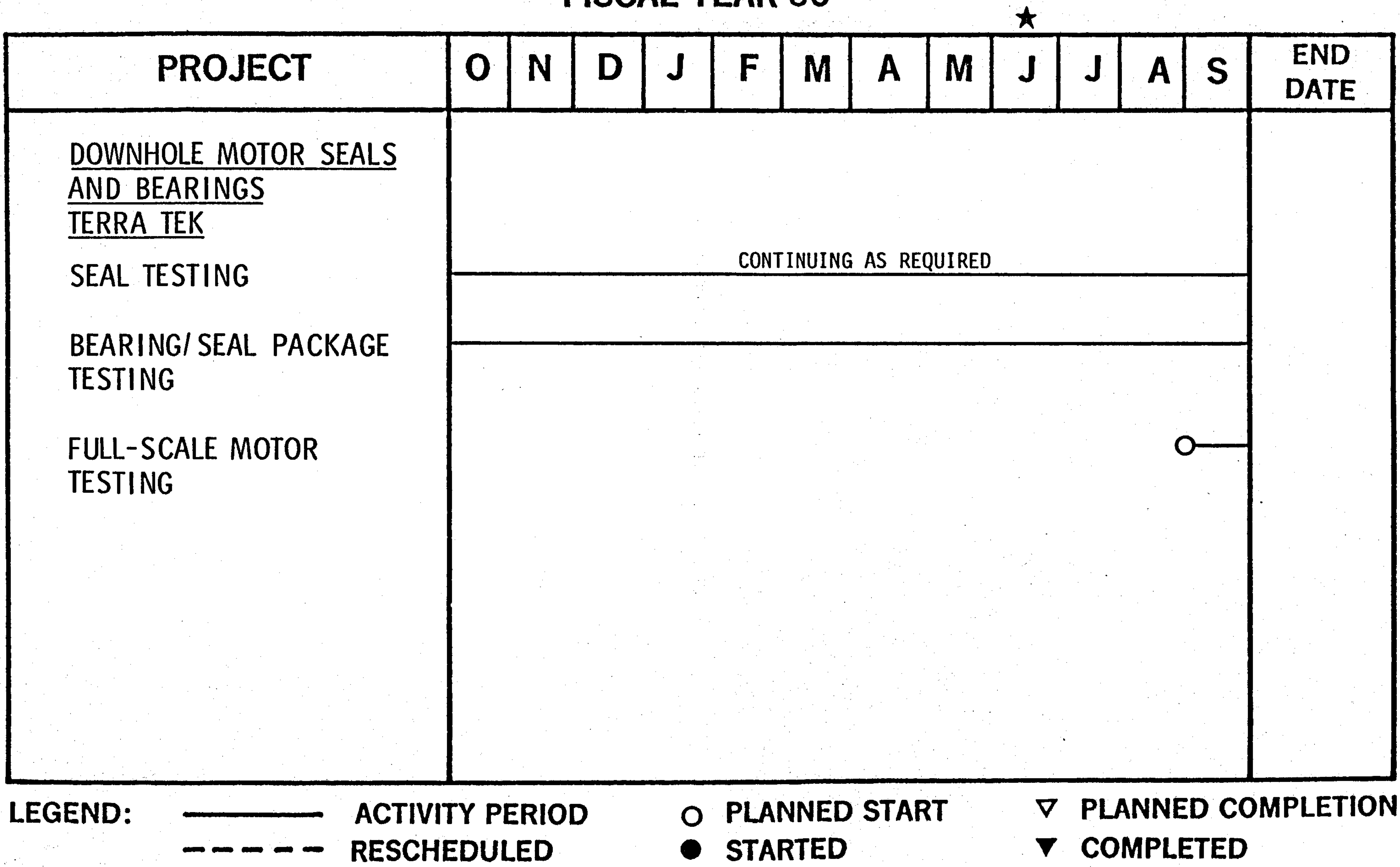

9.2 Improvement of Downhole Drilling-Motor Bearings and Seals

Contractor:	Terra Tek, Inc.
Principal Investigator:	G. Tibbitts (801) 582-2220, ext. 187
Contract Period:	1 November 1979 to 31 October 1980
Contract Number:	46-3053 (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 operate at a 121°C (250°F) circulation temperature.

Project Status

Facilities have been developed to test seals and bearing/seal packages at geothermal downhole conditions: 300°C (572°F) and 34.5 MPa (5000 psi). Selected standard seals have been tested to determine baseline performance. New seals have been designed in cooperation with the seal industry and tested in the laboratory. New bearing seals for downhole motors have been designed and will be laboratory tested in the bearing/seal package test facility. The bearing/seal test facility is now completed, and full-scale testing has begun. The present lubricant screening program test results have been completed and published. The lubricant test facility remains available for check-testing as required. Seal testing and evaluation are continuing.

Quarterly Progress

Seal Testing and Evaluation — Test No. 035 was completed during this reporting period. The total duration of the test was 34.6 hours. This is the second longest running test to date in the seal testing program. The test seal consisted of three Grafoil®-phosphor-bronze seal rings with Backup System III. In this test, Backup III consisted of four, 0.4-mm (0.016-in.) thick, flexing leaves. Details of the test conditions are shown in Table 22. Some of the observations resulting from this test are as follows:

1. There was a high torque initially, due to the wear-in of the flexing leaves. After a couple of hours, the torque dropped to below 136 N•m (100 ft/lb), where it remained during the duration of the test.
2. The seal leaked very slowly, i.e., periodically, during the test, and the test was terminated when 0.004 m^3 (1 gal) of lubricant had leaked past the test seal.

Table 22

Completed Seal Tests

Test No.	Seal Type	No. of Pressure Rings	Backup Rings	ΔP MPa (psi)	rpm	Duration h	Chrome Shaft Coating Finish (rms) μm (μin.)	Diametral Clearance: Shaft to Backup Rings mm (in.)
034	Grafoil®-phosphor-bronze	3	Backup III w/3 0.79-mm (0.031-in.) leaves	12.1/ 10.3 (1 750/ 1 500)	412	3.71	0.1 to 0.2 (4 to 8)	Flexing leaves 0.025 (0.001) Backup ring 4.32 (0.170)
035	Grafoil®-phosphor-bronze	3	Backup III w/4 0.4-mm (0.016-in.) leaves	10.3 (1 500)	412	34.6	0.1 to 0.2 (4 to 8)	Flexing leaves 0.025 (0.001) Backup ring 4.32 (0.170)
036	Canted Buna-N	2	9C aluminum-bronze	10.3 (1 500)	412	0	0.2 to 0.3 (8 to 12)	0.203 (0.008)
037	Grafoil®-phosphor-bronze	3	Backup I SAE 600 bronze	10.3 (1 500)	412	aborted	0.1 to 0.2 (4 to 8)	0.025 (0.001)

3. Inspection of the seals after the test showed that much less Grafoil® had been lost from the seal cavity in Test No. 035 than in previous tests with Grafoil® seals.

4. Inspection of the seal sleeve after the test showed that it had been worn much more than in previous tests with Grafoil® seals. The flexing leaves had worn a groove in the seal sleeve. A profile of the seal sleeve will be constructed to show the wear. The failure of the seal appeared to be due to the flexing leaves wearing out.

Test No. 036 was also completed during this reporting period (see Table 22). The test seal was the Generation II canted seal (Buna-N). This seal would not hold pressure, and the test was terminated. Inspection of the seals after the test showed that the outside diameter and height of the seals had shrunk slightly and, hence, would not seal properly.

Test No. 037, of the Grafoil®-phosphor-bronze seal with zero clearance Backup System I, had to be aborted (see Table 22). Two attempts were made to run this test. In each attempt, a new set of backup rings was machined to a 0.025-mm (0.001-in.) diametrical clearance with the shaft sleeve. Rotation was attempted after both test setups, and the seal tester was shut down immediately after torques in excess of 678 N.m (500 lbf.ft) were noted. A detailed analysis of the test will be presented in the Phase IV Semi-Annual Report, currently in preparation.

Test No. 038, of the hybrid assembly with "V" design with zero clearance Backup System III having 0.4-mm (0.016-in.) leaves, was started in the latter part of this reporting period. The results will be presented in the next quarterly progress report.

The following candidate seals were received from Utex Industries during this reporting period:

1. Hybrid assembly -- "V" design,
2. Hybrid assembly -- "Utex SF" design,
3. HTCR fabric -- "Utex SF" design,
4. Grafoil® — horizontal laminates, and
5. Mesh matrix seals.

With the receipt of the seals, all of the seals required to conduct the currently proposed seal tests (see Table 23) are on-hand.

A major modification to the seal tester was made during this reporting period. This modification involved the complete redesign of the heating system for the tester.

The downhole motor seal tester was originally designed for a maximum operating temperature of 316°C (600°F). This high-temperature requirement resulted in a design heat capacity for the tester of 30 kW. This high heat capacity prevented the use of band heaters in the original design because of the limited power density that can be obtained from this type of heater. As a result, the heater system incorporated 30 1-kW cartridge heaters in a heater carrier that surrounded the main vessel seal carrier.

Table 23

Proposed Seal Tests

Test No.	Seal Type	No. of Pressure Rings	Backup Rings	ΔP MPa (psi)	rpm	Chrome Shaft Coating Finish (rms) μm (μin.)	Diametral Clearance: Shaft to Backup Rings mm (in.)
038	Hybrid assembly "V" design	3	Backup III w/4 0.4-mm (0.016 in.) leaves	10.3 (1 500)	412	0.1 to 0.2 (4 to 8)	Flexing leaves 0.025 (0.001) Backup ring 4.32 (0.170)
039	Hybrid assembly "Utex SF" design	3	SAE 660 bronze	10.3 (1 500)	412	0.2 to 0.3 (8 to 12)	0.254 (0.010)
040	HTCR- "Utex SF" design	3	SAE 660 bronze	10.3 (1 500)	412	0.2 to 0.3 (8 to 12)	0.254 (0.010)
041	Grafoil®- horizontal laminates	3	Zero clearance SAE 660 bronze	10.3 (1 500)	412	0.1 to 0.2 (4 to 8)	0.025 (0.001)
042	Mesh matrix- copper wire	3	Sintered graphite	10.3 (1 500)	412	0.1 to 0.2 (4 to 8)	0.102 (0.004)
043	Mesh matrix- glass fiber	3	Sintered graphite	10.3 (1 500)	412	0.1 to 0.2 (4 to 8)	0.102 (0.004)
044	Mesh matrix- carbon fiber	3	Sintered graphite	10.3 (1 500)	412	0.1 to 0.2 (4 to 8)	0.102 (0.004)
045	Graphite- homogeneous	3	Zero clearance SAE 660 bronze	10.3 (1 500)	412	0.1 to 0.2 (4 to 8)	0.025 (0.001)

There is an inherent problem in using cartridge heaters in the seal tester. Space is limited inside the tester vessel, and the leads from the cartridge heaters must be bent at the junction with the heater in order to fit. This causes cracking of the ceramic insulation, which allows the heaters to short.

All of the seal tests are now being run at a temperature of 121°C (250°F). This temperature was established after the original design of the seal tester. Thus, the original design heat capacity of 30 kW is no longer required. Therefore, to solve the problem with the cartridge heaters, the heater carrier was removed from the main vessel seal carrier, and a band heater system was designed to fit directly around the main vessel seal carrier. These heaters have a power density of 35 W/in.^{2} and are 3.8 cm (1.5 in.) wide. There are a total of six band heaters, and the total heat capacity is 8.2 kW. Surrounding the band heaters is a blanket of insulation.

The control system for the band heater system was also redesigned. The old controller was a phase-angle-fired SCR power controller. This type of controller has some inherent problems for the seal tester heater system. A phase-angle controller can cause radio frequency interference (RFI), which will affect all of the other instrumentation in the seal tester. Also, the phase-angle-fired controller is complicated and difficult to troubleshoot. This type of controller is used in a situation in which the resistance of the heater changes with temperature. The band heaters do not change resistance with temperature.

A zero-voltage-switched SCR power controller was ordered and installed in the new heater system. This type of controller turns on when the waveform is near the zero voltage point, eliminating the RFI problem connected with the phase-angle-fired controller. Also, the zero-voltage-switched controller is simpler and easier to troubleshoot than the phase-angle-fired controller.

The new band heater system and zero-voltage-switched SCR power controller should increase the number of tests that can be performed in the seal tester and will allow completion of all of the testing scheduled for this program. The equipment has been installed and is functioning properly.

The seal tester drive train was also overhauled during this reporting period. The following overhaul procedures were carried out:

1. The drive belt for the 20-hp motor was replaced,
2. The slip ring was rewired, and new contacts were installed,
3. The right-angle drive was rebuilt, and worn seals and bearings were replaced, and
4. A new coupling was installed between the right-angle drive and the slip-ring assembly.

The beneficial effects of these modifications and the installation of the new shaft were evident during test No. 035. This test was completed with out disassembling the seal tester during the test. Thus, the test seals were not disturbed during the test.

Bearing/Seal Package Testing and Evaluation

A new floating piston for the bearing/seal package was ordered from Utex Industries. The piston, which was proposed by Utex Industries, consists of a one-piece, molded, bidirectional lip seal and is made of No. RD-239 HTCR material.

The new electrohydraulic flow control valve for the hydraulic drive motor was received during this reporting period. The new control valve has a maximum flow capacity of 0.004 m^3/s (60 gal/min), which is double the flow capacity of the existing flow control valve. New hoses and fittings for the hydraulic drive motor servovalve have been installed to accommodate the larger flow rate of the new hydraulic and servovalve system.

An attempt was made to operate the bearing/seal package hot water system during this reporting period. It was discovered that the water will not circulate by convection alone; a small circulation pump is required. A survey of pump manufacturers was made to locate a high-temperature, high-pressure circulating pump for the hot water system. More than 60 manufacturers were contacted. In addition, the chemical process, oil and gas, boiler, and nuclear industries were all consulted for pump recommendations.

The extreme temperature and pressure requirements for the pump eliminated most pumps from consideration. Two pumps were located that would meet the specifications. Both of these pumps are magnetically driven and have no shaft seals. One pump is manufactured by Autoclave Engineers, Inc., Erie, Pennsylvania, and the other pump is manufactured by the Kontro Company, Inc., Orange, Massachusetts. Although both pumps meet the specifications, it will not be practical to use either because of prohibitively high cost and long delivery times. The search for a suitable pump is continuing.

New cabling has been ordered for the bearing/seal package test facility controls. This cabling is shielded and will reduce the noise signals experienced during the last full-scale test of the bearing/seal package. The new cabling will be installed before the next test.

The housing adaptor for the Eastman motor (Part No. 79-74) was received during this reporting period.

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PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>SUPPORT OF SEAL AND BEARING RESEARCH MAURER ENGINEERING</u>													
FABRICATION AND DESIGN													OCT 1980

LEGEND: ——— ACTIVITY PERIOD; – – – – – RESCHEDULED; ○ 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 November 1979 to 31 October 1980
Contract Number:	46-3054 (Sandia)
Technical Consultant:	J. Finger (505) 844-8089

Project Objective

The objective of this project is to provide the required design, manufacturing, and post-test 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 under a subcontract with Terra Tek, Inc. Since November 1979, the required support services have been furnished under a separate contract with Sandia. Design of redundant seals and of the areas interfacing with the bearing/seal package is continuing.

Quarterly Progress

Motor Interface Parts -- Maurer Engineering shipped interface part No. 79-74 to Terra Tek. As of this date, all necessary interface parts have been delivered to Terra Tek.

Improved Floating Piston -- There are two candidate floating piston assemblies. One assembly utilizes a wear-compensating Grafoil® arrangement to seal on the inner sleeve and elastomers on the o.d. This assembly also is able to compensate for run-out and shaft whipping, because the outer diameter seal can float with respect to the inner sleeve seal. The main objections to this assembly are those encountered in manufacturing. The new 102-mm by 127-mm by 6.35-mm (4.0-in. by 5.0-in. by 0.25-in.) Grafoil® seal would require new tooling. The estimate for delivery is 6 to 8 weeks. Also, the number of parts in the assembly could possibly make this design cost prohibitive.

The single-piece piston design shown in Figure 46 was supplied as a lower cost, interim solution that might possibly work. The main objection is the use of all-elastomer seals.

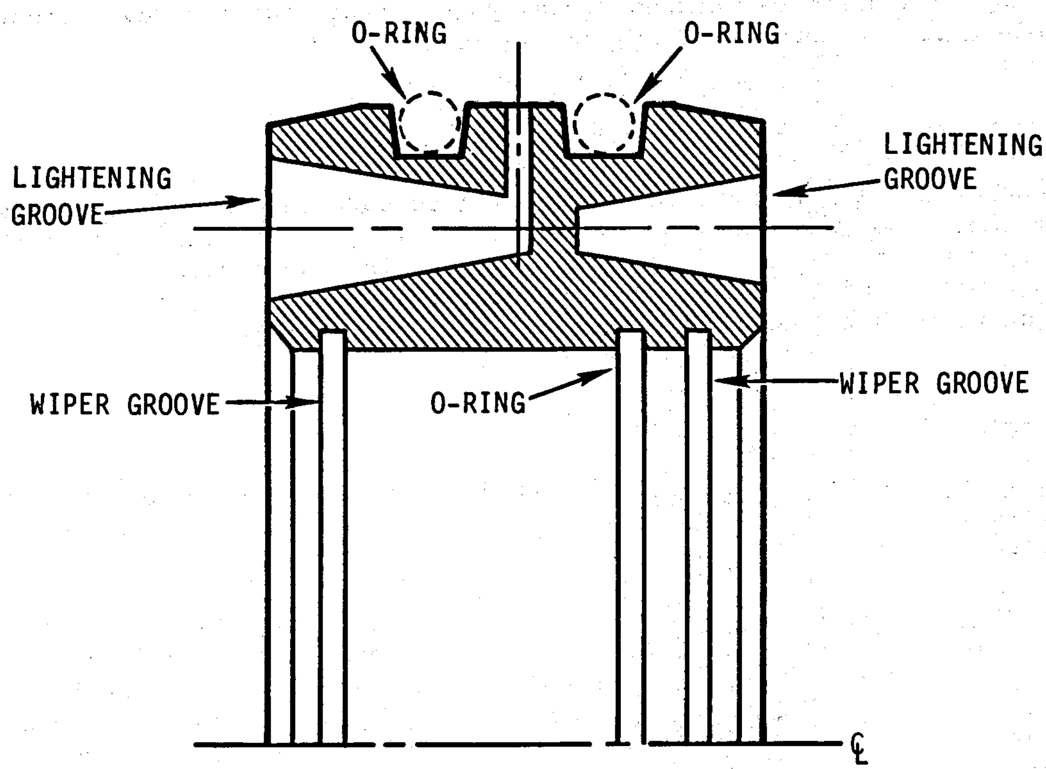

Figure 46. Single-Piece Piston Using All-Elastomer Seals

An alternative has been designed by Maurer Engineering utilizing a new high-temperature seal known as a Variseal. The assembly for a 19.7-cm (7.75-in.) floating piston is shown in Figure 47.

Both floating piston and lower rotary Variseals were designed previously by Maurer Engineering for use in LANSL's geothermal turbodrills. The Variseal piston worked well in the simulated downhole tests conducted at Terra Tek by Sandia and LANSL.

The Variseal floating piston assembly has been manufactured. When the Variseals necessary to outfit the assembly are delivered, the entire assembly can be shipped to Terra Tek.

Improved Redundant Seals — Design sketches have been made for several redundant-seal concepts. A basic decision that must be made in this area concerns the actual function which will trigger the redundant seal into action. Functions were discussed at some length in an earlier report (see Terra Tek TR78-58). Since automatic activation is desired, the seal could be made to activate when one of the following events occurs:

1. The leakage rate exceeds a certain set value,
2. The pressure drop across the redundant seal increases, or
3. A specified volume of lubricant has leaked past the primary seal. Leaked-volume activation can be accomplished by a floating-piston locator or a leak-volume metering system.

One possible design utilizes the Variseal. The design seals primarily in one direction, and, when the seals are unloaded, wear is insignificant. Therefore, a stack of Variseals would constitute a redundant assembly.

Improved Rotary Seals — The possibility of adapting the Variseal designs to the bearing/seal package is being investigated. Bronze housing rings and spacer were designed and manufactured so that the Variseal could be tested in the Terra Tek seal tester. The following parts have been sent to Terra Tek during this period:

Quantity	Description	
1	PN 80-83	Modified, end seal retainer
1	PN 80-84	Modified, backup spacer
4	PN 80-95-2	Variseal, double spring
4	PN 80-95-1	Variseal, single spring

Presently, there is no activity involving the Grafoil® seal systems.

Bearing/Seal Evaluation — Personnel at Maurer Engineering viewed the seals from Test No. 034. G. Tibbitts brought the seals to Houston for examination by both Maurer personnel and Utex Industries. Early opinions were that the move to thinner backup leaves is the next logical step.

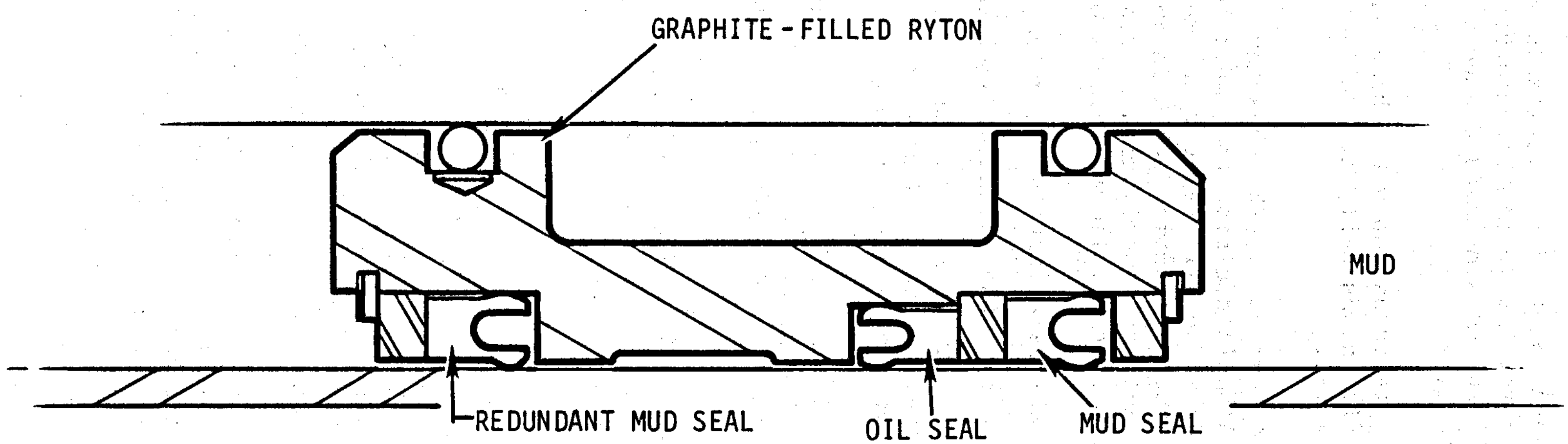

Figure 47. Assembly for a 19.7-cm (7.75-in.) Variseal Floating Piston Utilizing the Low Friction and Mass Properties of Graphite-Filled Ryton

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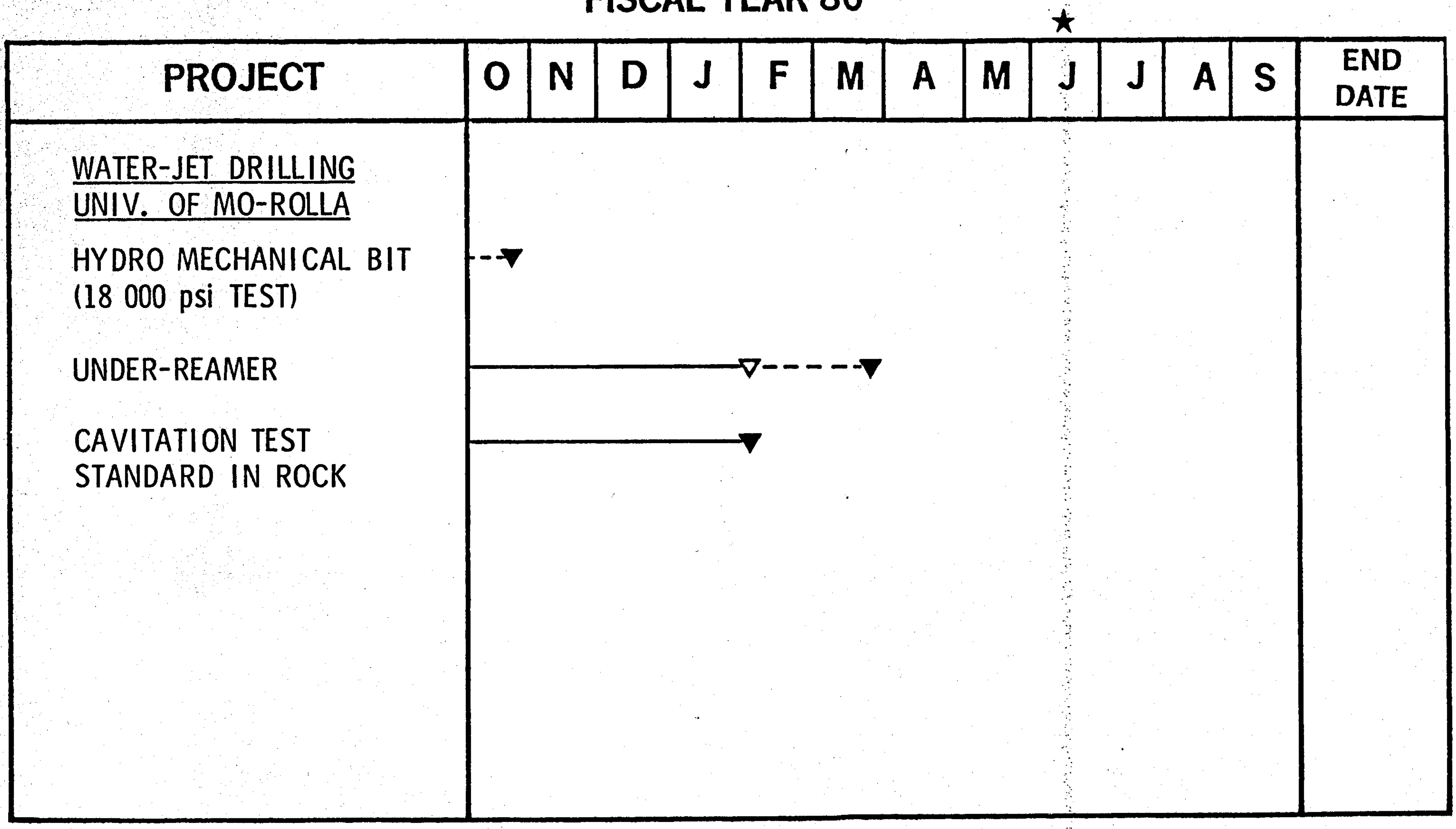

LEGEND: ——— ACTIVITY PERIOD; - - - - RESCHEDULED; ○ PLANNED START; ● STARTED; ▽ PLANNED COMPLETION; ▼ COMPLETED

9.4 Development of Geothermal Erosion Drilling Hardware

Contractor:	University of Missouri-Rolla
Principal Investigator:	D. A. Summers (314) 341-4311
Contract Period:	6 February 1979 to 31 March 1980
Contract Number:	13-2346 (Sandia)
Technical Consultant:	D. Glowka (505) 844-3601

Project Objective

The objective of this project is to continue work in erosion drilling for geothermal applications through investigations into the design, fabrication, and demonstration of hardware useful for geothermal well drilling and completion. There are three primary objectives of this project:

1. Development and demonstration of an erosion drilling under-reamer for use in geothermal injection wells,
2. Field testing of a hybrid water-jet/roller-cone bit, and
3. Development of a cavitation damage test standard for rock.

Project Status

All work under this project has been completed. A summary of the results of the investigation is presented in the quarterly progress section below. A final report is being prepared and will be published separately.

Quarterly Progress

Under-Reamer — The objective of this study was to determine the feasibility of developing a water-jet system to deeply under-ream geothermal production and injection wells. The purpose of this operation is to increase the flow rates and, therefore, minimize the number of wells required for each producing field. Specific requirements for the under-reamer consist of reaming a 22.9-cm (9.0-in.) borehole to a 1.8-metre (6.0-foot) diameter over a 61.0-metre (200-foot) interval at a depth of 1829 metres (6000 feet).

The approach taken in this study divided the work into two tasks. First, the effects of elevated ambient pressure on the rock-cutting ability of high-pressure jets were determined. Tests were conducted with nozzle pressure dopts of 68.9 MPa (10 000 psi) against Berea sandstone. It was found that, below 17.2 MPa (2500 psi) ambient pressure, the nozzle standoff distance must be less than 1.7 cm (0.7 in.), and the nozzle diameter must be greater than 1.5 mm (0.06 in.) in order for rock to be cut with pure water. These parameters place definite mechanical constraints on any under-reamer unit that would be placed downhole.

It was also found that the addition of polymer to the water in the concentration of 200 ppm increases the maximum allowable nozzle standoff distance to 4.8 cm (1.9 in.). Thus, if polymers were included in the under-reaming fluid, the mechanical constraints on the system could be reduced.

Further testing revealed that increasing the ambient pressure from atmospheric to 17.2 MPa (2500 psi) and the confining pressure from 0 to 41.4 MPa (6000 psi) decreases the depth of cut in Berea sandstone by a factor of 10. This result shows dramatically the effect of taking a high-pressure jet from the surface into a 1829-metre (6000-foot) borehole.

The second task in this study was to develop a concept for the mechanical design of the under-reamer device, to built a working portion of this device, and to test it at atmospheric pressure. This approach would negate the need to develop, in a feasibility study, a device that would work in a downhole environment.

The concept developed consists of four units mounted on two balanced arms. Each unit consists of a rotary coupling to which a nozzle on an extended tube is mounted. A hydraulic motor causes each nozzle to rotate about its coupling axis. In the downhole configuration, the balanced arms would be rotated about the borehold axis, resulting in the translation of each nozzle unit. Thus, each unit would sweep out an annular area 22.9 cm (9.0 in.) wide, and all four units together would under-ream a 91.4-cm (3.0-ft) radius hole. The arms could be folded parallel to the borehole axis for tripping-in and tripping-out and could be unfolded downhole to the under-reaming configuration.

A single unit of this device was built and tested at atmospheric pressure against Berea sandstone. The test was conducted under non-optimum conditions; i.e., the nozzle rotational velocity was not synchronized with the nozzle axis translating velocity to give complete removal of a thickness of rock in a single pass. In addition, the optimum nozzle standoff distance was not maintained. Under these conditions, a 35.6-cm (14.0-in.) hole was excavated at a rate of 0.46 m/h (1.5 ft/h).

The characteristics of a field-usable water-jet under-reamer can be projected from the results of this study and from the results of independent studies found in the literature. The characteristics of major interest relate to the pump and rig requirements as well as to the performance of such a system.

The pump needed for the system would be required to pump water or other non-abrasive liquids at pressures of 68.9 to 82.7 MPa (10 to 12 ksi) and flow rates of 2.2×10^{-3} m^3/s (35 gal/min). These requirements can be met with commercially available pumps.

The rig required for this operation would be fairly small, with a lifting capacity of approximately 31.8×10^3 kg (35.0 tons). This capacity suggests that a workover or truck-mounted rig could be used.

The projected performance of this system is an excavation rate of 4.2×10^{-5} m/s (0.5 ft/h) in Berea sandstone at a depth of 1829 metres

(6000 feet); thus, a 61.0-metre (200-foot) under-reaming interval would require 15 to 20 days for completion.

The results of this study and the projected system characteristics will be examined in order to determine the benefits of developing an under-reamer system for use in geothermal fields.

Hydromechanical Bit -- The objective of this task was to field test a hydromechanical bit developed under an earlier contract. The testing was to be conducted at shallow depths for comparison with conventional bit performance.

Initial results of field tests of the hydromechanical drill in drilling dolomite indicated that a jet pressure of 68.9 MPa (10 000 psi) must be exceeded before a jet assist improves performance. Above 82.7 MPa (12 000 psi), improvements of approximately 100% or better in drilling rate can be achieved using a single jet directed axially along the drill. Other jet orientations have achieved even higher rates. The field tests were concluded during October 1979. While an improvement in drilling rate was achieved where high-pressure water jets were directed across a quadracone bit (this combination comprising the hydromechanical bit), the practical problems of running the present bit design in a hole were such that it was recommended that this particular design not be further developed.

Cavitation Test -- The objective of this task was to develop a standard procedure for determining the resistance of rocks to cavitating-jet attack. The purpose of this objective was threefold. First, such a standard could be used to investigate the cavitation damage mechanism. Second, it is hoped that, eventually, a determination may be made concerning the relative resistance of different rock types to the attack of cavitating and, perhaps, conventional jets. Finally, the results of these studies could conceivably be used to develop better methods for utilizing the cavitation phenomenon in geothermal drilling.

Two methods for initiating cavitation damage were investigated. The first of these is the vibratory method. An American Society for Testing Materials (ASTM) standard for cavitation testing of metals locates the metal specimen at the tip of an ultrasonic transducer. The specimen is then submerged to a standard depth in water, and the transducer is vibrated at a frequency of 20 kHz. This vibration induces cavitation at the specimen face, which damages the specimen surface.

The investigation of the application of the vibratory method revealed that the machining of the transducer could not be easily accomplished. A modified procedure was therefore used, in which the rock specimen is held stationary below a vibrating titanium specimen. This arrangement results in cavitation inception between the two specimens and subsequent damage to the rock face.

Tests were carried out to determine the optimum conditions, which would be used as the standard. Following this determination, tests were conducted on three types of granite, three types of marble, a sandstone, and dolomite. Cumulative damage as a function of time was determined by measuring the weight loss of the samples after testing and drying for specified time periods. In addition, the damaged zones were inspected under a microscope to determine the characteristic results of cavitation attack on different rock types.

The results of this investigation were inconclusive. It was not possible to identify common characteristics that describe the effects of cavitation on similar types of rock. For example, some of the granites showed a response much closer to that of the marble than to that of the other granites. It was also not possible to correlate the response of rock to cavitation attack with the response to conventional-jet attack. For instance, dolomite is one of the most difficult rocks to penetrate with conventional jets, yet it was the rock most easily eroded by cavitation attack.

The second method that was investigated for inducing cavitation utilized high-pressure jets in a chamber at elevated ambient pressure. Tests were conducted to determine the optimum nozzle diameter, nozzle pressure drop, and ambient pressure to use as standard conditions. Under these standard conditions, tests were run on a suite of rocks and Plexiglas to provide a standardized sample for comparison with research conducted elsewhere. Again, three types of granite, three types of marble, sandstone, and dolomite were tested.

The results of these tests were more consistent than those conducted with the vibratory method. The cavitating-jet erosion mechanism appeared to be much the same for all samples tested. The cavity shape was similar in most cases, with the central cavity being much larger than the diameter of the impacting jet; in most cases, cracks grew out into the sidewalls of the cavity.

In addition, it was found that the data for mass loss vs jet impact time could be described for each rock type by the equation

$$\text{mass loss} = A(\text{time})^B ,$$

where A and B are constants for each rock type. It is possible that further research to determine these constants would allow identification of the cavitation erosion resistance of different rock types. However, the short-term benefits of further research are insufficient to justify further work under this program.

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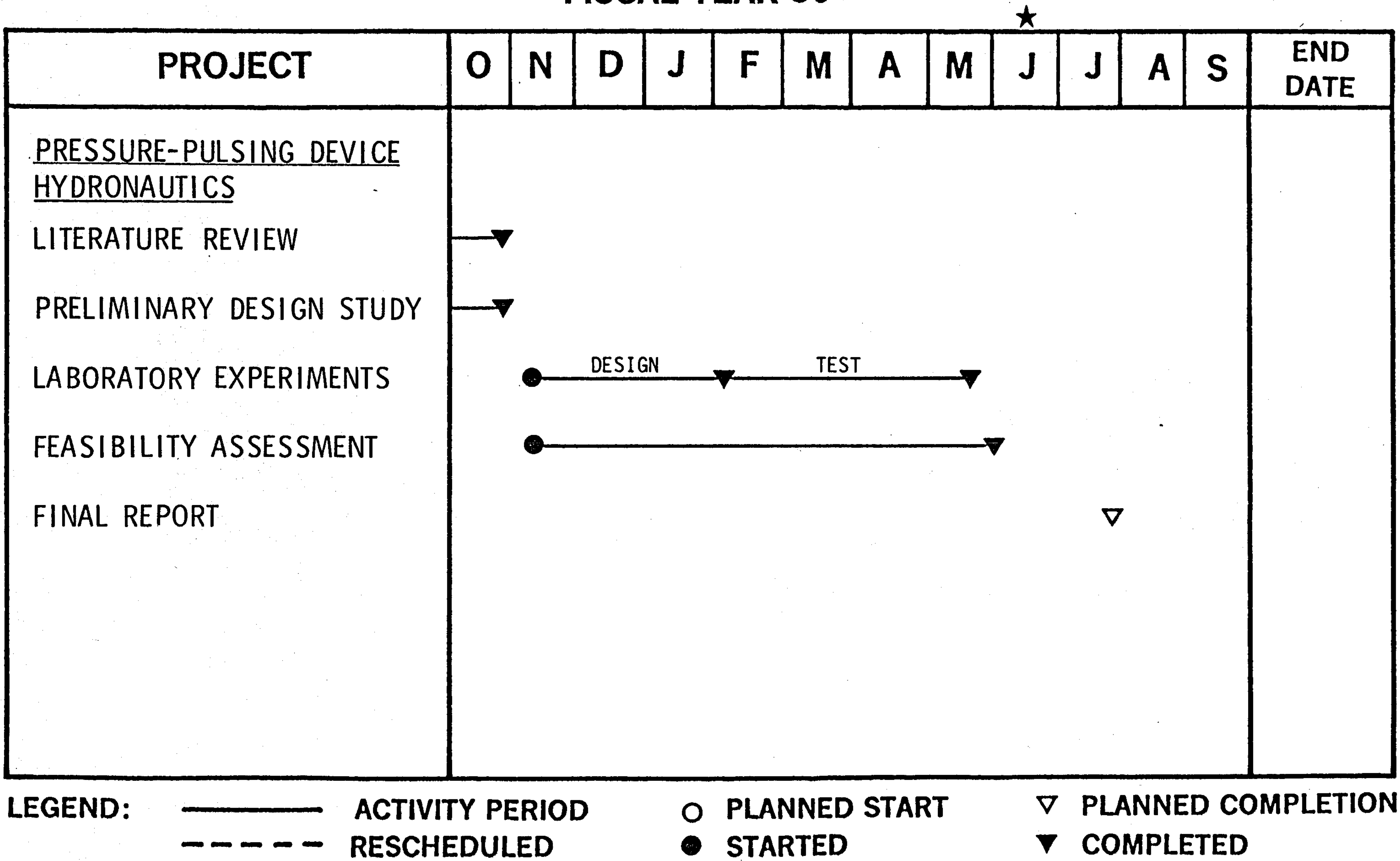

9.5 Feasibility and Design Study of a Downhole Pressure-Pulsing Device

Contractor:	Hydronautics, Inc.
Principal Investigator:	V. Johnson, Jr. (301) 776-7454
Contract Period:	1 August 1979 to 31 July 1980
Contract Number:	13-5111 (Sandia)
Technical Consultant:	D. Glowka (505) 844-3601

Project Objective

The objective of this project is to conduct a feasibility and preliminary design study of a downhole pressure-pulsing device for use with cavitating jets. This device would convert steady pressures supplied by the pump into pulsing nozzle pressures, thereby supplying higher-than-average pressures over one-half the cycle. The technique should greatly increase the effectiveness of cavitation erosion, inasmuch as tests have shown that rock cutting rates with Hydronautics' Cavijet® nozzles increase as the third power of nozzle pressure drops.

The design of this device will take into account an interesting characteristic of Cavijet®-induced cavitation. The shedding of toroidal vortices and the subsequent formation of cavities in the jet shear zone have been shown to occur with a high degree of periodicity. The pressure-pulsing device will essentially consist of a flow passage immediately upstream of the nozzle. The passage will be sized so as to resonate at the vortex-shedding frequency, thereby amplifying the small pressure pulses created by the vortex-shedding phenomenon.

Project Status

Preliminary design studies have been completed, along with a review of past research and literature on shear and oscillatory flows. Three nozzle concepts have been selected, designed, and fabricated. Laboratory testing of the nozzles has been completed, and preparation of the final report is underway.

Quarterly Progress

During the reporting period, laboratory testing was completed and analysis of the data carried out. Summaries of selected activities follow.

The Hydronautics high-pressure test loop modifications for visual observations were completed, and cavitation observations were made of Helmholtz, tuned-inline-resonant Cavijet® nozzles with various cavity volumes. These results were compared with similar observations made on the basic Cavijet® nozzle, conventional nozzles, and other resonant Cavijet® concepts. Initial results reveal that the incipient cavitation number for the tuned-inline, Helmholtz Cavijet® is approximately twice that of the basic

Cavijet®. Cavitation observations as well as rock erosion levels for the pulsed resonant nozzles were made.

Air tests were conducted on a variety of resonant-nozzle concepts, with particular attention given to the effect of minor geometrical changes on the amplitude of jet modulation.

Professor A. Ellis conducted tests in the University of California at San Diego (UCSD) test apparatus on the effects of forced excitation on jet structure and on the resulting cavitation. After some considerable effort, a successful magnetostrictive exciter was developed which permits adequate excitation amplitude at frequencies up to 15 kHz. Tests were carried out to determine the effect of excitation on the jet structure and on cavitation at the highest jet-speed capabilities of the test apparatus--91 m/s (300 ft/s).

The data obtained were analyzed, and some additional experimental tests in water, tests related to the rock cutting capability of the inline Helmholtz, resonator nozzle, were carried out. Also further tests in air, using an inline, Helmholtz, resonator nozzle to feed a smaller Cavijet® nozzle so as to passively excite the Cavijet® nozzle at the critical Strouhal number of 0.3, were carried out. Preliminary results in air indicate the feasibility of the concept. That is, it seems feasible to passively accomplish the results which were achieved by Professor Ellis at UCSD in water with active excitation.

A detailed review of the work carried out under the project was presented to Sandia in May 1980. Preparation of the draft final report was nearing completion at the close of the quarter. Details of the project findings will be reported in the next quarterly progress report.

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PROJECT	O	N	D	J	F	M	A	M	J ★	J	A	S	END DATE
<u>PERCUSSION DRILLING</u> <u>HAMMER AND BITS</u> <u>DRL</u>													
LABORATORY TESTS			● ——	————	—— ▼								

ADDITIONAL EFFORTS DEPENDENT ON ECONOMIC ANALYSIS

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

9.6 Testing of Percussion Drilling Hammers and Bits

Contractor:	Drilling Research Laboratory, Inc.
Principal Investigator:	A. Black (801) 583-4111
Contract Period:	15 December 1979 to 31 March 1980
Contract Number:	46-3173 (Sandia)
Technical Consultant:	J. Finger (505) 844-8089

Project Objective

The objective of this project is to evaluate percussion drilling devices which offer the potential advantages of high penetration rate and achievement of straight holes when drilling with low-density fluids in brittle rock.

Project Status

The project, currently limited to the laboratory testing of the penetration rate and high-temperature hammer performance of commercially available equipment, was initiated in the last quarter of 1979. The laboratory tests were completed last quarter. The test results are being evaluated with a view toward quantification of the potential economic benefits of percussion drilling operations. The findings of the evaluation will determine what additional efforts will be made to improve percussion drilling devices for geothermal well drilling.

Quarterly Progress

The results of the laboratory tests were summarized in the previous quarterly report. During this quarterly reporting period, the test results were analyzed in detail by Sandia. The report of this analysis is contained in Appendix E.

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PROJECT	O	N	D	J	F	M	A	M	J ★	J	A	S	END DATE
IMPROVED CAVIJET® NOZZLES HYDRONAUTICS													
INITIAL NOZZLE TEST (DRL)							▼						
MODIFY TEST FACILITY					● ———	——— ▼							
FLUID-DYNAMIC STUDIES							● ———	———	———	——— ▽			
ROCK CUTTING TESTS							● ———	———	———	——— ▽			
FINAL NOZZLE TESTS												▽	
NOZZLE CHARACTERIZATION TESTS													START FY 81
FLUID-DYNAMIC STUDIES (UCSD)							● ———	———	———	———	———	———	DEC 80
BIT TESTS (DRL)													START FY 81

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

9.7 Development of Improved Cavijet® Nozzles

Contractor: Hydronautics, Inc.
Principal Investigator: A. F. Conn (301) 776-7454
Contract Period: 18 February 1980 to 17 February 1981
Contract Number: 13-5129 (Sandia)
Technical Consultant: D. Glowka (505) 844-3601

Project Objective

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

Project Status

The initial nozzle tests at DRL and the modification of the Hydronautics test facilities have been completed. Rock cutting tests and cavitation inception studies have been initiated and are continuing.

Quarterly Progress

Initial Nozzle Tests -- The first task in this project was a test of the effectiveness of existing, full-size Cavijet® nozzles in cutting hard, impermeable rock such as granite. Although similar tests were conducted at the Hydronautics test facility in earlier research, these tests could not be run with full-size nozzles at nozzle pressures greater than 12.4 MPa (1800 psi) due to the limited available pump power. The jets proved capable of cutting granite at this pressure, but the depth of cut was a factor of 20 lower than those obtained in tests at the DRL with Indiana limestone and nozzle pressure drops of 16.6 MPa (2400 psi).

Extrapolated data suggest that obtaining a depth of cut in Georgia granite comparable to those obtained in Indiana limestone would require nozzle pressure drops of 43.4 MPa (6300 psi). This pressure and the required flow rates are within the capability of equipment at DRL. Accordingly, tests were conducted there in April 1980 to determine the validity of this extrapolation. A total of 61 runs was made on two specimens of Sierra white granite; 27 runs on the first specimen and 34 runs on the second.

Upon consideration of the available flows (about 10.1 ℓ/s [160 gpm] at 103 MPa [15 000 psi]), it was realized that only two full-scale nozzles could be simultaneously tested. For this reason, plus consideration of the major changes required in the existing tool to permit operation up to 52 MPa (7500 psi), it was decided to build a new "two-nozzle" tool. The design of this tool was initiated by NL/Hycalog. This new, two-nozzle tool was used for these tests, but the remainder of the test configuration was essentially the same as that used during the first phase of this program.

Another change was a vastly improved ratcheting mechanism that was created by DRL especially for the tests because of difficulties encountered during the first phase. This new ratcheting device worked perfectly, completely eliminating the frequent malfunctions in indexing the tool, which occurred throughout the earlier efforts in the wellbore simulator.

On the first rock specimen, both of the Cavijet® cavitating-jet nozzles had an orifice diameter of 5.2 mm (0.204 in.). One of these had the "plain" Cavijet® nozzle configuration; the other was a new type of Cavijet® cavitating-jet nozzle, which consisted of tandem orifices with an intervening, self-excited, resonant chamber. For convenience, the latter nozzle will be referred to as the "Pulsar," a "nickname" temporarily adopted for this class of Cavijet® cavitating-fluid jet nozzles.

To further examine size-scaling effects, the second rock was exposed to hole cutting tests by two Cavijet® nozzles, one having an orifice diameter of 2.6 mm (0.101 in.) and the second 7.2 mm (0.283 in.). Unfortunately, due to erosion damage on these nozzles and their subsequent repair, as discussed below, the configuration of their orifices was only approximately that of the original design. This condition had some effect on the test results, and attempts will be made to assess the magnitude of these configuration errors on the data that were obtained.

The ranges of the various test parameters were

1. Swivel (≈pump) pressure: 18.6 to 75.8 MPa (2700 to 11 000 psi),
2. Nozzle pressure drop, Δp: 9.0 to 51.3 MPa (1300 to 7440 psi),
3. Ambient borehole pressure, P_a: 0.8 to 51.2 MPa (122 to 7420 psi), and
4. Cavitation number: 0.02 to 5.58.

It should be emphasized that the foregoing ranges of parameters represent the external values achieved during the entire test series and that the maximum values of Δp and P_a were not utilized during any single test run. Indeed, the maximum swivel pressure that could be used was found to be only about 75.8 MPa (11 000 psi), despite the rated pump capacity of 103.4 MPa (15 000 psi). Therefore, since $P_{swivel} = \Delta p + P_a$, running with any combinations of Δp and P_a that exceeded the system limit of 75.8 MPa (11 000 psi) was precluded. This pressure limit on the DRL system during these tests was found to be at a connection between the aluminum segment of drill pipe, which serves as the load cell for sensing torques and bit weights, and the mating steel drill pipe segment. Twice, when the attempt was made to exceed 75.8 MPa (11 000 psi), this connection began to leak, requiring a shutdown and replacement of the O-ring. It was felt that this problem may have been caused by expansion of the aluminum pipe and could probably be dealt with in any future high-pressure efforts by substituting a steel drill pipe segment. Time restraints prevented an attempt at this solution during the present test series.

Another major problem, which was greatly minimized but not entirely eliminated, was erosion of nozzle orifices by suspended rock particles in the water used for these tests. Because water was selected as the working fluid for these runs to provide direct comparisons with the more extensive tests to be conducted at Hydronautics, and because of the long lead time required to fabricate carbide nozzles, all of the nozzles used in these tests were fabricated from stainless steel. During a first test run, the two nozzles were eroded to about twice their original combined area after less than 1/2 hour of attempts to achieve the desired test pressures and flows. Thus, it was necessary to repair these two nozzles by welding over the damaged orifices and then remachining to approximate the original configurations. As discussed, these repaired nozzles were subsequently used in the series of runs made on the second specimen of Sierra white granite.

To reduce this nozzle erosion problem, the entire system was thoroughly rinsed with fresh tap water. Outside water was used during the actual testing on a once-through basis instead of being recirculated in the normal fashion. Although this greatly reduced nozzle wear, it was not possible to remove all of the particles of rock from the complex DRL piping and pump system. Thus, measurable wear, which will be factored into the final analyses of the test results, did occur to all four nozzles.

Preliminary examinations of the test results are limited. Estimated hole depths were taken within the intact specimens, and the final measurements of depth, diameter, and volume are in progress at Hydronautics. Preliminary observations are as follows:

1. Nozzle pressure drops of at least 27.6 MPa (4000 psi) were required to create measurable damage in these Sierra white granite specimens, even at the exposure times of up to 5 minutes that were used for runs at the lower pressures of 10.3 and 17.2 MPa (1500 and 2000 psi).
2. The two plain Cavijet® cavitating-jet nozzles having orifice diameters of 2.6 mm and 7.2 mm (0.101 in. and 0.283 in.) produced substantially lower hole-cutting rates at the nominal nozzle pressure drop of 34.5 MPa (5000 psi) when compared to the other pair of 5.2-mm (0.204-in.) plain and Pulsar types of Cavijet® cavitating-jet nozzles. This enhanced cutting rate for the latter pair of nozzles was observed over the entire test range of cavitation numbers from about 0.2 to 1.3, which were used at the Δp of 34.5 MPa (5000 psi).

<u>Facilities Modification</u> -- Three viewing ports were installed in the Hydronautics high-pressure cell (HPC) and were successfully tested to a cell pressure of 20.7 MPa (3000 psi). These ports afford good visibility of cavitation phenomena during rock cutting, even at lower cavitation numbers.

A displacement device for in situ measurements of eroded hole volume was constructed, calibrated, and then installed in the chamber. This device significantly increases the rate of data acquisition because it reduces the number of times the chamber must be opened and the rock removed. The device has proven capable of providing sufficient accuracy and reproducibility and has already saved considerable time during some recent hole-cutting tests. Methods for visual, photographic, and pressure-pulsation data acquisition are now installed and operational.

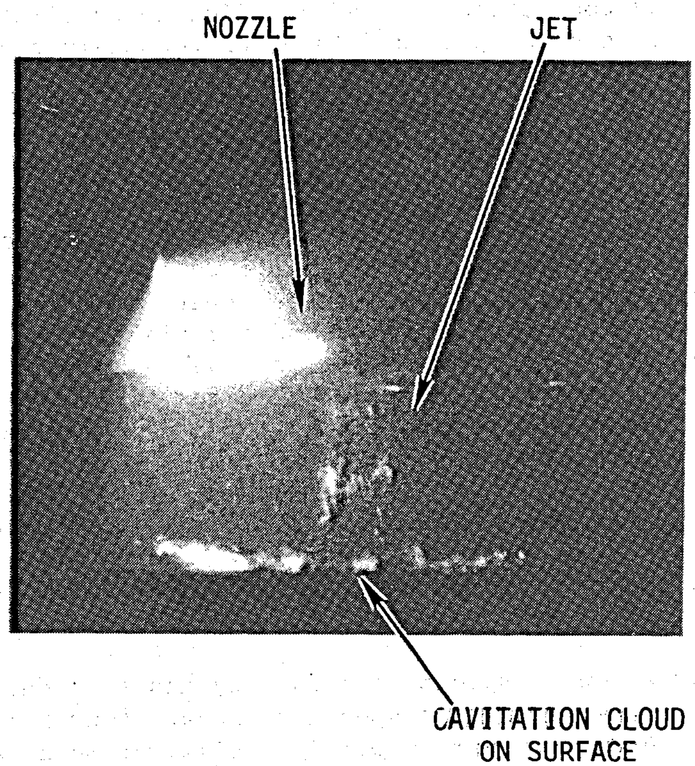
The modified facility will be used in the fluid-dynamic studies and rock cutting tests conducted at Hydronautics.

Fluid-Dynamic Studies — The fluid-dynamic studies will be used to identify changes in nozzle design that improve jet dynamics. Improvements are considered to be those that result in increased incipient cavitation numbers and in the development of more highly structured jets. High-speed still photography will be used to examine periodicity of vortex shedding and cavity size and intensity. Visual and aural detection of cavitation will be used to determine incipient cavitation numbers. Thus, both qualitative and quantitative measures of jet dynamics can be associated with changes in nozzle design in order to rate the relative merit of each change. Increases in incipient cavitation number and jet structure are the desirable results of a nozzle design change because these would increase the depth capability and/or lower the required nozzle pressure for effective rock cutting.

Several nozzle types have been tested for cavitation inception over a range of Reynolds numbers from about 0.4×10^6 to 1.5×10^6. The types tested were plain Cavijet®, Cavijet® with centerbody, vaned Cavijet®, passively "pulsed" Cavijet®, and a Smith Tool nozzle. The incipient cavitation number ranged from $\sigma_i = 0.3$ to 1.3, where the σ_i value depends on the nozzle type, the Reynolds number, and the means of detection. Visual and aural detection of cavitation inception gave comparable results, but these σ_i values were roughly 0.3 below the value that was sensed electronically. In the latter case, cavitation was disclosed by intermittent bursts of high-frequency pressure fluctuations greater than 10 kHz, which were seen as oscilloscope traces from a piezoelectric pressure transducer (PT) that is located in the wall of the HPC. The intensity of the pressure fluctuations sensed by the transducer rises to between 0.69 and 6.9 kPa (0.1 and 1.0 psi), rms, when the onset of cavitation is first perceived by the naked eye or by ear.

A typical photograph of cavitation bubbles viewed in the HPC is shown in Figure 48. In this view, a 6.9-mm (0.27-in.) diameter jet is impinging downward on a flat surface that is normal to the jet axis and nominally 22 mm (0.87 in.) from the orifice. The jet is shown at Reynolds number, $Re = 1.0 \times 10^6$, and cavitation number, $\sigma = P_a/\Delta p = 0.25$, i.e., somewhat below the values for visual (inception) perception, $\sigma_i = 0.35$, and PT perception, $\sigma_p = 0.65$. For this nozzle, the inception of visible bubbles was observed on or near the flat surface and up to about 10 mm (0.39 in.) from the jet centerline. At the lower cavitation number shown in the figure, bubbles are seen to surround the submerged jet and to cover the plate to about a 20-mm (0.79-in.) radius.

The assembly of a laser/photomultiplier system, such as that used by Professor Ellis at UCSD, is in progress for the optical detection of cavitation inception. The principal parts of the apparatus are available in-house. This instrumentation should prove more sensitive to cavitation inception than aural/visual detection and, unlike acoustic transducer signals, will not be affected by large pressure fluctuations that are created by resonating, pulsed nozzles.



DYNAMIC PRESSURE = 5.5 kPa (800 psi)
AMBIENT PRESSURE = 1.4 kPa (200 psi)
ORIFICE DIAMETER = 6.9 mm (0.27 in.)

Figure 48. Cavitating Jet in the Hydronautics High-Pressure Cell

Initial Rock Cutting and Final Nozzle Tests -- Nozzle designs identified as improving jet dynamics will be tested for their rock-cutting ability. This investigation will consist of measuring the dimensions of cuts produced by the jets in both permeable and impermeable rock specimens.

Due to the limited pump power available at the Hydronautics facility, tests against hard, impermeable rock, which require higher nozzle pressures, must be conducted with limited flow rates, requiring the use of nozzles that are smaller than full size. To ensure that the size effect does not radically alter the results, tests will be conducted at DRL with higher nozzle pressures and full-size versions of the designs tested at Hydronautics. By conducting the Hydronautics tests first, the test matrix for the DRL tests can be optimized in order to obtain the most useful data in the shortest possible time.

In preparation for these tests, investigations of techniques to calibrate the erosion strength of individual rock specimens are being made. It is anticipated that linear kerfs on the specimens' surface(s) that are cut with a jet at standard conditions of pressure, translation rate, etc., will serve as a calibration standard. Preliminary cuts in Berea sandstone specimens have shown that the variance in penetration depth is less for cuts made with the jet axis normal to the bedding planes than for cuts made with the axis across the bedding planes or in rough alignment with the planes. Hence, holes will be cut in "calibrated" sandstone with jets normal to the bedding plane in order to minimize the standard deviation of future measurements with regard to jet erosivity.

Eighty 15.24-cm (6-in.) cubes of Berea sandstone have been obtained for tests in the HPC. Holes will be made with the jet normal to the bedding plane, so that using just two faces of a cube will permit eight test holes to be made per specimen.

Some information on specimen uniformity has been developed from repetitive tests on two sandstone specimen faces. Four holes were made with each of two different 2.18-mm (0.086-in.) diameter nozzles in the two faces. Hole depth and volume were measured after 2, 4, 6, 9, and 12 seconds of jet drilling under submerged conditions with $\sigma = 0.105$ and a driving pressure of 6.895 kPa (1000 psig). One sample was observed to be lighter in color and more porous than the others.

Discounting differences in erosion due to the nozzles, one nozzle being of a resonant pulsing design, the variations in depth and volume that are attributable to specimen non-uniformity and test repeatability are summarized in Table 24 for a 9-second drilling.

The holes made in the dark specimen were more uniform than those made in the light specimen, but there was a significantly greater difference in holes between the two specimens than was shown for holes within each specimen. The difference in results between specimens was particularly notable with regard to the volume of material removed, because the volume removal rate was nearly 50% greater in the light-colored specimen. Hence, the need to "calibrate" the specimens to account for variations in erosivity is manifest. Even with calibration, the variation within specimens may not be

Table 24

Variations in Depth and Volume
Attributable to Specimen Non-Uniformity
and Test Repeatability

Sandstone Specimen	Mean Volume cm^3	(in.^{3})	Standard Deviation, %	Mean Depth mm	(in.)	Standard Deviation, %
Dark	7.2	(4.4)	8	14.2	(0.56)	5
Light	10.6	(6.5)	17	17.3	(0.68)	14

accounted for completely. Thus, replicative tests may be necessary to reduce confidence intervals.

The fluid-dynamics studies, along with the inital rock cutting and final nozzle tests, will provide data on the incipient cavitation number and on rock-cutting effectiveness against representative permeable and impermeable rock types for each nozzle design tested. Analysis of the results should identify nozzle design changes that significantly improve cutting ability at depth, with the goal being the identification of one or several nozzle designs that incorporate an optimum combination of these changes.

Nozzle Characterization Tests -- The cutting ability of the nozzle designs selected from the previous tests will then be characterized completely in these tests. Several nozzle sizes of each design selected for final consideration will be tested against several rock types at various values of cavitation number and Reynolds number. The rock types selected for these tests will be those which are likely to be encountered in geothermal environments and which have not been previously tested but have characteristics different from those tested in the initial rock cutting and final nozzle tests.

Fluid-Dynamic Studies -- The dynamics of jets produced by the selected nozzle designs will also be studied further at UCSD. High-speed motion photography will be used to study jet structures and determine periodicity of vortex shedding and cavity formation. Transient jet-impact pressures and cavitation intensities will also be measured in order to characterize more fully the ability of the jets to cavitate under pressure.

Bit Test — Conventional mechanical bits will be tested under identical simulated downhole conditions both with conventional and Cavijet® nozzles. The purpose of these tests is to assess the effects on penetration rate of substituting improved Cavijet® nozzles for the conventional nozzles normally used in the field. Conventional, currently available mud flow rates and pressures will be used in these tests. The rock types will be those likely to be encountered in geothermal drilling. It is anticipated that diamond and/or Stratapax™ bits will be employed in these tests.

If the above tasks demonstrate the superiority of improved Cavijet® nozzles over conventional nozzles, the result of this program will be the development of cavitating nozzle designs that significantly improve the performance of conventional drill bits while still using conventional pumping systems and drilling practices. Such a development would have the potential for creating rapid commercialization and extensive employment of the superior nozzles, because there would be essentially no additional capital, maintenance, or special manpower requirements to restrict their use.

APPENDIX A

Publications and Presentations

PUBLICATIONS AND PRESENTATIONS

Polycrystalline Diamond Compact Drag Bits for Geothermal Use, SAND79-1836J, S. G. Varnado, C. F. Huff, and P. Yarrington, Sandia Laboratories, World Oil, March 1980, pp 63-70.

The Development of New Technology for Drilling and Completing Geothermal Wells, SAND80-0832A, by S. G. Varnado, Sandia Laboratories, to the GRC Drilling School, Albuquerque, New Mexico, 24-26 March 1980.

The Development of New Technology for Drilling and Completing Geothermal Wells, SAND80-0832A, by S. G. Varnado, Sandia Laboratories, to the Seminars at the Ministry of Works and the Kingston, Reynolds, Thom, Allardice, Co., Wairakei-Auckland, New Zealand, 14-18 April 1980.

Considerations in the Use of Water Jets To Enlarge Deep Submerged Cavities, SAND80-7031, by D. A. Summers and Z. Sebastian, University of Missouri, to the 5th International Jet Cutting Symposium of the British Hydraulics Research Association, Hanover, West Germany, Sandia Contract No. 13-2346, 5-7 June 1980.

The Fluid Dynamics of Submerged Cavitating Jet Drilling, SAND80-7032, by Andrew F. Conn and Virgil E. Johnson, Jr., Hydronautics, Inc., to the 5th International Jet Cutting Symposium of the British Hydraulics Research Association, Hanover, West Germany, Sandia Contract No. 13-5129, 5-7 June 1980.

APPENDIX B

Modifications To GEOTEMP: Documentation

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MODIFICATIONS TO GEOTEMP: DOCUMENTATION

GEOTEMP Modifications

The modifications to the single-phase GEOTEMP code have been completed. These modifications give GEOTEMP the following additional capabilities:

1. Variable tubing flow areas,
2. Multiple fluids in the wellbore separated by interfaces, and
3. Deviated wellbores.

A series of test cases were devised to test the modifications, and base cases from the GEOTEMP user's manual were rerun to verify the modified code.

To handle these added capabilities, the input and output formats have been modified, and to illustrate these changes, a sample problem has been run that incorporates all of the input and output modifications. Figure B-1 shows the input data for this example. The first change from the original GEOTEMP input data is the CONTROL card shown on line 52. This control card allows the user to specify

1. The number of tubing sizes in the well,
2. The number of casing sizes in the well, and
3. The number of fluid types to be used in the analysis.

In the example, two tubing sizes, four casing sizes, and two fluids have been indicated. Lines 53 and 54 show the new TUBING card input. The TUBING card has the same general format as the CASING card but with slightly different interpretations. First, the tubing sizes are numbered consecutively from the top of the well to the bottom. With casing cards, the casings are numbered from the smallest to the largest. The setting depth defines the bottom of the interval of tubing, with the top of the interval defined by either the previous interval or the surface. In the output, the top and base of the tubing interval are printed based on this criterion.

The next new card is line 59, the GEOMETRY card. This card replaces the BOREHOLE card used in the original GEOTEMP program. The GEOTEMP card carries the following data:

1. Initial depth (equals total measured depth except when simulating drilling),
2. Total measured depth (i.e., total length of wellbore),
3. True vertical depth,
4. Depth at which well is deviated, and
5. Borehole diameter.

```
50   GEOTEMP2  TEST  DATA  :  INJECTION
52  CONTROL CARD           2    4    2
53 TUBING CARD             1    3.9580    4.5000    2000.0    2000.0
54 TUBING CARD             2    1.9580    2.5000    5000.0    3000.0
55 CASING CARD             1    8.6810    9.6250    5000.0    2200.0
56 CASING CARD             2    12.347     13.37    3000.0    2200.0
57 CASING CARD             3    19.124    20.000    1000.0    1000.0
58 CASING CARD             4    29.000    30.000     100.0     100.0
59 GEOMETRY CARD             5000.     5000.     4500.     2000.     40.00
60 INITIAL TEMPERATURE        70.0    145.00       70.      20.0
61 FLUID CARD              1        10.        15.       5.0  PRIMARY
62 FLUID CARD              2        10.        15.       5.0  ANNULAR
63 INITIAL FLUID           1    1    2    145.00      0.00
64 CHANGE CARD          1 0 1       70.        10.        10.
65 CHANGE CARD          1 0 2       70.       100.        20.
```

Figure B-1. Input Data for Sample Problem

In this example, the well deviates 30° at a depth of 2000 feet, resulting in a true depth of 4500 feet and a wellbore length of 5000 feet.

The input of fluid properties is changed from the original GEOTEMP through a new card, the FLUID card. All the fluids in the wellbore are now specified by identification numbers. For example, line 61 gives the FLUID CARD for fluid number 1. The entries on this card are

1. Fluid identification (I.D.) number,
2. Fluid density,
3. Plastic viscosity,
4. Yield point, and
5. User-specified name or comment.

The next new card introduced is the INITIAL FLUID card. This card specifies the initial state of the wellbore before calculation begins. The INITIAL FLUID contains the following information:

1. I.D. number of fluid initially in tubing and tubing annulus,
2. I.D. number of secondary flow fluid,
3. I.D. number of packer fluid in casing annuli,
4. Inlet temperature for secondary flow, and
5. Secondary flow rate.

The final change to the input format is a slight modification to the CHANGE card. The new CHANGE card gives the following information at each time to change data:

1. Flow option (same as old CHANGE card),
2. Secondary flow indicator (1-yes; 0-no),
3. I.D. number of fluid injected or produced,
4. Fluid inlet temperature,
5. Fluid flow rate, and
6. Time to change flow parameters.

Figure B-2 is the summary of the input data printed out by GEOTEMP. The first change is that the tubing configuration is printed separately from the casing program and that the top and bottom of each interval are printed rather than the casing setting depth. The next addition is the well geometry information. The total depth and wellbore diameter are always printed, but the depth of deviation and true vertical depth are printed for deviated wells only. The wellbore fluid properties have been revised to include the fluid I.D. number and the user-designated name. Finally, the wellbore fluids initial state is summarized.

Figure B-3 is the output of the first calculation time interval. This calculation is typical of the type of problem for which the original GEOTEMP was used. The only change in the output is that the fluid injected and the wellbore fluids are now indicated. Figure B-4 is the output of the second time interval. This calculation is more typical of the enhanced capability of the new version of GEOTEMP. First, note that fluid #2 is being injected into the wellbore filled with fluid #1. At the first time step, 10.01 days, fluid #2 has displaced fluid #1 to the depth of 3034 feet. At the end of the second time step, 10.06 days, fluid #2 has completely displaced fluid #1, and no further updates are necessary. By using CHANGE cards, any wellbore fluid arrangement can be generated. The

GEOTEMP2 TEST DATA : INJECTION

T U B I N G C O N F I G U R A T I O N

TUBING	ID, IN.	OD, IN.	TOP, FT.	BASE, FT.	CEMENT, FT.
1	3.958	4.500	0.	2000.	2000.0
2	1.958	2.500	2000.	5000.	3000.0

C A S I N G P R O G R A M

CASING	ID, IN	OD, IN	DEPTH, FT	CEMENT INTERVAL, FT
1	8.681	9.625	5000.	2200.
2	12.347	13.370	3000.	2200.
3	19.124	20.000	1000.	1000.
4	29.000	30.000	100.	100.

W E L L G E O M E T R Y

TOTAL DEPTH= 5000. FT.
BORE DIAMETER= 40.000 IN.
NOTE: DEVIATED WELL
DEPTH OF DEVIATION= 2000. FT.
TRUE VERTICAL DEPTH= 4500. FT.

W E L L B O R E F L U I D P R O P E R T I E S

FLUID TYPE NO. 1 PRIMARY

DENSITY= 10.0 LBM/GAL
PLASTIC VISCOSITY= 15. CENTIPOISE
YIELD POINT= 5. LBF/100FT2

FLUID TYPE NO. 2 ANNULAR

DENSITY= 10.0 LBM/GAL
PLASTIC VISCOSITY= 15. CENTIPOISE
YIELD POINT= 5. LBF/100FT2

W E L L B O R E I N I T I A L S T A T E

FLUID # 1 IN TUBING & TUBING ANNULUS
FLUID # 2 IN CASING - CASING ANNULI

Figure B-2. Summary of the Input Data Printed Out by GEOTEMP

S E T   V A R I A B L E S   AT TIME =   .000 DAYS
FLOWING OPTION = INJECTION
FLUID = 1 INJECTED INTO TUBING
FLUID = 1 IN WELL
INLET TEMPERATURE = 70. F
FLOW RATE = 10. GAL/MIN
TIME TO CHANGE DATA = 10.000 DAYS

TIME = 10.000 DAYS ITERATIONS = 1

T E M P E R A T U R E   D I S T R I B U T I O N

	RADIAL POSITIONS, FEET					
DEPTH, FT	.0	.3	1.7	3.3	5.5	50.0
-0.	70.0	70.0	70.0	70.0	70.0	70.0
200.	70.1	70.8	72.4	72.7	72.9	73.0
400.	70.4	71.9	75.2	75.8	76.1	76.4
600.	70.9	73.2	78.0	78.8	79.4	79.7
800.	71.6	74.4	80.9	82.0	82.6	83.1
1000.	72.5	75.8	83.8	85.1	85.9	86.4
1200.	73.5	77.7	86.5	88.1	89.1	89.8
1400.	74.7	79.5	89.4	91.3	92.4	93.1
1600.	76.1	81.4	92.4	94.4	95.6	96.5
1800.	77.6	83.3	95.3	97.6	98.9	99.8
2000.	79.3	85.4	98.2	100.7	102.2	103.1
2200.	80.8	90.2	102.2	104.1	105.2	105.9
2400.	82.2	92.1	104.8	106.8	108.0	108.7
2600.	83.6	94.1	107.4	109.5	110.7	111.5
2800.	85.1	95.8	110.0	112.2	113.5	114.3
3000.	86.7	97.9	112.7	114.9	116.2	117.1
3200.	88.3	100.6	115.0	117.5	118.9	119.9
3400.	90.1	102.7	117.7	120.2	121.7	122.7
3600.	91.9	104.9	120.3	122.9	124.5	125.5
3800.	93.8	107.1	123.0	125.6	127.2	128.3
4000.	95.7	109.4	125.6	128.4	130.0	131.0
4200.	97.6	111.7	128.3	131.1	132.8	133.8
4400.	99.6	114.0	130.9	133.8	135.5	136.6
4600.	101.7	116.3	133.6	136.6	138.3	139.4
4800.	103.8	118.7	136.3	139.3	141.1	142.2
5000.	105.9	121.0	139.0	142.0	143.8	145.0
5200.	147.8	147.8	147.8	147.8	147.8	147.8
5400.	150.6	150.6	150.6	150.6	150.6	150.6

Figure B-3. Output of the First Calculation Time Interval

```
S E T   V A R I A B L E S   AT TIME =    10.000 DAYS
        FLOWING OPTION = INJECTION
                 FLUID # 2 INJECTED INTO TUBING
                 FLUID # 1 IN WELL
        INLET TEMPERATURE =   70. F
        FLOW RATE =  100. GAL/MIN
        TIME TO CHANGE DATA =    20.000 DAYS

FLUIDS IN WELL UPDATED AT TIME=    10.010 DAYS
                      FLUIDS IN TUBING
                         FLUID # 2 FROM      0. FT.   TO    3034. FT.
                         FLUID # 1 FROM   3034. FT.   TO    5000. FT.
                      FLUIDS IN ANNULUS
                         FLUID # 1 FROM      0. FT.   TO    5000. FT.

FLUIDS IN WELL UPDATED AT TIME=    10.060 DAYS
                      FLUIDS IN TUBING
                         FLUID # 2 FROM      0. FT.   TO    5000. FT.
                      FLUIDS IN ANNULUS
                         FLUID # 1 FROM      0. FT.   TO    5000. FT.


TIME =    20.000 DAYS                                    ITERATIONS =  2

                T E M P E R A T U R E   D I S T R I B U T I O N
```

DEPTH, FT	RADIAL POSITIONS, FEET .0	.3	1.7	3.3	5.5	50.0
-0.	70.0	70.0	70.0	70.0	70.0	70.0
200.	70.0	70.7	72.3	72.6	72.8	73.0
400.	70.0	71.5	74.9	75.5	75.9	76.4
600.	70.1	72.3	77.5	78.4	79.1	79.7
800.	70.2	73.0	80.1	81.4	82.2	83.1
1000.	70.3	73.7	82.9	84.4	85.4	86.4
1200.	70.4	74.8	85.3	87.2	88.5	89.8
1400.	70.5	75.7	87.9	90.2	91.6	93.1
1600.	70.7	76.6	90.5	93.1	94.8	96.5
1800.	70.9	77.5	93.2	96.1	98.0	99.8
2000.	71.1	77.0	94.9	98.5	100.9	103.1
2200.	71.3	83.7	100.1	102.7	104.4	105.9
2400.	71.5	84.8	102.5	105.2	107.0	108.7
2600.	71.7	85.9	104.8	107.8	109.7	111.5
2800.	71.9	86.8	107.3	110.4	112.4	114.3
3000.	72.1	88.1	109.6	113.0	115.1	117.1
3200.	72.4	90.1	111.6	115.3	117.7	119.9
3400.	72.6	91.4	114.0	117.9	120.4	122.7
3600.	72.9	92.6	116.3	120.4	123.1	125.5
3800.	73.2	93.8	118.7	123.0	125.8	128.3
4000.	73.5	95.1	121.1	125.6	128.5	131.0
4200.	73.8	96.3	123.5	128.2	131.2	133.8
4400.	74.2	97.6	125.9	130.7	133.9	136.6
4600.	74.5	98.8	128.2	133.3	136.6	139.4
4800.	74.9	100.1	130.6	135.9	139.3	142.2
5000.	75.2	101.4	133.0	138.5	142.0	145.0
5200.	147.8	147.8	147.8	147.8	147.8	147.8
5400.	150.6	150.6	150.6	150.6	150.6	150.6

Figure B-4. Output of the Second Time Interval ability to change the wellbore fluid at any time is an especially useful consequence of the program's multiple fluid feature. For example, a drilling problem can be studied with greater accuracy by changing mud properties as the drilling progresses. For another example, the simulation of well production with changing flow rates and fluid composition can be accommodated.

Test Cases

Several test cases were run to verify that the modified GEOTEMP code was running properly. The first test was to rerun all of the test cases given in the GEOTEMP user's manual to show that the basic code still works properly. The results of these tests were satisfactory, and the output of these test runs is included in Appendix 2 of the documentation.

Two cases were run to test the variable tubing flow area. The first test, illustrated in Figure B-5, used three cases:

Case I--single 4.5-inch tubing
Case II--4.5-inch tubing to 2000 feet,
    2.5-inch tubing from 2000 feet to 5000 feet.
Case III--single 2.5-inch tubing.

The expected result of this test is that the temperatures predicted for Case II should fall between those of Cases I and III and, further, that Case II and Case I should be indistinguishable above 2000 feet and that Case II should approach Case III at depth. The results shown in Figure B-5 indicate that these trends are verified. The output for Cases I, II, and III are included in Appendix 3 of the documentation.

The second study used to test the variable tubing area used a "stacked" production model to simulate the variable area model. Both models were intended to solve the following boundary value problem:

> Fluid is produced at 10 gal/min through 2.5-inch tubing from 5000 feet to 3000 feet, where the tubing changes to 4.5 inches from 3000 feet to the surface. The bottomhole temperature is 145°F. How does the fluid exit temperature vary with time?

The stacked model is constructed by first running a single 2.5-inch tubing from 5000 feet to the surface. The temperatures predicted by this model at 3000 feet are then used as the inlet temperatures for another model--a single 4.5-inch tubing from 3000 feet to the surface. The exit temperatures from this model should be close to the exact solution. Figure B-6 compares the results of these two models. A particularly interesting result is that the transient response of the two models from 0.1 hour to 2.0 hours is nearly identical. Beyond 2.0 hours, the model approaches a nearly steady state, and the stacked model stays about 1°F below the multiple area model. This discrepancy is explained by the vertical heat transfer that is neglected by the "stacked" model. The complete "stacked" model output is included in Appendix 4 of the documentation.

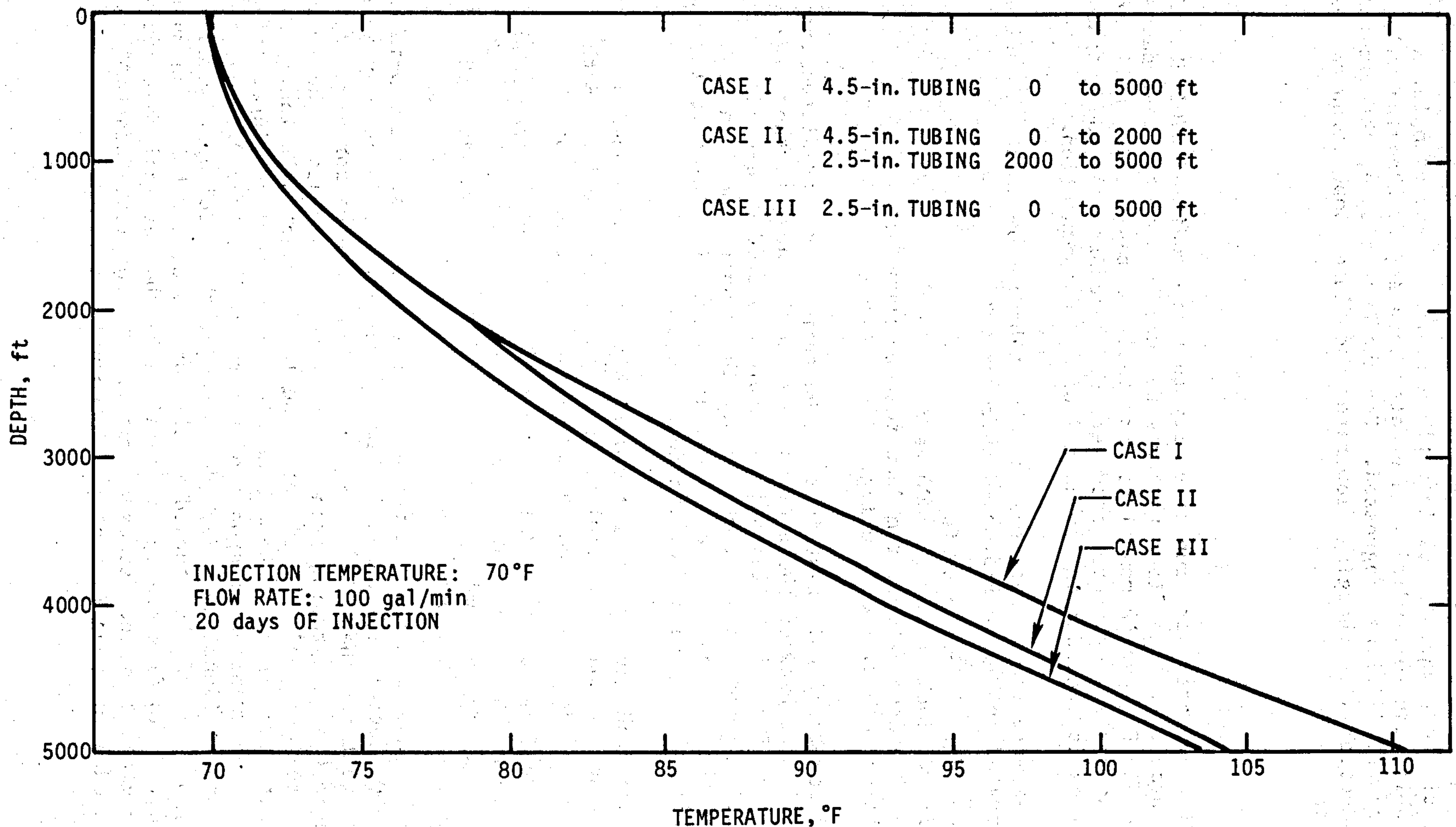


Figure B-5. Multiple Tubing Area Test: Injection Tubing Fluid Predicted Temperatures

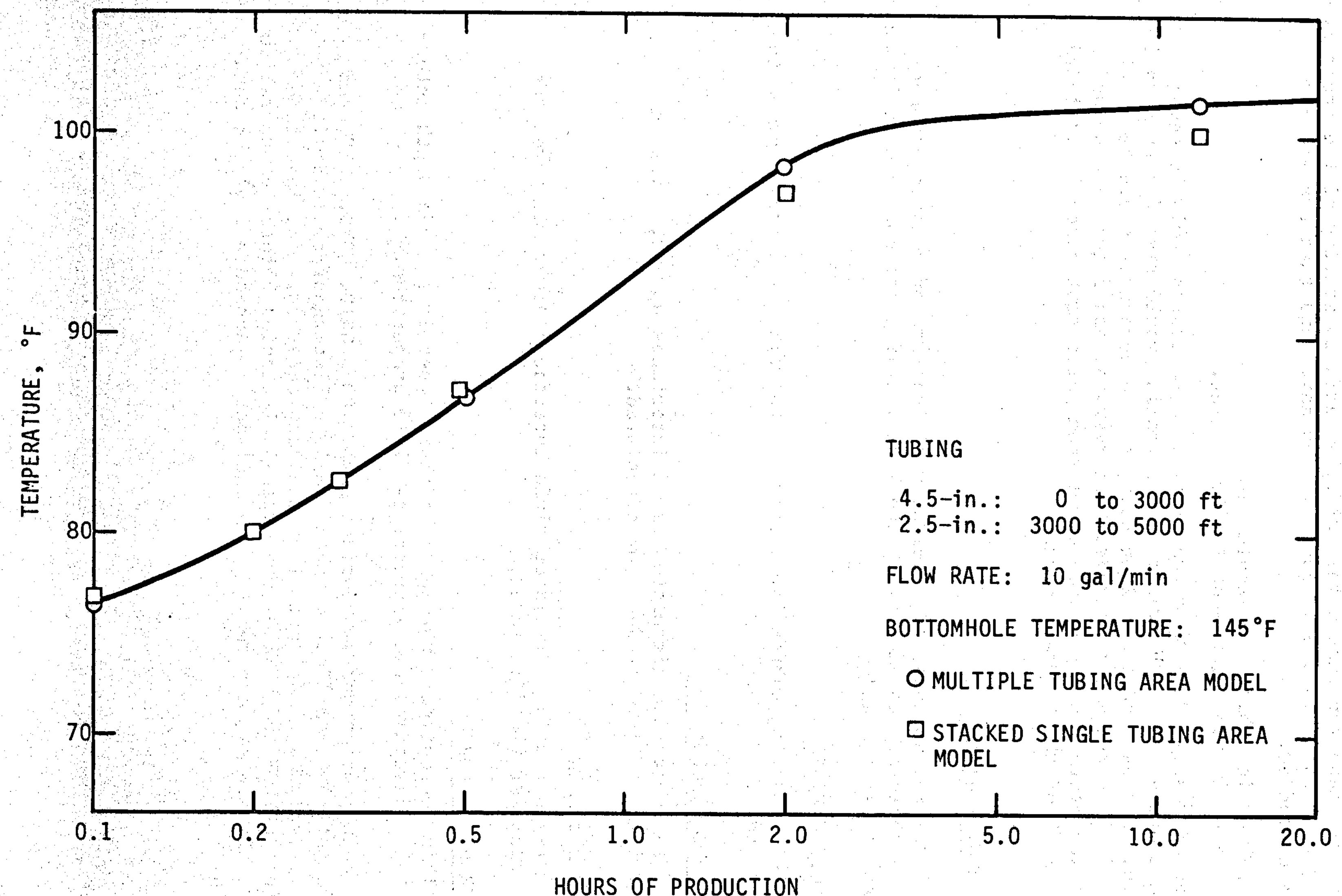


Figure B-6. Multiple Tubing Area Test: Production Fluid Exit Temperatures

The last case run tested the multiple fluid capability of the program. Water was circulated in the wellbore for 30 days, and then two shut-in cases were studied:

1. Water in tubing and annulus and
2. Water in tubing, cement in the annulus.

The expected results were that the initial temperatures would be equal, that the temperature of the water in the annulus would rise faster than in the cement annulus, and that, long term, the temperatures would be equal. Figure B-7 shows the expected short-term results, and Figure B-8 shows the expected long-term results. The output from these test cases is included in Appendix 5 of the documentation.

Program Modifications

Four new subroutines and internal modifications of existing subroutines were necessary to accomplish the Task 1 modifications. The following new subroutines were added:

FUNCTION KTUBE

This function subroutine determines the tubing interval, given the depth.

SUBROUTINE UPFLOW

This subroutine circulates fluid interfaces upward, given the volume of fluid produced or circulated.

SUBROUTINE DWNFLO

This subroutine circulates fluid interfaces downward, given the volume of fluid injected.

SUBROUTINE FDROP

This subroutine determines the fluid types in a given depth interval and returns the appropriate fluid properties.

The main program and subroutines READ, PROP, GRID, COND, COEF, and WELL have internal modifications. A complete listing of the modified program is included in Appendix 1 of the documentation. The interface subroutines UPFLOW and DWNFLO were extensively tested before incorporation into GEOTEMP. These test results are included in Appendix 6 of the documentation.

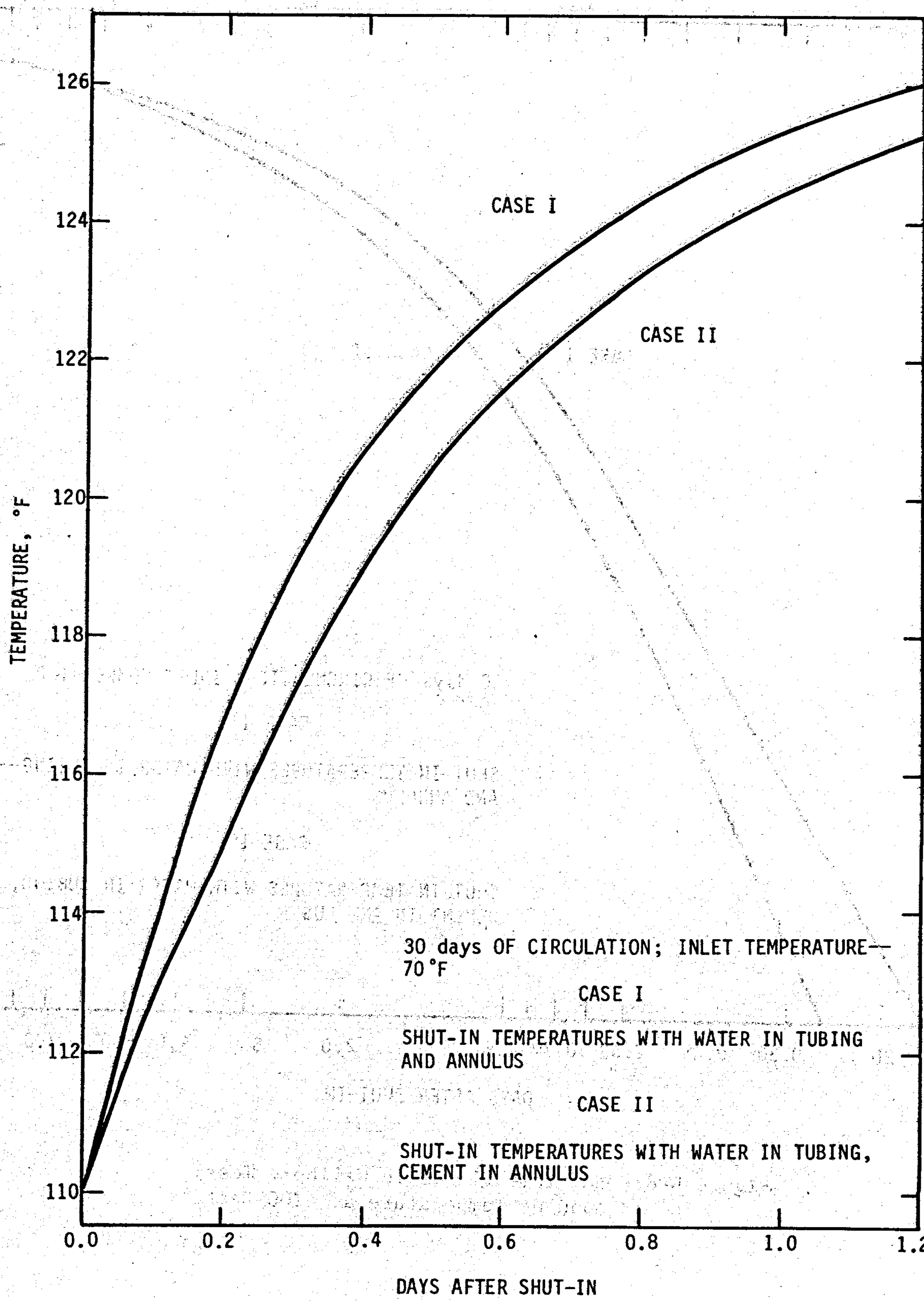


Figure B-7. Multiple Fluids in Wellbore Tests: Annulus Temperature at 4200 Feet

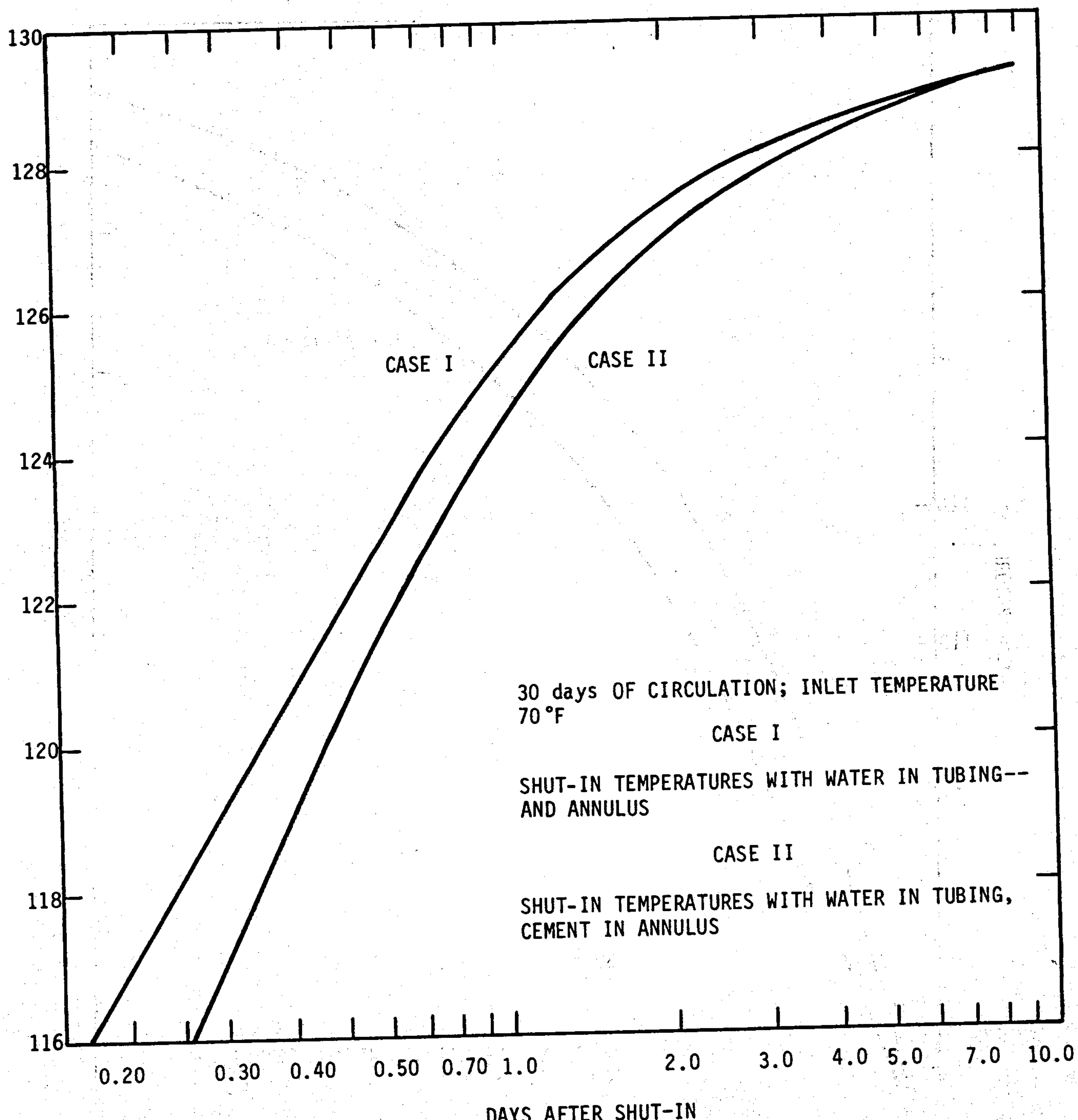


Figure B-8. Multiple Fluids in Wellbore Test: Annulus Temperature at 4200 Feet

APPENDIX C

Compressible Flow Model Proposed for GEOTEMP

COMPRESSIBLE FLOW MODEL PROPOSED FOR GEOTEMP

Introduction

The solution of a fluid flow problem requires the solution of three balance laws: balance of mass, momentum, and energy. By assuming incompressibility for the flowing fluid, the original GEOTEMP only had to solve the balance of energy equation and a simplified version of conservation of mass. The formulation of a compressible flow version of GEOTEMP, however, will require solution of all of the balance equations.

Several simplifying assumptions will be made in the analysis of the compressible flow problem:

1. One-dimensional flow.
2. No inertial effects -- steady flow.
3. Transient heat transfer.

The GEOTEMP thermal simulator will be used to solve the energy equation with only slight modifications, and a fluid flow simulator will be added to solve the mass and momentum equations. The simulators will be used sequentially, rather than simultaneously, to solve the overall flow-heat transfer problem. This is the same solution scheme used in the original GEOTEMP, where flow parameters are updated at each time step. The following procedures from each time step are executed:

1. The momentum and mass conservation equations are solved using the temperatures calculated in the previous time step.
2. The energy equation is solved for temperatures using the flow parameters determined in Step 1.

Because of the relatively high fluid velocities expected, the wellbore temperatures are not expected to vary much between time steps, thus allowing this sequential calculation. If, during testing, this assumption is not verified, then a method for simultaneous solution of Steps 1 and 2 may be necessary.

Compressible Flow

The implementation of the compressible flow simulator will be taken in four steps:

1. Prediction of flow properties in a constant area duct with friction and transient heat conduction.
2. Addition of solids in the gas flow in the annulus.
3. Inclusion of area change effects on flow parameters.
4. Simulation of flow conditions at the bit nozzles -- including choked flow and stationary shocks.

This report will be concerned with Step 1.

The wellbore considered for Step 1 consists of a constant area annulus. The tubing and annulus are subdivided into cells corresponding to the cells in GEOTEMP. Figure C-1 illustrates a typical cell, with flow entering the cell with parameters ρ_1, V_1, P_1, T_1 and leaving with parameters ρ_2, V_2, P_2, T_2. The entering parameters are assumed to be known, and the exit values are to be determined from the solution of the momentum equations:

$$\Delta p + (1/2\rho V^2) + 1/2 \int_{z_1}^{z_2} \rho V^2 \frac{f'}{D} dz + \int_{z_1}^{z_2} \rho g \cos \Theta \, dz = 0$$

Subject to mass conservation:

$$\rho_1 V_1 = \rho_2 V_2 = G$$

where

f' = the Darcy friction factor
G = the mass flow rate density
P = pressure
ρ = density
D = the hydraulic diameter
V = fluid velocity.

The momentum equation in this form, with temperature distribution given, is a non-linear integral equation. Rather than solving for the exact form of V(z), which cannot be done in general because of the non-linear nature of the equation, an approximate form of V(z) with arbitrary coefficients will be used, with the coefficients optimized to give the best approximation to the momentum equation. An obvious choice for V(z), with a particularly useful choice of arbitrary coefficient, is

$$V(z) = V_1 + (V_2 - V_1)\,(z - z_1)/(z_2 - z_1) \;,$$

where V_2 is the coefficient to be determined. Applying V(z) to the momentum equation gives

$$p\,(G/V_2, T_2) - p(\rho_1, T_1) + 1/2\, G\,(V_2 - V_1)$$

$$+ 1/2\, \frac{G}{D} \int f' \quad (V, T, \rho)\, [V_1 + V_2 - V_1)\xi]\, dz$$

$$+ gG \cos \Theta \int [V_1 + (V_2 - V_1)\xi]^{-1}\, dz = 0 \;,$$

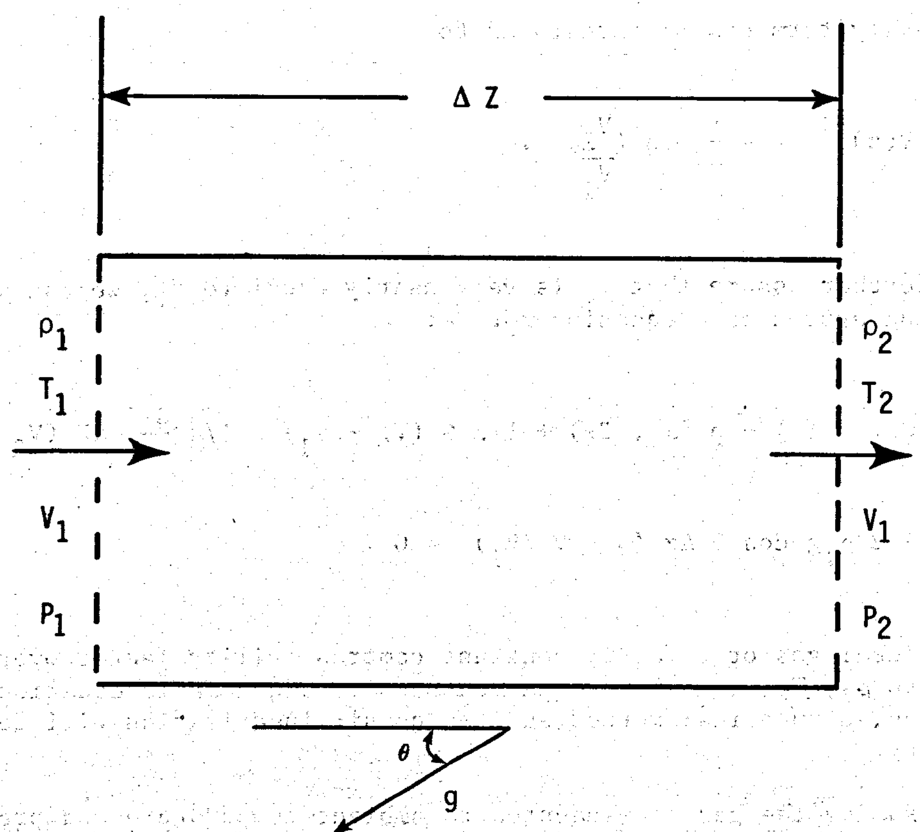


Figure C-1. Constant Area Flow Cell

where $\xi = (z - z_1)/(z_2 - z_1)$.

Assuming a fairly small variation in V, T, and ρ, we can set f' constant, evaluated at V_1, T_1, ρ_1. We can now perform the integration

$$\int f' V(z)\, dz = 1/2\, f' (V_2 + V_1)\, \Delta Z .$$

The gravity term can be integrated to

$$\int V(z)^{-1}\, dZ = \frac{\Delta Z}{\Delta V} \ln \left(\frac{V_2}{V_1}\right) .$$

If we further assume that V_2 is very nearly equal to V_1, we can write the following approximate equation for V_2:

$$P(G/V_2, T_2) - p(\rho_1, T_1) + 1/2\, G (V_2 - V_1) + 1/4 \frac{Gf'}{D} \Delta Z (V_2 + V_1)$$

$$+ 1/2\, \rho_1 g \cos \Theta\, \Delta z (3 - V_2/V_1) = 0 .$$

For an ideal gas or a fairly constant compressibility factor over the range ρ_1, T_1 to ρ_2, T_2, the above equation becomes a quadratic equation in V_2. Otherwise, a numerical method such as quasi-linearization will be necessary.

Assuming the gas is exhausted to ambient temperature and pressure at a given mass flow rate, the momentum equation is then solved cell by cell from the exhaust backwards to the inlet. Where the flow changes from annulus to tubing, an adiabatic flow assumption will be used until Step 4 is implemented. The results of this computation will be the flowing parameters in each cell plus the inlet pressure, so an additional use for this program is to size compressors for air drilling rigs.

APPENDIX D

Revised GEOTEMP Code Input Data Format
To Allow Variable Tubing Areas

REVISED GEOTEMP CODE INPUT DATA FORMAT
TO ALLOW VARIABLE TUBING AREAS

II. Input Data

II-1 Introduction

A necessary beginning for a thermal simulation is a complete definition of the geometry of the well to be modeled. Casings, tubing, and drill pipe are all defined by specifying the inside and outside diameters and the setting depth. In addition, the cement interval length is specified for each casing.

A tubing string, with as many as 10 intervals, where different tubing dimensions can be specified, is described for the well. As many as four casing strings outside the tubing can be specified. Tubing intervals are numbered from the top to the bottom of the well. Casing strings are numbered from the inside (smallest diameter) to the outside (largest diameter). Figure D-1 illustrates a completed well modeled for injection with one uniform tubing string and four casing strings. Note that the setting depth for each casing string must be less than that for the string immediately interior to it, i.e., an outer casing string is always shorter than those inside it. The tubing depths, however, may be freely specified.

Fluid properties are specified for the primary flowing fluids, secondary flowing fluid, and the annular fluid between casings. Each fluid is defined by three properties: density, plastic viscosity, and yield point. The specific heat capacity and thermal conductivity for each fluid are computed from the density. This computation, and the use of the viscosity parameters, are discussed in detail in Sections IV-3 and IX-5 of the Part I report.

Other data defined as input to the computer model are well dimensions, temperatures, and flow rates. The initial and final hole depths are defined, as is the surface borehole diameter. The initial and final hole depths are identical for production, injection, and circulation. However, for drilling, the initial depth may be zero and the total depth thousands of feet. It is possible to analyze resumption of drilling by setting the initial depth at some point downhole and estimating the downhole temperatures at the time of resuming drilling.

For deviated wells, additional information is needed: 1) the depth at which the well is deviated and 2) the measured vertical depth. The final hole depth noted above is interpreted to mean the true vertical depth.

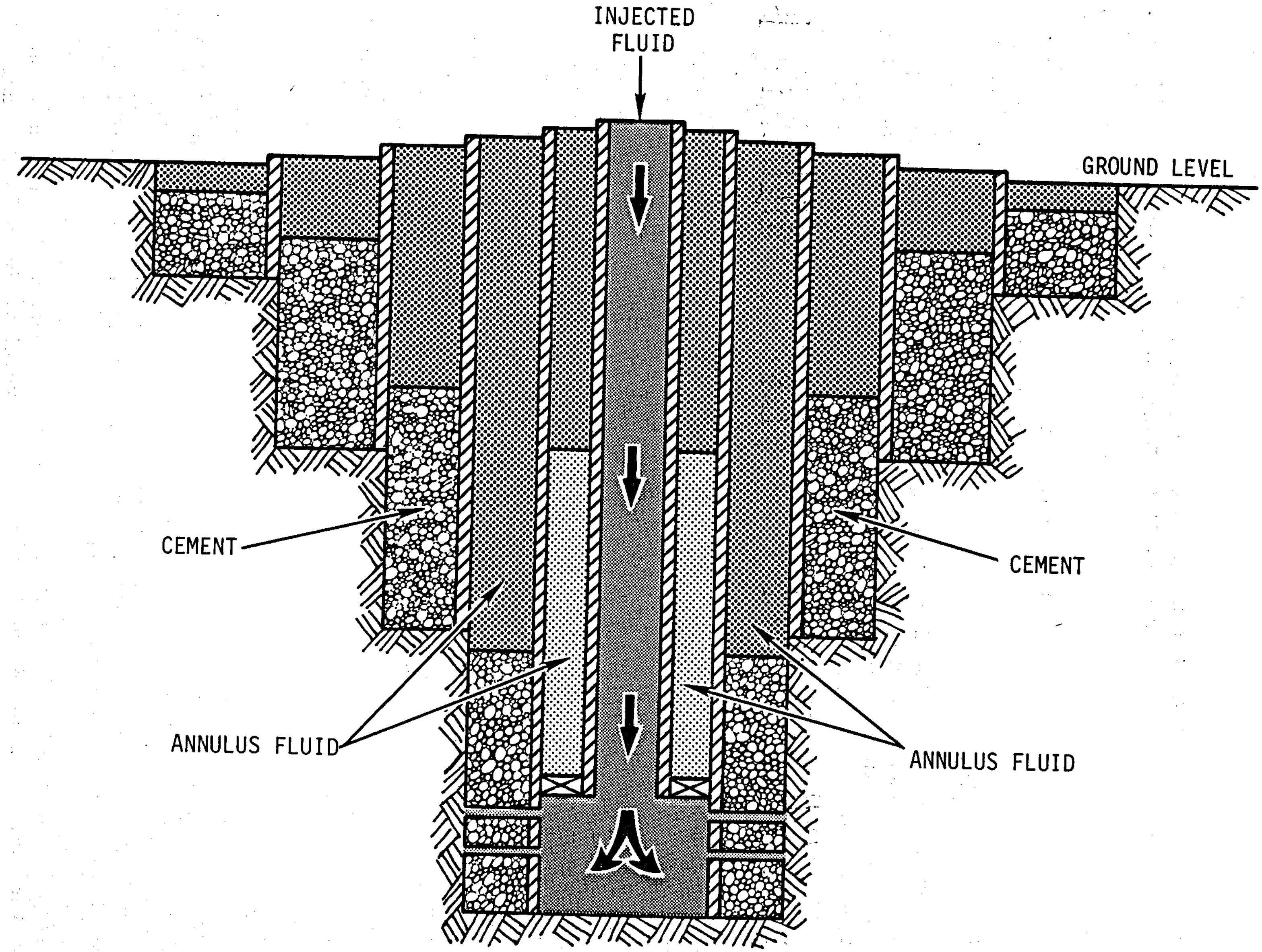


Figure D-1. Computer Model of Wellbore Completion for Production and Injection

An initial temperature distribution in the well and surrounding soil is specified. The goethermal gradients are approximated with two constants, which yields a temperature distribution like that given in Figure D-2. Two linear temperature functions are computed from the surface temperature, the bottomhole temperature, and an intermediate temperature and depth. This temperature distribution is used to set the initial distribution, the surface boundary temperatures and boundary temperatures 400 feet below the bottomhole depth, and the downhole boundary temperatures at the maximum radius.

Inlet fluid temperatures and flow rates are specified. During circulation, it is possible to account for fluid influx at the bottom of the hole. Fluid properties, inlet temperture, and flow rate may all be defined for this secondary fluid independent of the circulation. The parameters for the primary flowing fluid are allowed to change at any time and as often as necessary. A flowing option is specified at each change as one of the following:

1. Injection,
2. Production,
3. Forward circulation, and
4. Reverse circulation.

Also needed are the inlet temperature, volume flow rate, and fluid type. Each of these variables is held constant through every time step until the next change occurs at a specified time.

Drilling requires additional input information but uses essentially the same format. In addition to flow direction, inlet temperature, and flow rate, drilling requires the depth to which the well is drilled under these conditions and the number of hours per day that fluid is circulated. All of these variables may be changed at any specified time. Based on this information, a drilling rate is computed for the period each day during which fluid is circulated. Of course, depth does not change with time during the shut-in period of a day.

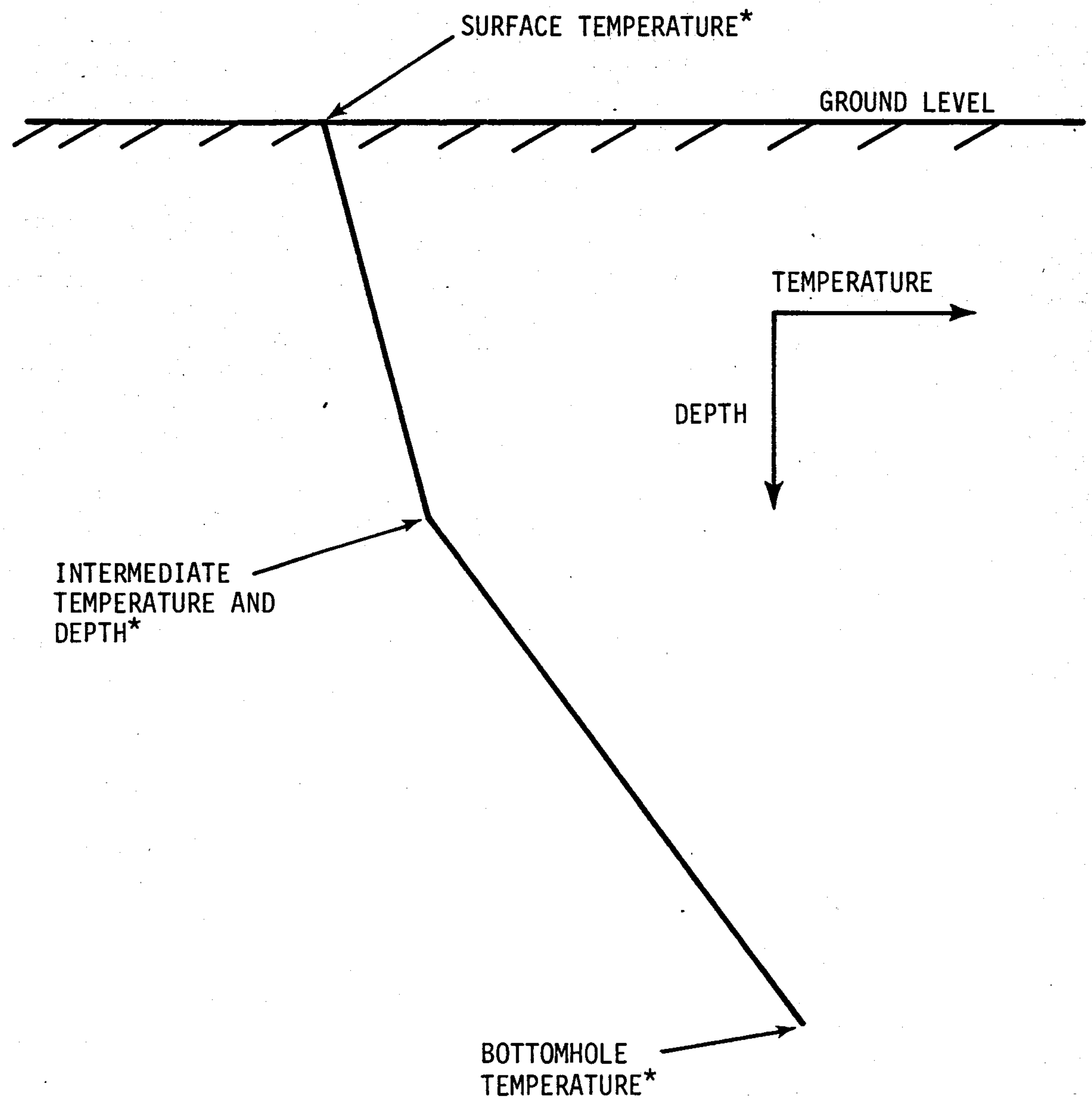
Thermal properties for all solid materials are defined in the program. The solids that are modeled in the computer code are

1. Cement,
2. Soil, and
3. Steel.

Although several types of each material exist, the thermal properties are not expected to vary significantly between types and are therefore not part of the input data. Of course, for several applications, a user may enter the program to redefine thermal properties for solids. The three thermal properties needed are

1. Density,
2. Specific heat capacity, and
3. Thermal conductivity.

These properties are discussed in more detail in Section IV-4 of the Part I report. The quantities presently employed by the thermal simulator are listed in Table II-1 in the documentation.



*DENOTES INPUT DATA

Figure D-2. Initial and Boundary Temperature Profiles

II-2 Data Formats

This section describes in detail how to input data to the model. The format for each card is specified, and the variables on the card are defined.

TITLE CARD:

This card allows any title to be printed on columns 1-80. Format (20A4)

Columns 1-80 Title

CONTROL PARAMETERS CARD:

This card inputs parameters necessary to specify the problem. Format (20X, 3I5)

Columns	21-25	Number of tubing intervals
	26-30	Number of casing strings
	31-35	Number of distinct fluids to be considered (i.e., primary, secondary, annular, etc.)

TUBING SPECIFICATION CARDS:

Each card defines an interval of tubing. Intervals are numbered consecutively from the top of the well to the bottom. Format (20X, I5, 4E10.0)

Columns	21-25	Tubing interval #
	26-35	Tubing inside diameter, inches
	36-45	Tubing outside diameter, inches
	46-55	Bottom of interval, feet
	56-65	Length of cement or annulus fluid outside tubing, feet.

CASING SPECIFICATION CARDS:

Each of these cards defines a string of pipe in the well; the order of presentation is immaterial. Format (20X, I5, 4F10.0)

Columns	21-25	Casing identification (I.D.) number (tubing not included)
	26-35	Inside diameter, inches
	36-45	Outside diameter, inches
	46-55	Setting depth, feet
	56-65	Interval length of cement or annulus fluid outside casing, feet.

BOREHOLE GEOMETRY CARD:

This card defines borehole dimensions. Format (20X, 5F10.0)

Columns	21-30	Initial depth, feet
	31-40	Total measured depth, feet

41-50 True vertical depth, feet
51-60 Depth of well deviation, feet
61-70 Borehole diameter, inches
(outside last casing outside diameter and cement).

Initial and total measured depth are equal for applications other than drilling.

INITIAL TEMPERATURES CARD:

This card defines the initial and boundary temperatures in the well and soil. Format (20X, 4F10.0)

Columns 21-30 Surface temperature, °F
31-40 Bottomhole temperature, °F
41-50 Intermediate temperature, °F
51-60 Intermediate depth corresponding to temperature in columns 41-50, feet.

FLUID PROPERTIES CARD:

This card has the fluid properties as measured at 70°F. Format (20X, I5, 3F10.0, 6A4)

Columns 21-25 Fluid I.D. number
26-35 Density, lb/ft^3
36-45 Plastic viscosity, centipoise
46-55 Yield point, $lbf/100\ ft^2$
56-79 Name of fluid or note of your choice.

INITIAL FLUID PARAMETERS CARD:

This card identifies the primary flowing fluid, the secondary flowing fluid, and the annular fluid; the secondary fluid flow rate; and the secondary fluid inlet temperature. Format (20X, 3I5, 2F10.0)

Columns 21-25 Primary fluid I.D. number
26-30 Secondary fluid I.D. number
31-35 Annular fluid I.D. number
36-45 Secondary fluid inlet temperature, °F
46-55 Secondary fluid flow rate, gal/min.

CHANGING FLOW PARAMETERS CARD:

This card contains flow parameters that are allowed to change at any time during a simulation. As many cards as needed may be used. Format (20X, 3I2, 5F10.0)

Columns 20-21 Flowing option selector
1 = injection
2 = production
3 = forward circulation
4 = reverse circulation

22-23	Secondary flow option 0 = no flow 1 = secondary flow
24-25	Primary fluid I.D. number
26-35	Primary fluid inlet temperature, °F
36-45	Primary fluid volume flow rate, gal/min
46-55	Time to read next card for change of variables, days
56-65	Hole depth at time to change variables, feet, (drilling only)
66-75	Circulation time per day, hours (drilling only).

APPENDIX E

Report on Percussion Drilling Tests

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REPORT ON PERCUSSION DRILLING TESTS

Introduction

This report describes tests of percussion drilling tools which were done at DRL, Salt Lake City, Utah, during February 1980. The purpose of the tests was threefold: (1) to compare the penetration rates of different hammers with each other and with conventional rotary drilling, (2) to measure and compare the hammer pulses at normal and high temperatures, and (3) to establish hammer life and failure modes at high temperature. The qualitative results were good for (1), poor for (2), and mixed for (3); a description of each part of the test follows.

Rate of Penetration (ROP)

For the ROP measurements, two "oilfield" hammers were rented and three "industrial" hammers were bought. Both types function according to the principle of a reciprocating piston striking an anvil, but the oilfield tools are threaded to accept a conventional roller bit, while an industrial tool uses a one-piece solid bit with tungsten carbide inserts. General descriptions of the hammers are given in Table E-1. The Ingersoll-Rand (I-R) DHD 360 is considerably smaller than the other hammers because it is designed to be used primarily with a 15.2- or 16.5-cm (6- or 6.5-in.) bit. This hammer is available with a 21.6-cm (8.5-in.) bit; however, this combination provides a performance comparison of a hammer that is smaller than normal for this size hole.

The baseline for the comparison of hammer penetration was the data from a Reed M-70, 20.0-cm (7.875-in.), insert bit run without hammer over a range of weights on bit and rotary speeds. These baseline data are plotted in Figure E-1. Each of the hammers was then run in samples of the same granite. The oilfield hammers used the same Reed bit as the baseline tests, and each of the industrial hammers used the bit with which it was equipped by its manufacturer.

Because the mechanism of rock breakage is slightly different for the two types of hammers, the test variables were also slightly different. The bits used in the industrial hammers are one-piece steel bodies with hemispherical tungsten carbide inserts (Figure E-2). The inserts are quite strong in compression but not in shear, so they can withstand heavy blows from the hammer but not high torques imposed by high weight on bit (WOB). The WOB was held constant at 22 241 N (5000 lb) (the manufacturers' approximate recommendation) for all three industrial hammers, and the air supply pressure and rotary speed were varied. The inserts in the roller bit do not experience the same kind of shear loading, so these assemblies can be run at higher WOB values. For the roller-bit/hammer tests, the rotary

Table E-1

General Descriptive Data on Hammers

Hammer	Hammer Diameter cm (in.)	Bit Diameter cm (in.)	Length with Bit cm (in.)	Length without Bit cm (in.)	Weight kg (lb)	Operating Air Pressure Range kPa (psi)	Air Consumption at 1 724 kPa (250 psi) (Blank Choke) m^3/s (ft^3/min) (standard)
TRW - Mission A63-15	16.2 (6.375)	20.3 (8.0)	159.9 (60.2)	139.7 (55.0)	159 (350)	690 to 1 724 (100 to 250)	0.51 (1 090)
TRW - Mission Hammerdril	17.2 (6.75)	20.0 (7.875)		177.8 (70.0)	259 (570)	690 to 2 413 (100 to 350)	0.49 (1 040)
Ingersoll-Rand DHD 360	13.7 (5.375)	21.6 (8.5)	129.5 (51.0)		98 (215)	1 034 to 2 413 (150 to 350)	0.27 (570)
Ingersoll-Rand DHD 2076	16.8 (6.625)	20.0 (7.875)		193.4 (76.1)	238 (525)		
Epley D-2	17.2 (6.75)	20.3 (8.0)	144.8 (57.0)		145 (320)	690 to 1 724 (100 to 250)	0.50 (1 070)

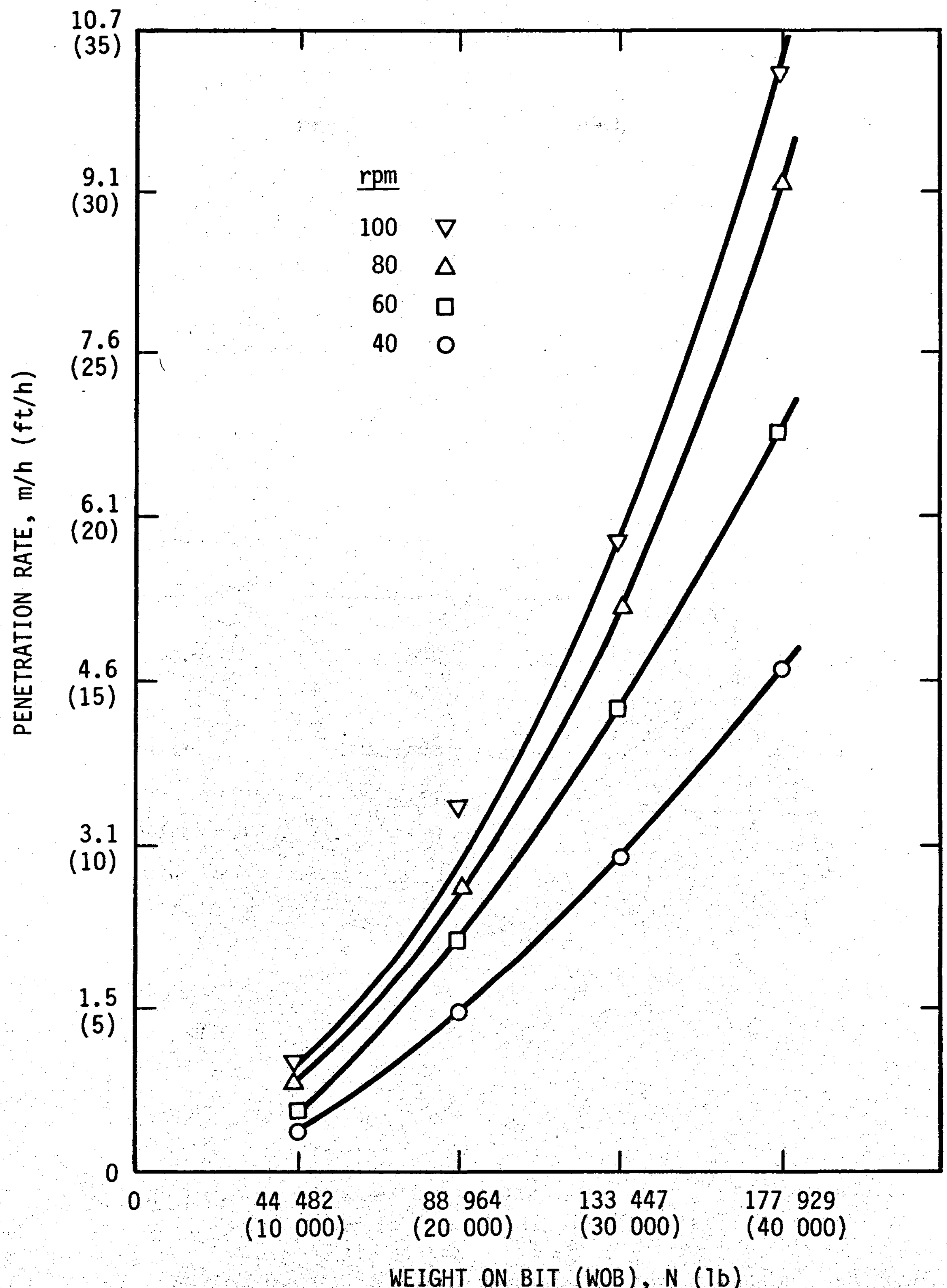

Figure E-1. Baseline Data from Reed 20-cm (7.875-in.), M-70, Tungsten Carbide Insert Bit: Rock--Sierra White Granite; Air Flow Through Bit--0.38 m^3/s (800 ft^3/min, Standard)

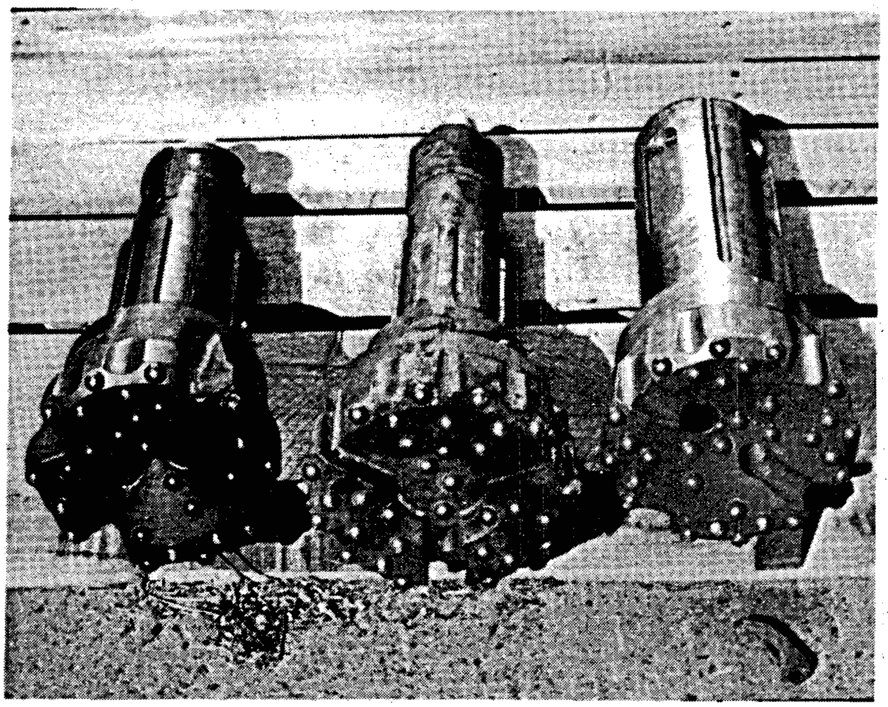

Figure E-2. Bits Used in Industrial Hammers: Left to Right--Mission, Ingersoll-Rand, Epley speed was held constant at 45 rpm, and the air supply pressure and WOB were varied. The rates of penetration are plotted for different conditions in Figures E-3 and E-4.

In general, the behavior illustrated by the curves is consistent with theoretical predictions; however, a few anomalous points should be discussed. Figure E-3 shows that the ROP of the oilfield hammers increased only slightly for large increases in bit weight. This result occurs because the force of the hammer blows is greater than the steady bit weight, and the change in bit weight is small compared to the total force of hammer blow plus bit weight. This behavior is also consistent with manufacturers' recommendations to operate the hammers with relatively low WOB.

Large changes in ROP are seen in Figure E-3 when the pressure of the air supply to the hammers is increased. When the pressure is raised, both the hammer-blow frequency and the energy per blow are increased. If it is assumed that there is a specific energy required in order to break a unit volume of rock, then the ROP should increase as the 3/2 power of the air pressure; with one exception, the curves in Figure E-3 show good agreement with this ratio. The exception is the 1896-kPa (275-psi) line for the I-R hammer, which shows a lower ROP than does the 1379-kPa (200-psi) line for the same tool. The reason for this result is not known, but a tentative explanation is suggested by the failure of this hammer in the next phase of testing. When an attempt was made to run the I-R 2076 against a load cell, the hammer would not operate. When apprised of the problem, the hammer rental company suggested that an internal air valve in the hammer probably had malfunctioned. The hammer was not disassembled to verify this suggestion, but is is possible that, whatever failure mode was involved, the mode had already begun during the 1896-kPa (275-psi) ROP test.

The average ROP of the hammers at 1379 kPa (200-psi) and 88 964 N (20 000 lb) WOB was approximately 4.6 m/h (15 ft/h); this rate compares with a ROP of 1.5 m/h (5 ft/h) for the same bit run without percussion at the same WOB and rotary speed.

It is commonly stated that hammers reduce drill string vibration in rough drilling conditions. There is considerable field experience in highly faulted formations that verifies this assumption, but the assumption is apparently not true in competent rock such as the granite samples used in these tests. Tables E-2 and E-3 show the high-frequency variations in torque and axial force measured by the strain-gaged sub in the DRL drill string. In general, the standard deviation of each variable is higher with the hammer than without. This result seems reasonable for the laboratory situation, but faulted formation and a longer, more flexible drill string might produce different behavior.

The penetration rates of the industrial hammers are shown in Figure E-4, plotted as envelopes of operating conditions. At each air supply pressure, penetration rates at different rotary speeds are plotted, and curves are drawn through the minimum and the maximum points. This format provides an envelope for each tool that shows its penetration rate as well as its sensitivity to rotary speed.

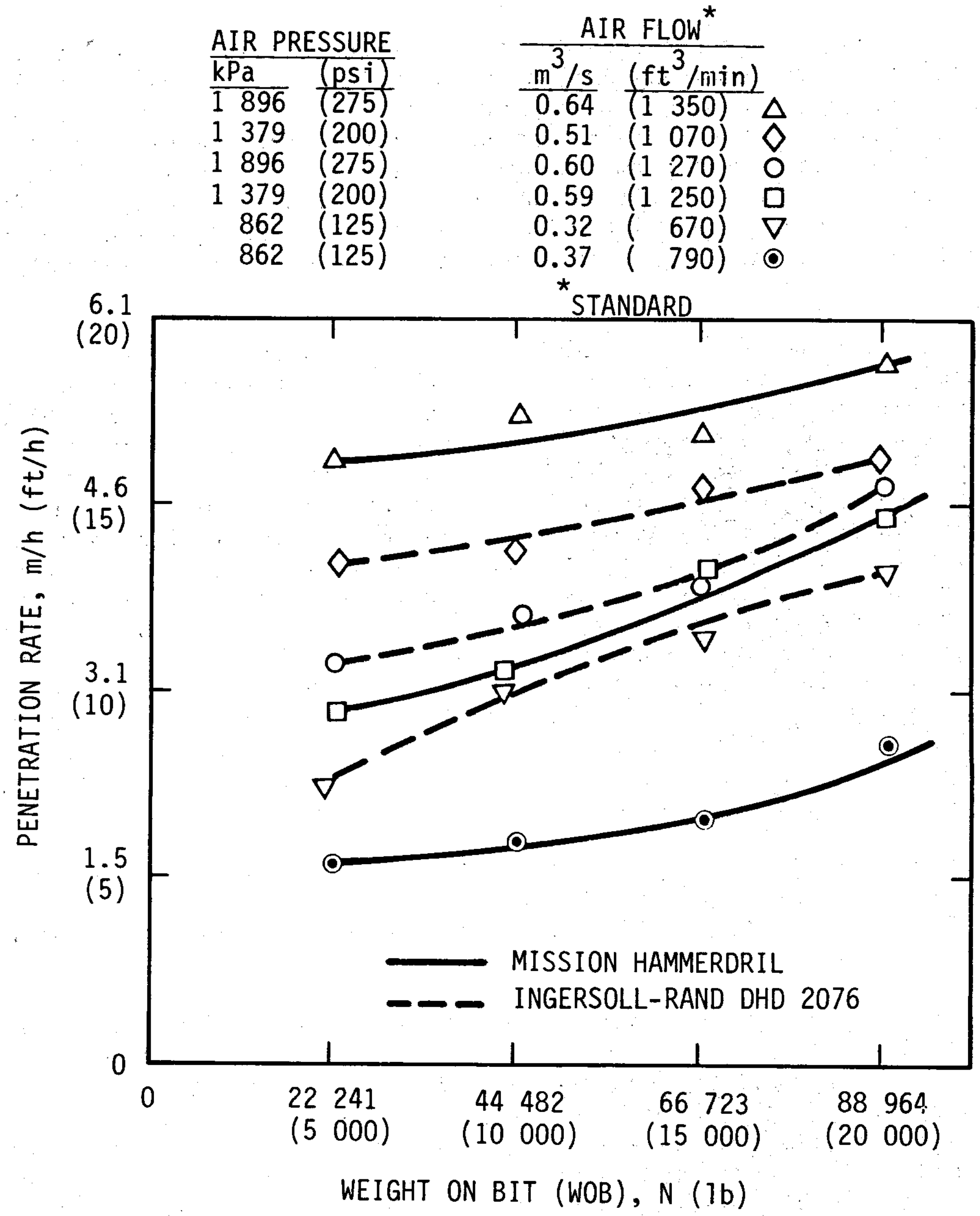

Figure E-3. Penetration Rates of "Oil Field" Hammers with Reed 20-cm (7.875-in.), M-70 Bit; Run at Varying Air Pressure and Weight on Bit; Rock--Sierra White Granite

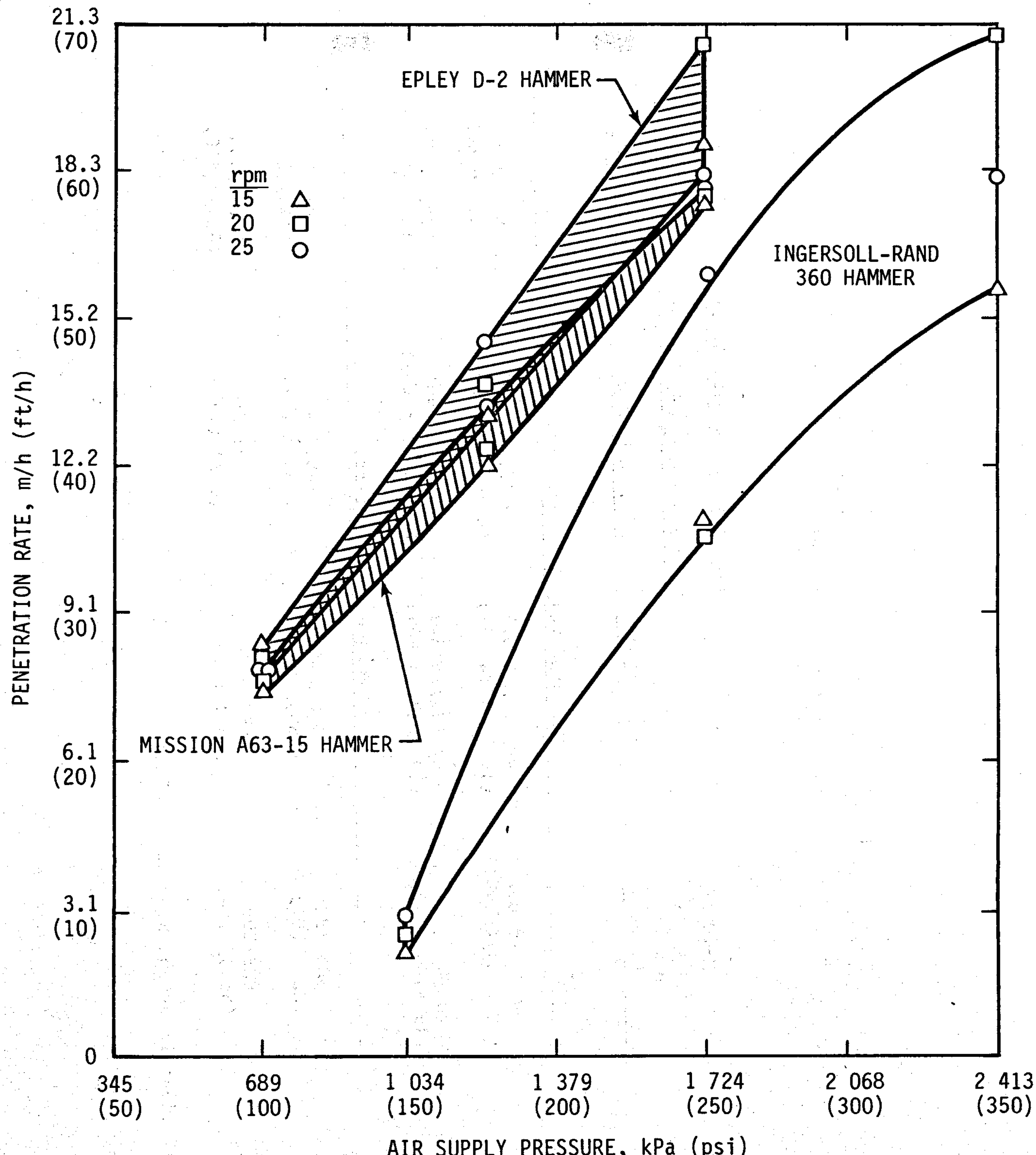

Figure E-4. Rates of Penetration for Industrial Hammers; Operating Envelopes Show Variance in Rates of Penetration Over Range of Air Pressure and Rotary Speed; Rock--Sierra White Granite

Table E-2

Comparison of Axial Force and Torque in the Drill String Operating with and without Hammer at Equal Weight on Bit and Rotary Speed

Nominal Weight on Bit N (lb)	M-70 without Hammer 40 rpm	Mission with Hammer, 40 rpm — Air Pressure, kPa (psi) 862 (125)	1 379 (200)	1 896 (275)
	Measured Weight on Bit, N (lb)*			
44 482 (10 000)	44 731/6 632 (10 056)/(1 491)	44 536/18 914 (10 012)/(4 252)	39 429/27 112 (8 864)/(6 095)	39 291/29 367 (8 833)/(6 602)
88 964 (20 000)	88 867/9 799 (19 978)/(2 203)	87 639/25 840 (19 702)/(5 809)	86 500/37 401 (19 446)/(8 408)	72 035/32 530 (16 194)/(7 313)
	Torque, N•m (lbf•ft)*			
44 482 (10 000)	305/123 (225)/(91)	388/128 (286)/(94)	480/243 (354)/(179)	697/285 (514)/(210)
88 964 (20 000)	629/209 (510)/(154)	898/420 (662)/(310)	1 192/224 (879)/(165)	1 199/350 (884)/(250)

*Values = Linear Intercept/Standard Deviation

Table E-3

Comparison of Axial Force and Torque in the Drill String Operating with and without Hammer at Equal Rate of Penetration: 5.5 m/h (18 ft/h)

	Mission Hammerdril	M-70 without Hammer 40 rpm 177 929 N** (40 000 lb)	M-70 without Hammer 70 rpm 133 447 N** (30 000 lb)
Axial* Force N (lb)	72 035/32 530 (16 194)/(7 313)	175 665/12 740 (39 491)/(2 864)	135 738/18 954 (30 515)/(4 261)
Torque* N•m (lbf•ft)	1 199/350 (884)/(258)	1 969/365 (1 452)/(269)	1 196/258 (882)/(190)

*Values = Linear Intercept/Standard Deviation

**Nominal weight on bit

As Figure E-4 shows, the industrial hammers have considerably higher penetration rates than do the oilfield hammers running at about the same air supply pressures and flow rates. This difference is primarily due to the more efficient transfer of energy from the reciprocating piston to the rock through the solid, one-piece drill bit. In the oilfield hammer, the piston blow is transmitted to the driver sub, then through a threaded connection to the bit body, and finally through the bit bearings to the cones. This system is much less rigid and therefore less efficient than the solid bit.

It is also apparent that there is a wide variation in penetration rate with rotary speed for some drilling conditions. The variation is also inconsistent, because the penetration rate does not always increase with rotary speed. The reason for this apparent inconsistency is not completely clear, but is seems to be a function of the penetration per revolution, the angular spacing of the gage carbides, and the formation being drilled. Since gage carbide wear also varies with rotary speed, the field practice is to establish some speed that will give an acceptable compromise between gage wear and penetration rate.

Figure E-4 also shows that, contrary to the prediction of theory, the penetration rate of the industrial hammers does not increase as the 3/2 power of the air supply pressure. The penetration rate, and blow frequency, below theoretical values are primarily caused by the increasing back pressure at the piston exhaust position. The flow restriction imposed by the air passage through the bit shank becomes more important as flow rate increases and, therefore, raises the pressure into which the piston exhausts. The increased pressure reduces the amount of work which the piston extracts from the air, and the energy per blow is reduced.

Figure E-5 is a comparison of the penetration rates of the hammers at a theoretical air compressor horsepower. Assuming that the air compressor inefficiencies are the same for all tests, the pressure and flow rate were used to calculate a theoretical power at each test point. The curves then give some indication of how efficiently each hammer and bit transform the energy of the compressed air into the energy of breaking rock. When the curve for the I-R 360 is inspected, three things should be remembered: (1) there may be an erroneous datum point that gives the curve a concave-upward shape; (2) this hammer is actually designed for a smaller hole than the other industrial tools; and (3) the I-R 360 bit was 21.6 cm (8.5 in.) compared to 20.3 cm (8 in.) for the Mission and Epley tools.

Pulse Measurement Tests

The objectives of this part of the testing were to compare the pulses of the industrial and the oilfield hammers and to compare the pulses of the industrial hammers at high and at normal temperatures. These data would have shown the actual force of the blows delivered to the rock and would have shown whether the performance of the hammers changed significantly at high temperature.

The test setup had a strain-gaged load cell beneath the bit (Figure E-6) and accelerometers mounted on the bit head (Figure E-7). One

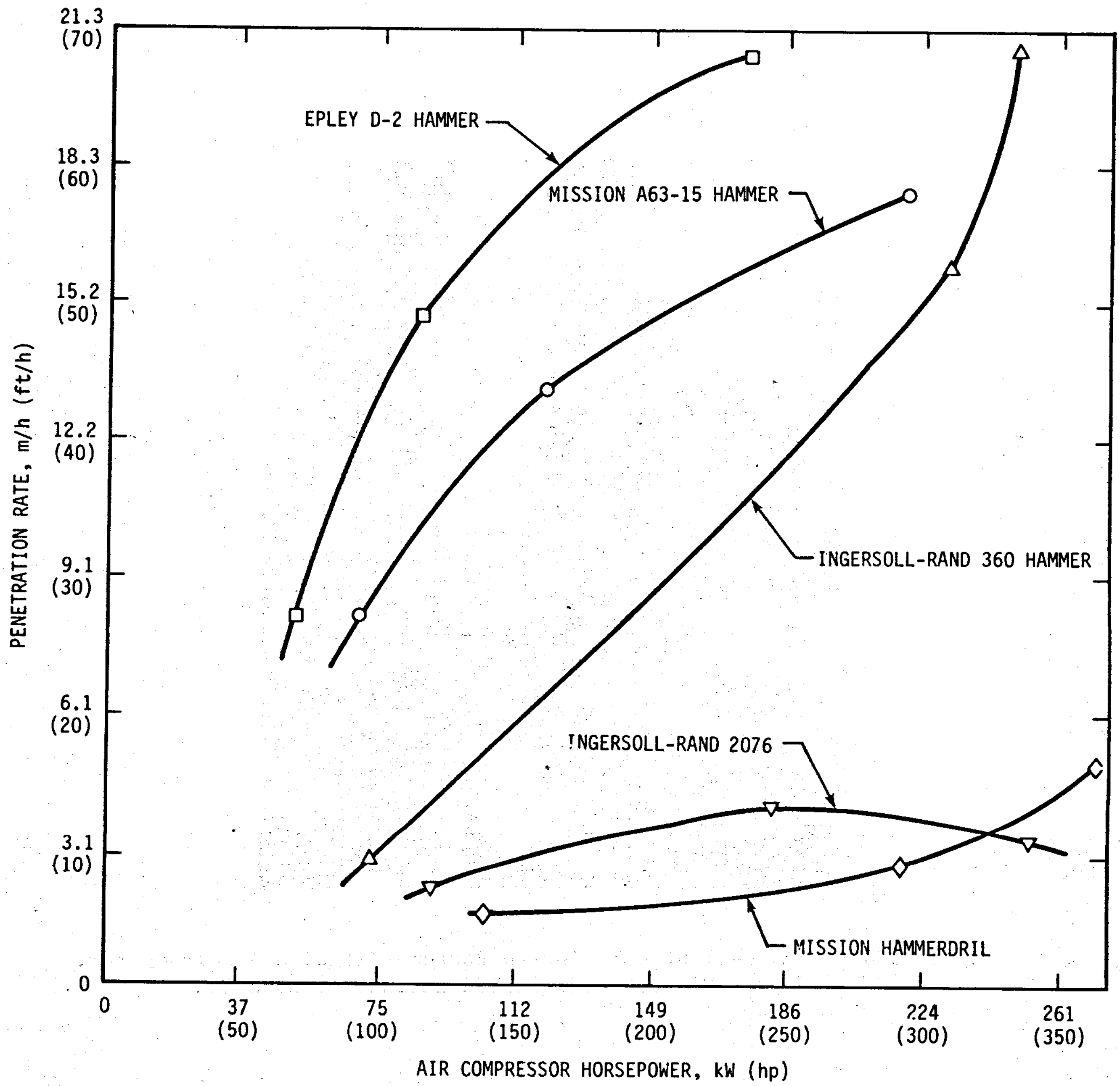

Figure E-5. Penetration as a Function of Theoretical Air Compressor Horsepower

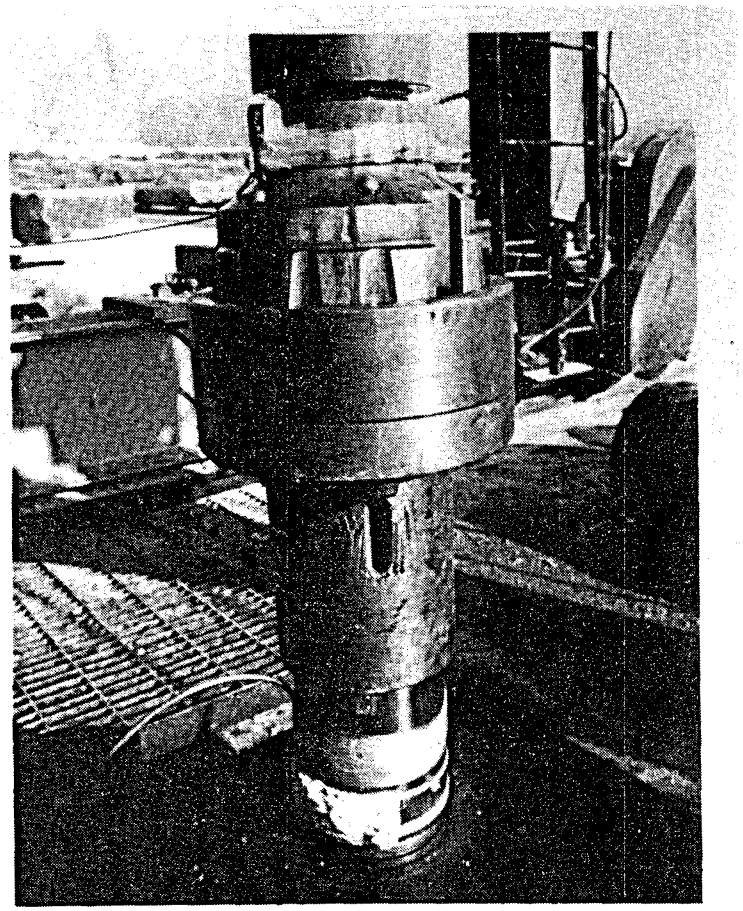

Figure E-6. Load Cell Stack: Top to Bottom--Bit with Accelerometer, Adapter Plate, Water-Cooled Extension, Load Cell

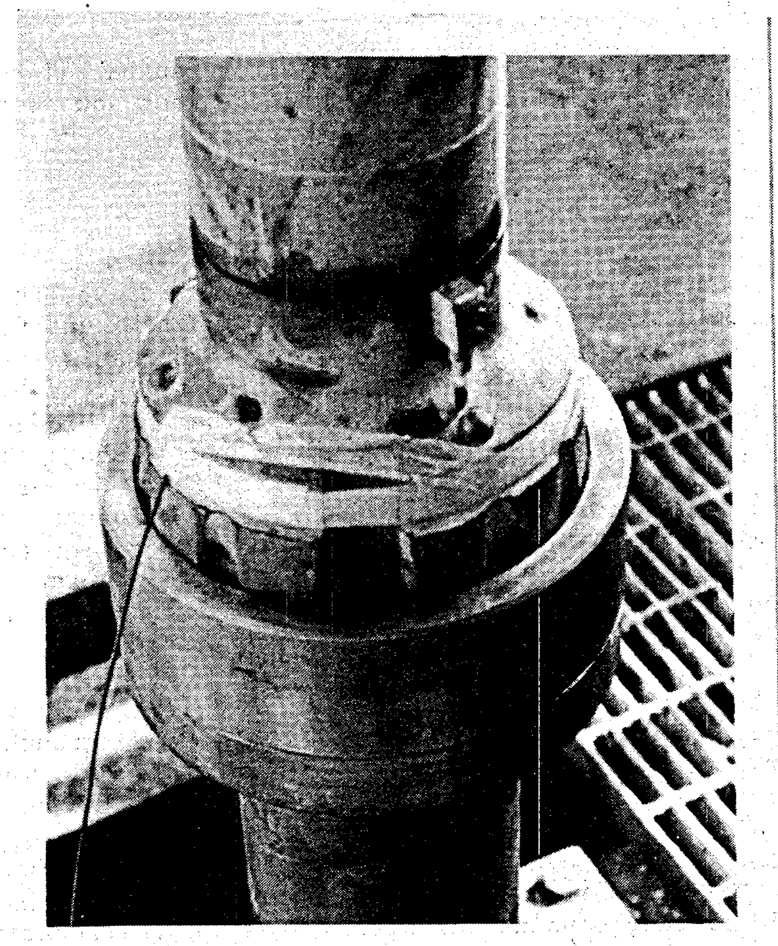

Figure E-7. Kistler 805A Mounting Block with Accelerometer oilfield and two industrial hammers were run in this setup. The net results were the destruction of two load cells and five accelerometers and the collection of essentially no useful data. The primary reason for this set of mishaps was the unexpected magnitude of the loads on the transducers. These high loads were apparently caused by the dynamic separation of the bit and the load cell plate and their subsequent impact as they rebounded back together. Some of the broken accelerometers were rated for 50 000 g service, so the loads imposed on them must have been considerably higher than that.

In general, it appears that the data desired can be had by redesigning the test apparatus, but the value of the data does not now justify the time and expense.

High-Temperature Tests

The objectives of this part of the testing were to verify the high-temperature operation of the industrial hammers and to identify any failure modes unique to the high temperature. The test setup was similar to that for normal rock drilling, except that the drilling target was a cast-iron billet and the air supply was heated by passing the air through a gas-fired heat exchanger. An insulated sub and swivel were used above the hammer, an insulated exhaust can surrounded the bottom part of the hammer, and the in-line oiler was filled with high-temperature Pacer lubricant. The test plan was to operate the hammers for 8 hours at 28°C (50°F) temperature increments from 177° to 260°C (350° to 500°F). At the end of each 8-hour operating period, the air supply temperature would be cycled to ambient and back to hot, with the hammer off bottom, to simulate tripping.

The first hammer tested was the Mission A63-15. The bit was placed against a cast-iron billet, and hot air that was passed through the hammer during a 1-hour period brought the A63-15 to 177°C (350°F). The rotary was then turned on, and the hammer was loaded to close the bit and begin drilling while maintaining the hot air flow. After about 4 minutes the hammer stopped; it was cooled by passing ambient air through it and was then disassembled. The Delrin foot valve in the top of the bit had shattered into approximately 10 pieces, causing the piston to stop reciprocating.

The Ingersoll-Rand DHD 360 was tried next, assuming that, because it had a metal foot valve, it would last longer at high temperature. The same starting procedure was used, and the I-R tool drilled for approximately 3 minutes before stopping. When the hammer was disassembled, the foot valve was found to be crushed and easily could be lifted out of the bit. Apparently the valve is held in place by some material which melted or softened enough to let the valve tube become misaligned and then be crushed by the piston.

While the I-R test was being prepared, the DRL machine shop made an aluminum (6061-T6) tube to replace the part in the Mission A63-15. This part was installed in the bit and was retained in place by dimpling the aluminum tube into the groove inside the bit. The hammer was assembled and the test repeated; the hammer ran for 52 minutes before stopping. The problem was once again the foot valve. It apparently had fatigued, because it had parted cleanly just at the point where the o.d. increased to form a positioning feature on the tube. This problem may have been aggravated by a tool mark on the tube, because the machined finish was rough.

At this point in the testing, it was concluded that plastic parts were not usable at the test temperature, so the Epley hammer, which has a plastic feed tube inside the piston as well as a plastic foot valve in the bit, was not run at 177°C (350°F).

During each of the high-temperature tests, the air temperature was measured at the hammer intake and exhaust. The exhaust air became significantly cooler once hammering began, and the air expansion in the piston replaced the orifice expansion of the temperature soak period. Both hammers produced expansion cooling of approximately 27°C (48°F), which could be significant in keeping the operating temperature low in a hot wellbore.

Although drilling time was short, the use of a cast-iron target appeared to have no effect on the bit. The bit penetrated approximately 15.2 cm (6 in.) into the billet and showed no visible wear on any of the carbides.

These test results indicate that off-the-shelf industrial hammers will not operate at geothermal temperatures but that there is no fundamental obstacle to their modification. Replacing the plastic valve parts with something else is not a trivial problem, because it is very important that the parts have the kind of fatigue-resistant resilience that the plastic gives. This design work can be done if a study of drilling economics shows that the high penetration rate of percussion justifies further development.

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