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**GEO THERMAL COMPAXT
GEO THERMAL COMPAXT™ DRILL BIT DEVELOPMENT**

Final Technical Report for the Period July 1, 1976 to September 30, 1982

**By
L. E. Hibbs, Jr.
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MASTER

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Schenectady, NY 12301**

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FOREWORD

This report covers the experimental results of the work accomplished on Contract No. DE-AC04-76ET27142, sponsored by the Division of Geothermal Energy, Department of Energy. The work was conducted during the period from July 1, 1976 to September 30, 1982. The initial DOE Program Manager was Clifton Carwile and later David Allen. At the beginning of Fiscal Year 1978, responsibility for supervision of this contract was delegated to Sandia Laboratories with Jon H. Barnette as the initial Project Engineer, followed by Charles Huff, David Wesenberg, and John Finger. Donald G. Flom was the General Electric Program Manager and Louis E. Hibbs, Jr., was the General Electric Principal Investigator. The major portion of the experiments conducted at General Electric Corporate Research and Development (GE-CRD) were performed by George C. Sogioian. K.J. Dunn of CRD performed the impact-fatigue experiments and with Minyoung Lee conducted the analysis of the results. The full-scale laboratory drilling tests at Tulsa University were under the direction of J.J. Azar. John F. Melaugh and Don Johnston, Tulsa University Drilling Research Projects, were instrumental in the performance of these tests, with R. Ojanen of the General Electric Carbology Systems Business Department assisting. Both the pressurized, elevated temperature "three-cutter" rock cutting experiments and the full-scale pressurized laboratory drilling experiments were carried out at the Drilling Research Laboratory, Terra Tek. Gordon A. Tibbetts and Alan D. Black of Terra Tek were responsible for modifying the geothermal test cell and making the necessary modifications to the pressurized drill rig to permit testing of larger bits than had been evaluated previously. Ranga Komanduri, GE-CRD, participated in the conduct of the pressurized, elevated temperature "three-cutter" tests and the analysis of the experimental results. The assistance of G.J. Hahn in statistical experimental design and interpretation and Miss Susan Weissman in conducting some of the earlier rock cutting experiments is gratefully acknowledged. Robert C. DeVries was extremely helpful in examination of the rock samples and Sal Alessi prepared the specimens for photomicrography. Charles Ward of Maurer Engineering and Arnold B. Bower of GE's Carbology Systems Business Department are acknowledged for their contributions in bit design and general drilling requirements. Valuable assistance during the course of this work was provided by representatives of the GE Specialty Materials Department, specifically Ed Efsic and Mahlon Dennis (both now with Strata Bit, Inc.), Larry Offenbacher (presently with Christensen, USA), and David Sitler. Instrumental in the fabrication of experimental polycrystalline diamond compact bits and providing

valuable assistance during field trials were Hsin Huang of Christensen, USA, Karl Kuhn of Smith Tool, and Charles Huff and Leonard Baker of Sandia Laboratories (and later with Petroleum Concepts, Inc.). Valuable discussions during the course of this work were provided by members of the GE-CRD staff, including H. Lown, Harley W. Lake, Andrew W. Urquhart (now with Lanxide), and Rodney E. Hannemen (now with Reynolds Aluminum, Inc.). The interest and essential support of this work by the Union Oil Company, and in particular Del Pyle, Don Ash, Dick Engebretsen, Harold Moss, Rich Greibling, Bob Riordon, Cliff Nerve and Gary Uhland is acknowledged. Others who participated and contributed in many ways included Bruce Walker and Coy Fielder of Christensen, USA; Lloyd Garner, Joe Vincent, Jim Kingsolver, Bill Baker and Ed Vizeriam of Smith Tool; John Sandstrom of Terra Tek's Drilling Research Laboratory; Sam Varnado, James Kelsey, and Max Newsom of Sandia Laboratories; Lou Hake and Wayne Miller of Petroleum Concepts, Inc.; Jerry Nalon, Jim Murray, and Joe Martis of GE Carboly Systems Business Department; and John Walker, Morris Skalka, and Clifton Carwile of DOE-Geothermal Energy Division.

SUMMARY

The objective of this program was to develop and demonstrate the performance of new drill bit designs utilizing sintered polycrystalline diamond compacts for the cutting edges. The scope included instrumented rock cutting experiments under ambient conditions and at elevated temperature and pressure, diamond compact wear and failure mode analysis, rock removal modeling, bit design and fabrication, full-scale laboratory bit testing, field tests, and performance evaluation. A model was developed relating rock cutting forces to independent variables, using a statistical test design and regression analysis. Experiments on six rock types, covering a range of compressive strengths from 8×10^3 psi to 51×10^3 psi, provided a satisfactory test of the model. Results of the single cutter experiments showed that the cutting and thrust (penetration) forces, and the angle of the resultant force, are markedly affected by rake angle, depth of cut, and speed. No unusual force excursions were detected in interrupted cutting. Wear tests on two types of diamond compacts cutting Jack Fork Sandstone yielded wear rates equivalent at high cutting speeds, where thermal effects are probably operative. At speeds below ~400 surface feet per minute (sfm), the coarser sintered diamond product was superior. The wear rate of a diamond compact tested by Sandia Labs on Texas Pink Granite was almost two orders of magnitude greater than the wear rate of the same product tested on Jack Fork Sandstone at General Electric. The higher wear rate is thought to be the result of cyclic impact loading due to the inhomogeneity of the massive quartzite in the Texas Pink Granite. Thermal effects at the cutter-rock interface could also be operative. Interrupted cuts on Jack Fork, using compacts with high negative back rake angles, generated some transgranular cracks in diamond compacts, indicating strong diamond-to-diamond bonding in the sintered layer. The shear strengths of three diamond compact/support bonds were measured at room temperature and at 350 °C, with one braze attachment giving a value of more than 90,000 psi at the higher temperature. Also, the ultimate strength of the diamond compact body was determined under cyclic loading. The fracture stress was reduced with increasing number of cycles, suggesting a fatigue-type failure. The failure load, corresponding to an infinite number of cycles, was far above the force observed in cutting rock under similar geometric conditions in a controlled laboratory experiment. Correlation of cutting forces with size distributions of rock debris yielded specific cutting energies per unit surface area. While greater than the energy required to create new surface, the specific energy for each rock is constant and roughly proportional to

rock hardness and modulus. Two bits were designed, constructed, and subsequently tested in a laboratory drilling rig. The criterion for design of the one bit was equal expenditure of horsepower per cutter as determined by the single cutter tests. The other bit was designed on a similar basis but with modifications for improved cutter cleaning. The performance of both bits (drilling marble), based on analysis of the penetration rate-bit weight relationships, was in good agreement with performance predicted by the prior single cutter experiments. Pressurized, elevated temperature, three-cutter experiments were conducted under conditions simulating a hydrothermal geothermal resource at about 3000 ft of depth. Rock cutting was primarily performed in granite, using polycrystalline diamond compact cutters attached to cemented tungsten carbide stud supports by the three brazing alloys previously evaluated, plus cutters utilizing an early version of Sandia Laboratories' diffusion bond. No serious deficiencies in any of the diamond compact attachments were observed but some diamond layer chipping and minor spalling was produced cutting the granite. Pregrinding the diamond compacts to dull the sharp edges was effective in eliminating chipping and spalling, but with significant loss in penetration rate. Although these three-cutter experiments were performed under conditions that were presumed to be rigorous, the tests failed to reveal a serious deficiency in the pocketed tungsten carbide stud design that became apparent in the first geothermal field drilling test. The first two polycrystalline diamond compact bits targeted for testing in a geothermal field were deliberately made 8-1/2 in. in diameter rather than the normal 8-3/4 in. so that they could be evaluated without the necessity of reaming to the bottom of the hole. One of these bits was a steel body, pocketed, stud-mounted cutter design and the other was a hard matrix, cast body design with the diamond compact cutters hand-brazed into preformed pockets in the bit body surface. These bits were first tested on a full-scale laboratory rig, drilling in a pressure vessel under conditions simulating depths down to 6000 ft. Tests were made drilling marble and sandstone to compare performance of the bits and reveal any serious design and/or structural defects. Tests were not performed in hard rock because appreciable wear prior to actual field testing was undesirable. Both bits performed well, the steel body stud type bit being the more aggressive of the two and showing less effect of depth on reduction in penetration rate than the hard matrix bit. However, the latter suffered no significant damage from testing, whereas more than half the diamond compact cutters on the steel body bit were found to be cracked. The damage was traced to the technique used to press-fit the studs in the bit body; the bit was returned to the vendor where the damaged cutters were re-

placed, using an improved interference fitting method. The repaired steel body, stud-type bit was tested in the Baca Field, NM; drilling andesite (the basement formation for this hydrothermal resource) using aerated water as the drilling fluid. The bit did not perform effectively, due to extensive fracture of the cemented tungsten carbide studs. Metallographic examination revealed that the fractures originated with internal cracks starting at the root of the pockets and that these cracks were due to thermally generated stresses developed when the diamond compact drill blanks were brazed to the studs. A new steel body bit was fabricated using an improved unpocketed stud design and replacement of the gage trimmer cutters with diamond compact wear pads, but otherwise identical to the prior bit. The new steel body bit and the hard matrix, cast body bit were tested in the Baca Field, NM; again drilling andesite, using aerated water. Both bits performed excellently, developing very high penetration rates at relatively low rotary speeds and low bit weights. The maximum penetration rates developed were: 170 ft/hr at 10,000 lb bit weight for the steel body, stud-type bit and 85 ft/hr at 15,000 lb for the hard matrix bit. In a practical sense, the stud-type bit was too aggressive and difficult to control because of the low bit weight requirement. The available drilling footages for those field tests were small; only about 50 ft per bit. After testing, both bits exhibited marked wear on the gage and periphery of the cutting structure and very little wear elsewhere. Some of the damage to the steel body bit was the result of heat checking of the peripheral carbide studs, caused by frictional heat due to insufficient end clearance. The diamond compact wear pads had prevented bit body wear at the limited number of locations where they had been placed. Following these promising field test results, Sandia Laboratories, the contract technical monitor, decided that all further bit development should be concentrated on the steel body, stud-type bit concept. Four additional bits, with 8-3/4 in. diameters, were designed and fabricated. Two of these were targeted for test in the Baca Field, NM, and two for test at the Geysers, CA. The basic cutting structure of the prior bit was retained, using a new stud design to provide greater end clearance and reduce heat checking damage. In addition, the cutter standoff was reduced (to a specified minimum of 0.350 in.) to reduce the aggressiveness of the bit design. The four gage trimmer cutters were replaced, but in this case they were ground to reduce spalling and chipping, and to assure that they were exactly "on-gage." Each bit was also fitted with 16 diamond compact wear pads. The two new bits tested in the Baca Field were evaluated in the hydro-thermal producing formation, a volcanic tuff. Drilling was again conducted using aerated water as the drilling fluid. These drilling ex-

periments were disappointing; very little penetration was obtained with either bit. Careful examination following the test revealed that the cutters in the center of the cutting structure had been installed with essentially no standoff from the bit body, a fabrication error which explained the lack of penetration. The field test was not entirely wasted, however. In order to reach the bottom of the hole both bits had to ream significant footage, 360 ft in one case and 200 ft in the other case. This was a good test of the gage trimmer cutters and the diamond compact wear pads, which performed excellently and prevented significant bit body wear. In addition, there was no carbide heat checking and no stud fracture with the stud-cutters employing the additional (20°) end relief. Also, examination of the small amount of diamond compact wear that was developed showed that this was abrasive wear only, indicating that the aerated water was a sufficiently effective coolant to prevent thermal damage to the diamond cutters. The bits would have drilled the volcanic tuff formation, effectively if the cutter standoff had been correct. After testing one of the bits targeted for the Geysers dry steam field on a full-scale laboratory rig (to reassure the contract technical monitor that the cutter standoff error had been corrected) a drilling test was conducted at the Geysers. This test was run in the graywacke steam producing formation, using air to remove the cuttings and to cool the bit. The cooling was not adequate to prevent accelerated diamond cutter wear and frictional heat generation was sufficient to reduce the cutter-stud braze joint strength to the point where the bonds failed and the cutters were detached. The carbide studs rapidly wore flush to the bit body so the bit could not penetrate the formation. The other bit targeted for the Geysers was not tested. Since the failure model for the bit tested at the Geysers was based on loss of diamond compact cutters due to shear failure of overheated, weakened braze bonds, one additional steel body, stud-type bit was fabricated, utilizing polycrystalline diamond compact cutters diffusion bonded to steel studs. It was anticipated that the diffusion bond would not exhibit sufficient loss in strength at the temperature developed by frictional heat while drilling in the Geysers to result in bond failure and loss of diamond compact cutters. Thus, although rapid diamond wear was expected, it was hoped that some quantitative measure of bit performance could be obtained. In spite of precautions taken to assure a clean hole, the diffusion bonded bit was apparently put down on a very hard object (such as a cemented tungsten carbide insert from the prior roller cone bit). A circular path of damage was created in the cutting structure which prevented effective drilling, but useful information was obtained. Outside of the circular region of severe damage, which included gross

plastic deformation of the steel studs, the diffusion bond did not fail, even though the diamond compacts had undergone enough wear to produce large amounts of frictional heat. A few cutters were lost due to impact but in these cases the failure occurred in the drill blank carbide substrate, not at the carbide-steel interface. The stiffness of steel studs is probably not great enough for rigorous geothermal drilling, but a carbide stud-diamond compact cutter assembly using a diffusion bond would be attractive for geothermal drilling applications where aerated water or mud could be utilized. A drilling cost analysis was made for the actual Baca Field case where successful polycrystalline diamond compact bit performance was achieved. The analysis, which developed the relationships between drilling performance indicators such as penetration rate, bit life, and footage drilled for different levels of drilling cost and bit cost, suggested that economic application of diamond compact bits in hydrothermal geothermal areas was feasible. More importantly, however, the analysis demonstrated that the ranges of bit performance necessary for optimum utilization (given specific bit costs and drilling cost values) were (1) relatively narrow and (2) well below the maximum drilling rates demonstrated during the actual field test. It is clear that this type of analysis should be made prior to the initiation of any future work to develop experimental bits targeted for specific applications in order to obtain accurate performance requirements as guides to design.

Section 1

INTRODUCTION

A. GENERAL BACKGROUND

The severe energy crisis which existed at the beginning of this program provided a strong incentive for more rapid development of geothermal energy resources. In pursuit of this goal, many documents had appeared which pointed toward the challenge and need for improved drilling technology. For example, at the Second United Nations Symposium on the Development and Use of Geothermal Resources, it was reported that to develop 20,000 MW electricity, a total of 8000 wells would be required.⁽¹⁾ This total included 600 wildcat wells to locate 100 fields of 200-MW capacity, 4000 successful producing wells, 1000 unsuccessful field-development wells, and 2000 injection wells. If these wells were to be drilled in 10 years, 100 drill rigs would be needed. This requirement for the number of wells was consistent with a Jet Propulsion Laboratory report of 1975 which stated that to generate 20,000 to 30,000 MW by geothermal means by 1985, an average of 1000 wells per year would have to be drilled over that 10-year period.⁽²⁾ To realize this amount of drilling would require not only that drill rigs and trained personnel be available, but also that the rigs be utilized as effectively as possible.

An Ad Hoc Committee on Technology of Drilling for Energy Resources reported in 1976 that for the rotary drilling equipment and techniques used for oil, gas, and geothermal energy recovery, the most significant improvements will be those that decrease the time that the rig is not drilling. Current estimates are that operating time spent in actual drilling is only about 40% for all onshore wells and 25% for all offshore wells, where more directional drilling occurs.⁽³⁾ Clearly, longer-lived bits would contribute significantly to reduced downtime by virtue of the lower number of trips (to change bits) needed. Improvements in instantaneous drilling (i.e., penetration) rates would also improve the overall drilling rate. Since for a given drill bit the bit life is, in general, an inverse function of the penetration rate, an appropriate trade-off is required - within each range of depths - to maximize overall drilling rates.

The drilling of geothermal wells is accomplished by the same rotary techniques as for oil and gas but, beyond the shallow depths near the surface, it becomes more complicated than oil/gas drilling, because of the formations encountered and the higher temperatures involved. Some of the factors which make geothermal hole production more difficult include the following:

- less accessible drilling locations
- a wide variety of strata making up the geothermal source system, which may include the overburden, cap, and aquifer
- the necessity in most cases to penetrate fractured, fissured, or porous rock
- high hole temperatures in the production zones, up to 350 °C
- corrosive and erosive environments due to superheated dry and/or wet steam, hot brines, and additional corrosive agents such as dissolved H₂S and other acidic constituents

Owing to the more severe environment in geothermal drilling, both drilling time and cost are increased. The formations are primarily of two varieties: sands of primary porosity and fractured, hard, abrasive igneous rocks. In the igneous formations, the usable life of the best hard-rock bits with tungsten carbide teeth may be 200 ft or less.⁽³⁾ This can nearly triple the drilling time over oil/gas drilling for equal footage.

Prior to the beginning of this contract, a survey was made by General Electric Corporate Research and Development (GE-CRD) of some of the more recent geothermal wells drilled in the Imperial Valley and the Geysers in order to gain more definitive information on the conditions encountered and drilling methods used. Typical information from one source included hole depth, type of formation, bit sizes and types, penetration rates, bit weights, rotary speeds, mud and airflow rates, mud weights and pH, and some sketchy information on flow line and bottom hole temperatures. Additional information was gained from several sources.^(1,4,6,7,8) As a result of the survey, a brief description of the more important geothermal areas in

the U.S. was provided in the first technical progress report on this contract.⁽⁹⁾ A summary of that description is given in Appendix A.

The costs for geothermal drilling at the beginning of this program are also given in Appendix A. In 1975 these costs ranged from \$300,000 to \$600,000 per well,⁽²⁾ depending upon rock types and depth requirements, with some unofficial reports placing the costs closer to \$1 million per well. Since that time, inflation has made the costs even higher but the factors entering into the calculation (i.e., rig cost, penetration rate, depth, trip time, bit cost, and number of bits required) remain the same. The early estimates of Sandia are probably still valid; they stated that costs per foot for current geothermal development drilling are averaging a factor of 2 to 4 higher than petroleum drilling, while hard-rock drilling is often a factor of 15 or more higher.⁽⁵⁾

B. BASIS FOR DIAMOND COMPACT APPROACH

Although several exotic methods for geothermal drilling have been proposed,⁽¹⁰⁾ it is clear that conventional rotary drilling will be the only generally feasible method for some time to come. The bulk of the geothermal drilling is accomplished using rock bits (roller bits) with cemented tungsten carbide inserts as the wear-resistant rock crushing elements. Although cemented tungsten carbide is not nearly so hard or wear resistant as natural diamond, the roller bit design can perform with some effectiveness in the fractured, broken strata inevitably encountered in geothermal sources. A major problem with roller bits is limited bearing life in the hot and corrosive conditions. A drag bit design would eliminate the necessity for bearings, but cemented tungsten carbide does not have the wear resistance and impact strength to perform effectively in this manner.⁽¹¹⁾

Diamond drag bits, fabricated with selected natural stones, are very effective for drilling medium hard to very hard homogeneous rock, provided adequate cooling and bit face cleaning (with mud or water) is provided. Unfortunately, geothermal well conditions frequently prevent these essential requirements from being maintained. Frequently, drilling must be accomplished without mud, to avoid damaging the geothermal source structure. Under these conditions of inadequate cooling and cleaning, natural diamond stones can literally burn up.

Natural diamond bits are fabricated from specially selected stones that have been rounded to eliminate sharp edges and points which can act as stress risers to promote crystal cleavage. Despite the diamond's superior hardness and abrasion resistance, it is highly susceptible to massive cleavage and fracture if subjected to impact in a favorable direction. The diamonds are attached to the bit body by means of specially formulated, abrasion-resistant matrix alloys. Although much development work has been carried out to formulate matrix alloys that actually chemically bond to the diamonds, these bonds are tenuous at best.

The basis for General Electric's approach in this program was to increase productivity and reduce costs for drilling of geothermal wells with a unique new class of materials - sintered polycrystalline diamond compacts. Developed by proprietary and patented superpressure processes at General Electric's Research and Development Center, the diamond compacts are dense, sintered, polycrystalline bodies with abrasion and wear resistance properties approaching those of natural diamonds but, because of the random crystal orientation, without natural diamond's directional wear properties and susceptibility to gross cleavage fracture.* Figure 1 compared the hardnesses of the compacts with other appropriate materials.

The sintered diamond compacts have been manufactured in sizes greater than 0.5 in. in diameter, and may be synthesized with the polycrystalline diamond body bonded to a substrate material capable of attachment to a bit body by a variety of methods. The diamond compacts offer the potential for the development of a "drag" bit with penetration rate capabilities equal to or greater than roller bits without the necessity for bearings, which can limit life in hostile geothermal hole environments.

* At the initiation of this program, the General Electric product was designated COMPAX diamond compacts. Later, General Electric introduced an additional trade name, STRATAPAX, to describe diamond compacts formulated specifically for rock cutting. These new compact grades were included in the program by an amendment to the original contract. During the remainder of this report, both names will be used interchangeably together with polycrystalline diamond compacts (PDC), a term which appears in many Sandia and DOE Reports.

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The high strength and hardness of sintered diamond compacts at high temperatures make these materials promising for use in fractured, broken strata, providing suitable bit designs could be developed. The immediate advantages of diamond compacts for geothermal drilling appeared to be the following:

- a. potential for increased bit life and penetration rates for lower drilling costs
- b. the markedly lower bit weights necessary*
- c. potential ability for compact bits to maintain gage†
- d. No bearings - bearing failure, along with gage wear, is a primary wear mode of rock bits

Polycrystalline diamond compacts had been evaluated in a number of oil/gas drilling experiments prior to this program, and some promising progress had been made. The basic sintered diamond compact (a polycrystalline diamond layer 0.020 to 0.025 in. thick) bonded to a cylindrical tungsten carbide substrate was the principal configuration used (see Figure 2), but alternative geometries were potentially possible as well.

* This would afford much better control in drilling both straight and directional holes. Also, the high temperatures and severe corrosion/erosion problems with drill pipe would be reduced if less strain were applied to the drill strings. Drill pipe is a major cost in the Geysers.

† This is the major wear mode for the presently used rock bits, and requires frequent reaming to maintain hole size.

Figure 1. Hot Hardness for Diamond, Cemented Tungsten Carbide and a Tool Steel

Figure 2. Schematic Illustration of a COMPAX[®] Diamond

Section 2

PROGRAM APPROACH

A. PROGRAM OBJECTIVE

The overall objective of this program was to develop and demonstrate the performance of a new type of drill bit design that would provide increased penetration rates and/or longer bit life utilizing sintered polycrystalline diamond compacts for the cutting edges. The improved bits were to be applicable to existing conventional rotary drilling methods (for hole size requirements in the 7- to 9-in. dia. range) and were to be designed to perform effectively in typical rock formations encountered in geothermal (and oil/gas) field exploration and development.

B. PROGRAM SCOPE

Laboratory evaluations and field trials (aimed principally at oil/gas production) prior to the inception of this program indicated that significant potential advantages were possible using polycrystalline diamond compact cutting edges in modified drag bits. The requirements for geothermal drilling include essentially all of those for oil/gas plus the necessity to penetrate a greater variety of rock types. These types include a greater number of broken and fractured strata as well as significant amounts of granite and/or granodiorite (for hot, dry rock-thermal energy utilization) encountered while drilling at temperatures up to twice those of oil/gas applications. Phase I of the program included several integrated primary tasks to provide both fundamental information and practical bit evaluations. These tasks may be broadly described as follows.

Instrumented Single-Cutter Laboratory Rock Cutting Experiments

These experiments were performed with machining equipment, such as a lathe, suitably instrumented to measure and record forces and force components. The interrelationships of cutting edge geometry, cutting speeds, penetration depths, material removal rates, and the cutting forces and specific energy requirements were established. Representative rock types were tested, covering the range of compressive yield strengths, hardnesses, and structures to be expected in geothermal and oil or gas environments.

Determination of Cutter Wear Rates and Analysis of Failure Modes

Single-edge rock cutting experiments were carried out to determine the effects of rock properties, machining parameters, and cutter geometries upon diamond compact wear rates, susceptibility to fracture, and other failure mechanisms. The experimental techniques were similar to those used in the earlier rock cutting tests but without sophisticated force measurement instrumentation, in order to increase system rigidity. Physical property (noncutting) experiments were also performed to assess the suitability of compact/support systems under conditions simulating those anticipated in geothermal environments. These tests included shear strength and ultimate strength measurements and impact tests, all at temperatures up to 350 °C.

Rock Removal Modeling

Based on instrumented single-cutter rock cutting experiments, the fracture characteristics of several types of rock were examined. An analysis was made of the particle size distribution produced in cutting rock as related to such parameters as penetration force, speed, cutting force, cutter geometry, and the physical properties of the rocks involved. The objective was to pinpoint the most effective conditions for diamond compact cutter utilization.

Design and Fabrication of Polycrystalline Diamond Compact Bits

Using information gained from the instrumented rock cutting experiments, plus prior laboratory and field test experience and recommendations by Maurer Engineering as an independent consultant, two diamond compact bits were designed and constructed. The designs were directed toward improved performance drilling for selected key rock types such as (1) limestone, (2) abrasive, relatively high compressive yield strength sandstone, (3) dolomite, and (4) very hard, tough rock such as granite.

Laboratory Tests of Bits at Atmospheric Pressure and Ambient Temperature

The bits just discussed were tested in the Tulsa University Drilling Laboratory working in conjunction with General Electric personnel, using a full-scale drilling rig. These tests were performed at atmospheric pressure and ambient temperature, using appropriate key rock materials. The major objectives were:

1. establish hydraulic requirements for optimum performance.

2. determine relationships between drilling variables (such as speed and bit weight) and penetration rates, power requirements, drilling efficiency,
3. identify necessary design modifications prior to field trials, and
4. identify the most promising operating conditions for field testing.

Phase II of the program was aimed at utilizing the information from Phase I, together with the results of more extensive laboratory tests under simulated pressure/temperature conditions, in the preparation, laboratory evaluation, and field testing of polycrystalline diamond compact drill bits. The tasks in this phase may be broadly described as follows.

Rock Cutting Tests in a Geothermal Test Cell

Three-cutter experiments were performed in a pressure vessel at the Drilling Research Laboratories of Terra Tek, Inc., capable of 5000 psi (static water pressure) at temperatures up to 315 °C. Cutting experiments were performed at speeds and cutter engagements representative of conditions expected in actual geothermal drilling. The primary objectives of this task were:

1. provide, for selected cases, a direct comparison of diamond compact cutter performance under simulated geothermal environment with the results of the ambient temperature, atmospheric pressure experiments performed previously,
2. determine the suitability of the diamond compact cutter attachment method for utilization in a geothermal environment, and
3. reveal potential problem areas in cutter-support design that might require modification prior to actual geothermal field trials.

Design and Fabrication of Modified Polycrystalline Diamond Compact Drill Bits

Two field trial bits were constructed. The design modifications for these bits were based on the results obtained from the tests performed in the Tulsa University Drilling laboratory and on the results of the single- and three-cutter tests as well as experience gained in General Electric's ongoing internal drilling programs, where applicable. Sandia Laboratories' computer program for optimum cutter layout was used in the design of one of these bits. The bits were designed for geothermal ap-

plications where some fluid is permissible during drilling and where operation is in medium to medium hard formations with bottom hole temperatures in the 200 °C and 300 °C range.

Full-Scale Laboratory Tests of Modified Drill Bits

Prior to field trials, the bits just described were tested at the Drilling Research Laboratory, Terra Tek, drilling under pressurized conditions with actual drilling mud. Pressure was varied from atmospheric to the pressure necessary to simulate depths to ~6,000 ft. Temperature simulation was not possible for these full-scale laboratory tests but other experimental conditions were varied as widely as possible to include the range of conditions that might occur during subsequent field trials. The major objectives of this task were:

1. identify differences in performance of the diamond compact bits when the rock was in a constrained and possibly plastic condition,
2. use actual drilling fluids to obtain more exact data on hydraulic requirements,
3. identify any minor bit modifications necessary prior to field trials, to assure the integrity of the bit structure, to assure adequate bit face cleaning, and to minimize bit erosion from high velocity mud flow and rock cuttings, and
4. identify any unanticipated changes in drilling procedures caused by pressure effects, prior to field trials.

The structural deficiencies of one of the bits made major changes in fabrication methods and extensive repairs necessary before field testing was possible.

Field Tests and Performance Evaluation

Three first-generation experimental polycrystalline diamond compact bits were tested in the Baca Field, NM, where wells were being drilled for high enthalpy hot water development. This was considered the second most desirable region for initial field testing because drilling could be conducted using an aerated water fluid which would provide some cooling for the diamond compact cutting structure. The formations in the Baca Field are highly abrasive volcanic tuff in the producing zone and

andesite in the underlying basement region. The first three bits were tested drilling the basement andesite. The results of these field tests were analyzed and the performance compared with the results of the laboratory drilling tests. Wear and failure mechanisms were identified and corrective measures documented for design of subsequent bits. (It should be noted that the most desirable region for the early field tests would have been the Imperial Valley, CA, where drilling is conducted using mud, drilling sandstone and shale formations for the development of a geothermal brine resource. However, no Imperial Valley test sites were made available during the course of this program.)

Design and Fabrication of Second Generation Polycrystalline Diamond Compact Bits

Based on the drilling performance and bit wear information, four more bits were designed and constructed. One pair of bits was fabricated for additional testing in the Baca Field, NM, and the other pair constructed with slightly different features for field evaluation at the Geysers, CA.

Field Tests of Second Generation Bits

The modified bits targeted for the Baca Field, NM, were tested in the volcanic tuff hydrothermal producing formation. Because these bits had to ream their way to bottom, a good evaluation of design modifications to reduce gage wear was obtained. However, due to a cutter stand-off fabrication error by the bit manufacturer, overall drilling performance could not be evaluated. A thorough bit wear and failure analysis was conducted. The Geysers region is a vapor-dominated geothermal area with a maximum dry steam temperature of 240 °C. The formation is principally graywacke, highly fractured in the reservoir section, and abrasive because of its high quartz content. The overburden confining pressure significantly increases the strength of the graywacke. In order to prevent damage to the formation in the producing zone, drilling must be conducted dry, using air to cool the bit and remove the cuttings from the hole. One of the bits targeted for the Geysers, CA, was tested. Excessive wear of the diamond compact composing the outer portion of the cutting structure, attributed to high frictionally-generated temperatures and poor cooling, resulted in failure of the diamond drill blank bonds, preventing the bit from performing effectively. The other bit of identical design was not tested.

Fabrication and Testing at the Geysers of an Additional Bit of Radically Different Design

The contract technical monitor proposed a different mode of failure for the bit tested at the Geysers. In an attempt to resolve this issue one additional bit was designed and constructed, using an alternative diamond compact drill blank attachment technique, an alternative cutter support material, and a markedly different cutter layout design. Although effective drilling was not anticipated (because of the high diamond wear rate observed with the prior bit) the test was prematurely terminated without resolving the failure mode issue because the cutting structure was damaged, apparently by junk in the hole. Careful examination did indicate that the alternative attachment method was promising for geothermal applications but that the alternative diamond drill blank support material was unsuitable due to insufficient stiffness.

Drilling Cost Analysis to Define Economic Polycrystalline Diamond Compact Bit Performance Requirements for the Baca Field, NM

After the successful Baca field demonstration with two of the first-generation polycrystalline diamond compact bits, a drilling cost analysis was made to define the penetration rate/bit life/drilling footage relationships (as functions of the depth range of hole section drilled) necessary to reduce costs by specific amounts. The analysis showed that the penetration rates achieved during the first Baca field tests were more than sufficient to effect significant cost savings but also showed that reduction in bit wear would have to be obtained before bit life or drilling footage requirements could be met. With the provision that accurate drilling cost information can be obtained for operations conducted with conventional bits, this drill cost analysis technique can be used to define drilling performance requirements for any type of advanced rotary oil/gas/geothermal drill bit under development. The results of the cost analysis may be reported in a manner that does not disclose cost information proprietary to the drilling contractor or the producer.

Section 3

DESCRIPTION OF THE EXPERIMENTAL APPROACH AND RESULTS

A. INSTRUMENTED SINGLE-CUTTER ROCK CUTTING EXPERIMENTS

1. EXPERIMENTAL DESIGN AND APPARATUS

Evaluation of the performance of COMPAX diamond tools "cutting" rock in experiments at CRD prior to this program, as well as tests performed by General Electric at other Company sites, at Tulsa University and by Sandia Laboratories in Albuquerque, NM clearly demonstrated that the rock cutting efficiency is dependent upon the independent (controllable) variables of the cutting system, as well as the rock physical properties. The forces acting on the diamond compact tool are a function of its shape, its angle of attack with the rock surface, the depth of cut, the strength and hardness of the rock, and, to a much lesser degree, of the cutting speed. Since the performance of an actual diamond compact bit is (in part) dependent upon the performances of its individual cutting elements (and their interaction), it was necessary to study individual diamond compact cutters in order to optimize their configurations for the various conditions under which they are required to function. Examples of failures of diamond compacts and/or their support structures in bit field tests clearly demonstrate the need for the information necessary to design and construct bits with sufficient structural integrity to minimize the chance for breakage and shortened tool life. The objective of these experiments was to obtain some of this cutter force information. Before the initiation of this program, all the rock cutting experiments at CRD were performed by turning a cylindrical rock core. Some wear studies are still being done in this manner. In order to (1) more closely simulate the cutting path of a compact on an actual bit, (2) increase the overall apparatus rigidity and stiffness, (3) permit utilization of rock specimens in a more easily obtainable shape, at lower cost, and (4) allow repetitive experiments to be performed under as close to identical conditions as possible, the single cutter experimental design was changed from turning a cylindrical surface to producing a spiral cut on a flat rock surface.

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2. ROCK CUTTING APPARATUS

The entire experimental apparatus used is shown in Figure 3. It consisted of a Pratt and Whitney tool room lathe, a special faceplate constructed to mount on the three-jaw chuck on which the rock specimen was mounted, a three-force component piezoelectric dynamometer attached to the lathe cross-slide, and the necessary electronic apparatus to amplify and record the dynamometer output signals. The face plate, or nest, to hold the rock specimens was constructed in the CRD machine shop. Made of 4340 steel, it provided capability for rigidly holding rock specimens up to 9 X 9 X 6 in. The 9 X 9 in. face is the one that was cut. Although mechanical clamping proved to be adequate to hold the rock in place, provisions were made to cement (using an epoxy resin) the rock to anchor bolts in the nest if the possibility of gross fracture presented itself. Figure 4 shows a rock specimen mounted on the machine. The spiral cutting path is clearly visible. An auxiliary pump was added to the experimental set-up to provide fluid coolant during cutting. By withdrawing coolant from the top of the sump the rock chips would settle to the bottom without clogging the circulation system. In addition, the sump capacity was doubled from ~8 to ~16 gal. A 40:1 water:soluble oil coolant was used. The soluble oil served no specific useful purpose in the actual rock cutting process other than preventing excessive machine rusting. Figure 5 shows the piezoelectric dynamometer mounted on the lathe cross-slide. It was firmly bolted in the position normally occupied by the compound. In order to be certain that the dynamometer would be firmly seated, the cross-slide was removed from the machine and the compound seat was ground to assure flatness. The piezoelectric dynamometer was manufactured by Kistler Instruments AG, Winterthur, Switzerland. It has the capacity to measure forces up to 2200 lbs in three mutually perpendicular directions. The dynamometer signals were fed into charge amplifiers, and from there to suitable read-out devices such as a high speed strip recorder or an oscilloscope. The dynamometer response was linear with respect to the applied load, and the cross-talk was so small that corrections were unnecessary. The dynamometer and charge amplifier frequency response was very high. In order to screen out undesired signals such as machine bearing noise, simple resistive-capacitive filters were constructed and inserted in the system between the charge amplifier and the force recording equipment. This helped to eliminate most (but not all) undesired signals without attenuating the lower frequency force fluctuations generated by the rock cutting action. There was a tendency for the charge amplifier signal to drift over extended time periods, but since the actual individual cutting tests were of short duration this drift was

easily corrected. In addition, the Hathaway light beam oscillograph recorder showed some tendency to blow fuses and burn out transistors and diodes, but not frequently enough to significantly retard progress. There was a suitable Sanborn recorder available as a backup in case the Hathaway device became unreliable.

Figure 3. Overall View of Rock Cutting Experimental Apparatus

Figure 4. Rock Cutting Machine Showing Method of Attaching Rock to Lathe Headstock

Figure 5. Piezoelectric Dynamometer with Diamond Compact Cutter in Place

3. EXPERIMENTAL DIAMOND COMPACT CUTTING TOOLS

One of our main objectives was to determine the relationship between cutter shape and performance. In order to accomplish this with a minimum of diamond compact grinding (this material is notoriously difficult to grind), three basic cutter shapes were chosen which could be obtained and utilized with very little extra preparation. These basic shapes included:

1. Pointed cutter (triangular) with either a 90° or 60° included angle.
2. Straight edge cutter.
3. Curved edge cutter (portion of a circular compact).

The curved (circular) cutting edge was the configuration that was most extensively tested in the field in experimental bits and in laboratory tests prior to this program. Only a limited amount of information on straight diamond compact cutting edges had been generated in laboratory experiments and a few early core drilling tests. The compacts that were obtained for this part of the program included the following commercially available COMPAX products:

PRODUCT NO.	DESCRIPTION
1520	90° included angle sectors cut from 0.539 in. diameter compacts. Nominal side length was 0.260 in., total thickness was 0.126 in., and the diamond layer was 0.020 in. thick.
1515	60° included angle sectors cut from 0.539 in. diameter compacts. Nominal side length was 0.244 in., total thickness was 0.126 in., and the diamond layer thickness was 0.020 in.
1525	Semicircular compacts (180°) with a straight edge length of 0.539 in., total thickness of 0.126 in. with a 0.020 in. diamond layer.
1575	Rectangular diamond compacts nominally 0.098 in. by 0.197 in. with a 0.020 in. diamond layer. Total thickness was 0.126 in.
1325	Semicircular diamond compacts (180°) with a straight edge length of 0.331 in., a 0.020 in. diamond layer, and an overall thickness of 0.126 in.

The basic tool design for the continuous spiral rock cutting experiments is illustrated in Figures 6 and 7. This was a 90° included-angle cutter, but the design for all three cutter shapes was the same, with the exception of the platform which supports the diamond compact. This, of course, conformed to the compact shape. The tools were machined from Cr-Mo-V steel bars (GE specification B5F5). In order to maximize stiffness during cutting, a separate tool was machined for each back rake used. The tool that is illustrated had a -25° back rake. The diamond compacts were brazed onto the tools, using Handy Harman Easy-Flo 45 braze. Figure 8 is a top view of a 90° included-angle compact tool mounted in the massive holder bar which was clamped in the dynamometer. The threaded hole in the top of the tool was provided to attach the "pointer" portion of a fixture used to set the desired side rake prior to testing. When cutting rock, this hole was plugged with a short screw to prevent the threads from becoming clogged with rock chips. Figure 9 shows a typical complete set of 90° included-angle pointed tools with negative back rakes from -5° to -45° . Early cutting experiments showed that -45° rake was excessive, so the straight and curved (round) edge cutter tool sets extended from -5° to -30° back rake (specifically -5° , -10° , -15° , -20° , -30°).

Figure 6. A 25° Negative Rake Tool Holder with Diamond Compact Brazed in Place (Side View)

Figure 7. A 25° Negative Rake Tool Holder with Diamond Compact Brazed in Place (Top View)

Figure 8. Diamond Compact Tool Clamped in Rectangular Bar Holder Which Fits the Dynamometer

Figure 9. Full Set of 90° Included Angle Pointed COMPAX^R Diamond Compact Tools

4. ROCKS

Six different kinds of rock suitable for testing were obtained. The basis for the choice of rock types was (1) reported compressive strength, where available, (2) hardness, (3) grain size [small, medium, large] (4) composition, and (5) availability. Ideally, a set of six rock types consisting of three pairs of medium-fine and medium-coarse grained materials of about 10,000 psi, 20,000 psi, and 30,000 psi compressive strength was desired. The rock types obtained were a compromise suite of materials chosen on the basis of availability and economy. Some consideration was given to selecting rocks from Western sources to represent expected geothermal drilling environments. However, it was concluded that adequate tests could be run at significant cost savings by using locally available materials with a range of properties encompassing those expected in geothermal holes. These materials and their sources are listed in Table 1. The ultimate compressive strength and the modulus of elasticity in compression was measured at CRD for four of the six materials listed in Table 1. The uniaxial strength of Graymont (Barre) granite was not measured because it was already been accurately determined by the Bureau of Mines. Shore hardness values were obtained on all six rock types. The compressive strength tests were made using small rectangular specimens (typically $1/2 \times 1/2 \times 1$ in.), employing a Model No. 1115 Instron machine. The crosshead velocity was 0.002 in./min in all cases. Particular care was taken in grinding the rock samples, using diamond grinding wheels, to assure that the sample surfaces were free of obvious cracks and that the top and bottom surfaces were parallel. In addition, the top and bottom surfaces were lubricated with a film of MoS_2 in order to reduce the frictional restraint between the specimens and the hardened tool steel anvils in the Instron machine. Five specimens of each rock type were tested, and the average value reported. The Shore hardness was measured using a conventional scleroscope equipped with a dial indicating the hardness value. Measurements on standard materials of known hardness showed that this device was operating satisfactorily. All six of the rock types listed in Table 1 were tested, using either flat diamond saw-cut surfaces or ground surfaces. Measurements made on highly polished surfaces were generally higher than saw-cut or ground surfaces and these values were discarded as not being representative of the rock under actual cutting or drilling conditions. Table 2 lists the property measurements made at CRD as well as similar data from other sources. Both polished samples and thin sections were prepared for microscopic examinations of all six rock types, a preliminary examination was made and photographs prepared of the polished specimens. A description of each, together with appropri-

ate photographs, is given below.

1. White Danby Marble. This is a relatively coarse and uniformly grained material. It appears to be very pure calcite, with very clean grain boundaries. The structure is highly twinned. (See Figures 10 and 11.)
2. Champlain Black Marble. This material contains a profuse distribution of small fossilized shellfish forms within a matrix of regular grains. The regular calcite grains are composed of a mixture of large and small secondary grains, primarily in or near grain boundaries. There are also significant amounts of highly regular euhedral grains, usually within the fossils, as well as some regions within the fossilized areas which are probably very fine grains of carbonate. In addition, there is a small amount of an unidentified, highly reflecting phase in or near the grain boundaries, plus a dark opaque phase. (See Figures 12 and 13.)
3. Belmont Rose Granite. Preliminary inspection indicates that this very uniform granite is predominantly composed of orthoclase feldspar, quartz and hornblende, and a dark opaque phase not yet identified. From the extent of the twinning, the feldspar is probably a calcium, sodium variety. There are reaction rims evident between the hornblende and the opaque phase (which is highly reflecting in thick polished specimens). There may also be a zircon phase present in small amounts. (See Figures 14 and 15.)
4. Graymont Granite. This is a typical Barre granite, medium to fine grained and uniform. The principal phases are feldspar and quartz, with some mica and a small amount of a bright reflecting constituent (opaque in transmitted light). The fine twinning structure in the feldspar indicates it is probably sodium, potassium rich. The quartz exhibits a wavy extinction, indicating it is highly stressed. There may also be a small amount of amphibole, probably hornblende. The amount of quartz in the Graymont Granite is greater than in the Belmont Rose Granite, and the Graymont appears to be slightly finer grained. (See Figures 16 and 17.)

5. Jack Fork Sandstone. This is well consolidated, strong sandstone, very high in quartz content. The quartz is a mixture of angular and worn grains, with the angular grains predominating. There is evidence of some quartz-to-quartz bonding between grains, which probably accounts for this material's high compressive strength. The principal bonding phase is not identified, but is probably fine grained mica, feldspar, clay, etc. There is also a small amount of a bright, reflecting phase. (See Figures 18 and 19.)
6. Verde Antique Marble, Serpentine, VT. This material has a very complicated structure. The principal phase is a fine grained serpentine, crossed by veins of various shades of green, white, and an occasional opaque vein. The white regions exhibit twinning, which indicate they may be calcite. There are regions that are bright in reflected light, which are possibly metallic compounds such as magnetic and pyrite. Preliminary examination revealed no evidence of quartz which is present in veins of California serpentine from the Geysers region. (See Figures 20 and 21.)

Table 1
ROCK SUITE FOR INSTRUMENTED CUTTING EXPERIMENTS
AND WEAR RATE AND FAILURE MODE ANALYSIS

	Rock Type	Source	Obtained From
(1)	White Danby Marble	Danby, VT	Vermont Marble Company Proctor, VT
(2)	Black Champlain Marble	Isle la Motte Lake Champlain, VT	Vermont Marble Company
(3)	Belmont Rose Granite	Belmont Township Ontario, Canada	Vermont Marble Company
(4)	Graymont Granite	Barre, VT	Vermont Marble Company
(5)	Jack Fork Sandstone	Arkansas	Tulsa U, Tulsa, OK
(6)	Verde Antique Marble (Serpentine)	Rochester, VT	Vermont Marble Company

Table 2
ROCK PROPERTIES

		Uniaxial Compressive Strength (psi $\times 10^3$)		Modulus of Elasticity in Compression (psi $\times 10^6$)		Hardness (Shore)		Shear Strength (psi $\times 10^3$)	
		CRD	Other	CRD	Other	CRD	Other	CRD	Other
(1)	White Danby Marble	7.89	9.80	4.43	9.74	33		1.90	Other - Vermont Marble Company
(2)	Black Champlain Marble	21.3		7.73		49			
(3)	Belmont Rose Granite		21.7		8.98	97			Other - Vermont Marble Company
(4)	Graymont Granite		27-29		6.5-6.7	92	87-90		Other - US Bureau of Mines
(5)	Jack Fork Sandstone	37.1		6.16		86			
(6)	Verde Antique Marble (Serpentine)	51.0*		11.3		70			

* Measurements ranged from 37.7 to 66.0×10^3 psi, depending upon veining in the samples.

Figure 10. White Danby Marble, 120X, Bright Field

Figure 11. White Danby Marble, 120X Polarized Light

Figure 12. Champlain Black Marble, 120X, Bright Field

Figure 13. Champlain Black Marble, 120X, Polarized Light

Figure 14. Belmont Rose Granite, 120X, Bright Field

Figure 15. Belmont Rose Granite, 120X, Polarized Light

Figure 16. Graymont Granite, 120X, Bright Field

Figure 17. Graymont Granite, 120X, Polarized Light

Figure 18. Jack Fork Sandstone, 120X, Bright Field

Figure 19. Jack Fork Sandstone, 120X, Polarized Light

Figure 20. Verde Antique Marble (Serpentine) 60X, Bright Field

Figure 21. Verde Antique Marble (Serpentine) 60X, Polarized Light

5. CONTINUOUS CUTTING OF HOMOGENEOUS ROCK

a. Experimental Design

As stated previously, the main object of performing these cutting tests was to determine the relationships between the independent cutter design variables, the rock characteristics, and the diamond compact cutter performance, as revealed by the cutting force magnitude and direction. This information, in turn, should be applicable to improved bit designs.

The principal independent variables for any given single point-rock cutting test are (1) the diamond compact cutter shape, (2) the cutting speed (3) the cutter back rake (positive, negative, and degree), (4) the depth of cut, and (5) the side rake, or angle between a normal cut to the cutter surface and the direction of cutter motion relative to the rock. Assuming five values for each variable (speed, back rake, depth of cut, and side rake) for each of three basic cutter shapes, the number of individual cuts required to fully evaluate a single rock type is very large. If the program included five to six rocks of different properties, a full factorial experiment would have required an obviously impossible number of individual cuts. In order to reduce the amount of tests to a workable number, a statistical technique was chosen that would permit prediction of diamond compact cutter performance from a fractional factorial experimental design, using regression analysis to obtain equations relating the dependent variable (i.e., cutting force) to the independent variables. A similar scheme was recently successfully employed to obtain Borazon^R compact cutting tool performance predictions in machining applications on high temperature superalloys. (13)

The statistical program used in this work is called STATPAC. It is a program for data analysis and fitting models to data, including summary statistics, data plots, and regression analyses. Initially written in batch FORTRAN for GE and HIS 600 and 6000 computers, a new version called INTERACTIVE STATPAC was developed, which can be utilized on the GECOS time sharing system from a teletype terminal. This interactive STATPAC program was the one used for the work reported here.

The STATPAC package uses a least squares linear regression analysis to fit relationships between a dependent variable, i.e., in our cases the resultant force on the diamond compact cutter, and the independent variables (such as cutting speed, depth of cut, back rake, side rake). In order to use this technique to analyze the data from a fractional factorial cutting experiment, first a model relating the dependent and independent variables must be chosen. In our case, a second order

model was chosen, where:

Y_R = Resultant force (in lbs.) of the three mutually perpendicular forces Y_x, Y_y, Y_u ,

X_1 = cutting speed (in sfm),

X_2 = Back rake (in degrees),

X_3 = Depth of cut (in inches),

X_4 = Side rake (in degrees).

$K, K_1, K_2, \dots$ are constants.

Using first and second order terms for the independent variables and including all possible second order independent variable interactions, the model equation was:

$$\begin{aligned} Y_R = & K + K_1 X_1 + K_2 X_2 + K_3 X_3 + K_4 X_4 + K_5 X_1^2 + K_6 X_2^2 \\ & + K_7 X_2^3 + K_8 X_2^4 + K_9 X_1 X_2 + K_{10} X_1 X_3 + K_{11} X_1 X_4 \\ & + K_{12} X_2 X_3 + K_{13} X_2 X_4 + K_{14} X_3 X_4 \end{aligned} \quad \text{Eq. (3)}$$

After the model was chosen, a matrix representing the individual cutting test cases making up the fractional factorial set was designed. For this program, five levels were chosen for each independent variable: designated as (1) very low, VL, (2) low, L, (3) medium, M, (4) high, H, and (5) very high, VH. The actual values for these levels are given in Table 3.

b. Experimental Results

The first fractional factorial experiment was performed cutting Champlain Black Marble, using 90° included-angle, pointed diamond compact cutters. The testing matrix is shown in Tables 4 and 5. Table 4 shows the levels chosen for the variables in each case, and the order in which the cutting tests were run. It should be noted that tests No. 29 through 32 were additional cuts not in the original fractional factorial design. These cuts were made in order to (1) plot some actual experimental points to observe trends, and (2) to check reproducibility of the experimental procedure. However, since each of the extra cuts was a separate independent test, the results were included in the data set used for the regression analysis.

Table 5 shows the actual values of the independent variables used and the force

values obtained. In addition, the calculated resultant force is given in two ways. Y_{xyz} is the resultant cutting force calculated, using all three mutually perpendicular measured force components (cutting force, F_z , normal thrust force, F_y , and side thrust, F_x). Y_{yz} is the resultant force calculated using only F_z and F_y , where:

$$Y_{xyz} = (F_x^2 + F_y^2 + F_z^2)^{1/2} \quad \text{Eq. (4)}$$

and

$$Y_{yz} = (F_y^2 + F_z^2)^{1/2} \quad \text{Eq. (5)}$$

It was apparent that the side thrust (F_x) was not a significant factor in the overall forces acting on the tool. This indicated that varying the side rake within the range chosen did not affect the total cutter forces appreciably, since the magnitude of the side thrust would be expected to be affected most by changing the side rake. In the case of metal cutting, where the workpiece normally fails after severe plastic deformation, side rake has significant effects. In the case of rock, where the cutting process is one of crushing and brittle fracture, the effects are apparently very small.

The first STATPAC regression analysis was run using all 32 of the cases given in Table 4. (It should be noted that the values of Y_{xyz} are generated internally in the statistical program and were only calculated separately and included in the data set to afford a direct comparison with Y_{yz} .) This initial analysis included all the possible independent variable terms as shown in Figure 3. The resulting 15-term equation predicting the resultant force Y_{xyz} had a standard deviation of 6.696 compared to the standard deviation of the measured resultant level of 33.21.

The results of the regression analysis indicated that, for this experiment on Champlain Black Marble, the side rake effects were not significant. Examination of residual resultant force values (observed values - predicted values) suggested that one data case (Test No. 26, Table 5) might be suspect. A cross-plot of X_3 and residuals also indicated the same thing. Therefore, the regression analysis was rerun, omitting this data case (31 out of 32 cases were used), and side rake (X_4) was omitted as an independent variable. The resulting 10-term equation for the resultant force was:

$$Y_R = K + K_1X_1 + K_2X_2 + K_3X_3 + K_4X_1^2 + K_5X_2^2 + K_6X_3^2 + K_7X_1X_2 + K_8X_1X_3 + K_9X_2X_3 \quad \text{Eq. (6)}$$

where

$$K = 55.92607$$

$$K_1 = 0.1558786 \times 10^2$$

$$K_2 = 4.080079$$

$$K_3 = -1243.853$$

$$K_4 = 0.2886110 \times 10^{-5}$$

$$K_5 = 0.8520565 \times 10^{-1}$$

$$K_6 = 25547.26$$

$$K_7 = 0.1187656 \times 10^{-2}$$

$$K_8 = 0.4951510$$

$$K_9 = -82.85103$$

Equation 6, predicting the resultant force, had a standard deviation of 3.836 compared to the standard deviation of the measured resultant level of 32.42. This was a significant improvement over the prior case using all 32 data cases and all four independent variables.

It was originally thought that the data from the test that was omitted (Test No. 26) was inaccurate due to excessive machine deflection under load. This test called for a depth of cut of 0.065 in. The depths of cut for all other tests were checked, using a special dial indicator with a sharp diamond point and found to be accurate. However, at 0.065-in. depth, the rock between the adjacent spiral cuts tended to spall, so there was no reliable reference surface for measurement. Therefore, the machine deflection was measured by introducing a hydraulic piston between the rock surface and the tool holder bar in the dynamometer. The total machine deflection over a thrust load range greater than any of the F_y forces observed was obtained. These data are shown in Figure 22. This showed that the maximum error in depth of cut due to "give" in the machining set-up would be less than 0.001 in., which was certainly not significant for a cut of 0.065 in. in depth.

In order to check the predictive accuracy of Equation 6, six additional cuts were made. The parameters and results of these tests are given in Table 6.

Equation 6 was solved for Y_r using depths of cut ranging from 0.01 in. to 0.05 in., speeds of 25, 300, and 600 sfm, and back rakes from -5° to -40° . These predicted resultant force values are plotted in Figure 23. The additional experimentally determined forces are also indicated in this figure (as data points) with arrows pointing to the predicted values. All these points lie almost within one standard deviation of the predicted values except for Tests E_1 and E_2 , which were made at a low back rake and high depths of cut. Otherwise, the regression analysis provided a very satisfactory fit.

Figure 23 clearly shows that the minimum force acting on the diamond compact cutter occurred with smaller and smaller back rakes as the depth of cut was increased. Minimizing the forces on the cutters should increase bit life by reducing compact wear forces and decreasing the chance for breakage. Since the cutter engagement on a diamond compact bit will decrease from the center of the bit to the outside (there is room for more cutters as the diameter is increased), this analysis indicates that the back rake should change with cutter position on the bit face. However, this is only a preliminary design concept. The relationships between the direction of the minimum force vector, the depth of cut, and the back rake must be determined in order to calculate the force components acting perpendicular and parallel to the COMPAX^{romanR} sintered diamond layer, to avoid undesirable stress conditions. Like other brittle materials, diamond compacts are strong when kept in compression and more easily damaged when subjected to tensile stresses.

A second regression analysis was made using the experimental results obtained cutting the Champlain Black Marble, in order to obtain a relationship between the independent variables and the angle of the resultant force vector. Since the effect of side rake was shown to be insignificant, the initial model was of the form:

$$\begin{aligned} \tan^{-1} \frac{F_z}{F_y} = & G + G_1 X_1 + G_2 X_2 + G_3 X_3 + G_4 X_1^2 \\ & + G_5 X_2^2 + G_6 X_3^2 + G_7 X_1 X_2 + G_8 X_1 X_3 + G_9 X_2 X_3 \end{aligned} \quad \text{Eq. (7)}$$

where

$$\tan^{-1} \frac{F_z}{F_y} = \text{Angle of Resultant Force Vector}$$

$G, \dots, G_9$ are constants determined by the regression analysis.

X_1 = speed

X_2 = depth of cut

X_3 = back rake angle

This initial analysis to obtain an expression for predicting the angle of the resultant force vector was made using the 32 cases shown in Table 5. Equation 7 had a standard deviation of 3.812 compared to the standard deviation of the measured resultant level of 6.112. The multiple correlation coefficient was 0.8509, and the index of determination was 72.40%. These results were not considered satisfactory, so a new model equation was chosen that included cubic terms for the independent variables. This 13-term equation was of the form:

$$\begin{aligned} \tan^{-1} \frac{F_z}{F_x} = & G + G_1 X_1 + G_2 X_2 + G_3 X_3 + G_4 X_1^2 + G_5 X_2^2 \\ & + G_6 X_3^2 + G_7 X_1^3 + G_8 X_2^3 + G_9 X_3^3 \\ & + H_1 X_1 X_2 + H_2 X_1 X_3 + H_3 X_2 X_3 \end{aligned} \quad \text{Eq. (8)}$$

Using the 32 cases shown in Table 5, plus the eight additional cutting tests making up Table 6 (40 cases in all), and model Equation 8, regression analysis gave a standard deviation about the equation of 2.757 compared to the standard deviation of the measured resultant of 6.288, a multiple correlation coefficient of 0.9310 and an index of determination of 86.68%. This was an improvement over the analysis obtained using model Equation 7.

Examination of residuals indicated that three of the 40 data cases were suspect and might be omitted. The regression analysis was rerun for the 37 remaining cases. The standard deviation about the equation was 2.041, compared with a standard deviation of the measured resultant level of 6.147. The multiple correlation coefficient was 0.9625, and the index of determination was 92.65%, again an improvement. The regression coefficients (constants) obtained were:

$$G = 15.14965$$

$$G_1 = -0.944883 \times 10^{-1}$$

$$G_2 = -3.213540$$

$$G_3 = 1028.030$$

$$G_4 = 0.3286612 \times 10^{-3}$$

$$G_5 = -1.307 \times 10^{-1}$$

$$G_6 = -16427.51$$

$$G_7 = -0.2898938 \times 10^{-6}$$

$$G_8 = -0.1463173 \times 10^{-2}$$

$$G_9 = 97368.36$$

$$H_1 = -0.8271785 \times 10^{-4}$$

$$H_2 = -0.6844056 \times 10^{-1}$$

$$H_3 = 4.911122$$

Solutions of Equation 8 for selected speeds, rake angles, and depths-of-cut, using 90° included-angle tools cutting Champlain Black Marble, are shown in Figures 24, 25, and 26. In contrast to the relationships between the magnitude of the resultant cutting force and cutting speed, as shown in Figure 23, where speed does not have as pronounced an effect as rake angle and depth-of-cut, the angle of the resultant force vector is significantly affected by cutting velocity. Consequently, when the resultant force vector is resolved into two mutually perpendicular force components (i.e., the cutting force action in the direction of the cutter velocity and the thrust, or penetration, force), the magnitudes of these forces will be markedly affected by all three independent variables including the speed.

The technique used for analysis of the experimental results for the first cutting experiment, as described above, was followed for all the tests performed subsequently. Excessive tendency for edge breakage was experienced at -45° back rake using the 90° included-angle, pointed diamond compacts, so the maximum value was reduced to -30° for the remainder of the experiments with the straight and round edge tools, the rake values selected being -5° , -10° , -15° , -20° , -30° , corresponding to VL, L, M, H, VH levels.

All tests were performed over a cutting speed range of 25 to 750 sfm, as shown in Table 3. The maximum depth of cut for the Product No. 1575 diamond compact cutter (straight edge) was reduced to 0.055 in., the levels used being 0.005 (VL), 0.020 (L), 0.030 (M), 0.040 (H) and 0.055 (VH). The depth of cut range for the Product No. 1515 diamond compact cutters (round edge) was 0.005 to 0.010 in. for spiral face cuts, as shown in Figure 4. The depth of cut was limited to 0.010 in. by the maximum available feed rate on the lathe cross slide. Since the width of the groove produced by the round diamond compact tool increased nonlinearly with increasing depth of cut, values of depth greater than 0.010 in. would produce overlapping cuts.

One experiment was performed cutting Jack Fork Sandstone with the Product No. 1515 diamond compacts (round edge) in a "turning" mode. The rock was in the shape of a cylindrical core approximately 6 in. in diameter. The groove cut was helical, the tool being advanced at a rate of 0.5 in. per revolution using the thread cutting feed control on the machine. Since the available feed rates were much greater than the maximum for the spiral face cuts, the depth of cut could be increased markedly. The levels used for this experiment were 0.006 (VL), 0.012 (L), 0.018 (M), 0.024 (H), and 0.030 (VH). The maximum depth of cut was not made larger because of overall reduced cutting system stiffness in the "turning" mode. In order to assure accuracy in this experiment, the actual groove depth was measured after each test cut and these values used for the analysis rather than the nominal depth of cut figures.

All of the instrumented single-cutter experiments except two were performed with sharp (not significantly dulled) diamond compact tools. The edges were examined after each test cut and resharpened by diamond grinding if noticeable wear or chipping had occurred. Two instrumented single-cutter experiments were performed, using Product No. 1575 diamond compacts (straight edges) where the tool flanks were ground to simulate worn cutters. The flank clearance was reduced to 2° for each cutter and a wear flat at least as great as the sintered diamond layer thickness produced in every case. These "worn" tool experiments were carried out using the spiral face cut set-up with White Danby Marble and Champlain Black Marble.

The instrumented single-cutter experiments performed are listed in Table 7, and the results of the STATPAC analysis in the form of coefficients to be used with Equations 6 and 8, are given in Tables 8 through 17. The ranges of values for the independent variables (speed, depth-of-cut, and rake angle) are also given in these tables. Since the regression analysis technique used is strictly a statistical one, it is not advised that the diamond compact cutter performance be calculated outside

of these limits, using the coefficients and constants reported.

Typical solutions to Equation 6 and 8 are shown graphically for a sharp, straight-edge diamond compact cutting Champlain Black Marble in Figures 27, 28, and 29. Note the significant difference in the effect of speed on the direction (angle) of the resultant force vector for the straight edge tool as compared to the 90° included-angle, pointed cutter (compare Figures 29 and 23).

Table 3
INDEPENDENT VARIABLE LEVELS FOR FIRST FRACTIONAL
FACTORIAL CUTTING EXPERIMENT

Level	Speed (sfm)	Back Rake (degrees)	Depth of Cut (inches)	Side Rake (degrees)
VL	25	-5	0.005	-8
L	100	-15	0.020	-5
M	300	-25	0.030	0
H	500	-35	0.040	+5
VH	750	-45	0.065	+8

Table 4

FIRST TEST MATRIX - CHAMPLAIN BLACK MARBLE

Test No.	Speed (X ₁)	Back Rake (X ₂)	Depth (X ₃)	Side Rake (X ₄)	Test Sequence
1	L	L	L	L	9
2	L	L	L	H	19
3	L	L	H	L	16
4	L	L	H	H	4
5	L	H	L	L	22
6	L	H	L	H	6
7	L	H	H	L	10
8	L	H	H	H	15
9	H	L	L	L	27
10	H	L	L	H	11
11	H	L	H	L	1
12	H	L	H	H	24
13	H	H	L	L	2
14	H	H	L	H	17
15	H	H	H	L	18
16	H	H	H	H	5
17	M	M	M	M	8
18	M	M	M	M	7
19	M	M	M	M	3
20	M	M	M	M	28
21	VL	M	M	M	13
22	VH	M	M	M	26
23	M	VL	M	M	25
24	M	VH	M	M	21
25	M	M	VL	M	20
26	M	M	VH	M	23
27	M	M	M	VL	12
28	M	M	M	VH	14
29	M	L	M	M	29
30	M	L	M	M	30
31	M	L	M	M	31
32	M	H	M	M	32

Table 5
EXPERIMENTAL RESULTS, CHAMPLAIN MARBLE,
90° INCLUDED ANGLE POINTED TOOL

Test	X ₁	X ₂	X ₃	X ₄	F _x	F _y	F _z	Y _{xyz}	Y _{yz}
1	100	-15	0.020	-5	-2	15	15	21.3	21.2
2	100	-15	0.020	+5	0	13	16	20.6	20.6
3	100	-15	0.040	-5	-2.5	35	43	55.5	55.4
4	100	-15	0.040	+5	3	33	42	53.5	53.4
5	100	-35	0.020	-5	1	45	35	57.0	57.0
6	100	-35	0.020	+5	0	48	30	56.6	56.6
7	100	-35	0.040	-5	10	100	75	125	125
8	100	-35	0.040	+5	8	93	75	119	119
9	500	-15	0.020	-5	-2.5	14	16	21.4	21.2
10	500	-15	0.020	+5	1	10	13	16.4	16.4
11	500	-15	0.040	-5	-4	32	44	54.6	54.4
12	500	-15	0.040	+5	3	30	47	55.8	55.7
13	500	-35	0.020	-5	0.5	30	27	40.4	40.4
14	500	-35	0.020	+5	0.5	37	30	47.6	47.6
15	500	-35	0.040	-5	6	87	80	118.	118
16	500	-35	0.040	+5	0	80	77	111	111
17	300	-25	0.030	0	0.5	36	37	51.6	51.6
18	300	-25	0.030	0	0.5	40	43	58.7	58.7
19	300	-25	0.030	0	0	36	35	50.2	50.2
20	300	-25	0.030	0	2	40	40	56.6	56.5
21	25	-25	0.030	0	0	43	37	56.7	56.7
22	750	-25	0.030	0	1.5	37	35	60.0	50.9
23	300	-5	0.030	0	5	35	28	45.1	44.8
24	300	-45	0.030	0	2.5	110	75	133	133
25	300	-25	0.005	0	-0.5	7	5	8.62	8.60
26	300	-25	0.065	0	19	75	77	109	108
27	300	-25	0.030	-8	0	35	35	49.5	49.5
28	300	-25	0.030	+8	-1	37	37	52.3	52.3
29	300	-15	0.030	0	-0.5	23	30	37.8	37.8
30	300	-15	0.030	0	0	24	25	34.7	34.7
31	300	-15	0.030	0	-0.5	23	27	35.5	35.5
32	300	-35	0.030	0	1	62	53	81.6	81.5

Table 6

ADDITIONAL TESTS TO CHECK PREDICTIVE CAPABILITY OF EQUATION 6

Test No.	Cutting Speed SFM	Back Rake (deg.)	Depth (in.)	Side Rake (deg.)	Resultant* Force F_{xyz} (Lbs.)
A	300	-15	0.01	0	12.3
B	300	-15	0.03	0	41.0
C	300	-15	0.04	0	60.2
D	300	-5	0.01	0	25.6
E ₁	300	-5	0.04	0	65.5
E ₂	300	-5	0.04	0	66.9
F	300	-25	0.01	0	16.6
G	300	-25	0.04	0	81.7

*Calculated from measured values F_x , F_y , F_z

Table 7

INSTRUMENTED SINGLE CUTTER EXPERIMENTS

<u>Rock</u>	<u>Cutter Edge Geometry</u>
White Danby	Straight (Sharp)
Champlain Black	0.100 inch wide
White Danby	Straight (Dull)
Champlain Black	0.100 inch wide
White Danby	Round (0.539 inch diameter)
Champlain Black	
Serpentine (VT.)	
Jack Fork Sandstone	
White Danby	Pointed (90° included angle)
Champlain Black	

Table 8
CONSTANTS AND COEFFICIENTS FOR USE WITH EQUATIONS 6 AND 8
FOR CHAMPLAIN BLACK AND POINTED CUTTER

Rock Type: Champlain Black Marble

COMPAX Product No.: 1520

Cutter Geometry: 90° included angle point

Cutting Edge Condition: Sharp

Cutting Speed Range: 25 to 750 SFM

Depth-of-Cut Range: 0.005 in. to 0.055 in.

Rake Angle Range: -5° to -45°

$K = 5.593 \times 10^1$	$G_2 = -3.214$
$K_1 = 1.559 \times 10^{-3}$	$G_3 = 1.028 \times 10^3$
$K_2 = 4.080$	$G_4 = 3.287 \times 10^{-4}$
$K_3 = -1.244 \times 10^3$	$G_5 = -1.307 \times 10^{-1}$
$K_4 = 2.886 \times 10^{-6}$	$G_6 = 1.643 \times 10^4$
$K_5 = 8.521 \times 10^{-2}$	$G_7 = -2.899 \times 10^{-7}$
$K_6 = 2.555 \times 10^4$	$G_8 = -1.463 \times 10^{-3}$
$K_7 = 1.88 \times 10^{-3}$	$G_9 = 9.737 \times 10^4$
$K_8 = 4.952 \times 10^{-1}$	$H_1 = -8.272 \times 10^{-5}$
$K_9 = -8.285 \times 10^1$	$H_2 = -6.844 \times 10^{-2}$
$G = 1.515 \times 10^1$	$H_3 = 4.911$
$G_1 = -9.449 \times 10^{-2}$	

Table 9

CONSTANTS AND COEFFICIENTS FOR USE WITH EQUATIONS 6 AND 8
FOR WHITE DANBY AND POINTED CUTTER

Rock Type: White Danby Marble

COMPAX Product No.: 1520

Cutter Geometry: 90° included angle point

Cutting Edge Condition: Sharp

Cutting Speed Range: 25 to 750 SFM

Depth-of-Cut Range: 0.005 in. to 0.055 in.

Rake Angle Range: -5° to - 45°

$K = 5.291 \times 10^1$	$G_2 = -3.237$
$K_1 = 1.625 \times 10^{-2}$	$G_3 = 9.372 \times 10^2$
$K_2 = 4.418$	$G_4 = -1.878 \times 10^{-6}$
$K_3 = -8.560 \times 10^2$	$G_5 = -1.358 \times 10^{-1}$
$K_4 = -2.433 \times 10^{-5}$	$G_6 = -7.310 \times 10^3$
$K_5 = 8.743 \times 10^{-2}$	$G_7 = 1.952 \times 10^{-8}$
$K_6 = 1.381 \times 10^2$	$G_8 = -1.620 \times 10^{-3}$
$K_7 = 5.769 \times 10^{-4}$	$G_9 = 8.010 \times 10^4$
$K_8 = 1.063$	$H_1 = -7.415 \times 10^{-4}$
$K_9 = -8.530 \times 10^1$	$H_2 = -3.582 \times 10^{-1}$
$G = 1.780 \times 10^1$	$H_3 = 2.126 \times 10^1$
$G_1 = -2.043 \times 10^{-2}$	

Table 10

CONSTANTS AND COEFFICIENTS FOR USE WITH EQUATIONS 6 AND 8
FOR CHAMPLAIN BLACK AND SHARP, STRAIGHT EDGE CUTTER

Rock Type: Champlain Black Marble

COMPAX Product No.: 1575

Cutter Geometry: Straight edge

Cutting Edge Condition: Sharp

Cutting Speed Range: 25 to 750 SFM

Depth-of-Cut Range: 0.005 in. to 0.055 in.

Rake Angle Range: -5° to -30°

$K = 2.141 \times 10^1$	$G_2 = -1.395$
$K_1 = 4.491 \times 10^{-2}$	$G_3 = 1.259 \times 10^3$
$K_2 = 1.685$	$G_4 = 6.488 \times 10^{-5}$
$K_3 = 2.051 \times 10^3$	$G_5 = -1.069 \times 10^{-1}$
$K_4 = -2.129 \times 10^{-5}$	$G_6 = -4.181 \times 10^4$
$K_5 = 1.022 \times 10^{-1}$	$G_7 = -4.483 \times 10^{-8}$
$K_6 = -1.854 \times 10^4$	$G_8 = -1.575 \times 10^{-3}$
$K_7 = 2.904 \times 10^{-3}$	$G_9 = 4.301 \times 10^5$
$K_8 = 1.534$	$H_1 = -2.032 \times 10^{-3}$
$K_9 = 6.673$	$H_2 = -3.084 \times 10^{-1}$
$G = 2.674 \times 10^1$	$H_3 = -1.120 \times 10^1$
$G_1 = -5.880 \times 10^{-2}$	

Table 11

CONSTANTS AND COEFFICIENTS FOR USE WITH EQUATIONS 6 AND 8
FOR WHITE DANBY AND SHARP, STRAIGHT EDGE CUTTER

Rock Type: White Danby Marble

COMPAX Product No.: 1575

Cutter Geometry: Straight Edge

Cutting Edge Condition: Sharp

Cutting Speed Range: 25 to 750 SFM

Depth-of-Cut Range: 0.005 in. to 0.055 in.

Rake Angle Range: -5° to -30°

$$K = 5.405$$

$$G_2 = -1.810$$

$$K_1 = 4.290 \times 10^{-2}$$

$$G_3 = 6.321 \times 10^2$$

$$K_2 = 5.805 \times 10^{-1}$$

$$G_4 = 1.172 \times 10^{-4}$$

$$K_3 = 1.460 \times 10^3$$

$$G_5 = -9.446 \times 10^{-2}$$

$$K_4 = -3.481 \times 10^{-5}$$

$$G_6 = -1.035 \times 10^4$$

$$K_5 = 3.869 \times 10^{-2}$$

$$G_7 = -7.843 \times 10^{-8}$$

$$K_6 = -1.825 \times 10^4$$

$$G_8 = -1.459 \times 10^{-3}$$

$$K_7 = 8.175 \times 10^{-4}$$

$$G_9 = 8.772 \times 10^4$$

$$K_8 = 8.502 \times 10^{-1}$$

$$H_1 = -7.354 \times 10^{-4}$$

$$K_9 = -2.134 \times 10^1$$

$$H_2 = 4.020 \times 10^{-1}$$

$$G = 3.328 \times 10^1$$

$$H_3 = 1.175 \times 10^1$$

$$G_1 = -8.201 \times 10^{-2}$$

Table 12

CONSTANTS AND COEFFICIENTS FOR USE WITH EQUATIONS 6 AND 8
FOR CHAMPLAIN BLACK AND DULL, STRAIGHT EDGE CUTTER

Rock Type: Champlain Black Marble

COMPAX Product No.: 1575

Cutter Geometry: Straight Edge

Cutting Edge Condition: Dull

Cutting Speed Range: 25 to 750 SFM

Depth-of-Cut Range: 0.005 in. to 0.055 in.

Rake Angle Range: -5° to -30°

$K = 3.804 \times 10^2$	$G_2 = -2.315 \times 10^1$
$K_1 = 1.246 \times 10^{-1}$	$G_3 = 5.774 \times 10^2$
$K_2 = 3.234 \times 10^1$	$G_4 = -1.429 \times 10^{-4}$
$K_3 = -4.147 \times 10^2$	$G_5 = -1.186$
$K_4 = 4.896 \times 10^{-5}$	$G_6 = -1.322 \times 10^4$
$K_5 = 8.006 \times 10^{-1}$	$G_7 = 1.185 \times 10^{-7}$
$K_6 = -3.629 \times 10^4$	$G_8 = -1.835 \times 10^{-2}$
$K_7 = 1.757 \times 10^{-2}$	$G_9 = 1.022 \times 10^5$
$K_8 = 2.329$	$H_1 = -1.598 \times 10^{-3}$
$K_9 = -2.021 \times 10^2$	$H_2 = 1.129 \times 10^{-1}$
$G = -1.221 \times 10^2$	$H_3 = -9.269$
$G_1 = 1.187 \times 10^{-2}$	

Table 13

CONSTANTS AND COEFFICIENTS FOR USE WITH EQUATIONS 6 AND 8
FOR WHITE DANBY AND DULL, STRAIGHT EDGE CUTTER

Rock Type: White Danby Marble

COMPAX Product No.: 1575

Cutter Geometry: Straight Edge

Cutting Edge Condition: Dull

Cutting Speed Range: 25 to 750 SFM

Depth-of-Cut Range: 0.005 in. to 0.055 in.

Rake Angle Range: -5° to -30°

$K = 5.369 \times 10^1$	$G_2 = 2.055 \times 10^{-1}$
$K_1 = 3.746 \times 10^{-2}$	$G_3 = 1.418 \times 10^3$
$K_2 = 2.904$	$G_4 = 1.844 \times 10^{-7}$
$K_3 = 6.145 \times 10^2$	$G_5 = 1.658 \times 10^{-3}$
$K_4 = -1.391 \times 10^{-5}$	$G_6 = 2.954 \times 10^5$
$K_5 = 4.482 \times 10^{-2}$	$G_7 = -2.549 \times 10^{-4}$
$K_6 = -1.856 \times 10^4$	$G_8 = 4.870 \times 10^{-2}$
$K_7 = -7.905 \times 10^{-4}$	$G_9 = 2.436 \times 10^1$
$K_8 = 8.998 \times 10^{-1}$	$H_1 = -2.160 \times 10^{-4}$
$K_9 = -7.101 \times 10^1$	$H_2 = 7.421 \times 10^{-2}$
$G = 1.177 \times 10^1$	$H_3 = -2.957 \times 10^4$
$G_1 = 4.591 \times 10^{-2}$	

Table 14
CONSTANTS AND COEFFICIENTS FOR USE WITH EQUATIONS 6 AND 8
FOR CHAMPLAIN BLACK AND ROUND CUTTER

Rock Type: Champlain Black Marble

COMPAX Product No.: 1515

Cutter Geometry: Round

Cutting Edge Condition: Sharp

Cutting Speed Range: 25 to 750 SFM

Depth-of-Cut Range: 0.005 in. to 0.010 in.

Rake Angle Range: -5° to -30°

$K = -4.049 \times 10^1$	$G_2 = -2.395$
$K_1 = 1.250 \times 10^{-2}$	$G_3 = -1.226 \times 10^3$
$K_2 = -8.778 \times 10^{-1}$	$G_4 = 7.345 \times 10^{-5}$
$K_3 = 1.334 \times 10^4$	$G_5 = -1.445 \times 10^{-1}$
$K_4 = -3.124 \times 10^{-5}$	$G_6 = 0$
$K_5 = 2.027 \times 10^{-2}$	$G_7 = -4.277 \times 10^{-8}$
$K_6 = -3.894 \times 10^5$	$G_8 = -2.738 \times 10^{-3}$
$K_7 = -1.117 \times 10^{-3}$	$G_9 = 1.206 \times 10^7$
$K_8 = 1.339$	$H_1 = -4.216 \times 10^{-4}$
$K_9 = 1.655 \times 10^2$	$H_2 = 1.746$
$G = 3.854 \times 10^1$	$H_3 = 4.363 \times 10^1$
$G_1 = -6.450 \times 10^{-2}$	

Table 15

CONSTANTS AND COEFFICIENTS FOR USE WITH EQUATIONS 6 AND 8
FOR WHITE DANBY AND ROUND CUTTER

Rock Type: White Danby Marble

COMPAX Product No.: 1515

Cutter Geometry: Round

Cutting Edge Condition: Sharp

Cutting Speed Range: 25 to 750 SFM

Depth-of-Cut Range: 0.005 in. to 0.010 in.

Rake Angle Range: -5° to -30°

$K = -5.122$	$G_2 = -7.863 \times 10^{-1}$
$K_1 = 1.941 \times 10^{-2}$	$G_3 = -2.758 \times 10^3$
$K_2 = 1.498$	$G_4 = 5.817 \times 10^{-5}$
$K_3 = 6.165 \times 10^3$	$G_5 = -4.392 \times 10^{-2}$
$K_4 = -1.905 \times 10^{-5}$	$G_6 = 0$
$K_5 = 4.786 \times 10^{-2}$	$G_7 = -4.395 \times 10^{-8}$
$K_6 = -2.858 \times 10^5$	$G_8 = -7.832 \times 10^{-4}$
$K_7 = -9.058 \times 10^{-5}$	$G_9 = 1.762 \times 10^7$
$K_8 = 8.702 \times 10^{-1}$	$H_1 = -8.049 \times 10^{-4}$
$K_9 = -7.032 \times 10^1$	$H_2 = 1.994$
$G = 5.546 \times 10^1$	$H_3 = 5.203 \times 10^1$
$G_1 = -5.713 \times 10^{-2}$	

Table 16

CONSTANTS AND COEFFICIENTS FOR USE WITH EQUATIONS 6 AND 8
FOR VERMONT SERPENTINE AND ROUND CUTTER

Rock Type: Vermont Serpentine

COMPAX Product No.: 1515

Cutter Geometry: Round

Cutting Edge Condition: Sharp

Cutting Speed Range: 25 to 750 SFM

Depth-of-Cut Range: 0.005 in. to 0.010 in.

Rake Angle Range: -5° to -30°

$K = -1.725 \times 10^2$	$G_2 = -2.695$
$K_1 = -5.119 \times 10^{-3}$	$G_3 = -2.891 \times 10^3$
$K_2 = -1.318$	$G_4 = 1.283 \times 10^{-4}$
$K_3 = 5.838 \times 10^4$	$G_5 = -1.750 \times 10^{-1}$
$K_4 = -7.796 \times 10^{-6}$	$G_6 = 0$
$K_5 = -1.030 \times 10^{-1}$	$G_7 = -8.555 \times 10^{-8}$
$K_6 = -3.782 \times 10^6$	$G_8 = -3.133 \times 10^{-3}$
$K_7 = -1.052 \times 10^{-3}$	$G_9 = 1.651 \times 10^7$
$K_8 = 3.440$	$H_1 = -1.668 \times 10^{-4}$
$K_9 = -3.057 \times 10^2$	$H_2 = 5.523 \times 10^{-1}$
$G = 4.018 \times 10^1$	$H_3 = -2.931 \times 10^1$
$G_1 = -7.465 \times 10^{-2}$	

Table 17

CONSTANTS AND COEFFICIENTS FOR USE WITH EQUATIONS 6 AND 8
FOR JACK FORK SANDSTONE AND ROUND CUTTER

Rock Type: Jack Fork Sandstone

COMPAX Product No.: 1515

Cutter Geometry: Round

Cutting Edge Condition: Sharp

Cutting Speed Range: 25 to 750 SFM

Depth-of-Cut Range: 0.005 in. to 0.030 in.

Rake Angle Range: -5° to -30°

Rake Angle Range: -5° to -30°

$K = -1.557 \times 10^2$	$G_2 = 7.641 \times 10^{-2}$
$K_1 = 3.306 \times 10^{-1}$	$G_3 = 8.094 \times 10^2$
$K_2 = -2.815$	$G_4 = 2.919 \times 10^{-5}$
$K_3 = 2.442 \times 10^4$	$G_5 = -1.123 \times 10^{-2}$
$K_4 = -3.214 \times 10^{-4}$	$G_6 = -1.331 \times 10^5$
$K_5 = 1.444 \times 10^{-1}$	$G_7 = 4.775 \times 10^{-9}$
$K_6 = -3.474 \times 10^5$	$G_8 = -1.585 \times 10^{-4}$
$K_7 = 6.709 \times 10^{-3}$	$G_9 = 3.634 \times 10^6$
$K_8 = 4.498$	$H_1 = -3.827 \times 10^{-5}$
$K_9 = 4.680 \times 10^2$	$H_2 = 1.707 \times 10^{-2}$
$G = 2.564 \times 10^1$	$H_3 = -4.687 \times 10^1$
$G_1 = -3.539 \times 10^{-2}$

Figure 22. Rock Cutting Machine Stiffness

Figure 23. Predicted Resultant Cutting Forces Cutting Champlain Black Marble

Figure 24. Predicted Relationship Between Resultant Angle and Cutting Speed for 90° Included Angle Tool Cutting Champlain Black Marble

Figure 25. Predicted Effect of Rake Angle on Resultant Angle for 90° Included Angle Tool Cutting Champlain Black Marble

Figure 26. Predicted Effect of Depth of Cut on Resultant Angle for 90° Included Angle Tool Cutting Champlain Black Marble

Figure 27. Effect of Rake Angle on Predicted Resultant Force and Angle for Straight Edge Diamond Compacts Cutting Champlain Black Marble, 25 SFM

Figure 28. Effect of Rake Angle on Predicted Resultant Force and Angle for Straight Edge Diamond Compacts Cutting Champlain Black Marble, 300 SFM

Figure 29. Effect of Speed on Predicted Resultant Force and Angle for Straight Edge Diamond Compacts Cutting Champlain Black Marble, -15° Back Rake

6. INTERRUPTED CUTTING EXPERIMENTS

a. Experimental Design

In addition to the designed instrumented single-cutter experiments described above, which provided predictive performance capability for sintered diamond compacts cutting a variety of rock types, a series of 10 single-cutter experiments were carried out under severe interrupted cutting conditions. These experiments were performed by mounting the 9 X 6 in. blocks of rock in the nest on the lathe in the same manner as used for the spiral face cuts, but moving the dynamometer-toolholder to a position where the 90° corners of the rocks could be cut. This resulted in four severe interrupted cuts per revolution.

In order to obtain a sufficient length of cut (~3-1/2 in.), the toolholder bar was extended several inches further out from the dynamometer. Careful checking indicated that this did not significantly affect the dynamometer calibration or sensitivity, but some reduction in overall system stiffness did result from this change.

The rock and the diamond compact tools evaluated are given in Table 18 together with the experimental test conditions. The feed was set at 0.152 in/rev for all cuts in order to assure that no overlapping of the grooves in the rock occurred. The coolant served no purpose other than to reduce dusting and keep the machinery from rusting. The -21° back rake used for the Product No. 1575 diamond compact cutters was unintentional. The original test plan called for -15° rake but careful examination of the experimental results showed significant discrepancies between actual and predicted forces, and a check revealed that the toolholder for the straight edge cutters had been mistakenly constructed with a -21° rake instead of -15°.

b. Experimental Results

The cutting and thrust forces were recorded on the same high speed oscillograph chart recorder used for the spiral face cuts described previously. Additional cuts were made in order to examine the force-time traces on an oscilloscope. In no instance was there a spike in either the cutting or thrust force trace that could be attributed to the impact of the cutting edge in moving from air into the rock material. This was disappointing but not entirely unexpected, since similar experiments performed at CRD prior to this contract had yielded the same results. It had been hoped that the use of the piezoelectric dynamometer, with its very high frequency response and reduced damping capacity, would show hitherto unobserved phenomena.

The results obtained from the 10 interrupted cutting experiments listed in Table 18 are given in Tables 19-23. In general there was good agreement between the actual experimental forces measured and those values predicted by using Equations 4 and 6, together with the appropriate regression analysis constants and coefficients. Figures 30-33 show the comparison of measured vs. predicted forces for a straight edge tool cutting White Danby Marble and Champlain Black Marble at ~300 sfm. It should be noted that the agreement at the lower cutting speeds is not quite as good.

Some difficulty was experienced with slight corner chipping of the Product No. 1575 straight edge diamond compacts during interrupted cutting of Champlain Black Marble and Vermont Serpentine, and two of these tools fractured cutting Graymont and Belmont Rose Granite at ~300 sfm. In all cases where tool failure was observed, the tests were rerun with new diamond compacts.

The Product No. 1325 diamond compacts held up remarkably well. No significant edge wear occurred cutting any of the rocks except the granites, and in these cases only slight microchipping or edge rounding, except for one instance of a macrochip at 571 sfm on Belmont Rose Granite. The round tool configuration was obviously more impact resistant than the straight edge cutter design.

Table 18
INTERRUPTED CUT EXPERIMENTS

Rocks Used

White Danby
Champlain Black
Serpentine (Vt.)
Graymont Granite
Belmonte Rose Granite

Cutter Geometries

Straight Edge
Round Edge (0.330 in. ϕ)

Test Conditions

Nominal Speed Range: 40-550 SFM
Depth Range: 0.005-0.015 in.
Cutter Rake: -15° (Round tools - #1325 COMPAX)
 : -21° (Straight tools - #1575 COMPAX)
Coolant : 40:1 Water-soluble oil
Feed : 0.152 in. /revolution

Table 19

**RESULTS OF INTERRUPTED CUTTING EXPERIMENTS
ON CHAMPLAIN BLACK MARBLE**

Cutting Tool	Speed (sfm)	Rake (degrees)	Depth (inch)	Thrust Force (lb.)	Cutting Force (lb.)
Straight edge (#1575 COMPAX)	41.5	-21	0.005	22	20
	"	"	0.010	34	32
	"	"	0.015	48	50
	90	-21	0.005	24	21
	"	"	0.010	37	32
	"	"	0.015	47	45
	297	-21	0.005	28	19
	"	"	0.010	38	30
	"	"	0.015	46	41
	520	-21	0.005	26	18
	"	"	0.010	38	29
	"	"	0.015	47	38
	43	-15	0.005	17	15
	"	"	0.010	31	32
	"	"	0.015	44	50
Round edge (#1325 COMPAX)	100	-15	0.005	19	17
	"	"	0.010	32	30
	"	"	0.015	44	45
	311	-15	0.005	22	18
	"	"	0.010	34	30
	"	"	0.015	44	44
	545	-15	0.005	24	15
	"	"	0.010	35	28
	"	"	0.015	48	38

Table 20

**RESULTS OF INTERRUPTED CUTTING EXPERIMENTS
ON WHITE DANBY MARBLE**

<u>Cutting Tool</u>	<u>Speed (sfm)</u>	<u>Rake (degrees)</u>	<u>Depth (inch)</u>	<u>Thrust Force (lb.)</u>	<u>Cutting Force (lb.)</u>
Straight Edge (#1575 COMPAX)	41	-21	0.005	16	10
	"	"	0.010	38	18
	"	"	0.015	38	20
	89	-21	0.005	16	12
	"	"	0.010	28	17
	"	"	0.015	40	24
	299	-21	0.005	17	14
	"	"	0.010	28	20
	"	"	0.015	36	26
	517	-21	0.005	20	15
	"	"	0.010	32	25
	"	"	0.015	42	36
	45	-15	0.005	12	11
	"	"	0.010	24	20
	"	"	0.015	38	32
Round Edge (#1325 COMPAX)	95	-15	0.005	11	11
	"	"	0.010	24	21
	"	"	0.015	40	32
	311	-15	0.005	18	15
	"	"	0.010	22	22
	"	"	0.015	34	34
	548	-15	0.005	10	15
	"	"	0.010	24	25
	"	"	0.015	34	32

Table 21

**RESULTS OF INTERRUPTED CUTTING EXPERIMENTS
ON VERMONT SERPENTINE**

Cutting Tool	Speed (sfm)	Rake (degrees)	Depth (inch)	Thrust Force (lb.)	Cutting Force (lb.)
Straight Edge (#1575 COMPAX)	41	-21	0.005	32	27
	"	"	0.010	70	65
	"	"	0.015	78	74
	90	-21	0.005	36	24
	"	"	0.010	58	45
	"	"	0.015	80	65
	299	-21	0.005	32	17
	"	"	0.010	55	36
	"	"	0.015	78	55
	523	-21	0.005	32	16
	"	"	0.010	53	27
	"	"	0.015	75	46
	43	-15	0.005	34	26
	"	"	0.010	78	60
	"	"	0.015	80	75
Round Edge (#1325 COMPAX)	94	-15	0.005	38	30
	"	"	0.010	57	50
	"	"	0.015	77	70
	309	-15	0.005	34	25
	"	"	0.010	50	40
	"	"	0.015	70	65
	545	-15	0.005	35	22
	"	"	0.010	55	43
	"	"	0.015	67	52

Table 22

**RESULTS OF INTERRUPTED CUTTING EXPERIMENTS
ON GRAYMONT GRANITE**

<u>Cutting Tool</u>	<u>Speed (sfm)</u>	<u>Rake (degrees)</u>	<u>Depth (inch)</u>	<u>Thrust Force (lb.)</u>	<u>Cutting Force (lb.)</u>
Straight Edge (#1575 COMPAX)	39	-21	0.005	42	26
	"	"	0.010	78	50
	"	"	0.015	98	65
	94	-21	0.005	41	22
	"	"	0.010	85	45
	"	"	0.015	100	55
	311	-21	0.005	30	16
	"	"	0.010	63	30
	"	"	0.015	85	43
	548	-21	0.005	42	15
	"	"	0.010	70	27
	"	"	0.015	95	42
	41	-15	0.005	46	18
	"	"	0.010	75	35
	"	"	0.015	95	55
Round Edge (#1325 COMPAX)	89	-15	0.005	54	22
	"	"	0.010	83	38
	"	"	0.015	92	55
	295	-15	0.005	54	21
	"	"	0.010	85	43
	"	"	0.015	98	55
	517	-15	0.005	56	23
	"	"	0.010	98	40
	"	"	0.015	115	55

Table 23

**RESULTS OF INTERRUPTED CUTTING EXPERIMENTS
ON BELMONT ROSE GRANITE**

<u>Cutting Tool</u>	<u>Speed (sfm)</u>	<u>Rake (degrees)</u>	<u>Depth (inch)</u>	<u>Thrust Force (lb.)</u>	<u>Cutting Force (lb.)</u>
Straight Edge (#1575 COMPAX)	44	-21	0.005	56	30
	"	"	0.010	90	44
	"	"	0.015	117	65
	95	-21	0.005	51	22
	"	"	0.010	83	35
	"	"	0.015	107	50
	315	-21	0.005	40	14
	"	"	0.010	77	27
	"	"	0.015	103	42
	552	-21	0.005	43	15
	"	"	0.010	76	27
	"	"	0.015	107	40
	42	-15	0.005	45	13
	"	"	0.010	88	27
	"	"	0.015	113	42
Round Edge (#1325 COMPAX)	93	-15	0.005	64	17
	"	"	0.010	90	27
	"	"	0.015	108	40
	311*	-15	0.005	29	12
	"	"	0.010	53	28
	"	"	0.015	75	35
	541	-15	0.005	58	14
	"	"	0.010	80	25
	"	"	0.015	107	37

*Force measurements for 311 sfm obviously erroneous

Figure 30. Effect of Depth on Cutting Force - Champlain Black

Figure 31. Effect of Depth on Thrust Force - Champlain Black

Figure 32. Effect of Depth on Cutting Force - White Danby

Figure 33. Effect of Depth on Thrust Force - White Danby

B. COMPAX^R WEAR RATE AND FAILURE MODE ANALYSIS

1. SINGLE-EDGE ROCK CUTTING EXPERIMENTS

Wear rate determination for diamond compacts in the laboratory is a much more tedious process than cutting force measurement, due to the extreme resistance to wear exhibited by these materials. In order to assure that the wear mechanisms are the same as those operating on an actual drill bit, the compacts should be run against a material with properties similar to formations encountered in practice (i.e., an actual rock of known properties) under conditions of speed, cutter engagement, etc., close to anticipated bit requirements. If the speed of the compact relative to the rock is increased markedly in order to accelerate the wear rate, the danger of generating excessive temperatures at the interface exists, with a consequent change in wear mechanism from abrasive to thermal and/or reactive.

In order to obtain measurable amounts of wear in reasonable lengths of time, Jack Fork Sandstone was the rock chosen, because of its relatively high strength, its fine-grained, homogeneous composition, and its very abrasive character. The diamond compact wear tests were performed, turning cores of this material in a manner analogous to turning metal, using the same machine used for the force measurements described in the preceding section. Round compacts were tested, using a standard Carboloy RATR-16-4 indexable insert toolholder. The pocket for this holder was modified to take a 0.331-in dia. diamond compact, providing a -5° back rake and a -5° side rake. All the wear tests were performed under standard conditions of 0.005 in/rev feed and 0.020 in. depth of cut. The cutting speed was varied in order to obtain a graphical relationship between speed and volumetric diamond compact wear rate. All tests were performed using a soluble oil (40:1 water to oil) by volume to flood the compact cutter and cutting zone.

The volume of diamond compact wear was calculated from measurements made before and after testing. Figure 34 is a photograph of a compact with a large amount of wear, showing a typical wear land (note that the wear flat extends into the tungsten carbide substrate). The wear volume was estimated using the equation

$$V = \left[\frac{\pi r^2 \theta}{360} - \frac{r^2 \sin \theta}{2} \right] \quad \text{Eq. (9)}$$

where:

v = wear volume

r = radius of the diamond compact

t = thickness of the diamond compact layer

θ = angle subtended by radii from the center of the compact to the outer edges of the wear land, so

$$\sin \frac{\theta}{2} = \frac{\ell}{d},$$

$$\text{or } \sin^{-1} \frac{\ell}{d} = \frac{\theta}{2}, \text{ where:}$$

ℓ = average width of the wear land in the diamond compact layer,

d = compact diameter

The wear rate was calculated by dividing the wear volume by the cutting time.

Two types of compacts were tested, a fine-grained material (Series 1300, Product No. 1330) and a coarser-grained material (Series 2300, Product No. 2330). The experimental results are summarized in Table 24 and shown graphically in Figure 35.

The wear rates for both types of diamond compacts were about the same above 400 sfm, indicating that a thermal wear mechanism may have been starting to predominate. This could have been oxidation, chemical reactivity, or thermal fatigue in addition to simple microchipping due to abrasion. At speeds below about 400 sfm, the difference in wear resistance became evident. At the lower interface temperatures (due to lower cutting speed) the wear mechanism was predominately microchipping abrasive wear.

Examination of the worn diamond compacts used in these experiments revealed no gross fracture or cracking. However, experience in actual drilling tests showed that edge cracking sometimes occurs. Since impact was not intentionally introduced in the wear tests, an experiment was devised to include this feature. Four slots were milled into a Jack Fork Sandstone core parallel to its cylindrical axis, equally spaced around the circumference. The slots were approximately 1/4 in. wide by 1/2 in. deep. This core was turned using No. 2330 compacts (coarse grained), at -5° , -10° , -30° and -45° back rakes, using cutting speeds of ~ 100 and 270 sfm. The nominal depth of cut was 0.020 in., and the feed was increased to the point where a helical groove was produced in the core surface (the cutting path did not overlap

itself).

Tests at -5° , -10° , and -30° back rakes produced no appreciable damage to the diamond compacts other than slight edge chipping. The cuts at -45° back rake resulted in no immediately obvious gross damage, but closer examination of these diamond compacts revealed surface cracks in the diamond layer, approximately parallel to the cutting edges, and about 0.010 to 0.020 in. back from the edge. The cracks went through both grain boundaries and through individual diamond grains indicating a high degree of diamond-to-diamond bonding in the sintering layer.

Although the high negative rake, slotted rock tests did not produce any gross diamond compact fracture, it was evident that continued cutting under this high impact conditions would eventually produce significant edge chipping. Since the diamond compacts were used without any additional shaping, in the right circular cylinder form, as the back rake was increased the end (flank) clearance was increased an equal amount. Therefore, at a high negative rake such as -45° the sintered diamond layer was not supported well by the tungsten carbide substrate. If the cutting force component is sufficiently large, which is the case at the instant of impact after the cutter has traversed a void (at which time the thrust force component is essentially zero), the unsupported diamond layer could conceivably be sheared off the tool. Reducing the cutter end clearance should increase the support for the sintered diamond layer when high negative rakes are used, and thus reduce compact cracking.

It is improbable that crack generation in high negative rake angle cutters will be a serious problem in actual bit performance, since the analysis of the single-cutter force measurement experiments indicates that optimum rake angles should probably not exceed -25° .

The wear rates measured by continuous cutting of Jack Fork Sandstone were low compared to those cutting larger grained tough materials such as granite. For example, a rough calculation was made of the wear rate of a No. 1330 compact tested by Sandia Laboratories. This compact, attached to a tungsten carbide slug, was tested cutting Texas Pink Granite at about 0.040 in. depth of cut, using a -20° back rake. The total length of cut was about 8000 ft and the speed was 100 sfm. About $1/3$ of the total diamond layer was worn away, or about 0.57×10^{-3} in.³ The cutting time was estimated at 80 minutes, so the volumetric wear rate was $\sim 7.1 \times 10^{-6}$ in.³/min. The maximum wear rate measured continuously, cutting the Jack Fork Sandstone was 0.382×10^{-6} , which is almost 20 times less. The compressive strength of Jack Fork Sandstone was determined to be 37×10^3 psi, compared to 23.5×10^3 psi reported for Texas Pink Granite. It is obvious that compact failure mechanisms other than simple

abrasive wear predominated in the Sandia Labs experiment, probably impact effects associated with the inhomogeneous rock structure (including large quartzite inclusions) which caused gross chipping and thermal wear effects after appreciable tool wear.

Table 24

WEAR RATES OF COMPAX^R DIAMOND COMPACTS CUTTING JACK FORK SANDSTONE

COMPAX [®] Type (Product No.)	Test No.	Cutting Speed (sfm)	Volumetric Wear Rate (in ³ per minute)
1330	1	100	0.0097×10^{-6}
1330	2	350	0.0553×10^{-6}
1330	3	360	0.0678×10^{-6}
1330	4	510	0.382×10^{-6}
2330	1	152	0.0048×10^{-6}
2330	2	260	0.0166×10^{-6}
2330	3	320	0.0383×10^{-6}
2330	4	375	0.123×10^{-6}
2330	5	500	0.326×10^{-6}
2330	6	500	0.170×10^{-6}
2330	7	540	0.120×10^{-6}

Figure 34. Wear Land of Compact After Test on Jack Fork Sandstone

Figure 35. COMPAX^R Diamond Compact Wear Rates Cutting Jack Fork Sandstone

2. PHYSICAL PROPERTY MEASUREMENTS

The major purpose of the instrumented single-cutter experiments already described was to accumulate basic information on the performance of the sintered diamond compact cutter for utilization in experimental bit designs, in order to maximize drilling efficiency. In addition to those experiments, work was performed to (1) determine the actual shear strengths of diamond compact-support bonds and (2) determine the ultimate strength of the diamond compact body under cyclic loading conditions that might approach those existing in actual geothermal drilling. In the experiments performed, major emphasis was placed on measurements at elevated temperatures: 350 °C for shear strength and 300 °C for ultimate strength tests.

a. Shear Strength Measurements of Diamond Compact-Support Structures

Introduction

Attachment integrity was essential if a viable sintered diamond compact bit was to be developed for improved drilling in geothermal resource formations. Experience using diamond compact bits for gas/oil drilling operations had demonstrated the possibility of cutter loss during drilling, although the precise mechanism(s) for detachment was seldom obvious by "post-mortem" examination of used bits. Braze line failure, brought about by braze erosion, shearing of the bond due to excessive forces acting on the cutters, or a combination of both, probably accounted for some diamond compact cutter losses. Since the hole temperatures for geothermal drilling are significantly higher than the usual oil/gas environments, reduced hardness (wear resistance) and strength could be anticipated for the brazing alloys used to attach the diamond compact cutters to their support structures.

In situations where relatively soft materials are joined using a brazing alloy such as Easy Flow 45 (silver base alloy containing Cu, Zn, and Cd), the impact and fatigue strengths of the composite structure can be close to the strengths of the materials joined, provided relatively thin braze lines are achieved. However, in our case the substrate of the diamond compact cutter was cemented tungsten carbide. In addition, experience has shown that the cutters had to be supported by a high modulus material in order to minimize chances of cutter failure by brittle fracture. Thus, we were restricted to brazing together material much stronger than the brazing alloys available. In this situation the strength of the joint is governed by the brazing alloy properties.

In many engineered structures, designs can be used that increase the braze joint areas and remove the joints from regions of maximum applied stresses. In ef-

fect, this is equivalent to improving the brazing alloy properties. However, this was not a viable approach to our preliminary geothermal bit design target. Consequently, we took the approach of identifying the best methods of making reproducible, thin braze joints without internal voids or flaws (such as flux pockets), using applicable brazing materials with increased strength and hardness.

The brazing alloy recommended for attachment of sintered diamond compacts to cemented tungsten carbide supports was Easy Flow 45. According to Handy and Harman Technical Bulletin No. T-4, silver alloy-brazed, low carbon steel joints exhibit short time tensile and shear strengths as given in Table 25 (Note: values taken from curves and are only approximate).

On the other hand, data taken from information compiled by Handy and Harman on a wide variety of silver alloy braze joints subjected to creep and stress rupture tests are given in Table 26.

The precise nature of the stress applied to a sintered diamond compact in a bit actually drilling an oil/gas or geothermal well will never be known. However, we can assume that the cutter attachment joint will be subjected to a combination of impact, fatigue and steady state stress; in other words, to a stress condition probably within the conditions described for Tables 25 and 26. Using a Product No. 2530 STRATAPAX^R diamond compact drill blank (0.526 in. dia.) as an example, and assuming a braze joint of 0.217 in.² (100% braze, no flux pockets or voids, braze line thickness $\leq$ 0.002 in.), the shear strength of the attachment at 315 °C (600 °F), for short time shear (impact) conditions is ~2332 lb. On the other hand, for steady-state shear, the load necessary to produce deformation in the attachment zone is between 217 and 543 lb. Results of single-point instrumented rock cutting tests demonstrated that forces sufficient to produce shear loading in the 200-500 lb range were very probable, and it was not unreasonable to imagine forces of 2000 lbs on a single cutter under impact or high loading rate conditions on an actual bit drilling in a fractured formation or when the bit may be rocking and bouncing on the bottom of the hole. Thus, although the foregoing estimates may have been somewhat speculative, it appeared that conventional EF-45 braze joints were marginal in strength for geothermal drilling applications where the bottom hole temperatures were relatively high.

To attempt to measure, in the laboratory, the performance of modified braze attachments under conditions that duplicate the temperature and forces acting on diamond compacts in actual geothermal drilling operations would have been a very costly and probably technically impossible task. Indeed, this evaluation was one of the principal objectives of the drilling field tests scheduled later in this program.

However, proprietary sintered diamond compact attachment studies carried out through a parallel General Electric Company program had resulted in methods to produce improved, higher strength braze joints without producing any damage or degradation to the thermally sensitive sintered diamond cutting edge. Improved braze joint strengths were attributed to (1) elimination of flux pockets and essentially all voids, (2) significantly thinner braze joint thickness than is obtained by conventional tool brazing techniques, (3) uniform braze line thickness, (4) improved wetting of the cemented carbide parts to be joined, and (5) in two instances, utilization of stronger, harder braze alloys. These modified attachments were tested for shear strength at temperatures up to 350 °C, in air, in order to obtain sufficient information to assist in making the correct choice of attachment for the experimental bits to be constructed later. The experimental technique used is described, and the results obtained are given below.

Experimental Method

In order to have maximum assurance that the specimens were tested in shear, with the minimum possibility of tensile stresses being applied, a torsion technique was used. A schematic drawing of the experimental set-up is shown in Figure 36. The test specimens were square samples ground from Product No. 2530 STRATAPAX^R blanks after these diamond compacts had been brazed to Carboloy Grade 55B cemented carbide supports. The "'gripping fixtures'" indicated in Figure 36 did not actually grip the samples. These fixtures consisted of square pockets accurately machined to receive the specimens with sufficient (but not excessive) clearance to permit self alignment. Figure 37 is a photograph showing the overall apparatus, with the tube furnace open. Not visible in the upper crossbar of the test machine is the bearing for the top torsion shaft. This bearing was mounted in a ball and socket fitting that was free to move in order to provide additional self-aligning capability. Two thermocouples were used, one for furnace temperature control, and the other for precise sample temperature measurement. This thermocouple was inserted through a hole provided in the top grip so that its junction was resting on the top of the sample itself.

Before starting each elevated temperature shear test, the specimens were held at temperature for 30 minutes after the inner thermocouple had indicated that the desired temperature had been reached. The load cell output was recorded on a chart recorder, and the maximum value obtained (prior to braze joint failure) was used for the shear strength calculation.

The shear stress at failure was calculated from the equation:

$$\sigma_s = \frac{F \times R}{0.208 a^3} \quad \text{Eq. (10)}$$

where:

σ_s = shear stress

F = load cell output in pounds

R = length of moment arm from axis of rotation to load cell (12 inches)

a = length of side of square test specimen (0.290in.)

Experimental Results

Three attachments were evaluated: an "improved" Easy Flow-45 bond, and two others, designated "A" and "B". Shear strengths at room temperature and 350 °C are given in Table 27 for the EF-45 and "A" bonds, and at 350 °C for the "B" joint. The data reported are the averages of several values in each case.

Failure of the EF-45 and "A" braze joints was confined to the joint regions only, in all cases. For the "B" attachment, failure initiated in the braze joint, but traveled into the cemented tungsten carbide in every case. Room temperature tests were not performed on Attachment "B" because the strength was high enough to result in damage to the "grips."

The torsional shear test conditions described above lie between the "short time" (impact) and the creep or stress rupture test conditions (with respect to rate of applied stress) for which shear strengths are given in Table 25 and 26. If no improvement in the EF-45 bond had been achieved, we might have expected the experimental shear values to lie between 6 and 33 Ksi (at room temperature) and between ~2.5 and 8.5 Ksi (for the hot tests). The shear strength obtained with the modified EF-45 attachments were greater than the highest predicted values, however. This is evidence that an improvement in bond strength was obtained by the modified brazing technique, for the reasons stated earlier.

All three of the braze attachments tested at 350 °C by torsional shear were used for pressurized-elevated temperature "three cutter" experiments carried out in Terra Tek Geothermal pressure vessel, cutting rock at 315 °C. The performance of these braze joints is described later in this report in the section devoted to those experiments.

b. Ultimate Strength and Impact-Fatigue Measurements

Introduction

The primary purpose of these experiments was to investigate the ultimate mechanical strength of sintered diamond compacts under dynamic cyclic loading, both at room temperature and at a higher temperature near 300 °C, with an angle of impact similar to that of a rock drilling system. Initially, a Jack Fork Sandstone surface was chosen to be impacted by the sintered diamond compact cutter, in order to closely simulate the condition of a rock drilling system. But the diamond compact was so strong that it made a large indentation on the rock surface at the relatively low load of 200 to 300 lbs, and with increasing load, it merely penetrated into the rock without increasing the local stress. After 10^5 cycles, no damage was observed on the sintered diamond compact. Since it was impossible to find the ultimate strength of the compact using Jack Fork Sandstone, cemented tungsten carbide was chosen to be the surface impacted by the diamond compact cutter in subsequent tests. With this combination, failure of the compact at the edge was finally observed at fairly high loading. The results show that the fracture stress is reduced as the total number of cycles is increased, suggesting a fatigue-type failure. Since diamond is an extremely brittle substance, fatigue effects, if they occur, must arise in a different way from the usual process in metals, which involves plastic deformation and work-hardening. Possibly some irreversible processes are occurring in the specimen which involve opening and incomplete closure of subcritical cracks, followed by gradual growth of these small cracks due to cyclic stress.

It is to be noted here that the compact cutter in the present test was subjected to much more severe local stress than the reported stress on the cutting edge of compacts in a rock cutting system.

In the following section, the experimental method is described, and the results discussed. A possible failure mechanism is proposed, based on an approximate stress analysis of the specimen and on examination of SEM micrographs of the damaged area.

Experiments and Results

The test specimens were Product No. 2530 STRATAPAX^R round diamond drill blanks. The blanks were brazed to carbide studs and then pressed into pockets of steel holders. The interference between the diameter of a carbide stud and the pocket diameter in a steel holder was about 0.001 in. This sample holder (compact/stud system) was positioned into a jig fixture as shown in Figure 38. The whole assembly was then attached to a dynamic test machine as shown schematically in Figure 39. The machine

was manufactured by the Lawrence Division of CGS Scientific Corporation (Model 109). It was a completely integrated Electro-Hydraulic Servo-Control System consisting of an electronic console, a load or reaction frame, and a hydraulic pumping station. The applied force could be controlled in either tension or compression in the form of a sinusoidal sawtooth or square wave function. For this work, a sinusoidal form was chosen and only the compression mode was used.

From the instrumented rock cutting experiments it was learned that for a given type of rock, the diamond compact experienced a resultant force which varied in both magnitude and direction, depending upon the cutting speed, depth of cut, and rake angle chosen. The diamond compact cutter generally experienced the least resultant force at a negative rake angle between 10 and 20°. Based on this information, these experiments were designed in such a way that the diamond compact test specimen had a negative rake angle of 15°, a resultant angle of 40°, and a depth of cut of 0.050 in. The schematic details are shown in Figure 40. During the test, the dynamic test machine provided a cyclic force, partially simulating the condition that a diamond compact would experience in real rock drilling. Hence, the direction of the resultant force which the rock exerted on the diamond compact cutter was aligned along the direction of the stroke of the actuator.

In order to insure good contact with a measurable area while the specimen was cyclically loaded, a tungsten carbide (Carboloy Grade 55B) cylinder with a straight groove across the flat surface on one end was fitted into a stainless steel holder (Figure 40). One side (surface A) of the groove had an angle of 35° with respect to the flat cylindrical end and was designed to make intimate contact with the diamond compact surface. The other side (surface B) of the groove had an angle of 40° with respect to the flat end and made point contact with the diamond compact edge under an initial low load. As load was increased, surfaces A and B were deformed plastically. By measuring the contact area, the maximum normal stresses σ_A and σ_B could be estimated.

For a preset functional load, the actuator received the command signal and moved upward until the carbide cylinder hit the specimen. The force was continuously increased according to the prescribed functional form and was sensed by the load cell at the top of the machine. When the load reached a maximum, the actuator moved downward and the cycle repeated according to the preset frequency. The cycling force varied between zero and a preset maximum load in a sinusoidal manner and was generally of negative sign, i.e., in a compression mode. For frequencies below 10 Hz, impact conditions could be obtained by adjusting the mean level of the signal wave, such that at the end of the unloading cycle, the command signal was in a ten-

sion mode. At that stage the carbide cylinder would leave the specimen momentarily. As soon as the signal became negative, the carbide cylinder moved upward and hit the specimen again. However, for frequencies higher than 10 Hz, the actuator could not respond fast enough to provide impact. The carbide cylinder would then always be in contact with the specimen with a minimum force of about 10 to 20 lb.

Although we had an impact situation for low frequencies, the experiment was not designed to measure such parameters as impact velocity and energy transfer.

Each specimen was subjected to a force between zero and the maximum load for a given number of cycles. The specimen was then taken out and examined under a microscope. If there was no visible damage, the specimen was put back and stressed for an additional number of cycles. This process was repeated until failure was observed. The results are shown in Figure 41. A data point was recorded for the total number of cycles at which a specimen was found to have failed (i.e., edge fractured). The error bar on the plot was extended back to the total number of cycles where the specimen was last examined and found to have no visible damage. Clearly, failure occurred between these two numbers of cycles. The failure was defined as any visible crack slit or chipped-off edge. Of the 14 specimens tested, only one had a crack slit on the edge without complete failure. The remaining specimens chipped in a very similar manner. For the high temperature tests, the specimen was preloaded to approximately 60 lb. The temperature was increased to 300 ± 10 °C and held there until thermal equilibrium was reached. The specimen was then cycled in the same way as in the room temperature test. The results are also shown in Figure 42. These show a similar relationship of load versus total cycles to failure as an S-N curve for ordinary fatigue. For data below 10^5 cycles, cycling frequencies as high as 30 Hz were used. Within the limits of these data, no effects of frequency on failure were observed. Also, there was no appreciable difference between the high temperature results at 300 ± 10 °C and those at room temperature.

Table 25

TENSILE AND SHEAR STRENGTHS OF Ag-BASE BRAZING ALLOYS

Temperature (°C)	Tensile Strength (Ksi)	Shear Strength (Ksi)
25	53	33
300	21	12
315	19	11
350	16	8.5

Table 26

CREEP STRENGTHS OF Ag-ALLOY BRAZE JOINTS

Temperature (°C)	Minimum Shear Stress for Failure in < 1000 hrs (Ksi)	Maximum Shear Stress Without Creep (Ksi)
25	~ 6	~ 3
315	~ 2.5	~ 1

Table 27

SHEAR STRENGTHS OF BRAZED JOINTS

Attachment Type	Room Temperature Max. Shear Strength (Ksi)	350 °C Maximum Shear Strength (Ksi)
EF-45	57.5	19.7
"A"	80.9	48.5
"B"	----	93.4

Figure 36. Schematic Diagram of Torsional Shear Test Apparatus

Figure 37. Overall View of Torsional Shear Test Apparatus

Figure 38. Schematic View of the Specimen Jig Fixture for Incorporation into a Dynamic Test Machine

Figure 39. Schematic Diagram of the Dynamic Test Machine

Figure 40. Closeup View of the Test Specimen in Contact with the Carbide Cylinder

Figure 41. Maximum Force in Cyclic Loading Versus the Total Number of Cycles that Lead to Failure of the Sintered Diamond Compact

Figure 42. General Fracture Pattern of the Test Specimen

3. ANALYSIS AND DISCUSSION

The general shape of the fractured edge of most of the broken diamond compacts had a pattern, shown in Figure 42(a). The direction of the crack was generally the same as that of the maximum shear stress, suggesting that failure occurred by shear. When the diamond compact was in contact with the groove on the carbide cylinder, there were two normal stresses σ_A , σ_B acting on the edge of the specimen, as shown in Figure 42(b). The stress distribution within the edge was predominantly compressive. The propagation of any microcracks within the specimen or of cracks from surface flaws would be suppressed. However, it was possible for cracks to form and propagate under shear stress, aided by a small tensile stress near the shear plane. The maximum shear stress, $\sim 1/2 \sigma_B$, occurred at 45° with respect to the compact surface, as shown in Figure 42(c). Another shear stress, $\sim 1/2 (\sigma_B - \sigma_A)$, occurred at 45° with respect to the compact edge, as shown in Figure 42(d). Both shear stresses would promote crack growth in a step-by-step brittle manner until a critical condition was reached, at which rapid failure would occur.

Pictures showing typical crack patterns are shown in Figures 43(a), (b), and (c), where one can see the crack running along the direction of the maximum shear stress.

Specimen No. 1 failed for a 0 to 1500 lb-cycle at a total of 10^5 cycles. The contact area was measured, and the normal stresses σ_A and σ_B were estimated to be:

$$\sigma_A \sim 90,000 \text{ psi}$$

$$\sigma_B \sim 700,000 \text{ psi}$$

The corresponding maximum shear stresses were:

$$1/2 \sigma_B \sim 350,000 \text{ psi}$$

$$1/2 (\sigma_B - \sigma_A) \sim 305,000 \text{ psi}$$

If one extrapolates the curve in Figure 41 back to a single cycle, it indicates that a maximum force of 3500 lb would be necessary to break the diamond compact in a single stroke. Assuming the contact area remained the same (correct to a first degree approximation), this would correspond to a normal stress σ_B of 1,633,000 psi, or a maximum shear, $\sim 1/2 \sigma_B$, of 817,000 psi. These values should be the upper bound of the real stress, because the contact area would be slightly larger.

Westergaard, Muskhelishvili, and others have treated the problem of a linear elastic crack-tip field due to an applied shear force (for reviews see Lawn and Wilshaw¹⁴). For the special case of plane-crack geometry as shown in Figure 44(a), the analytical solutions for the neighboring elastic field of the crack tip based on

some simplified assumptions are:

$$\sigma_{ij} = \frac{K_{II}}{(2\pi r)^{1/2}} \begin{cases} \sigma_{xx} & -\sin(\theta/2)[2 + \cos(\theta/2)\cos(3\theta/2)] \\ \sigma_{yy} & \sin(\theta/2)\cos(\theta/2)\cos(3\theta/2) \\ \sigma_{xy} & \cos(\theta/2)[1 - \sin(\theta/2)\sin(3\theta/2)] \end{cases} \quad \text{Eq. (11)}$$

The angular component f_{ij} of the stress σ_{ij} ,

$$\sigma_{ij} = K_{II}(2\pi r)^{1/2} f_{ij}(\theta) \quad \text{Eq. (12)}$$

is plotted and shown in Figure 44(b). Note that there is a small tensile stress f_{yy} , due to the applied shear force. It is this stress component which promotes growth of the crack. The maximum tensile stress close to the tip of the crack is about one-fifth of the shear stress. If, as an approximation, the maximum shear, $1/2 \sigma_B$ (=817,000 psi), for a single cycle is multiplied by this factor, it yields a tensile stress of 163,000 psi. The real value should be less than this (perhaps around 100,000 psi), depending on the actual value of the contact area. Note the excellent agreement between this value and the transverse rupture strength (TRS) value, in three-point bending, of 120,000 psi as measured by Gigli¹⁵ and confirmed by experiments performed at General Electric CRD. The TRS is essentially equal to the maximum tensile stress.

It could be hypothesized that the shock wave due to impact loading contributes to failure. When a shock wave is reflected from the backside of a specimen, a tensile pulse is generated and, if sufficiently great, this can promote crack growth. Since in the present experiments the specimen was not hit by a high velocity impact and was in contact with the carbide cylinder for 90% of the cycle duration at relatively low frequency, it is believed that this factor was negligible in the failure mechanism in this experiment.

In order to investigate the fracture mechanism further, several SEM pictures were taken for specimens No. 1, 3, and 8. These were typical of all of the specimens tested. The crack surface close to the edge had an irregular shape with many pulverized diamond particles present, while the rear area of the crack surface exhibited a more clearly defined pattern with many large cleavage planes. Figure 45(a) shows the overall view of the crack surface of specimen No. 8. Figure 45(b) was taken at an area close to the edge, while Figure 45(c) was taken at

an area in the back. One can clearly see the difference between the two surfaces. Specimen No. 3 was the only one that had a crack slit without complete fracture of the edge. Pictures were taken of the crack slit at the cylindrical surface of the diamond compact. Figure 46(a) shows one end of the crack slit, inclined 45° to the top surface of the diamond compact, and Figure 46(c) shows the opposite end of the same crack, also with a 45° inclination to the top surface. Figure 46(b) is a magnified view of 46(a), at 1600X. One can see that the crack slit is rather large. However, the top corner of the cracked edge (not shown in Figure 46) is still strongly bonded to the compact, and it could not be broken apart with several severe blows with a hammer. Specimen No. 3 was probably representative of the first stage of failure for a specimen such as No. 8. If it had been cycled further, it might have produced a chipped-off edge like specimen No. 8. Close inspection of Figure 46(a) shows that specimen No. 3 included many diamond grains on both sides of the crack slit.

A possible explanation of the effect observed is that the crack slit was first formed at the edge and was then opened up step-by-step in a brittle manner due to the cracked surfaces rubbing against one another, aided by abrasion from the diamond wear debris trapped in the crack. These tiny diamond particles also served to obliterate the crack pattern. When a critical crack length was reached, the compact failed in an abrupt manner. Figures 45 and 46 indicate an initially clean fracture surface obscured by the microchipping process, leaving a surface which was a combination of irregular cleavage patterns and an intergranular fracture surface with much small diamond debris present.

In a real rock drilling system, the stress distribution would be more complicated than in the present experiment. The relatively high speed rock particles could also provide a local shock impact effect.

From a typical rock cutting experiment, discussed earlier, the resultant force experienced by the compact cutter in a rock cutting system at a negative rake angle of 15° and a depth of cut of 0.050 in. was about 70 to 120 lb, depending on the cutting speed. This figure is far below the asymptotic value for the failure load, i.e., the approximately 800 lb corresponding to an infinite number of cycles as shown in Figure 41. This fact suggests that a mechanical fatigue effect is not expected to be important in the idealized rock drilling system, i.e., in the absence of other potential factors such as high local shock impact.

4. CONCLUSIONS

- a. The fracture stress of a diamond compact was reduced under cyclic loading.
- b. The fracture of a diamond compact in these experiments was a shear-mode brittle fracture. Crack growth requires very large shear stresses because of the high strength of the diamond crystallites and the strong bonds present between diamond grains in these sintered compacts. Crack propagation is promoted by a relatively small tensile stress component at the tip of the crack, due to the large applied shear forces.
- c. SEM observations showed a more irregular fracture pattern for the crack surface close to the edge, and a cleaner transgranular type of fracture pattern at the back of the crack surface.
- d. The conditions for a rock drilling system in practice are not the same as in this experiment. The former may involve more shock impact loading and other factors not considered in this study. However, it is noted that the failure load corresponding to an infinite number of cycles is far above the reported value of force for cutting rocks under similar geometric conditions in a controlled laboratory experiment.

Figure 43. Optical Photomicrographs Showing the General Fracture Pattern of a Test Specimen

Figure 44. a. Plane-Crack Under an Applied Shear Force and the Crack-Tip Stresses in Rectangular and Polar Coordinate Components

Figure 44. b. Angular Distribution of Crack-Tip Stresses

Figure 45. a. SEM Micrograph Showing the Overall View of the Crack Surface of Specimen No. 8 (24X)

Figure 45. b. SEM Micrograph Showing the Area of the Crack Surface Close to the Edge for Specimen No. 8 (320X)

Figure 45. c. SEM Micrograph Showing the Area in the Back of the Crack Surface for Specimen No. 8 (320X)

Figure 46. a. SEM Micrograph Showing the Crack Slit of Specimen No. 3 (560X)

Figure 46. b. Magnified View of 46(a) (1600X)

Figure 46. c. SEM Micrograph Showing the Crack Slit at the Other Side of Specimen No. 3 (560X)

C. ROCK REMOVAL MODELING

1. INTRODUCTION

One of the first characteristics that was observed in cutting rock specimens with sintered diamond compact tools using an instrumented lathe to measure cutting forces was the reduction in the specific energy with increasing depth of cut (obtained by increasing the thrust force to provide greater penetration of the diamond tool into the rock). As early as August 1972, Livesay and Melaugh at Tulsa University clearly demonstrated that there were significant reductions in rock removal specific energy with increases in penetration force while making helical path cuts turning Carthage Marble. These experiments, performed for General Electric, were the first instrumented rock cutting evaluations of sintered diamond compacts with the specific objective of determining feasibility of applying this material to rock drilling. This relationship has been shown many times since, both within General Electric and by others. The efficiency of rock removal is not only a direct function of penetration force (depth of cut) but, to a lesser degree, also of cutting speed, and indirectly a function of cutter shape and geometry. Livesay and Melaugh, in their early experiments, showed that natural diamond stones, with a roughly spherical shape, were up to 20 times less efficient than circular sintered diamond compacts with relatively sharp cutting edges.

The first sintered diamond compact bit ever constructed, a flat plate design employing 0.320 in. dia. compact cutters attached to cemented tungsten carbide studs at a slight negative rake angle was also tested by Melaugh on the full-scale laboratory drilling rig at Tulsa University for General Electric in March 1973. This bit exhibited the same characteristics as single cutters, i.e., penetration work decreased as bit weight was increased. (Penetration work is expressed as HP-hours per foot of bit penetration. With the use of the appropriate conversion constants, penetration work can be converted to specific energy, which is foot-pounds/cubic inch of rock removed. We shall refer to this as volumetric specific energy.) Figures 47 and 48 are typical examples of the results obtained by Livesay and Melaugh. Note that the specific energy requirements for natural diamond bits are much higher than for sintered diamond compact bits. The natural bit range is from Delinger. (16) Figure 49 is from early work performed by GE CRD using single diamond compact cutters to cut Jack Fork Sandstone. The volumetric specific energy for a given penetration force was higher for this stronger rock material, which was to be expected.

Examination of single-cutter experimental results indicates that the volumetric specific energy is primarily a function of cutter engagement with cutting speed having only a secondary effect. Analysis of actual laboratory full-scale bit drilling tests shows the same trend: increased efficiency with increasing bit weight (for bits with equivalent sharp sintered diamond compact cutters).

Accumulation of volumetric specific energy requirements for particular cutter configurations or particular bit designs in various rock formations can provide useful information for predicting performance and estimating drilling parameter requirements. However, information of this sort is primarily empirical in nature and gives us little insight into the real potential of improved cutter materials and designs for increasing drilling performance. In addition, it provides no means to relate rock cutting performance to rock properties or environmental conditions that may significantly modify rock properties in ways that increase ease of drilling.

The explanation for the reduction in volumetric specific energy with increasing cutter engagement is relatively obvious, the rock is being removed in larger pieces. Simple visual examination of the cuttings produced by single point tools in the laboratory confirms this, as do Melaugh's early drilling tests where the rock chip size distributions for the larger particle fractions were determined. In addition, comparison of the maximum size rock chips produced by both a diamond compact bit and natural diamond bits dramatically showed the reason for the increased rock drilling efficiency of the diamond compact bit.

Fundamentally, creating rock chips is a process of creating surfaces. The smaller the particle size the greater is the surface area generated. For brittle materials such as rocks the total fracture energy should be proportional to the surface area generated if all the energy is consumed in creating new surface. The specific fracture surface energy (energy per unit fracture area) should then be approximately equal to twice the surface energy, $\gamma_s = 1.3 \times 10^3$ for quartz, 1.2×10^3 for fused silica, 2.8×10^3 for mica and 5×10^3 for MgO. Measurements of the force per unit area required to extend cracks in these materials agree generally with the computed values. Discussions of environmental effects in the determination of surface energies by cleavage experiments (e.g., in mica) have been presented by Bowden and Tabor.(17)

Experiments in comminution of brittle materials have been performed in which the work of comminution has been measured (see, for example, Bikerman,(18) Martin,(19) or Fairs,(20) and compared to the surface area generated. The ratio of work to surface area created was essentially constant, the value depending upon the material ground (this is sometimes referred to as "Rittinger's Law"). Conversion

of the comminution work to energy yielded surface energy values which were obviously several orders of magnitude too high. It was concluded that the bulk of the mechanical energy input in the grinding process (probably $\gg 90\%$) was converted to heat. The efficiency of the rock cutting process using sintered diamond compacts should be much greater than the comminution process (as well as demonstrably more efficient than the predominantly crushing action of natural diamonds) because of the more favorable tool geometry and mechanical properties of the compacts. Consequently, the fraction of mechanical energy used to fracture the rock should be much larger than in comminution and that portion ultimately converted to heat through friction, relaxation of elastic deformation and plastic deformation processes, as well as the energy consumed in acceleration of rock fragments, should be significantly reduced.

Figure 47. Effect of Rake Angle on Rock Removal Efficiency

Figure 48. Specific Energy as a Function of Penetration Force in Drilling Carthage Marble.

Figure 49. Penetration Work as a Function of Bit Weight

2. EXPERIMENTAL APPROACH

In this program, an experiment was designed with the particular objective of measuring the energy per unit area of rock surface created for several rock types while cutting these materials with sintered diamond compact tools. If this experimental value approached the magnitude of the specific energies for brittle materials predicted by Lawn and Wilshaw it would provide us with a better feel for the present level of diamond compact rock cutting efficiency and the potential for further improvement. In addition, if the experimentally determined values were essentially constant for each particular rock type but differed significantly for different rocks, we should have a less empirical measurement which represents drillability as related to rock properties rather than to drilling system and process parameters.

The experimental procedure used was the following:

1. Rock specimens were cut (in a turning mode) using Product No. 1575 diamond compact cutters (straight edge, 0.100 in. wide). The back rake was -15° and the feed was 0.152 in. This produced a helical groove in the workpiece. All cuts were made dry, and the cuttings were retained in a large plastic bag which encased the workpiece, tool and toolholder, and lathe chuck. The cutting speed was varied by approximately an order of magnitude for two of the rocks cut and the depth of cut was varied by a factor of ~ 5 for three rocks. Cutting and thrust forces were measured using the same dynamometer described earlier in this report.
2. The rock fragments were screened, using a set of 14 sieves, ranging from 1/2 in. to 400 mesh (U.S. Standard). The weight of each rock particle fraction was measured. The rock particles were inspected using a microscope to determine the general shapes produced, in order to obtain a more accurate estimate of the surface area generated than would be obtained assuming spherical particles. The particles were classified as either roughly cubic or flat, disk shaped. The relative proportion of cubes to disks was estimated for each sieve size and the volume and surface area for each sieve size was calculated using a simple computer program. The sum of the surface areas for all sieve sizes gave the total surface area generated for a particular cutting test.
3. Using the information obtained from the cutting force measurements and the rock particle size analysis, the volumetric specific energy, the area specific energy, and the specific area (area-to-volume ratio) were calculated.

Tables 28 and 29 show the detailed results of the experiment cutting Champlain Black Marble. Table 28 contains the force measurements and calculated rock volume and surface area data together with the experimental cutting conditions. Table 29 shows the calculated values for the volume and surface area specific energies, as well as the specific area results obtained.

An identical experiment was carried out cutting White Danby Marble, except the depths of cut ranged from 0.021 to 0.101 in. In addition, similar tests were performed cutting Jack Fork Sandstone and Belmont Rose Granite, although only one cutting speed was used for each of these cases. The same trends for specific area and volumetric specific energy were obtained. The values for the area specific energy were essentially constant for each rock, but the magnitudes were different from rock type to rock type. This was the result anticipated. Table 30 lists the experimentally determined average value for the area specific energy in each case.

Table 28
EXPERIMENTAL DATA CUTTING CHAMPLAIN BLACK MARBLE

Test No.	Cutting Speed (sfm)	Actual Depth of Cut (in.)	Cutting Time (min)	Thrust Force (lb)	Cutting Force (lb)	Weight of Rock Cut (g)	Volume of Rock Cut		Surface Area Generated	
							(in ³)	(cm ³)	(in ²)	(cm ²)
1	32	0.009	1.05	60	63	19.4	0.438	7.185	673	4340
2	33	0.019	1.03	95	90	41.8	0.945	15.48	888	5730
3	34	0.050	1.05	120	150	132.9	3.00	49.22	1392	8986
4	92	0.018	0.38	90	90	62.1	1.404	23.0	1578	10,179
5	92	0.048	0.37	110	130	121.1	2.737	44.85	1250	8064
6	301	0.008	0.12	50	45	11.0	0.248	4.07	460	2965
7	300	0.020	0.12	75	80	41.1	0.929	15.22	877	5657
8	300	0.042	0.12	90	110	114.2	2.581	42.30	1426	9200

Table 29

ENERGY/AREA RELATIONSHIPS IN CUTTING CHAMPLAIN BLACK MARBLE

Test No.	Total Energy Input			Depth of Cut	Specific Area		Volumetric Specific Energy		Area Specific Energy	
	(ft-lb)	(ergs) $\times 10^7$	(cal.)		(in ⁻¹)	(cm ⁻¹)	$\left(\frac{\text{ft-lb}}{\text{in}^3}\right)$	$\left(\frac{\text{ergs}}{\text{cm}^3}\right)$	$\left(\frac{\text{ft-lb}}{\text{in}^2}\right)$	$\left(\frac{\text{ergs}}{\text{cm}^2}\right) \times 10^6$
1	2117	2870	686	0.009	1537	604	4833	3994	3.15	6.61
2	3059	4147	991	0.019	940	370	3237	2679	3.44	7.23
3	5355	7260	1734	0.050	464	183	1785	1475	3.85	8.08
4	3146	4265	1019	0.018	1124	443	2241	1854	1.99	4.19
5	4425	6000	1433	0.048	457	180	1617	1338	3.67	7.44
6	1625	2203	526	0.008	1855	729	6552	5413	3.53	7.43
7	2880	3905	933	0.020	944	372	3100	2566	3.28	6.90
8	3960	5369	1282	0.042	552	217	1534	1269	2.78	5.84
Ave. all tests:									3.21	6.72
Ave. without test 4:									3.39	7.08

Table 30

EXPERIMENTAL AREA SPECIFIC ENERGIES FOR FOUR ROCK TYPES

Rock Type	Elastic Modulus in Compression (psi) $\times 10^6$	Shore Hardness	Ave. Area Specific Energy	
			$\left(\frac{\text{ft-lb}}{\text{in}^2}\right)$	$\left(\frac{\text{ergs}}{\text{cm}^2}\right) \times 10^6$
White Danby Marble	4.43	33	1.59	3.34
Champlain Black Marble	7.73	49	3.39	7.08
Jack Fork Sandstone	6.16	86	3.68	7.74
Belmont Rose Granite	8.98	97	4.71	9.89

3. DISCUSSION OF EXPERIMENTAL RESULTS

It can be seen from examination of the calculated values for specific area (ratio of surface area to volume) in Table 29 that the average rock particle size increases with increasing depth of cut. This is experimental verification of earlier visual observations in tests at CRD, and explains the reduction in volumetric specific drilling energy with increasing bit weight. The specific area values do not change significantly with cutting speed (at equivalent depths of cut) indicating that this independent controllable variable does not play a major role in the rock fracture process. Examination of the calculated values of specific area for all four rocks tested reveals that there is no marked difference between values obtained at similar depths of cut, which indicates that the rock particle size and shape distribution for all the rock types is the same under equivalent cutting conditions. This is also illustrated in Figure 50, which shows the specific area data points plotted against depth of cut without regard to rock type or cutting speed.

The area specific energy values reported in Table 29 are significantly larger (by a factor of 10^3) than the surface energies for very brittle materials ($\sim 10^3$ ergs/cm²) determined by other means. However, they are in the right order of rank, i.e., the smallest value for the weakest rock and the largest value for the strongest. Since the rock types used are brittle materials, it would not be expected that very much energy would be expended in plastic deformation or stored energy. A more logical explanation would lie in the particular method used for determining surface area.

In the experiments reported in Tables 28-30, the surface areas of the -400 mesh rock particle fractions were calculated assuming an average maximum dimension per particle of 37 microns, which is the largest size that could pass through the sieve. If indeed the average particle size for these -400 mesh fractions were as small as 1 microns, the surface area would be increased by a factor of 10^3 . In fact, this would make the surface areas of the -400 mesh fractions so great that the surface area values for all the >400 mesh particles would be insignificant. Also, no account was taken of the effect of the surface roughness of the rock fragments on their area. A surface factor of two would not be unreasonable, and it could even approach six for larger particles.(18)

Nine representative -400 mesh fractions from the four rock types were analyzed for particle size distribution, using a Coulter Counter apparatus. The average particle size was markedly less than 37 microns, but not as small as 1 micron. Analysis of these data indicated an increase in surface area as great as 10^2 . Program

priorities and objectives did not permit further re-examination of all the -400 mesh samples and recalculation of the area surface energies. However, it is significant that the more accurate surface area values did not indicate a change in the essential results of the experiment. The experimentally determined area surface energy values would still be constant for each rock type, only the magnitude would change, and that in a direction closer to the expected value. The effect upon specific area should also be the same.

The ultimate usefulness of these results will lie in the degree to which specific energy values can be correlated with rock properties measured by techniques other than cutting or drilling. A very preliminary start in this direction was explored. Figure 51 shows the relationship between the experimentally determined area specific energy and the best values available for the elastic modulus in compression for the four rock types tested. A similar relationship holds for Shore Hardness, which is not surprising since the rebound hardness must be related to the elastic modulus.

Figure 50. Specific Area as a Function of Depth of Cut

Figure 51. Correlation Between Area Specific Energy in Cutting and Elastic Modulus in Compression

4. CONCLUSIONS

The experimental determination of an energy value related to surface energy (or fracture surface energy) for rocks, which is specific for each particular rock type and is independent of rock cutting conditions such as speed and depth of cut (i.e., thrust force or bit weight), is a valuable first step towards developing improved (less empirical) methods for rock removal systems based on rock properties and tool geometry. Experimentally determined area surface energies, calculated using more accurate surface area values, should be closer to the theoretical surface energy for brittle materials than those determined by others and, furthermore, will still be specific for particular rock types. The magnitudes of the area surface energies indicate that the sintered diamond compact cutting edge is an efficient rock fracturing device in comparison to a comminution process.

The experiments described here were performed using only one cutter size and geometry, a 0.100 in. wide sharp straight edge sintered diamond compact with a -15° back rake. A change in tool edge shape, degree of sharpness, and rake angle would change the stress field in the rock being cut, and consequently, unlike cutting parameters such as speed or depth of cut, effect change in the experimentally determined area specific energy. In a similar manner, the effects of fluids containing surface active constituents which modify rock fracture properties might be investigated successfully by the technique described. However, further experimentation beyond correcting the surface area measurement and recalculating the specific energy and specific area values was outside the scope of the present bit development program. Additional work of this type would require a separate, more fundamentally oriented program.

D. PRELIMINARY BIT DESIGN AND CONSTRUCTION

1. BIT DESIGN

Two bits were designed, constructed, and subsequently tested in the Tulsa University Drilling Laboratory. These bits, which were designated "'B'" and "'D,'" differed essentially only in the diamond compact cutter distribution on the bit face. Major emphasis will be placed first on the design rationale for Bit B, and the significant differences in design concepts for Bit D will be discussed later.

As a first step in the development of an improved bit for geothermal drilling, the information obtained from the single-cutter and wear rate experiments was used to determine the shape, cutter attack angle, and number and distribution of diamond compact cutters for an 8-3/4-in. dia. bit. It should be kept in mind, however, that even the optimum bit cutter design (assuming an optimum design can be identified) is only a partial solution to the problem. Efficient introduction of drilling fluids (mud, air, or air/water) into the cutting zone for adequate bit face cleaning and cooling must ultimately be considered, and this hydraulic system must be compatible with the diamond compact cutter design. Also, the harsh environments of geothermal formations place strenuous performance demands on all the materials making up the bit, as well as perhaps requiring new and novel manufacturing techniques to produce a product with the overall structural integrity necessary to attain the goals of increased penetration rates, longer bit lives, and reduced drilling costs. Solutions to all of these technical problems were being vigorously pursued, both within the General Electric Company and by other laboratories and manufacturers in the energy technology sphere at the same time this program was underway.

Because the successful down-hole performance of a new bit requires the right combination of all the above ingredients, and because the immediate specific objective of our program at the time was to determine if the performance of a diamond compact drag bit could be "'built in'" by design concepts developed through single-cutter rock cutting experimental data, these first bits were assembled for laboratory evaluation only. Materials and manufacturing techniques used for successful laboratory and oil/gas field tests were employed in bit construction. Thus, major emphasis was placed upon the diamond compact cutter distribution design to be tested in the relatively undemanding and controlled conditions of a full-scale drilling laboratory.

Any new bit must start with some basic design criteria, plus some specific performance objectives and operating parameters. The utilization of diamond compact

cutters, which remove material in a mode in which shear and gross fracture predominate over crushing and fracture, was new and unique enough that there were no established criteria on which to base bit designs. Three criteria were proposed which seemed reasonable (there are probably more). These are:

1. equal rock volume or equal rock area removal per cutter,
2. equal wear rate per cutter, and
3. equal power expended per cutter to remove the rock (equal horsepower per cutter).

The first criterion was under investigation by another laboratory, and a computer program was being developed to specify the diamond compact cutter locations to meet this objective. The second criterion may be the ultimate answer since it infers that the bit designed in this way will last until everything wears out simultaneously (no weak links). However, our observations on diamond compact wear, as noted earlier in this report, showed that, for abrasive conditions, wear rate expressed as diamond wear volume per unit of time increases with speed.*

Until we have more complete information on the relationship of wear mechanisms with speed, temperature, forces acting on the sliding interfaces, etc., it is not probable that a drag bit configuration can be designed in which the outer diamond compact cutters will not wear out first.

Therefore, the single-cutter experimental results obtained cutting Champlain Black Marble with straight edge tools were used to assist in determining the number and distribution of diamond compacts for a bit based on the third criterion, equal horsepower per cutter.

The specific objective was a bit that would drill at a penetration rate of 25 ft/hr at a rotary speed of 100 rpm in a formation of ~20 ksi compressive strength. This relatively low rotary speed is in line with conventional geothermal drilling practice where higher speeds lead to excessive bit wear. The bit diameter chosen was 8-3/4 in., which is typical for the lower sections of geothermal wells.

A value of -15° was chosen for the cutter back rake because the results of the single-cutter experiments indicated this was close to the optimum for minimizing forces acting on the diamond compacts in the speed range they would operate. The maximum cutting speed at the periphery of the bit was 229 sfm at 100 rpm. The dia-

Experimental investigations conducted by General Electric CRD subsequent to the work described in this report have demonstrated that the volumetric wear of polycrystalline diamond compacts cutting a rock is proportional to the length of cut and independent of speed, providing that there is no change in wear mechanism due to increased frictional heat with increasing speed. The exponential relationship shown in Figure 35 of this report is due to changes in the wear mechanism resulting from this thermal degradation at high speeds.

mond compact cutter shape chosen was the straight edge, for several reasons. First, since the design penetration rate was 25 ft/hr, the maximum depth of cut for a single cutter would be 0.050 in. at 100 rpm. This permitted the cutter standoff from the bit body to be reduced to 0.250 in. from 0.500 in. by using 180° (semicircular) diamond compacts (Product No. 2525 STRATAPAX^R Drill Blanks), straight edge down, and still have sufficient space to remove the cuttings. The reduced standoff would provide added strength to the bit. Secondly, essentially complete bottom hole coverage would be obtained at all depths of penetration of the cutters (i.e., over a range of bit penetration rates), which would greatly simplify the analysis of actual performance in the subsequent full-scale laboratory drilling tests. Finally, the cross-sectional area of rock cut by a straight edge cutter is a linear function of the depth cut within the design limits. This simplified the calculations necessary to determine the number of equally spaced cutters required at any given radial position on the bit face in order to equalize the horsepower/cutter values. The bit crown profile chosen (see Figure 52) was similar to prior experimental diamond compact drag bits that had performed successfully. It was also similar to the profile of natural diamond bits used in medium hard formations and was thought to be a reasonable starting point for a geothermal bit design.

Using the equations generated by the STATPAC program to predict the values of the resultant force vectors for straight edge diamond compacts cutting Champlain Black (compressive strength ~20 ksi) Marble, a simple computer program was written to calculate the horsepower for -15° back rake cutters as a function of cutter engagement depth and radial position on the bit face, for a bit rotating at 100 rpm. An example of this information is shown graphically in Figure 53. Next, a position was chosen fairly close to the center of the bit face and the number of cutters operating at this radius arbitrarily chosen (available space and nozzle placement requirements had some bearing on this decision). This starting position is shown as radius No. 3 in Figure 54, which is a crosssection through the bit showing the radial locations of concentric circles of diamond compact cutters. Knowing the number of cutters, the depth-of-cut for each cutter was determined (in this case it was 0.025 in.) and the horsepower level obtained. This was the desired horsepower for all the remaining compacts on the bit. At each succeeding radial-position (from 4 through 10) the cutter speed was calculated, and using the information shown in Figure 53 the depth-of-cut per cutter was determined for the prescribed horsepower. Since the sum of the depths of cut of all the cutters on any given circle must add up to 0.050 in., the number of diamond compacts at each radial position was easily determined.

The hp/cutter values shown on Figure 54 were not all exactly 0.419 (the chosen value) because fractional numbers of cutters could not be used where the design calculations called for them. Also, the three innermost compacts operate at significantly lower horsepower because the cutting speed on this portion of the bit is very low. Figure 55 is a sketch of the bit face, with the locations of each cutter indicated. Note the equal spacing of cutters at each radial location.

Again using the equations generated by the STATPAC program, a computer program was written to calculate the thrust force for straight edge cutters, as a function of cutting speed and depth of cut. Knowing this information (F_T on Figure 56), it was a simple matter to calculate the vertical force (F_V) on each cutter. The sum of all the vertical forces was the design bit weight (neglecting hydraulic lift-off forces) to obtain 25 ft/hr penetration rate at 100 rpm.

The designed locations of the cutters (see Figure 55) for Bit B did not seem to be optimum with respect to bit face and cutter cleaning. In some regions the drilling fluids might have a relatively tortuous path to follow to provide adequate cooling and removal of rock chips. Therefore, the second bit (Bit D) was designed with improved cutter cleaning in mind. Using the same bit body profile, again with 10 radial locations for the diamond compact cutters, the cutters were positioned in straight lines on 12 equally spaced radii (30° apart). This preliminary cutter layout is shown in Figure 57. Note that this initial design called for six nozzles, located as close to the center of the bit as possible.

The final bit designs are shown in Figures 58 and 59, which are the working drawings. Figure 60 shows the cemented carbide stud design used. Significant rearrangement of the cutter locations was necessary for Bit B in order to avoid interference of adjacent studs (note regions marked with dotted lines on Figure 55) and to accommodate the necessary nozzles. Two diamond cutters had to be eliminated (one in radial location (3) and one in radial location (9) leaving a total of 53. In addition, the equal angular separation of cutters at each radial location could not be maintained for locations (2), (3), (5), and (6). However, these necessary changes did not markedly affect the principal design objective: equal horsepower per cutter at the designed drilling condition, 100 rpm, 25 ft/hr penetration rate. Table 31 gives the predicted values for hp/cutter, thrust force/cutter, and torque/cutter for the initial design and the actual constructed design for Bit B.

In contrast to Bit B, actual construction of Bit D required very few changes from the original design layout. The number of nozzles was reduced from six to four, and the angular separation of the cutters at radial location (2) was changed a few degrees to accommodate the central nozzle. The predicted values for hp, thrust,

and torque for Bit D are given in Table 32.

The final design for both bits included gage cutters, nine for Bit B and six for Bit D, to provide gage wear protection since this type of wear is frequently a significant factor in reducing effectiveness in geothermal drilling operations. The gage cutters were Product No. 2525 STRATAPAX^R drill blanks, at -15° rake, attached to the same cemented carbide stud design as used for the bit face cutters. The concept of using diamond compacts to reduce gage wear is valid. However, the particular design adopted for these experimental bits was poor, and corrective measures were necessary during full-scale laboratory drilling tests. This is discussed later in this report.

Table 31
PREDICTED VALUES FOR HP, THRUST, AND TORQUE FOR BIT B
AS DESIGNED AND AS CONSTRUCTED

Radial Location	ORIGINAL LAYOUT No. of Cutters	CONSTRUCTED LAYOUT No. of Cutters	ORIGINAL LAYOUT			CONSTRUCTED LAYOUT		
			HP/Cutter	Thrust/Cutter (lb)	Torque/Cutter (ft-lb)	HP/Cutter	Thrust/Cutter (lb)	Torque/Cutter (ft-lb)
1	1	1	0.117	215.8	6.16	0.117	215.8	6.16
2	2	1	0.210	176.9	11.8	0.205	172.1	11.4
2		1				0.231	180.9	12.2
3	2	1	0.419	223.0	21.3	0.320	188.4	16.8
3		1				0.466	250.9	24.5
4	4	3	0.367	171.9	20.0	0.457	192.9	24.0
5	5	1	0.398	132.2	20.4	0.533	160.2	28.0
5		2				0.364	127.3	19.1
5		2				0.332	120.5	17.4
6	6	3	0.419	125.1	21.9	0.494	138.5	25.9
6		3				0.390	120.4	20.4
7	8	8	0.419	114.9	21.8	0.415	114.9	21.8
8	9	9	0.403	85.9	21.1	0.401	85.9	21.1
9	10	9	0.419	83.6	22.1	0.435	85.4	17.0
10	9	9	0.416	56.1	21.9	0.416	56.1	21.9
Total	56	54	22.2	6148	1167	21.9	5985	1097

Table 32

PREDICTED VALUES FOR HP, THRUST, AND TORQUE FOR BIT D
AS DESIGNED AND AS CONSTRUCTED

Radial Location	ORIGINAL LAYOUT No. of Cutters	CONSTRUCTED LAYOUT No. of Cutters	ORIGINAL LAYOUT			CONSTRUCTED LAYOUT		
			HP/Cutter	Thrust/Cutter (lb)	Torque/Cutter (ft-lb)	HP/Cutter	Thrust/Cutter (lb)	Torque/Cutter (ft-lb)
1	1	1	0.117	215.8	6.16	0.117	215.8	6.16
2	1	1	0.261	199.0	13.7	0.238	184.7	12.5
2	1	1	0.175	150.5	9.21	0.209	168.3	11.0
3	3	3	0.320	188.4	16.8	0.320	188.4	16.8
4	3	3	0.457	192.9	24.0	0.457	192.9	24.0
5	3	3	0.535	160.6	28.1	0.535	160.6	28.1
6	3	3	0.532	144.9	27.9	0.532	144.9	27.9
6	3	3	0.298	102.6	15.7	0.298	102.6	15.7
7	3	3	0.621	146.5	32.6	0.621	146.5	32.6
7	3	3	0.346	102.9	18.2	0.346	102.9	18.2
8	3	3	0.616	111.4	34.4	0.616	111.4	34.4
8	3	3	0.358	80.1	18.8	0.358	80.1	18.8
9	3	3	0.679	112.1	35.7	0.679	112.1	35.7
9	3	3	0.392	80.1	20.6	0.392	80.1	20.6
10	3	3	0.601	70.4	31.6	0.601	70.4	31.6
10	3	3	0.380	53.0	20.0	0.380	53.0	20.0
Total	42	42	19.0	5203	996	19.0	5208	996

95%

Figure 52. Experimental Bit Profile (Bits B and D)

-15° BACK RAKE, STRAIGHT EDGE, CHAMPLAIN BLACK

Figure 53. Predicted Design Horsepower per Cutter Requirements as a Function of Cutter Placement and Rock Engagement

Figure 54. Specifications for Number and Location of Cutters for 8-3/4-inch Bit (Bit B)

Figure 55. Original Layout of Cutters for Bit B

Figure 56. Predicted Bit Weight for 8-3/4-inch Bit to Obtain 25 ft/hr Penetration Rate at 100 RPM. (Bit B)

Figure 57. Original Layout of Cutters for Bit D

Figure 58. Final Design for Bit B

Figure 60. Cemented Carbide Stud Design

2. BIT CONSTRUCTION

The experimental bits were constructed under a subcontract to Carboloy Systems Business Department, General Electric Company, Detroit, Michigan. The cemented tungsten carbide studs and nozzle inserts were Carboloy Grade 55B. The STRATAPAX^R drill blanks were induction-brazed to the studs using Handy Harmon Easy Flow 45 silver-copper base brazing alloy and the appropriate recommended flux. This work was done at Carboloy's Detroit facility. The bit bodies were machined from AISI 4340 steel. All machining, plus attachment of the cutters by interference fit pressing into the bit bodies was done at the Cleveland Machine Co., Cleveland, Texas. After assembly and inspection the bits were shipped directly to Tulsa University for full-scale laboratory testing.

Figures 61 through 64 are photographs of Bits B and D. These photographs were taken after completion of laboratory drilling experiments described in the next section of this report. The strap shown in Figures 63 and 64 was welded around the gage section of Bit D at the Tulsa University Drilling Laboratory for reasons that are explained later.

Figure 61. Photograph of Bit B

Figure 62. Top View of Bit B

Figure 63. Photograph of Bit D

Figure 64. Top View of Bit D

E. INSTRUMENTED LABORATORY TESTING OF COMPAX^R DIAMOND COMPACT BITS

1. INTRODUCTION

The two 8-3/4 in. dia. STRATAPAX^R blank bits described in the preceding section of this report were taken to the University of Tulsa and tested using the Petroleum Engineering Department's full-size laboratory drilling apparatus. The major objectives of these experiments were: (1) to determine the relationships between drilling variables such as bit weight, rotational speed, fluid flow, and bit performance indicators such as penetration rate, power requirements, and torque, (2) to obtain a direct comparison between actual performance and that predicted by the results of the instrumented single-cutter experiments run previously, (3) to observe, if possible, the effects of changes in hydraulic conditions on bit performance, and (4) to identify critical design and/or fabrication technique changes necessary before beginning construction of bits targeted for well-bore simulation and field trials.

2. EXPERIMENTAL PROCEDURE

The two rock types were chosen for test: Carthage Marble and Texas Pink Granite. The Carthage Marble was selected because this rock material has been used in the past for many drilling experiments, including tests with experimental sintered diamond compact bits. In addition, Carthage Marble's physical properties lie between those of White Danby and Champlain Black marbles, which were used extensively in the prior instrumented single-cutter experiments. It was anticipated that if the bit design criteria based on the predictive capability of the instrumented single-cutter results were valid, then the performance of the experimental bits drilling Carthage Marble (such as rate of penetration, torque, and horsepower) should fall between the predicted performance of these bits drilling Champlain Black and White Danby Marble. A comparison of properties for these three rocks is given in Table 33.

Texas Pink Graphite was chosen as the other test rock because of its extreme toughness and abrasiveness, particularly in "drag" bit drilling applications. Single-cutter experiments using sintered diamond compacts performed by the Drilling Projects Division, Sandia Laboratories, had demonstrated that this rock type, with its large quartzite crystallites, was a rigorous test material producing accelerated cutter wear and providing a severe test of diamond compact-support assembly strength. It was thought that drilling Texas Pink Granite would reveal any serious deficiencies in experimental bit structural strength. As will be shown by the drilling test results, this turned out to be true.

All drilling in the laboratory was done using water as the drilling fluid. The Tulsa University facility was not equipped to handle drilling muds as a matter of course. The nozzles used in both the bits tested were all 14's (14/32 in. dia.). Table 34 lists the ranges of independent conditions used for the tests performed.

The bits were run at each operating condition only long enough to establish equilibrium. All data were recorded on a multichannel recorder. This information included (1) depth drilled (as a function of time), (2) rpm, (3) weight on bit, (4) torque, (5) flow rate, and (6) pressure drop across the bit. The instantaneous penetration rate and the horsepower were calculated later. Bit B was tested first drilling Carthage Marble followed by Texas Pink Granite. Instability problems prompted a modification of the gage of Bit D, which was done at Tulsa University, and then this bit was tested drilling Carthage Marble.

Table 33

PHYSICAL PROPERTIES OF ROCKS MEASURED BY CRD, GE COMPANY

<u>Rock Type</u>	<u>Uniaxial Compressive Strength (ksi)</u>	<u>Modulus of Elasticity in Compression (psi x 10⁶)</u>	<u>Shore Hardness</u>
White Danby Marble	7.89	4.43	33
Carthage	13.46	6.60	40
Champlain Black Marble	21.3	7.73	49

Table 34

FULL-SCALE DRILLING TEST CONDITIONS

<u>Bit</u>	<u>Rock</u>	<u>Bit Weight Range (lbs.)</u>	<u>R. P. M. Range</u>	<u>Flow Rate Range (gpm)</u>
B	Carthage Marble	3000 - 5000	50 - 200	220 - 432
B	Texas Pink Granite	10,000 - 25,000	100	432
D	Carthage Marble	2500 - 10,000	50-200	220 - 432

3. EXPERIMENTAL RESULTS AND DISCUSSION

The drilling test results for Bit B are given in Table 35, which includes the calculated penetration rates and horsepower values as well as the information taken directly from the multichannel recorder charts. The tests were run in the order given in the table. The distance drilled and the time values represent the portions of the depth traces on the charts where the slope was constant and could be used to calculate penetration rate. The total depth drilled and drilling time for each data point were much greater than these values.

Bit B generated a great deal of vibration drilling Carthage Marble, particularly at the highest speed and bit weight used. This instability limited the weight on bit to a maximum of 5000-lb. An early test at 200 rpm, 5000-lb bit weight could not be repeated due to excessive lateral instability. The test was terminated when the side thrust was so great that it moved the large block of Carthage Marble. Examination of the hole showed that the diameter was significantly enlarged in local areas due to the cutting action of the gage compacts. These gage cutters are clearly shown in Figure 62. Since the bit could not be followed by an effective stabilizer (the maximum hole depth in the rock was only 30 in.), there was nothing to restrict lateral movement of the bit. Any sideways motion would result in lateral rock cutting by the gage compacts, thus increasing the instability.

Bit B drilled the very tough Texas Pink Granite effectively until a diamond compact cutter was lost. Unfortunately, the cutter lost was the one cutting the center of the hole. This cutter had no back-up, so its cemented carbide stud then proceeded to act as a bearing surface. Figure 65 is a photograph of this stud after completion of all the tests on Texas Pink Granite. Note the large amount of wear produced by rubbing against the granite. The lost diamond compact was recovered by screening the rock chips retained by the shale shaker. Figure 66 shows the very poor braze attachment which resulted from the bonding procedure in use at the time these bits were made. Apparently, a large amount of flux was trapped at the compact-support interface, markedly reducing the actual area brazed. In addition, the braze layer was too thick. This failure clearly demonstrated the need for improved attachment techniques, which have subsequently been developed in separate Company-sponsored programs.

Bit D was constructed with similar gage wear protection cutters. Like Bit B, no gage bearing surfaces were provided for stability, so it was evident that this bit would have to be modified before testing. The solution used is shown in Figure 63. A steel strap was formed and welded to the bit body to provide a gage bear-

ing surface. Even after this modification, some slight instability was still observed, and careful examination of the bit revealed that two of the cutters extended very slightly past the steel gage strap but not more than 0.030 in. Even this slight cutting action was sufficient to promote some sideways instability, so the cutters were de-brazed (as shown in Figure 63). All subsequent tests ran very smoothly.

Bit D was only tested in Carthage Marble. Again, a cutter was lost due to a poor braze attachment, but this cutter was in the crown area of the bit, where it was backed up by two others. Therefore, the bit continued to function satisfactorily. The experimental test results for Bit D are summarized in Table 36. The tests were run in the order given in the table.

Figures 67 and 68 are plots of some of the experimentally determined penetration rates and torques vs. bit weight for Bit B drilling Carthage Marble. Figure 69 shows the relationship between horsepower and instantaneous penetration rate. All the results are shown as the best straight line fits to the experimental data.

The bit weight necessary to obtain a penetration rate of 25 ft/hr at 100 rpm, as shown on Figure 67, was about 5500 lb. This was less than the design bit weight of 5985 lb (for Champlain Black Marble), as it should have been, since Carthage Marble has a lower compressive strength and hardness than Champlain Black. There was a noticeable effect of flow rate upon penetration rate at 50 rpm for equivalent bit weights. Some of the difference may have been due to hydraulic liftoff at the higher flow rate. Torque was also affected by flow rate, as shown in Figure 68, but there was no noticeable change in the horsepower to rotate the bit (see Figure 69).

Figures 70, 71, 72, 73, and 74 show both the experimental results drilling Carthage Marble and the predicted values for penetration rate, torque, and horsepower drilling Champlain Black and White Danby Marble. As anticipated, the predicted penetration rates bracket the experimental values. The experimental torque for Bit B at 220 gpm flow rate falls where expected but the 432 gpm data does not. Experimentally determined horsepower is within the predicted region above about 18 ft/hr penetration rate.

In a similar manner, Figures 75 through 82 are curves for Bit D, showing the relationships between penetration rate, torque and bit weight, and the relationship between horsepower and penetration rate. As with Bit B, the penetration rate was greater at 220 gpm flow rate than 432 gpm for any given value of bit weight (see Figures 75 and 76), but the effect of changing the flow was not as pronounced. The same effect of flow rate on torque was also observed (see Figures 77 and 78). In addition, horsepower was essentially independent of the flow rate over the range

tested. Figure 79 is a composite plot of all horsepower data at 220 and 432 gpm.

The experimental values for penetration rate were bracketed by the predicted values for Champlain Black and White Danby Marble, as anticipated (see, for example, Figure 80). In a similar manner, as shown in Figures 81 and 82, the experimentally determined horsepower and torque results were close to the ranges expected.

Bit D was slightly more aggressive than Bit B with respect to the bit weights necessary to obtain the same penetration rates, and torque values for Bit D were somewhat lower. This may have been due to the fact that Bit D had fewer diamond compact cutters and thus attained greater localized stresses to penetrate and fracture the rock than Bit B for a given weight on bit. However, the mechanical horsepower necessary to obtain a given penetration rate was not significantly different for the two bits. At 200 rpm the horsepower-penetration rate relationship was almost identical for both bits.

The full-scale laboratory drilling tests did not show clearly that bit face cleaning was superior for either design. Examination of the horsepower-penetration rate relationships indicated that flow rates below 220 gpm would probably have been satisfactory to remove the cuttings for the laboratory test conditions used, although a lower flow rate would not be realistic in the field where other requirements are paramount.

The reason for the significant difference in the pressure drops across the bits at 432 gpm flow rate (750 psi for Bit B compared to 525-550 psi for Bit D) is not clear. It is probably related to nozzle positioning. One of the nozzles in Bit B may have been operating in a partially clogged condition.

Table 35

FULL-SCALE LABORATORY DRILLING TEST RESULTS FOR BIT B

Rock	Rotational Speed (rpm)	Bit Weight (lb)	Flow Rate (gpm)	Pressure Drop (psi)	Torque (ft-lb)	Distance Drilled (in)	Time (sec)	<u>Calculated</u>	
								ROP (ft/hr)	Power (hp)
Carthage	200	3000	432	750	250	1	45	6.7	9.5
	200	5000	432	750	650	4	33	36.4	24.8
	50	3300	220	150	500	2	55	10.9	4.8
	50	4200	220	150	900	1.5	30	15	8.6
	50	5000	220	150	1200	5	75	20	11.4
	50	3000	432	750	300	1	60	5.0	2.9
	50	4000	432	750	500	1	40	7.5	4.8
	50	5000	432	750	700	3	63	14.3	6.7
	100	3000	432	750	300	2	75	8	5.7
	100	4000	432	750	450	2	35	17.1	8.6
	100	5000	432	750	650	5	70	21.4	12.4
	200	3000	432	750	250	2	75	8	9.5
	200	4000	432	750	400	3	40	22.5	15.2
	200	5000	- Not able to run, bit unstable						
Texas Pink	100	10,000	432	750	825	0.3	35	2.6	15.7
	100	15,000*	432	750	1350	2	100	6	25.7
	100	20,000	432	750	1500	0.75	80	2.8	28.6
	100	25,000	432	750	1750	1	65	4.6	33.3

*Rig stalled - lost center cutter.

Table 36

FULL-SCALE LABORATORY TEST RESULTS FOR BIT D DRILLING CARTHAGE MARBLE

Rotational Speed	Bit Wgt.	Flow Rate	Pressure Drop	Torque	Distance Drilled	Time	<u>Calculated</u>	
							ROP	Power
(rpm)	(lb)	(gpm)	(psi)	(ft-lb)	(in)	(sec)	(ft/hr)	(hp)
50	2500	432	525	325	1	70	4.3	3.1
50	5000	432	525	925	2	30	20.0	8.8
50	7500	432	525	1400	3	30	30.0	13.3
50	10,000	432	525	1950	5	30	50.0	18.6
100	2500	432	550	250	1	70	4.3	4.8
100	5000	432	550	750	2	25	24.0	14.3
100	7500	432	550	1350	5.7	30	57.0	25.7
100	10,000	432	550	1800	9	35	77.1	34.3
150	2500	432	525	300	1	30	10.0	8.6
75	2500	432	550	300	1	65	4.6	4.3
75	5000	432	550	850	2	25	24.0	12.1
75	7500	432	550	1350	3	20	45.0	19.3
75	10,000	432	550	1850	7	32.5	64.6	26.4
50	2500	220	125	425	3	195	4.6	4.0
50	5000	220	125	975	5	85	17.6	9.3
50	7500	220	125	1600	4	32	37.5	15.2
50	10,000	220	125	2050	6	35	51.4	19.5
75	2500	220	125	400	2	95	6.3	5.7
75	5000	220	125	900	2	30	20.0	12.9
75	7500	220	125	1500	3.9	25	46.8	21.4
75	10,000	220	125	1950	6.8	30	68.0	27.8
100	2250	220	125	350	2	85	7.1	6.7
100	5000	220	125	850	4	45	26.7	16.2
100	7500	220	125	1400	6	30	60.0	26.7
100	10,000	220	125	1850	8.3	30	83.0	35.2
150	2500	432	525	200	2	140	4.3	5.7
150	5000	432	525	650	4	45	26.7	18.6
150	7500	432	525	1075	3	17.5	51.4	30.7
150	10,000	432	525	1525	7	25	84.0	43.6
200	2500	432	550	225	2	85	7.1	8.6
200	5000	432	550	575	2.5	25	30.1	21.9
200	7500	432	550	1000	4.7	20	70.5	38.1
200	10,000	432	550	1450	9.7	30	97.0	55.2
200	10,000	300	250	1600	8.25	20	123.8	60.9
200	10,000	220	125	1600	7.4	20	111.0	60.9

Figure 65. Cemented Carbide Stud after Loss of Diamond Compact in Texas Pink Granite Test

Figure 66. Evidence of Poor Braze Attachment for Center Diamond Compact/stud. Actual braze regions are the smaller areas which appear recessed in the photograph.

Figure 67. Penetration Rate as a Function of Bit Weight for Bit B Drilling Carthage Marble

Figure 68. Torque as a Function of Bit Weight for Bit B Drilling Carthage Marble

Figure 69. Horsepower vs Penetration Rate for Bit B Drilling Carthage Marble

Figure 70. Comparison of Predicted and Experimental Penetration Rates for Bit B at 50 rpm

Figure 71. Comparison of Predicted and Experimental Penetration Rates for Bit B at 100 rpm

Figure 72. Comparison of Predicted and Experimental Penetration Rates for Bit B at 200 rpm

Figure 73. Comparison of Predicted and Experimental Torque for Bit B at 50 rpm

Figure 74. Comparison of Predicted and Experimental Horsepower for Bit B at 50 rpm

Figure 75. Penetration Rate vs Bit Weight for Bit D Drilling Carthage Marble with 220 gpm Flow Rate

Figure 76. Penetration Rate vs Bit Weight for Bit D Drilling Carthage Marble with 432 gpm Flow Rate

Figure 77. Torque vs Bit Weight for Bit D with 220 gpm Flow Rate

Figure 78. Torque vs Bit Weight for Bit D with 432 gpm Flow Rate

Figure 79. Horsepower vs Penetration Rate for Bit D Drilling Carthage Marble

Figure 80. Comparison of Predicted and Experimental Penetration Rate for Bit D at 100 rpm

Figure 81. Comparison of Predicted and Experimental Torque for Bit D at 50 rpm

Figure 82. Comparison of Predicted and Experimental Horsepower for Bit D at 100 rpm

4. CONCLUSIONS

1. Bit performance at atmospheric pressure can be predicted to a reasonable degree of accuracy from analysis of single-cutter experiments. Conversely, single-cutter experiments can be effectively used to design a bit based on the equal hp/cutter criterion.
2. The lower limit of flow rate for efficient bit face cleaning of a STRATAPAX^R blank bit drilling a brittle (not plastic) formation is probably below that required to carry the rock fragments out of an actual hole in the field. This minimum flow rate may or may not be adequate for diamond compact cutter cooling.
3. Reliable attachment of STRATAPAX^R blanks has been identified as a major technical requirement to be met before a viable STRATAPAX^R blank bit can become a reality. Conventional hand brazing methods will not suffice. Thus, the attachments discussed earlier in this report (see, for example, Table 27), which were actually developed after the Tulsa tests, are of considerable importance.

F. PRESSURIZED, ELEVATED TEMPERATURE, THREE-CUTTER EXPERIMENTS

1. INTRODUCTION

For direct comparison with single-cutter experiments at room temperature and atmospheric pressure, described earlier in this report, and for evaluation of compact-stud attachments, rock-cutting experiments were conducted at increased pressure and elevated temperature. To improve the dynamic stability of the rock-cutting apparatus, a "three-cutter" configuration was chosen instead of a "single-cutter" arrangement. The diamond compact cutters were No. 2530 STRATAPAX^R drill blanks located 120° apart (Figure 83). These were used to cut and enlarge the bore of a pre-bored rock cylinder (Figure 84) in the geothermal test cell at the Drilling Research Laboratories, Terra Tek, Inc., Salt Lake City, Utah. Appropriate modifications of the test cell were required to facilitate the three-cutter tests. The original test plan called for five experiments (one at room temperature, ambient pressure, and the other four under simulated geothermal conditions) on each of two rocks: Jack Fork Sandstone and Sierra White Granite. Unfortunately, of the four Jack Fork Sandstone samples cored, all but one had extensive cracks and internal defects and were not usable. Since Jack Fork Sandstone was one of the rocks used in the previous single-cutter experiments, a single good rock specimen was used to conduct a base line experiment at room temperature and atmospheric pressure, using -15° rake cutters attached to pocketed, cemented carbide studs. This experiment also afforded the opportunity to test the apparatus, which had not been used previously for rock cutting. The remaining nine tests were performed on Sierra White Granite. One of these nine experiments was also conducted at ambient temperature and atmospheric pressure.

Since a primary objective was to test the attachment of the diamond compact to the cemented carbide stud, various bonds were evaluated based on careful consideration of the conditions to be encountered in a geothermal well. In addition to Easy Flo 45, the attachments included diffusion bonding, provided by Sandia Labs, and two additional attachments (identified as "A" and "B" in this report) which exhibited higher shear strengths at 350 °C than Easy Flo 45. The shear strengths of these alloys were discussed earlier in this report in the section on property measurements.

Two series of tests were conducted with an intervening three-week period to allow analysis of test results from the first series before conducting the second. Some of the diffusion-bonded attachments failed in the first series of tests but

none of the brazed cutters failed. Prior to the second set of tests, some of the brazed cutters were intentionally dulled by grinding large wear flats on them (Figure 85). The purpose of these wear flats was to increase the frictional heat generated during cutting and rubbing, thereby providing a more rigorous test of attachment integrity. Unless otherwise stated, all 'three-cutter' tests were conducted at 315 °C, 2000 psi, in a static water environment with the cutters rotating at 100 rpm. About 110 in.³ of rock was bored in each test. Table 37 lists the conditions under which the various geomothermal rock drilling simulation tests were conducted.

Table 37
RESULTS OF THREE-CUTTER TESTS

Test No.	Rock	Cutters		Conditions in the Geothermal Vessel		Test Conditions		Remarks
		Attachment	Back Rake Angle (degrees)	Pressure (psf)	Temperature (°C)	Speed (rpm)	Maximum Bit Weight (lbs)	
1	Jack Fork Sandstone	Easy Flow 45	-15	Atmospheric	Room Temp.	25, 50 & 100	900	Some wear and spalling of the cutters. Braze attachments remained intact.
2	Sierra White Granite	Diffusion Bonding (unpocketed)	-25	2000	315	25 & 100	up to 1200	Some wear and spalling of the cutters. One cutter became detached at the beginning of the test and the other part-way through the test. (Bonding failed).
3	Sierra White Granite	Diffusion Bonding (unpocketed)	-25	2000	315	100	300 (mostly at 100)	Practically no wear. Bonds remained intact.
4	Sierra White Granite	'A'	-15	2000	315	100	850	Some wear and spalling of the cutters. Attachments remained intact.
5	Sierra White Granite	Easy Flow 45	-15	2000	315	100	900	One cutter turned 90 during the test. Attachments remained intact. Some wear and spalling of the cutters.
6	Sierra White Granite	Diffusion Bonding (pocketed)	-15	Atmospheric	Room Temp.	100	1500	The axis of the cutter shaft and that of the prebored rock were offset by more than 1/4 inch due to poor core preparation. This caused chatter and vibration, and reduced the penetration rate.
7	Sierra White Granite	'B'	-15 (with two intentionally dull wear flats by grinding)	2000	315	100	1700	Very little wear. Smooth finish in the bored rock, no vibration. Penetration rates lower than with sharp cutters. Attachments remained intact. Penetration rate was very low up to a minimum bit weight.
8	Sierra White Granite	'A'	-15 (with two intentionally dull wear flats by grinding)	2000	315	100	2000	Very little wear. Smooth finish in the bored rock, no vibration. Penetration rates lower than with sharp cutters. Attachments remained intact. Penetration rate was very low up to a minimum bit weight.
9	Sierra White Granite	Easy Flow 45	-15 (with two intentionally dull wear flats by grinding)	2000	315	100	2300	Very little wear. Smooth finish in the bored rock, no vibration. Penetration rates lower than with sharp cutters. Braze joints remained intact. Penetration rate was very low up to a minimum bit weight.
10	Sierra White Granite	Diffusion Bonding	-25 'sharp'	2000	315	100	1900	Some wear and spalling of the cutters. One cutter became detached near the end of the test. Penetration rates much higher than with dulled cutters. Linear variation of penetration rate with bit weight; absence of minimum threshold weight.

Figure 83. Plan View of 'Three-cutter' Arrangement Showing Diamond Compacts 120° Apart

Figure 84. Schematic of Prebored Rock Cylinder in Geothermal Test Cell

top view

front view

side view

Figure 85. Three Views of Diamond Compact Cutter Showing Intentional Dulling Made by Grinding Large Flats

2. EXPERIMENTAL APPARATUS

The simulated geothermal apparatus consisted of a drilling rig, a geothermal vessel, and associated equipment, power, instrumentation and controls.

Terra Tek's Drilling Research Laboratory drill rig is mounted on rails to enable positioning at various stations for well bore simulation tests, geothermal rock drilling tests, and other experiments. The drilling platform can be located at different heights to accommodate various length tools. This platform contains a drive shaft with a dc power drive to permit continuously variable rotational speed up to 500 rpm and torques up to 5000 ft-lbs. Hydraulic feedback and a servo-controlled power supply enable drilling to be conducted either under constant bit weight or at constant penetration rate.

The geothermal cell was a 16-in. dia. by 60-in. long pressure vessel converted from the muzzle end of a Naval gun barrel. It had an 8-in. inside working diameter and a 24-in. working length. The prebored rocks used in these tests were about 8 in. in outside diameter and 18 in. long. The vessel was equipped with 24 kW heating elements to heat the contents of the vessel up to 315 °C. Thermocouples were provided to measure and monitor the temperature in the vessel and various seals were provided to prevent leakage. Figure 86 is a cross section of the geothermal test cell, showing its salient features.

The Drilling Research Laboratory drill rig is controlled, and all data are collected in an area that can be isolated from the rig proper for safety purposes. This area is shown in Figure 87. For normal wellbore drilling operations all the experimental data from the instrumentation on the rig are collected by a computer, where the necessary calculations are performed to provide a fast printout on a terminal-printer in the control room. This information includes time, bit rotational speed, bit penetration rate, weight-on-bit, torque, mud flow rate, swivel pressure, confining pressure, ram pressure and bore pressure. In addition, bit penetration and bit weight are plotted as a function of time on a two-pen recorder, and fluid flow rate, swivel pressure, bore pressure, torque and bit rpm are recorded on a multichannel strip recorder.

For the geothermal three-cutter experiments described here the computer printout was not needed because the test cell pressure was maintained at a constant 2000 psi and there was no fluid flow. The two-pen recorder was used to record the cutting head travel (penetration) and the force acting normal to the rock surface being cut (bit weight). Torque, bit weight, and penetration were also recorded on the multichannel strip recorder. An example of the data plotted by the two-pen

recorder is shown in Figure 88. This is the actual log of Test 7 described later.

Figure 86. Cross Section of Pressurized, Elevated Temperature, Geothermal Test Cell

Figure 87. Instrumentation Control Panel for Geothermal Test Cell

Figure 88. Typical Log Sheet of Bit Weight and Penetration vs. Cutting Time

3. TEST PROCEDURE

The prebored rock cylinder was first placed inside a steel container "A" (Figure 89). A small gap was purposely provided between the steel container and the rock to accommodate possible effects such as shock and vibration due to slight misalignment between the casing and the rock. This was accomplished by filling the gap with fine sand and four copper wires 90° apart. The cutters were then mounted on their assembly (Figure 90) and placed inside the bottom steel container (Figure 91). The connecting shafts on either side of the cutter assembly were then attached and the top, bottom, and side steel containers were assembled (Figure 92). It was then lowered into the geothermal vessel and the lid of the vessel was closed and the shaft from the cutter assembly connected to the drive shaft by a universal joint. The geothermal vessel was given an additional support by means of spring-controlled chains (Figure 93). About two hours were required for this assembly under ideal conditions.

The pressure vessel was completely filled with water and pumped to a pressure of 2000 psi. The inlet valve was closed, isolating the pressure vessel, and the heaters were activated. The pressure was maintained at 2000psi by bleeding off the increased water volume created by thermal expansion. About two hours were required to heat the geothermal vessel to 315 °C and reach steady-state conditions. During the heating cycle, the instrumentation was calibrated. Each drilling test took between 15 and 60 minutes depending on the penetration rates used. Cooling, depressurizing, and disassembly of the apparatus for examination of the rock and cutters took about two hours. Rock cuttings from the bottom of the steel container were collected and stored for examination. Occasionally, the total time required was lengthened due to replacement and repair of parts. On the average, no more than one test could be conducted in any one drilling day.

Figure 89. Pre-bored Rock Cylinder Inside Steel Container

Figure 90. Three Cutters Mounted on Their Assembly

Figure 91. Three-cutter Assembly in Bottom Steel Container

Figure 92. Assembly of Pre-bored Rock and Cutters in Retainer Case

Figure 93. Pre-bored Rock Cylinder in Geothermal Test Cell Supported by Spring Controlled Chains

4. TEST RESULTS

The test conditions and condensed experimental results are summarized in Table 37. A more detailed description of each test is given below, including observations of any cutter wear and failure. The experimentally determined values for the penetration-bit weight and torque-bit weight relationships, as well as penetration rates, are shown in appropriate graphical form.

a. Test 1

This test was conducted on Jack Fork Sandstone at room temperature and atmospheric pressure, using -15° rake cutters. The STRATAPAX^R diamond compacts were attached to the pocketed, cemented carbide studs using Easy Flow 45 braze. Three cutter speeds (25, 50, and 100 rpm nominal) were used, and the bit weight was increased gradually in 100-lb increments to 800 lb. Figures 94 and 95 show the variation of penetration rate and torque, respectively, with bit weight for the three different speeds. Due to the low bit weight and the fact that Jack Fork is very tough (~ 35 ksi unconfined compressive strength), the penetration rates in this test were rather low (maximum of about 3.5 ft/hr). The penetration rate increased with speed and with bit weight. Some spalling and microchipping of the cutters was observed.

b. Test 2

This test was the first experiment conducted at 315°C , 2000 psi pressure. It was performed on Sierra White Granite, using -25° back rake, diffusion-bonded, unpocketed, sharp cutters. The diffusion-bonded cutters were provided by Sandia Labs. The speed was initially 25 rpm and subsequently increased to 100 rpm. The bit weight was increased in increments of ~ 300 lb up to 1500 lb at 25 rpm and up to 1200 lb at 100 rpm. Figure 96 shows the variation of penetration rate with bit weight at two cutter speeds. Due to higher bit weights and the rock being easier to cut than Jack Fork Sandstone, the penetration rates were higher, especially at higher cutter speeds. At 1200 lb thrust the penetration rate was 15 ft/hr at 25 rpm and 22 ft/hr at 100 rpm. Two of the diffusion bonds failed, one at the start and the other about halfway through the test. The third cutter remained intact and did most of the cutting up to 1500-lb bit weight. Some spalling and microchipping of the cutters was noted.

c. Test 3

A second set of -25° back rake diffusion bonded cutters was tested on Sierra White Granite at 315°C and 2000 psi. The speed was maintained at 100 rpm throughout this experiment. Because two of the diffusion bonds had failed during Test 2, the bit weight was significantly reduced for Test 3. It was anticipated that this would reduce the penetration rate sufficiently to provide enough cutting time to provide a measurable amount of diamond wear. The bit weight was held at 200 to 300 lb for the first 7.5 minutes and then reduced to 100 lb for the remainder of the test. The total cutting time was 60 minutes, and the average penetration rate was 1.21 ft/hr. None of the diffusion bonds failed and the diamond compact cutting edges were not measurably worn, nor were they chipped or spalled. The granite was not abrasive enough to wear the sintered diamond material at the relative slow cutting speed employed.

d. Test 4 and 4A

This experiment was conducted cutting Sierra White Granite at 315°C , 2000 psi using -15° back rake STRATAPAX^R drill blanks attached to the studs with braze alloy "A." Shear strength experiments described earlier in this report showed this alloy produced markedly stronger bonds at elevated temperatures than the Easy Flo 45 copper-silver alloy. Test 4, run at 100 rpm and 100 to 300 lb thrust was terminated prematurely when the rig thrust control malfunctioned and the bit weight increased suddenly to 1760 lb. The penetration rate reached 76 ft/hr and the torque increased to 1000 ft/lb. At this point a weld in a universal joint in the drive shaft failed.

The drive shaft was repaired and the experiment resumed (Test 4A). The remainder of the granite was cut at 100 rpm and 850 lb thrust without incident. The penetration rate at 850 lb thrust was 34 ft/hr. None of the cutter braze joints failed. There was a small amount of spalling of the diamond cutting edges, probably caused by the abrupt termination of Test 4 when the weld failed, leaving the cutters engaged with the rock without rotation.

e. Test 5

This experiment was run using three -15° back rake STRATAPAX^R cutters attached to cemented tungsten carbide studs with Easy Flo 45 brazing alloy. The test was conducted cutting Sierra White Granite at 315°C and 2000 psi, at 100 rpm and 900 lb thrust, to duplicate as closely as possible the conditions for Test 4A, run

previously.

The cutters penetrated the first two inches of the granite slowly (5.3 ft/hr). At this point there was a momentary drop in thrust, from 900 to 775 lb, together with a corresponding drop in torque from 180 to 110 ft-lb. Within 10 seconds the thrust and torque returned to their original values and the penetration rate increased to 25.7 ft/hr, where it remained until the experiment was completed.

When the pressure vessel was opened, it was discovered that one of the cutters had rotated 90° so that the diamond surface was facing the center of rotation of the cutter assembly. The rotation, due to insufficient press fit interference, moved the diamond edge almost, but not quite, entirely out of the cutting zone. It seems probable that the cutter rotated slightly at the beginning of the experiment, creating an inefficient rock cutting condition, which would account for the initial low penetration rate (5.3 ft/hr). The momentary perturbation in thrust and torque probably took place when the cutter completed its rotation. The apparatus ran smoothly, without noticeable vibration, with only two unequally spaced cutters. The rotated cutter must have taken some of the thrust and stabilized the system even though it did not remove rock. The slightly reduced penetration rate (25.7 ft/hr) compared to 34 ft/hr for Test 4A supports this hypothesis.

It should be noted that the two diamond compacts that remained to cut effectively were not symmetrically positioned but were 120° from each other. The leading cutter should have removed twice as much rock as the trailing one with this non-symmetrical arrangement.

The diamond edge of the rotated cutter was fractured and the other cutters exhibited a small amount of wear and spalling.

f. Test 6

This was the first test in the second series. It was conducted on Sierra White Granite using -15° rake, pocketed, diffusion-bonded STRATAPAX^R cutters at room temperature and atmospheric pressure at 100 rpm. The bit weight was gradually increased in steps up to 1500 lb. Figure 97 shows the variation of penetration rate and torque with bit weight. As can be noted from the figure, the maximum penetration rate at 1500 lb bit weight was only 11 ft/hr, much lower than the previous elevated temperature, high pressure test. Severe vibration of the geothermal vessel and oscillations in bit load occurred. On examining the core,

the reason for the vibration was apparent. The center of the hole and the center of the drive shaft were not concentric (offset by about 1/4 in.). As a result, each cutter removed varying amounts of rock during each rotation. The width varied from less than 3/8 in. to over 5/8 in.

The two-pen chart recorder used to monitor bit weight and penetration while the experiment was being conducted indicated that the thrust force varied more than usual but the damping of the instrument masked the actual magnitude of the thrust force fluctuation. The bit weight record made using the multichannel strip chart recorder showed that for all bit weights above 100 lb the force fluctuated rapidly back and forth from zero to the desired value. Therefore, the cutting action resembled a combination rotary-pneumatic drilling process rather than a conventional rotary drag bit process. Also, the average thrust force at each step was much lower than the desired value. These factors were responsible for the penetration rate being lower than anticipated.

The diamond cutting edges were not badly damaged, which was surprising, considering the severe impact they must have undergone. None of the diffusion bonds failed.

g. Test 7

This experiment was the first of three utilizing diamond compact cutters that were intentionally dulled by grinding. Each cutter was ground on the end to produce a flat surface perpendicular to the rotational axis and on the outer edge to produce a flat surface perpendicular to the radius of the three cutter assembly and tangent to the circumference of rotation. These ground surfaces are shown in Figure 85. The straight cutting edge produced by grinding was approximately 0.251 in. long and each wear flat area was approximately 0.022 in.².

Test 7 was conducted using -15° back rake, pocketed cutters brazed to the studs with brazing alloy 'B', which had a higher shear strength than Easy Flo 45. The test was carried out cutting Sierra White Granite at 2000 psi and 315 °C. The rotational velocity was kept at 100 rpm for the entire experiment. The bit weight was increased rapidly to 900 lb and then raised in 100-lb increments to 1700 lb. The penetration rate was very low (less than 0.5 ft/hr) until the bit weight exceeded 1000 lb. Above this value the penetration rate increased rapidly and linearly, reaching 11 ft/hr at 1600 lb. Penetration rate and torque are plotted as a function of bit weight in Figure 98.

The diamond compact cutting edges that were produced by grinding the wear flats appeared to be significantly stronger and more wear-resistant than the sharp edges tested in Tests 1 through 6. There was no macrochipping or spalling and only uniform microchipping of the diamond crystallites at the edges. One flat on the side of each cutter rubbed against the bored surface of the rock, leaving a smooth surface on the granite, indicating stable operation. Such a flat might aid in maintaining gage in full-scale rock drilling. The braze between the diamond compact cutters and the cemented tungsten carbide studs remained intact during the test.

h. Test 8

This experiment was a repeat of Test 7, using a new set of preground diamond compact cutters. The cutters were attached to the cemented tungsten carbide studs with brazing alloy designated 'A'. The bit weight was raised quickly to 900 lb and then increased in 100-lb increments to a maximum value of 2000 lb. The results were almost identical to the Test 7 results, and are shown graphically in Figure 99. The penetration rate was low below 1000 lb and increased rapidly and linearly above this weight. The penetration rate was 18 ft/hr at 1900 lb.

As in Test 7, there was no macrochipping or spalling of the diamond compact cutters and only uniform microchipping of the diamond crystallites at the edges. The braze attachment remained intact during the test and the finish on the bored Sierra White Granite was good.

i. Test 9

The same rock type, pressure vessel condition, drilling procedure and diamond compact cutter configurations were used for this test as for Tests 7 and 8. The only difference was the brazing alloy used to bond the diamond compact drill blanks to the -15° back rake tungsten carbide studs. In this case the alloy used was Easy Flo 45, the lowest melting alloy of the three used for these experiments.

As for the prior two experiments, the bit weight was increased rapidly to 900 lb. Following this initial bit weight setting, the weight was increased in 200-lb increments to 2100 lb and then in 100-lb steps to 2300 lb. The penetration rate and torque are plotted as a function of bit weight in Figure 100. The maximum penetration rate attained was 10 ft/hr.

The diamond compact cutters were carefully examined after Test 9 was completed to

determine if they exhibited sufficient wear or damage to explain the significantly lower penetration rates achieved for this test, as compared to Tests 7 and 8. No cutters were detached during Test 9 and no macrochipping or spalling was observed. Wear at the diamond edges was confined to microchipping, identical with the prior tests with preground cutters. There was some braze line erosion at the rubbing interface between the cutter and the rock and indications of a slight amount of plastic deformation of the braze alloy, but the cutters had not moved from their original positions in the pockets in the cemented carbide studs. There was no obvious evidence that would account for the low penetration rates.

Just prior to commencing Test 9 one of the pressure vessel seals started to leak very slightly. Although the leak was not great enough to stop the experiment, an attempt to repair the leak was made. While this repair was underway, the connection to the thrust strain gages was accidentally broken and had to be repaired. A quick gage calibration check was made and the test was started. It is possible that the strain gage calibration was incorrect and actual bit weights were 600 to 700 lb lower than the recorded values.

j. Test 10

The final test was conducted cutting Sierra White Granite, using -25° back rake, diffusion-bonded diamond compact cutters supplied by Sandia Laboratories. These cutters, bonded to unpocketed studs, were the same ones used for Test 3. They were still sharp and essentially undamaged by the prior test. Test 10 was run in the pressure vessel at 2000 psi and 315°C . The rotation speed was 100 rpm.

The bit weight was raised rapidly to 900 lb and then increased stepwise to 1900 lb in 200-lb increments. The test ran smoothly without excessive vibration. The penetration rate increased linearly from 900 lb to 1900 lb thrust, reaching a maximum value of 45.5 ft/hr. The torque also increased in a linear manner, with a maximum value of approximately 230 ft-lb. The relationships between penetration rate, torque and bit weight are shown in Figure 101. Extrapolation of the penetration rate - bit weight curve indicates that the threshold thrust necessary for effective drilling was about 300 lb, much lower than the corresponding value for the intentionally dulled cutters (~1000 lb).

Just as this test was terminated, one of the diffusion bonds failed, preventing the recording of a reliable torque measurement at 1900-lb bit weight. Examination of the cutters (including the detached one) after completion of the experi-

ment revealed some chipping and spalling of the diamond compact edges. The extent of the damage was about the same as occurred in Tests 1, 2, 4, and 5.

Figure 94. Variation of Penetration Rate with Bit Weight at Different Cutter Speeds in Test No. 1

Figure 95. Variation of Torque with Bit Weight at Different Cutter Speeds in Test No. 1

Figure 96. Variation of Penetration Rate with Bit Weight at Two Cutter Speeds in Test No. 2

Figure 97. Variation of Penetration Rate and Torque with Bit Weight in Test No. 6

Figure 98. Variation of Penetration Rate and Torque with Bit Weight in Test No. 7

Figure 99. Variation of Penetration Rate and Torque with Bit Weight in Test No. 8

Figure 100. Variation of Penetration Rate and Torque with Bit Weight in Test No. 9

Figure 101. Variation of Penetration Rate and Torque with Bit Weight in Test No. 10

5. DISCUSSION

a. STRATAPAX^R Blank Diamond Compact Cutter Attachment Integrity

Three different braze attachments were tested including a conventional silver base alloy (Easy Flo 45) and two alloys that exhibited higher shear strengths over a range of temperature from ambient to 350 °C. These cutters were all used at -15° back rake, attached to "pocketed" cemented tungsten carbide studs. In addition, cutters mounted on -15° rake pocketed and -25° rake unpocketed studs were provided by the Drilling Projects Division, Sandia Laboratories. These STRATAPAX^R blank cutters were attached by a hot isostatic press diffusion bonding technique under development by Sandia Labs.

There were no attachment failures of any of the brazed diamond compact cutters. Particularly noteworthy was Test No. 5, at 315 °C. In this instance one of the cutter studs rotated 90° due to insufficient interference when it was pressed into place. This rotation caused the thrust force on this cutter to be directed in a manner that put the braze line in tension. The unsupported polycrystalline sintered diamond layer fractured at the cutting edge but the braze bond survived. The cutters used in Test No. 5 were brazed with Easy Flo 45, the weakest of the alloys used.

Examination of the braze lines exposed when the cutters were intentionally dulled by grinding revealed no damage after drilling Sierra White Granite at 315 °C. There was slight evidence of braze erosion and perhaps possible plastic flow of the Easy Flow 45 braze alloy used for Test No. 9. The damage was almost insignificant, however.

The -15° rake, pocketed, diffusion-bonded cutters used in Test No. 6 performed well, under very rigorous conditions, without any evidence of attachment failure. Although this experiment was performed at room temperature, there were severe vibrations and cyclic forces acting on the cutters because the axis of rotation of the three-cutter assembly was not concentric with the center of the precored rock specimen. These diffusion-bonded cutters would, in all likelihood, have remained attached if the experiment had been carried out hot. A good diffusion bond should not be significantly weakened by increasing the temperature a few hundred centigrade degrees.

Two -25° rake diffusion-bonded cutters became detached during the first half of Test No. 2. Examination of the diamond compacts recovered with the rock cuttings indicated that failure was because only a small percentage of the available surface

area was actually bonded to start with. The remaining cutter performed well, however, sustaining a large part of the 1200 lb thrust load without failure of the bond. One diffusion bonded cutter was lost at the end of Test No. 10. Examination of this cutter and its support stud again indicated that only a small part of the available surface area was actually bonded.

(It should be noted that the diffusion-bonded STRATAPAX^R diamond compact cutters provided by Sandia Laboratories were prepared early in Sandia's bonding development program. Middleton and Finger⁽²⁰⁾ at Sandia Laboratories have recently described the final results of this program, including the details for the process that will produce diffusion bonds at least as strong as the presently used brazed joints. Diffusion bonding is the primary attachment method utilized by one polycrystalline diamond compact bit manufacturer.)

b. STRATAPAX^R Blank Diamond Compact Wear

Some microchipping wear and minor diamond layer spalling occurred during the experiments performed with sharp diamond compact cutters, both -15° and -25° rake, with one exception, which was Test No. 3. The conditions for this experiment were much less rigorous than the other nine. The average thrust force acting on each compact in Test No. 3 was 33 lb, and the maximum about 100 lb.

Slight spalling of the cutter surfaces, which only removed a small portion of the total sintered diamond layer thickness, was generally confined to the gage point of each cutter (the edge tangent to the enlarged bore surface of the rock specimen). This minor spalling type of wear did not occur in every case.

Microchipping edge wear was minor in all cases where it was detected. There was no significant difference in the degree of wear comparing cutters tested at room temperature with those used at 315 °C, but it was not anticipated that such a relatively small increase in temperature would have any pronounced effect upon the diamond compact wear properties. In addition, the duration of the individual experiments was not long enough to generate measurable microchipping wear.

The intentional dulling of the diamond compact cutters, produced by grinding two flats (one perpendicular and one parallel to the feed direction) on each compact resulted in an unanticipated benefit. Although the thrust force (bit weight) necessary to maintain a given penetration rate was markedly increased as expected (to be shown later), the wear resistance was also dramatically improved. No spalling occurred with any of the preground cutters. The spalled area visible in the front view of the cutter shown in Figure 85 was the result of previously testing it in the "sharp edge" condition. Also, microchipping edge wear was reduced. Tests per-

formed using the "intentionally dulled" diamond compact cutters exhibited much less vibration than those performed with "sharp" cutting edges and the surfaces of the rock specimens drilled were smooth.

The cutting edge included angle for a "sharp" diamond compact is 90° , and a cutter with a -15° back rake has a 15° clearance angle. This means that a portion of the diamond layer (which is hard but brittle) is not supported by a tough, cemented carbide substrate. The high local stress acting upon this unsupported edge, amplified by vibrations induced by nonuniform rock fracture and perhaps by instability of the drilling system, can cause initial microchipping of the polycrystalline diamond layer. Microchipping can cause additional internal flaws which may eventually be the necessary ingredient to cause the spalling wear that was observed.

Each diamond compact cutter that was ground had a zero clearance angle behind the straight portion of the cutting edge. This strengthened the edge by increasing the included angle to 105° . In addition, the diamond layer was entirely backed up by the tougher cemented tungsten carbide substrate. Thus, microchipping of the edge was reduced, as well as the spalling tendencies.

The concept of increasing the cutting edge included angle to achieve additional strength is not unique. It is standard practice in some metal cutting operations where edge integrity is essential to optimize performance and maximize tool life. Where brittle tools are used, such as oxides and Borazon* cubic boron nitride compacts, preconditioning the cutting edges by honing or grinding a narrow land is necessary to prevent premature edge failure.

c. STRATAPAX^R Blank Diamond Compact Cutter Performance Analysis

The results of four of the 10 tests could not be used to evaluate the performance of the diamond compact cutters. Test No. 2 had to be eliminated because cutters were detached, Test No. 5 because a cutter stud support turned 90° , and Test No. 6 because of nonconcentricity of the cutter assembly rotational axis and the cored rock axis. The loss of the No. 6 test data was particularly unfortunate because it prevented a direct comparison of Sierra White Granite drilling characteristics with those of Jack Fork Sandstone, which had been previously evaluated by the instrumented single-cutter experiments described earlier in this report. Examination of the results of Test No. 9, which should have been very similar to Tests No. 7 and 8, indicated that the bit weight calibration was apparently significantly in error so the results of this test were also eliminated.

* Registered trademark of the General Electric Company, USA.

The results of the remaining six experiments were examined. Tests No. 4, 3, and 10 were used to examine the effect of back rake angle on penetration rate and torque and Tests No. 4, 7, and 8 provided information on the effects of "sharp" and "dull" cutters on performance. The results of Test No. 1 (Jack Fork Sandstone) provided quantitative information for diamond compact cutters removing rock under simulated drilling conditions, which could be compared with information obtained by controlled laboratory single-cutter experiments where the conditions were quite dissimilar to actual drilling.

Figures 102 through 107 show the quantitative data in graphical form. Torque and penetration rate, are plotted against bit weight, with the actual data points shown. The drawn lines represent the least squares best fit to the data. Straight line fits were used in all cases, even though in some instances an exponential or power function gave slightly better agreement with the experimentally determined results. It was felt that insufficient information was known on the relationships between torque, penetration rate, and bit weight to justify the use of any curves other than straight lines.

1. Rake angle effects. Figures 102 and 103 show the relationships between the penetration rate, torque, and bit weight for -15° and -25° back rake sharp cutters drilling Sierra White Granite. Penetration rate (Figure 102) was greater for any given bit weight (thrust force) for the -15° rake cutters. This was the anticipated result, based on our prior single-cutter laboratory experiments using rocks with a wide variety of properties. These experiments indicated that penetration rate (which is proportional to depth of cut) would be maximized for cutter rake angles in the -15° to -20° range, compared at equal cutting speeds. Figure 103 indicates that the torque for the -15° rake cutters was greater than the torque for the -25° rake cutters, at constant bit weight. Again, this was the expected result. Torque is proportional to the cutting (or drag) force. Since the depth of cut for the -15° rake cutter was greater than for the -25° rake cutters at any given thrust force, the drag force necessary to remove the larger volume of rock should also have been larger, as was observed.

2. Dull vs. sharp cutter effects. Figures 104 and 105 show the relationships between penetration rate, torque, and bit weight for -15° back rake sharp (Test No. 4) and dull (Tests No. 7 and 8) cutters drilling Sierra White Granite. From Figure 104 it is easily seen that, for the dull cutters, much higher thrust forces were necessary to achieve penetration rates equal to those for the sharp cutters. Since the thrust force for the dull cutters was distributed over a much larger area of the

rock surface (see Figure 85, Top View), significantly greater forces were necessary to raise the stress concentration to the value necessary to penetrate and fracture the rock. The threshold thrust force necessary to initiate significant penetration into the Sierra White Granite was approximately 950-1150 lb for the dull cutters. Bit weights below these values produced negligible rock removal rates. On the other hand (see both Figures 102 and 103) the threshold thrust force for sharp cutters, regardless of back rake angle appeared to be about 100 lb.

Although it is not readily apparent from a cursory examination of the torque-bit weight relationships (see Figure 105), the cutting (drag) forces were very close to the same for sharp and dull cutters when penetration rates were equal. Using the best fit equations for the penetration rate-bit weight and torque-bit weight relationships, the torque was calculated over a range of penetration rates from 5 to 20 ft/hr for the sharp cutters (Test No. 4) and the dull cutters (average values of Tests No. 7 and 8). The results are given in Table 38.

These results are reasonable. The cutting (drag) force is proportional to the measured torque. When the penetration rates are equal for both sharp and dull cutters, the volume of rock removed per cutter per revolution is also the same. Consequently, the cross-sectional area of the groove in the rock is essentially the same for sharp and dull cutters, so equal cutting forces should be anticipated, neglecting frictional effects.

3. Prediction of drilling forces. The major reason for the extensive instrumented laboratory single-cutter experiments conducted prior to the work described here was to obtain information to predict the forces acting on STRATAPAX^R diamond compact cutters, as an aid to future bit design. If a simple straight edge cutter shape is used, a direct relationship between the laboratory single-cutter results and a bit utilizing straight edge cutters can be made. Indeed, two bits designed with this shape of diamond compact cutting edge were constructed and tested on a full-scale laboratory drill rig. The performance characteristics of these bits (bit weight, penetration rate, torque, horsepower, etc.) were very close to the values predicted using the single-cutter experimental results.

If the diamond compact cutter shape used is not rectangular (for example, a circular cutter), prediction of bit performance becomes difficult. The reason for this is apparent if the differences in the manner in which the rock is removed is examined. When rock is cut by one circular cutter, using a lathe or vertical boring mill, the cross section of the groove produced in the rock is a segment of a circle, slightly distorted by the negative back rake of the cutter. Actually, it is a seg-

ment of an ellipse. On the other hand, a cutter on a bit travels in a circular path but moves progressively into the rock in a direction parallel to the rotational axis. The cross section of the groove produced is similar to a thin crescent moon. It is, in fact, the area produced by the intersection of two identical, slightly overlapping ellipses.

A preliminary analysis indicates that the cutting (drag) force for a circular cutter can be approximately predicted if laboratory single-cutter data are available on the same rock material. In our case, extensive results had been obtained cutting Jack Fork Sandstone in the laboratory. Thus, an attempt to predict the forces that were actually measured under simulated drilling conditions in Test No. 1 could be made. The results of this test are shown graphically in Figures 106 and 107. The data for the penetration rate-bit weight relationship at 47 rpm were somewhat suspect, so the analysis was confined to 23 and 98 rpm only.

The approach taken to predict the cutting (drag) forces was as follows:

1. The assumption was made that, for cutters with the same back rate, cutting at the same speed, the drag forces would be equal for equal cut groove cross-sectional area, regardless of the shape of this groove cross section.
2. The cross-sectional area of the crescent shape cut by a single cutter in Test No. 1 was calculated for chosen penetration rates and rotational speeds.
3. The depth of cut required to produce segment-shaped, grooved cross-sectional areas equal to the areas in (2), above, were calculated.
4. These "effective" depths of cut were utilized to calculate the predicted drag forces, based on the model developed earlier by the single-cutter experiments.

The results of this analysis are shown in Table 39. The agreement between the actual measured drag forces and the predicted forces is relatively good. It should be noted that the effective back rake value used (as indicated in Table 39) was -13.05° , rather than the nominal -15° figure. Examination of Figure 83 will show that the cutters were mounted so the studs tilted outward. This was done to provide enough clearance to prevent the cutter assembly body and the studs from rubbing against the bore surface of the rock. The tilt angle was 30° . A simple calculation will show that the effect of this tilt was to reduce the back rake angle by 1.95° . Tilting the cutters also changed the effective side rake (measured at the tangent point between the cutter and the bore surface) from zero to -7° . The principal effect of correcting the side rake value was to reduce slightly the width of cut value used to calculate the "effective" depths of cut.

This technique will not work to predict the thrust forces. A detailed analysis of this complex problem is beyond the scope of this program but the results of some preliminary analytical efforts suggest a more thorough study would be warranted.

Table 38

TORQUE AND PENETRATION RATE FOR SHARP AND DULL
CUTTERS DRILLING SIERRA WHITE GRANITE

Penetration Rate (ft./hr.)	<u>Torque (ft.-lbs)</u>	
	<u>Sharp Cutters</u>	<u>Dull Cutters</u>
5	75.70	84.1
10	104.0	104.2
15	132.3	124.3
20	160.6	144.4

Table 39

COMPARISON OF PREDICTED AND MEASURED CUTTING FORCES
DRILLING JACK FORK SANDSTONE

(Using the actual back rake angle of -13.05°)

<u>Rotational Speed (rpm)</u>	<u>Penetration Rate (ft./hr.)</u>	<u>Measured Cutting Force (From Test No. 1) (lb.)</u>	<u>Predicted Cutting Force (From Single Cutter Experiments (lb.)</u>
23	0.5	27.5	19.0
23	1.0	46.9	42.2
23	1.5	66.2	55.7
23	2.0	85.6	67.0
98	1.0	17.3	6.3
98	2.0	34.4	23.9
98	3.0	51.5	36.2
98	4.0	68.6	45.2

Figure 102. Effect of Bit Weight on Penetration Rate for Diamond Compacts of Two Different Rakes (-15° and -25°) Cutting Sierra White Granite

Figure 103. Effect of Bit Weight on Torque for Diamond Compacts of Two Different Back Rakes (-15° and -25°) Cutting Sierra White Granite

Figure 104. Effect of Bit Weight on Penetration Rate for ''Sharp'' and ''Dulled'' Diamond Compacts Cutting Sierra White Granite

Figure 105. Effect of Bit Weight on Torque for ''Sharp'' and ''Dulled'' Diamond Compacts Cutting Sierra White Granite

Figure 106. Effect of Bit Weight on Penetration Rate for Diamond Compacts Cutting Jack Fork Sandstone at Three Speeds

Figure 107. Effect of Bit Weight on Torque for Diamond Compacts Cutting Jack Ford Sandstone at Three Speeds

6. CONCLUSIONS

1. The successful completion of the pressurized, elevated temperature "three-cutter" experiments demonstrated that the test facility used can provide useful information on rock drilling phenomena under more rigorous conditions than is generally available outside full-scale field tests. However, the test geometry clearly did not represent cutting conditions which exist in the critical center region of a rock bit.
2. All three types of braze attachments performed satisfactorily at elevated temperature. For some geothermal drilling applications it may be better to use the braze alloys designated as "A" and "B" rather than the lower shear strength silver base alloy.
3. Microchipping wear and minor, local spalling of the diamond compact cutters can be markedly reduced by pregrinding the cutting edges to increase the cutting edge included-angle and provide complete backup support for the diamond layer. However, at the same bit weight, the penetration rate is significantly reduced with the preground cutters.
4. Increasing the threshold bit weight by pregrinding the diamond compact cutters to eliminate the clearance angle may be advantageous in that it raises the bit weight requirements to levels that can more easily be controlled by the methods available in the field. However, there may be undesirable long-term effects of eliminating the cutter clearance angle which are not yet known.
5. Cutting (drag) forces apparently are not affected by the degree of "sharpness" or "dullness" of the diamond compact cutters when drilling hard (brittle) rock.
6. Reasonable predictions of cutting forces under "simulated" drilling conditions can be made using laboratory single-cutter experimental results. The method is based on equal cross-sectional areas of rock removed and promises to reduce the problem created by differences in cutter shape between the laboratory experiments and the bit.

G. DESIGN AND FABRICATION OF FIRST GENERATION POLYCRYSTALLINE DIAMOND CUTTER COMPACT BITS FOR LABORATORY EVALUATION AND FIELD TRIALS

Following the pressurized, elevated temperature experiments at Terra Tek's drilling laboratory, described in the preceding section of this report, two bits were designed and fabricated for full-scale laboratory drilling evaluation, to be followed by testing in the field at a suitable geothermal site. These bits, designated S-1 and C-1, included features developed from the prior drilling experiments conducted at Tulsa University as well as cutter attachments tested during the three-cutter experiments conducted at Terra Tek. Essentially, the design of Bit No. S-1 was a modification of our earlier Bit B design and the design of Bit No. C-1 was similar to Bit D. There were some basic differences, such as cutter shape and back rake angle, which will be discussed later.

On the advice of the Union Oil Company, at whose geothermal drilling sites these bits were eventually evaluated, 8-1/2 in. bit diameters were selected. It was Union Oil's intent to test the bits in the bottom section of a geothermal hole. Thus, the 8-1/2 in. dia. was sufficiently undersize to reach the bottom of an 8-3/4 in. hole without the necessity of reaming. It was planned that the geothermal site for evaluation of these bits would be at Jemez Springs in the Valles Caldera region of New Mexico. The formation is volcanic in nature, with predominantly basaltic lavas and tufts composing the hydrothermal producing zone. Deeper, there is crystalline granite with a gradual change from large quartz crystals to mainly feldspar. The temperature is in the range of 200 to 260 °C. The drilling fluid would be aerated water.

As discussed in Section 3D, there are at least three criteria on which to base a bit design: (1) equal rock volume removed per cutter, (2) equal wear rate per cutter, and (3) equal expenditure of power per cutter. In addition, the profile of the bit crown must be tailored to the formation to be drilled, i.e., a relatively blunt profile for medium hard to hard formations, such as anticipated here, as opposed to a relatively pointed profile for soft formations. The kind of drilling fluid required by the formation to maintain desired hole characteristics also enters into the design insofar as nozzles and bit cleaning are concerned.

Bit No. S-1 was a steel body bit, fabricated by Smith Tool Company, Irvine, California. The design criterion selected was equal volume of rock removed per cutter per revolution, and the Sandia-Brigham Young University computer program⁽²¹⁾ for cutter layout, based on this criterion, was utilized for the initial cutter positioning. Several additional cutters were added to the outer two rows to reduce

cutter engagement and provide added wear resistance. A drawing of the bit body profile, without cutters except for those on the gage, is shown in Figure 108. As indicated by the cutout on the left hand side of the drawing, the steel bit body was machined in two sections, which were subsequently welded to form the complete body.

Figure 109 shows the design layout of cutters and nozzles on Bit No. S-1. The view is directly along the centerline axis of the bit. The numbered circles indicate the positions of the studs to which the diamond compact cutters are attached, the concentric circles indicating recesses for the equal-length studs so that the desired standoff in each case is achieved. The ellipse within each circle is the projection of the respective diamond compact face at that position. There were 38 full-round polycrystalline diamond compact cutters (General Electric Product No. 2530-T STRATAPAX^R drill blanks) on the bit face. In addition, there were four gage cutters (General Electric Product No. 2525-T drill blanks). The gage cutters are shown in Figure 109 below bit face cutters Nos. 23, 26, 28 and 30 and in Figure 108. Additional bit body wear protection was provided by Smith Tool mining grade cemented tungsten carbide buttons pressed into the gage of the bit. These are also shown in Figure 108.

The studs to which the polycrystalline diamond compacts were brazed were GE Carboloy Grade 231 cemented tungsten carbide. This material is 90% tungsten carbide with 10% cobalt binder, and its primary usage is mining applications where very high toughness is desired. Figures 110 and 111 are drawings of the studs used for the cutting structure (full-round cutters) and the gage trimmers (half-round cutters), respectively. These were 'pocketed' studs with a -20° rake angle and a 20° end clearance angle. The diamond compact cutters were attached to the studs, using Handy Harmann Easy Flo 45 copper-silver base brazing alloy (m.p. $\sim 620^{\circ}\text{C}$) in a forming gas atmosphere (10% H_2 , balance N_2). The protective atmosphere was used to reduce the oxidation of the tungsten carbide studs, which had been ground to the specific diametrical dimension required for press fitting into the bit body.

The bit body was constructed so that 30 of the 38 stud-mounted cutters making up the cutting structure could be interference fitted by pressing parallel to the bit rotational axis. This simplified the tooling necessary to support the bit body during the press fitting operation. Only cutters Nos. 31 through 38 and the four gage trimmer cutters required tilting of the bit body to carry out the interference fitting step. (See Figure 109 for the location of these cutters).

Five nozzles were provided for Bit No. S-1, located in a pattern similar to Bit No. B. These were replaceable, screw-in nozzles of the type used by Smith Tool Co. for roller cone bits. Replaceable nozzles were used to permit adjustment of the to-

tal nozzle cross-sectional area to conditions encountered in the field. At the time this bit was constructed the exact field test hydraulic requirements and drill rig pumping capacity were not known. The bit was designed for a water flow rate of 425 gpm to obtain good bit face cleaning.

Figure 112 is a schematic illustration of the approximate profile of the cutter envelope of Bit. No. S-1, generated by the Sandia Laboratories STRATAPAX^R computer program. This profile or bottom hole pattern is approximate because the program did not take into account the cutter back rake, but is adequate to show the degree of cutter overlap. Note that for cutters 1 through 30, no cutter followed exactly the same path as any other and that for the two outermost sets of four (31 through 34 and 35 through 38) the cutters in each set completely overlapped each other.

Figures 113 and 114 are detailed drawings that accurately describe the bit body dimensions and contouring, the exact locations of all the stud-mounted cutters and the accurate locations of the wear pad inserts and the nozzles. They are precise for the first two types of bits fabricated by Smith Tool on this program (Types S-1 and S1, Modified) and, with very minor changes, to accommodate the 1/4-in. increase in bit diameter are suitable to describe the last two types of bits fabricated (types S-2A and S-2B). Fabrication of bits types S-1, modified, S-2A and S-2B are covered later in this report. Figure 115 is a photograph of Bit No. S-1 as fabricated before testing.

The second bit constructed for eventual field test purposes was a 8-1/2 in. dia. hard matrix bit, which was fabricated by Christensen Diamond Products, USA, Salt Lake City, Utah. The polycrystalline diamond compact cutting structure was similar to that of Bit D, which had been tested successfully at Tulsa University. The overall bit design was generated through discussions with Christensen's Diamond Technology Center, where actual design and fabrication was conducted. This bit, designated No. C-1, had two unique features not incorporated in any prior diamond compact drag bit. First, the innermost cutters were located so that they did not cut the very center of the hole. The rock core that was formed would be removed through a hole in the center of the bit body and ejected through the side of the bit below the skirt. This "core ejector" concept was included in the design to avoid the problem that occurred while testing Bit B at Tulsa University when the central diamond compact cutter became detached and its tungsten carbide support wore rapidly, developing a flat bearing surface which prevented further effective bit penetration. Second, the outermost diamond compact cutters were positioned slightly (~0.010 in.) under gage and natural diamond drill stones were set in the bit to cut to gage. It was felt at the time that these drill stones, which would not be re-

quired to remove a large volume of rock, would exhibit greater wear resistance than the polycrystalline diamond compacts, and thus reduce the rate of bit gage wear.

Figures 116 and 117 are drawings of the bit profile and the layout of the cutters and nozzles, and represent the initial design concepts. There were some minor changes made in the final cutter and nozzle layout which are discussed later. Figures 118 and 119 are photographs of the finished bit.

The polycrystalline diamond compacts used for Bit No. C-1 were General Electric's Product No. 2530-LS-T STRATAPAX^R drill blanks. These cutters consisted of General Electric Product No. 2530-NC STRATAPAX^R blanks attached to the ends of right circular cylinders of cemented tungsten carbide to form cutters with extended substrates. The overall length, including the sintered diamond layer, was 0.520 in. and the diameter of the extended substrate was 0.529 in. The attachment was an early version of the General Electric 'LS' braze bonding technique, using a high-strength, high-temperature alloy. The brazing material used was alloy 'A,' discussed earlier in this report in the section on physical property measurements. The diamond drill blanks were hand brazed in cavities provided in the cast hard matrix bit body, using a low temperature Ag-Cu alloy (i.e., Easy Flo 45). The cutters were oriented with a -15° back rake and a zero degree side rake.

The original design called for 43 diamond compact cutters, positioned so as to cut 15 concentric circles, as shown in Figure 117. The numbers on the cutters refer to the concentric circular paths, not to specific individual cutters. Cutters with the same numbers followed exactly the same path. Thus, there were two cutters on the first (smallest) circle, two on each of the second, third, and fourth, three on the fifth and sixth circles, and so on. Except for the outermost two circles, the cutters were arranged in six radial rows, or wings, to promote fluid flow over the diamond surfaces to enhance cleaning. When the bit was actually constructed, six additional cutters were added, one each to circular paths No. 4, 6, 7, 13, 14, and 15, to make a total of 49. Figure 119, is a photograph of the bit face. The locations of the six additional drill blanks can be determined by comparing this photograph with the drawing in Figure 117. A second modification was the introduction of two fluid channels leading into the central core hole. These channels were provided to divert more of the fluid through the center of the bit to wash the broken core sections through and out of the core ejector.

Figure 120 is a cross section of half of Bit No. C-1, showing the profile of the cutter envelope and the cutter overlap. The upper numbers in the circles depicting the cutters are the cutter path designations and the lower numbers indicate the number of cutters for each path. In contrast to Figure 117, this cutter layout

represents the bit-cutting structure as it was actually fabricated, not as it was initially designed.

Bits No. S-1 and C-1 were tested using the pressurized wellbore simulator at the Drilling Research Laboratory, Terra Tek, prior to evaluation in the field. The detailed results of these full-scale laboratory drilling experiments are given in the next section of this report, including the assessment of the damage to and the defects revealed in Bit No. S-1, which had to undergo some design changes and extensive repair before being taken to the field for evaluation.

Figure 108. Bit Body Profile, Bit No. S-1

Figure 111. Stud Design for Gage Cutters 39 Through 42, Bit No. S-1

Figure 112. Cross Section of Half of Bit No. S-1 Showing the Profile of the Cutter Envelope

NOTES:
1. 120 RMS FINISH EXCEPT AS SHOWN.

LTR.	REVISION	DATE	APP.	DET. QTY.	DESCRIPTION	MATERIAL
	1				BODY CONTOUR MACHINING	DATE 3-14-20
						DRN. M. BALL
					8 1/2 DIA. STRATAPAX DRAG BIT	CKD.
						APP.
						RD1133

Figure 113. Bit Body Machining Details, Bit No. S-1

Figure 114. Cutter Stud and Wear Pad Location Details, Bit No. S-1

Figure 115. Bit No. S-1

Figure 116. Schematic of the Outer Profile of Bit No. C-1

Figure 117. Design Layout of Cutters and Nozzles for Bit No. C-1

Figure 118. Side View of Bit No. C-1 Showing Core Ejection Port in the Bit Shank

Figure 119. End View of the Cutting Structure for Bit No. C-1

Figure 120. Cross Section of Half of Bit No. C-1 Showing Profile of Cutter Envelope

H. FULL-SCALE, PRESSURIZED, LABORATORY DRILLING EXPERIMENTS WITH POLYCRYSTALLINE DIAMOND COMPACT BITS NOS. S-1 AND C-1

1. INTRODUCTION

Prior to taking the first-generation polycrystalline diamond compact bits to the field for evaluation in actual geothermal holes, these bits were tested using the full-scale pressurized drilling rig at the Drilling Research Laboratory, Terra Tek, Salt Lake City, Utah. These preliminary experiments were performed for the following reasons:

1. To gain some early information on the performance characteristics of the bits, such as the relationships between weight on bit, rotary speed and penetration rate,
2. To determine if the nozzle placements and designed fluid flow rate were adequate to assure effective bit face cleaning,
3. To test the structural integrity of the bits,
4. To reveal any major design concept flaws (i.e., cutter placements, cutter rake angles, stud retention and standoff, the effectiveness of the core ejector concept, etc.), and
5. To provide a general comparison of the drilling performance of the steel body stud design and the cast, hard matrix bit body design.

2. EXPERIMENTAL PLAN

The drilling schedule consisted of 16 experiments. Two rock types were utilized for each bit, with the experimental conditions adjusted for four nominal simulated depths; 0, 2000, 3000, and 6000 ft. The simulated depth was determined, assuming that one lb/in.² of axial overburden stress was equivalent to one foot of depth. Three rotary speeds were utilized for each experiment, nominally 50, 85, and 115 rpm, and bit weight was varied over a nominal range of 1000 to 20,000 lb. The fluid (mud) flow rate was held as constant as possible at a nominal value of 400 gpm.

The three-cutter experiments (described in Section 3, F) performed at the Drilling Research Laboratory, using a specially designed "geothermal" pressure vessel, demonstrated the capability of polycrystalline diamond compact cutters to effectively function in hot, hard rock environments. These experiments also demonstrated the likelihood of producing some degree of cutter damage, particularly edge chipping and diamond layer spalling under abusive rock-cutting conditions. Since the principal objectives of the full-scale pressurized laboratory drilling experiments were to ex-

amine the drilling characteristics of the bits as related to drilling parameters and to identify any major design deficiencies, rock types were chosen that would provide a suitable environment with reduced risk of cutter damage of the type encountered during the three-cutter experiments. In addition, rocks that would clearly respond to the pressures applied in the wellbore simulator were desirable in order to obtain depth-penetration rate-bit weight-torque information.

At the time the full-scale laboratory drilling experiments were conducted it was not definitely known where the first field trials would be run. As indicated previously (Section 3, G, Design and Fabrication of the First Generation Bits), it was anticipated that the initial field tests would take place in the Baca Field, NM, drilling in an andesite formation using aerated water. However, other possibilities existed such as drilling in the Imperial Valley, CA (abrasive sedimentary rock, using mud) or at the Geysers, CA (very hard, abrasive graywacke, using air alone). It was not feasible to obtain rock cores with properties similar to these widely different geothermal formations. Therefore, the rocks chosen were Colton Sandstone and Carthage Marble. Both of these materials were well characterized, readily available, and had been used previously in full-scale laboratory drilling experiments. Colton Sandstone was used by Terra Tek for earlier wellbore investigations for ERDA, testing roller cone bits, and Carthage Marble was one of the rocks tested earlier in this program at the Tulsa University drilling laboratory, using polycrystalline diamond compact bits constructed specifically for that occasion (see Section 3, E, this report). The properties of Colton Sandstone and Carthage Marble are given in Table 40.

A brief description of the Drilling Research Laboratory wellbore simulator test facility is given in Section 3, G and is not repeated here except to note the differences in setup and procedures from the earlier "geothermal" cutting experiments in the areas of rock preparation, pressurization, data acquisition, and data reduction. A more comprehensive description of the operation of the wellbore apparatus is given by Black, Green, and Rogers. (22)

a. Rock Preparation and Assembly

The rock specimens for the pressurized drilling experiments were 15-9/16 in. dia. cores, 36-in. long, providing 32 in. of drilling depth each. The atmospheric pressure (zero depth) drilling experiments were conducted using blocks of rock approximately 3 ft X 5 ft long by 3 ft high.

The cores were jacketed with special urethane sleeves to isolate the rock from the hydraulic fluid used to apply the radial pressure, and then sealed by metal end

caps which had provisions for access to the rock for the ram used to apply the axial load and for the bit and drilling fluid. The jacketed, end capped core was then attached to part of the wellbore pressure vessel top plug. This assembly (shown in Figure 121) was inserted into the pressure vessel and the remaining part of the plug, containing the rotary shaft, the high-pressure rotary seal, the drill bit, and the vessel seals was installed.

b. Pressurization

In operating the wellbore simulator there are restraints on the relative magnitudes of the ram, confining and bore pressures that may be used in order to avoid fracturing the rock core specimen. This is due to the development of the borehole during drilling, which reduces the cross-sectional area of the rock. Thus, the axial stress (σ_z^*) at the top (annular) portion of the core is different than the axial stress (σ_z) at the bottom of the rock specimen. This situation is shown in Figure 122.

The axial stress in the borehole annulus (σ_z^*) may be calculated using Equation (13) below.

$$\sigma_z^* = \frac{P_{\text{ram}} A_{\text{ram}} + P_{\text{conf}} (A_{\text{rock}} - A_{\text{ram}}) - P_{\text{bore}} A_{\text{bore}}}{A_{\text{rock}} - A_{\text{bore}}} \quad \text{Eq. (13)}$$

where:

P_{ram} = the pressure applied to the bottom of the rock cylinder,

A_{ram} = the area of the ram,

P_{conf} = the confining pressure,

A_{rock} = the area of the rock across its diameter,

P_{bore} = the bore (mud) pressure, and

A_{bore} = the cross-sectional area of the borehole.

Below the borehole, P_{bore} and A_{bore} are zero, and Equation (13) becomes:

$$\sigma_z = \frac{P_{\text{ram}} A_{\text{ram}} + P_{\text{conf}} (A_{\text{rock}} - A_{\text{ram}})}{A_{\text{rock}}} \quad \text{Eq. (14)}$$

where:

σ_z is the simulated overburden stress.

According to Tibbitts and Black⁽²³⁾ if the borehole annulus fails, the failure will be in shear and the maximum principal stresses may be approximated by those

developed in a thick-walled pressure cylinder. In this case, the maximum principal stresses (i.e., maximum axial stress $[\sigma_z^*]$, maximum radial stress $[\sigma_r]$, and maximum tangential stress $[\sigma_\theta]$ are:

$$\sigma_z = \sigma_z^* \quad \text{Eq. (15)}$$

$$\sigma_r = -P_{\text{bore}} \quad \text{Eq. (16)}$$

$$\sigma_\theta = \left(\frac{b^2 + a^2}{b^2 - a^2} \right) P_{\text{bore}} - \left(\frac{2b^2}{b^2 - a^2} \right) P_{\text{conf}} \quad \text{Eq. (17)}$$

where:

a = the borehole radius, and

b = the rock cylinder radius.

If a constant value for the ratio of P_{conf} to σ_z is chosen (for our purposes, $P_{\text{conf}}/\sigma_z = 0.7$), Equation (14) may be used to obtain P_{ram} expressed as a function of P_{conf} . Substituting this into Equation (13) provides a solution for the maximum axial stress, σ_z^* , in terms of P_{conf} and P_{bore} . Thus, all three maximum shear stresses, σ_z^* , σ_r , and σ_θ are functions of P_{conf} and P_{bore} , and the maximum shear stress may be determined using Mohr's circle convention. By plotting the calculated maximum shear stress as a function of confining pressure for a range of borehole (mud) pressures a family of curves may be obtained. By superimposing the strength curve for each rock type (determined independently by triaxial strength tests) on the maximum shear stress-confining pressure plot, the safe operating conditions for the wellbore simulator will be defined. Using this technique it was determined that, for values of σ_z up to 6000 psi (equivalent to simulated depths down to 6000 ft) neither the Colton Sandstone nor the Carthage Marble would fail if the ratio of P_{conf} to σ_z was maintained at 0.7 and the ratio of P_{bore} to σ_z was maintained at 0.5.

It should be noted that the choice of $P_{\text{bore}}/\sigma_z = 0.5$ was not made by chance. The mud weight used for these experiments was held as close as possible to 9 lb/gal, and a 9-lb mud produces a hydrostatic pressure in a wellbore of 0.468 lb/in² per foot of depth.

c. Data Acquisition

The Drilling Research Laboratory drill rig servocontrol permits operation at either constant bit weight, constant penetration rate, or constant torque. For the experiments described here, penetration, bit weight, torque, mud flow rate, mud pressure at the swivel and mud borehole pressure were recorded on both analog

(chart) and digital recording equipment. In addition, the digital record provided instantaneous penetration rate, confining pressure, ram pressure and rotary speed.

A complete digital data printout was obtained approximately every two seconds. The constant bit weight servocontrol mode was utilized to obtain steady state drilling conditions for each bit weight-rotary speed combination selected. A two-pen X-Y chart recorder, providing continuous record of bit weight and penetration, was used to visually monitor the progress of each experiment and provide guidance for the rig operator. The digital data printout was the source of the actual data reported below.

These wellbore simulator drilling experiments were conducted over a time span of eight days. To be certain that the drilling mud properties did not change appreciably, mud weight, plastic viscosity, apparent viscosity, filtration, yield point, initial gel and 10-minute gel were measured at the conclusion of each experiment.

d. Data Reduction

As noted above, for each drilling situation examined, the bit weight was kept as constant as possible in order to establish steady-state conditions. This resulted in from three to nine complete sets of usable digital printout data for each condition. To reduce this large amount of information to a reasonable size, the digital data for each steady-state condition were averaged to obtain one value for each of the parameters, which included rotary speed (RPM), bit weight, penetration rate (ROP), torque, confining pressure, ram pressure and bore pressure. The axial overburden stress, σ_z , was calculated using Equation (14) and the average confining and ram pressure values. For the rock core diameter (15-9/16 in.) and ram diameter (11 in.) used, Equation (14) can be reduced:

$$\sigma_z = 0.4996 P_{\text{ram}} + 0.5004 P_{\text{conf}} \quad \text{Eq. (18)}$$

Assuming that the overburden stress for average deep hole drilling is one lb/ft.² of depth, the simulated depth (in feet) was taken to be equivalent to σ_z (lb/in.²).

Table 40

ROCK DESCRIPTIONS AND PROPERTIES

CARTHAGE MARBLE (Burlington Limestone)

Description	Light uniform gray, fine-grained, compact limestone containing numerous fossil fragments, cemented, crystalline texture. Quarried in Carthage, Missouri.
Properties	Bulk density = 2.67 gm/cc Porosity = 1 to 2 % Unconfined Strength = 14500 psi Unconfined Modulus = 5.8 million psi Confined Strength = 25000 psi at 4000 psi confining pressure

COLTON SANDSTONE

Description	Green River Eocene Graywacke, typical of deep reservoir rocks, gray sandstone, bedded. Quarried in central Utah.
Properties	Bulk density = 2.38 gm/cc Porosity = 10.9 % Unconfined strength = 7600 psi Unconfined modulus = 2.8 million psi Confined Strength = 30000 psi at 10000 psi confining pressure

Note - These descriptions and properties provided by Terra Tek, Salt Lake City, Utah.

Figure 121. Jacketed Rock Core Specimen Prepared for Mounting in the Wellbore Simulator Pressure Vessel

Figure 122. Pressures and Stresses Acting on a Rock Core Specimen in the Wellbore Simulator Pressure Vessel

3. EXPERIMENTAL RESULTS

a. Drilling Performance

Table 41 lists the 12 drilling experiments together with the nominal confining, ram, and bore pressures for each experiment. The experiment numbers are the designations assigned by the Drilling Research Laboratory. The nominal overburden stress figures are the calculated values obtained with Equation (18) using the nominal confining and ram pressures.

Tables 42 and 43 list the mud properties measured after each drilling experiment, together with the actual average mud flow rate. The nominal flow rate (not given in the table) was 400 gpm for all experiments.

Tables 44 through 47 contain all of the pertinent experimental results for both bits drilling both rock types. These are the data obtained after data reduction of the digital printouts in the manner described in the preceding section. The values given in the DEPTH columns are the depths equivalent to the calculated values for the axial (overburden) stress, using the measured compressive and ram pressures.

A comparison of the actual simulated depth values in Tables 44 through 47 with the appropriate nominal overburden stress values in Table 41 shows that, in every case, the actual axial stress attained was slightly higher than the target value. This was not critical because analysis of drilling performance was based upon actual, not nominal simulated depth. However, since the simulated depth values were consistently slightly greater than intended, the bore pressures were carefully checked to determine if the wellbore was over- or underpressurized (i.e., was the wellbore pressure greater or less than the hydrostatic pressure that would have been developed by the same mud in a real well of equal depth?). In all but one experiment the wellbore was slightly overpressurized, the excess pressure ranging from a minimum of 22 psi to a maximum of 303 psi. The exception was Experiment No. C-1-S. In this case the rig operator incorrectly set the nominal (target) value for the ram pressure at 5030 psi instead of 4022 psi, which resulted in a nominal overburden stress of 3504 psi. The nominal bore pressure was not adjusted upward to 1752 psi so an underpressurized condition (~ 100 psi) resulted. Analysis of the drilling performance of Bit No. C-1 did not show that this slight underpressurization had an identifiable effect.

The control of the rotary speed was quite good. The experiments were performed using three nominal speeds, 50, 85, and 115 rpm. Examination of all the experimental data showed that spreads in speed for these nominal values were 49.5 to

51.2 rpm, 83.6 to 87.0 rpm, and 113.0 to 119.0 rpm, with one exception. During Experiment No. C-1-S the rotary speed was measured at 97.0 rpm for the portion of the experiment that was targeted for 85 rpm. (See Table 45, Data Sets 37 through 42.) Considering how narrow the range in actual speed about the 85 rpm nominal value was for all the other experiments, this was probably an error on the part of the rig operator, not a malfunction in the rotary control.

Visually comparing the penetration rate and bit weight figures given in Tables 44 through 47 shows that the steel body, stud-type bit (Bit No. S-1) was more aggressive than the cast, hard matrix bit (Bit No. C-1); that is, less bit weight was required to attain equivalent penetration rates. Comparing bit performance in this way only provides qualitative information, however, and gives little useful insight regarding other performance characteristics, such as torque-penetration rate relationships. Therefore, the experimental results were examined in more detail to obtain a more quantitative perspective of bit performance.

Penetration rate was plotted as a function of bit weight for each of the rotary speed - simulated depth, rock type, or bit type - combinations that made up the 12 drilling experiments. For each of these conditions the best fit curve was also determined. These penetration rate-bit weight plots are shown in Figures 123 through 138. Figures 123 through 126 show the effect of bit weight on penetration rate for the C-1 bit drilling marble, and Figures 127 through 130, the effect of bit weight on penetration rate for the C-1 bit drilling sandstone. Figures 131 through 134 and Figures 135 through 138 show the same relationships for the S-1 bit.

All of the penetration rate-bit weight data for the S-1 bit was fitted using a straight line. Similarly, a straight line fit was best for all of the results obtained drilling sandstone with the C-1 bit, with one exception, 50 rpm and zero depth (see Figure 127). In contrast, the penetration rate-bit weight relationship for the C-1 bit drilling Carthage Marble was clearly nonlinear. Satisfactory fits for these data plus the single nonlinear case for the C-1 bit drilling sandstone were obtained using a power function of the form:

$$Y = a + bx + cx^2 \quad \text{Eq. (19)}$$

where:

Y = penetration rate

X = bit weight

The Carthage Marble cuttings produced under pressurized drilling conditions packed easily and had a tendency to stick to the bits. This sticking tendency,

although not severe, was more pronounced with the C-1 bit than with the S-1 bit. In addition, part of the cuttings generated by the hard matrix bit had to be removed through the central core ejector. The packing characteristics of the marble probably reduced the efficiency of ejection of the cuttings and the core from the center of the hole. Less than optimum bit face cleaning was probably the reason for the nonlinear penetration rate-bit weight relationships shown in Figures 124 through 126. The cutter standoff was greater in the case of the steel body stud-type bit (S-1), resulting in better bit face cleaning and the linear penetration rate-bit weight characteristics shown in Figures 132 through 134.

The C-1 bit also exhibited a nonlinear penetration rate-bit weight relationship drilling marble at atmospheric pressure (zero depth), but in this case the rate of change of the penetration rate with increasing bit weight was positive, just the opposite to the performance observed for pressurized conditions. There is no obvious explanation for this performance characteristic, which was not observed drilling the marble at atmospheric pressure with the steel body, stud-type bit. Some speculation may be done, however. At atmospheric pressure (no confining pressure) the rock should fail in a brittle manner, and the efficiency with which the rock will be fractured will increase as the applied stress increases. If the cutter geometry is such that highly localized concentrated stresses are maintained as the bit weight increases, and if the cuttings produced do not become gummy and sticky, so that efficient bit face cleaning can be maintained, the rate of change of penetration rate with increasing bit weight should be positive, up to a certain point, beyond which the drilling fluid can no longer effectively remove the cuttings from the wellbore.

Bit No. C-1 did not exhibit the same drilling characteristics with the Colton Sandstone at atmospheric pressure as it did with the tougher Carthage Marble (compare Figure 127 with Figure 123). The penetration rate was much greater in the sandstone than in the marble at equivalent bit weight. At the slow rotary speed (50 rpm) the cutter engagements necessary to attain the measured penetration rate were large fractions of the total cutter standoff for cutters near the center of the bit face. This condition reduced the effectiveness of the drilling fluid to remove the cuttings and became more pronounced with increasing bit weights.

Bit No. S-1 did not display any of the nonlinear penetration rate-bit weight characteristics of Bit No. C-1. This was probably due to two distinct differences in the design of Bit No. S-1, compared to Bit No. C-1. First, the stud-mounted cutter design did not provide as much clearance around the cutting edge as the cutter attachment method used for the hard matrix bit. At large cutter engagement values the sides of a stud can actually contact the rock and bear some of the load,

thus reducing the stress concentration acting on the rock and reducing the cutting efficiency. Second, the cutter standoff was markedly greater for bit No. S-1 than for Bit No. C-1, which improved bit face cleaning and rock cuttings removal efficiency. These two design characteristics, a "duller" cutter and better bottom hole cleaning, may have counteracted each other to produce the linear penetration rate-bit weight relationship observed with Bit No. S-1.

Using the curves provided in Figures 123 through 138, the performance of the two bits may be compared under the same conditions of rotary speed, bit weight, and simulated depth. It is apparent that the steel body, stud-type bit was markedly more aggressive than the cast, hard matrix bit under all drilling conditions for both sandstone and marble. The plotted data also show that, for both bits, there was a significant dropoff in penetration rate with increasing simulated depth. However, the relationship between penetration rate and depth is not quantitatively described by the penetration rate-bit weight curves so a further analysis was made in an attempt to do so. Using the best fit equations for the penetration rate-bit weight relationships, data files relating penetration rate to simulated depth for selected rotary speeds and bit weights were obtained. These data were in turn curve fitted, using the form:

$$\log Y = a + bx + cx^2 \quad \text{Eq. (20)}$$

where:

Y = penetration rate

X = simulated depth

Excellent fits were obtained. Figures 139 through 146 illustrate the results of this analysis for eight selected conditions of bit type, rock type, and rotary speed. Each figure shows the predicted penetration rate-simulated depth relationship for five selected bit weights from 4000 to 20,000 lb.

Examination of these predicted penetration rate-depth curves shows that the effect of depth (overburden pressure) is more pronounced for sandstone than marble, drilling with either bit, and that the cast, hard matrix bit (No. C-1) performance was reduced more than the steel body, stud-type bit (No. S-1). The curves also suggest that, for optimum performance in deep holes, polycrystalline diamond compact bits should be run at speeds as high as possible, taking into account permissible bit wear rates and the capability of the drilling equipment.

The Drilling Research Laboratory wellbore simulator rig is a very powerful tool capable of operating safely while developing bit torque far in excess of the torque

that would be permitted in the field. As a consequence, a bit can be tested under extremely rigorous conditions where unrealistically high penetration rates are produced. The drilling experiments described in this report are a case in point. The torque transducer was calibrated with an upper limit of 5076 ft-lb and this limit was exceeded several times. A great deal of the data taken included torque values in the 3000 to 5000 ft-lb range. By comparison, the torque limit for most actual drilling operations using 8-in. bits is about 2500 ft-lb, to reduce the chances of twisting off the drill string.

The torque-penetration rate relationship was examined for all tests at the lowest (50 rpm, nominal) and highest (115 rpm, nominal) speeds for both bits and both rock types. For every case examined, torque was a linear function of penetration rate. In addition, for equal penetration rates at a given rotary speed, the torque was the same for either bit. This is shown in Figures 147 through 150, where the combined torque-penetration rate experimental results for both Bit No. C-1 and Bit No. S-1 are plotted.

Figures 147 through 150 clearly illustrate the strengthening effect of the confining and axial pressures upon the rock. The torque necessary to maintain a given penetration rate is markedly greater at a simulated depth of 6000 ft than it is at zero depth (atmospheric pressure). Also, comparing Figure 147 with Figure 148 and Figure 149 with Figure 150, the advantage gained by increasing the rotary speed is evident. The torque at any given penetration rate is significantly reduced as the speed is increased. In addition, if an arbitrary upper limit of 2500 ft-lb is assumed for actual drilling operations, the torque-penetration rate curves show that the penetration rates that may be realized will be significantly lower than experimental drilling results predict if torque is not taken into consideration.

b. Bit Damage

Both bits were carefully examined at the conclusion of the laboratory drilling experiments. The cast, hard matrix bit (No. C-1) sustained no significant damage to either the cutting structure or the bit body. There was some microchipping of the polycrystalline diamond compact cutting edges but not enough dulling of the cutters to impair the bit's performance in a future field test. The natural diamond gage cutting structure was not damaged and there was no visible wear or dulling of the natural diamonds attached to the periphery of the core ejector entrance to assist in cutting the core.

The steel body, stud-type bit (No. S-1) exhibited a large amount of cutting structure damage as well as some damage to the gage cutters. This damage is summa-

rized below:

Cutting structure: Five of the polycrystalline diamond compact cutters were fractured through both the sintered diamond layers and the cemented tungsten carbide substrates, the fractures extending to the braze joints, with a loss of up to one-third of the cutter areas. Figures 151 through 154 show the damage to four of these cutters. Eighteen more cutters were cracked entirely across the sintered diamond table, with the cracks extending into, and in some cases, through the cemented carbide substrate to the braze joint. Figures 155 and 156 are examples of these cracks. One cutter (the compact nearest to the center of rotation of the bit) was spalled, with the loss of about one-quarter of the diamond table area. Six cutters were chipped at the cutting edges, with the chips extending into the cemented carbide substrates. The remaining eight cutters making up the bit face exhibited no damage or very slight microchipping, which was not considered to be significant.

Gage cutters: One of the four half-round gage cutters was badly spalled in the diamond layer. The cutter diametrically opposing this one was misaligned and badly chipped on the corners of the diamond cutting edge. The stud supporting this cutter was rotated about 20° from its specified position. The misalignment probably occurred during bit fabrication. In addition, this cutter protruded 0.050 in. further from the bit body than it should have. The other two gage cutters were undamaged but they were both set out from the bit body too far; 0.050 in. in one case and 0.020 in. in the other case.

Bit body damage: There was no visible damage to the steel bit body but none was anticipated in the absence of gross fracture of the cutting structure diamond and cemented carbide parts. The wellbore simulator drilling experiments were not of long enough duration to produce measurable erosive or abrasive wear.

There were no cracks or fractured diamond compact cutters on the cast, hard matrix bit after the wellbore simulator drilling experiments, yet this bit experienced the same high torque and bit weights as Bit No. S-1. This suggested that the cracked cutters and the subsequent fracture of five of the cutters originated with damage incurred during bit assembly; specifically, when the studs were interference fitted into the bit body. A check with the bit fabricator (Smith Tool) disclosed that difficulty had been encountered during the press fitting operation. This was attributed to the 20° end clearance angle on the studs. All of the fabricator's prior experience in assembling polycrystalline diamond compact bits involved press fitting studs with only 5° of end clearance. The hardened steel punches used to drive the studs into the undersized holes tended to slip sideways and had to be modified to bear on the diamond surface to keep them in place. Unfortunately, this

tooling tended to load the diamond compacts on or very close to the cutting edge. In addition, the diametrical interference used for all of the cutters on the bit face was between 0.003 and 0.004 in., a larger than necessary value which required excessively high forces to press the studs in place.

It was apparent that Bit No. S-1 had to be repaired before it could be tested in the field. Based on the damage assessment given above, the decision was made to replace 28 of the diamond cutter stud assemblies on the bit face and all four of the gage cutter assemblies. At the time, it was anticipated that a field test site would be available in the very near future and that there would not be sufficient time for the bit fabricator to develop a reliable method to press fit studs with 20° end clearance with confidence that the diamond compacts would not be damaged. A set of studs with varying end clearances was supplied to Smith Tool in order to determine the minimum clearance angle that could be used without creating pressing problems. This angle turned out to be 4°. This value was so small as to be considered almost insignificant. In anticipation that the field test formation would be abrasive enough to wear away the end of the carbide stud sufficiently to provide some end clearance, a decision was made to go with replacement stud-cutter assemblies with zero end clearance, and thus eliminate press fitting tooling slippage entirely, insuring that the polycrystalline diamond compacts would not be damaged during bit fabrication.

Concurrently with the press fitting tests run by Smith Tool, a hoop stress and thermal expansion study was made by GE CRD to determine the minimum diametrical interference that would serve to keep the cutter in place in the geothermal drilling test environment. This diametrical interference turned out to be about 0.00075 in., markedly less than the 0.003 to 0.004 in. value used previously. The interference fit range agreed upon for the replacement cutters was 0.001 to 0.0015 in. The damaged diamond compacts were debrazed and the studs removed from the bit body by Smith Tool using an electrical discharge technique that did minimal damage to the steel. After the stud holes were re honed and accurately measured, new stud-mounted cutters were prepared, with the stud diameters ground to provide the specified diametrical interference. The replacement cutters were press fitted into the bit without any problems.

It should be noted that the choice of 0.003 to 0.004 in. diametrical interference by Smith Tool was not unreasonable. At the time Bit No. S-1 was fabricated, very little work had been done with steel body, stud-type polycrystalline diamond compact bits and bit manufacturers had not progressed far on the learning curve for this technology. The bits fabricated by GE Carboloy Systems Department for the

full-scale laboratory drilling experiments conducted at Tulsa University, described earlier in this report, used diametrical interferences in the 0.003 to 0.004 in. range. Extremely high pressing forces were required to assemble these bits but damage to the diamond compacts was avoided because the half-round cutter design provided a much larger area on the end of the cemented carbide stud for the press fitting tooling and a low (5°) end clearance was used, which reduced tool slippage. Additionally, a large diametrical interference is routinely used by Smith Tool, as a manufacturer of roller cone bits, to press fit cemented carbide inserts in the cones. The carbide inserts are subjected to higher unit loading than the loads anticipated for diamond compact drag bits and the direction of the applied stress acting on a carbide insert constantly changes direction as the cone rolls over the formation. High hoop stress is necessary to prevent the cone material from deforming and permitting the carbide insert to fall out or fracture due to insufficient support.

Table 41

NOMINAL CONFINING, RAM AND BORE PRESSURES USED TO TEST BITS NOS. C-1 AND S-1
WITH THE WELLBORE SIMULATOR AT THE DRILLING RESEARCH LABORATORY, TERRA TEK

Experiment No.	Bit No.	Rock Type	Nominal Pressures			Nominal Overburden
			Confining (psi)	Ram (psi)	Bore (psi)	Stress (psi)
C-1-M	C-1	M*	1980	4022	1500	3001
C-2-M	C-1	M	3960	8043	3000	6000
C-3-M	C-1	M	1254	2547	950	1890
C-2A-M	C-1	M	Atmospheric			0
C-1-S	C-1	S**	1980	5030	1500	3504
C-2-S	C-1	S	3960	8043	3000	6000
C-3-S	C-1	S	1254	2547	950	1890
C-1A-S	C-1	S	Atmospheric			0
S-1-M	S-1	M	1980	4022	1500	3001
S-2-M	S-1	M	3960	8043	3000	6000
S-3-M	S-1	M	1450	2735	1050	2092
S-2A-M	S-1	M	Atmospheric			0
S-1-S	S-1	S	1980	4022	1500	3001
S-2-S	S-1	S	3960	8043	3000	6000
S-3-S	S-1	S	1477	3000	1116	2238
S-1A-S	S-1	S	Atmospheric			0

M* = Carthage Marble

S** = Colton Sandstone

Table 42

DRILLING MUD FLOW RATES AND PROPERTIES FOR THE WELLBORE SIMULATOR TESTS
WITH BITS NOS. C-1 AND S-1 AT THE DRILLING RESEARCH LABORATORY, TERRA TEK

Experiment Number	Flow Rate (gpm)	Mud Wgt (lb/gal)	Plastic Viscosity (cp)	Apparent Viscosity (cp)	Filtration (ml)
C-1-M	412	8.7	11	14	11
C-2-M	407	8.9	10	13	12
C-3-M	414	8.9	9	12.5	11
C-2A-M	412	9.1	7	12	—
C-1-S	408	8.8	10	13	11
C-2-S	410	8.8	11	13	12
C-3-S	410	8.9	10	13	—
C-1A-S	414	9.1	7	12	—
S-1-M	426	9.0	8	12	—
S-2-M	433	9.0	7	11.5	10
S-3-M	437	9.1	9	12	11
S-2A-M	436	9.1	7	12	—
S-1-S	428	8.9	9	12	12
S-2-S	433	9.0	9	11	12
S-3-S	432	9.0	9	12	11
S-1A-S	437	9.1	7	12	—

Table 43

ADDITIONAL DRILLING MUD PROPERTIES FOR THE WELLBORE SIMULATOR TESTS
WITH BITS NOS. C-1 AND S-1 AT THE DRILLING RESEARCH LABORATORY, TERRA TEK

Experiment Number	Yield Point (lb/100 sq ft)	Initial Gel (lb/100 sq ft)	10 Minute Gel (lb/100 sq ft)
C-1-M	6	2	5
C-2-M	6	2	4
C-3-M	7	2	3
C-2A-M	10	3	4
C-1-S	7	2	5
C-2-S	4	2	4
C-3-S	6	2	4
C-1A-S	10	3	4
S-1-M	8	2	—
S-2-M	9	2	4
S-3-M	7	3	5
S-2A-M	10	3	4
S-1-S	5	2	3
S-2-S	5	2	2
S-3-S	7	3	5
S-1A-S	10	3	4

Table 44

**EXPERIMENTAL RESULTS FOR WELLBORE DRILLING TESTS
ON CARTHAGE MARBLE USING BIT NO. C-1**

Data Set	Rop (ft/hr)	Torque (ft-lb)	Bit Wgt (lb)	rpm	Depth (ft)
1.	3.34	269	1960	50.2	0
2.	14.33	739	3968	50.2	0
3.	27.73	1265	6109	50.2	0
4.	46.23	1842	8019	50.2	0
5.	57.10	2155	10135	50.2	0
6.	4.22	261	2201	84.4	0
7.	13.78	628	4013	84.4	0
8.	32.60	1085	6069	84.4	0
9.	55.34	1629	7996	84.4	0
10.	75.55	1991	9636	84.4	0
11.	4.58	247	2035	18.3	0
12.	17.69	600	4035	118.3	0
13.	46.05	1092	6170	118.3	0
14.	71.81	1603	7917	118.3	0
15.	6.23	914	3963	51.0	1932
16.	11.26	1627	7667	51.0	1932
17.	24.60	3255	15237	51.0	1932
18.	29.42	4361	21697	51.0	1932
19.	6.42	933	4093	51.0	1932
20.	24.06	3793	18032	51.0	1932
21.	27.19	3862	17969	51.0	1932
22.	16.99	1546	7757	86.0	1942
23.	34.04	3032	15176	86.0	1942
24.	42.66	3922	21561	86.0	1942
25.	9.35	893	4151	86.0	1942
26.	37.74	3345	18176	86.0	1942
27.	22.44	1473	7659	117.0	1942
28.	40.83	2954	15295	117.0	1942
29.	54.00	3891	21687	117.0	1942
30.	8.80	806	4235	117.0	1942
31.	52.76	3649	18191	117.0	1942

Table 44 (Cont'd)

**EXPERIMENTAL RESULTS FOR WELLBORE DRILLING TESTS
ON CARTHAGE MARBLE USING BIT NO. C-1**

Data Set	Rop (ft/hr)	Torque (ft-lb)	Bit Wgt (lb)	rpm	Depth (ft)
32.	9.57	1598	7830	51.0	3055
33.	23.60	3501	16194	51.0	3055
34.	23.05	3201	15389	51.0	3055
35.	21.88	3331	15950	51.0	3055
36.	25.08	4486	21823	51.0	3055
37.	24.45	4422	21911	51.0	3055
38.	16.39	1545	8082	85.0	3059
39.	32.86	3100	15680	85.0	3059
40.	38.94	4050	22150	85.0	3059
41.	6.56	832	4275	85.0	3059
42.	33.35	3717	18248	85.0	3059
43.	18.70	1409	7545	116.0	3047
44.	37.94	2788	14958	116.0	3047
45.	48.63	3790	21418	116.0	3047
46.	1.94	639	2793	51.0	6015
47.	8.95	1757	7578	51.0	6015
48.	17.14	3496	15099	51.0	6015
49.	23.44	4921	21699	51.0	6015
50.	3.98	972	3867	51.0	6015
51.	19.19	4024	17908	51.0	6015
52.	13.03	1605	7475	85.0	6020
53.	26.37	3298	14913	85.0	6020
54.	31.57	4301	21487	85.0	6020
55.	6.42	948	3952	85.0	6020
56.	29.29	3753	17872	85.0	6020
57.	15.66	1597	7393	114.0	6024
58.	34.47	3271	14978	114.0	6024
59.	40.09	4348	21457	114.0	6024
60.	8.36	1004	3924	114.0	6024
61.	37.35	3852	17898	114.0	6024
62.	37.33	3838	17752	114.0	6024
63.	40.61	4065	17942	114.0	6024

Table 45

**EXPERIMENTAL RESULTS FOR WELLBORE DRILLING TESTS
ON COLTON SANDSTONE USING BIT NO. C-1**

Data Set	Rop (ft/hr)	Torque (ft-lb)	Bit Wgt (lb)	rpm	Depth (ft)
1.	12.54	329	1528	50.0	0
2.	15.53	360	1602	50.0	0
3.	34.21	618	2206	50.0	0
4.	80.24	1476	4415	50.0	0
5.	95.02	2042	6365	50.0	0
6.	58.06	1040	3785	50.0	0
7.	92.33	1716	5620	50.0	0
8.	41.98	536	2148	87.0	0
9.	89.19	987	3129	87.0	0
10.	127.79	1354	4018	87.0	0
11.	34.43	394	1775	118.0	0
12.	46.08	534	2242	118.0	0
13.	8.23	135	1733	118.0	0
14.	49.72	544	2736	118.0	0
15.	83.48	792	3291	118.0	0
16.	104.55	986	2723	118.0	0
17.	13.59	281	2297	118.0	0
18.	16.58	1504	7712	51.0	1937
19.	24.19	2724	15312	51.0	1937
20.	21.12	2368	21627	51.0	1937
21.	18.09	1823	11152	51.0	1937
22.	9.52	887	3845	51.0	1937
23.	35.57	2396	15460	86.8	1943
24.	33.67	2591	21459	86.8	1943
25.	27.14	1886	11110	86.8	1943
26.	13.60	896	3784	86.8	1943
27.	33.37	2006	15167	115.3	1914
28.	47.49	2751	21535	115.3	1914
29.	25.82	1471	10857	115.3	1914
30.	11.62	1548	7275	51.0	3516
31.	11.55	1474	7248	51.0	3516

Table 45 (Cont'd)

**EXPERIMENTAL RESULTS FOR WELLBORE DRILLING TESTS
ON COLTON SANDSTONE USING BIT NO. C-1**

Data Set	Rop (ft/hr)	Torque (ft-lb)	Bit Wgt (lb)	rpm	Depth (ft)
32.	14.91	1908	14798	51.0	3516
33.	14.12	1942	14625	51.0	3516
34.	13.59	2053	14765	51.0	3516
35.	18.05	2527	21250	51.0	3516
36.	17.80	2633	21140	51.0	3516
37.	25.01	2078	14567	97.0	3521
38.	24.36	2077	14550	97.0	3521
39.	26.64	2162	14604	97.0	3521
40.	38.63	2764	21136	97.0	3521
41.	35.27	2817	21019	97.0	3521
42.	32.58	2994	21114	97.0	3521
43.	16.60	1147	7236	118.0	3560
44.	19.08	1254	7286	118.0	3560
45.	30.06	2143	15365	118.0	3560
46.	40.13	2537	21410	118.0	3560
47.	46.08	2554	21447	118.0	3560
48.	10.39	1535	7362	50.2	6020
49.	16.20	2293	14962	50.2	6020
50.	12.21	1800	14823	50.2	6020
51.	13.60	2789	21333	50.2	6020
52.	6.35	966	4809	50.2	6020
53.	10.34	1009	7335	85.8	6028
54.	9.58	1050	7352	85.8	6028
55.	17.19	1857	14820	85.8	6028
56.	22.98	2589	21381	85.8	6028
57.	9.39	972	4783	85.8	6028
58.	13.61	1047	7291	118.0	6045
59.	25.61	2093	15605	118.0	6045
60.	31.92	2666	21030	118.0	6045
61.	14.01	1007	4657	118.0	6045
62.	14.00	981	4665	118.0	6045

Table 46

**EXPERIMENTAL RESULTS FOR WELLBORE DRILLING TESTS
ON CARTHAGE MARBLE USING BIT NO. S-1**

Data Set	Rop (ft/hr)	Torque (ft-lb)	Bit Wgt (lb)	rpm	Depth (ft)
1.	11.54	599	3056	49.5	0
2.	9.73	583	3030	49.5	0
3.	25.34	1006	5098	49.5	0
4.	35.83	1496	7196	49.5	0
5.	53.82	2030	9206	49.5	0
6.	10.85	516	3305	83.6	0
7.	29.15	909	5288	83.6	0
8.	47.47	1330	7272	83.6	0
9.	77.79	1946	9319	83.6	0
10.	93.02	2357	11115	83.6	0
11.	13.84	468	3222	118.3	0
12.	42.57	917	5356	118.3	0
13.	56.72	1242	7320	118.3	0
14.	103.83	1893	9594	118.3	0
15.	4.45	873	3919	50.0	2076
16.	12.43	1828	7938	50.0	2076
17.	23.00	2964	11877	50.0	2076
18.	36.93	4313	14771	50.0	2076
19.	12.41	1591	5896	50.0	2076
20.	5.57	712	3857	84.2	2087
21.	20.83	1744	7850	84.2	2087
22.	39.57	2999	11966	84.2	2087
23.	53.19	4103	14938	84.2	2087
24.	16.52	1400	6019	84.2	2087
25.	7.20	686	3881	116.5	2084
26.	28.05	1759	7850	116.5	2084
27.	53.15	3079	11874	116.5	2084
28.	72.83	3925	15077	116.5	2084
29.	11.99	1070	5899	116.5	2084
30.	33.53	2282	9817	116.5	2084

Table 46 (Cont'd)

**EXPERIMENTAL RESULTS FOR WELLBORE DRILLING TESTS
ON CARTHAGE MARBLE USING BIT NO. S-1**

Data Set	Rop (ft/hr)	Torque (ft-lb)	Bit Wgt (lb)	rpm	Depth (ft)
31.	4.78	836	3784	51.2	3005
32.	14.70	2019	7879	51.2	2975
33.	20.85	3036	11840	51.2	3005
34.	27.00	4262	14773	51.2	3005
35.	10.14	1537	5722	51.2	3005
36.	37.13	5064	17676	51.2	3005
37.	4.55	665	3744	85.6	3003
38.	16.51	1713	7715	85.6	3003
39.	37.26	3222	11809	85.6	3003
40.	50.93	4236	14877	85.6	3003
41.	13.43	1321	5720	85.6	3003
42.	5.25	738	3750	116.0	3008
43.	22.64	1865	7711	116.0	3008
44.	49.36	3147	11809	116.0	3008
45.	59.79	3794	14441	116.0	3008
46.	13.69	1189	5779	116.0	3008
47.	3.38	963	3856	51.0	6034
48.	9.00	2070	7973	51.0	6034
49.	14.20	3236	12010	51.0	6034
50.	19.83	4247	14870	51.0	6034
51.	4.02	907	4156	85.2	6034
52.	13.78	1914	8191	85.2	6034
53.	28.56	3341	12199	85.2	6034
54.	35.80	4404	15042	85.2	6034
55.	31.84	4429	16279	85.2	6034
56.	6.10	898	3831	113.0	6042
57.	17.34	1884	7872	113.0	6042
58.	35.75	3327	11907	113.0	6042
59.	46.84	4438	14896	113.0	6042
60.	41.09	4164	16312	113.0	6042

Table 47

**EXPERIMENTAL RESULTS FOR WELLBORE TESTS
ON COLTON SANDSTONE USING BIT NO. S-1**

Data Set	Rop (ft/lb)	Torque (ft-lb)	Bit Wgt (lb)	rpm	Depth (ft)
1.	11.60	193	1037	50.2	0
2.	10.54	188	1055	50.2	0
3.	33.80	535	2069	50.2	0
4.	60.80	943	3108	50.2	0
5.	78.05	1257	4072	50.2	0
6.	8.77	153	1066	84.8	0
7.	47.83	554	2102	84.8	0
8.	84.73	929	3078	84.8	0
9.	103.87	1413	3683	84.8	0
10.	12.44	156	1129	119.0	0
11.	67.65	566	2100	119.0	0
12.	116.10	951	3132	119.0	0
13.	76.13	701	2637	119.0	0
14.	26.24	1623	3930	51.0	2370
15.	44.44	3196	9526	51.0	2370
16.	56.49	4817	15016	51.0	2370
17.	30.53	1431	3823	85.3	2373
18.	60.96	3090	9629	85.3	2373
19.	95.54	4500	14935	85.3	2373
20.	43.95	1779	4118	115.0	2370
21.	83.26	3123	9538	115.0	2370
22.	101.68	4543	14870	115.0	2370
23.	19.76	2500	7433	51.0	3024
24.	35.14	4292	14886	51.0	3024
25.	51.05	5076	21403	51.0	3024
26.	33.76	2337	7375	85.7	3053
27.	58.72	4257	14836	85.7	3053
28.	76.38	5076	21412	85.7	3053
29.	37.68	2042	7407	113.7	3046
30.	78.89	4123	14868	113.7	3046

Table 47 (Cont'd)

EXPERIMENTAL RESULTS FOR WELLBORE TESTS
ON COLTON SANDSTONE USING BIT NO. S-1

Data Set	Rop (ft/lb)	Torque (ft-lb)	Bit Wgt (lb)	rpm	Depth (ft)
31.	106.13	5076	20858	113.7	3046
32.	12.42	1535	3729	51.0	6028
33.	21.98	3090	9466	51.0	6028
34.	27.92	4232	14834	51.0	6028
35.	16.79	2344	6340	51.0	6028
36.	30.10	3890	12306	51.0	6028
37.	18.40	1473	3771	84.8	6026
38.	31.17	2952	9338	84.8	6026
39.	40.69	3966	14933	84.8	6026
40.	27.13	2378	6214	84.8	6026
41.	39.89	3617	12244	84.8	6026
42.	35.83	2745	9120	114.4	6028
43.	54.41	4212	14664	114.4	6028
44.	35.68	2427	6563	114.4	6028
45.	51.86	3540	12464	114.4	6028

Figure 123. Drilling Experiment No. C-2A-M

Figure 124. Drilling Experiment No. C-3-M. Simulated Depths Were: 1932 ft (51 rpm), 1942 ft (86 rpm) and 1949 ft (117 rpm)

Figure 125. Drilling Experiment No. C-1-M. Simulated Depths Were: 3054 ft (51 rpm), 3059 ft (85 rpm) and 3047 ft (116 rpm).

Figure 126. Drilling Experiment No. C-2-M. Simulated Depths Were: 6015 ft (51 rpm), 6019 ft (85 rpm) and 6024 ft (114 rpm).

Figure 127. Drilling Experiment No. C-1A-S

Figure 128. Drilling Experiment No. C-3-S. Simulated Depths Were: 1938 ft (51 rpm), 1943 ft (87 rpm), and 1914 ft (115 rpm).

Figure 129. Drilling Experiment No. C-1-S. Simulated Depths Were: 3516 ft (51 rpm), 3520 ft (97 rpm), and 3560 ft (118 rpm).

Figure 130. Drilling Experiment No. C-2-S. Simulated Depths Were: 6019 ft (50 rpm), 6028 ft (86 rpm), and 6045 ft (118 rpm).

Figure 131. Drilling Experiment No. S-2A-M

Figure 132. Drilling Experiment No. S-3-M. Simulated Depths Were: 2076 ft (50 rpm), 2088 ft (84 rpm), and 2084 ft (117 rpm).

Figure 133. Drilling Experiment No. S-1-M. Simulated Depths Were: 3005 ft (51 rpm), 3003 ft (86 rpm), and 3008 ft (116 rpm).

Figure 134. Drilling Experiment No. S-2-M. Simulated Depths Were: 6035 ft (51 rpm), 6035 ft (85 rpm) and 6042 ft (113 rpm).

Figure 135. Drilling Experiment No. S-1A-S

Figure 136. Drilling Experiment No. S-3-5. Simulated Depths Were: 2369 ft (51 rpm), 2373 ft (85 rpm) and 2370 ft (115 rpm).

Figure 137. Drilling Experiment No. S-1-S. Simulated Depths Were 3024 ft (51 rpm), 3053 ft (86 rpm) and 3046 ft (114 rpm).

Figure 138. Drilling Experiment No. S-2-S. Simulated Depths Were: 6028 ft (51 rpm), 6025 ft (85 rpm) and 6032 ft (114 rpm).

Figure 139. Predicted Penetration Rate for Bit No. C-1 Drilling Carthage Marble at 51 rpm, as a Function of Simulated Depth for Selected Bit Weights up to 20,000 lb.

Figure 140. Predicted Penetration Rate for Bit No. S-1 Drilling Carthage Marble at 116 rpm, as a Function of Simulated Depth for Selected Bit Weights up to 20,000 lb.

Figure 141. Predicted Penetration Rate for Bit No. C-1 Drilling Colton Sandstone at 50 rpm, as a Function of Simulated Depth for Selected Bit Weights up to 20,000 lb.

Figure 142. Predicted Penetration Rate for Bit No. C-1 Drilling Colton Sandstone at 118 rpm, as a Function of Simulated Depth for Selected Bit Weights up to 20,000 lb.

Figure 143. Predicted Penetration Rate for Bit No. S-1 Drilling Carthage Marble at 51 rpm, as a Function of Simulated Depth for Selected Bit Weights up to 20,000 lb.

Figure 144. Predicted Penetration Rate for Bit No. S-1 Drilling Carthage Marble at 116 rpm, as a Function of Simulated Depth for Selected Bit Weights up to 20,000 lb.

Figure 145. Predicted Penetration Rate for Bit No. S-1 Drilling Colton Sandstone at 51 rpm, as a Function of Simulated Depth for Selected Bit Weights up to 20,000 lb.

Figure 146. Predicted Penetration Rate for Bit No. S-1 Drilling Colton Sandstone at 116 rpm, as a Function of Simulated Depth for Selected Bit Weights up to 20,000 lb.

Figure 147. Combined C-1 and S-1 Torque Results Drilling Carthage Marble at 50 rpm, 0 and 6000 ft Simulated Depths, Plotted as Functions of Penetration Rate.

Figure 148. Combined C-1 and S-1 Torque Results Drilling Carthage Marble at 115 rpm, 0 and 6000 ft Simulated Depths, Plotted as Functions of Penetration Rate.

Figure 149. Combined C-1 and S-1 Torque Results Drilling Colton Sandstone at 50 rpm, 0 and 6000 ft Simulated Depths, Plotted as Functions of Penetration Rate.

Figure 150. Combined C-1 and S-1 Torque Results Drilling Colton Sandstone at 115 rpm, 0 and 6000 ft Simulated Depths, Plotted as Functions of Penetration Rate.

Figure 151. Polycrystalline Diamond Compact Cutter No. 2, Bit No. S-1. Approximately One-quarter of the Compact Was Lost Due to Fracture Originating at the Sintered Diamond Layer Surface.

Figure 152. Compact Cutter No. 15, Bit No. S-1, Exhibiting the Same Failure Mode as Cutter No. 2. Note Additional Crack in the Cemented Carbide Stud.

Figure 153. Compact Cutter No. 19, Bit No. S-1, Showing the Same Failure Mode as Cutter No. 2.

Figure 154. Compact Cutter No. 24, Bit No. S-1, Exhibiting the Same Failure Mode as Cutter No. 2. About One-third of the Compact Was Detached.

Figure 155. Compact Cutter No. 10, Bit No.S-1. (The cracks penetrated the cemented carbide substrate to the braze joint but no appreciable part of the cutting edge was lost.)

Figure 156. Compact Cutter No. 17, Bit No. S-1. (The crack penetrated the cemented carbide substrate to the braze joint.)

I. BIT NO. S-1 FIELD TEST AND FAILURE ANALYSIS

1. FIELD TEST - BIT NO. S-1

An attempt was made to test the steel body stud-type polycrystalline diamond compact bit (No. S-1) in a hydrothermal well being drilled by the Union Oil Company in the Baca Field, Valles Caldera, north of Albuquerque and west of Los Alamos, NM. The drill site was located at an elevation of about 9800 ft above sea level. Figure 157 shows the site.

The producing zone of this geothermal resource was primarily Bandolera Tuff and the basement formation was andesite. Drilling in the tuff and into the basement rock was conducted using aerated water instead of mud because of the high hole temperature and to reduce the hydrostatic pressure to avoid lost circulation and/or plugging the hot water access to the bore hole. The drilling fluid had amine type additives to control the pH between 10.5 and 11.5 to reduce corrosion.

The hole in which Bit No. S-1 was tested had already been drilled through the producing zone and approximately 250 ft into the basement rock, and was, in fact, a producing hydrothermal well. The STRATAPAX^R bit went into the hole at 6250 ft with permission to drill to 6500 ft if possible. The bore hole deviation from the vertical was 22° to 6250 ft, and this deviation may have been one of the contributing factors to the lack of success of the test. The original drilling program called for casing to be set to 3000 ft and the hole completed using 8-3/4 in. dia. bits. The expectation was that the hole would be essentially vertical when completed. However, problems had been encountered at about 4500 ft, which required the hole to be plugged just below the bottom of the casing at 3000 ft and kicked off to redrill the 8-3/4 in. section, resulting in the 22° vertical deviation.

The bit preceding the diamond compact bit was a Smith Tool 7JA, 8-3/4 in. rock bit, which made 241 ft of hole in 15 hours rotating time (16.06 ft/hr) with between 15×10^3 and 20×10^3 lb bit weight. The drill string included 10 sections of 7-in. drill collar, a monel collar near the bit, and a reamer. The remainder of the string was 4 1/2 drill pipe and the total weight on the hook was about 151,000 lb. The drilling fluid was water plus air (217 gpm water and 2000 cfm air) and the rotating speed was 45-50 rpm. The 7JA bit was carefully examined when it was removed from the hole. It exhibited very little wear and no significant loss of gage.

The reamer and monel collar were removed from the string and the diamond compact bit attached using a cross-over sub. An additional 6-in. collar was added, to make the weight on the hook about 150×10^3 lb at 6250 ft. The bit went into the

hole with the largest nozzles available (20/32 in.) in order to reduce the pressure drop across the bit.

When the experimental diamond compact bit reached the bottom of the hole, the Kelly bushing was still several feet above the rotary table. Knowing exactly where bottom is can be very difficult for the driller in hot geothermal wells because the drill string will increase several feet in length due to thermal expansion. Nevertheless, it would have been more desirable to have engaged the rotary bushing and established rotation and circulation before reaching bottom, rather than setting the bit down with an unknown amount of weight on it. After removing a joint of drill pipe, the Kelly bushing was engaged, circulation and rotation started, and the bit carefully lowered to bottom.

The original test plan called for carrying out a series of "drill off" experiments over a rotary speed range of 40 to 80 rpm, starting each test at a relatively high bit weight (i.e., 30×10^3 lb) and observing the time-weight on bit relationship. In theory, this technique will quickly indicate the optimum bit weight for each rotary speed used. In practice, it was unsuccessful. The rotary speed as read from the dial indicator on the rig flow was very erratic, varying as much as ± 15 rpm from the desired figure. The first experiments were conducted at a nominal speed of 50 rpm. The drop off in bit weight with time never showed any reasonable trends. Increasing the speed to 60 rpm (nominal) did not provide any improvement and an attempt to test the bit at 70 rpm resulted in excessive speed fluctuations. After about an hour of attempted "drill off" experiments, this approach was abandoned.

The bit was then run at 50 rpm (nominal), 285 gpm water, 2000 cfm air at bit weights from 15,000 to 25,000 lb for two hours. At the end of this time no measurable penetration had been made and the bit was withdrawn from the hole. It had undergone severe damage to all the cutters from the crown outwards, to all four gage protective cutters, and had experienced severe gage wear on the bit body itself. Figure 158 shows the bit before testing and Figures 159 and 160 show the damage produced during the field test. Since further drilling was obviously impossible, the bit was taken to Sandia Laboratories, Albuquerque, where two essentially undamaged stud diamond compact cutter assemblies were removed by electrical discharge machining. It was then sent to GE-CRD, Schenectady for detailed inspection and failure analysis.

Figure 157. Drill Rig on Site in Baca Field, Early Morning of Day of Test. Elevation approximately 9800 ft.

Figure 158. Bit No. S-1 Prior to the Field Test. (Twenty-eight studs and STRATAPAX cutters were replaced on the bit face as well as all four gage protection studs and cutters by Smith Tool following the pressure vessel wellbore simulation experiments at Terra Tek, Salt Lake City, Utah.)

Figure 159. Overall View of Bit No. S-1 After Testing, Showing Extensive Damage to the Bit Face Cutters and the Severe Gage Wear Produced

Figure 160. View of the Face of Bit No. S-1 Showing Severe Fracture of the Cemented Carbide Studs Which Support the STRATAPAX Cutters

2. FAILURE ANALYSIS - BIT NO. S-1

Examination of Bit No. S-1 following the abortive field test in the Baca Field, New Mexico revealed major damage of three sorts; (1) broken cemented carbide studs, (2) a missing carbide stud plus one that had turned in its hole, and (3) heavy diametrical wear on the bit body. There were also heavily damaged diamond compact blanks, plus some missing blanks, but it appeared that this was primarily associated with the carbide support stud failures and not due to a basic weakness in the braze attachment technique used in manufacturing the bit.

✓ Figure 161 is a drawing showing the numbered locations of all the cutters and nozzle locations. As mentioned previously, the bit was taken from the field test site to Sandia Laboratories for a preliminary inspection, and to have two essentially undamaged studs removed. These were studs at locations No. 8 and 10. Figure 162 showing the entire bit face, was taken at GE-CRD, Schenectady after these two studs had been removed. Table 48 summarizes the condition of each of the cemented carbide studs and diamond compact blanks.

Examination of Table 48 and Figure 162 shows that there are three regions on the bit face that apparently represent different modes and degrees of failure for the stud-diamond compact cutter assemblies. This, in turn, gives us some insight into what may have occurred while the bit was in the hole. Fourteen studs in the crown region of the bit face (No. 11 through 24 inclusive) were broken off almost flush with the body in a way that suggests a single crack originating near the root of the cutter pocket which propagated all the way across the stud diameter. Each of these studs apparently broke off in one piece under application of an excessive load. On the other hand, with the exception of stud-cutter assemblies No. 36 and 38, the major damage mode in the outer (peripheral) region of the bit face (No. 25 through 35 plus No. 37) was different. In most cases the carbide stud fractured in vertical layers starting from the back side and the diamond compacts broke when there was insufficient supporting material remaining. There was also some gross diamond compact chipping and grooving type of wear and two instances where the cutters were lost with significant portions of the pockets remaining. In contrast to these two failure modes, there was no serious damage to the studs in the center of the bit (locations No. 1 through 10 inclusive). There was only relatively minor diamond edge chipping for these 10 cutters.

The two undamaged studs that were removed from the center of the bit were sectioned along the stud cylindrical axis perpendicular to the diamond compact cutter surface so that the cemented carbide studs could be examined for cracks in the re-

gion near the back of the pocket into which the diamond cutters were brazed. The suspected cracks were found in both studs, as shown in Figures 163 and 164. Higher magnification revealed braze alloy in the cracks (See Figures 165 and 166). An unused stud-diamond compact cutter assembly, which had been sent to Smith Tool, was obtained and sectioned. This was also cracked, with braze alloy in the crack (see Figures 167 and 168). Obviously the presence of braze alloy in the cracks negated the possibility that the carbide was cracked when the studs were press fitted into the bit body. The only question that remained was when the cracks occurred. An unbrazed stud from the same lot that was used for this bit was sectioned. Figure 169 shows that no cracks were present. Apparently, the studs were cracked during the brazing process when the material was subjected to nonuniform heating, giving rise to high thermal stress gradients. The locations of the cracks observed also suggest that the relatively sharp angles made by the stud pocket chamfer create a condition favorable for generation of locally high stresses. It is possible that almost every stud in Bit No. S-1 was cracked in the same manner as the ones that were examined.

Figures 170, 171, and 172 are photographs of the remaining portions of stud No. 22, 23, and 24 in the crown section of the bit body. In each photograph the small remaining portion of the pocket can be seen on the right. It is apparent from these pictures that a brittle fracture originated at the pocket and traversed almost all the way across the stud from right to left. Figure 170, stud No. 22 is an excellent example of this kind of failure. Figure 173 is a photograph taken from the side showing the fractured tips of the same three studs (in the foreground of the photograph) protruding above the bit body. The fractured carbide edges are still sharp and show no evidence of wear. This was typical of the entire crown area of the bit face. In addition, there was no evidence of wear on the face of the bit body itself as might have been expected after rubbing for three hours against rock. The only conclusion that can be drawn is that the bit was never seated in the bottom of the hole while it was rotating.

Figures 174 through 181 show the wear and failure modes typical of the studs and diamond compacts located on the outer portion of the bit face. Figures 174 and 175 are two views of cutter No. 27, which was the least damaged of cutters No. 25 through 38. The principal damage is a wear groove through both the diamond compact and the cemented carbide stud. There is some minor chipping and spalling of the diamond compact but the cemented carbide stud is intact. More typical of this region of the bit face are the conditions shown in Figures 176 and 177 (cutter No. 28), Figure 178 (cutter No. 26) and Figure 179 (cutter No. 33). The same wear groove can be seen in all cases plus additional diamond compact fracture, although most of the

diamond compact remains in each case. However, the cemented carbide studs have begun to fail by delamination fracture from the back side. This type of failure could be caused by either (1) an internal shock wave reflection or (2) surface heat checking on the ends of the studs from frictional heat.

Extreme carbide delamination failure is shown in Figure 180 (cutters No. 32 and 37) and Figure 181 (cutter No. 34). Note that, even with this severe damage, parts of cutters No. 32 and 34, remained attached to the cemented tungsten supports.

Steel alloy temperature sensitive elements had been inserted into the face of the bit body during its manufacture. These were removed after the field test and returned to Smith Tool for inspection. The temperature sensor locations are shown in Figure 162 as the small holes to the left of cutter locations No. 10 and 14. Smith Tool concluded that the bit body had reached a maximum temperature of 525 °F, which was very close to the bottom hole temperature anticipated by Union Oil Co.

Extensive damage was done to the four gage cutters, diamond compacts No. 39 through 42 (see Figure 161). Cutters No. 39 and 41 had extensive fracture damage to both the diamond compacts and the cemented tungsten carbide studs. No. 40 suffered similar damage and had also rotated about 20°. Cutter No. 42 was entirely missing. Careful examination of the hole showed that it was clean, very smooth (no indication of galling when the stud was pressed in), with a slight indication of broaching on one side as if the stud had been started in slightly out of alignment. The edges of the hole were still sharp and undeformed so the stud was not forced out by a side thrust. The inside diameter of the hole was carefully measured and found to be 0.6395 in. Since the cemented tungsten carbide stud was 0.6400 in., the room temperature diametrical interference was only 0.0005 in. Due to the difference in thermal expansion of the steel and the carbide, the diametrical interference at 525 °F was zero, which suggests how the stud was lost. Exactly when the loss occurred is not known, but it probably happened early in the field test, perhaps before rotation of the bit was begun.

There was significant bit body gage wear that resulted from three hours of bit rotation. The total diametrical wear was almost 1/4 in., but there was no wear of the steel on the bit face. The worn steel surface looked as if it had been machined, including the formation of sharp metal burrs where the gage intersected the junk slots. The absence of wear on the bit face plus the severe gage wear point to the conclusion that the bit never reached the bottom of the hole after the kelly bushing was engaged and rotation was started. Since the well bore was inclined 22°, any tungsten carbide stud debris which was created when the bit first hit bottom would have accumulated in the lower side of the hole, and this very dense material

would not necessarily have been washed out when circulation began. Thus, the bit probably rode on this debris just above bottom and cut a shoulder into the side of the hole. Broken carbide studs may have been forced into the andesite formation, providing the very hard material necessary to "machine" away the bit gage. This also explains how the three remaining gage cutters were "worn" down flush with the reduced gage diameter. Rubbing against rock would not have produced equal amounts of wear on the cemented tungsten carbide studs, the diamond blanks and the much softer steel bit body.

When the bit was removed from the hole it was noted that one of the nozzles was missing (See Figure 162). Examination of the nozzle port showed no evidence that suggested that the nozzle became unscrewed during the test. The other four nozzles were still tightly screwed into place. It is our opinion that the nozzle was not in place when the bit was tested. The bit was started into the hole at about 2 am and, with the poor lighting conditions on the rig floor, a missing nozzle set in a deep recess in the bit body could have gone unnoticed. The bit was shipped from California with all five nozzles installed, but this was not the first time a nozzle with a cemented carbide sleeve disappeared, and probably will not be the last.

Although the field test of polycrystalline diamond compact Bit No. S-1 was disappointing, several beneficial lessons were learned.

1. Pocketed cemented tungsten carbide studs should not be used with brazed diamond compact cutters, due to the formation of cracks in the studs created during the brazing process. Unpocketed studs which have no potential stress risers, together with the best high-temperature brazing process, should eliminate this problem.
2. The braze alloy used, although not as strong as the one available later, was sufficient to retain the STRATAPAX^R cutters, even though the bit body temperature reached at least 525 °F.
3. The delamination failure mode observed for the studs on the outer section of the bit face indicates that the end clearance was not sufficient to prevent excessive frictional heat created by the cemented carbide rubbing against hard rock. However, provision of adequate stud end clearance made interference press fitting of the studs into a steel bit body very difficult and risky. New stud configurations and improved techniques for interference fitting to the bit body should be developed and incorporated in the design and fabrication of future bits.
4. The concept of gage wear protection cutters was not unsound, but problems in

accurate location of these cutters (see the wellbore simulation test results discussed earlier) and retention of these parts suggested that the present design should be discontinued until better interference fitting techniques were available. However, additional gage wear protection using diamond compacts pressed in flush with the bit body in a manner analogous to the use of cemented tungsten carbide inserts might be used.

5. The question of the necessity of providing hard-facing erosion protection on the face of the bit body remained unresolved. With the air-water mixtures used in the Baca Field there was no evidence of erosion wear any place on the bit body, including the nozzle parts. However, since the bit did not rotate on bottom, the splashback effect which could have caused localized erosion was not operative. Also, premature loss of all the crown cutters and studs may have changed the circulation characteristics and eliminated a great deal of potential turbulent flow.
6. If possible, future field tests should not be attempted in holes that are markedly nonvertical, although there may not be much choice or control over this condition. In addition, to be certain that the bit does not receive excessive loading when it initially reaches bottom, the Kelly bushing should be engaged and both rotation and circulation started at least one joint of drill pipe before the bottom of the hole is reached.

Although much was learned of a materials and bit fabrication nature the actual cutting structure was not evaluated. Consequently, the decision was made to fabricate an additional diamond compact stud-type bit, to be designated Bit No. S-1, Modified. The cutter layout would be the same as Bit No. S-1, but unpocketed cemented carbide studs would be used and stud-mounted gage cutters would not be used. In their place would be eight diamond compact blanks mounted with the top (circular) surfaces flush with the bit body. This bit would be fabricated by Smith Tool, Irvine, California.

Table 48

**RESULTS OF EXAMINATION OF STRATAPAX
CUTTERS AND STUDS AFTER FIELD TEST OF BIT NO. S-1**

Cutter No.	Stud & Cutter Essentially Undamaged	Stud Broken Off Flush With Body	Some Stud & Cutter Remaining	Some Stud Remaining. Cutter Gone.	Comments
1	x				Slight edge chipping
2	x				Edge spalled
3	x				Very slight edge wear
4	x				Very slight edge chip
5	x				Small portion cutter missing. Maybe cracked during press fitting.
6	x				Edge chip-out
7	x				Edge chip-out and slight wear
8	x				Stud with cutter removed by Sandia Labs
9	x				Small edge chip and edge wear
10	x				Stud with cutter removed by Sandia Labs.
11		x			Broken at root of pocket. Sharp tungsten carbide corners remaining. No wear of the tungsten carbide.
12		x			Identical to cutter No. 11
13		x			Identical to cutter No. 11
14		x			May have fractured below root of pocket. Some damage due to removal of adjacent stud No. 10.
15		x			Same as cutter No. 11.
16		x			Same as cutter No. 11
17		x			Same as cutter No. 11, but slight carbide wear
18		x			Same as cutter No. 11
19		x			Same as cutter No. 11
20		x			Same as cutter No. 11
21		x			Same as cutter No. 11
22		x			Same as cutter No. 11
23		x			Same as cutter No. 11
24		x			Same as cutter No. 11
25				x	Most of pocket remaining. Stud delaminated from back side. Significant amount of tungsten carbide wear.
26			x		About 1/2 of cutter remaining. Stud delaminated from back side. Marked wear of stud above remaining cutter.
27			x		About 2/3 of cutter remaining. Groove wear in end of tungsten carbide stud. No delamination or other fracture of stud.
28			x		About 2/3 of cutter remaining. Groove wear in end of stud plus delamination from back side.
29			x		Same as cutter No. 28. Also crack in stud which would have lead to further delamination type fracture.
30				x	About 2/3 of pocket remaining. Stud delaminated from back side. Groove wear in end of stud.

Table 48
RESULTS OF EXAMINATION OF STRATAPAX
CUTTERS AND STUDS AFTER FIELD TEST OF BIT NO. S-1

Cutter No.	Stud & Cutter Essentially Undamaged	Stud Broken Off Flush With Body	Some Stud & Cutter Remaining	Some Stud Remaining. Cutter Gone.	Comments
31			x		About 1/3 of cutter remaining. Stud delaminated from back. Also groove wear.
32			x		1/4 of cutter left with very little tungsten carbide backup. Fracture appeared to be more like studs Nos. 11-24 than gradual delamination from back.
33			x		Same as cutter No. 31, except slightly more than 1/2 of the cutter remaining.
34			x		About 1/2 of cutter remains. Fracture of stud appears to have originated at middle of pocket, but this may have been preceded by delamination failure. No wear. All remaining edges still sharp.
35				x	Fractured at root of pocket. Sharp tungsten carbide edges protruding above bit body with no wear.
36		x			May have failed in similar manner to cutter No. 35 and then fractured further small pieces at a time. Some sharp tungsten carbide edges remaining.
37				x	About 1/10 of pocket remaining. Failure by delamination from back side. Very sharp edges left with no evidence of wear.
38		x			Brittle fracture originating at root of pocket. Very sharp edges remaining except at gage where some wear is evident.
39			x		(Gage wear protection cutter) about 1/3 of cutter remaining. Failure by delamination from back side of stud. Groove wear in tungsten carbide.
40			x		(Gage wear protection cutter). Same as cutter No. 39 except delamination more severe. <i>Stud rotated slightly in hole.</i>
41			x		(Gage wear protection cutter) same failure as cutter No. 39.
42		STUD MISSING.			Hole in bit body was clean, smooth. Evidenced of slight broaching on one side. Hole diameter was measured and found to be 0.6395 inch. <i>Only 0.0005 inch interference.</i> This is not sufficient to maintain any interference between bit body and stud at 525°F.

Figure 161. Cutter and Nozzle Locations, Polycrystalline Diamond Compact Bit No. S-1

Figure 162. Photograph of Bit Face After the Test in New Mexico. Note that two cutters, No. 8 and 10, have been removed from the bit body

Figure 163. Section Through Stud Removed from Cutter Location No. 8, Showing Crack Originating at Chamfer at Bottom of Pocket. 75X

Figure 164. Section Through Stud Removed from Cutter Location No. 10, with Crack Similar to Cutter Stud No. 8. 75X

Figure 165. Crack in Cutter Stud No. 8 at Higher Magnification. Braze alloy is present in the crack. 750X

Figure 166. Crack in Cutter Stud No. 10 at Higher Magnification than Figure D. Braze alloy has penetrated the crack. 750X

Figure 167. Section Through Unused Brazed Stud - Diamond Compact Cutter Assembly, Showing Crack in the Tungsten Carbide Stud. 75X

Figure 168. Higher Magnification Photograph of Stud in Figure G, Revealing that the Braze Alloy Had Penetrated Into the Crack. 750X

Figure 169. Section Through an Unused Cemented Tungsten Carbide Stud from the Same Lot Used to Fabricate Bit No. S-1. There are no cracks visible in this specimen. 75X

Figure 170. Remaining Portion of Stud at Cutter Location No. 22. Failure was by brittle fracture originating at the root of the pocket.

Figure 171. Remaining Portion of Stud at Cutter Location No. 23. (Brittle fracture failure originating at root of pocket.)

Figure 172. Remaining Portion of Stud at Cutter Location No. 24. (Brittle fracture like studs No. 22 and 23.)

Figure 173. Side View of Sharp Tips of Studs at Cutter Locations No. 22, 23, 24 Showing Tungsten Carbide Protruding Above Steel Bit Body. Note no evidence or wear of bit body face.

Figure 174. Cutter No. 27 as Viewed from Front. (Note some diamond layer spalling plus groove wear on top.)

Figure 175. Cutter No. 27 as Viewed from the Back. (Note there is no fracture of the tungsten carbide stud.)

Figure 176. Cutter No. 28 as Viewed from the Front. (Diamond compact blank has fractured and the stud has extensive groove wear.)

Figure 177. Cutter No. 28 as Viewed from the Back. (The stud has delaminated by a vertical brittle fracture.)

Figure 178. Cutter No. 26 as Viewed from the Top. (The diamond compact blank has fractured diagonally. (There is significant groove wear on the top of the stud, which has delaminated from the backside.)

Figure 179. Cutter No. 33, as Viewed from the Top. (Fracture and wear are essentially the same as cutters No. 26 and 28.)

Figure 180. Extreme Carbide Stud Delamination Failure of Cutter Location No. 32 and 37. [A small portion of cutter No. 32 is still attached to its stud. (Right hand cutter in photo)]

Figure 181. Extreme Carbide Stud Delamination Failure at Cutter Location No. 34.
(Note that part of the diamond compact blank is still attached to the stud.)

J. DESIGN AND FABRICATION OF BIT NO. S-1, MODIFIED, AND MODIFICATION OF BIT NO. C-1

1. BIT NO. S-1, MODIFIED, DESIGN CHANGES AND FABRICATION

As soon as it was determined that there would be an opportunity for another drilling test in the Baca Field, NM, a second stud-type steel body polycrystalline diamond compact bit was fabricated by Smith Tool, Irvine, California. The new bit, designated Bit No. S-1, Modified, was identical to the original one, No. S-1, except for the following modifications.

1. The cutters making up the bit face cutting structure (cutters No. 1 through 38) were changed to GE's new No. 2542 STRATAPAX^R blank stud cutter assembly, consisting of the No. 2530-NC STRATAPAX^R polycrystalline diamond compact drill blank attached to an unpocketed Carboly Grade 55B cemented tungsten carbide stud. The cutter back rake was -20° , as before, and the end clearance angle was -5° . The compacts were attached to the studs using GE's new high-strength "LS" brazing process. The new stud was designed so that, with the diamond compact drill blank attached, the tip of the cutting edge was offset the same distance from the cylindrical axis of the stud as with the pocketed stud used previously. Consequently, the locations of the stud holes in the new bit body did not have to be changed from those for Bit No. S-1. (It should be noted that the primary reason for the development of the No. 2542 STRATAPAX^R blank stud cutter was evidence of cracks in the pocketed stud provided by the field test of Bit No. S-1.)
2. The half-round, straight-edge, stud-mounted polycrystalline diamond compact gage cutters (No. 39 through 42 in the original Bit No. S-1 design) were omitted entirely. There were two reasons for this. First, it was felt that the sharp corners of the diamond cutting edges might be subject to high stress concentrations that would increase the chances of spalling and fracture of the diamond layer. Second, it was not known if the braze joint would provide sufficient strength (without the additional pocket support) to guarantee retention of the cutter. With the omission of the gage cutters, the narrow ribs which had been cut back to provide clearance for these cutters were extended to the full bit diameter to provide additional bearing surface. These modifications are noted in Figure 182, and the new No. 2542 STRATAPAX^R blank stud cutter design is shown in Figure 183.
3. Because the stud-mounted gage cutters were removed, gage wear protection had to be increased by other means. This was accomplished by replacing eight of the

16 cemented tungsten carbide wear pads with diamond compacts. This modification is shown in Figure 184. The diamond compact wear pad design is shown in Figure 185. The "LS" bonding process was used to attach the No. 2330 STRATAPAX^R drill blank to the additional tungsten carbide support necessary to press fit the part into the bit body, with the diamond surface flush with the side of the bit.

Figures 186, 187, and 188 are photographs of Bit No. S-1, Modified, taken at the Baca Field site before testing. Figure 186 shows the overall bit profile and Figure 187 is a closer side view. The diamond compact wear pads are just visible in this picture. Figure 188 is a view of the bit face, showing the cutting structure and nozzle locations.

2. ENLARGEMENT OF THE NOZZLES IN BIT NO. C-1

The high altitude of the Baca Field geothermal drilling sites reduces the efficiency of the air compressors so it is necessary to use the largest possible bit nozzles in order to minimize restriction of the airflow. The nozzles in Bit. No. C-1, as fabricated, were small enough to cause airflow problems. Since these cemented tungsten carbide nozzles were an integral part of the bit body they could not be replaced. To increase the total nozzle cross-sectional area, the bore of each nozzle was bored out, using electrical discharge machining, to the maximum internal diameter possible, 0.5 in. This provided a total cross-sectional area (six nozzles) of 1.18 in.², which proved to be adequate for Baca Field drilling with aerated water.

Figure 184. Gage Protection Wear Pad Changes Made for Bit No. S-1, Modified.

Figure 185. Polycrystalline Diamond Compact Wear Pad Used at Locations A and B on Bit No. S-1, Modified.

Figure 186. Side View of Bit No. S-1, Modified.

Figure 187. Close-up Side View of Bit No. S-1, Modified.

Figure 188. View of the Cutting Structure and Nozzle Locations on Bit No. S-1, Modified.

K. FIELD TESTS AND BIT WEAR ANALYSIS FOR BITS NO. C-1 AND S-1, MODIFIED

1. FIELD TEST DESCRIPTIONS AND DRILLING RESULTS

Tests with both bits were conducted in the bottom section of a new well drilled on the same site where the prior test with Bit No. S-1 (see Section 3, J, this report) was carried out. Drilling was again performed in andesite, the basement formation for the Baca hydrothermal field. Like the prior test, the hole deviated significantly from vertical, this time 21° . The bottom hole rock temperature was $> 500^{\circ}\text{F}$.

The hard matrix polycrystalline diamond compact bit, No. C-1, was tested first. Fourteen 6-3/4 in. drill collars made up the bottom hole assembly; no stabilizers or reamers were used. The weight on the hook was 122,000 lb. The drilling fluid was aerated water, composed of about 2100 ft³/min air and 170 gpm water. The Kelly bushing was set in the rotating table and rotation and fluid circulation started well before the bit reached bottom. Depth in was 5513 ft for the No. C-1 bit test, and depth out was 5562 ft; a total of 51 ft was drilled (Note: a 100-ft section was all that was allotted to test both bits.) No problems were encountered during the test and essentially all the bit weight-rotary speed-penetration rate information obtained was usable, but because the bit was very aggressive the quantity of data was limited. These test results are summarized in Table 49. Examination of these data shows that, over a speed range of 40 to 70 rpm and for all bit weights from 12,000 to 20,000 lb, the polycrystalline diamond compact drag bit penetrated the formation at rates markedly greater than those that could be expected using medium to hard formation roller cone insert bits. The results from Table 49 are plotted in Figures 189 and 190.

Due to the design and method used to fabricate the hard matrix bit, the cutter standoff (the distance from the tip of the diamond compact cutting edge to the surface of the bit body) was less than the compact diameter. The thickness of the zone available for rock cuttings removal was this standoff dimension minus the cutter engagement into the rock formation. Near the center of the bit cutting structure the cuttings removal zone thickness was greatly reduced when the maximum penetration rates were reached. For example, at 40 rpm and 70 ft/hr the cutter engagements for the innermost cutters approached 1/4 in., leaving little space for removal of cuttings. At 70 rpm and 85 ft/hr the cutter engagements were somewhat less but the volume of cuttings to be removed was greater. It is probable that the highest penetration rates achieved were close to the maximum values that could have been expect-

ed without the bit choking on its cuttings, and that those penetration rates were only reached because the formation was brittle and the rock fragments produced were granular and did not tend to pack and stick. The core cutter and ejector at the center of the bit may have assisted in the removal of some of the cuttings.

Bit No. S-1, Modified, was tested using the same fluid flow rates and the same bottom hole assembly as Bit No. C-1. Five No. 18 (18/32 in.) nozzles were used. Bit No. S-1, Modified, was even more aggressive than Bit No. C-1 and the permissible drilling footage was rapidly used. Depth in was 5564 ft, depth out was 5660 ft. Penetration rates up to 170 ft/hr were obtained with bit weights no greater than 10,000 lb. The very limited data obtained are summarized in Table 50. The aggressive nature of the bit in the brittle andesite formation made control of the bit weight difficult. At 5000 lb weight-on-bit manual control was possible but with 10,000 lb at rotary speeds above 40 rpm the automatic drilling control was necessary, and even this was inadequate. Bit weights reported in Table 50 as 10,000 lb are nominal values. These bit weights were certainly greater than 5,000 lb, but actually may never have reached 10,000 lb.

The penetration rate-rotary speed data for Bit No. S-1, Modified, are plotted, for both nominal bit weights, in Figure 191. It is apparent that the measured penetration rate of 170 ft/hr at 60 rpm was close to the maximum that the bit could have produced. The engagement for the inner portion of the central diamond compact cutter was greater than 1/2 in. at these conditions, indicating that the bit body was almost, if not actually, in contact with the formation. The central nozzle next to this cutter may have helped by providing the clearance for rock chip removal.

The "relative torque" figures given in the tables were taken from the chart recorder in the rig doghouse and do not represent actual torque values, but are proportional to actual torque. As such, they are useful for comparison purposes. The upper "relative torque" values for Bit No. S-1, Modified, were consistently less than those for Bit No. C-1, even though the stud-type bit produced higher penetration rates at lower bit weights and lower rotary speeds. The lower "relative torque" figures may indicate that bit face cleaning was superior for Bit No. S-1, Modified, due primarily to the greater cutter standoff for this bit. Also, the hard matrix bit (No. C-1) may have been pinching in the hole. Unlike Bit No. S-1, Modified, the outermost cutters did not quite cut to gage. This bit depended upon natural stones set in the bit body to remove the last small fraction of the rock to produce the finished hole diameter. These "gage" stones exhibited relatively severe damage, indicating that they did not perform efficiently.

Table 49

BIT NO. C-1 BACA FIELD DRILLING TEST RESULTS

Nominal Bit Wgt (lb)	Rotary Speed (rpm)	Penetration Rate (ft/hr)	Relative Torque	Hole Section Drilled (depth in feet)
5000	40	(Developed bottom hole pattern)		5513-5515
15000	40	45	150-200	5515-5518
15000	40	48	-	5518-5522
20000	40	60	100-250	5522-5526
20000	40	72	100-250	5526-5532
20000	40	(Drilled to end of Kelly)		5532-5533
15000	60	60	150-200	5533-5538
15000	70	85.7	140-220	5538-5543
12000*	70	50.7*	140-210	5543-5544
12000	70	43.6	140-210	5544-5548
12000	60	30	140-200	5548-5553
15000	60	60	150-200	5553-5558
9000	60	12	150-190	5558-5564

*Bit weight and penetration rate questionable

Table 50

BIT NO. S-1, MODIFIED, BACA FIELD DRILLING TEST RESULTS

Nominal Bit Wgt (lb)	Rotary Speed (rpm)	Penetration Rate (ft/hr)	Relative Torque	Hole Section Drilled (depth in feet)
5000*	40	75	150-175	5564-5569
10,000*	40	105	140-180	5569-5577
5000*	50	100	130-190	5577-5582
5000?	50	75	140-190	5582-5588
5000*	50	100	-	5588-5593
10,000**	60	170	140-190	5593-5600
10,000**	50	156	140-190	5600-5606
10,000**	40	113	140-190	5606-5610

* Manual drilling control.

? Bit weight value questionable.

** Automatic drilling control set for 10,000 lb. bit weight. Actual bit weights may have been less because the hoist brake control could not keep pace with the high penetration rates.

Figure 189. The Relationship Between Penetration Rate and Rotary Speed at Constant Bit Weight for Bit No. C-1, Drilling Andesite at Baca Location No. 1

Figure 190. The Relationship Between Penetration Rate and Bit Weight at Constant Rotary Speed for Bit No. C-1, Drilling Andesite at Baca Location No. 1

Figure 191. The Relationship Between Penetration Rate and Rotary Speed at Constant Bit Weight for Bit. No. S-1, Modified, Drilling Andesite at Baca Location No. 1

2. BIT WEAR AND DAMAGE

The cast, hard matrix polycrystalline diamond compact bit (No. C-1) came out of the hole with relatively severe wear to seven of the cutters, and a significant degree of damage to the natural diamonds set in the bit body to cut the hole to size. There was no visible wear of the natural diamonds set in the orifice of the central core ejector opening, and no damage to the natural diamonds placed on the skirt of the bit to reduce bit body gage wear. There was also no visible evidence of damage to the cast bit body. In spite of the cutter damage this bit was still usable when the test was concluded.

Figure 192 shows the locations of the damaged cutters. The distribution of damage was quite nonsymmetrical, which was unexpected because the bit ran smoothly throughout the test. Figures 193 through 195 are photographs of five of the worn cutters, Figure 193 showing the severe wear to cutter No. 25, Figure 194 showing the severe wear to cutters No. 28 and 36, and Figure 195 showing the wear to cutters No. 38 and 39. The scooped-out profiles of the wear scars, which extend the entire length of the tungsten carbide substrate, suggest that the wear was initiated by severe chipping or spalling of the cutting edges, with loss of the sintered diamond, leaving the unprotected carbide to wear away rapidly against the abrasive formation. If the severely damaged cutters had worn in a purely abrasive, microchipping manner, or, in the case of the outermost cutters which were cutting at the highest speed, by accelerated wear due to frictionally generated heat damage, severe wear should have developed on cutters on the other side of the bit (i.e., cutter No. 46). This was not the case, however. Cutter No. 46 can be seen at the top edge of Figure 196. There is only a small wear scar on this cutter, adjacent to the cutting edge. Similarly, cutter No. 43, which is visible at the left center of Figure 193, exhibits very little wear.

A possible explanation for the nonsymmetrical wear pattern is that the seven badly worn cutters were prematurely damaged when the diamond compacts were brazed (by hand) into the bit body. Bit No. C-1 was probably the first bit of its size fabricated by Christensen, USA, and reliable techniques for manufacture were still in the early development stage. A small amount of localized heat damage to the edges of the diamond cutters could have gone undetected until the bit was subjected to the rigors of the geothermal drilling environment.

Figure 196 shows the damage sustained by the natural diamonds set in the bit to cut the gage. The predominate failure mode was fracture of the individual diamonds, but sufficient stones were retained to function as intended for the duration of the

field test. The crushing, grinding mode of rock removal performed by rounded, dull diamond crystals was not efficient enough to prevent excessive overloading at the unanticipated high bit penetration rates achieved. Nevertheless, this experimental design did permit the outer diamond compact cutters to be removed sufficiently inward from the circumference of the bit to avoid the "zero feed" condition (rubbing the rock surface with essentially no depth of cut or engagement) that previous experience indicated may lead to rapid wear. The minimal wear developed on the outermost cutters on Bit No. C-1 (with the exception of those that may have been prematurely damaged) contrasted sharply with the gross wear of the unprotected gage cutters on Bit S-1, Modified, to be described next.

The diamond compact cutter and tungsten carbide stud wear developed by the steel body bit, No. S-1, Modified, was confined to two extremes; either excessive or minimal (slight cutting edge chipping). The wear distribution was symmetrical and all significant damage was confined to the outermost eight cutters, No. 35 through 38, which were set to cut to gage, and No. 31 through 34 which were placed just inside (but overlapping) and leading the four outer cutters. Figure 197 shows the damaged cutters' positions in the cutting structure. Figures 198 through 201 are photographs of the eight outer cutters, clearly showing the damage indicated on Figure 197. In particular, the manner in which cutters No. 35 (Figure 200) and 38 (Figure 198) wore should be noted. The worn surface, in each case, is almost parallel to the side of the bit body: a good example of the result of the "zero feed" condition mentioned previously. There is almost no wear on the tops of the cutters, that is, there is no significant wear developed by advancing (or "feeding") engagement that produced rapid penetration. Cutters No. 36 and 37 also exhibited the same wear geometry, but the photographs do not show this as clearly.

One braze joint attachment failed. This is shown in Figure 199 (Cutter No. 32). The back of this cutter stud fractured and was lost. A similar stud failure occurred with cutter No. 33 (Figure 198). This stud delamination was apparently caused by the propagation of a surface crack developed by the frictional heat generated when the worn tungsten carbide stud rubbed against the rock. Figure 202 is a higher magnification photograph of the worn surface of cutter No. 36, showing a crack in the tungsten carbide stud a short distance behind the braze joint. If the drilling test had continued, this cutter stud would have probably failed like cutters No. 32 and 33.

Figure 203 is a photograph of eight cutters in the main body of the cutting structure, away from the outer edge. None of these diamond compacts underwent any significant wear other than slight edge chipping. This was typical of the condition

of all the cutters on the bit with the exception of the eight outer cutters discussed above. Cutters that always advanced into the rock formation and did not rub the rock did not wear to any great degree.

The wear of the peripheral diamond compact cutters was accompanied by wear of the steel bit body. This is shown in Figure 204. Note that most of the bit body wear terminated at the uppermost diamond compact wear pads which had been pressed into the bit flush with the surface. The wear of the steel exposed the edges of the sintered diamond layers, which then cut the wall of the hole to size. These small compacts performed remarkably well as cutters considering that the thickness of the diamond layer was only ~0.025 in. thick. A closer view of the manner in which the exposed diamond wear pad protected the body of the bit is provided in Figure 200. The diamond compact wear pad can be seen below cutter No. 35, at the bottom of the photograph. If more of these small diamond compacts had been provided, mounted closer to the intersection of the bit face and side wall, the wear rate of the principal gage cutters might have been reduced.

Figure 192. Locations of the Severely Worn Diamond Compact Cutters on Bit No. C-1

Figure 193. Worn Cutter No. 25

Figure 194. Worn Cutters No. 28 and 36

Figure 195. Worn Cutters No. 38 and 39

Figure 196. Damaged Natural Diamond Gage Cutters

Figure 197. Location of the Major Cutter Damage on Bit No. S-1, Modified

Figure 198. Cutters No. 33 and 38

Figure 199. Cutters No. 32 and 37

Figure 200. Cutters No. 34 and 35

Figure 201. Cutters No. 31 and 36

Figure 202. Crack in Tungsten Carbide Stud of Cutter No. 36

Figure 203. Cutting Structure Away from Outer Edge of Bit. Cutter numbers are: 6, 8, 12, 17 in the foreground, 13, 18, 27 in the middleground and 28 in the background.

Figure 204. Side View of Bit No. S-1 Modified, Showing the Bit Body Wear

L. DRILLING PERFORMANCE - DRILLING COST ANALYSIS, BACA FIELD

The results of the tests with polycrystalline diamond compact bits No. C-1 and S-1, Modified, demonstrated the capability of these types of drag bits to achieve markedly higher penetration rates at lower bit weights than conventional insert-type roller cone bits operating in the same geothermal environment. The field tests also clearly indicated that wear of the outer portion of a diamond compact bit cutting structure, with accompanying loss of gage (already a problem with conventional roller cone bits, necessitating frequent reaming operations), would be a major factor in limiting bit life if not overcome. The total footage drilled by either experimental bit was insufficient to permit bit life to be reasonably estimated. However, since the capability to effectively drill the hard, hot formation was demonstrated, it was reasonable to make some preliminary estimates of the drilling performance that would be required in order to match or reduce the drilling costs incurred using conventional drill bits, keeping in mind that viable polycrystalline diamond compact bits would be considerably more expensive than the bits being used.

In order to estimate drilling performance requirements for more efficient but more costly bits, it was first necessary to calculate drilling cost with conventional bits. The basic cost equation was:

$$C_F = \frac{C_R \left(\frac{D}{R_P} + t_t + t_o \right) + C_B}{D} \quad \text{Eq. (21)}$$

where:

- C_F = drilling cost (\$/ft)
- C_R = rig cost (\$/hr)
- D = hole interval drilled (ft)
- R_P = penetration rate (ft/hr)
- t_t = trip time (hr)
- t_o = additional time required unique to the particular geothermal drilling operation.
- C_B = bit cost (\$)

Since we were interested in comparative costs for only the drilling operations, completion costs were not included in Equation (21). Drilling fluid costs and special auxiliary equipment costs were included in the rig cost (C_R). The information necessary to make the drilling cost calculation was obtained from the Union Oil Company and Smith Tool. Union Oil provided specific confidential figures with the

understanding that they would not be made public and Smith Tool requested that rounded numbers be used for conventional bit costs. The baseline roller cone insert bit cost used was \$2500.

Equation (21) may be rewritten as:

$$C_F = \frac{C_R \frac{D_o + D_i}{R_d} + \frac{D_o - D_i}{K} + \frac{D_o - D_i}{R_P} + C_B}{D_o - D_i} \quad \text{Eq. (22)}$$

where:

D_o = depth out (ft)

D_i = depth in (ft)

R_d = rate at which drill pipe can be taken out of
and put into the hole, in ft/hr

K = constant unique to Baca Field operations

Selecting 5500 ft (representative of the depth at which our drilling experiments had been conducted) as the "depth out" (D_o) value, and using the bit life and penetration rate figures provided by Union Oil, the hole interval drilled was determined and from this the value for "depth in," (D_i).

Using Equation (22), the baseline drilling cost was calculated.

By rewriting Equation (22), penetration rate (R_P) could be calculated for selected bit costs, using drilling costs equal to or a known fraction of, the roller cone bit drilling cost, over a range of "depth in" (D_i) values, where:

$$R_P = \frac{D_o - D_i}{\frac{C_F(D_o - D_i) - C_B}{C_R} - \frac{D_o + D_i}{R_d} + \frac{D_o - D_i}{K}} \quad \text{Eq. (23)}$$

$$\text{Since: Bit Life} = \frac{D_o - D_i}{R_P} \quad \text{Eq. (24)}$$

the necessary information could be obtained to show the relationship between penetration rate and bit life (for hypothetical bits of various costs) that represented the drilling performance requirements to break even with the baseline drilling cost or reduce drilling costs selected percentages below the baseline cost.

Figures 205, 206, and 207 show this relationship graphically. Figure 205 shows the penetration rate-bit life requirements to match the baseline drilling cost using bits costing \$5000, \$10,000, \$15,000 and \$20,000. Figures 206 and 207 show the penetration rate-bit life requirements to match the baseline drilling cost or to reduce this cost by 15% and 30%, for bits costing \$10,000 and \$15,000, respectively.

These curves all have one notable similarity; there is a (relatively) narrow range of penetration rate-bit life values in which to operate. Attempting to increase either penetration rate or bit life excessively drives the requirement for the other parameter into the region of diminishing returns.

By manipulating the data generated to plot the curves in Figure 205, remembering that the hole interval drilled was the difference between "depth out" and "depth in," drilling footage-penetration rate requirements for breakeven drilling costs were calculated and are depicted graphically in Figure 208. These curves show quite clearly that the proper operating regions of a bit costing from \$5000 to \$20,000 lies between about 30 and 70 ft/hr in order to match the drilling cost of the conventional roller cone bit. A penetration rate below 30 ft/hr would require excessive drilling footage for a \$5000 bit and a penetration rate greater than 70 ft/hr would not produce significant reduction in the drilling footage requirement for a \$20,000 bit.

A penetration rate capability to operate over the entire 35 to 70 ft/hr range was demonstrated by both experimental bits, but as noted earlier, the amount of wear incurred drilling only about 50 ft raised the question as to viability over the long haul. If we assume that bit cost would be at least \$15,000, and the "depth out" would be 5500 ft, at least 800 ft of hole would have to be produced at a penetration rate of 60 ft/hr to break even costwise. The time in the hole would be 13.3 hours. The major design emphasis for the next generation bits should be reduction of gage wear and, for a stud-type bit, reduction in aggressiveness to provide better control of penetration rate. Bit No. S-1, Modified was so aggressive as to be essentially uncontrollable. Its average penetration rate was 128 ft/hr, at bit weights between 5000 and 10,000 lb. This penetration rate was far too high for efficient operation, according to the drilling cost analysis described here.

Figure 205. Penetration Rate - Bit Life Relationships, as Functions of Bit Cost, to Achieve Drilling Costs Equal to Conventional Roller Cone Bit Drilling Costs in the Baca Field, NM

Figure 206. Penetration Rate - Bit Life Relationships Necessary to Reduce Drilling Costs in the Baca Field, NM, for a \$10,000 Bit

Figure 207. Penetration Rate - Bit Life Relationships Necessary to Reduce Drilling Costs in the Baca Field, NM, for a \$15,000 Bit

Figure 208. Drilling Footage - Penetration Rate Relationships, as Functions of Bit Cost, to Achieve Drilling Costs Equal to Conventional Roller Cone Bit Drilling Costs in the Baca Field, NM

M. DESIGN AND FABRICATION OF SECOND GENERATION STEEL BODY DIAMOND COMPACT BITS;
TYPES S-2A AND S-2B

1. BACKGROUND INFORMATION

When this program reached the stage at which bit fabrication and testing in the field became the primary task, the technical monitoring function for this contract was transferred from the Geothermal Energy Division of DOE to the Geothermal Drilling and Completion Technology Development Program, Sandia Technology Development Program, Sandia National Laboratories, Albuquerque, NM. The new technical monitor was assigned the responsibility and authority to identify and procure field testing sites. After concluding the promising 1st generation bit field tests (Bits No. C-1 and S-1 Modified) at the Baca Field location in New Mexico, a decision had to be made regarding the type of bit to be utilized for the balance of the program. The Sandia organization strongly recommended that the steel body, stud-type polycrystalline diamond compact bit concept be emphasized and, in addition, that the drilling target be expanded to include both hydrothermal and dry steam geothermal formation (i.e., the Baca Field and the Geysers Field). To this end, Sandia Laboratories provided, as part of the funding for a concurrent GE-CRD subcontract with Sandia (Contract No. 13-9406) sufficient funds to fabricate two additional bits to be included in and reported as part of this DOE contract field testing plan.

Concurrent with this DOE supported program, Sandia Laboratories was conducting an extensive geothermal technology program, a significant part of which was devoted to polycrystalline diamond compact drill blank attachment development (diffusion bonding) and steel body, stud-type diamond compact design, fabrication, and testing. In its role as technical monitor, Sandia Laboratories understandably considered the bit fabrication and field testing phase of this contract as an integral part of its overall program, and the decision to proceed with steel stud-type bits to be in line with its own program objectives.

The Sandia Laboratories subcontract to GE-CRD noted above was conducted by the same individual who was principal investigator for this DOE program. Although the Sandia subcontract was principally devoted to investigations of polycrystalline diamond compact wear mechanisms under rigorous conditions simulating the geothermal environment, a portion of the effort was consultation and assistance to Sandia's geothermal drilling program. This included assistance in arranging for, conducting, and reporting the results of, full-scale laboratory drilling tests with polycrystalline diamond compact bits, performed at the Drilling Research Laboratory, Terra Tek,

Salt Lake City, Utah. These experiments, which were conducted using preheated air as the drilling "fluid" to partially simulate the geothermal drilling environment in the Geysers, CA, were described in detail in the final report for Sandia Laboratories Contract No. 13-9406.⁽²⁴⁾ The favorable results of the hot air drilling experiments were responsible in part for the decision to attempt to drill the Geysers' very abrasive graywake formation with diamond compact bits.

2. BIT DESIGN AND FABRICATION

The results of the test in the Baca Field, NM, with Bit No. S-1, Modified, demonstrated that the basic cutting structure design was effective in penetrating hard volcanic formations, but that two major problems should be addressed in redesigning the bit; the original bit design was overly aggressive and gage wear was excessive. It appeared that both problems could be reasonably reduced without extensive changes in the overall design. Since Smith Tool had acquired valuable experience and expertise while constructing the two previous steel body, stud-type diamond compact bits, this organization was chosen to build the second-generation bits.

It was anticipated that the drilling tests in the Baca and Geysers fields would be conducted in the producing formations of the holes, requiring 8-3/4 in. dia. bits rather than the 8-1/2 in. dia. bits which were tested drilling into the basement andesite formation below the producing zone in the Baca Field. Since the basic cutting structure (cutter layout) of the prior 8-1/2 in. bits provided more than adequate coverage and cutter redundancy it was only necessary to make slight adjustments in the locations of the eight outermost stud-mounted cutters to extend coverage the additional 1/4 in. The locations of the remaining 30 cutters and the nozzles were not changed from the original design. This simplified the fabrication of the second-generation bits.

To try to reduce the aggressiveness of the bit design (to increase somewhat the weight-on-bit necessary to produce a given penetration rate and improve drilling control) the 25 outermost stud-mounted diamond compact cutters were changed from the GE No. 2542 design (-20° back rake, 5° end clearance) to a -25° back rake, 25° end clearance design using No. 2530-NC STRATAPAX^R drill blanks attached to cemented tungsten carbide studs of the Sandia Laboratories design. This stud is shown in Figure 209. The diamond compact drill blanks were attached by the "LS" bonding process (using a high-temperature brazing alloy). Laboratory single-cutter experiments and drilling tests by Sandia Laboratories had shown that the increased back rake would increase the thrust force (or bit weight) necessary to penetrate rock and

should reduce the overall aggressiveness of the bit design. The Sandia-type stud was also selected because the 25° end clearance would reduce the area of cemented tungsten carbide rubbing against the rock formation after the diamond compact cutters had undergone appreciable wear. Examination of Bit No. S-1, Modified, which utilized studs with 5° end clearance, revealed surface cracks in some of the cemented tungsten carbide caused by frictional heat which, in two cases, resulted in stud fracture. The innermost 13 stud-mounted cutters retained the -20° back rake, 5° end clearance design because Smith Tool did not feel that 25° end clearance studs could be press fitted into this portion bit body without a great degree of difficulty. Since significant cutter wear was not anticipated in the center of the bit face, use of the 5° end clearance stud-cutter design was acceptable.

In order to increase the strength of the cutting structure and reduce the chances of breaking studs in the event of severe impact loading, the cutter standoff (distance from the cutter tip to the bit body) was reduced to 0.350 in. The standoff could not be reduced without counterboring the bit body to provide a recess for the bottom portions of the diamond compact drill blanks. A conventional concentric counterbore would reduce the length of the stud shank that was press fitted into the body. To provide some additional support for the stud, Smith Tool's eccentric counterbore concept was used. The eccentric counterbore provided some additional stud support at the back side of the stud shank where it was in contact with the counterbore wall. (The eccentric counterbore also created some press fitting problems, which are noted later.)

The four large stud-mounted gage cutters, which were on the original steel body bit (No. S-1) but removed from the second bit (No. S-1, Modified) because they were not considered necessary since the bit was put in an oversize hole and total drilling footage was limited, were replaced. These stud-mounted gage cutters were made from standard No. 2542 stud-cutters by carefully grinding back the tip of the diamond compact 0.050 in., creating a straight edge with a cemented tungsten carbide flat behind it. There was no end relief angle, so that the stud could be accurately pressed into the bit body until the diamond edge was flush with the surface of the steel side rib. Care was taken to assure that these gage cutters (noted as No. 2532 on Figures 210 and 211) did not protrude beyond the surface of the bit body. The half-round gage cutters on Bit No. S-1 had not been carefully positioned and protruded out from the body in varying distances ranging from 0.010 to 0.050 in. Care was taken to assure that sufficient diametrical interference was used to prevent the gage cutter studs from rotating during use, as had occurred with one of the gage cutters on Bit No. S-1.

Bit No. S-1, Modified, was fitted with 16 wear pads, half of which were No. 2330 STRATAPAX^R diamond compact drill blanks attached to cylindrical cemented tungsten carbide supports and half of which were cylindrical tungsten carbide only. These wear pads had been press-fitted into the wide ribs of the bit body with the circular ends flush with the steel rib surface. For the second-generation bits, 16 wear pads were again used, but all of them were No. 2330 STRATAPAX^R diamond compact drill blanks, four inserted into each wide rib. The wear pad locations were staggered from rib to rib, to provide more complete hole wall coverage. These diamond compact wear pads were identical to those used for Bit No. S-1, Modified.

Four second-generation bits were fabricated. All four incorporated all of the modifications described above. In addition, one pair of bits, designated Type S-2A had four additional gage protection cutters not added to the other pair, which were designated Type S-2B. Figure 210 shows the cutter layout for the Type S-2A bits, with the changes from the design of Bit No. S-1, Modified noted. The additional gage cutters were identical to the small diamond compact wear pads, but were inserted into the bit body junk slot walls tangent to the intersections of the narrow ribs and junk slot surfaces. They were positioned just above (closer to the bit face) the large gage protection cutters. In these positions, the small diamond compacts would be canted to the hole wall and act as additional cutters. Figure 212 is a photograph of a Type S-2A bit as fabricated. The additional small gage cutters may be seen in this picture.

The pair of bits designated Type S-2B differed from Type S-2A in that cutters No. 35 through 38 were located so that the diamond compacts extended at least 0.050 in. beyond the bit gage diameter of 8.75 in. (See Figure 211). After assembly, the two Type S-2B bits were shipped to General Electric's Specialty Materials Department where these cutters were ground back to the gage. This provided a flat surface on the outside of the cutters which was intended to slow down the wear rate as the cutters rubbed against the hole wall. This feature can be seen in Figure 213, which is a photograph of a Type S-2B bit before testing.

Figure 214 shows the cutting structure of these bits. The eccentric counter-bore is evident, as well as the two types of stud-mounted cutters used. Figure 213 shows these features as well.

Smith Tool had no problems press fitting the No. 2542 STRATAPAX^R stud-cutters, but encountered problems with the Sandia stud-cutter design due to the rounded end of the stud and the 25° end relief angle. At the time this work was in progress, Petroleum Concepts, Inc. had just been established, located in Albuquerque, NM. The PCI personnel were former Sandia people who had developed the stud-cutter design and

were experienced in using it. PCI was engaged to assist and instruct Smith Tool in the necessary press fitting techniques. Figures 215 and 216 show the PCI fixture and tooling, with a Type S-2A bit body in place.

The Type S-2A bits were targeted for testing in the Baca Field, NM. The Smith Tool bit numbers were SPX-013 and SPX-014. The Type S-2B bits were targeted for testing in the Geysers Field, CA. These were Smith Tool bits No. SPX-015 and SPX-016.

Figure 211. Type S-2B Bit Cutter Layout, with Modifications

Figure 212. Finished Type S-2A Bit. (Additional small gage cutter can be seen inserted in junk slot wall just above large gage protection cutter mounted in the narrow rib.)

Figure 213. Finished Type S-2B Bit. (Note ground flats on outside surfaces of outer cutters to reduce wear generated by rubbing against the hole wall.)

Figure 214. Photograph of the Bit Face of a Finished Type S-2A Bit, Showing the Cutter Layout and Nozzle Locations. (The eccentric conterbore can be seen.)

Figure 215. Petroleum Concepts, Inc. Fixture and Tooling to Press Fit the -25° Back Rake, 25° End Relief Stud Cutters Into a Type S-2A Bit Body. (Setup shown is for inserting cutters parallel to the bit axis.)

Figure 216. Same as Figure 215, but Set Up to Press Fit Stud-cutters at an Angle to the Bit Axis

N. BACA AND GEYSERS FIELD TESTS AND FULL-SCALE LABORATORY DRILLING TESTS OF BIT TYPES S-2A AND S-2B

1. BACA FIELD TEST, BIT TYPE S-2A

a. Field Test Summary

The two 8-3/4 in. Type S-2A polycrystalline diamond compact bits fabricated by Smith Tool, were tested in the field at Baca Location No. 1, Sandoval County, New Mexico. Unlike the drilling test performed in the same area with the 8-1/2 in. dia. Type S-1, Modified diamond compact bit, when very high penetration rates were achieved drilling andesite, the results of these experiments drilling Bandolier Tuff were negative. Only about seven feet of hole were made over a period of several hours with two bits (Smith Tool bit No. SPX-013 and SPX-014). Although many possible reasons for the lack of drilling performance were proposed while testing was in progress, including differences in fracture characteristics of the volcanic tuff compared to andesite, pinching of the bit gage and gage cutter wear, allowing the bit body to bottom out at the bit periphery, careful examination of the bits on the day following the field test showed that lack of diamond compact cutter standoff from the bit body for cutters in the center of the cutting face was the reason the bits would not drill. Penetration of these cutters (in particular the No. 1 cutter tangent to the center of rotation) was so limited that the stresses necessary to fracture the formation could not be achieved before the center inverted conical section of the body contacted the rock, effectively preventing any increase in the stress applied to the rock and also blocking fluid flow through the central nozzle. Thus, the bits rested on a combination of fine rock chips and solid rock confined to the center section of the cutting structure and could not penetrate except by a very slow rock wearing mechanism.

The reduction in cutter standoff for the center cutters was a manufacturing and fabrication error. The Type S-2A bit design was a modification of the successful Bit No. S-1, Modified. Relatively extensive design changes were made, including the cemented tungsten carbide stud design and rake angle for cutters No. 15 through 39 on the cutting face, a slight overall reduction in cutter standoff (minimum standoff was specified as 0.350 in.), the addition of polycrystalline diamond compact gage trimmers (two types) and the addition of 16 diamond compact gage wear pads. However, no design changes were intended for the central conical section of the bit. Unfortunately, the cutter standoff error was not observed until after the field tests were conducted.

b. Testing Details and Bit Wear

The polycrystalline diamond compact bits (Type S-2A, Smith Tool identification No. SPX-013 and SPX-014) were tested by arrangement with the Union Geothermal Company of New Mexico.

The bit just ahead of the first diamond compact bit was a Smith Tool 8-3/4 in. dia. carbide button rock bit, Type 5GA. This bit drilled 529 ft in ~16 rs rotating time (~32/hr) at 70 rpm with 50,000 lb weight on the bit. The drilling fluid was 304 gpm water and 1050 cfm air. This was significantly more water and less air than used when Bit No. S-1, Modified was tested. The penetration rate for the roller cone bit was also greater than was being achieved at the time of the prior field test.

The bottom hole assembly included a three-point reamer immediately above the bit, a monel collar, three stabilizers, a shock sub, and sixteen 6-1/2 in. drill collars. The total string weight at 4367 ft, when this bit was removed, was ~125,000 lb. The same bottom hole assembly (with new three-point reamers) and the same hydraulics were used for both diamond compact bits except that the shock sub was removed before testing the second one.

The 5GA rock bit was under gage from 1/8 in. and 1/4 in. after use. One cone was frozen and the other two were loose due to bearing wear. Consequently, the first diamond compact bit (No. SPX-013) had to ream the final 360 ft (12 joints of drill pipe) to reach bottom at 4367 ft. Reaming was done at 40 rpm, with weight-on-bit varying, but restricted to a maximum of 5000 lb. Almost six hours were used to ream, including a 15-minute period of rotation with no bit weight when circulation was temporarily lost. Torque was 150 relative (on a scale of 500) initially and rose to 200 for the last hour.

The original plan for testing the first experimental bit was to try several rotary speeds, varying the bit weight to preliminarily identify a near optimum rpm-weight combination and then run the bit at these conditions for 8-10 hours. The bit would then be removed and examined. However, penetration was so slow and sporadic that no rotary speed-bit weight-penetration rate relationships could be determined. A total of 19 rotary speed-bit weight combinations were tried covering a rotary speed range from 40 to 80 rpm and a bit weight range from 5000 lb to 30,000 lb. The torque varied from 140 to 240 (relative) but there was no correlation with rotary speed or the weight on the bit. After about 5 ft of total penetration, this bit was removed for examination. The bit was approximately 1/8 in. under gage, due to wear of the four outermost cutters (No. 35 through 38). Other than this wear, apparently

due to reaming 360 ft before reaching bottom, there was no significant damage. The bit was essentially in a "green" condition. Figure 217 is a photograph of bit No. SPX-013 after testing, showing the good condition of the diamond compact cutting structure. Figure 218 is another view of this bit. The wear of the outermost cutters can be seen, together with the corresponding bit body wear. Note that the body wear terminated at the large gage wear prevention cutters, which were still in good condition, together with the small gage wear cutters and diamond compact wear pads.

Because, at this time, it was not evident why the first bit did not drill effectively, the second diamond compact bit (Smith Tool No. SPX-014) was put in the hole. For this test the shock sub was removed from the bottom hole assembly. The trip in had to be halted 200 ft from bottom (almost seven joints of drill pipe) to attach the kelly, start circulation, and commence reaming. After reaming for approximately 15 minutes the drilling engineer decided to try to push the bit down the hole. After stopping rotation and circulation, the remainder of the first joint, and three more joints were dropped into the hole, using up to 25,000 lb of weight. However, bottom could not be reached this way. Rotation and circulation were re-established and the final 90 ft finished by reaming at 50 rpm, 5000-10,000 lb weight.

This bit behaved exactly like the first one when drilling was commenced. Only very slow, sporadic penetration was observed. Seven combinations of rotary speed and bit weight were tried, varying the rpm from 50 to 70 and the weight from 15,000 to 28,000 lb. The torque varied from 140 to 200 (relative), again with no correlation with rotary speed and weight on the bit. After a total penetration of about 2 ft the bit was pulled.

There was extensive fracture damage to the gage cutters and studs and to several cutters just inside the cutting structure periphery. There was also relatively severe damage to the gage wear protection cutters, and noticeable vertical score marks on the surfaces of the junk slots. Most of this damage was caused by trying to force the bit into the hole without rotation or circulation. There was no damage to the center portion of the cutting structure and no significant diamond compact wear, only the fracture damage noted above.

Figures 219 and 220 are photographs taken the day following the field test, showing the cutting structure of bits No. SPX-013 and SPX-014, respectively. The lack of sufficient cutter standoff at the center of the bit is illustrated, in particular for cutters No. 1 through 4. At this time the construction of the other pair of bits, Type S-2B had not been completed. Smith Tool was alerted to the

cutter standoff error in time to avoid an identical mistake with the bits targeted for testing at the Geysers.

At the conclusion of the additional full-scale laboratory drilling tests described below, one of the worn outermost cutters (No. 37) was removed from bit No. SPX-015 for microscopic examination to identify the predominate wear mode of the sintered diamond layer. Optical microscopic examination before and after subjecting the wear land to an intense silicon carbide grit blast revealed no evidence that the polycrystalline diamond material had been thermally damaged by the frictional heat generated rubbing against the hot rock. The wear mode was predominately microchipping of individual diamond grains, typical of abrasive wear. The aerated water used was adequate to cool the diamond cutters and prevent thermally accelerated wear.

Figure 217. Cutting Structure of Bit No. SPX-013 After Testing in the Baca Field, NM

Figure 218. Side View of Bit No. SPX-013 Showing Wear of the Outermost Cutters, the Gage Protection Cutters and the Bit Body

Figure 219. Central Portion of the Face of Bit No. SPX-013, Showing the Insufficient Cutter Standoffs

Figure 220. Photograph of Bit No. SPX-014 Showing Insufficient Cutter Standoff at the Center of the Cutting Structure

2. ADDITIONAL LABORATORY DRILLING TESTS, BITS NO. SPX-013 AND SPX-016.

Although we had no reservations about the reason for the inability of the Type S-2A bits to drill effectively; namely, the unintended lack of sufficient cutter standoff, Sandia Laboratories, as the program technical monitor, insisted that this be confirmed by an additional drilling test under controlled laboratory conditions. Sandia also strongly recommended that one of the Type S-2A bits targeted for the Geysers be tested in advance of the field test. There were no provisions for additional laboratory drilling experiments in this contract, so the tests were conducted at the Drilling Research Laboratory, Terra Tek, as part of Sandia's program to evaluate polycrystalline diamond compact bits of its own design. The results of these additional drilling experiments are summarized here to preserve the continuity of this report.

In order to have a benchmark, or basis for comparison, the bits were tested drilling Carthage Marble at atmospheric pressure, using water as the drilling fluid, so that drilling performance could be compared with the results of tests with Bit No. S-1, extensively tested earlier in this program at the same laboratory. The bits tested were Smith Tool No. SPX-013 (Type S-2A) and No. SPX-016 (Type S-2B). Tests were run at 50 rpm and 100 rpm (both bits), over a weight-on-bit range of 5000 to 15,000 lb (Bit No. SPX-013) and 5000 to 12,500 lb (Bit No. SPX-016), using 300 and 400 gpm flow for Bit No. SPX-013 and only 400 gpm for Bit No. SPX-016. Two different nozzle sets were used with Bit No. SPX-016, either 5-10s or 5-20s. The nozzles for Bit No. SPX-013 were all 20s.

Bit No. S-1 was used as a benchmark because its cutting structure was similar enough to the Type S-2A and Type S-2B cutter layouts that its speed-bit weight-penetration rate characteristics should also be similar if the newer bits were constructed according to design specifications.

Tables 51 and 52 show the results of the drilling tests in Carthage Marble for Bits No. SPX-013 and SPX-016, respectively. Comparing penetration rate at equivalent rotary speed and bit weight for the two bits, it is readily apparent that Bit No. SPX-013, which did not drill effectively in the field, performed very poorly in the laboratory also.

Table 53 shows the performance of Bit No. S-1, drilling Carthage Marble at atmospheric pressure at two speeds, 49.5 and 83.6 rpm. Although the speeds and the bit weights given in the table are not exactly the same as in Tables 51 and 52, they are close enough to compare performance for the three bits. The comparison shows that Bit No. SPX-016, which had the proper cutter standoff, was as effective as Bit

No. S-1 in drilling the marble and that Bit No. SPX-013, with its inadequate cutter standoff, was an order of magnitude less effective, in terms of penetration rate. By using the data in Table 53, the best fit relationships between penetration rate and rotary speed for the bit weights used for the laboratory drilling tests with Bits No. SPX-013 and SPX-016 were determined for Bit No. S-1. The "predicted" or best fit penetration rate values for Bit No. S-1 were calculated for the exact test conditions used so direct performance comparisons could be made. These comparisons are given in Tables 54 and 55. Note (Table 54) that increasing the flow rate did not improve the poor performance of Bit No. SPX-013. Table 55 shows that the performance of Bit No. SPX-016 was almost identical to that of Bit No. S-1, and that enlarging the nozzle cross-sectional area actually slightly reduced its effectiveness. The table also shows that slightly reducing the cutter standoff to 0.350 in. and increasing the negative rake angle of 24 of the diamond compact cutters by five degrees to -25° did not reduce the aggressiveness of the cutting structure as expected, at least not while drilling the relatively soft Carthage Marble.

Table 51
LABORATORY TEST RESULTS DRILLING CARTHAGE MARBLE
WITH BIT NO. SPX-013 AT ATMOSPHERIC PRESSURE
(Nozzles were all 20s. Fluid was water.)

Rotary Speed (rpm)	Penetration Rate (ft/hr)	Bit Wgt (lb)	Torque (ft-lb)	Flow Rate (gpm)
50	0.5	5000	500	300
50	1.0	5000	530	300
50	2.8	7500	980	300
50	4.0	7500	1080	300
50	3.8	7500	1186	300
50	6.5	10000	1500	300
50	5.5	10000	1500	300
50	12.0	15000	2900	300
100	1.5	5000	485	300
100	4.5	7500	800	300
100	8.0	10000	1080	300
100	13.9	12500	1390	300
100	22.0	15000	3200	300
100	2.0	5000	460	400
100	7.0	10000	1050	400
100	12.0	12500	1350	400
100	15.0	15000	1600	400

Table 52

LABORATORY TEST RESULTS DRILLING CARTHAGE MARBLE
WITH BIT NO. SPX-016 AT ATMOSPHERIC PRESSURE
(Water flow was 400 gpm.)

Rotary Speed (rpm)	Penetration Rate (ft/hr)	Bit Wgt (lb)	Torque (ft-lb)	Nozzle
50	28	5000	1200	5-10s
50	43	7500	1700	5-10s
50	56	10000	2490	5-10s
100	46	5000	1100	5-10s
100	65	7500	1730	5-10s
100	91	1000	2390	5-10s
100	43	5000	1080	5-20s
100	62	7500	1625	5-20s
100	58	7500	1525	5-20s
100	82	10000	2275	5-20s
100	120	12500	2800	5-20s

Table 53

LABORATORY TEST RESULTS DRILLING CARTHAGE MARBLE
WITH BIT NO. S-1 AT ATMOSPHERIC PRESSURE
(Fluid was 9.1 lb/gal bentonite base mud.)

Rotary Speed (rpm)	Penetration Rate (ft/hr)	Bit Wgt (lb)	Torque (ft-lb)
49.5	11.5	3056	599
49.5	9.7	3030	583
49.5	25.3	5098	1006
49.5	35.8	7196	1496
49.5	53.8	9206	2030
83.6	10.9	3305	516
83.6	29.2	5288	909
83.6	47.5	7272	1330
83.6	77.8	9319	1946
83.6	93.0	11115	2357
118.3	13.8	3222	468
118.3	42.6	5356	917
118.3	56.7	7320	1242
118.3	103.8	9594	1893

Table 54
 CALCULATED PENETRATION RATES FOR BIT NO. S-1
 COMPARED TO PENETRATION RATE TEST RESULTS FOR BIT NO. SPX-013,
 AS FUNCTIONS OF ROTARY SPEED AND BIT WEIGHT

Rotary Speed (rpm)	Bit Wgt (lb)	Bit No. S-1	Bit No. SPX-013	
		Penetration Rate (ft/hr)	(300 gpm) Penetration Rate (ft/hr)	(400 gpm) Penetration Rate (ft/hr)
50	5000	23.0	0.5, 1.0	
50	7500	40.4	2.8, 4.0, 3.8	
50	10000	57.9	6.5, 5.5	
50	12500	75.3		
100	5000	31.6	1.5	2.0
100	7500	61.6	4.5	
100	10000	91.5	8.0	7.0
100	12500	121.4	13.9	12.0

Table 55
 CALCULATED PENETRATION RATES FOR BIT NO. S-1
 COMPARED TO PENETRATION RATE TEST RESULTS FOR BIT NO. SPX-016,
 AS FUNCTIONS OF ROTARY SPEED AND BIT WEIGHT

Rotary Speed (rpm)	Bit Wgt (lb)	Bit No. S-1	Bit No. SPX-016 (10 nozzles)	
		Penetration Rate (ft/hr)	Penetration Rate (ft/hr)	Penetration Rate (ft/hr)
50	5000	23.0	28	
50	7500	40.4	43	
50	10000	57.9	56	
50	12500	75.3		
100	5000	31.6	46	43
100	7500	61.6	65	62.58
100	10000	91.5	91	82
100	1250	121.4		120

3. GEYSERS FIELD TEST, BIT TYPE S-2B

a. Field Test Summary

The final scheduled field test for this program was carried out at the Geysers Field, California, performed with the permission and assistance of Union Oil Co., Geothermal Division, Santa Rosa, California. The test results were negative due to extreme wear of the outer portion of the bit cutting structure. Only one of the two available bits was tested (Bit No. SPX-015); the other was later shipped to the Drilling Technology Division, 4741 Sandia Laboratories, Albuquerque, NM for examination and a decision on a possible additional alternative testing site. A summary of the Geyser's field test is given below, followed by a discussion on the bit failure mechanism.

The 8-3/4 in. dia. Type S-2B polycrystalline diamond compact bit was tested in a well that was already producing steam and drilling was being conducted with air at 2300 to 2400 ft³ plus about 3 gpm of an aqueous anticorrosive agent. The formation was very abrasive graywackie, and the bottom hole temperature was ~480 °F. The bit used prior to the diamond compact bit was a Hughes HT55 bit, which drilled 128 ft in 5 hours. This bit came out of the hole 5/16 in. under gage due to the abrasive drilling conditions. A new Smith Tool 7GA bit was utilized to ream the hole before the STRATAPAX^R bit test and it came out of the hole ~1/8 in. under gage.

When the experimental Type S-2B bit (Smith Tool No. SPX-015) went into the hole, it was necessary to connect the kelly and ream the last 30 ft to bottom. Reaming was done at 65 rpm, with air and no excessive torque was observed. Total reaming time was about 10 minutes. Depth-in was 6701 ft and hole deviation from the vertical was ~24°.

The bottom hole assembly included a three-point near bit reamer, a 30-ft monel collar, and two stabilizers separated by another 30-ft collar. Including the additional drill collars and drill pipe, the total string weight was about 175,000 lb.

The initial rotary speed was 55 rpm. Bit weight was gradually increased (in 5000 lb increments) from 5000 to 25,000 lb but there was no measurable penetration. After 1/2 hr the air pressure had increased from 380 psi to 500 psi. When the bit was picked off the bottom the pressure dropped to the original value, indicating that the bit might be wearing in a way to restrict the return flow of air out of the hole annulus. The rotary speed was increased to 78 rpm and the experiment repeated at 5000, 10,000 and 15,000 lb weight on the bit. Again, no measurable penetration was obtained and the air pressure increased significantly with the bit rotating on

bottom. After about an hour, drilling was terminated. It should be noted that the torque remained relatively low and uniform throughout the drilling test, and did not change appreciably with changes in rotary speed or weight on bit.

A preliminary examination of the bit after testing revealed that 14 diamond compact cutters mounted on the Sandia design -25° rake studs were missing. These were the 14 outermost cutters (as measured by radial distance from the center of the bit). The cemented carbide support studs for the nine outermost cutters were worn flush with the bit body and the remaining six cutterless studs were worn away progressively less and less, starting with about two-thirds of the stud worn away and ending with about one-quarter of the stud removed. The remaining ten -25° rake diamond compact cutters were intact with little evidence of wear.

The central section of the bit contained 14 of the older style -20° rake stud cutters. One of these studs had fractured, causing some minor damage to nearby -20° cutters. However, this damage was not sufficient to eliminate drilling capability by this portion of the cutting structure. Figure 221 is a photograph of Bit No. SPX-015, showing the severe wear of the outer portion of the cutting structure and the face of the bit body. Note that the studs worn flush with the body surface showed no evidence of fracture and that there were no grooves, gouges, or other evidence on the bit indicating that the cutters had been lost by carbide stud failure. Figure 222 is a photograph showing the condition of the central portion of the bit. The remains of the -20° rake stud-cutter that fractured can be seen in the upper right portion of the photograph (at about 2 o'clock relative to the center of the bit). The fractured stud was cutter No. 12. The damage to some of the other -20° rake cutters was apparently caused by the broken fragments from the cutter.

At the completion of the field test, Bit No. SPX-015 was shipped to Sandia Laboratories for examination by the contract monitor.

b. Bit Failure Analysis

Shortly after the Geysers field test, Sandia Laboratories proposed a bit failure model based on the hypothesis that the diamond compact braze attachment technique used produced a braze joint that contained a brittle or low melting phase, developed through a "hot short" type of solidification reaction, which made the bond susceptible to failure under impact conditions. The Sandia model proposed that, during the drilling test at the Geysers, the sintered diamond compacts spalled within the diamond layers and that the increased forces brought about by this damage to the cutters resulted in eventual shear and fracture of the bond joints and detachment of the cutters. However, initial examination of the bit showed no evidence of signifi-

cant spalling of the diamond compacts remaining on the bit. While it is probable that the bit failure resulted from loss of diamond compact cutters through a braze joint failure (there were partially worn carbide studs on the bit without diamond compact cutters), the cutter attachment failure was more likely the result of loss of bond strength due to the high frictional heat developed rather than impact. The combination of hot, tough, abrasive rock and poor cooling of the cutters would have given rise to thermal degradation of the sintered polycrystalline diamond layer and greatly accelerated wear. As the area of the rubbing interface between the rock formation and cutter increased, so did the amount of heat generated, until the braze joint reached a temperature at which its strength was no longer sufficient to retain the diamond compact under the shear stress acting upon it. This same failure mechanism had been observed earlier in the full-scale laboratory, hot-air drilling experiments conducted under Sandia contract No. 13-9406. After the successful hot-air drilling tests conducted with Nugget Sandstone, the same diamond compact bit was used to drill granite, again with preheated air as the drilling fluid. This experiment was an intentional "overkill," with the purpose of rapidly dulling the bit so it could be retested drilling sandstone in the worn condition. The granite experiment was abruptly terminated when, with a bit weight of 35,000 lb, 12 diamond compact cutters became detached from their supporting studs. Eleven of these cutters were recovered. They were badly worn, but spalling of the diamond layer was not the controlling wear mechanism. Microscopic examination showed that the wear mode was severe thermal degradation of the sintered diamond structure at the rock-cutter rubbing interface. Braze alloy remaining on both the recovered diamond compacts and the tungsten carbide studs indicated that the detachment occurred within the braze joint. The steel bit body surface surrounding the studs that had lost cutters was blue; evidence of the high temperature developed by frictional heat. Cutter loss was quite apparently caused by overheating the braze joint material, not by impact failure of a brittle "hot short" alloy.

At our request, Sandia Laboratories removed cutters No. 23 and 24 from Bit No. SPX-015 for our examination. According to the pattern of wear observed for Bit No. SPX-015, these two cutters would have been the next ones to become detached had drilling not been terminated. The cutters were worn, but had not spalled. Microscopic examination of the worn surface of the sintered diamond layers showed that the wear mode was one of thermal degradation. Cross-sectional examination of the braze joints showed no evidence of incipient failure, such as cracks, that would suggest damage due to severe impact.

The significant conclusion to be drawn from these and other drilling tests is that the method of attachment used has proven unsuitable only for the most rigorous drilling conditions existing, namely air drilling at the Geysers. The method of bonding was one of the steps, if not the most important step, in the chain of developments that has enabled polycrystalline diamond compact bits to make a major contribution towards improving drilling performance and reducing drilling costs in the oil/gas industry worldwide.

Figure 221. Overall View of Bit No. SPX-015, Showing the Severe Wear of the Outer Portion of the Cutting Structure and the Face of the Bit Body

Figure 222. Center of Bit No. SPX-015, Showing Fractured Stud-cutter No. 12 and Damage to Other Cutters When No. 12 Failed

4. DISPOSITION OF THE UNUSED TYPE S-2B DIAMOND COMPACT BIT, SMITH TOOL NO. SPX-016.

The results of the Geysers field test with Bit No. SPX-015 made it clear that another test at the same location with an identical bit would be misguided. At a subsequent meeting with the program technical monitor, agreement was reached to try to identify a more suitable geothermal test site, where drilling would be conducted using mud or water for improved cutter cooling. A tentative site was identified with the assistance of Smith Tool in the Imperial Valley, CA. Drilling was to be conducted using a geothermal mud. In anticipation of using this opportunity to evaluate Bit No. SPX-016, the bit was returned to Smith Tool, where diamond compact cutters that had been removed by Sandia Laboratories were replaced. The bit was then returned to GE-CRD, Schenectady, NY. The welds holding the nozzles were removed so that nozzles suitable for the hydraulic conditions in the Imperial Valley could be attached at the drilling site. In addition, the length of the bit body ribs were reduced about 1-1/2 in. and additional steel removed from the trailing portions of the wide ribs to reduce the contact area against the hole wall.

Unfortunately, the testing of this bit in the Imperial Valley did not materialize. After the bit had been reconditioned, a decision was made by Sandia Laboratories to utilize the test site for evaluation of another diamond compact bit which had been procured as part of its own bit development program.

Bits No. SPX-015 and SPX-016 (Type S-2B) had been fabricated using the additional funds provided specifically for this purpose on Sandia subcontract (No. 13-9406). Therefore, Bit No. SPX-016 was returned to Sandia Laboratories upon completion of that contract, as part of the unconsumed materials inventory.

0. FABRICATION AND TESTING OF DIFFUSION BONDED PCI BIT NO. 8F-1062 (TYPE 2G1) AT THE GEYSERS, CA

1. INTRODUCTION

When the field test in the Imperial Valley, CA, of the Type S-2B polycrystalline diamond compact bit (Smith Tool Bit No. SPX-016) was cancelled, and this bit was returned to Sandia Laboratories, there were still sufficient contract funds to fabricate and test one additional experimental bit. It was apparent that, in order to complete the contract within a reasonable time frame, it would not be possible to search for other test sites. Consideration was given to returning to the Baca Field, where success had been achieved drilling with aerated water, but operations there had slowed down and there were no test dates available in the near future. Union Oil was agreeable to further testing in the Geysers, where drilling activity was being increased.

Reviewing the results of the first Geysers field test, it was concluded that useful information might be gained from another test, if certain conditions were met; specifically (1) if an alternative diamond compact attachment technique was used and (2) if the experimental bit could be put into an oversize hole. A different attachment that was less susceptible to loss of strength with increasing temperature might permit some drilling footage to be accomplished before cutter wear became prohibitive. If the bit could be set on bottom without prior wear from reaming and if the initial load was distributed over the cutting structure uniformly enough to prevent overstressing any individual cutters, the chance of some success would be improved. Union Oil agreed that, if another test were conducted, an 8-3/4 in. experimental diamond compact bit could be tested immediately following the last conventional larger diameter bit.

Sandia Laboratories had developed a diffusion bonding process for attaching diamond compact cutters to supporting studs (both steel and cemented tungsten carbide). Some of these cutters had been evaluated during the full-scale laboratory, hot-air drilling tests referred to earlier in this report, and their performance had been promising. No diffusion-bonded cutters had been lost during a test drilling granite, during which 12 braze joints had failed.

The diffusion-bonding process for attaching diamond compact cutters to drill bits for oil/gas drilling applications had been commercialized by Petroleum Concepts Inc., Midland, TX. PCI's engineering and technical staff was, in large part, composed of the former Sandia people who had developed the diffusion-bonding technique.

(See References (25), (26), (27) for background on this process.) PCI agreed to fabricate and assist in testing a diffusion bonded, steel body, stud-type polycrystalline diamond compact bit for this contract.

2. DESIGN OF TYPE 2G1 PCI BIT NO. 8F-1062

Drawings showing the details of the PCI Type 2G1 bit are provided by Figures 223, 224, and 225. Figure 223 shows the overall shape and dimensions of the bit body. Figure 224 shows the locations of the six equally spaced junk slots and the fluid ports. Since the bit was to be run on air, it was not necessary to make provisions for erosion resistant cemented carbide nozzles. Six of the seven nozzles were made significantly larger than those that would have been provided for a bit to be run on mud, to reduce the air pressure drop across the bit to the level of the pressure drop across an 8-3/4 in. roller cone bit used for air drilling at the Geysers. Figure 224 also shows the locations of the three stud-mounted, full-round diamond compact gage trimmers mounted 120° apart (Cutters No. 38, 39, and 40). Additional bit body wear protection was provided by 24 cemented tungsten carbide inserts pressed flush into the bit body, four inserts into each rib as shown in Figure 224. The locations of the 37 diamond compact cutters making up the cutting structure are shown in Figure 225. Thirty-five of the 37 cutters were composed of No. 2530-NC STRATAPAX^R diamond compact drill blanks diffusion bonded to steel studs. The diamond compact-steel stud cutter is shown in Figure 226. The metal collar around the diamond compact was added to hold the cutter in place during diffusion bonding. The cutter back rake is -25°, and the position of the diamond compact cutting face relative to the stud axis is identical to the -25° back rake stud-cutters used in the Type S-2A and S-2B bits. Two of the diamond compact cutters (No. 11 and 16 in Figure 225) were diffusion bonded to cemented tungsten carbide studs. These -25° rake stud-cutters were identical in all respects except for the attachment to the -25° rake stud cutters used for the Smith Tool bits.

Although it is not easily seen by examining Figure 225, 30 of the cutters were positioned to form six spirals of five cutters each, starting 60° apart from the outside of the bit at a point above the leading edge of each rib and turning into the center in a clockwise direction. Thus, the leading cutter in each spiral group was the outermost cutter. Six additional cutters (not part of the spiral pattern) were positioned at the top of each junk. Figure 227 is a photograph of the cutting structure, which was taken at the Geyser's test site. The spiral pattern can be seen in this photograph. The spiral pattern is noted here, not because the concept was new (other bit manufacturers have used it), but because the clockwise spiral in-

ward was unique to PCI. Other manufacturers bits have used a counterclockwise-inward spiral. PCI's experience suggested that this design might provide more efficient cutting action and better bit stability.

Figure 228 is another photograph taken at the Geysers test site showing the bit profile. One of the three diamond compact gage trimmer cutters can be seen in this figure.

3-289

GO GAUGE = 8.750

PC PETROLEUM CONCEPTS, INC. <small>PO BOX 10000 DALLAS, TEXAS 75210 TEL 214-343-1000</small>							
<table border="1"> <tr> <td>DATE</td> <td>7-1-82</td> </tr> <tr> <td>BY</td> <td>JPC</td> </tr> <tr> <td>CHKD</td> <td></td> </tr> </table>	DATE	7-1-82	BY	JPC	CHKD		8 3/4 BODY 8FX
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Figure 223. Bit Body Design, PCI Type 2G1 Bit

95070

3-290

VIEW A-A
6 PLCS

HOLE LOC	ROTARY ANGLE	RADIUS	TILT ANGLE	X	Y
A	90	300	0°	300	0
B	25	1938	↑	819	-1.756
C	90	↑	↑	1938	0
D	150	↑	↑	969	1.678
E	210	↑	↑	-969	1.678
F	270	↑	↑	-1938	0
G	335	1938	0°	819	-1.756

PC PETROLEUM CONCEPTS, INC. <small>PORT OFFICE 2000 E. 10TH AVE. DENVER, COLORADO 80202</small>	
MADE FROM PC1-8008	DESCRIPTION 8 3/4" - MOD 2G1 FLD PORTS - JUNK SLOTS
QTY 3 REV A	DATE 1/8/80 BY JPC CHKD JPC PC1-8F-2271

Figure 224. Junk Slot and Fluid Port Designs, PCI Type 2G1 Bit

95/10

24 BIT FACE PROJECTION FROM OFFSET CENTER TO E OF STAR HOLE

EQ NOZZLE = 12,28,28,28,28,28,28

MOD 261: GEOTHERMAL SPECIAL BIT

PETROLEUM CONCEPTS, INC. 7001 GARDEN CITY BLVD. GARDEN CITY, NEW YORK 11530-4000	
ORDER NO. MADE FROM PC-1-2008	ORDER NO. 8 3/4 - MOD 2G1 -copy to- INFOSTAT: 4
QUANTITY 2	QUANTITY JPL
QUANTITY A	QUANTITY PC-4F-2271

Figure 225. Stud-cutter Locations, PCI Type 2G1 Bit

Figure 226. PCI Diffusion Bonded -25° Rake Steel Stud-Diamond Compact Cutter

Figure 227. PCI Bit No. 8F-1062, Showing the Cutting Structure, Before Testing

Figure 228. PCI Bit No. 8F-1062, Side View, Before Testing

3. DRILLING TEST RESULTS

The bit before the PCI type 2G1 diamond compact bit was a 10-5/8 in. Reed 73JA insert bit. This bit made 90 ft of hole in 3-1/4 hr at 65 rpm, with 55,000 lb weight-on-bit. The airflow was 2400 ft³/min, with one gpm of a liquid anticorrosion agent added. Air pressure was about 400 psi. Depth out for the Reed bit was 5241 ft, the formation was graywacke, and the hole was already emitting copious amounts of steam.

The bottom hole assembly used with the PCI type 2G1 diamond compact bit included: (extending from the bit up) a modified "Drillco" roller reamer, a sub, a 30-ft (6-in. dia.) drill collar, a blade stabilizer, another 30-ft collar, and another blade stabilizer. The drill string included 11 more 6-in. collars and the total string weight was 128,000 lb.

The "modified" roller reamer next to the bit was a conventional reamer to which Sandia Laboratories had attached, in three groups of four, 12 polycrystalline diamond compact cutters diffusion bonded to supports bolted to the reamer body. We had not been informed that this reamer was to be tested, but Sandia Laboratories had made the arrangement with Union Oil so the reamer was included in the bottom hole assembly. It was a poor choice of test conditions for the reamer, as it turned out, so Sandia did not obtain a useful evaluation of this tool.

The PCI bit was run into the hole very carefully. With a stand of pipe (3 joints) yet to go, the kelly was engaged and the air circulation started (2400 cfm, 450 psi pressure). Before rotation could be started the air pressure jumped to about 1000 psi, as if some of the bit ports were plugged. Rotation was started at 40 rpm and after about seven minutes the air pressure dropped to the initial value of 450 psi. The bit was lowered to bottom very slowly, taking over an hour, including connection time for three joints. The bit was put on bottom at 44 rpm and 10,000 lb bit weight. The bit weight was increased to 12,000 lb and in five minutes the bit drilled two feet (24 ft/hr penetration rate). Penetration then abruptly stopped and the air pressure rose to 600 psi. The bit was lifted off bottom and the pressure dropped. The bit was returned to bottom and the bit weight raised to 19,000 lb. The bit drilled about one more foot in 10 minutes with the air pressure remaining at 540 psi. The bit was lifted off bottom to permit the pressure to bleed off and then returned to bottom several more times. No additional measurable footage was made, even at 27,500 lb, so the test was terminated.

When the bit came out of the hole, it was apparent why the air pressure had risen and penetration had stopped. The cutting structure had been totally destroyed

in a circular path about an inch wide. The radius of the center of this path, which was concentric with the axis of rotation was about 3-1/4 in., or just outside of the center of the stud for cutter No. 16. When the bit body touched the bottom a seal was formed surrounding the air ports located in the center of the bit face. Figure 229 is a photograph of the entire bit after testing. The circular damage path is clearly visible. Damage to some of the cutters outside this path can also be seen, but that damage was not extensive. There was no evidence of wear or other damage to the steel bit body. The gage trimmer cutters were slightly worn but had done their job of maintaining gage for the small amount of hole that was drilled.

The steel studs in the severely damaged area had been either plastically deformed, worn away, or both. Figures 230 through 235 are closeup photographs taken around the bit to show the damage details. The stud for cutter No. 17 (Figure 230) was split and pushed aside in two directions. Cutters No. 23 and 29, to the left of cutter No. 17, are missing. The detachment failure was at the diffusion bond interface. Cutter No. 35, behind cutter No. 29, was badly worn but the diffusion bond did not fail. Figure 231 shows severe plastic deformation to the steel stud of cutter No. 15 (the diamond compact is missing) and wear damage to cutter No. 21 (the diamond compact was detached) and cutter No. 36 (the diamond compact is still attached). Figures 232, 233, and 234 illustrate similar wear and damage to other parts of the bit.

Figure 235 is of particular interest in that it shows the worn condition of the remains of the cemented carbide stud for cutter No. 16. If this stud fractured, the break must have been very close to the diamond compact because there was no evidence of fracture in the remaining material. Our prior experience with carbide stud fracture in steel body bits leads us to expect evidence that includes (1) cracks in the remaining carbide extending below the bit body surface and (2) score and gouge marks on the bit body from the hard fractured debris. None of this evidence was present. Since the carbide stud could not plastically deform to any significant degree, the worn shape of the remaining part provides some clue as to how the bit damage occurred. The cross section of the worn surface was almost exactly circular, with a diameter slightly greater than 5/8 in. This is the approximate diameter of a diamond compact stud or a cemented tungsten carbide insert from a roller cone bit. It would have taken something as hard as tungsten carbide to produce the wear on stud No. 16. A detached diamond compact, imbedded in the rock at the bottom of the hole, might have done similar damage but would have, in all probability, also produced machining type cuts and grooves on the bit body.

The five possible sources for a hard object of the right dimensions and shape to produce the bit damage were (1) a carbide or diamond part from the bit itself, (2) the modified reamer, (3) the previous bit, (4) the rock formation, and (5) an object inadvertently dropped in the hole or the drill string during the trip in. Item (1) above, has already been discussed. The modified reamer was examined for damage. Almost all of the diamond compacts were fractured and/or detached but the failures were in the carbide substrates of the compact and no large parts were broken off. The high velocity air stream would have carried the fractured diamond compact fragments out of the hole. The Reed bit which preceded the PCI bit was not examined personally by the writer. It was assumed that normal routine by the driller would include inspection of every bit coming out of the hole to avoid putting a new bit on junk left on the bottom.

It is certainly possible to encounter exceptionally hard inhomogeneities in many formations, some of which, such as massive quartzite or chert can tear up a diamond compact bit, but the probability of creating the type of wear and damage that did occur is small indeed.

It is futile to speculate on the chance that something was accidentally dropped in the hole, except to point out that something foreign was present someplace in the system to retard the airflow shortly after the air was turned on because the pressure went up to 1000 psi for a short period of time before dropping to 450 psi.

A conclusive evaluation of the worth of the diffusion bond per se for geothermal drilling applications was not obtained, but examination of worn cutters outside of the path of total destruction indicated that the steel stud-diffusion bond combination was not tough enough to withstand the combination of high temperatures developed by friction and the high localized stresses developed attempting to penetrate the hard rock, which resulted in plastic deformation of the studs that contributed to failure of diamond compact bonds. Where the studs and attached diamond compacts underwent large amounts of wear without evidence of stud plastic deformation, the diffusion bonds did not fail, in contrast to the brazed joints used for the Type S-2B bit. Cemented tungsten carbide studs with diffusion-bonded diamond compacts might be a better cutting element for air drilling in the Geysers, although the evidence to date indicates that the diamond compact wear resistance is not sufficient, with present bit design concepts, to provide much hope for economic success.

It is worthwhile to comment on the earlier statement that this field test was a poor choice for evaluation of the reamer that Sandia Laboratories had modified by

the addition of polycrystalline diamond compact cutters. The reamer in no way contributed to the poor bit performance, but the poor bit performance certainly prevented a fair test of the reamer. Because the 8-3/4 in. PCI bit followed a 10-5/8 in. roller cone bit, the reamer was rotated in an oversize hole. The only contact the reamer diamond compact cutters could have had with the hole wall would have been intermittent, impact contact that would promote cutter fracture. The tool never had a chance to do what it was designed to do.

Figure 229. PCI Bit No. 8F-1062, After Testing at the Geysers, CA

Figure 230. Severe Bit Damage. Cutter No. 17 is in the center of the picture

Figure 231. Severe Bit Damage. Cutter No. 15 is in the center of the picture

Figure 232. Severe Bit Damage. Cutter No. 18 is in the center of the picture

Figure 233. Severe Bit Damage. Cutter No. 19 is in the center of the picture

Figure 234. Severe Bit Damage. Cutters No. 14 and 20 are in the center of the picture

Figure 235. Severe Bit Damage. Cutter No. 16, which had a cemented tungsten carbide stud, is in the center of the picture

P. CONCLUDING REMARKS

The work performed on this contract was conducted during the period of time when the utilization of sintered polycrystalline diamond compact bits for deep hole drilling developed from its infancy to a viable tool for the drilling industry. The primary purpose of this program - to develop the technology needed for bits applicable to the harsh geothermal drilling environment - was a notably difficult task which met with limited success. However, the spinoff of the results of our investigations to the oil/gas drilling industry was highly effective and contributed significantly to the rapid growth of polycrystalline diamond compact bit use in this area.

Much of the information in this report, particularly the experimental results generated in the controlled laboratory tests (and subsequently evaluated in the field) will not seem new to the informed reader. However, this program was dynamic in the sense that the information developed was rapidly disseminated to those who had a need for it. There was a close working relationship and constant communication between the contractor and Sandia Laboratories, the program technical monitor. Sandia Laboratories very efficiently passed information to those in the drilling industry who could use it and incorporated the information in its own bit development programs. In addition, the structure of the program required close cooperation between the contractor, bit manufacturers, and a major producer. This, plus the fact that the contractor was uniquely positioned as the original developer of the sintered polycrystalline diamond compact concept, opened many informal lines of communication. Also, timely publication and appropriate presentations further stimulated information dissemination.

It would be inappropriate (as well as tedious) to summarize all of the results and accomplishments of this program here. It is appropriate, though, to comment briefly on those items which had the greatest impact upon the development and utilization of polycrystalline diamond compact bits as well as items that the authors consider significant enough to emphasize.

1. The information gained from the instrumented single-cutter rock cutting tests, together with the Sandia computer program for optimum polycrystalline diamond compact cutter layout, produced a steel body, stud-type bit design which formed the basis for the designs of many successful bits utilized for oil/gas drilling.
2. The "wing" type steel body bit designed from information developed from in-

strumented single-cutter experiments served as the basis for the design of the original large hard matrix polycrystalline diamond compact bit fabricated in the United States without stud-mounted cutters. This bit, which performed successfully in a geothermal environment, clearly demonstrated the feasibility of using right circular cylindrical cemented tungsten carbide supports for the diamond compact cutters. This type of "bonded, long substrate" cutter has become the state-of-the-art diamond compact design for hard matrix full-face and coring bits.

3. The full-scale laboratory drilling tests utilizing a pressure vessel to simulate overburden and confining pressure quantitatively demonstrated the drilling efficiency differences between polycrystalline diamond compact bits and conventional roller cone bits. These experiments also (a) alerted the industry to the potential for developing excessive torque with diamond compact bits, with the real danger of twist-off failures at high penetration rates while drilling tough formations, and (b) revealed damage to stud-mounted cutters caused by improper press fit tooling and excessive diametrical interference. Better press fitting techniques were developed and a method for determining adequate but not excessive interference was devised.
4. The first geothermal field test of a steel body, stud-type polycrystalline diamond compact bit demonstrated that the pocketed stud design was subject to fracture caused by built-in stress risers at the back of the compact seat. Brittle fracture failures were traced to cracks created by thermal stresses developed during brazing. This inherent weakness was eliminated by adopting a new nonpocketed stud design from Sandia Laboratories, together with a higher temperature brazing alloy and an improved brazing technique developed by General Electric. The nonpocketed stud cutter utilizing the improved bond is the standard for today's polycrystalline diamond compact steel body bits.
5. The geothermal field tests were instrumental in revealing different modes of wear for polycrystalline diamond compacts and identifying the limiting thermal degradation wear mechanism which occurred during air drilling at the Geysers geothermal field. Additional diamond compact wear investigations were conducted on a parallel Sandia Laboratories subcontract and General Electric is continuing its own fundamental wear studies and the development of more wear resistant diamond compact materials.
6. Excessive bit wear observed for field tests conducted where aerated water provided cooling for the diamond compact cutters was confined to cutters on the bit periphery, accompanied by rapid bit body gage wear. Polycrystalline dia-

mond compacts inserted into the bit body wall, flush with the steel surface, reduced the gage wear markedly. Utilization of diamond compacts in this manner has been adopted by at least one manufacturer of oil/gas polycrystalline diamond compact bits and was the key factor in obtaining bit runs of greater than 13,000 feet. (28)

7. Almost all of the work conducted on this contract was performed in an effort to find solutions to materials and design problems, and some success was achieved in these areas. The one task that was not directly materials or design oriented was the relatively simple economic analysis of the Baca Field drilling system. The results of this task defined more clearly than any other the critical target toward which the work should be directed. This drilling system analysis could have been done entirely independently of the remainder of the work. In the event that programs similar to this one are considered, it is recommended that, prior to program definition or as an "up front" program requirement, systems analysis and/or modeling is conducted to better identify the critical targets and objectives of the work to be performed.

Section 4

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APPENDIX A

Diamond Compact Cutter Studies for Geothermal Bit Design

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Diamond Compact Cutter Studies for Geothermal Bit Design

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As a prerequisite to design of a geothermal drill bit using diamond compact cutters, the rock cutting characteristics of these compacts have been studied in a series of instrumented single-cutter continuous and interrupted turning tests on hard, high-compressive strength sandstone and other rocks of known properties. A range of compact rake angles was used and cutting forces were measured. Rake angles affected cutting efficiency (specific energy) at light cuts but were less significant at high penetration forces more characteristic of bit weights used in drilling. In continuous turning, cutter forces exhibit regular, repeating variations probably related to the alternate crushing and fracturing modes which the rock undergoes. In interrupted cutting, forces drop to zero, as expected, while passing through a void but on subsequent impact the forces are no greater than measured in continuous cutting. Thus, force fluctuations when cutting a composite of hard and soft rock should not be significantly greater than those generated in cutting each rock separately. Of considerable interest is the fact that cutting forces were found initially to be independent of speed over the tenfold speed range and low depths of cut covered. More sophisticated cutting experiments covering a wider range of conditions and rock types showed a significant effect of speed on force. However, the effects of changing speed were not as great as those of geometry and depth of cut. The results of these experiments have been used in generation of a preliminary bit design.

Bit Design Requirements

Environment. The proper design of drill bits for geothermal drilling of exploration and production holes depends heavily on the specific environments and formations to be encountered. In general, the drilling methods for geothermal wells are the same as those used by the gas/oil industry; namely, conventional rotary drilling techniques. However, a variety of factors frequently make geothermal hole production more difficult even though the drilling depth requirements may not be as great as for oil/gas. These factors include:

- Less accessible drilling locations.
- A wide variety of strata making up the geothermal source system which may include the overburden, cap, and aquifer.
- Almost always the necessity to penetrate fractured, fissured, or porous rock.
- High hole temperatures in the production zones, up to 662°F (350°C).
- Corrosive and erosive environments due to superheated

dry and/or wet steam hot brines, and additional corrosive agents such as dissolved H₂S and other acidic constituents.

A survey and review of geothermal regions reveals that the Northern California coast ranges, which includes the Geysers, consist mainly of young, silicic volcanic fields. Hot igneous rock is the source of magma. The Geysers contain intensely faulted and fractured Franciscan graywacke sandstone at depths of 824-2516 m (2700-8250 ft) and also contain minor shale, quartz, chert, greenstone, serpentine, and jasper deposits. A drystream field may have a maximum temperature of 250°C (482°F) but drill-bit temperatures can be considerably higher (up to 480°C (896°F)) because of frictional heating and possibly inefficient cooling.

The Salton Trough, or Imperial Valley region, contains geothermal reservoirs, primarily hot water with temperatures to 370°C (698°F). The reservoirs are fractured, cemented sandstone of Pliocene age along with clays and clay shales. Formations extending downward from the surface include alluvium, sandstone and shale, and hard, silicified, metamorphosed sandstone and shale. The rock is mainly soft (shallow) to medium hard (deep).

Other geothermal regions exhibit some variations from the formations encountered in the Geysers and in the Imperial Valley. For example, the High Cascade Mountain region is characterized by outpourings of andesitic and basaltic lavas. The western range of the Basin and Range province, centered in

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NOTE: Appropriate SI Conversion Units—1 lb = 0.4536 kg, 1 in. = 2.54 cm, 1 ft = 0.3048 m

Nevada but extending also into Oregon and California, consists of young silicic and basaltic volcanism and faulting. Temperatures can exceed 200°C (392°F). The eastern belt of this province lies west of Wasatch Front and extends across Utah and into southern Idaho. The rock formations are primarily alluvium underlain by fractured granite. Exploratory drilling in broad, fractured rock at Roosevelt Hot Springs, Utah, yielding hot water and steam, has indicated temperatures of ~ 200–260°C (~ 392–500°F). The Rio Grande Rift is characterized by young silicic and basaltic igneous rocks and contains interbedded tuff and andesites. A water reservoir at Valles Caldera, New Mexico, has a temperature above 260°C (500°F). The Snake River Plain of Idaho and Oregon contains formations primarily of young basalts. There are some hard metamorphic rocks consisting of quartzite and schist at 1525-m (5000-ft) depths. The Northern Gulf of Mexico Basin extends from Yucatan to the Florida Peninsula and forms a part of the Gulf Coast geosyncline. Formations are primarily sand beds and clay. Temperatures to 270°C (518°F) have been reported. Hot water reservoirs are trapped in the lower sand beds by mud layers and are consequently under very high pressure. The deep geopressured zones have not yet been exploited, but if the resource is found to be of commercial value, drilling will proceed to depths of 4574 m (15,000 ft).

Reservoir temperature alone does not determine bit temperature and bit wear. For example, the reservoir temperatures are lower in the Geysers than in the Imperial Valley. However, the higher hardness, abrasiveness and strength of the Geysers formation lead to higher frictional heating. Also, to preserve the desired structure of the geothermal well, a shift from drilling with mud to drilling with air is made as soon as consistent gray-wacke is reached. Because of the poorer heat transfer characteristics of air relative to mud or water, the heat generated in drilling is not carried away as readily as desired.

This brief review shows that geothermal resource areas encompass a broad spectrum of geological formations involving different degrees of drilling difficulty. In the Imperial Valley region the temperatures may reach 370°C (698°F), yet drilling muds help to alleviate somewhat the problems of frictional heating and this has resulted in fewer drill-bit problems than in the Geysers. Abrasive materials exist at significant depths where the rock has metamorphosed. Because of the large amount of drilling activity currently underway in the Imperial Valley, this area is a prime candidate for drilling studies involving diamond compact bits and the work reported here has been aimed primarily at such formations.

Economics. An Ad Hoc Committee on Technology of Drilling for Energy Resources reported in 1976 that "for the rotary drilling equipment and techniques used for oil, gas, and geothermal energy recovery, the most significant improvements will be those that decrease the time that the rig is not drilling. Current estimates are that operating time spent in actual drilling is only about 40 percent for all onshore wells and 25 percent for all offshore wells, where more directional drilling occurs" [1]. Clearly, longer-lived bits would contribute significantly to reduced downtime by virtue of the lower number of trips (to change bits) needed. Improvements in instantaneous drilling (i.e., penetration) rates would also improve the overall drilling rate. Since for a given drill bit the bit life is, in general, an inverse function of the penetration rate, an appropriate tradeoff is required—within each range of depths—to maximize overall drilling rates.

The cost of drilling has increased over the years as might be expected. In 1945 the average depth of an oil/gas well was 1064 m (3489 ft) and the average cost was \$31,401 per well (\$9 per ft) [2]. In 1973 there were 26,244 oil and gas wells drilled in the United States, totalling 41.7 million linear m (136.7 million ft) [1]. The average depth of these wells was 1588 m (5207 ft) and the average cost was \$117,152 per well (\$22.50 per ft). The cost depended markedly on the depth drilled, the average cost per well

being \$99,000 for a depth interval of 1525–2287 m (5000–7499 ft) and \$2,008,000 for a depth of 6100 m (20,000 ft) and over. This increase results not only from the longer times required for round trips to change bits but also because of lower penetration rates in the more highly stressed rocks. Maurer has shown that even in "soft" rock, i.e., rock with a compressive strength < 48.3 MPa (7000 psi), the drilling rate is decreased from 46 m (150 ft) per hour at a well depth of 1830 m (6000 ft) to 1.8 m (6 ft) per hr at a well depth of 7320 m (24,000 ft) [3].

Beyond the shallow depths near the surface, the drilling of geothermal wells becomes more complicated than oil/gas drilling because of the formations encountered and the higher temperatures involved. Owing to the severe environment, both drilling time and cost are increased. In the igneous formations, the usable life of the best hardrock bits with tungsten carbide teeth may be 61 m (200 ft) or less [1]. This can nearly triple the drilling time over oil/gas drilling for equal footage. It is reported that the average cost of a geothermal well in 1975 was \$300,000 to \$600,000 per well, depending on rock types and depth requirements [4]. Unofficial reports have placed some recent geothermal drilling costs at closer to \$1 million per well. The *Geothermal Handbook* [5, p. 22], reports geothermal drilling rates in the neighborhood of 30.5–61 m (100–200 ft) per 24 hr day. The cost of drilling ranges from \$70 to \$100 per ft.

The costs just cited represent the total costs associated with drilling a well, that is, setup, logging, reaming, tripping, and other nondrilling costs plus the costs incurred while the drill bit is rotating and removing material. Examination of conventional rock-bit drilling records from the East Mesa region of the Imperial Valley yield an average bit life of about 18 hr for holes averaging 830 m (6000 ft) in depth. The bit lives are, however, extremely variable. The penetration rates decrease markedly in an exponential manner with increasing depths ranging from ~ 21.4 m/hr (70 ft/hr) at shallow depths to about 3.05 m/hr (10 ft/hr) at depths of 2440 m (8000 ft). (Other reports have indicated penetration rates at this depth closer to 6 ft/hr [1.83 m/hr].) An equation which represents the relationship between penetration rate and depth is

$$P_R = Ae^{-Bd} \quad (1)$$

where P_R is penetration rate, d is depth, and A and B are const.

This change in penetration rate with depth can be factored into a numerical equation for calculating the drilling cost:

$$\text{cost} = R \sum (\Delta d/P_R + t) + nS \quad (2)$$

where R = rig cost, Δd is the depth increment selected for numerical evaluation, t = trip time (dependent on depth), S = bit cost and n = number of bits. For a typical case involving conventional rock bits we can use values of R = \$500/hr, t = $d/1000$ (hr) and S = \$2000.

By choosing a small value for Δd (i.e., 100 ft [30.5m]) a numerical integration can be performed to calculate bit rotating time and cost as a function of depth. Choosing appropriate bit life values, the number of trips and bits required can be determined. Substituting these values in equation (2) yields the total drilling cost.

Calculations of costs for drilling the depth interval from 4000–8000 ft (1220–2440 m) using the conditions for the East Mesa region described above illustrate the relative importance of penetration rate and bit life. Maintaining a bit life of 18 hr, but decreasing penetration rate to 60 percent of the standard (varying with depth) rate will increase costs by 66 percent. On the other hand, maintaining the standard penetration rate and decreasing bit life to 60 percent of the normal 18-hr average (10.8 hr) will only increase costs by 24 percent. This indicates that drilling costs under these conditions respond more sensitively to penetration rate than to bit life and that design emphasis should be placed on increasing penetration rates for maximum economic advantage.

Cutter/Rock Relationships Required for Bit Design. The design criteria for a geothermal bit are not greatly different from those for an oil/gas bit, with appropriate allowance for the different formations and environments encountered. In the case of a bit based on diamond compacts, a larger difference probably arises from the particular mode of cutter/rock interaction peculiar to a compact bit. That is, the diamond compacts can be so positioned as to primarily shear the rock rather than to effect a crushing action as in tricone roller (rock) bits or a rubbing and crushing action as in the case of diamond single crystal drag bits. Basically, it would appear that an understanding of some of the following relationships are needed in geothermal bit design:

- (a) the effect of cutter size on rate of material removal and on torque;
- (b) the effect of the degree of cutter overlap on cutting efficiency, i.e., penetration rate, force, rock removal, and cutter wear;
- (c) penetration rate as a function of rotational speed and cutter size;
- (d) the effect of rotational speed on force and cutter wear rate;
- (e) the effect of cutter geometry, e.g., side rake, back rake and clearance on penetration rate, force, and cutter wear rate; and
- (f) variation of these parameters as required by the range of rock properties encountered in geothermal formations.

The diamond compact cutter studies discussed in this paper have been aimed at clarifying some of these relationships and the results have been used for a preliminary bit design.

Experimental Approach

Evaluation of the performance of STRATAPAXTM diamond blank tools "cutting" rock in experiments at General Electric Corporate Research and Development (CRD) as well as tests performed by General Electric at other company sites, at Tulsa University and by Sandia Laboratories in Albuquerque, N.M. have clearly demonstrated that the rock cutting efficiency is dependent upon the independent (controllable) variables of the cutting system, as well as the rock physical properties. The forces acting on the diamond compact tool are a function of its shape, its angle of attack with the rock surface, the depth of cut, the strength and hardness of the rock and (perhaps, although to a much lesser degree), a function of the cutting speed. Since the performance of an actual diamond compact bit will be dependent upon the performance of its individual cutting elements, it is necessary to study individual diamond compact cutters in order to optimize their configurations for the various conditions under which they will be required to function. Examples of failure of diamond compacts and/or their support structures in bit field tests clearly demonstrate the need for the information necessary to design and construct bits with sufficient structural integrity to minimize the chance for breakage and shortened tool life. The objective of the work described in this paper is to obtain this cutter information.

Experimental Apparatus. Up to the initiation of our Energy Research and Development Administration (ERDA) supported program, all the rock cutting experiments at CRD were performed by turning a cylindrical rock core and some diamond compact wear studies are still being done in this manner. A Lebow strain gage dynamometer formerly used for metal cutting studies was modified to measure the thrust (normal) and drag (cutting) forces for these early experiments, the results of which will be discussed briefly later in this paper. However, the strain gage system suffered from two major deficiencies, a lack of overall cutting system stiffness and slow response time which prompted significant experimental design changes for the GE-ERDA program.

Fig. 1 Overall view of rock-cutting experimental apparatus

First, in order to 1) more closely simulate the cutting path of a compact on an actual bit, 2) increase the overall apparatus rigidity and stiffness, 3) permit utilization of rock specimens in a more easily obtainable shape, at lower cost, and 4) allow repetitive experiments to be performed under as close to identical as possible conditions, the single cutter experimental design was changed from turning a cylindrical surface to producing a spiral cut on a flat rock surface. Second, a three force-component piezoelectric dynamometer was obtained with very high stiffness and rapid response time. The entire improved experimental apparatus is shown in Fig. 1. It consists of a Pratt and Whitney tool room lathe, a special face plate constructed to mount the rock specimen on a 3-jaw chuck, a 3-force component piezoelectric dynamometer attached to the lathe cross slide, and the necessary electronic apparatus to amplify and record the dynamometer output signals.

The face plate or nest to hold the rock specimens, constructed of 4340 steel, provides the capability for rigidly holding rock samples up to $22.9 \times 22.9 \times 15.2$ cm ($9 \times 9 \times 6$ in.). Provisions were made to back up the mechanical clamping of the rock by means of anchor bolts set in epoxy resin, but this has not been necessary so far. Fig. 2 shows a rock sample mounted on the machine. The spiral cutting path is clearly visible.

Fig. 3 shows the piezoelectric dynamometer mounted on the lathe cross slide. It was firmly bolted in the position normally occupied by the compound. In order to be certain that the dynamometer would be firmly seated, the cross slide was removed from the machine and the compound seat was ground to assure flatness.

This dynamometer, manufactured by Kistler Instruments AG, Winterthur, Switzerland, has the capacity to measure forces up to 9786 N (2200 lb) in three mutually perpendicular directions. The signals are fed into charge amplifiers, and from there to suitable read-out devices such as a high-speed strip recorder or an oscilloscope. The dynamometer response is linear with respect to the applied load, and the cross talk is so small that corrections are unnecessary.

An auxiliary pump was added to the apparatus to provide fluid coolant during cutting. A 40:1 water: soluble oil mixture was used to prevent excessive machine rusting. Comparison of cutting forces with oil emulsion and straight water indicated no

TMTrademark, General Electric Company, USA.

Fig. 2 Rock-cutting machine showing method of attaching rock to lathe headstock

Fig. 3 Piezoelectric dynamometer, with diamond compact cutter in place

measurable effects due to the oil.

The machine stiffness (static) was measured in the direction of the axis of rotation (normal to the surface of the rock specimen) by introducing a hydraulic piston between the rock surface and the tool holder bar in the dynamometer. Head stock and dynamometer (cross slide) deflections as functions of applied load were determined using sensitive dial indicators, and these values added to give the total deflection. The results are shown in Fig. 4.

During the subsequent instrumented single diamond compact cutter rock cutting experiments, at depths of cut as great as 0.165 cm (0.065 in.) in one case, the magnitudes of the thrust

Fig. 4 Rock-cutting machine stiffness

forces were below values necessary to produce machine deflections of 0.0025 cm (0.001 in.). Measurements of rock groove depths showed that deviations in actual depths-of-cut from planned depths-of-cut were not significant and within the limits of accuracy of the overall experimental measurements. In contrast, machine deflection in earlier experiments cutting the cylindrical surface of rock cores was excessive, necessitating measurement of actual depth-of-cut following each test. For example, setting the machine for a nominal depth of 0.076 cm (0.030 in.) cutting Jack Fork Sandstone could produce a groove depth of only 0.046-0.048 cm (0.018-0.019 in.) using a 0.818-cm- (0.322-in-) dia round STRATAPAX blank tool.

Experimental Materials. Three basic STRATAPAX blank cutter shapes were chosen for the single-point rock-cutting experiments utilizing the modified apparatus. These were:

- (a) pointed cutter (triangular) with a 90-deg included angle;
- (b) straight edge cutter, 0.254 cm (0.100 in.) in width;
- (c) curved edge cutter (portion of a circular) 1.369-cm- (0.539-in-) dia STRATAPAX drill blank).

The curved (circular) cutting edge is the configuration that has been most extensively tested in the field in experimental bits and in laboratory tests prior to this program. STRATAPAX drill blanks of 0.818-cm (0.322-in.) diameter were used in the early instrumented single-cutter experiments turning Jack Fork Sandstone.

The basic tool design for the continuous spiral rock-cutting experiments is illustrated in Figs. 5 and 6. The tool shown is a 90-deg included-angle cutter, but the design for all three cutter shapes was the same with the exception of the platform which supports the diamond compact. This, of course, must conform to the compact shape. The tools were machined from Cr-Mo-V steel bars and in order to maximize stiffness during cutting, a separate tool was machined for each back rake used. The tool illustrated has a -25-deg back rake. The diamond compacts were brazed onto the tools, using a suitable low temperature brazing alloy. These tools were constructed with round shanks which were clamped into a carefully machined massive rectangular bar fitted to the dynamometer. This design, while maintaining overall system rigidity, permitted the side rake of the diamond compact cutters to be set at any desired value from neutral (0 deg) up to 8 deg either direction from neutral.

Six different kinds of rock suitable for testing were obtained. The basis for the choice of rock types was: 1 reported compressive strength, where available; 2 hardness; 3 grain size (small, medium, large); 4 composition; and 5 availability. Ideally, a set of six rock types consisting of three pairs of medium-fine and

Fig. 5 25-deg negative rake toolholder with diamond compact brazed in place (side view)

Fig. 6 Same as Fig. 5 (top view)

medium-coarse grained materials of about 69 MPa (10,000 psi), 138 MPa (20,000 psi), and 207 MPa (30,000 psi) compressive strength was desired. The rock types obtained were a compromise suite of materials chosen on the basis of availability and economy. Consideration was given to selecting rocks from Western sources to represent expected geothermal drilling environments. However, it was concluded that an adequate test program could be run at significant cost savings by using locally available materials with a range of properties encompassing those expected in geothermal holes. These materials and their sources are listed in Table 1.

The ultimate compressive strength and the modulus of elastic-

ity in compression were measured at our laboratory for four of the six materials listed in Table 1, and Shore hardness values were obtained on all six rock types. Table 2 lists the property measurements made in this laboratory, together with values reported by other sources. In addition to the physical property measurements, both polished specimens and thin sections were examined for all the rock materials used. These petrographic descriptions are not included in this paper for the sake of brevity, but will be given in detail in the final report to ERDA on this program.

Experimental Scope and Results

The primary purpose of the experiments using individual diamond compact tools was to obtain information useful for improved bit design. This includes the early instrumented single cutter continuous cutting and interrupted cutting experiments, the more sophisticated instrumented single cutter experiments for which the apparatus and materials have been described in some detail, the diamond compact wear measurements under very abrasive conditions. The results of typical early single cutter experiments will be touched upon briefly, as will the wear results. Maximum attention will be paid to the single cutter spiral cutter experiments utilizing the modified apparatus with maximum stiffness.

Early Rock-Cutting Experiments. The pre-ERDA program rock "turning" investigations at CRD were limited almost exclusively to small (~ 0.813 -cm- (0.320-in-)) diamond compacts cutting Jack Fork sandstone. Each test cut followed a helical path, so that the diamond compact continuously cut fresh rock. These experiments were laborious and slow, because no more than three test cuts could be made before the rock cylinder had to be resurfaced. The maximum cutting speed was limited by the diameter of the rock sample and the "safe" spindle rpm. Exact duplication of cutting speed was impossible because the rock diameter was constantly decreasing. The depth of cut was limited to about 0.051 cm (0.020 in.) because of machine and workpiece deflection and also by the maximum allowable safe thrust force, particularly when the rock diameter became quite small.

In spite of the drawbacks of this experimental technique, significant information on the performance and potential of diamond compacts was obtained. Experiments were performed where the cutting speed was varied from ~ 9.15 m/min (30 ft/min) to slightly above 91.5 m/min (300 ft/min), the depth of cut was varied from a few thousandths of an inch to ~ 0.051 cm (0.020 in.), and the negative back rake of the cutter was varied from -5 deg to -45 deg. The most significant conclusions drawn from this work were:

(a) The forces necessary to "cut" the rock were minimized at negative cutter back rake angles between -10 deg and -20 deg independent of speed and depth of cut.

(b) Within the limits of accuracy of the experiments, the rock cutting forces were independent of cutting speed. This is shown in Fig. 7 for a -5 -deg back rake tool, and was found to be true for all the cases investigated.

Table 1 Rock suite for instrumented cutting experiments and wear rate and failure mode analysis

	Rock type	Source	Obtained from
1	White Danby marble	Danby, Vt.	Vermont Marble Company
2	Black Champlain marble	Isle la Motte Lake Champlain, Vt.	Proctor, Vermont Vermont Marble Company
3	Belmont Rose granite	Belmont Township Ontario, Canada	Vermont Marble Company
4	Graymont granite	Barre, Vt.	Vermont Marble Company
5	Jack Fork sandstone	Arkansas	Tulsa U, Tulsa, Okla.
6	Verde Antique marble (serpentine)	Rochester, Vt.	Vermont Marble Company

Fig. 7 Effect of depth on drag force for turning Jack Fork sandstone with diamond compact, -5-deg back rake

(c) The efficiency of rock removal, (expressed as the specific energy) improved as depth of cut increased, as shown in Fig. 8.

A limited number of tests were performed during these early experiments that subjected the diamond compacts to impact forces. This was accomplished by machining 0.635×0.635 cm (0.25×0.25 in.) rectangular grooves in the surface of the Jack Fork sandstone parallel to the cylindrical axis. It was anticipated that greater than normal cutting (drag) forces would be observed where the diamond compact tool passed through the void in the rock and encountered solid material again. This did not prove to be the case. Both measured force components (drag and thrust) dropped to zero in the groove, and instantly rose to the same levels seen for continuous cutting without a slotted rock. (Since the response time of the strain-gage dynamometer system was relatively slow, these experiments were repeated later using the piezoelectric system, which has excellent high frequency response. The test results were the same using both dynamometer setups.)

It should be noted that, although the diamond compacts have exceptional hardness, strength and wear resistance because of the diamond-to-diamond bonding within the polycrystalline sintered structure and the random orientation of the individual diamond crystallites, they can be damaged by improper use. For

example, if an excessive rake was used (i.e., -30 deg, -45 deg) surface cracks approximately parallel to the cutting edge could be generated that would eventually result in fracture. When a high negative rake is employed, a significant portion of the sintered diamond layer is unsupported by the cemented carbide substrate and is subjected to a bending moment under impact conditions and continual fatigue conditions during normal continuous cutting. (Even when continuously cutting competent rock, the rock failure mode is alternately crushing and shearing, producing continual force variations as high as 50 percent of the average drag or thrust force.) A detailed analysis of the basic mechanisms of wear and fracture of diamond compacts has been given by Hibbs and Lee [6].

Diamond Compact Wear Rates. Bits developed for use in drilling geothermal wells must operate in harsh environments. Formation temperatures will be significantly higher than oil/gas wells, the formations can be expected to be generally abrasive (in some instances extremely abrasive), and drilling practice for geothermal production can frequently result in inadequate bit cooling. These conditions are ideal for accelerating the wear rates of materials, even diamond compacts. Therefore, a wear rate investigation was conducted, as described in the following.

Table 2 Rock properties

	Uniaxial compressive strength (psi $\times 10^3$) ^(a)		Modulus of elasticity in compression (psi $\times 10^6$)		Hardness (shore)		Shear strength (psi $\times 10^3$)		
	CRD	Other	CRD	Other	CRD	Other	CRD	Other	
1 White Danby marble	7.89	9.80	4.43	9.74	33			1.90	Other—Vermont Marble Company
2 Black Champlain marble	21.3		7.73		49				
3 Belmont Rose granite		21.7		8.98	97				Other—Vermont Marble Company
4 Graymont granite		27-29		6.5-6.7		87-90			Other—U.S. Bureau of Mines
5 Jack Fork sandstone	37.1		6.16		86				
6 Verde Antique marble (serpentine)	51.0 ^(b)		11.3		70				

^(a) 1 psi = 0.006894757 MPa

^(b) Measurements ranged from $37.7-66.0 \times 10^3$ psi, depending upon veining in the samples.

Fig. 8 Effect of rake angle on rock removal efficiency

Wear-rate determination for diamond compacts in the laboratory is a much more tedious process than cutting force measurement due to the extreme resistance to wear exhibited by these materials. In order to assure that the wear mechanisms are the same as those operating on an actual drill bit, the compacts should be run against a material with properties similar to formations encountered in practice (i.e., an actual rock of known properties) under conditions of speed, cutter engagement, etc., close to anticipated bit requirements. If the speed of the compact relative to the rock is increased markedly in order to accelerate the wear rate, the danger of generating excessive temperatures at the interface exists, and consequently bringing about a change in wear mechanism from abrasive to thermal and/or reactive.

In order to obtain measurable amounts of wear in reasonable lengths of time, Jack Fork Sandstone was the rock chosen, because of its relatively high strength, its fine grained, homogenous composition and its very abrasive character. The diamond compact wear tests were performed turning cores of this material in a manner analogous to turning metal, using the same machine used for the force measurements described in the preceding section. Round compacts were tested, using a standard Carboly RATR-16-4 indexable insert toolholder. The pocket for this holder was modified to take a 0.841-cm- (0.331-in-) dia diamond compact, providing a -5-deg back rake and a -5-deg side rake. All the wear tests were performed under standard conditions of 0.0127 cm (0.005 in.) revolution feed and 0.051 cm (0.020 in.) depth of cut. The cutting speed was varied in order to obtain a

Fig. 9 Worn compact wearland

graphical relationship between speed and volumetric diamond compact wear rate. All tests were performed using a soluble oil (40:1 water to oil) to flood the compact cutter and cutting zone.

The volume of diamond compact wear was calculated from measurements made before and after testing and the wear rate determined by dividing by the total cutting time. Fig. 9 is a photograph of a compact with a large amount of wear, showing a typical wear land (note that the wear flat extends into the tungsten carbide substrate).

Two types of compacts were tested, a fine-grained material (COMPAX^R blank Series 1300) and a coarser-grained material (STRATAPAX blank series 2300). The experimental results are summarized in Table 3 and shown graphically in Fig. 10.

Table 3 Wear rates of compax^R diamond compacts cutting Jack Fork sandstone

COMPAX ^R type	Test no.	Cutting speed (sfm)	Volumetric wear rate (in ³ per min) ^(a)
1330	1	100	0.0097 × 10 ⁻⁶
1330	2	350	0.0553 × 10 ⁻⁶
1330	3	360	0.0678 × 10 ⁻⁶
1330	4	510	0.382 × 10 ⁻⁶
2330	1	152	0.0048 × 10 ⁻⁶
2330	2	260	0.0166 × 10 ⁻⁶
2330	3	320	0.0383 × 10 ⁻⁶
2330	4	375	0.123 × 10 ⁻⁶
2330	5	500	0.0326 × 10 ⁻⁶
2330	6	500	0.170 × 10 ⁻⁶
2330	7	540	0.120 × 10 ⁻⁶

(a) 1 in. = 2.54 cm

The wear rates for both types of diamond compacts are about the same above 122 m/min (400 surface ft per min (sfm)), indicating that a thermal wear mechanism may be starting to predominate. This could be oxidation, chemical reactivity or thermal fatigue in addition to simple microchipping due to abrasion. At speeds below about 122 m/min (400 sfm), the difference in wear resistance becomes evident. At the lower interface temperatures (due to lower cutting speed) the wear mechanism is predominantly microchipping abrasive wear. The diamond compact made with the larger diamond grains was found to have greater resistance to abrasive wear in these experiments.

The wear-rate speed curves shown in Fig. 10, are obviously non-

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Fig. 10 Diamond compact wear rates cutting Jack Fork sandstone

linear. The curve for the 2330 material (a STRATAPAX rock-drilling diamond compact grade) was fitted by the equation:

$$WR = Ae^{BX}$$

where WR = volumetric wear rate, in³/min

X = cutting speed, ft/min

$A = 7.621 \times 10^{-10}$

$B = 0.012049$

The actual values of the constants A and B are not significant since they only apply to a specific controlled laboratory experiment. The fact that the wear rate is an exponential function of speed (roughly translated into interface temperature) does have significance however. It seems possible that diamond compact drag bits designed for hot, abrasive geothermal environments may be limited somewhat slower rotary speeds than bits developed for cooler, less abrasive formations.

Fractional Factorial Diamond Compact Rock-Cutting Experiments. An extensive series of single cutter experiments were performed using the rock materials and cutter configurations described earlier in this paper with the modified apparatus for spiral face cuts. The objective of these experiments was to obtain sufficient information on the performance of individual diamond compact tools cutting a variety of rocks of differing properties to serve as a basis for the initial design of a geothermal drag bit. The information generated by the prior rock turning experiments cutting Jack Fork sandstone was valuable in that it demonstrated the potential for diamond compact bits and the general trends to be expected in the relationships between the principal variables involved. However, the early cutting experiments did not provide sufficient information on the cutter/rock relationships suggested in the beginning of this paper to provide an adequate basis for bit design.

The principal independent variables for any given single-point rock-cutting test are: 1 the diamond compact cutter shape; 2 the cutting speed; 3 the cutter back rake (positive, negative, and degree), 4 the depth of cut; and 5 the side rake, or angle between a normal to the cutter surface and the direction of cutter motion relative to the rock. Assuming five values for each variable (speed, back rake, depth of cut and side rake) for each of three basic cutter shapes, the number of individual cuts required to fully evaluate a single rock type is very large. If the program is to include five to six rocks of different properties, a full factorial experiment would require an obviously impossible number of individual cuts. In order to reduce the amount of tests to a workable number, a statistical technique was chosen that would permit prediction of diamond compact cutter performance from a fractional factorial experimental design, using regression analysis to obtain equations relating the dependent variable (i.e., cutting force) to the independent variables. A similar scheme was recently employed successfully to obtain BZN⁷ compact cutting-tool performance predictions in machining applications on high-temperature superalloys [7].

The statistical program used in this work is called STAT PAC. Initially written in batch FORTRAN for GE and HIS 600 and 6000 computers, a new version called INTERACTIVE STAT-PAC has been developed which can be utilized on the GECOS time sharing system from a teletype terminal. This interactive STATPAC program is the one used for the work reported here.

The STATPAC program uses a least-squares linear regression analysis to fit relationships between a dependent variable, i.e., in our case the resultant force vector on the diamond compact cutter, and the independent variables (such as cutting speed, depth of cut, back rake, side rake). In order to use this technique

to analyze the data from a fractional factorial experiment, first a model relating the dependent and independent variables must be chosen. In our case, a second-order model was chosen, where, for example,

Y_R = resultant force of the three mutually perpendicular forces Y_x, Y_y, Y_z , lb

X_1 = cutting speed, sfm

X_2 = back rake, deg

X_3 = depth of cut, in.

X_4 = side rake, deg

K, K_1, K_2 = const to be determined

Using first- and second-order terms for the independent variables and including all possible second-order independent variable interactions, the model equation was:

$$Y_R = K + K_1X_1 + K_2X_2 + K_3X_3 + K_4X_4 + K_5X_1^2 + K_6X_2^2 + K_7X_3^2 + K_8X_4^2 + K_9X_1X_2 + K_{10}X_1X_3 + K_{11}X_1X_4 + K_{12}X_2X_3 + K_{13}X_2X_4 + K_{14}X_3X_4$$

After the model was chosen, a matrix representing the individual cutting test cases making up the fractional factorial set was designed. For this program, five levels were chosen for each independent variable; designated as: 1 very low, VL, 2 low, L, 3 medium, M, 4 high, H, and 5 very high, VH. Typical values for these levels are given in Table 4.

The test matrix used for all fractional factorial experiments consisted of a minimum of 32 data points. Since, for a spiral cut across the face of the rock, the speed is constantly changing it was possible in some cases to obtain two data points per cut, so the 32 data points could be obtained with only 28 spiral cuts.

Using the STATPAC program to obtain the relationship between the resultant cutting force and the independent variables quickly revealed that there was no significant effect due to changing the side rake of the diamond cutter within the limits chosen. Inspection of the experimental data showed the horizontal forces measured parallel to the rock face (the side thrust) were very small compared to the force components normal to the rock surface (penetration force) and the forces acting parallel to the cutting direction (drag or cutting force). Since the major effect of hanging the side rake would be to change the magnitude and/or direction of the side thrust, and the experimental data indicated this effect was trivial, side rake was subsequently fixed at 0 deg and eliminated as an independent variable.

A modified test matrix was designed, still composed of 32 data points. The independent variables were speed, depth of cut and back rake. Two forces were measured, the cutting (or drag) force and the penetration force. Thus, the resultant force vector was defined as lying in the plane of the measured force components. This greatly simplified the model equation for the angle (direction) of this vector. The final equations for magnitude and direction of the resultant force vector were essentially the same as the original model, except that the equation predicting the resultant force magnitude consisted of ten terms and the equation predicting the angle the resultant force vector makes with a direction normal to the rock surface contained thirteen terms.

Tabulating and reporting the values for all the coefficients for the equations generated by the STATPAC program for three different diamond compact cutter geometries, cutting five different rock materials is beyond the scope of this paper and would serve no useful purpose. This information will be provided in an appropriate later report to ERDA. However, some graphical results are useful to show the trends observed.

Figs. 11 and 12 show the predicted resultant force magnitude and direction for a straight-edge diamond compact cutting

⁷Trademark General Electric Company, USA.

Fig. 11 Effect of rake angle on predicted resultant force and angle for straight-edge diamond compacts cutting Champlain Black marble, 7.62 m/min (25 sfm)

Fig. 12 Effect of rake angle on predicted resultant force and angle for straight-edge diamond compacts cutting Champlain Black marble, 31.5 m/min (300 sfm)

Champlain Black Marble (~ 138 MPa (20 ksi) compressive strength) for depths of cut from 0.025–0.127 cm (0.01–0.05 in.), varying the back rake from -5 deg to -30 deg, for two speeds, 7.63 and 91.5 m/min (25 and 300 sfm). These plots clearly show the minimum in cutting force that was observed in the earlier turning tests in Jack Fork sandstone. The optimum back rake appears to be about 91.5 m/min (-15 deg at 300 sfm) and about -10 deg at 7.63 m/min (25 sfm), which is in good agreement with earlier tests.

The reversal in resultant angle with increasing back rake is not understood at this time, but this trend decreases with increasing speed.

Fig. 13 Effect of speed on predicted resultant force and angle for straight-edge diamond compacts cutting Champlain Black marble, -15 -deg back rake

Fig. 13 shows the predicted relationships of the resultant force vector with speed at a fixed back rake of -15 deg. There is no significant effect of speed on cutting forces at low depths of cut (0.508 cm (0.020 in.) and less), again in general agreement with the earlier rock turning tests. However, speed becomes a significant factor at larger depths of cut and higher speeds.

Early in the program selected independent cutting tests were performed after the designed experiments were completed to check the accuracy of the predicted resultant cutting force vectors. Good agreement was obtained, with most values falling within 10 percent of the predicted values over the range of parameters chosen. Maximum differences occurred at the extreme values of back rake (-5 deg and -45 deg) where the fewest data points were included in the test matrix. These resultant force vector values seldom differed from predicted values by more than 15 percent.

Utilization of Diamond Compact Single-Cutter Experimental Results in a Preliminary Bit Design

As a first step in the development of an improved bit for geothermal drilling, the information obtained from the single cutter and wear rate experiments has been used to determine the shape, cutter attack angle, number and distribution of diamond compact cutters for a 22.2-cm- (8-3/4-in.-) dia bit. It should be kept in mind, however, that even the optimum bit cutter design (assuming an optimum design can be identified) is only a partial solution to the problem. Efficient introduction of drilling fluids (mud, air or air/water) into the cutting zone for adequate bit face cleaning and cooling must ultimately be considered and this hydraulic system must be compatible with the diamond compact cutter design. Also, the harsh environments of geothermal formations place strenuous performance demands on all the materials making up the bit, as well as perhaps requiring new and novel manufacturing techniques to produce a product with the overall structural integrity necessary to attain the goals of increased penetration rates, longer bit lives and reduced drilling costs. Solutions to all of these technical problems are being vigorously pursued by manufacturers in this energy technology sphere.

Because the successful down-hole performance of a new bit requires the right combination of all the foregoing ingredients, and because the immediate specific objective of our program is to

Table 4 Typical independent variable levels for fractional factorial cutting experiments

Level	Speed (sfm)	Back rake (deg.)	Depth of cut (in.)	Side rake (deg.)
VL	25	-5	0.005	-8
L	100	-15	0.020	-5
M	300	-25	0.030	0
H	500	-35	0.040	+5
VH	750	-45	0.065	+8

determine if the performance of a diamond compact drag bit can be "built in" by design concepts developed through single cutter rock cutting experimental data, this first bit was assembled for laboratory evaluation only. Materials and manufacturing techniques used for successful laboratory and oil/gas field tests were employed in bit construction. Thus, the major emphasis could be placed upon the diamond compact cutter distribution design to be tested in the relatively undemanding and controlled conditions of a full-scale drilling laboratory.

Any new bit must start with some basic design criteria, plus some specific performance objectives and operating parameters. The utilization of diamond compact cutters which remove material in a mode in which shear and gross fracture predominate over crushing and fracture is new and unique enough that there are no established criteria on which to base bit designs. Three criteria have been proposed which seem reasonable (there are probably more). These are:

- 1 equal rock volume or equal rock area removal per cutter
- 2 equal wear rate per cutter, and
- 3 equal power expended per cutter to remove the rock (equal horsepower per cutter).

The first criterion is under investigation by another laboratory and a computer program is being developed to specify the diamond compact cutter locations to meet this objective. The second criterion may be the ultimate answer since it infers that the bit designed in this way will last until everything wears out simultaneously (no weak links). However, our observations on diamond compact wear, as noted earlier in this report, show that, for abrasive conditions, wear rates increase exponentially with speed. Until we have more complete information on the relationship of wear rates with speed, temperature, forces acting on the sliding interfaces, etc., it is not probable that a drag-bit configuration can be designed in which the outer diamond compact cutters will not wear out first.

The single cutter experimental results obtained cutting Champlain Black marble with straight edge tools were used to assist in determining the number and distribution of diamond compacts for a bit based on the third criterion, equal horsepower per cutter.

The specific objective was a bit that would drill at a penetration rate of 7.63 m (25 ft) per hr at a rotary speed of 100 rpm in a formation of ~ 138 MPa (20 ksi) compressive strength. This relatively low rotary speed is in line with conventional geothermal drilling practice where higher speeds lead to excessive bit wear. The bit diameter chosen was 22.2 cm (8-3/4 in.), which is typical for the lower sections of geothermal wells.

A value of -15 deg was chosen for the cutter back rake because the results of the single cutter experiments indicated this was close to the optimum for minimizing forces acting on the diamond compacts in the speed range they would operate. The maximum cutting speed at the periphery of the bit is 69.8 m/min (229 sfm) at 100 rpm. The diamond compact cutter shape chosen was the straight edge, for several reasons. First, since the design penetration rate is 7.63 m/hr (25 ft/hr), the maximum depth of cut for a single cutter is 0.127 cm (0.050 in.) at 100 rpm. This permitted the cutter standoff from the bit body to be reduced to 0.637 cm (0.250 in.) from 1.27 cm (0.500 in.) by using 180 deg (semi-circular) diamond compacts, straight edge down, and still have sufficient space to remove the cuttings. The reduced standoff

would provide added strength to the bit. Second, essentially complete bottom hole coverage would be obtained at all depths of penetration of the cutters (i.e., over a range of bit penetration rates), which would greatly simplify the analysis of actual performance in the subsequent full scale laboratory drilling tests. Finally, the cross-sectional area of rock cut by a straight-edge cutter is a linear function of the depth cut within design limits. This simplified the calculations necessary to determine the number of cutters required at any given radial position on the bit face in order to equalize the horsepower/cutter values. The bit crown profile chosen (see Fig. 14) was similar to prior experimental diamond compact drag bits that have performed successfully. It is also similar to the profile of natural diamond bits used in medium-hard formations and was thought to be a reasonable starting point for a geothermal bit design.

Fig. 14 Experimental bit profile

-15° BACK RAKE, STRAIGHT EDGE, CHAMPLAIN BLACK

Fig. 15 Predicted design horsepower per cutter requirements as a function of cutter placement and rock engagement

Fig. 16 Specifications for number and location of cutters for 22.2-cm (8 3/4-in.) bit

Fig. 17 Predicted bit weight for 22.2-cm (8 3/4-in.) bit to obtain 7.63 m/hr (25 ft/hr) penetration rate at 100 rpm

Using the equations generated by the STATPAC program to predict the values of the resultant force vectors for straight edge diamond compacts cutting Champlain Black marble, a simple computer program was written to calculate the horsepower for -15-deg back rake cutters as a function of cutter engagement depth and radial position on the bit face, for a bit rotating at 100 rpm. An example of this information is shown graphically in Fig. 15. Next, a position was chosen fairly close to the center of the bit face and the number of cutters operating at this radius arbitrarily chosen (available space and nozzle placement requirements have some bearing on this decision). This starting position is shown as radius no. 3 in Fig. 16 which is a cross section through the bit showing the radial locations of concentric circles of diamond compact cutters. Knowing the number of cutters, the depth-of-cut for each cutter was determined (in this case it was 0.064 cm (0.025 in.) and the horsepower level obtained. This is the desired horsepower for all the remaining compacts on the bit. At each succeeding radial-position (from 4 through 10) the cutter speed was calculated, and using the information shown in Fig. 15 the depth of cut per cutter was determined for the prescribed horsepower. Since the sum of the depths of cut of all the cutters on any given circle must add up to 0.127 cm (0.050 in.), the num-

ber of diamond compacts at each radial position was easily determined.

The HP/cutter values shown in Fig. 16 are not all exactly 0.419 (the chosen value) because fractional numbers of cutters could not be used where the design calculations called for them. For example, at radial position no. 4, the calculated number of cutters was obviously greater than three and less than four, so four cutters were used. Also, the three innermost compacts operate at significantly lower horsepower because the cutting speed on this portion of the bit is very low.

Again using the equations generated by the STATPAC program, a computer program was written to calculate the thrust force for straight-edge cutters, as a function of cutting speed and depth of cut. Knowing this information (F_T in Fig. 17), it was a simple matter to calculate the vertical force (F_v) on each cutter. The sum of all the vertical forces is the design bit weight (neglecting hydraulic lift-off forces) to obtain 7.63 m/hr (25 ft/hr) penetration rate at 100 rpm.

This experimental bit has been constructed and scheduled for evaluation on a full scale laboratory drill rig. The major objective of this test is to compare actual drilling performance with that predicted by the design techniques which were developed from single cutter experiments. The drilling test findings will be used to modify the design methods (if necessary) in order to begin construction of diamond compact bits for evaluation in actual geothermal drilling operations.

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