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**GEOTHERMAL COMPAX^R DRILL BIT
DEVELOPMENT**

Semi-Annual Technical Report, July 1—
December 31, 1976

By
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Work Performed Under Contract No. EX-76-C-01-2360

General Electric Company
Corporate Research and Development
Schenectady, New York

U. S. DEPARTMENT OF ENERGY
Geothermal Energy

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PREFACE

This report covers the results of work accomplished during the period of July 1 to December 31, 1976 on Contract No. EX-76-C-01-2360 sponsored by the Division of Geothermal Energy, ERDA. Mr. Clifton Carwile is the ERDA Program Manager, Dr. D. G. Flom is the GE Program Manager, and Mr. L. E. Hibbs, Jr., is the GE Principal Investigator.

The assistance of Dr. G. J. Hahn in experimental design and interpretation and of Miss S. R. Weissman and Mr. G. C. Sogioian in conducting the experiments is gratefully acknowledged. Dr. R. C. DeVries has been extremely helpful in examination of the rock samples and Mr. S. Alessi has prepared the specimens for photomicrography. Mr. C. Ward of Maurer Engineering and Mr. A. Bower of GE's Carboloy Systems Business Department are acknowledged for their consultation in bit design and general drilling requirements. Helpful discussions during the course of this work have been held with A. W. Urquhart, R. E. Hanneman, and H. W. Lake, Jr., all of CR&D.

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TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	v
SECTION I, INTRODUCTION	1
SECTION II, PROGRAM SCOPE	9
3.1 Task I: Laboratory Test Program of COMPAX Diamond for New Drill Designs Using Key Rock Types	9
3.1.1 Instrumented Laboratory Rock Cutting Experiments Utilizing Single-Edge Compacts	9
3.1.2 COMPAX Diamond Cutter Wear Rate Determi- nation and Failure Mode Analysis	9
3.1.3 Rock Removal Modeling.	9
3.2 Task II: Design, Fabrication, and Evaluation of Modified COMPAX Diamond Bits.	11
3.2.1 Design and Fabrication of Modified COMPAX Diamond Bits.	11
3.2.2 Instrumented Laboratory Testing of Modified COMPAX Diamond Bits.	11
SECTION III, DESCRIPTION OF THE EXPERIMENTAL APPROACH AND RESULTS TO DATE	13
Instrumented Single-Cutter Rock Cutting Experiments (3.1.1) ..	13
Experimental Design and Apparatus.	13
Rock Cutting Apparatus.	13
Experimental Diamond Compact Cutting Tools.	16
Rocks.	20
Experimental Design.	30
COMPAX Wear Rate and Failure Mode Analysis (3.1.2)	48
Cutting Experiments (3.1.2.1)	48
Preliminary Design of Modified COMPAX Diamond Compact Bits (3.2.1)	54
SECTION IV, REFERENCES	59
SECTION V, APPENDIX A	
Attachment Studies.	61
APPENDIX B	
Meetings.	63

LIST OF ILLUSTRATIONS

<u>Figure</u>	<u>Title</u>	<u>Page</u>
1	Hot Hardness for Diamond, Cemented Tungsten Carbide and a Tool Steel	6
2	Schematic Illustration of a COMPAX ^R Diamond Compact..	7
3	Overall View of Rock Cutting Experimental Apparatus . . .	14
4	Rock Cutting Machine Showing Method of Attaching Rock to Lathe Headstock.	15
5	Piezoelectric Dynamometer, with Diamond Compact Cutter in Place	16
6	25° Negative Rake Tool Holder with Diamond Compact Brazed in Place (Side View)	18
7	25° Negative Rake Tool Holder with Diamond Compact Brazed in Place (Top View)	19
8	Diamond Compact Tool Clamped in Rectangular Bar Holder Which Fits the Dynamometer	19
9	Full Set of 90° Included Angle Pointed COMPAX ^R Diamond Compact Tools Used for the 1st Cutting Experiment on Champlain Black Marble.	20
10	White Danby Marble, 150X, Bright Field	24
11	White Danby Marble, 150X Polarized Light.	25
12	Champlain Black Marble, 150X, Bright Field	26
13	Champlain Black Marble, 150X, Polarized Light	27
14	Belmont Rose Granite, 150X, Bright Field.	28
15	Belmont Rose Granite, 150X, Polarized Light.	29
16	Graymont Granite, 150X, Bright Field.	31
17	Graymont Granite, 150X, Polarized Light	32
18	Jack Fork Sandstone, 150X, Bright Field.	33
19	Jack Fork Sandstone, 150X, Polarized Light.	34
20	Verde Antique Marble (Serpentine) 75X, Bright Field.	35
21	Verde Antique Marble (Serpentine) 75X, Polarized Light.	36
22	Dolomite (Vt.) 150X, Bright Field.	37
23	Dolomite (Vt.) 150X, Polarized Light	38
24	Rock Cutting Machine Stiffness	45
25	Predicted Resultant Cutting Forces Cutting Champlain Black Marble.	47
26	Wear Land of Compact After Wear Test on Jack Fork Sandstone	50
27	COMPAX ^R Diamond Compact Wear Rates Cutting Jack Fork Sandstone	52
28	Schematic Illustration of a COMPAX ^R Diamond Compact Cutter/Tungsten Carbide Support System	55

LIST OF TABLES

<u>Table</u>	<u>Title</u>	<u>Page</u>
I	Rock Suite for Instrumented Cutting Experiments and Wear Rate and Failure Mode Analysis	21
II	Rock Properties.	23
III	Independent Variable Levels for 1st Fractional Factorial Cutting Experiment	40
IV	First Test Matrix - Champlain Black Marble	41
V	Experimental Results, Champlain Marble, 90° Included Angle Pointed Tool	42
VI	Additional Tests on Champlain Marble to Check Predictive Capability of Eq. 2	46
VII	Wear Rates of COMPAX ^R Diamond Compacts Cutting Jack Fork Sandstone	51

Geothermal COMPAX^R Drill Bit Development

L. E. Hibbs, Jr. and D. G. Flom

ABSTRACT

The overall scope of this Geothermal COMPAX^R Drill Bit Development Program includes instrumented rock cutting experiments, diamond compact wear and failure mode analysis, rock removal modeling studies, bit design and construction, and full-scale laboratory bit testing. This report describes results obtained from instrumented single-diamond compact cutter experiments, wear and failure mode analysis, and preliminary bit design concepts.

A model has been developed relating rock cutting forces to the independent diamond cutting variables, using a statistical test design and regression analysis. The model has been tested with additional independent cutting data and a satisfactory fit obtained. Experiments on two rock types (with compressive strengths of 8×10^3 psi and 21×10^3 psi respectively) have been completed and a third has been initiated. Preliminary analysis of single cutter experimental results indicates that optimum rake angles for cutters on an actual bit will be a function of each cutter's engagement (depth of cut).

Wear test results on five types of COMPAX^R diamond compacts (Product No.'s 1330 and 2330) continuously cutting sandstone under non-impact conditions are reported. Wear rates for both types were equivalent at high cutting speeds, where thermal effects were thought to be operative. At speeds below ~400 sfm, the coarser sintered diamond product was superior.

The wear rate of a diamond compact tested by Sandia Labs on Texas Pink granite was calculated and found to be almost two orders of magnitude greater than the wear rate of the same product as determined by CR&D. The higher wear rate is thought to be the result of cyclic impact loading and thermal effects at the cutter-rock interface. Test results are also discussed for interrupted cuts with high negative back rake angles which generated cracks in diamond compacts.

Preliminary bit design concepts have been developed, including various options dependent upon compact attachment techniques, bit body materials, and available technology for actual construction.

Diamond compact attachment is discussed in the Appendix of this report. GE CR&D initiated a program to identify the best interface materials and minimum pressure requirements for diffusion bonding, following Sandia Labs' successful demonstration of this technique. A diffusion bond that survived a vigorous rock cutting test in Albuquerque has been metallographically examined by CR&D and the results transmitted to Sandia Labs.

SECTION I

INTRODUCTION

Geothermal drilling for exploration and production is accomplished by methods generally 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 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 350°C.
- Corrosive and erosive environments due to superheated dry and/or wet steam, hot brines, and additional corrosive agents such as dissolved H_2S and other acidic constituents.

Prior to the beginning of contract work, a survey was made 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 air flow rates, mud weights and pH, and some sketchy information on flow line and bottom hole temperatures.

Since the formations in the Imperial Valley are sandstone and shale, with some clay, all drilling is done with mud to prevent the hole from collapsing. Drilling records showed maximum flow line temperature of ~195°F. All holes were about 6000 ft., with 10-5/8 inch diameter rock bits being used from about 2000 ft. to hole bottom. Penetration rates at the 5000-6000 ft. level were generally 25-30 fph at 20×10^3 lb. bit weight. Rotary speeds were ~90 rpm, using 9.1 lb. mud at a pH from 8.5-10. The principal drilling problems are bit wear due to the extremely abrasive nature of the sand-shale formation, and mud gelling problems when circulation is stopped for any significant time period for bit changes or well logging.

Records for drilling in the Geysers area showed hole depth to vary from 6000-9000 ft. Formations are principally graywacke below ~ 1000 ft., with frequent mixtures of graywacke with quartz, chert, serpentine and jasper. Drilling was entirely with rock bits, 17-1/2 inch diameter to ~ 2000 ft., 12-1/4 inch diameter to ~ 6000 ft. and 8-3/4 inch diameter bits to hole bottom. Bit weights were high, as much as 35×10^3 lb. with the 8-3/4 inch bits and up to 60×10^3 lb. with 12-1/4 inch diameter bits. Penetration rates ranged from 10 to 30 fph at 6000-9000 ft. depths, with the average probably between 10 and 20 fph.

Although there was some variation from well to well, typical drilling procedure was to drill with mud to about 6000 ft. (in some cases deeper), and then shift to air at ~ 2500-3000 cubic feet/min. The rotary speeds were lower than in the Imperial Valley, with the average rpm ~ 65-70. The same speed range was used regardless of bit diameter. Mud weights were greater than in the Imperial Valley, with one notation of 10.1 lb. mud. The mud weight variation was also greater. The pH varied from 8 to 11.5. The drilling records seemed to indicate that a very alkaline mud was desirable, but that maintaining pH was difficult.

The temperature records for drilling in the Geysers were sketchy, but some information was available. Mud flow line temperatures reached about 205°F at the 6000 ft. level and one air flow line temperature of 330°F was recorded at 6200 ft. A maximum bottom hole temperature of 435°F was recorded at 6200 ft. depth. No data were available on bottom hole temperature below this depth. Steam production from these wells varied from 30×10^3 to 216×10^3 lb./hr.

Information obtained from the Bureau of Reclamation on the East Mesa site in the Imperial Valley revealed typical formations to be sands, clays, clay shales and moderately cemented sandstones. These formations are very abrasive, causing short bit life. Since the East Mesa bottom hole temperatures range from 370-400°F, severe mud problems are encountered when circulation is stopped to change bits or log the hole.

The mud (hydraulics) problems during trip times are even more severe in the Salton Sea area and at the Mexican geothermal sites at Cerro Prieto (near Mexicali, south of El Centro). Bottom hole temperatures in the Salton Sea vicinity can reach 500°F, and nearly 700°F at Cerro Prieto.

During a visit to a specific well site in the East Mesa, drilling was being conducted at a 6000 ft. depth using an 8-3/4 inch diameter F-2 rock bit, at about 60 rpm, 28×10^3 lb. bit weight. The formation was 60 percent sand (stone) and 40 percent clay (shale). The mud was being circulated at 400 gpm with 2000 psi. Mud viscosity was 45-50 (sec/qt.); mud weight was 9.1 lb. A

mud cooling tower was being employed, with flow line temperatures of 140°F in and 160°F out. Some bit and stabilizer torque problems were being experienced, so some oil had been added to the mud for lubrication. The hydrocarbon addition could be clearly discerned at the shake-out screen where more volatile fractions were boiling out of the mud.

Penetration rates were generally good in the Imperial Valley, down to about 4000 ft., where rates usually slow down markedly. Below 4000 ft. depth, penetration rates are about 500 ft/day (slightly more than 20 ft/hr).

In a visit to a well site in the Geysers it was learned that the formations are primarily graywacke below about 4000 ft., with much greenstone and serpentine above the graywacke. In the drilling procedure observed, a shift is made from mud to air as soon as consistent graywacke is reached. The air volume is 4000-5000 cfm, requiring about 2500 psi at the compressor units in order to obtain these conditions. In addition, from one to five gallons per minute of water, containing proprietary corrosion inhibitors, is injected with the air, to minimize drill pipe corrosion. Most of the drilling is done with 12-1/2 and 8-3/4 inch diameter carbide button rock bits.

The bottom hole temperatures encountered in the Geysers can be as high as 450-500°F in dry holes at depth. With steam flowing, the maximum temperature is ~ 500°F. An experimental bit containing fusible temperature indicators in the bit body near the bearings revealed that the temperature of the bit, (when drilling with air in a hole with a bottom hole temp. = 500°F) was 700°F. There may be some cooling effect due to air expansion in the roller cone side of the nozzles but this is counteracted by frictional heat generated by the bit rubbing against rock. The carbide buttons are probably running at 700°F (371°C) or higher.

As noted before, the major bit wear is on the gage. This includes wear of the outer row of buttons on the roller cones, and even more rapid wear of the shirt tail section of the bit body.

Localized wear here rapidly exposes the roller cone bearings. Bit manufacturers have attempted to improve bit life by (1) introducing internal passages to force some air through the bearings, for cooling and cleaning, and (2) hard surfacing the shirt tail with WC weld overlays or WC button inserts. This has produced some improvement, but nothing significant.

Penetration rates for rock bits range from 10 to 25 ft/hr. The higher rates are obtained in what is described as "micro-graywacke", which is fine-grained, softer, and will swell somewhat when immersed in water. It may have some clay constituents in it. The lower penetration rates are typical of "normal" graywacke, which is harder. Samples were obtained of

each, plus greenstone and serpentine. The "normal" graywacke appears to contain significantly greater amounts of quartz-like regions, which would contribute to its toughness. The greenstone also has a large amount of discrete quartz-like regions.

Another geothermal site, where drilling requirements are not quite as rigorous as in the Geysers, is in the Valdes Caldera (Baca Field) in New Mexico.

The Valdes Caldera site is inside a volcano crater at about 9000 ft. elevation. This is a hydrothermal site (hot water). The formation is volcanic (very abrasive, but probably not as tough as the Geysers). Bottom hole temperature is 550°F at 8000 ft. Drilling practice is slightly different. Air is used (~2000 cfm) mixed with water (100 gpm, pH 10.5 due to alkaline additives). Flow line temperature is ~200°F. The air-water mixture is ~70°F in and 180 to 200°F out. Bit temperatures are not known, but probably less than bottom hole temperatures. Rotary speed is 60-90 rpm.

The Valdes Caldera is representative of the most common type of geothermal energy source. There are 600 of these hydrothermal sites identified in the U.S. The Geysers dry steam field is a special case. There are only three others known, one in Italy, one in Japan, and a newly discovered one in the Phillippines.

It is clear that a sophisticated technology has been developed to permit drilling in hostile geothermal environments. This technology includes specialized methods, equipment, and materials for the entire operation, from the surface equipment to the rock bits, as well as modified methods for well cementing, packing, and logging.

Although there are several exotic methods (Ref. 1) for drilling that show potential for increased efficiency and productivity, such as laser drilling, spark erosion (cavitation) drilling, and thermal (rock melting) methods, these will not become viable drilling systems for many years to come. For at least the next decade, conventional rotary drilling will be the only generally feasible method.

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 (Ref. 2) and impact strength to perform effectively in this manner.

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 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 primary attachment mechanism is mechanical, which requires more than half of each stone to be within the matrix. Thus, the diamonds project only a small distance from the bit body. Since some open space must be maintained to clean the bit face and cool the stones, the diamond bit penetration rate is limited. In addition, the matrix that is effective in holding the diamonds under conditions of relatively constant compressive loading is inadequate to hold them under the cyclic impact stresses produced in fractured or fissured rock.

The basis for General Electric's approach in this program is to increase productivity and reduce costs for drilling of geothermal wells with a unique new class of materials -- sintered diamond compacts. Developed by proprietary and patented superpressure processes at General Electric's Research and Development Center, the COMPAX 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 compares the hardnesses of the compacts with other appropriate materials.

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

The sintered diamond compacts have been manufactured in sizes greater than 0.5 inch 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 COMPAX 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. The high strength and hardness of sintered diamond compacts at a high temperatures make these materials promising for use in fractured, broken strata, when suitable bit designs are developed.

The immediate advantages of diamond compacts for geothermal drilling may be summarized briefly as follows:

- (a) Potential for increased bit life and penetration rates for lower drilling costs.
- (b) The markedly lower bit weights necessary. This affords 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 was applied to the drill strings. Drill pipe is a major cost in the Geysers.

- (c) Potential ability for compact bits to maintain gage. This is the major wear mode for the presently used rock bits, and requires frequent reaming to maintain hole size.
- (d) No bearings. Bearing failure, along with gage wear is a primary wear mode of rock bits.

COMPAX diamond compacts have been evaluated in a number of oil/gas drilling experiments to date, and some promising progress has been made. The basic sintered diamond compact (a polycrystalline diamond layer 0.020 to 0.025 inch thick) bonded to a cylindrical tungsten carbide substrate has been the principal configuration used to the present time (see Fig. 2), but alternative geometries are potentially possible.

Figure 2. Schematic Illustration of a COMPAX^R Diamond Compact

SECTION II

PROGRAM SCOPE

The overall objective of this program is to develop and demonstrate the performance of a new type of drill bit design that will provide increased penetration rates and/or longer bit life, utilizing high pressure, sintered polycrystalline diamond compacts for the cutting edges. The improved bits are to be applicable to existing conventional rotary drilling methods (for present hole size requirements in the 7 to 9 inch diameter range) and to perform effectively over the wide range of rock formations encountered in geothermal (and oil/gas) field exploration and development.

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 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. The program includes several integrated primary tasks to provide both fundamental information and practical bit evaluations. The scope of the present contract includes the following tasks and subtasks:

3.1 TASK I: LABORATORY TEST PROGRAM OF COMPAX DIAMOND CUTTERS AS A BASIS FOR NEW DRILL DESIGNS USING KEY ROCK TYPES

3.1.1 Instrumented Laboratory Rock Cutting Experiments Utilizing Single-Edge Compacts

These experiments are being performed with 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 are to be established. A representative set of rock types is being tested covering the range of compressive yield strengths, hardnesses, and structures that would be expected in geothermal and oil or gas.

These laboratory experiments include (1) continuous cutting of homogeneous rock samples, (2) interrupted cuts to determine effects of impact, and (3) a limited number of tests on "composite" rock samples simulating conditions encountered when a bit is drilling from one type of stratum into another.

3.1.2 COMPAX Diamond Cutter Wear Rate Determinations and Failure Mode Analysis

3.1.2.1 Single-edge rock cutting experiments are to be carried out to determine the effects of rock properties, machining parameters, cutter geometries, etc. upon COMPAX wear rates, susceptibility to fracture, and other failure mechanisms. Conditions and geometries that lead to failure of the COMPAX cutter support system are to be identified. Experimental techniques are similar to those used in subtask 3.1.1 but without sophisticated force measurement instrumentation, in order to increase system rigidity. Interrupted cuts are included, and at least two modifications of the polycrystalline COMPAX compact system will be evaluated, the major difference being the diamond compact particle size distribution.

3.1.2.2 Physical property (noncutting) experiments are to be performed to assess the suitability of COMPAX/support systems under conditions simulating those encountered in geothermal environments. These tests include:

1. Shear strength measurements, at temperatures up to 350°C on COMPAX diamond compact/support systems, including both the currently available COMPAX/slug design and at least two modifications. The major purpose of these tests is to determine the strength of the COMPAX/support interface bond.
2. Ultimate strength measurements for the present COMPAX/slug system and at least two advanced modifications, performed at temperatures up to 350°C, to determine the stress conditions most likely to result in failure and to assist in bit design for maximum strength. Test specimen loading will simulate the varying conditions thought to exist in actual drilling, so that a variety of stress conditions can be analyzed.
3. Impact tests to simulate the excursion from average cutter loads that occur continuously in rock drilling, particularly in fractured strata. The tests are to be performed at elevated temperatures (up to 350°C) and will include some actual COMPAX diamond compact-rock combinations. The direction of applied load on the cutter will be varied, to create different stress conditions and to identify the principal failure mechanisms.

3.1.3 Rock Removal Modeling

A series of carefully instrumented single-cutter rock cutting experiments will be performed, similar to those of 3.1.1, in which the fracture characteristics of several types of rock will be examined. A comparison with the rock

removal mechanisms of conventional rock drills and natural diamond bits will be made. An analysis of the particle size distribution of rock cutting as related to other parameters will be carried out in order to:

- Pinpoint the most effective conditions for COMPAX cutter utilization.
- Compare the efficiency of COMPAX diamond compacts with conventional rock drills and natural diamonds.
- Determine the extent to which improved bit performance can approach the maximum theoretical efficiency.

Included in this rock removal modeling study will be an analysis of the relative degrees of compressive versus tensile fracture modes of failure for rocks of different properties, as related to drilling parameters such as speed, penetration force, cutting force, and cutter geometry.

3.2 TASK II: DESIGN, FABRICATION, AND EVALUATION OF MODIFIED COMPAX DIAMOND BITS

3.2.1 Design and Fabrication of Modified COMPAX Diamond Bits

Using information gained from the experiments described in Task I, in subsection 3.1, plus prior laboratory and field test experience, together with recommendations by an independent consultant, modified COMPAX bits will be designed and constructed. The designs will be 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. The bit designs will take into consideration the requirement that they be applicable to conventional drilling systems, and of diameters representative of present geothermal hole sizes.

3.2.2 Instrumented Laboratory Testing of Modified COMPAX Diamond Bits

The modified bits described in 3.2.1 will be tested by an independent laboratory working in conjunction with General Electric personnel and an independent consultant, using a full scale drilling rig. These full scale drilling tests will be performed at atmospheric pressure and ambient temperature, using appropriate key rock materials. The major objectives to be accomplished will be:

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.
4. Identify most promising operating conditions for field testing.

While the current contract carries only through instrumented laboratory testing of modified COMPAX diamond bits, it is clear that a complete evaluation of the bits must also include preliminary field tests and final drill bit design, fabrication and testing. Also, predictive performance modelling and economic analyses must ultimately be conducted to provide a comparison with conventional drill economics.

The scope of the present report includes instrumented laboratory rock cutting experiments (3.1.1), COMPAX diamond cutter wear rate determinations (3.1.2.1), and preliminary design of modified COMPAX diamond bits (3.2.1).

SECTION III

DESCRIPTION OF THE EXPERIMENTAL APPROACH AND RESULTS TO DATE

1. INSTRUMENTED SINGLE-CUTTER ROCK CUTTING EXPERIMENTS (3.1.1)

a. Experimental Design and Apparatus

Evaluation of the performance of COMPAX^R 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 U 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 (in part) dependent upon the sum of the performances of its individual cutting elements (and their interactions), it is necessary to study individual diamond compact cutters in order to optimize their configurations for the various (and varied) conditions under which they will be 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 this subtask is to obtain this cutter force information.

Up to the initiation of this ERDA 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 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.

b. Rock Cutting Apparatus

The entire experimental apparatus used is shown in Fig. 3. It consists of a Pratt and Whitney tool room lathe, a special face plate constructed to mount on the 3-jaw chuck on which the rock specimen is mounted, a 3-force component piezoelectric dynamometer attached to the lathe cross-slide, and

Figure 3. Overall View of Rock Cutting Experimental Apparatus

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 provides capability for rigidly holding rock specimens up to 9 x 9 x 6 in. The 9 x 9 in. face is the one that is cut. Although mechanical clamping has been adequate to hold the rock in place up to now, provisions were made to cement (using an epoxy resin) the rock to anchor bolts in the nest if the possibility of gross fracture presents itself. Fig. 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 adequate fluid coolant during cutting. By withdrawing coolant from the top of the sump the rock chips can settle to the bottom without clogging the circulation system. In addition, the sump capacity was doubled from ~ 8 to ~ 16 gallons.

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

A 40:1 water:soluble oil coolant is used. The soluble oil serves no specific useful purpose in the actual rock cutting process, but does prevent excessive machine rusting.

Fig. 5 shows the piezoelectric dynamometer mounted on the lathe cross-slide. It is 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 is 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 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. The dynamometer

Figure 5. Piezoelectric Dynamometer, with Diamond Compact Cutter in Place

and charge amplifier frequency response is 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 has helped to eliminate most (but not all) undesired signals without attenuating the lower frequency force fluctuations generated by the rock cutting action. There is a tendency for the charge amplifier signal to drift over extended time periods but since the actual individual cutting tests are of short duration this drift is easily corrected. In addition, the Hathaway light beam oscillograph recorder has shown some tendency to blow fuses and burn out transistors and diodes, but not frequently enough to significantly retard progress. There is a suitable Sanborn recorder available as a back-up in case the Hathaway device becomes too unreliable.

c. Experimental Diamond Compact Cutting Tools

One of the main objectives of sub-task 3.1.1 is 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 include:

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 is the configuration that has been most extensively tested in the field in experimental bits and in laboratory tests prior to this program. A limited amount of information on straight diamond compact cutting edges has also been generated in laboratory experiments and some early core drilling tests.

The compacts that were obtained for sub-task 3.1.1 of this program included the following commercially available COMPAX^R products:

<u>Product No.</u>	<u>Description</u>
1520	90° included angle sectors cut from 0.539 in. diameter compacts. Nominal side length is 0.260 inch, total thickness is 0.126 inch, and the diamond layer is 0.020 inch thick.
1515	60° included angle sectors cut from 0.539 inch diameter compacts. Nominal side length is 0.244 inch, total thickness is 0.126 inch, and the diamond layer thickness is 0.020 inch.
1525	Semi-circular compacts (180°) with a straight edge length of 0.539 inch, total thickness of 0.126 inch with a 0.020 inch diamond layer.
1575	Rectangular diamond compacts nominally 0.098 inch by 0.197 inch with a 0.020 inch diamond layer. Total thickness is 0.126 inch.
1325	Semicircular diamond compacts (180°) with a straight edge length of 0.331 inch, a 0.020 inch diamond layer, and an overall thickness of 0.126 inch.

The basic tool design for the continuous spiral rock cutting experiments is illustrated in Figures 6 and 7. This is a 90° included-angle cutter, but the design for all three cutter shapes is 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 (GE specification B5F5). In order to maximize stiffness during cutting, a separate tool was machined for each back rake used. The tool illustrated has a -25° back rake. The diamond compacts were brazed onto the tools, using Handy Harman Easy-Flo 45 braze.

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

Figure 8 is a top view of a 90° included-angle compact tool mounted in the massive holder bar which is clamped in the dynamometer. The threaded hole in the top of the tool is provided to attach the "pointer" portion of a fixture used to set the desired side rake prior to testing. When cutting rock, this hole is plugged with a short screw to prevent the threads from becoming clogged with rock chips. Figure 9 is the complete set of 90° pointed tools used for the first cutting experiment which is reported in detail later in this report.

Figure 7. 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 Used for the 1st Cutting Experiment on Champlain Black Marble

d. Rocks

Six different kinds of rock suitable for testing have been obtained, and a seventh kind has been identified which may be obtained later in the program. 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 are 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 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 I.

TABLE I

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

Rock Type	Source	Obtained From
(1) White Danby Marble	Danby, Vermont	Vermont Marble Company Proctor, Vermont
(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, Vermont	Vermont Marble Company
(5) Jack Fork Sandstone	Arkansas	Tulsa U, Tulsa, Okla.
(6) Verde Antique Marble (Serpentine)	Rochester, VT	Vermont Marble Company
[(7) Dolomite*	Vermont	Vermont Marble Company]

*Tentative - physical tests indicate desirable properties, but special order is required since this material is only quarried by blasting at present.

The ultimate compressive strength and the modulus of elasticity in compression has been measured at CRD for five of the seven materials listed in Table I, above. The same measurements will be made in the two remaining materials (Belmont Rose and Graymont Granite). Shore hardness values have been obtained on all seven rock types.

The compressive strength tests were made using small rectangular specimens typically 1/2 x 1/2 x 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 MoS₂ 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 seven of the rock types listed in Table I 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 II 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 examination of all seven rock types. A preliminary examination has been made and photographs prepared of the polished specimens. A preliminary description of each, together with appropriate photographs, is given below. A more complete description of each rock type used, together with photographs from the thin section examination, will be included in a later report.

- (1) White Danby Marble. (See Figs. 10 and 11). 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.
- (2) Champlain Black Marble (See Figs. 12 and 13). 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 smaller 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.
- (3) Belmont Rose Granite (See Figs. 14 and 15). 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.

Table II
ROCK PROPERTIES

	Uniaxial Compressive Strength (psi x 10 ³)		Modulus of Elasticity in Compression (psi x 10 ⁶)		Hardness (Shore)		Shear Strength (psi x 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 - U.S. Bureau of Mines
(5) Jack Fork Sandstone	37.1		6.16		86				
(6) Verde Antique Marble (Serpentine)	51.0*		11.3		70				
(7) Dolomite (Vermont)	30.1		8.00		54				

*Measurements ranged from 37.7 to 66.0 x 10³ psi, depending upon veining in the samples.

Figure 10. White Danby Marble, 150X, Bright Field

Figure 11. White Danby Marble, 150X Polarized Light

Figure 12. Champlain Black Marble, 150X, Bright Field

Figure 13. Champlain Black Marble, 150X, Polarized Light

Figure 14. Belmont Rose Granite, 150X, Bright Field

Figure 15. Belmont Rose Granite, 150X, Polarized Light

- (4) Graymont Granite (See Figs. 16 and 17). 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 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.
- (5) Jack Fork Sandstone. (See Figs. 18 and 19.) This is a 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.
- (6) Verde Antique Marble (Serpentine, Vt.) (See Figs. 20 and 21.) 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 which are bright in reflected light which are possibly metallic compounds such as magnetite and pyrite. Preliminary examination revealed no evidence of quartz which is present in veins of California serpentine from the Geysers region.
- (7) Dolomite, Vt. (See Figs. 22 and 23.) This is a fairly pure, homogenous, dense carbonate. The grain boundaries are relatively clean, with some evidence of recrystallization at the boundaries. There is a small amount of a bright reflecting phase near the recrystallized regions. There may be traces of metallic compounds. The overall grain structure is not as regular or as large as the White Danby marble.

e. Experimental Design

As stated previously, the main object of performing the cutting tests in sub-task 3.1.1 is 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.

Figure 16. Graymont Granite, 150X, Bright Field

Figure 17. Graymont Granite, 150X, Polarized Light

Figure 18. Jack Fork Sandstone, 150X, Bright Field

Figure 19. Jack Fork Sandstone, 150X, Polarized Light

Figure 20. Verde Antique Marble (Serpentine) 75X, Bright Field

Figure 21. Verde Antique Marble (Serpentine) 75X, Polarized Light

Figure 22. Dolomite (Vt.) 150X, Bright Field

Figure 23. Dolomite (Vt.) 150X, Polarized Light

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 of 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 (Ref. 3).

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 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 package uses a least squares linear regression analysis to fit relationships between a dependent variable i. e., in our case 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 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_z ,

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 are constants.

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

$$\begin{aligned}
 Y_R = & K + K_1 X_1 + K_2 X_2 + K_3 X_3 + K_4 X_4 + K_5 X_1^2 + K_6 X_2^2 \\
 & + K_7 X_3^2 + K_8 X_4^2 + K_9 X_1 X_2 + K_{10} X_1 X_3 + K_{11} X_1 X_4 \quad (\text{Eq. 1}) \\
 & + K_{12} X_2 X_3 + K_{13} X_2 X_4 + K_{14} X_3 X_4
 \end{aligned}$$

After the model is chosen, a matrix representing the individual cutting test cases making up the fractional factorial set is 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 III.

TABLE III
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

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 IV and V. Table IV shows the levels chosen for the variables in each case, and the order in which the cutting test were run. It should be noted that tests No.'s 29 through 32 are 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 IV

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 V
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 V shows the actual values of the independent variables and the force values obtained. In addition, the calculated resultant force is given in two ways. Y_{xyz} is the resultant 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:

$$Y_{xyz} = (F_x^2 + F_y^2 + F_z^2)^{1/2}$$

and

$$Y_{yz} = (F_y^2 + F_z^2)^{1/2}.$$

It is apparent that the side thrust (F_x) is not a significant factor in the overall forces acting on the tool. This indicates that varying the side rake within the range chosen does 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, particularly with a sharp, pointed tool which creates very high stress concentrations. The side rake effect may prove to be more significant with straight or curved diamond compact cutters particularly in the worn or dull condition. The results of the regression analysis (shown later) also indicated that, for this experiment on Champlain Black Marble, the side rake effects were not significant.

The first STATPAC regression analysis was run using all 32 of the cases given in Table IV. (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 Eq. 1. The resulting fifteen 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. Examination of the lower and upper limits of the least squares estimates of the coefficients (K_1 through K_{14}) with 95 percent confidence limits indicated that all but four of the dependent variables terms could be dropped. A second regression analysis, using only the X_2 , X_3 , X_2^2 and X_2X_3 terms, gave a second equation relating Y_{xyz} and the dependent variables. The standard deviation was 6.579 (a slight improvement, but not enough).

Examination of residual resultant force values (observed values - predicted values) suggested that one data case (Test No. 26 Table V) might be suspect. A crossplot of X_3 and residuals also indicated the same thing. Therefore, the regression analysis was re-run omitting this data case (31

out of 32 cases were used). A final equation with eight terms was obtained. The standard deviation was 3.771 and the form of the equation was:

$$Y_{xyz} = K + K_1 X_1 + K_2 X_2 + K_3 X_3 + K_4 X_2^2 + K_5 X_3^2 + K_6 X_1 X_2 + K_7 X_2 X_3, \quad (\text{Eq. 2})$$

and where:

$$\begin{aligned} K &= 51.63247 \\ K_1 &= 0.1881682 \times 10^{-1} \\ K_2 &= 4.095348 \\ K_3 &= -1118.6 \\ K_4 &= 0.8537052 \times 10 \\ K_5 &= 25875.5 \\ K_6 &= 0.1209143 \times 10^{-2} \\ K_7 &= -83.29329. \end{aligned}$$

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 inches. 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 adjacent spiral cuts tends to spall, so there is 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 Fig. 24. This shows that the maximum error in depth of cut due to "give" in the machining set-up would be less than 0.001 in., which is certainly not significant for a cut of 0.065 in. in depth.

The regression analysis suggests that there is no significant effect due to changing the compact tool side rake within the limits of -8° to $+8^\circ$. Inspection of the experimental data had also indicated this. The upper and lower limits of the least squares estimate of the speed term coefficient indicated this term was not significant also, but a slight significance was seen for the speed/back-rake interrelation, so the $K_1 X_1$ and $K_6 X_1 X_2$ terms were both included in the final equation. All of our prior experience cutting rocks with diamond compacts has suggested that the cutting forces are independent of cutting speed. The regression analysis indicates that if there is a speed effect, it is very small.

Figure 24. Rock Cutting Machine Stiffness

In order to check the predictive accuracy of Eq. 2, six additional cuts were made. The parameters and results of these tests are given in Table VI.

Eq. 2 was solved for Y_{xyz} 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 Fig. 25. 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. With some additional data at the extreme cutting conditions, the model can be further refined if it appears that this is necessary.

TABLE VI

ADDITIONAL TESTS TO CHECK PREDICTIVE CAPABILITY OF EQ. 2

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

Fig. 25 clearly shows that the minimum force acting on the diamond compact cutter occurs with smaller and smaller back rakes as the depth of cut increases. Minimizing the forces on the cutters should increase bit life by reducing compact wear rates 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 sintered diamond layer, to avoid undesirable stress conditions. Like all brittle materials, diamond compacts are strong when kept in compression and more easily damaged when subjected to tensile stresses.

A second regression analysis will be 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 has been shown to be insignificant, the model will be of the form:

$$\tan^{-1} \frac{F_z}{F_y} = K + K_1 X_1 + K_2 X_2 + K_3 X_3 + K_4 X_1^2 + K_5 X_2^2 + K_6 X_3^2 + K_7 X_1 X_2 + K_8 X_1 X_3 + K_9 X_2 X_3 \quad (\text{Eq. 3})$$

Figure 25. Predicted Resultant Cutting Forces
Cutting Champlain Black Marble

Once both the magnitude and direction of the resultant force vector can be predicted, the forces acting in any particular direction on either the rock or the diamond compact can be calculated directly. In addition, the cutting efficiency can be easily determined.

The rock cutting tests for the fractional factorial experiment with 90° included angle pointed compact tools on the White Danby Marble have also been completed. Since the side rake did not appear as a significant dependent variable cutting the Champlain Black marble, this variable was dropped, which reduced the minimum number of individual cuts for the test matrix to eighteen. In order to obtain a better regression analysis fit at the extreme values of the independent variables, four additional cuts were performed, for a total of twenty-four. Parameters identical to the Champlain Black Marble tests were used for speed, back rake and depth of cut, except that the VH value for depth was reduced from 0.065 to 0.055 inch.

The analysis of the test results on White Danby Marble is being performed presently. In addition, a block of Graymont Granite has been prepared for testing and will be started next. At the completion of these three fractional factorial experiments covering a range of rock properties from $\sim 7 \times 10^3$ to $\sim 30 \times 10^3$ psi compressive strength and 33 to 92 shore hardness, an initial attempt will be made to include the rock properties in the analysis relating cutting performance to the independent (controllable) variables.

As soon as the cutting tests on the Graymont granite are concluded, the tests using a different diamond compact cutter design (straight cutting edge) will be started.

2. COMPAX WEAR RATE AND FAILURE MODE ANALYSIS (3.1.2)

a. Cutting Experiments (3.1.2.1)

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 preceeding 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 inch diameter 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/revolution 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) to flood the compact cutter and cutting zone.

The volume of diamond compact wear was calculated from measurements made before and after testing. Figure 26 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

$$V = \left[\frac{\pi r^2 \theta}{360} - \frac{r^2 \sin \theta}{2} \right] \cdot t \quad (\text{Eq. 4})$$

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

Figure 26. Wear Land of Compact After
Test on Jack Fork Sandstone

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 VII and shown graphically in Figure 27.

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

COMPAX ^R 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}

The wear rates for both types of diamond compacts are about the same above 400 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 400 sfm, the difference in wear resistance becomes evident. At the lower interface temperatures (due to lower cutting speed) the wear mechanism is predominately microchipping abrasive wear. We would expect the diamond compact made with the layer diamond grains to have greater resistance to abrasive wear, as observed.

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 one quarter inch wide by one half inch deep. This core was turned using No. 2330 compacts (coarse grained),

Figure 27. COMPAX^R Diamond Compact Wear Rates
Cutting Jack Fork Sandstone

at -5° , -10° , -30° and -45° back rakes, using cutting speeds of ~ 100 and 270 sfm. The nominal depth of cut was 0.020 inch, 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, cut 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 inches back from the edge. The cracks went through both grain boundaries and through individual diamond grains inciding a high degree of diamond-to-diamond bonding in the sintered layer.

Although the high negative rake slotted rock tests did not produce any gross diamond compact fracture, it was evident that continued cutting under these 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 gross 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 will probably not exceed -25° .

The wear rates measured by continuous cutting of Jack Fork Sandstone are 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 (Charles F. Huff, Drilling Research Division). This compact, attached to a tungsten carbide slug, was tested cutting Texas Pink Granite at about 0.040 inch 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} cubic inches. The cutting time was estimated at 80 minutes, so the volumetric wear rate was $\sim 7.1 \times 10^{-6}$ cubic inches per minute. The maximum wear rate measured continuously cutting the Jack Fork Sandstone was 0.382×10^{-6} , which is almost twenty 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 which caused gross chipping and thermal wear effects after appreciable tool wear. This compact is being thoroughly examined by scanning electron microscopy. Any additional information will be reported to Sandia and included in our future reports.

Work will be initiated on sub-task 3.1.2.2 Physical Properties, as soon as sufficient information is obtained from the analysis of the Instrumented Cutting Experiments to define the principle force vectors acting on the cutter-support assemblies. These experiments will be performed primarily at elevated temperatures simulating geothermal drilling conditions.

3. PRELIMINARY DESIGN OF MODIFIED COMPAX DIAMOND COMPACT BITS (3.2.1)

The instrumented rock cutting experiments just discussed have been aimed at providing information needed for bit design. A preliminary design based on this information has been initiated taking into account also the experience gained in the fabrication and testing of compact bits prior to the start of this program. A brief review of this experience is given in the next few paragraphs.

The first attempts to drill rock with COMPAX diamond compacts, prior to this program, were carried out in the laboratory with small core drills in which the compacts were placed in the bit body with the flat (top) diamond surface facing outward. Attachment was obtained by the use of infiltrant brazing alloys similar to those used for holding mined diamonds in drill bits. Rock removal was achieved by the same crushing, abrading action obtained by natural diamond stones. These initial core drilling tests were successful in that they demonstrated that the polycrystalline sintered diamond compacts had sufficient hardness and strength to drill difficult, hard, nonuniform materials such as concrete, as well as granite; they also helped to suggest alternative compact geometries that would be more efficient.

Examination of the compacts in these core drills, as well as brazed single-point cutting tools being developed in a parallel program, indicated that compact properties might deteriorate if they were subjected to excessive temperatures when being attached to tool bodies. An experimental program was carried out which defined the temperature limits for COMPAX thermal stability, identified suitable brazing alloys within the temperature stable region, and resulted in the first COMPAX/cemented tungsten carbide support system, suitable for use in drag bits. This COMPAX diamond compact/tungsten carbide slug assembly is illustrated schematically in Fig. 28.

Figure 28. Schematic Illustration of a COMPAX[®] Diamond Compact Cutter/Tungsten Carbide Support System

Attaching the diamond compact to the cemented carbide support and subsequently attaching the support to the drill bit body by pressing into an undersize hole (interference fit) had two obvious advantages:

- Brazing time-temperature cycles could be minimized and controlled.
- The diamond compact could be mounted so that the diamond edge penetrates the rock (high unit loading for efficient rock fracture) and material removal effected more by shearing action than compressive fracture. (The shear strength of brittle materials is significantly lower than the compressive yield strength.)

The first experimental COMPAX bits assembled for full scale laboratory drilling tests were a simple flat-plate design. Penetration rates in Carthage marble (tests aimed primarily at evaluation of hydraulic requirements for this markedly different cutter design) were very high, and performance in drilling Berkeley Grey granite (known to wear natural diamond bits rapidly) was very promising.

The first two bits suitable for actual testing in the field for oil/gas drilling were 7-7/8 inches in diameter. During the field test of the first bit, erosion of the steel mud jets caused eventual pressure loss and inadequate bit face cleaning which reduced the penetration rate. However, penetration rates were as high as 112.5 ft/hr at 10,000 lb bit weight before excessive nozzle erosion occurred. No significant wear was noted in the diamond

compact although three compacts were lost, apparently by braze failure associated with an improper mud flow pattern, and two tungsten carbide slugs were fractured.

The second 7-7/8 inch COMPAX bit was provided with tungsten carbide mud nozzle liners. Over 1000 feet of hole was drilled, even though the available mud pumping capacity was inadequate for the design. Penetration rates were as great as 132 ft/hr, and the test was discontinued only because of hole deviation, probably due to lack of stabilizers. Several COMPAX diamond compacts were lost, apparently as a result of braze failure and carbide stud design, but no evidence of significant COMPAX diamond compact wear was found.

During the same period that the first oil/gas bits were tested in the field, a COMPAX core drill of improved design was tested in the drilling of hematite deposits in Michigan. In contrast to the first core drills, these bits were constructed in a manner that provided a predominantly shearing action on the rock. Minimal fracture and loss of diamond compacts was observed, although loss of o.d. gage did occur by abrasive wear. The formation was extremely tough, consisting of alternate inclined layers of ore and quartz.

The loss of COMPAX diamond compacts through apparent braze failures encountered in oil/gas field drilling tests prompted additional research to improve the shear strength of the compact/tungsten carbide slug interface. Re-design of the compact pocket on the cemented carbide support, plus the introduction of induction brazing techniques for better time-temperature cycle control, resulted in a significant increase in side shear strength, while maintaining the overall strength of the tungsten carbide supporting slug.

Two oil/gas bits with a modified COMPAX diamond compact/tungsten carbide slug design were tested subsequently. One bit was run for 33 hours, drilling a total of 1420 feet in soft, homogenous sandstone at an average penetration rate of 43 ft/hr. This was approximately 15 percent greater penetration during actual drilling than conventional steel bits in the same strata; additionally drilling this footage with the steel bits would have required trip time and costs for three conventional bits. The field test was terminated by the loss of a tungsten carbide nozzle liner. The second COMPAX bit was then put in the hole, but after a short drilling period it suffered extensive damage which was initially attributed to hard, fractured, inhomogeneous Moenkopi shale which is very difficult to drill. Later it was found that junk, including the carbide nozzle lost from the first bit, had not been removed from the hole before the second COMPAX bit test was started.

A third generation COMPAX bit modification, designed for improved bit face cleaning and potential use with highspeed down-hole drill motors, was

included in further full-scale laboratory drilling experiments. Promising results were obtained at high rotary speeds, but heat cracking was observed in the carbide support slugs. The maximum permissible bit weights before fracture of the present COMPAX diamond compact/tungsten carbide slug system were tentatively identified, as well as the limiting torque values.

Based on this past experience with observations on the modes of rock removal with compacts, and from discussions with our independent consultant (Charles Ward of Maurer Engineering), it appears that the following relationships are needed as a minimum for input to the geothermal bit design:

- 1) The effect of cutter size on rate of material removal and on torque
- 2) The effect of the degree of cutter overlap on cutting efficiency, i. e., penetration rate, force, rock removal, etc.
- 3) Penetration rate as a function of rotational speed and cutter size
- 4) The effect of rotational speed on force
- 5) The effect of cutter geometry, e. g., side rake, back rake and clearance on penetration rate and force
- 6) Variation of these parameters as required by the range of rock properties encountered in geothermal formations.

Assuming that the above information is available, it is necessary to determine whether a bit can indeed be fabricated utilizing optimum design features determined from single cutter experiments. We have tentatively selected a design involving a spiralling array of concentric compact cutters mounted on studs set into the bit body.

In making this selection at least four options were considered for the fabrication of a diamond compact geothermal bit, not all of which incorporate studs or inserts:

- Option 1 - Machine the bit body out of a suitable steel, bond the compacts to carbide or hard alloy studs, then press the studs into the bit body.
- Option 2 - Choose a bit body material, such as a hard steel, to which compacts can be bonded directly.
- Option 3 - Utilize a hard matrix material for the bit body and bond compacts directly to this material.

Option 4 - Braze WC inserts to the bit body and then bond compacts to the inserts.

The reasons for choosing a compact/stud arrangement for the preliminary design rather than setting the compacts into a matrix are as follows:

- 1) A matrix material bit body, suitable for many oil/gas drilling applications, may not have the temperature capability needed for geothermal drilling.
- 2) The technology is not yet mature for attaching compacts directly to a conventional bit body. Brazing has not yet been successful here.
- 3) It has been demonstrated that compacts can be brazed or diffusion-bonded to studs.
- 4) Hard matrix material for the bit body may not withstand erosion by hot rock debris at the bottom of a geothermal hole.
- 5) A stud design is compatible with fabrication procedures in about 90 percent of the bits now being used.

The bit will be made in two parts and subsequently screwed or fitted together followed by a final welding operation. This method of fabrication will serve at least two useful purposes. First, it will allow easier positioning of the crown, or working, part of the bit during attachment of the inserts. Second, it will allow more secure attachment of the nozzles to prevent them from "blowing" during drilling.

The size of the bit will be 8-3/4 inch in diameter. Compacts will be included on the gage section as well as on the crown section of the bit. It is planned that two bits will be constructed, one utilizing brazed compact/studs and one utilizing diffusion-bonded compact/studs.

Detailed design work will proceed during the next reporting period, culminating in Laboratory Testing at Tulsa University.

SECTION IV

REFERENCES

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2. C. M. Perrott and P. M. Robinson, "Mechanisms of Wear of Tungsten Carbide-Cobalt Tools. 1: Rock Drilling and Cutting Application," Journal of the Australian Institute of Metals, Vol. 19, No. 4, December 1974, pp. 229-240.
3. D. G. Flom, F. W. Gorsler, and R. M. Chrenko, Diamond and Borazon^T CBN Compact Tool Technology Program, AFML-TR-76-168, November 1976.

SECTION V

APPENDIX A

ATTACHMENT STUDIES

Although development of methods for improved attachment of COMPAX^R diamond compacts to bit bodies is not specifically a part of CRD's ERDA contract work statement (ERDA is funding attachment studies at Sandia Labs), a compact attachment bond which will withstand higher temperatures than the present brazing technique may be critical to the success of the program. Consequently, we are pursuing this objective independently of the ERDA contract, but will report progress along with our normal ERDA reporting requirements.

At present there appear to be several alternatives to brazing. We have explored the possibility of inertia welding. Very preliminary experiments indicate that it is feasible to inertia weld cemented tungsten carbide (which is the substrate of the COMPAX^R diamond compact) to a variety of alloys, including 4340 steel, Vascomax 300 maraging steel and cobalt base alloys, providing the proper inertia welding machine parameters can be established and suitable surface preparation is identified. The equipment used for exploratory tests could not be adjusted to dissipate energy at the weld interface rapidly enough to obtain satisfactory results in every case, but welds were obtained between carbide and Vascomax 300. Attempts to inertia weld tungsten carbide to tungsten carbide were unsatisfactory because of machine pressure deficiency, but feasibility was indicated. Some further exploratory tests are planned. However, development of inertia welding techniques for actual viable COMPAX bit systems will require an extensive, long term program which we are not prepared to pursue at the present time. Because of other attachment schemes to be discussed, this should not delay initiation of bit design on this program.

Preliminary experiments aimed at obtaining a "hybrid" diffusion bond at temperatures below 700°C and moderate pressure (5000 - 10,000 psi) have been performed at CRD. The objective is to form an initial bond using a reactive and a non-reactive metal combination at the interface under modest pressure, and then modify the interface properties by heat treatment below 700°C at low pressure or atmospheric pressure. Initial results indicate some potential for success.

Sandia Labs (Newsom and Huff) have demonstrated that excellent diffusion bonds can be obtained between tungsten carbide and tungsten carbide using high pressure at ~ 600°C for several hours. They have extended these experiments to hot isostatic pressing at ~ 45,000 psi (~ 1/2 pressure initially used).

Since Sandia does not plan (according to Newsom) to extend this diffusion bonding technique to any combinations other than the successfully demonstrated WC-Ni-WC system and some experiments to diffusion bond WC to a hard matrix, CRD has initiated an exploratory program to examine alternate bonding materials. In addition, experiments are planned using the most promising material combinations to establish the minimum pressure requirements. If the pressure can be reduced significantly the number and size of available suitable autoclaves will be markedly increased.

As noted in the text, a diamond compact successfully tested by Sandia Labs (Huff) is being examined by CRD. This is a compact that was diffusion bonded by Sandia to a WC support. The bond interface has been examined by CRD and found to be excellent. No degradation of the cemented carbide adjacent to the Ni layer was seen. The results of this examination have been transmitted to Charles Huff, along with photographs of the bond zone. The details will be given in Sandia's report on diffusion bonding.

APPENDIX B

MEETINGS

<u>Date</u>	<u>Place</u>	<u>Participants</u>
7/16/76	CRD, Schenectady, NY	J. J. Azar, Tulsa U. A. W. Urquhart, GE L. E. Hibbs, Jr., GE H. W. Lake, Jr., GE
8/24/76	CRD, Schenectady, NY	Charles Ward, Maurer Eng. D. G. Flom, GE L. E. Hibbs, Jr., GE
9/24/76	Vermont Marble Company Proctor, Vermont	H. L. Curtis, Vt. Marble Co. D. G. Flom, GE L. E. Hibbs, Jr., GE
10/7/76	CRD, Schenectady, NY	M. M. Newsom, Sandia Labs C. Huff, Sandia Labs C. Ward, Maurer Eng. L. E. Hibbs, Jr., GE A. Bower, GE
10/8/76	CRD, Schenectady, NY	C. Carwile, ERDA J. Walker, ERDA E. Ferrero, ERDA M. M. Newsom, Sandia Labs C. Huff, Sandia Labs C. Ward, Maurer Eng. A. Bower, GE M. Goldman, GE M. Aven, GE A. W. Urquhart, GE H. W. Lake, Jr., GE R. C. DeVries, GE L. E. Hibbs, Jr., GE D. G. Flom, GE

Appendix B (Cont'd)

<u>Date</u>	<u>Place</u>	<u>Participants</u>
12/8/76	Sandia Labs Albuquerque, N.M.	M. M. Newson, Sandia C. F. Huff, Sandia J. A. St. Clair, Sandia R. F. Ashmore, Sandia H. Togami, Sandia R. Randich, Sandia G. Kominiak, Sandia L. E. Hibbs, Jr., GE M. Dennis, GE W. Daniels, GE