DRILLING RESEARCH AT SANDIA LABORATORIES

M. M. NEWSOM
Sandia Laboratories

BACKGROUND

Drilling is required for the exploration and production of almost all forms of energy and mineral resources found in the earth. Current drilling activity in this country is large and working near the industrial capacity. For example, the petroleum industry alone drilled approximately 145 million feet of hole in 1974 at an average cost of $24 per foot. The uranium industry drilled an additional 22 million feet to bring the total drilling cost to almost $4 billion in 1974. This figure was exceeded in 1975 and projections for 1976 are higher still. Using today's rotary technology, the cost of drilling for petroleum increases exponentially with hole depth as shown in Fig. 1. The future development of geothermal resources will pose even more severe problems to the drilling industry. The more competent basement rocks at elevated temperatures are more difficult to drill, and footage costs are factors of two to four higher than for comparable depth sedimentary drilling. If improved drilling technology is not developed, this expense, coupled with the shortage of rigs and trained crews, could severely limit the timely development of this resource.

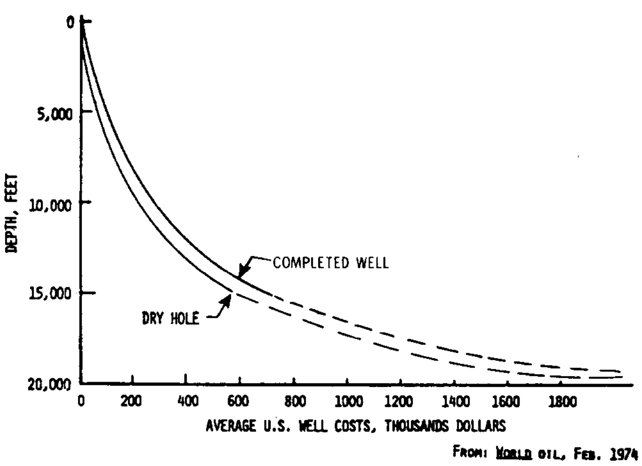

FIG. 1 AVERAGE U.S. WELL COSTS VERSUS DEPTH

Drilling technology could become a limiting factor in future energy development if ways are not found to increase the footage drilled and reduce the costs per foot. Significantly increasing the active rig count does not seem to be a viable option due to the very long lead time associated with new rig deliveries and the severe shortage of trained personnel.

DRILLING RATE

One solution to improved drilling is to drill at a faster rate. Instantaneous drilling rate is related to the power applied to the rock face and the energy required to remove a unit of rock (specific energy). For a given size borehole, this relationship is parabolic:

(Drilling Rate) (Specific Energy) = Constant

This relationship is illustrated in Fig. 2. It can be seen that either the power applied must be increased or the efficiency of rock removal must be greatly improved if the drilling rate is to be improved. Conventional drilling is limited to approximately 50 hp applied to the rock face, and the specific energy would have to be greatly reduced to significantly increase the drilling rate. Therefore, novel drilling techniques with the potential for lower specific energy, higher applied power, or both, should be investigated.

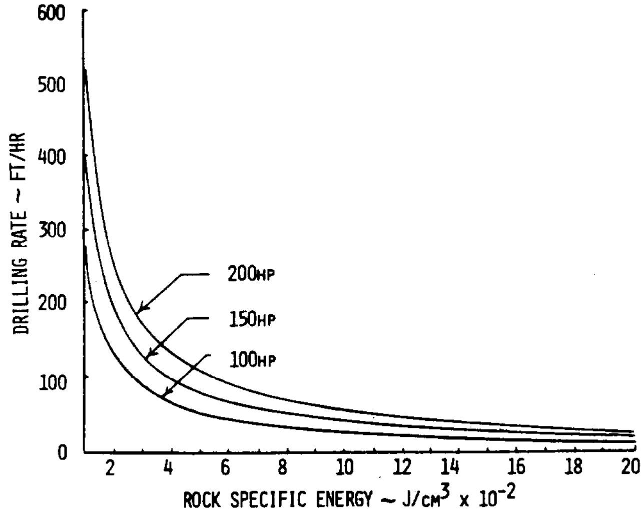

FIG. 2 — DRILLING RATE FOR 8-INCH-DIAMETER HOLE VERSUS ROCK TOUGHNESS

The average drilling rate is even more important. This includes the effect of instantaneous drilling rate, the time to replace worn bits (trip time), and the time it takes to connect additional drill pipe. This relationship is:

$$\text{Average Drilling Rate} = \frac{\text{Distance Drilled per Bit}}{\text{Trip Time} + \text{Rotation Time} + \text{Connection Time}}$$

This relationship indicates how the average drilling rate can be improved by parameter variations; however, it gives little indication of the economics involved. To investigate drilling economics the following parameters are defined:

T = trip time
C = rig cost/unit time
B = bit cost
L = bit life (time)
R = instantaneous drilling rate (distance/unit time)
$\overline{C}$ = rotating cost/unit length

Then $\overline{C} = \dfrac{(T + L)\,C + B}{RL} = \dfrac{C}{R}\left(1 + \dfrac{1}{K}\right)$

where K is:

$$\frac{L}{T + B/C} \quad \text{(nondimensional bit life)}$$

Assuming that the bit life (L) is an unspecified function of R and that T, B, and C are essentially independent of R, then:

$$\frac{R}{\overline{C}}\frac{d\overline{C}}{dR} = -\left[1 + \frac{R}{K(K+1)}\frac{dK}{dR}\right]$$

The cost breakeven point is when $d\overline{C}/dR = 0$; using this value and rearranging the above equation, one has:

$$-\frac{dR}{R} = \frac{dK}{K(K+1)}$$

Integrating this from an initial rate (R_o) to a final rate (R) and from initial bit life (K_o) to a final bit life (K) one obtains:

$$R/R_o = \frac{(1 + 1/K)}{1 + 1/K_o}.$$

With a known value of K_o, a cost breakeven curve (R/R_o vs. K/K_o) can be generated as shown in Fig. 3. For a given K_o, any point lying above the appropriate curve represents a drilling cost improvement. To illustrate the use of the curves, suppose a drilling system has the following characteristics:

L = 25 hr T = 4 hr R_o = 25 ft/hr
C = \$1000/hr B = \$1000/bit

From these, K_o = 5. Suppose a modification would allow a factor of two increase in drilling rate (R/R_o = 2), what could be the sacrifice in bit life to be of equal economic value? From example (1) of Fig. 3, K/K_o = 0.143 or a factor of 7 in bit life reduction is allowed. Any bit life greater than 1/7 K_o

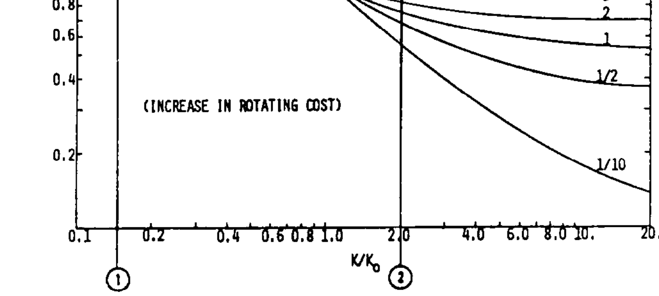

FIG. 3 — DRILLING COST BREAKEVEN

would save money. Similarly, for any new bit with an increased bit life of 2, ($K/K_o = 2$), the resulting drilling rate must be within 90% ($R/R_o = 0.9$) to be economically equal (see example (2), Fig. 3).

Based upon this analysis, this drilling research program is primarily directed at improving the average drilling rate. Specifically, methods for improving instantaneous drilling rate and reducing the number of trips required for bit changes are being investigated.

CONTINUOUS CHAIN DRILL BIT (CCDB)

A long-life, slim-hole drilling system has long been sought by the drilling industry. If long-life bits can be developed, slim holes will be less expensive due to reduced casing, bit, and rig costs, particularly in exploratory drilling. A long-life, slim-hole bit is currently under development (Fig. 4). The cutting mechanism would be by drag action due to rotation of the rotary table and drill pipe as in normal rotary drilling. The bit cutting surface is formed as a long chain. The face of the chain will be surfaced with diamonds set in a tungsten carbide matrix. The bottomhole cutting surface consists of six chain segments. When this surface wears out, a new cutting surface can be cycled into place by pulling off the bottom and decreasing mud pressure. This will rotate a new section of chain into place by allowing a spring, piston, paw/assembly, loaded by mud pressure, to cycle the chain drive. The bit may then be returned to bottom and drilling continued.

The concept has the potential for long downhole life which will improve the average drilling rate. This design has also shown that the instantaneous penetration rate can be increased by reducing the number of diamonds per unit area in the matrix.

There was considerable disagreement over whether or not this design would drill at all when it was first conceived. To test its drilling ability, four low-cost prototypes (Fig. 5) were fabricated by Christensen Diamond Products Co. and tested at the Reed/Terra-Tek Deep Drilling Research Laboratory at Salt Lake City.

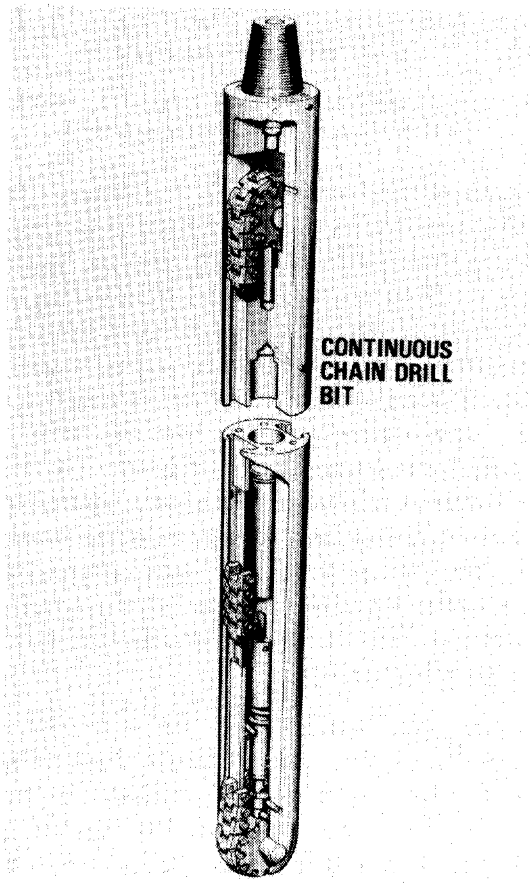

FIG. 4 —CONTINUOUS CHAIN DRILL BIT

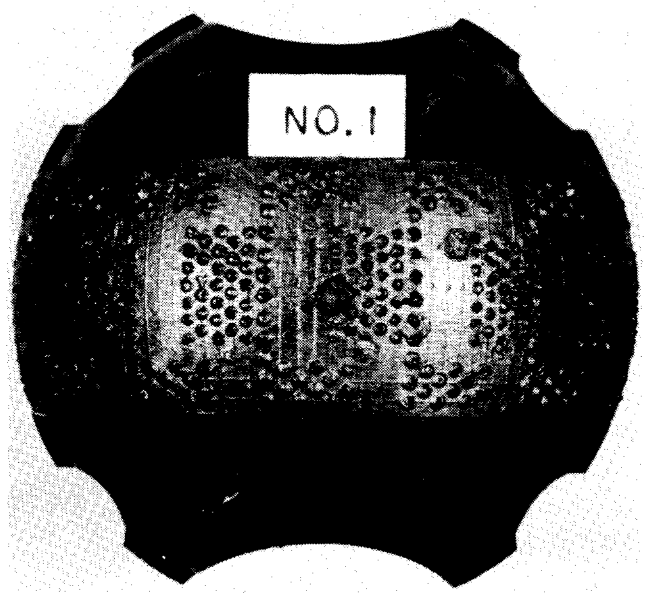

FIG. 5 –FIXED PROTOTYPE—CONTINUOUS CHAIN BIT

Drilling rates were compared against the rates of standard diamond bits in Berea sandstone, Carthage marble, Texas pink granite and Sierra white granite. These tests demonstrated a significant improvement in instantaneous penetration rate in the harder rock as shown in Fig. 6. In soft rock, considerable bit balling was observed due to inadequate bottomhole cleaning. One of the prototype bits was reworked to improve bit hydraulics and retested. These results are shown in Fig. 7, and it can be seen that significant improvement was made. These results are considered to be encouraging, and two new prototypes are currently being fabricated with improved diamond patterns and hydraulics. These will be tested in the near future and a full prototype of this system should be completed by late summer if these tests are successful.

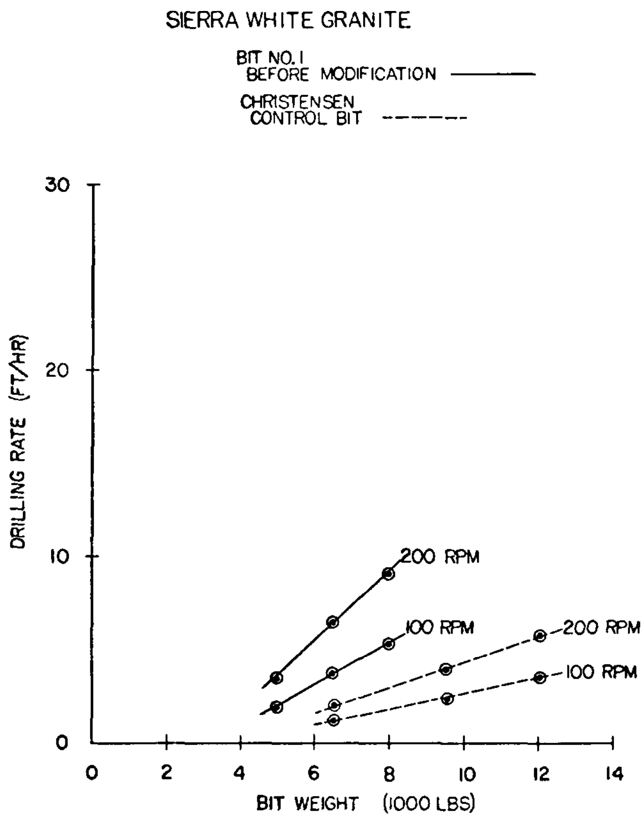

FIG. 6— CONTINUOUS CHAIN BIT LABORATORY DRILLING RATE SIERRA WHITE GRANITE

DOWNHOLE CHANGEABLE BIT

A novel technique is being developed to change the cutting surface of a roller cone bit downhole (Fig. 8). Conceptually, the bit would contain a number of new cutting heads in a downhole magazine. When a cutting head wears, as determined by measurements made on the drilling platform, the old head can be cycled into the magazine and a new one cycled into the drilling position. This is accomplished by folding the gauge

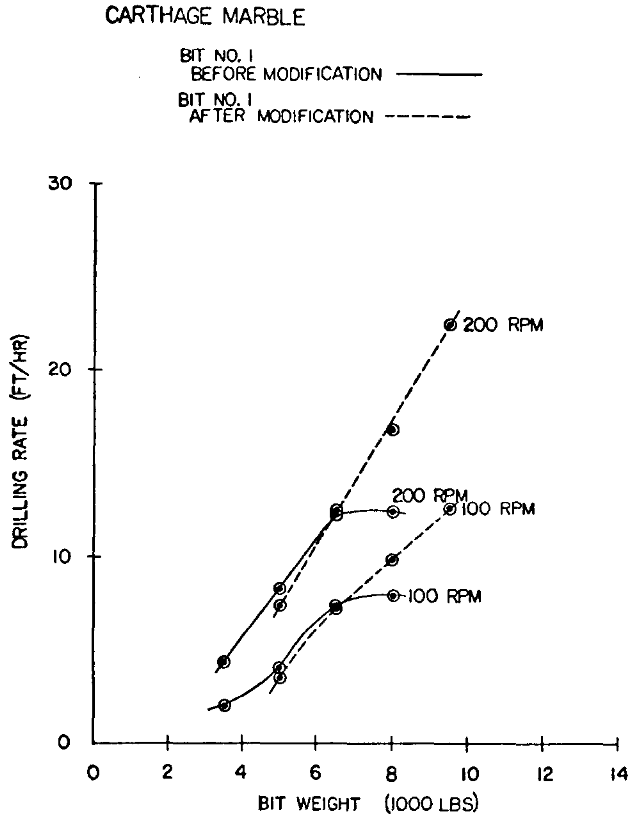

FIG.—7 CONTINUOUS CHAIN BIT IMPROVED HYDRAULICS CARTHAGE MARBLE

cutters to allow clearance prior to rotating the head out of place. The cutter head consists of the gauge cutters mounted on a folding support and frame and the center hole cutters. Locks are used to rigidly position the head for drilling. Several new cutter heads can be stored in one side of the bit, joined by lengths of chain to the cam followers attached to the heads. Appropriately placed bars are attached to the chain for indexing the cutter heads. This bit will allow cutter head changes without tripping the drill pipe (withdrawing the drill pipe from the borehole). If bit life and penetration rates comparable to current roller bits can be achieved, this system can result in considerable savings of time and money in deep drilling operations.

A prototype roller cone assembly has been developed cooperatively with Reed Tool Company that fits the configuration allowed in this bit assembly (Fig. 9). Due to the severe space limitations imposed by this design, the journal bearings and cones were approximately one-half the

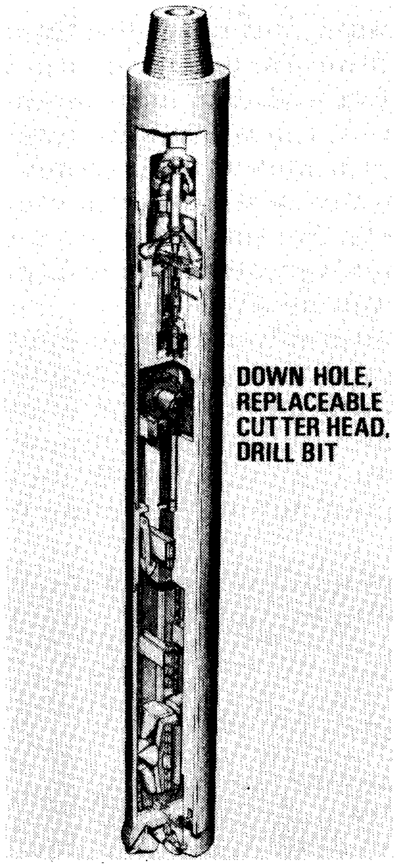

FIG. 8 DOWNHOLE CHANGEABLE BIT

diameter of comparable-size tricone bits. Two prototypes of this drilling head have been tested at the Reed drilling simulator in Danbe marble and Texas pink granite. The penetration rates achieved (Fig. 10) were comparable to a conventional Reed bit up to 5000 lb/in. of bit loading. At 40,000 lb total load, the journals suffered structural failure as shown in Fig. 11. To be competitive in penetration rate, the cutter head must be strengthened to accept loads comparable to a tricone bit. A redesign is currently in progress that is considering a hybrid roller cone/Compax and a straight Compax configuration. The Compax element is a man-made diamond cutting surface currently in development by the General Electric Company. Both of these designs offer promise of improving both the strength and penetration rate, and prototypes will be tested by late summer.

TERRA-DRILL PROGRAM

In an effort to improve the performance of current rotary drilling system in hard rock, the Terra-

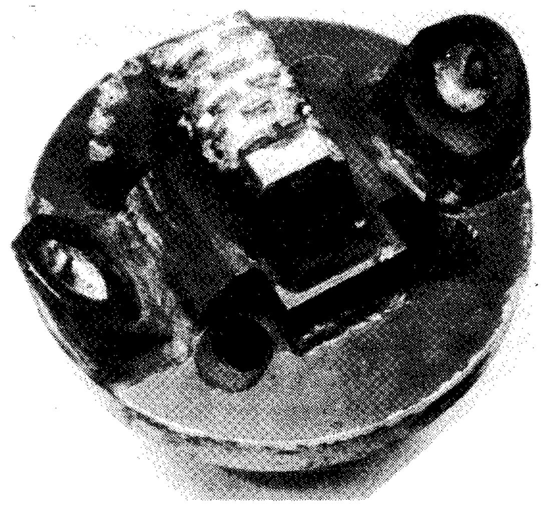

FIG. 9 DOWNHOLE CHANGEABLE BIT PROTOTYPE

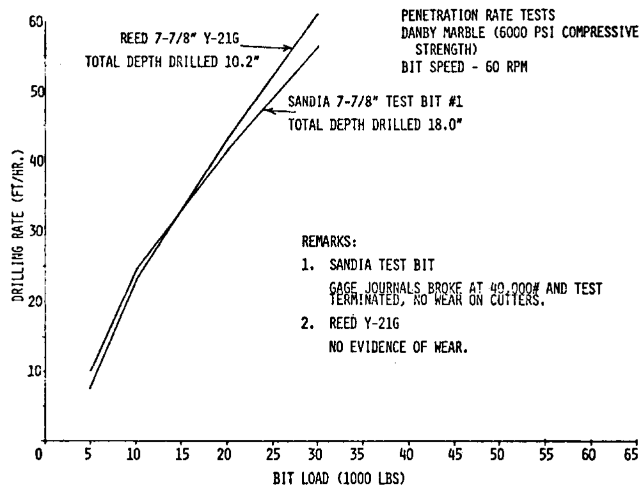

FIG. 10 DOWNHOLE CHANGEABLE BIT DRILLING RATE DANBE MARBLE

SANDIA DRILL BIT

REED STANDARD TRI-CONE DRILL BIT

FIG. 11 DOWNHOLE CHANGEABLE BIT JOURNAL FAILURE

Drill was conceived. The Terra-Drill combines the technology of terradynamics with that of the rotary rock bit. As a projectile penetrates a rock, it creates many fractures which in turn weakens, if not comminutes, the rock. This drill design concept is based on the supposition that highly fractured rock can be drilled easier than unfractured, homogeneous hard rock. The small projectiles launched by this drill penetrate and weaken the rock ahead of the bit and the rock bit cuts the hole to gauge. This concept is shown in Fig. 12. A Terra-Drill-aided rock bit should drill more footage per unit time and the bit should have increased downhole life, both of which result in improved integrated drilling rate.

In order to test the basic concept upon which this design is based, an in situ drilling test was designed and conducted. The drilling rate of a conventional rotary bit in a Madera limestone formation was established for only one drilling variable, bit weight. All other parameters were held constant using air as the drilling fluid, with one type and size of bit at one rotary speed. For comparison purposes, the rock was fractured by small penetrators and drilling was repeated with this bit.

A projectile configuration was selected for testing, based on previous experience in terradynamics with projectiles fired into rock in the laboratory. A 1/4-in. diameter, 1-1/2 in. long projectile with a conical nose 3/8-in. long was fired at 3700 fps. It was made of oil-hardened drill rod, heat-treated to maximum

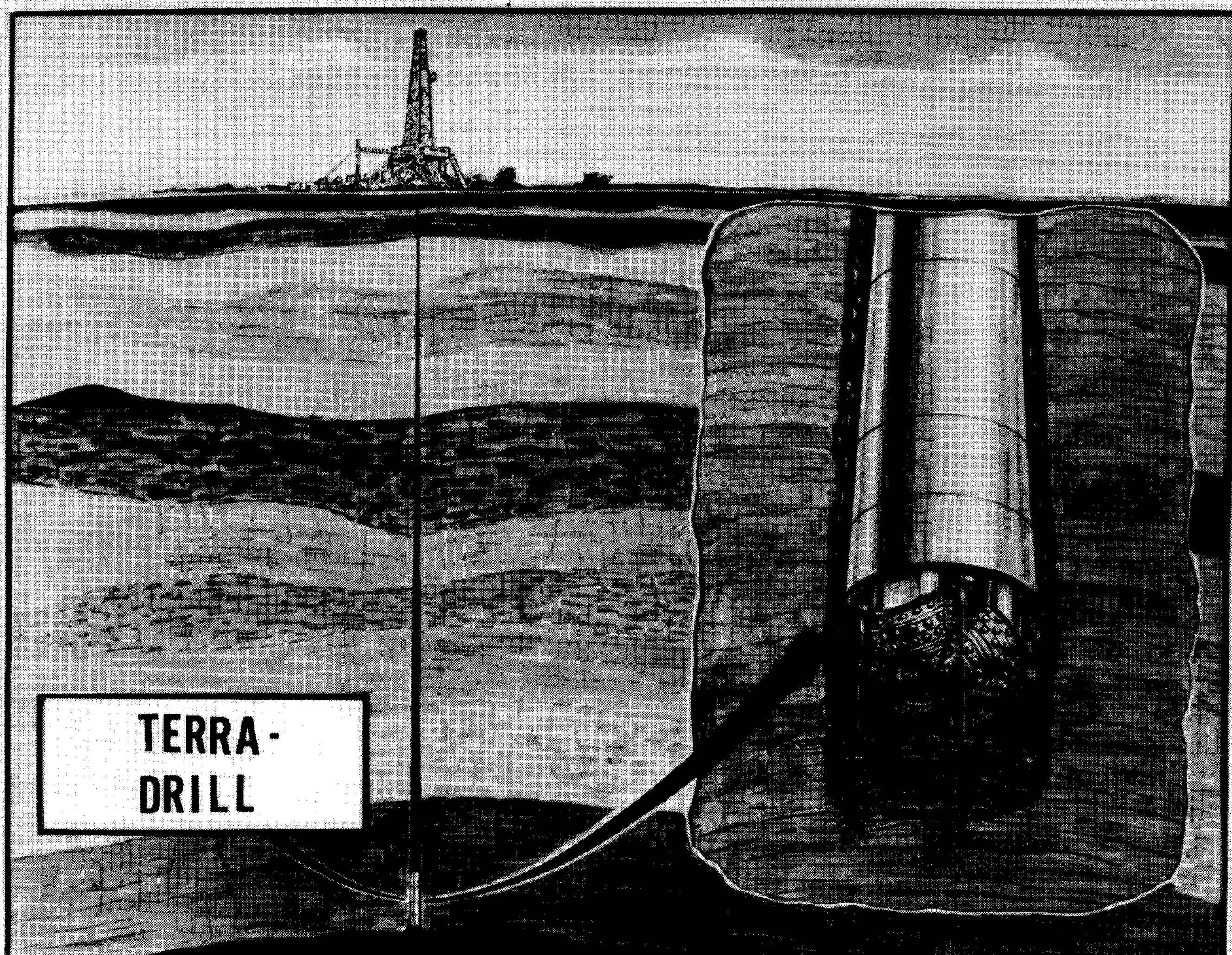

FIG. 12 TERRA DRILL

hardness. This projectile penetrated approximately 3-1/2 in. of Madera limestone in laboratory tests. For the field tests, three of these projectiles were fired simultaneously in a pattern spaced 120° apart on a 6-in. diameter circle. A fixture holding three launchers was fabricated and standard small arms cartridge components were used to accelerate the projectiles.

In the field test, a pilot hole was drilled and the unaided drilling rate established. The bit and drill stem were then removed, and the three-barrel gun assembly was lowered to the bottom of the hole and fired. The gun assembly was then removed, the bit and drill stem replaced in the hole with the proper weight applied, and the bit was rotated, recording the time to drill 6 in. beyond the position of the bottom of the hole prior to firing the projectiles. The 6-in. test distance was chosen from projectile penetration results observed in laboratory tests. This procedure was repeated several times for each weight on the bit. Figure 13 shows the original drilling rate as well as the projectile-aided drilling rate. The maximum spread in data points is indicated by the band. As can be seen, the drilling rate was improved by a factor of almost two.

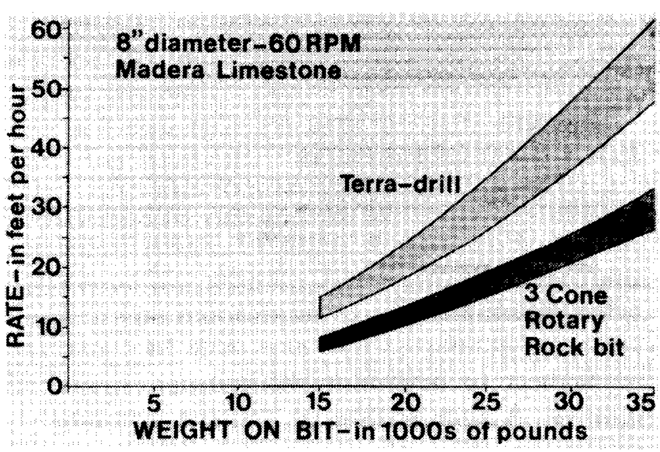

FIG. 13 -TERRA-DRILL PENETRATION RATE—MADERA LIMESTONE

These results were acquired for only a single set of drilling parameters in a single geological formation, but are encouraging enough to interest us in pursuing a more detailed research program for hard rock drilling.

Current work this year is centered on selecting the optimum projectile configuration, a preliminary design of the downhole ordnance system, and repeating the field experiment in a harder crystalline rock formation.

THE SPARK DRILLING SYSTEM

A drilling technique is under investigation which could greatly reduce the need for changing bits in deep holes and which also offers the potential for improved rock removal efficiency and higher penetration rates. This bit consists of a downhole electrical pulse generator system which discharges high energy, precisely timed, short duration pulses between an array of electrodes. The electrodes are located near the rock surface that is to be fractured. The spark discharge in liquid creates a high magnitude compressive wave in the drilling fluid, followed by cavitation and subsequent bubble collapse. It is thought that these shocks and wave interactions combine to remove rock primarily by spallation. These phenomena are illustrated in Fig. 14. Cavitation and the resulting rock spallation have been shown to require the minimum amount of energy per volume of rock removed. This method may become more efficient as the static pressure increases (the deeper the better). The circulating drilling mud removes the broken rock and cools the generator.

Spark drilling has been studied by several investigators over the past 20 years and while a high drilling potential has been reported, little has been done to understand the phenomena involved. Our initial efforts have been concentrated in three primary areas of concern: definition of the spark-generated environment; understanding of the rock fracture mechanisms, and definition of a long-life bit design.

SPARK CHARACTERIZATION

The electrohydraulic effect is used for numerous applications including metal forming; however, the physics of this process is poorly understood. An understanding of the spark channel energy density and energy distribution is required for hydrodynamic analysis and a study is underway to determine these characteristics. Tap water does not break down instantaneously even with voltage gradients of 2 million volts/cm applied. Before breakdown, a volumetric-like resistance energy loss

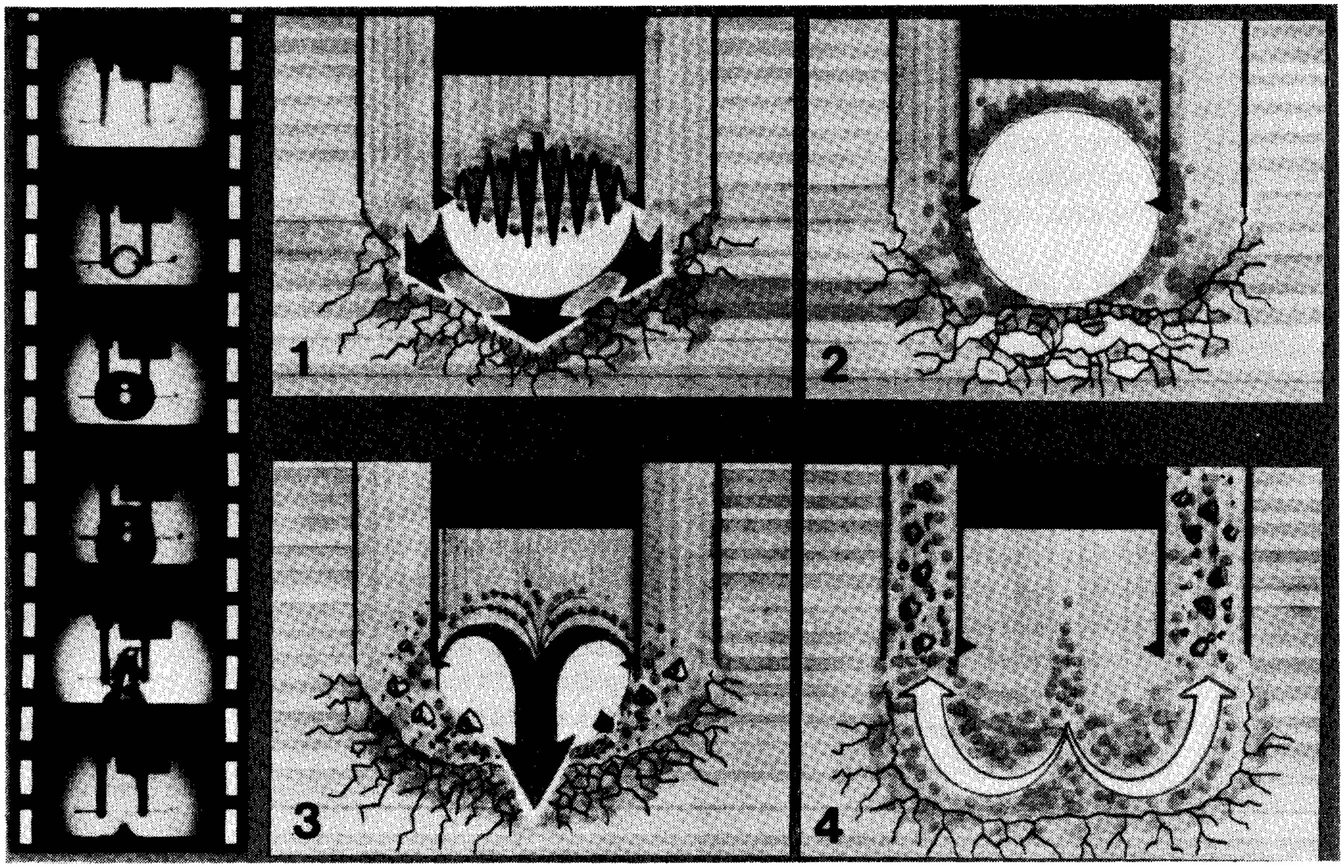

FIG. 14 SPARK DRILL PHENOMENA

is observed. Photographic analyses of the arc have been made and show a definite arborescence around the cathode prior to discharge (Fig. 15). Present efforts are directed toward defining the spark energy density in such a discharge.

Shock wave pressure magnitudes have been experimentally determined by both photographic streak records (Fig. 15) and direct near-field-pressure measurements using a newly developed lithium-niobate transducer. This represents the first reported near-field-pressure measurement near an arc in water.

Both one and two-dimensional hydrodynamic analyses have been completed based on these measurements. With the one-dimensional analyses, scaling laws for the spark-generated environment have been developed. Two-dimensional analyses have indicated that the spark-generated bubble will collapse unsymmetrically, forming a jet toward the nearest solid surface. Parametric studies have also been completed which show the relationship between the compressive rock failure threshold and the required pulse generator energy.

ROCK FAILURE STUDY

Laboratory spark drilling experiments have been conducted on Indiana limestone, Berea sandstone, charcoal granite, and diorite. Thin-section petrographic analyses of the exposed rock samples are being conducted by Texas A & M University researchers to determine the principal modes of failures. A thin section of Indiana limestone is shown in Fig. 16. Typically, sandstone and limestone fractures are extensional in nature, are intergranular, and the direction of the fractures are both tangential to and parallel to the bottom of the hole. Diorite exhibits both radial and tangential fractures with radial fractures predominating in the granite. Fractures are not observed until several sparks have been discharged on the rock surface; therefore, both fatigue and crack propagation studies are being conducted to determine the predominant rock failure mechanism.

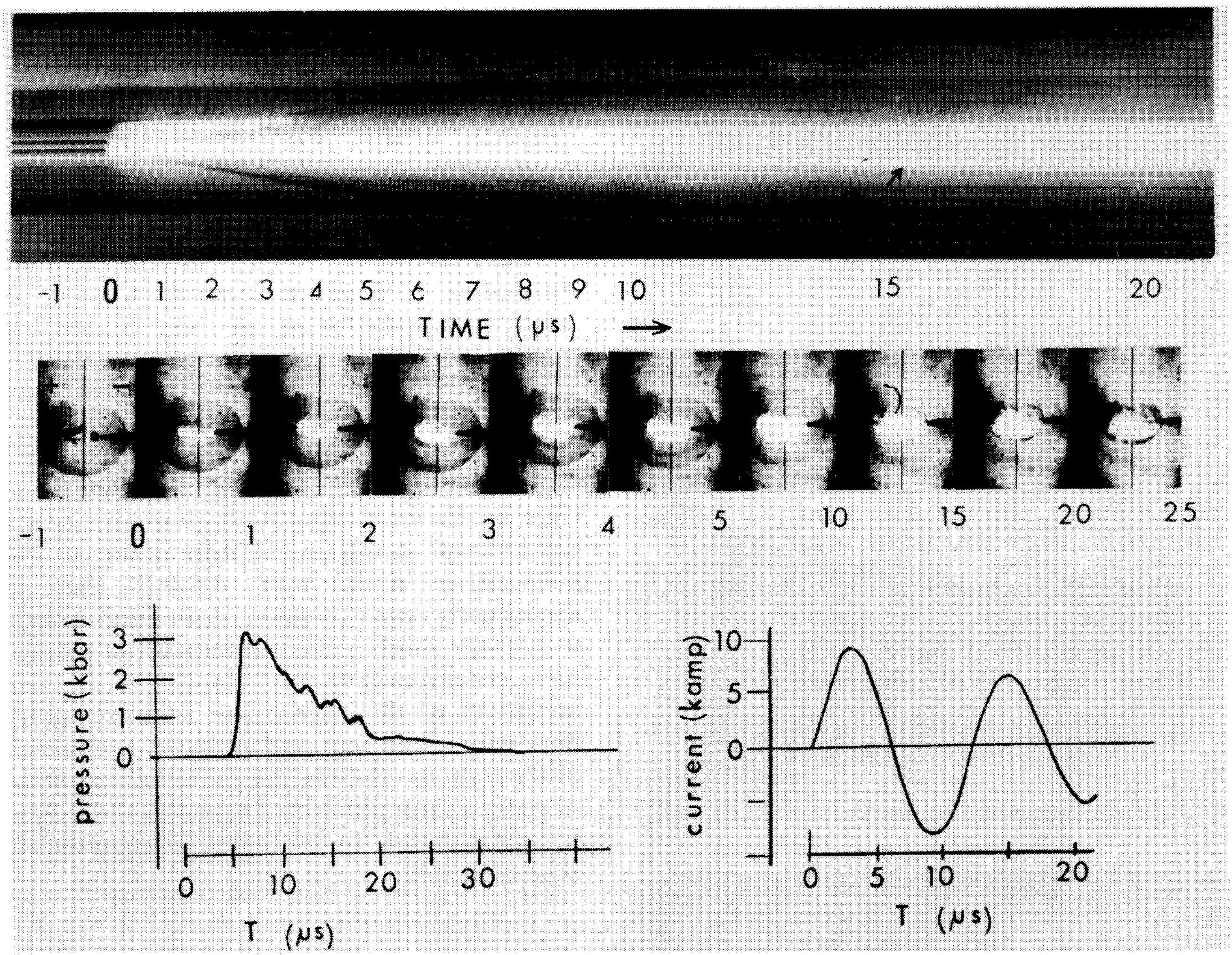

FIG. 15 SPARK DRILL TYPICAL DATA

DRILL BIT DEVELOPMENT

The initial experimental efforts in this program were directed at duplicating the early Russian drilling data. Bit designs based on published data made hole at rates comparable to the published rates. The bit life, when working against the more competent rock, was measured in minutes, however. A spark system should have a bit life approaching 100 hours at an input power of 150 hp. Since past design failed in a short time while working at 4 hp, it was obvious that work must be expended in this area.

The generation of high spark channel pressures requires rapid spark current rise times. To obtain a rapid rise, a large voltage-to-inductance ratio is required. The present spark drill pulse generator can provide 1×10^{11} amp/sec current rises at 50kv. The pressure resulting from this spark causes serious structural damage to electrode insulation near the spark channel. To date, no insulator has been found that can survive the repeated pressure pulses. This implies that the electrode must be bare near the discharge, and careful attention must be paid to field gradients to prevent arcing at undesired locations. A prototype bit that is based on these principles has been designed and tested. This electrode configuration shows promise for long-life operation.

We are currently designing and building a larger spark generator that will deliver approximately 25 hp to the rock face. Energy per discharge will be approximately 1000 Joules at a repetition rate of 20

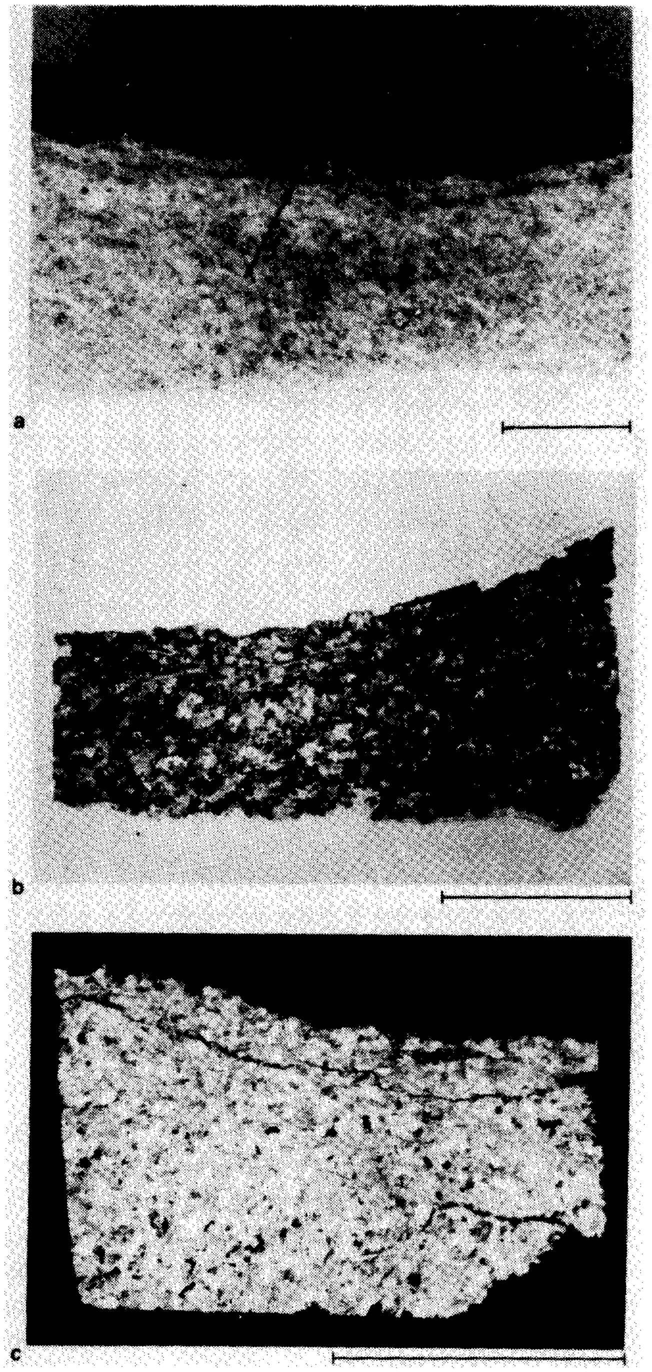

FIG. 16—THIN SECTION—SPARK-DRILLED INDIANA LIMESTONE

pulses per second. This energy level should be sufficient to establish laboratory drilling rates, determine bit life and assess the feasibility of a spark drilling system. This generator should be in operation by May, 1976.

CONCLUSIONS

In all of its work in energy-related areas, Sandia is attempting to form cooperative programs with appropriate industry groups from the very early stages. It is felt that this is critical to the future success of these programs, for several reasons. If the broad experience and existing technology of industrial laboratories can be combined with the high technology of the National Laboratories on the right problem set, significant, near-term progress can be made in solution to these problems. Early cooperative work with industry can also significantly speed commercialization of emerging technology which is the true measure of success in these endeavors. For these reasons, project teams composed of the appropriate industrial groups, university researchers, and engineers and scientists of the National Laboratories have been assembled to address these problems. In general, the reception to this approach, in the industries contacted, has been favorable.