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GEOTHERMAL DRILLING RESEARCH IN THE UNITED STATES

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INTRODUCTION

At the present time, geothermal wells cost several times as much as conventional oil wells of comparable depth, as shown in Fig. 1. The high cost of these wells is an impediment to the timely development of geothermal energy in the U.S. These higher costs are attributed to temperature, formation, erosion, and corrosion effects which are encountered in current geothermal drilling operations. Geothermal formations are typically hard and hot (up to 350°C). These factors combine to cause low penetration rate and short bit life. In addition, most formations are below hydrostatic pressure. Drilling with air, mist, and other low density fluids is, therefore, a common practice, and corrosion is a severe problem with these fluids. The Division of Geothermal Energy (DGE) of the U.S. Department of Energy (DOE) has initiated a program of drilling and completion technology development which is aimed at reducing the cost of geothermal wells. Specific goals have been set for this program. These are to develop the technology required to reduce the cost of drilling and completing geothermal wells by 25% by 1983, and by 50% by 1987.

Sandia Laboratories has been selected by DOE/DGE to manage this technology development program. The program is currently addressing the development of improved drilling hardware, drilling fluids, lost circulation control techniques, completion technology, and advanced drilling and completion systems. The research and development required in this program is conducted primarily through contracts with private industry, with some in-house research conducted at Sandia. An advisory panel composed of industry, university, and government participants has been formed to assist in the definition of the R&D tasks that are required to meet the goals of the program. This panel meets semi-annually to review the status of the program and to provide guidance to the program manager.

In order to assess the progress of the program toward the stated goals and to define areas for research and development that have high cost reduction potential, a geothermal well cost simulator has been developed. This computer model simulates the operations involved in drilling and completing a geothermal well and computes the cost associated with each operation. The model can then be used to assess the cost/benefit ratio of new technology prior to initiating the development of the technology. A sample output from this model is shown in Fig. 2a. This plot illustrates a typical drilling and completion operation in The Geysers field. Drilling mud is used to a depth of approximately 6500 ft, then a conversion is made to air drilling when the high temperature zones are encountered. This well experienced very few problems. Of the total time required to complete the well, approximately 47% of that time was spent in actual drilling operations. Using this information, the effect of improved technology can be determined. As an example, the effect on overall well cost of a new bit having increased penetration rate is shown in Fig. 2b. Here the percentage reduction in well cost is plotted as a function of bit life (expressed as a percentage of that obtainable with a conventional bit). Two curves are shown. One assumes an increase in instantaneous penetration rate of a factor of two, the other a factor of three. If these increased rates can be achieved while maintaining bit life comparable to conventional bits, well cost reductions of between 7 and 17% are possible. (The cost of the new bit is assumed to be $1000 per inch of bit diameter.) This sample calculation indicates the procedure which is being used to define promising technology development areas.

A second example, shown in Fig. 3a, serves to illustrate the variety of problems which are encountered in geothermal drilling. In this well, which was drilled in Utah, severe problems were encountered, particularly with lost circulation. A considerable amount of money was spent in trying to set cement plugs to circumvent the lost circulation problem. This resulted in a high well cost, and only 29% of the total cost of the well is attributable to the actual drilling operation. The results of an investigation into the effect of increased penetration rate on this well are shown in Fig. 3b. Here, very little benefit is obtained by tripling the instantaneous penetration rate because of the many problems associated with drilling and completing this particular well. These two examples indicate the varying degrees of impact on well costs that are possible through drilling technology improvements. They further illustrate the need for a broadly based technology development program which addresses increased penetration rate as well as other problems such as lost circulation, drilling fluids, and completion techniques. Based on the results of this type of analysis, technical areas requiring research and development have been identified. Current R&D activities in each of these areas will be presented in the remainder of this paper.

DRILLING HARDWARE

Geothermal Roller Cone Bits

A project to design and develop improved three-cone roller bits for geothermal applications is underway. The project has two thrusts -- one, to substitute high temperature steels in unsealed bits, and two, to develop high temperature seals and lubricants for sealed bearing bits.

Experimental bits incorporating steels that have higher hardness at high temperature have been fabricated and have demonstrated improved performance in field testing at The Geysers. The experimental bits have unsealed bearings for use in air drilling. Fig. 4 is a cutaway view of a bit lug showing the new materials used in the experimental geothermal bit. Of particular importance is the use of harder gauge row inserts to reduce loss-of-gauge problems. Table I lists the materials used in two versions of the experimental bit and in the conventional bit. Testing at The Geysers with these experimental bits has shown that the new design increased bit life by approximately 30% over the conventional design and could result in an overall reduction of 4% in geothermal well cost if bits using these materials were used in The Geysers. One bit manufacturer is evaluating the use of these materials in a commercial bit.

The development of sealed geothermal bits is presently emphasizing the testing of high temperature seals and lubricants and the design and development of non-elastomeric seals for use in these bits. Both seal and lubricant testers have been fabricated, and these testers are presently being used to investigate the lifetimes of several different elastomeric seals and the performance of high temperature lubricants. To date, several fluorocarbon elastomeric seals have shown promise for long life at high temperature. Forty different lubricants have been tested at high temperature. The most successful to date is an experimental grease from Pacer Lubricants designated PLX014. A Viton o-ring seal (Parker No. 4205) recently ran for 107 hours without failure at 150°C in the seal tester using this new lubricant. The seal had been soaked at 260° C for 2 hours prior to testing. This new lubricant is now commercially available from Pacer under the trade name "Geobond".

Further attempts at developing sealed bearing bits are emphasizing metal-to-metal and plastic seals. Fig. 5 shows an artist's concept of a roller cone with a newly-designed spring-loaded face seal. In this design, the Kalrez o-ring is used in a non-rotating situation, and the seal is formed between the lug and the metal face. Testing of this seal has been accomplished with excellent results.

Polycrystalline Diamond Compact Bits

Polycrystalline diamond compacts (PDC) are man-made diamonds that have demonstrated superior performance in cutting both rock and metal. A project is underway to develop and demonstrate the performance of bits using these cutters in the geothermal environment. Fig. 6 is a picture of a bit designed and built by Christensen Diamond Products. This bit was recently tested in a geothermal well in New Mexico and demonstrated an increase in penetration rate of 50% over a conventional roller bit. Fig. 7 is a picture of a bit designed by General Electric and fabricated by Smith Tool Company. This bit mounts the PDC on studs to give increased penetration rate. It was tested in a geothermal well in November, 1978, however, catastrophic failures of the posts used to support the cutters occurred. The cause of the failure has been attributed to stress raisers which occurred because of the pocketed design of the tungsten carbide posts. A new post design has been used in the fabrication of a new bit of similar design. Recent testing of this bit in a geothermal well in New Mexico has indicated that increases in penetration rate of factors of two to four over that achieved with conventional bits are obtainable. Further tests are being conducted to quantify bit life.

Continuous Chain Drill

The Chain Drill is a concept that allows replacement of the bit cutting surfaces without removing the bit from the hole. The system is designed to reduce well cost by reducing the time spent in replacing worn bits. The system utilizes a continuous chain of cutting surfaces. Individual links of the chain are impregnated with diamonds, and PDC are utilized in the nose of the bit. As the cutting surfaces become worn, a cycling mechanism can be activated from the surface which will advance a new set of links into the cutting position. At the present time, 15 sets of new chain links can be carried in one cartridge. The cycling sequence involves the proper application of mud pressure and the use of a coil spring in the bit assembly to produce the cycling force. Fig. 8 shows a cutaway view of the system, while Fig. 9 shows a close-up of the chain links and the diamond cutting surfaces. This bit has recently been field tested [1] at the Nevada Test Site in granite with a compressive strength of approximately 15,000 psi. During this test the bit was cycled 85 times downhole, demonstrating the overall reliability of the cycling mechanism. Six sets of chain links were used to drill a total of 250 feet which yields an average of 41.6 ft per link set. Conventional diamond bits averaged 28 ft of drilling in this formation. Problems with the mud system were encountered which led to plugging of the hydraulic nozzles in the bit on several occasions. This forced a removal of the bit from the hole more frequently than was desired. However, this was a problem with the mud system and not with the bit itself. In June, 1980 a second field test will be conducted using an improved mud system. If this test is successful the technology will be transferred to industry.

DRILLING FLUIDS

Test Equipment

The high temperatures and corrosive environments encountered in geothermal drilling place severe requirements on the drilling fluids utilized. Commonly used drilling muds, such as bentonite, are unsuitable for use at the high temperatures encountered in geothermal wells. Sufficient mud testing has been accomplished to demonstrate the existence of a large discrepancy between ambient rheological data as normally taken in mud laboratories and the actual characteristics of the fluid under dynamic downhole conditions. To provide for an understanding of the characteristics of the drilling fluids under simulated downhole conditions, two test facilities have been constructed. The first, at the University of Oklahoma, is a flow-loop which can be used to measure the rheological properties of drilling muds at temperatures up to 288°C (550°F) and at pressures up to 20.7 MPa (3,000 psi) [2]. This loop has been utilized to screen several commercially available drilling fluids and to test an experimental mud which was developed under the DOE/DGE program. This loop is now operational and is available for use by private industry. A test facility with increased capabilities, specifically, temperatures to 371°C (700°F) and 138 MPa (20,000 psi), is under construction by NL Baroid. This test facility is being constructed on a cost-sharing basis between DOE and Baroid. When complete, it will be used to test a variety of drilling fluids at simulated downhole conditions.

Mud Research

Static aging tests of commercially available muds indicate that all exhibit high temperature gelation, high viscosity, high filtration rates, and poor corrosivity characteristics at temperatures above 177°C (350°F). Maurer Engineering, under funding from DOE, has developed an improved drilling fluid for use under high temperature conditions. The composition of the fluid is shown in Table II. The major constituent of the fluid is sepiolite clay, and brown coal is used as a thinner. This fluid has exhibited good characteristics at temperatures up to 260°C (500°F). A field test of this mud was conducted in May of 1980. Preliminary results indicate a successful test.

In addition to testing new formulations of muds, a basic research program directed at understanding clay morphology as a function of temperature is underway at Texas Tech University. Of specific interest are bentonite, sepiolite, and attapulgite clays. In preliminary testing, it has been observed that sepiolite clay exhibits a needle-shaped structure at room temperature. Under exposure to temperatures of 250-300°C, however, the needle-shaped structure undergoes a transition to a flake-type (smectite) structure. This transition at least partially accounts for the good performance of sepiolite-based clays at high temperature. This work is in its infancy and is directed at an understanding of the basic chemistry involved in the formulation of geothermal drilling fluids.

Inert Fluids

Because many geothermal reservoirs exhibit pressure gradients which are less than normal hydrostatic, and because they are typically highly fractured, it is frequently necessary to drill with air, mist, or foam rather than mud. In general, when air drilling is utilized, the oxygen in the air, combined with the H_2S, CO_2 and water vapor present in the wellbore, provides a mechanism for significantly enhanced corrosion rates. To control this costly problem, efforts are underway to develop a portable nitrogen generation unit for providing an inert drilling fluid.

The design specifications for the unit are that it supply 1200 standard cubic feet per minute of nitrogen at pressures of 400 psi with less than 5 parts per million of oxygen. Two approaches are being taken. The first involves the conversion of diesel exhaust gas into a gas having low oxygen content by the combustion of the exhaust gas with diesel fuel in the presence of a catalyst. Laboratory studies utilizing a small diesel engine are underway to determine the constituents of the product gas and the lifetime of the catalyst. Should these tests prove encouraging, the scale-up of this system to a field portable unit will be initiated. The second approach involves the cryogenic separation of nitrogen from air. While this is commonly done in laboratory situations, the development of a portable unit which can be set up in a matter of hours has not yet been accomplished. Recently, Production Operators has acquired a small portable unit that utilizes an improved heat exchanger tray design. A field test of this unit is scheduled for the fall of 1980. A field test using liquid nitrogen trucked to the rig location will be conducted in the Baca location of New Mexico in August, 1980. During this test, corrosion rates with the standard drilling fluid and then with the nitrogen will be measured and compared to determine the cost reduction potential of the concept.

Foam Fluids

Foam drilling fluids are sometimes used in oil and gas drilling, but at high temperatures most of the available foams either become unstable or highly corrosive. Sandia Laboratories has initiated a program aimed at developing high temperature foams which are suitable for geothermal drilling. A number of existing surfactants have been screened to determine their high temperature aging characteristics. The tests involve measuring the time required for the foam to lose fifty percent of its weight by drainage, before and after aging at 260°C for two hours. In addition, pH values are recorded before and after aging. Table III presents recent results of the initial screening tests. Surfactants which emerge from the initial screening process will be further tested in simulated geothermal brines and at higher pressure to determine the most promising candidates for a field test.

LOST CIRCULATION CONTROL

Because most geothermal reservoirs are highly fractured in nature, the problem of lost circulation is encountered in practically every geothermal well. This problem adds significantly to the cost of drilling and completing the wells, not only because of the need to replace the lost drilling fluids, but also because of the extreme care required to properly complete the well through these lost circulation zones. The development of new lost circulation control materials which are capable of operating at high temperature has been initiated. In addition, mechanical techniques, such as the use of wellbore patches and concentric drill pipe, are under study. Instruments which can locate and define the width and orientation of fractures are being developed to assist in the design of placement tools to be used with the lost circulation materials.

COMPLETION TECHNOLOGY

The completion of a geothermal well involves the placement of pipe in the well and the attachment of the pipe to the formation. Because of the high thermal stresses induced in the casing when the well is placed on production, it is necessary to obtain very competent bonds between the pipe and the formation. The lack of a good cement bond can lead to casing buckling and collapse and can also allow for corrosion to occur behind the casing. To prevent this, high temperature cements are required. Currently, the Division of Geothermal Energy is funding research directed at developing improved high temperature cements. Most of these cements involve the use of polymers at some stage in their formulation [3]. In addition to this development, analyses of thermally induced stresses and cement placement techniques are being conducted. A study of the failure modes of casing has recently been completed by Completion Technology Company [4]. This study has identified the need for achieving high quality cementing and will be used in formulating the future completion technology development program.

In addition to assuring long-lived, competent completions for the well, the problem of wellbore scaling is being addressed. Several laboratories are investigating chemical techniques for controlling scale. Under the Geothermal Drilling and Completion Program, the development of equipment to remove scale from the wellbore is being conducted. Recently, Daedalean Associates, Inc., has demonstrated the use of high pressure cavitating water jets for removing scale from the pipes in a geothermal test facility [2]. During this test, silica scale was removed from the pipes at nozzle pressures of 8,000-10,000 psi. A preliminary economic analysis of the use of this system indicates that it provides a cheaper method for removing scale than the conventional process of acid presoak followed by wire brushing. In addition, this tool has been tested for wellbore descaling in a flowing geothermal well at shallow depths. The primary difficulty with using the cavitating system for cleaning deep wells is that the wellbore is under pressure, and this reduces the cavitation intensity. In general, it will be necessary to increase the pressure drop across the nozzle to provide for successful operation of the wellbore cleaning system. An investigation of the pressure requirements is presently underway. A field test of the concept is scheduled for June, 1980.

ADVANCED DRILLING AND COMPLETION SYSTEMS

The major emphasis in the Geothermal Drilling and Completion Technology Development Program is currently on the 25% cost reduction goal. In order to achieve the 50% cost reduction goal, it is felt that the problems of lost circulation, drilling fluids, and completion technology must be solved, but in addition, extremely rapid rates of penetration must be achieved. Current estimates are that the penetration rate must be increased by factors of 5 to 10 over the existing rate in order to achieve the goals of the program.

To assist Sandia and the DOE in formulating a program directed at achieving the stated goals, a workshop was held in

January, 1979 with 50 participants from government, universities, and private industry. Many advanced and novel drilling systems were discussed. In view of the program goals, the workshop recommended the development of the following systems [5]: 1) high-speed downhole motors and bits, 2) high pressure water jet drilling used in conjunction with mechanical rock breakage schemes, and 3) percussion drilling systems.

In support of the first system, geothermal turbodrills have been built by Maurer Engineering and are being developed by several other motor manufacturers. The Sandia/DOE program is supporting the design, development, and testing of bearing and seal packages for use on downhole motors in the goethermal environment. The Drilling Research Laboratory has fabricated a bearing and seal tester as well as a very large facility for testing an entire downhole motor under simulated geothermal drilling conditions. Current seal designs are utilizing grafoil and beryllium copper Chevron seals, and the use of non-elastomeric seals in this application is also being investigated. The goal of this program is to develop seals capable of operating for 200 hours under circulating temperatures of 125°C. Several seal designs have been tested [2]. The most promising uses grafoil as the sealing element and beryllium copper as the back-up ring. The maximum lifetime achieved to date is approximately 45 hours. A bearing and seal package designed under this program has been utilized in field testing of the Maurer turbodrill at Los Alamos Scientific Laboratory's Hot Dry Rock experiment in July of 1979. Performance of the turbodrill and bearing and seal package were very satisfactory; however, the bit life was extremely short due to the high rotational speeds involved. Recently, polycrystalline diamond compact bits have been fabricated for testing with high speed downhole motors. Testing of these bits is planned for the fall of 1980.

High pressure water jet drilling has been under study by several different major oil companies for approximately fifteen years. Recently, however, the use of jets which are designed to create cavitation in the flowing fluid have shown the ability to reduce the pressure which is required to cut hard rock. The design and use of these jets in conjunction with conventional roller cone bits and polycrystalline diamond compact bits is presently under study. Hydronautics, Inc., is studying the cavitation phenomena as a function of wellbore pressure [6]. The design of high pressure surface equipment, i.e., 5000-7500 psi, is thought to be necessary to develop a drilling system using the cavitation phenomena. This work will be included as a future activity in the Sandia/DOE program.

Percussion drills have been developed and tested in oil and gas drilling for a number of years. The systems offer little or no improvement in penetration rate in ductile rocks. However, brittle rocks are frequently encountered in geothermal drilling. Percussion hammers offer the potential for improving penetration rates in these types of formations. The use of percussion hammers at high temperatures, however, requires further study. Several hammers have been purchased and evaluated in laboratory testing under simulated geothermal conditions to identify the failure modes in the hammer and the bits [7]. Very high rates of penetration were achieved (70 ft/hr in granite) but hammers operated for only a few minutes at high temperature. The failures are attributable to the use of plastic parts in the air flow path in the hammer. It appears to be relatively easy to design the hammers to operate at high temperature. Modifications are planned. Should these prove successful in laboratory testing, field tests will follow.

CONCLUSION

The Sandia/DOE program is a broadly based technology development program directed at improving techniques for drilling in hostile environments. Specific goals have been set for the program, and private industry is participating with Sandia in conducting the R&D required to meet these goals. The problems of bits, drilling fluids, lost circulation control, and completion technology in high temperature, corrosive environments are being addressed at present. The development of advanced drilling systems will be emphasized in future program activities.

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TABLE I. BIT COMPONENT MATERIALS

Experimental Bits

Timken CBS-600 steel spindles

M-50 steel rollers and balls

M2 steel thrust button

Carboloy 90 gauge row inserts

Type OCR-763

Carboloy 248 bushing

Reed "tube metal" hardfacing

Type OCR-764

M-50 steel bushing

Cabot #1 Mod. stelite hardfacing

Control Bits

Reed Y 73 JA

8620 steel spindles

S-2 solar steel rollers and balls

M-2 steel thrust button

Carboloy 231 inserts

430 steel bushings

Cabot #1 Mod. stelite hardfacing

TABLE II. COMPOSITION OF GEOTHERMAL MUD

Water	1.0 bbl
Sepiolite	15.0 lb
Bentonite	5.0 lb
Brown Coal	20.0 lb
Sodium Polyacrylate	2.5 lb
Sodium Hydroxide	2.0 lb

PROMISING SURFACTANTS FROM INITIAL SCREENING

CHEMICAL TYPE	TRADE NAME	TIME TO 50%/WT. DRAINAGE (MIN.) ORIG.	AGED	DELTA % DRAINAGE	pH ORIG.	DELTA	AGED FOAM CELL STRUCTURE
ALPHA OLEFLIN SULFONATE	SULFRAMIN 14/16 AOS	7.84	7.38	-5.87	5.66	-2.73	GOOD
PROPRIETARY	THERMOFOAM BW-D	8.63	7.16	-17.0	9.74	+0.23	GOOD
ALKYL ARYL SULFONATE	NINEX N-300	8.74	6.95	-20.4	6.65	-0.28	GOOD
ALKYL ARYL POLYETHER SULFONATE	TRITON X-200	5.12	4.94	-3.51	6.62	+0.78	GOOD
COCO BETAINE	VELVETEX BC	6.83	4.90	-28.3	6.94	+1.82	GOOD
ETHOXYLATED FATTY ALCOHOL	WITCONOL SN-90	3.42	4.11	+20.3	5.83	-0.02	GOOD

NOTES: 1. DENSITY 45 ± 5.0 kg/m^3
2. SOLUTION: 1.0%/WT AS RECEIVED
3. INITIAL SCREENING CONTINUING

Sandia Laboratories

DRILLING TECHNOLOGY

Table III. Initial screening tests on high temperature surfactants

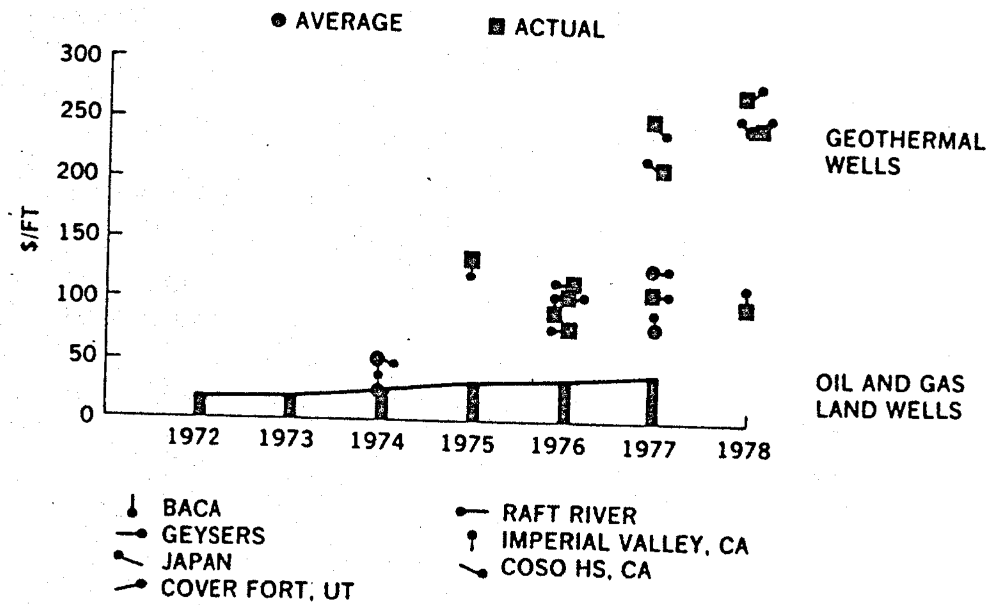

Fig. 1 Trend in well costs

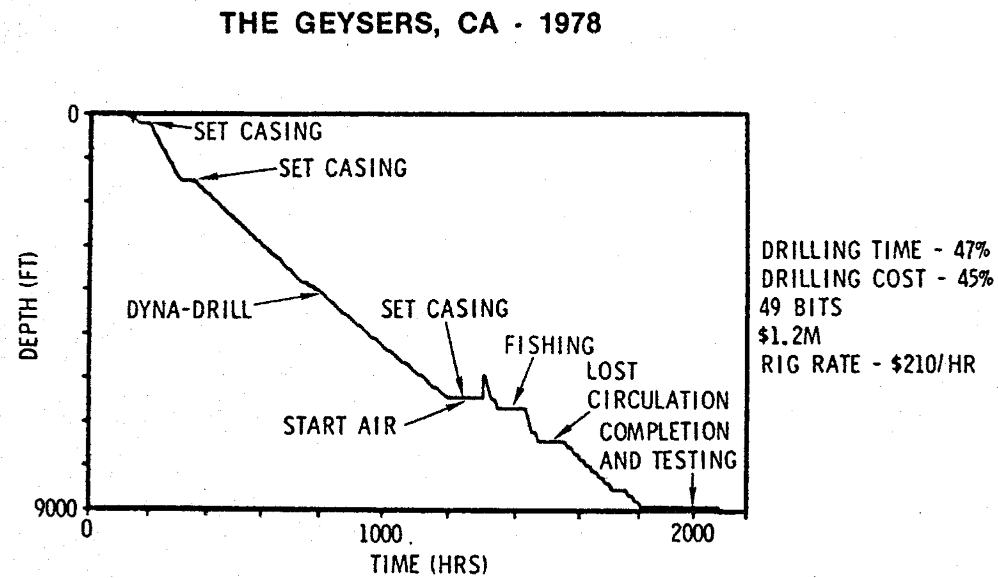

Fig. 2a Drilling operations curve for a Geysers well

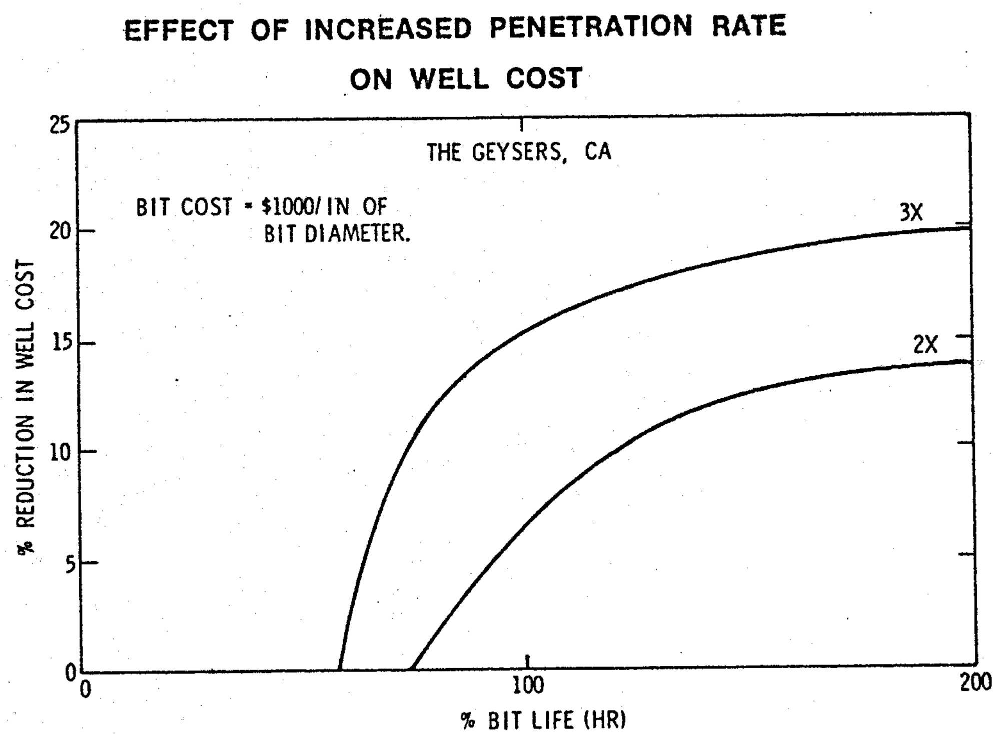

Fig. 2b Effect of increased penetration rate on well cost

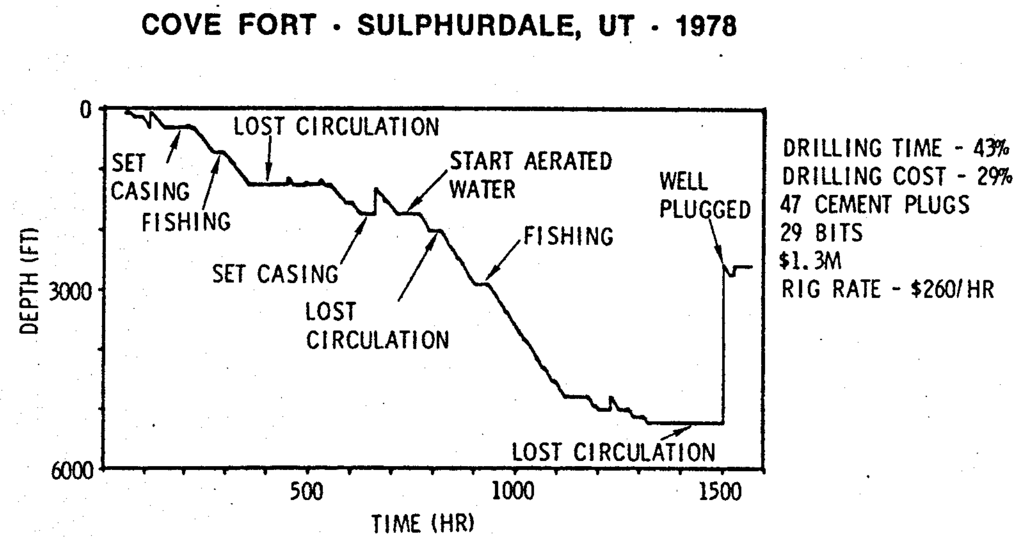

Fig. 3a Drilling operations curve for a Utah well

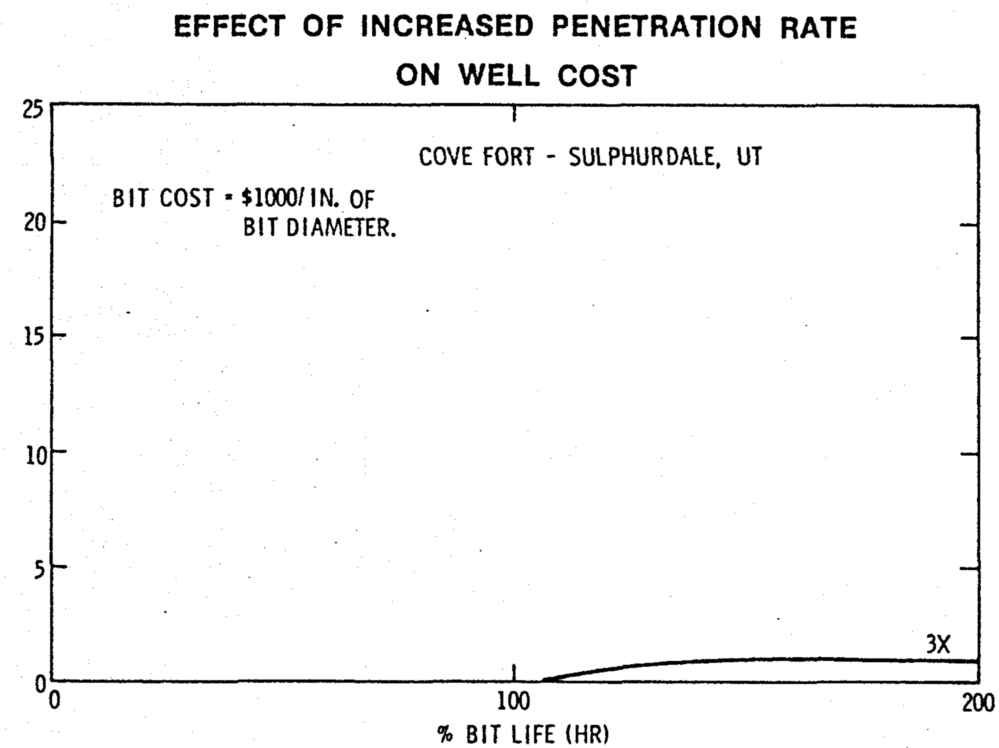

Fig. 3b Effect of increased penetration rate on well cost

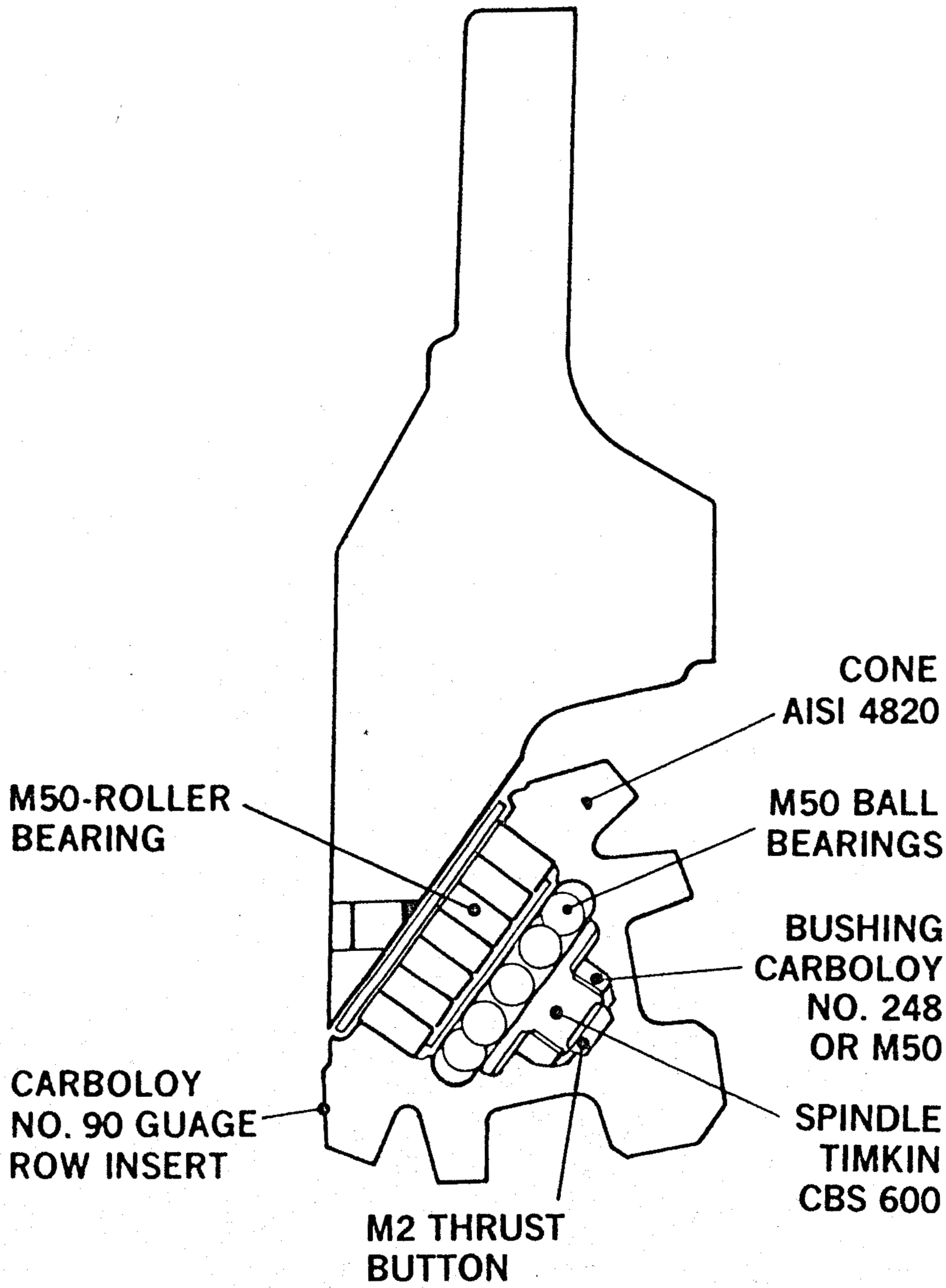

Fig. 4 Geothermal roller cone bit cutaway showing new materials

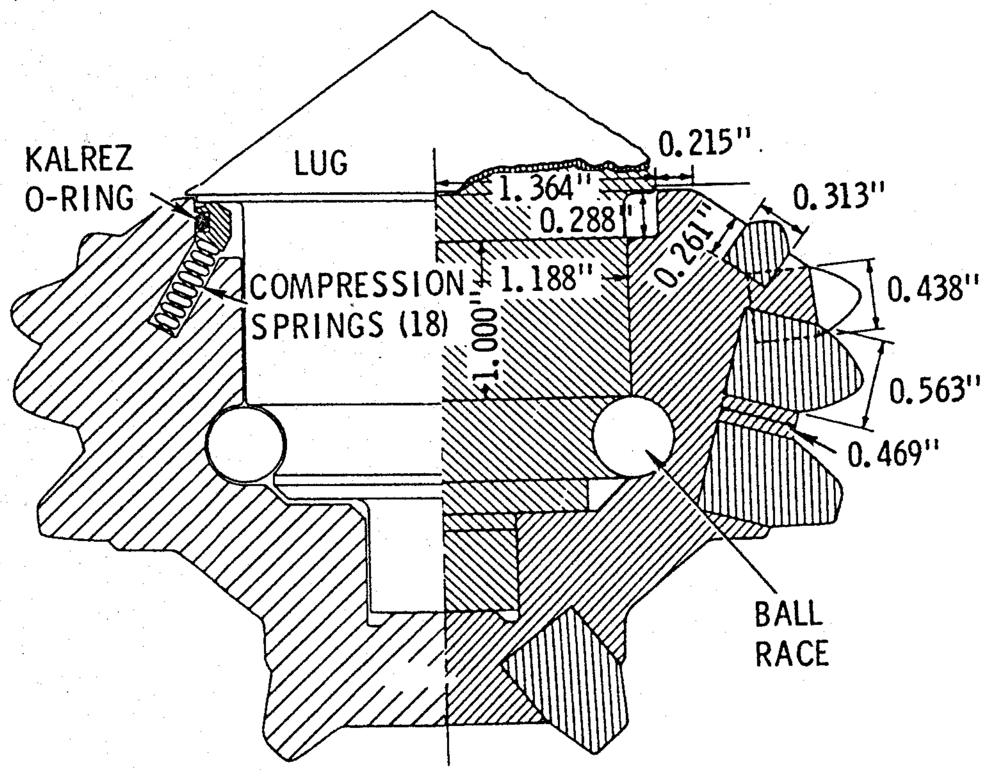

Fig. 5 Geothermal roller cone bit

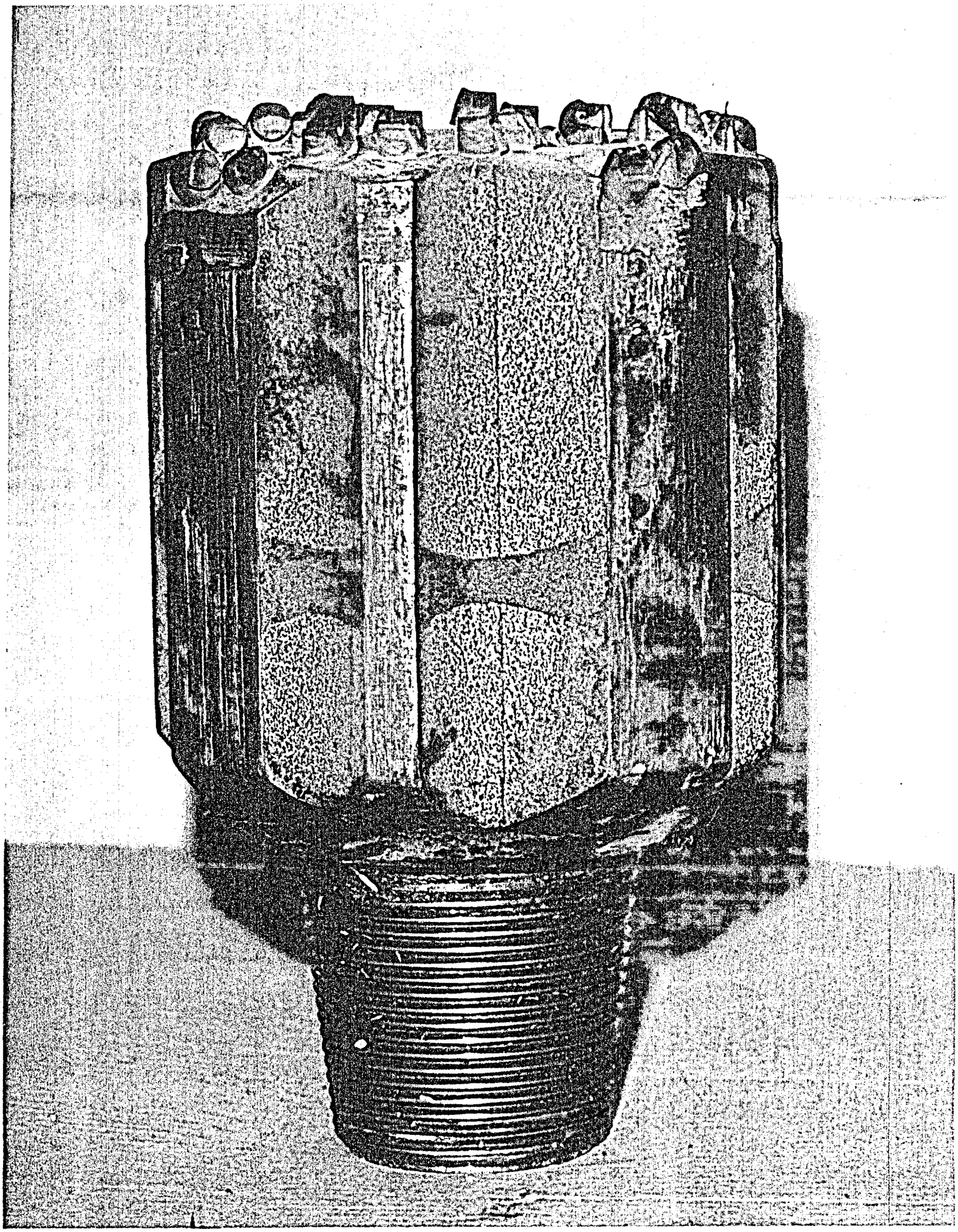

Fig. 7 Bit using stud-mounted PDC

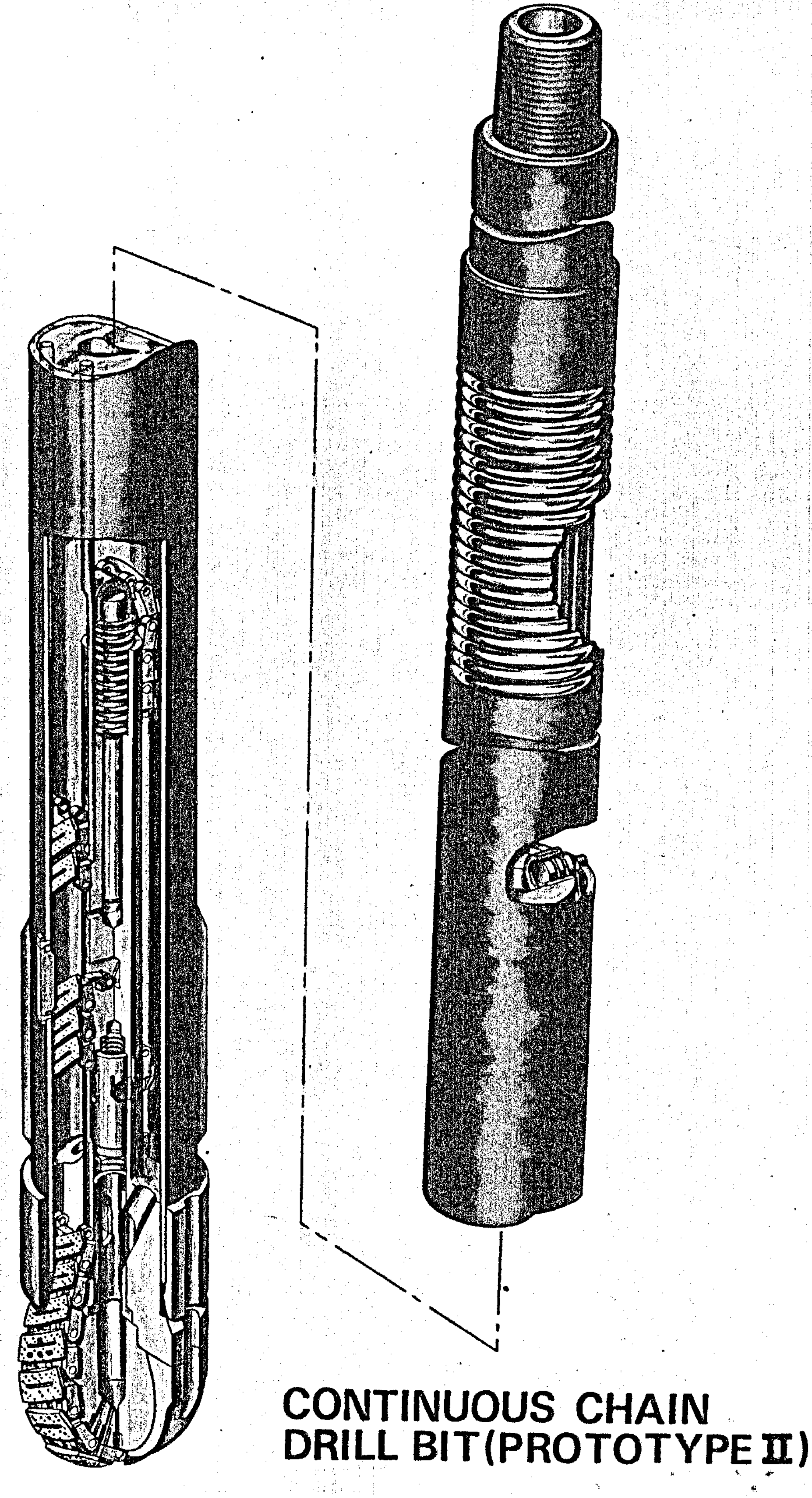

Fig. 8 Artist concept of chain drill

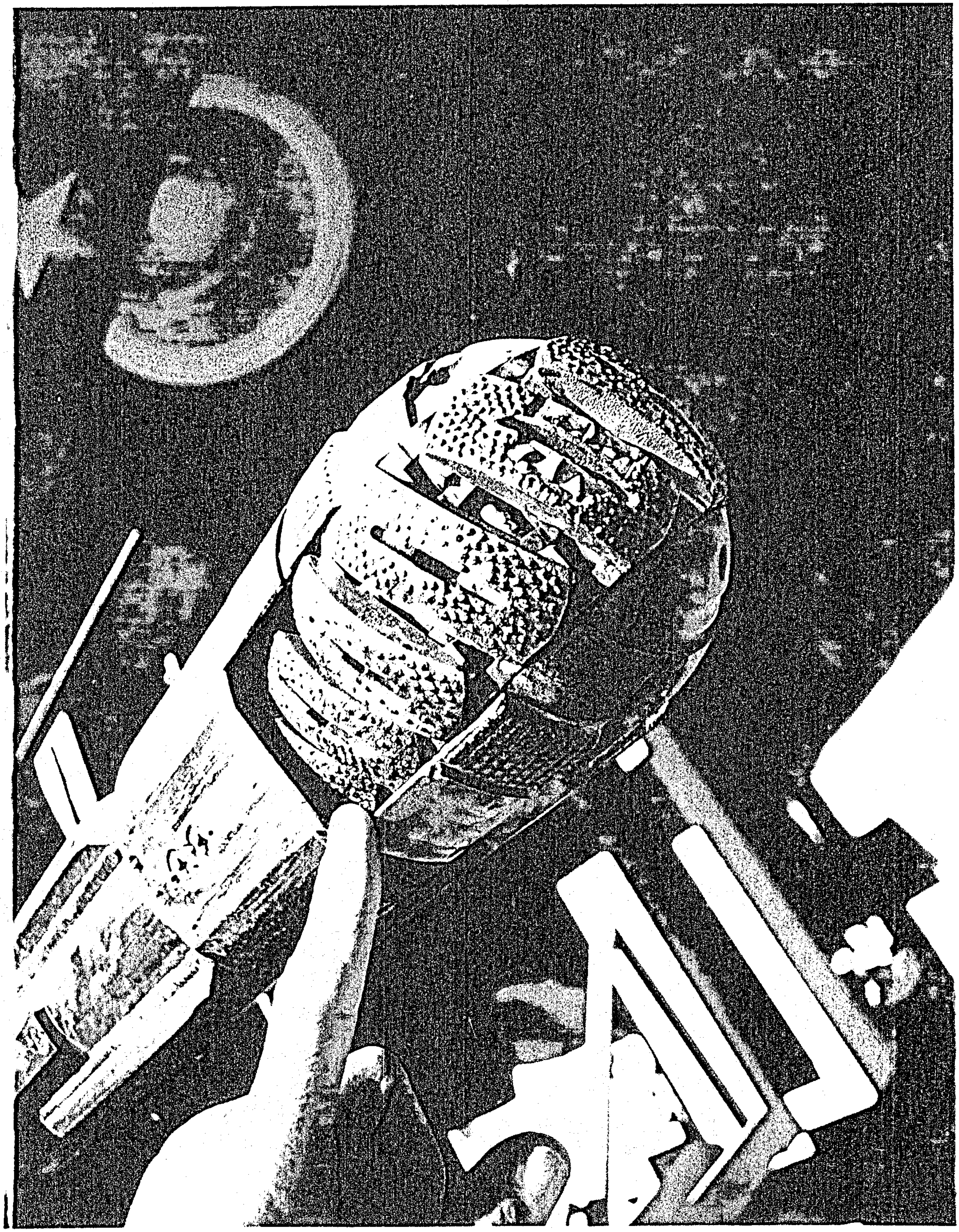

Fig. 9 Head of chain drill