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DEVELOPMENT OF ADVANCED SYNTHETIC-DIAMOND DRILL BITS FOR HARD-ROCK DRILLING

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KEY WORDS
polycrystalline diamond compact (PDC), synthetic-diamond bits, impregnated-diamond bits, thermally stable polycrystalline (TSP), hard-rock drilling, geothermal drilling, single-cutter testing

PROJECT BACKGROUND AND STATUS

If the bit life and penetration rate of bits used in geothermal drilling could both be doubled, a 15% reduction in geothermal well costs would result. Technology development in the field of synthetic-diamond bit design has the potential for providing such improvements. Based on Sandia’s prior history with the development of polycrystalline diamond compact (PDC) bits, Sandia renewed its program in this area in 1992.

A large number of companies were contacted and a comprehensive program proposal on synthetic-diamond drill bit technology development was written. The proposal was presented to the Drilling Engineering Association for review and evaluation in February 1993. After favorable review, the DOE Office of Fossil Energy approved funding for the program under the Natural Gas and Oil Technology Partnership (NGOTP). This funding was received in August 1993. Joint-work, cost-shared contracts were placed with each company, and the program was begun at the end of October 1993. Additional funding was received from the DOE Office of Geothermal Technologies in FY94. Overall funding for the program was shared equally by industry, DOE Fossil Energy, and DOE Geothermal in FY95. The NGOTP funding was depleted in FY95, but funding by DOE Geothermal has continued.

At the beginning of the program, it was anticipated that the initial effort would be completed within two years. Due to a variety of reasons (less funding than expected, the need to build new testing equipment, mergers and reorganizations of the companies) the projects were not completed in two years. It is now expected that an additional two years will be required to complete the ongoing, cost-shared projects and that additional work will be identified at the end of that period to further develop promising technologies.

PROJECT OBJECTIVES

The hard, abrasive, and fractured rock formations drilled to access geothermal reservoirs are generally considered beyond the capabilities of current synthetic-diamond bit technology. However, the inherent cutting efficiency and lack of moving parts of synthetic-diamond bits make them an ideal prospect for future increases in penetration rate and bit life in hard formations. The hard-rock drill bit program is a national laboratory-industry cooperative research and development program aimed at developing synthetic-diamond drill bits capable of economically drilling into hard-rock formations.

Technical Objectives
Reduce geothermal drilling costs by increasing penetration rates and bit life over those attainable with current roller-cone bits;

Extend the range of application of synthetic-diamond bit technology into harder formations;

Expected Outcomes

- Develop an optimized PDC claw cutter design combining the abrasion resistance of diamond and the impact resistance of tungsten carbide.
- Develop advanced thermally-stable polycrystalline (TSP) drill bits capable of handling the higher temperatures associated with hard-rock geothermal drilling.
- Optimize a Track-Set PDC bit, effectively reducing lateral vibrations and impacts in hard rock.
- Develop advanced impregnated-diamond bits utilizing new diamond coating technology and specifically developed to increase penetration rates in hard rock.

APPROACH

Several drill bit and cutter companies have teamed with Sandia National Laboratories to work on four different projects as part of a cooperative effort to advance the state of the art in synthetic-diamond drill bit design and manufacture. Each project explores a different approach to synthetic-diamond cutter and bit design and builds on each respective companies’ capabilities and current product interests. Sandia’s role is to assure integration of the individual projects into a coherent program and to provide unique testing and analytical capabilities where needed.

Research and development is being conducted in the design of PDC cutters and bits, impregnated-diamond bits, and thermally-stable polycrystalline (TSP) bits. The objective of each project is to develop drill cutters and bits that drill faster and last longer in hard-rock formations. The development of these hard-rock bits would mean lower-cost and faster drilling in natural gas, oil, and geothermal reservoirs.

The companies that have have teamed together with Sandia to work on these projects are listed below with the corresponding projects.

- **Dennis Tool Company** is optimizing the design of the claw cutter by combining single-cutter wear testing with thermal and stress numerical modeling. The project will result in a claw cutter that has been optimized for hard rock drilling.

- **Security DBS** is optimizing the design of their Track-Set drill bit. A variety of cutter tests will be performed to analyze the track-set cutting structure. The results of the tests will be utilized in a force/wear bit model for Track-Set bit design.

- **Hughes Christensen Company** is improving impregnated-diamond bit performance in hard rock. A mechanistic drilling model for impregnated bits is being developed with the aid of laboratory drilling tests. The final model will be used to develop bit designs for specific hard-rock
applications.

- **Maurer Engineering and Slimdril International** are improving the design of TSP drill bits in hard rock by using results from single-cutter wear testing to design and fabricate three different TSP bits. The bits will be evaluated both in the laboratory and in the field.

- **Amoco Production Research** participates in the program by providing expertise related to field testing and use of PDC bits and by making available their Catoosa Test Facility for use in evaluating concepts related to hard-rock synthetic-diamond bit design.

Sandia National Laboratories provides technical program management, comparative cutter wear testing, linear testing of cutting force and rock/cutter interaction, and numerical thermal and mechanical stress analysis.

**RESEARCH RESULTS**

Work conducted on each project in FY96 is described below. This work is further described in a conference paper written in FY95 and presented in FY96.

**Claw Cutter Optimization**

A parametric numerical analysis of claw cutter design was continued. Multiple claw cutter geometries employing various groove widths, groove spacings, groove depths, and diamond thicknesses were analyzed with a numerical stress code to determine cutter stresses under typical operating conditions. The analysis was divided into two steps, thermal and mechanical stress computations. The thermal stress calculations were completed in FY95, and the mechanical stress calculations were completed in FY96. The final step in the process was to superimpose the thermal and mechanical stresses to determine the total stresses in each cutter configuration. This allowed the optimal configuration based on minimal stresses to be identified. The results now await verification with laboratory wear tests.

These wear tests are being conducted in the Cutter Wear Test Facility, which became operational in FY96. This facility consists of a laboratory drilling machine designed to efficiently drill multiple holes in a large rock sample for comparative wear testing. The test cutter is mounted on a coring bit and experiences cutter interaction similar to that experienced by a cutter on an actual drill bit. Cutter speeds, forces, and a fluid environment typical of those that exist in downhole drilling are possible to duplicate in this facility. Problems with the facility's hydraulic system were overcome, and baseline cutter wear rates were established with a conventional PDC cutter. The facility was found to be capable of producing very repeatable results under realistic rock cutting conditions in hard rock. Claw cutters of various geometries are now being tested to verify the results of the numerical modeling.

**Track-Set Bit Optimization**

An initial matrix of linear, single-cutter tests was completed in FY96 to support this project. A detailed compilation of data from these tests was transmitted to the industry partner, Security DBS, to facilitate advanced design efforts—including modeling of Track-Set bit configurations.

For the test program, a three-axis dynamometer yielded continuous measurements of the orthogonal penetration, drag, and side forces on a cutter as it scored a rock specimen. Parametric studies probed
the dependence of the force components on rock type and cutter configuration and wear. Three different rocks were used (Sierra White Granite, Tennessee Marble, and Berea Sandstone) to represent a wide range of rock strength and abrasive characteristics.

For each of these materials, force data were obtained using three different test methods: (1) backrake-angle/siderake-angle tests that characterized the variation of cutter forces with changes in the backrake angle and siderake angle of a sharp, chamfered PDC cutter that was operated at selected cutting depths in newly surfaced rock; (2) engagement-angle tests that used a worn PDC cutter to incrementally deepen the same groove, thereby quantifying the dependence of cutter forces on the "engagement" angle defined by the rock contact arc along the cutter periphery; and, (3) restoration-force tests that determined the forces involved during cuts where a previously generated, full-engagement-angle (180°) groove was incrementally widened by the same worn PDC cutter that initially created it. The latest test results confirmed previous observations of significant lateral stabilization of the cutter by the groove, thereby validating the Track-Set bit concept. Limited backrake-angle/siderake-angle test data were also acquired for prototype boron sub-oxide cutters that were supplied by the New Mexico Institute of Mining and Technology for evaluation.

**TSP Bit Optimization**

The Cutter Wear Test Facility was used in FY96 to test another disk-shaped TSP cutter supplied by the industry partner, Maurer Engineering. The cutter was supplied to Maurer by a proprietary source, who wished to remain anonymous because of the experimental nature of the cutter. In fact, the manufacturer was not confident in the cutter's wear resistance, and the test results in the CWTF bore out this lack of confidence. Unlike the TSP disk cutter tested in FY95 using a vertical mill instead of the CWTF, this cutter experienced much higher wear rates than a conventional PDC cutter. This demonstrates that results obtained with one cutter cannot necessarily be generalized to all cutters of the same general type. Further testing of TSP cutters in the CWTF is planned for FY97.

**Impregnated-Diamond Bit Optimization**

Under this project, hundreds of feet of rock have been drilled in a laboratory drilling machine at Hughes Christensen. A wide range of matrix materials, diamond grit size, diamond grade, and diamond concentrations have been investigated. Bit wear rates were measured in several different rock types considered to be typical target formations for this type of bit. Bit wear rates are being used to identify bit characteristics that lead to reduced bit wear. A large volume of data has been gathered that will help optimize impregnated-diamond bit design for a given rock type. Most of the experimental work was completed in FY96. A team of researchers has now been assembled at Hughes Christensen to use this data to improve their impregnated bit design process.

**FUTURE PLANS**

The contracts with the industry partners have been extended for two additional years. This will allow the work outlined in the original program plan to be completed. At that time, the projects will be evaluated to determine the bit design approaches that have the greatest potential for improving hard-rock drilling. Additional work may then be initiated to further advance the technology related to those approaches.
INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

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