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**PROGRAM PLAN FOR THE DEVELOPMENT OF
ADVANCED SYNTHETIC-DIAMOND DRILL BITS
FOR HARD-ROCK DRILLING**

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ABSTRACT

The advanced synthetic-diamond drill bit project is a cooperative national lab-industry research program aimed at developing synthetic-diamond drill bits capable of drilling into hard-rock formations. The hard, abrasive, and fractured rock formations drilled to access geothermal reservoirs are generally considered beyond the capabilities of current polycrystalline diamond compact (PDC) bit technology. Roller bits, which are generally used for this application, suffer from inherently low penetration rates, accelerated bit wear, and often severe loss of hole gauge and roller bearing failure. Predictions show that doubling penetration rate and bit life in the drilling of a geothermal well would result in a 15% reduction in the overall well cost.

Eight companies have teamed with Sandia Labs to work on five projects as part of a cooperative effort to advance the state of the art in synthetic-diamond drill bit design and manufacture. The eight companies are: DBS (a Baroid Company), Dennis Tool Company, Hughes Christensen Company, Maurer Engineering, Megadiamond, Security Diamond Products, Slimdril International, and Smith International. The objective of each project is to develop advanced bit technology that results in new commercial products with longer bit life and higher penetration rates in hard formations. Each project explores a different approach to synthetic-diamond cutter and bit design and, consequently, uses different approaches to developing the technology. Each of these approaches builds on the 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. One additional company, Amoco Production Research, will provide synthetic-diamond drill bit research expertise and field testing services for each project in the program.

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Representatives of each of the companies included in this program did a great deal of work in directing the program and defining the scope of the research; without them, this program would not be possible.

TABLE OF CONTENTS

I. BACKGROUND, MOTIVATION, AND OBJECTIVE	1
A. Need for Exploration and Development	1
B. Current Synthetic-Diamond Bit Capabilities and Limitations	2
1. Polycrystalline Diamond Compact (PDC) Bits.	2
2. Impregnated Diamond Drill Bits.	4
3. Thermally Stable Polycrystalline (TSP) Drill Bits	5
C. Technical Approach of the Program.	5
D. Impact of the Program	6
II. SUMMARY OF FY92 WORK	7
A. Industry Discussions and Program Development	7
B. Scoping Study	8
III. PLANNED PROGRAM FOR 1993-95	9
A. Advanced PDC Cutter Development and Bit Design with Smith International and Megadiamond	9
1. Project Description	9
2. Statement of Work	10
3. Planned Budget	13
4. Schedule	15
B. Optimization of Track-Set Cutting Structure with Security Diamond Products	16
1. Project Description	16
2. Statement of Work	16
3. Planned Budget	18
4. Schedule	20
C. Claw Cutter Optimization with Dennis Tool Company and DBS, a Baroid Company	21
1. Project Description	21
2. Statement of Work	21
3. Planned Budget	23
4. Schedule	25
D. Optimization of Impregnated Diamond Drill Bits with Hughes Christensen	26
1. Project Description	26
2. Statement of Work	26
3. Planned Budget	28
4. Schedule	29
E. Advanced TSP Drill Bit Development with Maurer Engineering and Slimdril International	30
1. Project Description	30
2. Statement of Work	30

TABLE OF CONTENTS (cont.)

3. Planned Budget	33
4. Schedule	34
F. Concept-Development Field Testing with.....	35
Amoco Production Research	
1. Project Description	35
2. Statement of Work.....	36
3. Planned Budget	37
4. Schedule	38
IV. BUDGET SUMMARY FOR 1993-95	39
A. Budget for Sandia Work	39
B. Summary of Total Budget for 1993-95	41
V. REFERENCES	42

I. BACKGROUND, MOTIVATION, AND OBJECTIVE

A. Need for Exploration and Development

In spite of the increased exploration efficiency resulting from improvements in technologies such as seismic analysis and measurement-while-drilling, domestic oil production has outstripped reserves addition by an average of one billion barrels per year since 1977. Total domestic oil reserves have fallen almost every year since 1970, and it is likely that imports will continue to provide at least one-half our total consumption. It is clear that a decline in the domestic oil industry has a negative impact on national issues ranging from balance-of-payments deficit to fuel supply security in times of crisis.

The ability of the geothermal industry to contribute to the nation's energy supply is also dependent on drilling to prove and access available reserves. Well costs represent 35-50% of the total costs of a typical geothermal power project. The potential of geothermal power in this country will not be fully realized unless additional significant reserves can be proven and accessed through a vigorous exploration and development program.

Without addressing the political and institutional issues affecting the price of petroleum and geothermal power, an effective contribution to both industries is the development of technology that encourages domestic exploration and development by lowering the costs of drilling, completing, and producing petroleum and geothermal wells. The maturity of United States oil and gas production means that future petroleum exploration will almost certainly be in deeper, harder, hotter formations than have been common in the past. Similarly, geothermal resources are almost always located in or beneath hard, abrasive, and fractured rock formations. Consequently, this program addresses technology improvements for reducing costs associated with drilling hard formations.

A recent study by Maurer Engineering [1] found that about 70% of the total time associated with drilling a deep (>14,700-ft) gas well is spent drilling ahead (i.e., "turning to the right") and tripping. The bit penetration rate and bit life, therefore, have major impacts on well costs. If both penetration rate and bit life could be doubled, an average 20% reduction in drilling costs would result. A study by Sandia National Laboratories reached similar conclusions for geothermal drilling. A generic well-cost model was used to examine the cost impacts of various potential technology improvements. A 15% reduction in well costs was predicted to result from a hypothetical doubling of bit life and penetration rate. Technology development in the field of synthetic-diamond bit design has the potential for providing such improvements in bit performance in both petroleum and geothermal hard-rock drilling.

In FY92, \$105,000 were allocated to Sandia through the DOE-sponsored Oil Recovery Technology Partnership to initiate work on the development of advanced synthetic-diamond drill bits for hard-rock applications. This project was initiated for several reasons: (1) a successful synthetic-diamond, hard-rock drill bit would have a sizable effect on drilling costs in many applications; (2) there is significant enthusiasm

in the drilling industry for government-industry cooperation in this area; and (3) the project would build on an extensive body of PDC bit research previously conducted by Sandia in support of the geothermal energy program.

The thrust of the first-year effort in this area was to determine industry interest in a joint development program, to solicit ideas and plans for technical work, and to develop a comprehensive program plan for a joint development program. This document is a result of that effort.

B. Current Synthetic-Diamond Bit Capabilities and Limitations

The economics of drilling for petroleum or geothermal reserves is a strong function of the types of drill bit selected for the job. PDC bits, for example, often account for over \$100,000 of savings per bit run in appropriate rock formations. Achieving a lower cost-per-foot is often a matter of achieving the correct balance between the instantaneous penetration rate and bit life.

The maximum rate of penetration for a given bit design and rock type is primarily a function of the size of the cutters on the bit. Larger cutters tend to be more efficient and result in greater penetration rates, in general. Bit life, on the other hand, depends primarily on the strength, impact-resistance, and abrasion-resistance of the cutter materials. Discussed below are some of the parameters that affect the penetration rate and life of the various types of synthetic-diamond drill bits.

1. Polycrystalline Diamond Compact (PDC) Bits

Bits with large (e.g., 1/2" diameter) PDC cutters are widely used by the oil and gas industry in medium-soft to medium-hard formations, primarily for drilling production wells where the lithology is reasonably well known. In these circumstances PDC bits are very effective because their rock-cutting action is inherently efficient, giving them much higher rates of penetration (ROP) than comparable roller bits. If the cutters stay intact, the bits' lack of moving parts also contributes to long life, reducing bit replacements and trips. These advantages have, in many case histories, more than offset the higher procurement cost of PDC bits and have led to an increasing PDC market share in the oil patch.

The corresponding disadvantage of PDC bits is that cutter degradation can lead to sudden and complete bit failure. Experience shows that this kind of failure usually occurs in hard and/or fractured rock, such as that typically encountered in geothermal drilling and frequently found as stringers in either exploration or infill petroleum drilling. Bit replacement, especially if unexpected, is expensive in terms of tools and trips, so companies often forego the advantages of drilling with PDC bits in geothermal drilling and in petroleum drilling where hard stringers may be encountered. As a result PDC bits have not found significant application in geothermal drilling or in petroleum exploratory drilling.

When drilling hard, fractured formations with PDCs there are two general modes of cutter wear and failure: abrasive and impact. Thermally accelerated abrasive wear occurs in hard-rock drilling when cutter temperatures exceed approximately 350°C [2]. Extreme thermal stresses, caused by temperature gradients and differential thermal expansion between the diamond and the tungsten carbide compact, greatly exacerbate normal abrasive wear mechanisms in addition to causing tensile cracking of the microstructure. At temperatures above 650°C, differential thermal expansion between the diamond grains and the entrapped cobalt in the PDC causes further microfracturing of the diamond structure. Improved cutter materials and processing techniques are necessary to overcome the thermal limitations of PDC cutters in hard-rock applications.

Impact failure of PDC cutters is caused by dynamic loading resulting from fractures, hard-rock stringers, or vibration due to unbalanced forces on the bit. Proper cutter placement can force-balance the bit and eliminate much of the bit-induced vibration [3]. Smith International employs a computer design code developed at Sandia to achieve this force balancing as one of the design features incorporated into some of their bits.

Amoco Production Research has developed and licensed methodology for designing anti-whirl bits that are also effective in eliminating most bit-induced vibration [4]. Amoco's approach entails placement of the cutters such that the net cutter force acting on the bit has a significant side component. This bit side force is directed toward a low-friction pad on the side of the bit, which balances the bit and reduces vibration during drilling.

Security Diamond Products is developing track-set technology as a technique for reducing bit vibration in hard rock drilling [5]. The track-set concept employs redundant cutters placed at specific radial locations on the bit such that each track or groove in the bottom of the borehole is much deeper than is normal with conventional PDC bit designs. In hard rock, such deep tracks provide a significant stabilizing effect on cutters by preventing or retarding lateral movement and vibration.

In addition to improved bit design techniques to further prevent and mitigate downhole vibration, improvements in cutter designs and materials are needed to impart inherent hard-rock cutting capability to PDC cutters. Significant strides toward cutters with greater impact resistance have been made in recent years with the introduction of claw cutters by DBS and Dennis Tool Company [6] and the introduction of dome cutters by Smith International and Megadiamond [7].

The claw cutter differs from conventional PDC cutters in that the tungsten carbide substrate to which the diamond layer is attached is grooved before being placed on top of the polycrystalline diamond powder in the diamond press. This produces a sintered product in which diamond fills the grooves in the tungsten carbide substrate, resulting in alternating ribs of tungsten carbide and diamond that run parallel to the cutting direction. During cutting, the tungsten carbide ribs wear faster than the diamond ribs, resulting in diamond "claws" that impose significant stress concentration on the rock surface and maintain rapid rock penetration as the cutters wear. The layering of tungsten carbide and diamond also improves the shock

resistance of the cutters several-fold and has been shown to improve bit life in harder rock formations.

Dome cutters employ a convex-shaped diamond surface on the leading face of the cutter. This configuration creates an effective rake angle that is variable with the depth of cut, allowing smaller effective rake in soft rocks at high penetration rates and greater effective rake in hard rocks at low penetration rates. This results in effective rake angles that more closely match the optimal rake angles required for increased cutting efficiency and cutter life in various rock types. Dome cutters also provide some degree of side rake, which has been shown to be beneficial for improved bottomhole cleaning and faster penetration. Improved shock resistance with dome cutters has been obtained by employing transition layers between the PDC face and the tungsten carbide compact. Field testing has demonstrated that dome cutters successfully drill much harder rock formations than are possible with conventional PDC cutters.

A major goal of this program is to build on the potential demonstrated by these new types of PDC cutters and advanced bit design concepts to further improve their hard-rock drilling capabilities. This will be done by conducting fundamental studies to better understand the rock and cutter failure modes prevalent in hard-rock drilling and by optimizing cutter materials and bit designs through analytical and experimental study.

2. Impregnated Diamond Drill Bits

Impregnated diamond bits are routinely used in drilling very hard rocks where roller bits and PDC bits have short lifetimes. This includes a large fraction of boreholes drilled with slim-hole coring rigs for minerals exploration and scientific study of geothermal systems. Slim-hole drilling techniques are also increasingly being studied, developed, and used for petroleum and geothermal exploration.

An impregnated bit consists of numerous small diamonds, either natural or synthetic, that are imbedded in a metal matrix. The matrix is designed to wear away, exposing the diamonds that cut the rock. The cutting loads are distributed over many cutting elements, thereby maintaining individual diamond loads at a low level. In extremely hard formations, where high temperatures can develop at the cutter-rock interface, the high-temperature capability of pure diamond gives impregnated bits their advantage over PDC bits. Furthermore, when a diamond does fracture or fall out, it is quickly replaced by another diamond that is exposed by the wearing matrix.

Because of the small exposure of the diamond cutters, however, impregnated bits inherently drill slower than PDC and roller bits. Penetration rates below 5 ft/hr are common with impregnated bits. If the imbedded diamonds could be given greater exposure in the balance between matrix wear and diamond retention, greater depths of cut and higher penetration rates would result.

New diamond coating technology developed by Hughes Christensen Company for surface-set diamond bits has the potential for improving diamond retention and allowing greater diamond exposure [8]. A goal of the program is to apply this

technology to impregnated diamond bits and to develop a technique for optimizing impregnated diamond drill bit design for any specified hard-rock environment.

3. Thermally Stable Polycrystalline (TSP) Drill Bits

Like PDC cutters, thermally stable polycrystalline (TSP) cutters are a sintered diamond product in which cobalt is used as a catalyst to help bond together individual diamond grains into a larger diamond structure. TSP is made when the cobalt is leached from the diamond structure, thereby eliminating the stresses caused by differential thermal expansion between the diamond and the cobalt. As a result, TSP cutters are thermally stable to at least 1200°C and are therefore less susceptible to the thermal damage prevalent in hard-rock drilling.

Without the cobalt in the diamond structure of the TSP, however, it has not been possible to bond the diamond to a tungsten carbide substrate for structural support and impact resistance. Furthermore, the cobalt leaching process embrittles the diamond structure, thereby making it more susceptible to mechanical damage. Consequently, TSP cutters are inherently smaller than PDC cutters, and TSP bits generally drill at much lower penetration rates.

The tradeoff between bit life and penetration rate with TSP bits in hard rock has not yet been fully explored. Maurer Engineering and Slimdril International have recently completed a laboratory study for the Gas Research Institute that demonstrated dramatic improvements in bit performance using larger TSP cutters than had previously been tested [9]. A goal of the program is to evaluate several design options for hard-rock TSP bits and to determine the potential for using such bits to reduce drilling costs in exploratory drilling.

C. Technical Approach of the Program

Eight drill bit companies have teamed together to conduct five projects as part of a cooperative national laboratory-industry effort to advance the state of the art in synthetic-diamond drill bit design and manufacture. These projects comprise a variety of approaches to bit design and, consequently, a variety of approaches to developing the technology. Each of these approaches builds on the respective companies' capabilities and current product interests. In addition, Amoco Production Research will participate in the program by providing field testing services and expertise related to PDC bit design and field operation. Sandia's task is to assure integration of the individual projects into a coherent program and to provide unique testing and analytical capabilities where needed.

The state of the art is different in each branch of synthetic-diamond bit technology being pursued in this program. In the case of impregnated diamond and TSP bits, specific technologies and designs are being developed, and the most direct method of evaluating such technologies and designs is to build and test drill bits in the laboratory. In the case of claw-cutter PDC bits, optimization of specific cutter configurations can best be accomplished with numerical stress modeling and single-

cutter testing to characterize cutter performance and wear. Single-cutter tests and enhancement of cutter force and wear models are necessary and will be undertaken to optimize the design of track-set cutting structures. To further advance the state of the art in dome cutters and transition layers, it has been concluded that a more fundamental understanding of rock and cutter failure mechanisms in hard rock drilling is necessary, and appropriate studies are planned.

For the purposes of program management and funding, the work conducted by the bit manufacturers will be performed under contract to Sandia. Common features of each study include the following:

- Each contractor's first task will be to establish a performance benchmark based on current hard-rock drilling capabilities. This data will be used to measure each contractor's progress under this program.
- Each contractor will target cutter and bit designs toward a specific set of hard rock types. To assure some commonality in the program, the contractors will consult with Sandia in the selection of these rock types.
- Promising designs will be tested in the laboratory and, ultimately, in the field by drilling the selected rock types. Data collected in drilling tests will allow a comparison of the performance of these designs with the benchmarks. Such data will assist the bit manufacturers to commercialize the new bits developed under this program.
- Each contractor will be provided up to four days of field testing at Amoco's Catoosa Test Facility. These field tests may serve a variety of functions, such as providing information about the downhole drilling environment, evaluating bit design concepts, or benchmarking bit performance. Field test plans will be developed by Sandia and each contractor. Amoco's expertise in PDC bit field applications will be used to evaluate and help optimize these test plans.
- A final report summarizing the results of each project will be written by each contractor. Although details related to specific bit designs, manufacturing processes, and other aspects will remain proprietary to the respective companies, much of the information developed under this program will become part of the open literature.

In addition to program management and consultation with the contractors, Sandia will also perform several research tasks. These tasks include single-cutter testing and wear evaluation, cutter thermal and stress analyses, rock properties measurements, and rock-cutter interaction studies. Detailed descriptions of the four projects, including Sandia's tasks, are included in Section III of this program plan.

D. Impact of the Program

The program will serve as a catalyst for the development of hard-rock, synthetic-diamond drill bits. Because of the scarcity of research funds in the drilling industry,

improvements to existing bit technology would evolve slowly without the planned DOE support. The support would provide targeted funding for hard-rock drilling research that would otherwise be unavailable. It would also make the technical resources available at Sandia National Laboratories available to the bit companies.

The new technologies and commercial bits that result from this work will help the U. S. diamond-bit industry maintain its leadership position in worldwide bit technology and sales. If the program is successful in developing bits capable of drilling harder rock, significant reductions in exploration and development costs are expected in both the petroleum and geothermal industries worldwide.

II. SUMMARY OF FY92 WORK

The primary objective of the first year's effort was to define the research, development, testing, and evaluation necessary to develop advanced synthetic-diamond drill bits for hard rock applications. In order to best accomplish this objective, two tasks were initiated:

1. Discussions with various bit design, manufacturing, and operating companies to help determine general industry needs and interest in participating in joint development efforts with the Department of Energy and Sandia National Laboratories; and
2. A technical scoping study to assist in defining appropriate directions for future work.

A. Industry Discussions and Program Development

During the course of the first year's work, the following companies and institutions were contacted:

Amoco Production Research
Chevron Drilling Services
DBS, a Baroid Company
Dennis Tool Company
Exxon Production Research
Hughes Christensen Company
Hycalog
Longyear Company
Maurer Engineering/Slimdril International
Security Diamond Products
Smith International/Megadiamond
Terra Tek
Reed Tool Company
University of California-Berkeley

Follow-on discussions were initiated with those indicating particular interest. The primary purpose of these discussions was to determine the current state of synthetic-diamond drill bit technology, whether there is an industry need for improved hard-rock bits, and the extent of industry interest in participating in a joint development effort with DOE and Sandia.

The promise of higher penetration rates and longer bit life has fueled continuous interest in the industry in the development of advanced synthetic-diamond bits for harder formations. This interest is demonstrated by the number of ongoing industry programs in bit design and development. Many of the parties contacted during these discussions have research capabilities and interests in improved synthetic-diamond drill bits for harder formations. Research budgets, however, have been extremely limited due to the downturn in drilling worldwide.

The enthusiasm for DOE support of their bit development programs is demonstrated by the willingness of a number of companies to match DOE funds with internal funds and in-kind services. The general consensus among the companies is that previous PDC research conducted by Sandia under DOE sponsorship has been extremely useful to the industry, and they are eager to participate with Sandia in a renewed research effort in this area.

It is also generally felt that joint DOE/industry developments would work best as individual partnerships, as opposed to development led by a consortium. Some of the preference for partnerships stems from concerns over proprietary information. These concerns were expressed in more than one discussion. Most companies are reluctant to enter into an agreement that may require them to reveal sensitive data and information concerning design practices or manufacturing processes. The willingness to work as competing companies toward a common objective, however, is very encouraging from both the technical and programmatic standpoints.

Individual project plans were received from each of the six industry teams. Discussions were held between Sandia and company representatives to develop the necessary details for inclusion in this document as a comprehensive program plan. Information related to other companies' plans was not shared among the companies by Sandia until the details were agreed upon by each respective company.

B. Scoping Study

In parallel with the industry discussions and program development, a technical study to characterize the claw cutter and to maximize its efficiency in hard-rock drilling was initiated with Dennis Tool Company and DBS. This study required Dennis Tool to supply claw cutters in various configurations, Sandia to perform single-cutter testing and wear evaluation, and DBS to build and test core bits employing claw cutters.

Because of contracting difficulties, the initiation of this study was delayed until September, 1992. A single-cutter testing facility has been developed, and several tests of baseline PDC cutters have been completed. However, single-cutter testing of

the claw cutters has not yet been completed. Consequently, the study was expanded in scope and magnitude and included as part of the program for 1993-95.

III. PLANNED PROGRAM FOR 1993-95

A. Advanced PDC Cutter Development and Bit Design with Smith International and Megadiamond

1. Project Description

Smith International and Megadiamond plan a multi-year program to study fundamental rock failure and bit wear mechanisms in hard rock, then build upon the findings to design, fabricate, and test hard-rock PDC cutters and bits. Based upon the success of their domed cutters in rocks harder than those normally drilled with PDC cutters, Smith and Megadiamond believe that greater understanding of hard-rock drilling mechanisms is necessary to take full advantage of the hardness and abrasion resistance of synthetic diamond.

Smith and Megadiamond will team with Sandia to perform the following:

- Define and characterize hard-rock formations that represent a drilling challenge for current PDC bit technology, including a determination of engineering properties and definition of appropriate model rocks for use in laboratory drilling tests;
- Conduct laboratory tests and investigate cutter failure and wear mechanisms;
- Develop laboratory testing methods that duplicate cutter failure mechanisms experienced in hard-rock drilling;
- Conduct laboratory cutting tests and investigate rock failure mechanisms;
- Develop alternative cutter designs that take advantage of the results of the rock and cutter failure studies;
- Fabricate and initiate laboratory testing of alternative cutter designs.

During later phases of the project, laboratory cutter tests will be completed, full-scale bits employing the best cutter designs will be laboratory tested, additional design software development will be undertaken, and field testing will be initiated. Field testing will be expanded, bit designs will be optimized for hard-rock drilling, and commercialization of the bits will be initiated.

2. Statement of Work

Task 1 - PDC Bit Performance Benchmarking

Smith and Megadiamond will document the current state of their PDC technology for drilling hard rock. This will be done by selecting and documenting existing, appropriate laboratory or field case histories where a rock specimen, formation interval, or stringer was considered to be a challenging rock for existing dome-cutter PDC bits because of rock strength. Comparative data obtained with impregnated diamond bits or roller bits in the same drilling environment will also be documented, if available. This task will be done in conjunction with Task 2.

Examples of data useful for benchmarking include rock type, drilled intervals, bit penetration rates, bit wear, bit life, drilling costs, drilling practices, and other available bit performance data. Data pertaining to the location, well, lease, operator, customer, and drilling depth may be considered proprietary and withheld from the documentation, at Smith's and Megadiamond's discretion. Field tests at Amoco's Catoosa Test Facility may be used to provide this benchmarking data.

This benchmarking data will be used for gaging improvements made in hard-rock PDC bit design and, in general, for measuring the progress made in developing technology under this project.

Task 2 - Definition and Characterization of Hard Rock

Smith and Megadiamond will select one or more rock types, consistent with the results of Task 1, that typify hard-rock drilling and can be obtained in samples adequate for laboratory drilling. These rock types will be tested by Sandia to determine engineering properties which can include, but are not limited to:

- mechanical properties (unconfined compressive strength, in situ compressive strength, Young's modulus, Poisson's ratio, shear strength, fracture toughness, sonic velocity, and angle of internal friction)
- porosity;
- clay mineralogy;
- abrasivity (quartz content, grain size, angularity, iron content);
- drillability (thermal properties, cutter/rock friction coefficient, impact characteristics); and
- in-situ formation characteristics (bed thickness, dip angles).

The Mohr's envelope for these rock type(s) will be determined, and typical rock failure modes will be characterized. Smith will analyze and evaluate the results of these tests. Based on these results, a model rock will be selected for laboratory tests.

The rock type(s) tested under this task will also be evaluated by Smith in terms of the responses each invoke on the various well logs that are typically run in petroleum wells, such as sonic velocity and gamma ray logs. This will determine which logs are most useful in evaluating rock drillability with PDC bits in the field.

Task 3 - Development of Laboratory Test Methods

Smith and Megadiamond will characterize and prioritize the failure modes experienced by current PDC cutters in hard-rock drilling and determine what measurements are necessary to fully characterize the downhole environment (shock, vibration, abrasion) of PDC bits cutting hard rock. Sandia, in consultation with Smith, will make these measurements at Amoco's Catoosa Test Facility or a similar facility. Smith/Megadiamond and Sandia will then develop laboratory test methods that duplicate these failure modes. Methods that simulate both the dynamic failure mode and abrasive wear will be developed. Existing test facilities at Sandia will be used to the extent possible, although it is anticipated that new testing hardware will also be procured, designed, and fabricated.

The hardware and testing procedures developed under this task will be used as screening methods to evaluate the relative performance of different cutter materials and design configurations. All details related to the hardware and testing procedures will be placed in the public domain and be available to the industry as standard test methods.

Task 4 - Rock-cutter Interaction Testing and Analysis

Sandia will conduct laboratory single-cutter testing at atmospheric pressure to investigate rock failure modes during drag cutting. Smith/Megadiamond will consult with Sandia during these studies and provide the necessary cutters. Rock samples will be examined to develop mechanistic models for the PDC cutting process in hard rock. These models will consist of qualitative and, to the extent possible, quantitative descriptions of the rock failure modes. These failure modes will be related to rock properties, such as angle of internal friction and fracture toughness, to evaluate the effects that changes in rock properties have on rock failure mechanisms. The results will be used to identify possible cutter geometry changes that could lead to increased rock fracturing and greater cutting efficiency.

This task will be conducted in parallel with Tasks 5 and 6 so that changes in cutter geometry can be evaluated in terms of rock failure modes. This information will be used to evaluate rock failure hypotheses related to cutter geometry and as a screening method for identifying the most favorable cutter geometries from the standpoint of cutting efficiency and rock failure.

Task 5 - Cutter Failure Testing and Analysis

Sandia will conduct laboratory testing of single cutters to identify cutter wear and failure modes and investigate fracture propagation mechanisms in the cutter materials. Both dynamic testing and abrasive-wear testing will be performed. Smith/Megadiamond will provide the necessary cutters and provide their expertise in a

consulting capacity. Mechanistic models of the cutter wear and failure processes will be developed and used to identify possible material or configuration changes that could make PDC cutters more resistant to wear and failure in hard-rock drilling. This evaluation and analysis will be done jointly by Smith/Megadiamond and Sandia.

This task will be conducted in parallel with Tasks 4 and 6 so that changes in cutter geometry, materials, and processing can be evaluated in terms of cutter failure modes. This information will be used to evaluate cutter failure hypotheses and as a screening method to identify the most favorable cutter design changes from the standpoint of cutter life under hard-rock drilling conditions.

Task 6 - Development of Alternative Hard-Rock Cutter Designs

Based on the results of the previous tasks, Smith and Megadiamond will develop concepts for alternative PDC cutter designs for hard-rock drilling. Alternative cutter configurations, materials, and fabrication processes are examples of concepts that may be developed. At least two major alternative cutter designs are expected to be developed.

Task 6 will be conducted in parallel with Tasks 4 and 5 to allow an iterative approach to cutter design and testing. Identified rock and failure modes will be used to guide the development of alternative cutter materials and designs; and the new designs will be tested to evaluate the failure mode models and to screen the new designs for use in hard-rock drilling.

Cutter designs developed under this task will be used in full-face bits that will be designed, fabricated, and tested in the laboratory and in the field under hard-rock drilling conditions in later phases of this project.

Task 7 - Hydraulic Design for Hard-Rock Bits

Smith will conduct tests in its flow visualization test stand to develop design concepts for bit hydraulics designs for hard-rock drilling. Existing bit body designs for moderately hard formations will be run in the test stand to identify regions of flow stagnation, recirculation, unintentional cross-flow, and other possible design deficiencies. Design changes needed to correct these deficiencies will be developed and evaluated in further testing. General criteria for the hydraulics design of hard-rock PDC bits will be developed.

Information developed in this task will be used in later phases of this project to help guide the design of full-face bits for hard-rock drilling.

Task 8 - Monthly and Final Report Writing

Smith International/Megadiamond will write monthly letter progress reports. They will also co-author with Sandia a final report that contains as a minimum the following:

- 1) Results of the PDC bit benchmarking task;
- 2) Descriptions of the rock formation evaluations and a listing of the engineering properties of the rock types tested;
- 3) Descriptions and designs of laboratory testing methods developed;
- 4) Laboratory cutter test results and descriptions of test analyses;
- 5) Descriptions of any mechanistic models developed for rock failure modes and cutter wear and failure modes;
- 6) General descriptions of alternative cutter designs, including unique aspects of the designs; and
- 7) General descriptions of the bit hydraulics tests.

Details related to the design and fabrication processes for alternative cutters will remain proprietary to Smith and Megadiamond. Raw cutter test data, raw bit hydraulics test data, and details related to specific hydraulics designs will also remain proprietary to Smith and Megadiamond.

3. Planned Budget

The total budgeted cost for the two years covered by this program is \$257k. Smith International and Megadiamond would provide one-half the funding, \$128.5k, and the DOE would provide the remainder, \$128.5k. The budget is distributed among the various tasks as listed below.

PLANNED 1993-95 BUDGET ADVANCED PDC CUTTER DEVELOPMENT AND BIT DESIGN WITH SMITH INTERNATIONAL AND MEGADIAMOND

	<i>Subtotal</i>	
<i>Task 1 - PDC Bit Performance Benchmarking</i>		
Data collection, analysis, and documentation	\$2,800	\$2,800
<i>Task 2 - Definition and Characterization of Hard Rock *</i>		
Project management and engineering analysis	7,260	
Materials	6,000	
Travel and training	<u>2,000</u>	
	15,260	15,260
<i>Task 3 - Development of Laboratory Test Methods *</i>		
Project management and engineering analysis	7,260	
Materials	6,000	
Travel and training	<u>2,000</u>	
	15,260	15,260

* Work conducted by Sandia is budgeted in Section IV of this report.

<i>Task 4 - Rock-Cutter Interaction Testing and Analysis *</i>		
Project management and engineering analysis	17,260	
Materials	6,000	
Travel and training	<u>2,000</u>	
	25,260	25,260
<i>Task 5 - Cutter Failure Testing and Analysis *</i>		
Project management and engineering analysis	17,260	
Materials	6,000	
Travel and training	<u>2,000</u>	
	25,260	25,260
<i>Task 6 - Development of Alternative Hard-Rock Cutter Designs</i>		
Design, process engineering, and materials	136,000	
Project management and engineering analysis	7,260	
Materials	6,000	
Travel and training	<u>2,000</u>	
	151,260	151,260
<i>Task 7 - Hydraulic Design for Hard-Rock Bits</i>		
Project management and hydraulic design	\$7,260	
Test engineering, testing, and materials	9,000	
Travel and training	<u>2,000</u>	
	18,260	18,260
<i>Task 8 - Monthly and Final Report Writing *</i>		
Monthly letter reports	840	
Final report	<u>2,800</u>	
	3,640	<u>3,640</u>
	TOTAL	\$257,000

* Work conducted by Sandia is budgeted in Section IV of this report.

4. Schedule

The schedule for this project is shown below. The number of months represent time since the start of the project, which is assumed to be September 1, 1993.

**PLANNED 1993-95 SCHEDULE
ADVANCED PDC CUTTER DEVELOPMENT AND BIT DESIGN
WITH SMITH INTERNATIONAL AND MEGADIAMOND**

	----- MONTHS -----											
	2	4	6	8	10	12	14	16	18	20	22	24
Task 1	X	X										
Task 2	X	X	X									
Task 3	X	X	X	X	X							
Task 4					X	X	X	X	X	X	X	X
Task 5					X	X	X	X	X	X	X	X
Task 6								X	X	X	X	X
Task 7									X	X	X	X
Task 8	X	X	X	X	X	X	X	X	X	X	X	X

B. Optimization of Track-Set Cutting Structure with Security Diamond Products

1. Project Description

Security Diamond Products will investigate methods of enhancing their track-set cutting structure and to explore this cutting structure's ability to provide for more stable bit rotation and extend PDC bit applications into harder formations. This will be accomplished through the enhancement of current modeling techniques and the testing and evaluation of several track-set configurations. Security Diamond Products and Sandia will complete the following:

- Current force and wear models will be evaluated to establish their correlation with actual drilling in the field;
- Single cutter tests will be conducted to explore the alternative engagement geometries and wear modes which result from the track-set configuration;
- Cutter force and wear models will be enhanced in accordance with the findings from the above steps;
- Dual-cutter tests will be conducted with various track-set configurations; and
- Field tests will be conducted with bits incorporating features indicated by previous modeling and testing.

2. Statement of Work

Task 1 - PDC Bit Performance Benchmarking

Security will establish and document the current limits of their products in drilling hard rock. This will be accomplished by the documentation of both field and laboratory case histories. Emphasis will be put on determining and documenting the pertinent data to establish drillability numbers for hard rock applications. Similar data will also be documented for various natural diamond, TSP, and rolling cone applications.

Examples of data useful for benchmarking include rock type, drilled intervals, bit penetration rates, bit wear, bit life, drilling costs, drilling practices, and other available bit performance data. Data pertaining to the location, well, lease, operator, customer, and drilling depth may be considered proprietary and withheld from the documentation, at Security's discretion. Field tests at Amoco's Catoosa Test Facility may be used to provide this benchmarking data.

This information will be used to measure progress of the project in its effort to extend PDC applications into hard rock formations.

Task 2 - Current Force and Wear Modeling Evaluation

Security will conduct a program to compare field performance to the results of current wear models. This includes the development of a device and methodology to be used to establish wear geometries and amounts on dulled bits. This will be done to help identify possible limitations in the current modeling techniques. Correlations between both force and wear modeling and field results may also be established. This process may also identify alternative formation characteristics other than compressive strength which fundamentally affect drilling and wear characteristics.

These findings will help guide the enhancement of the force and wear modeling techniques.

Task 3 - Single Cutter Testing of Alternative Engagement Geometries

Sandia will conduct instrumented single cutter testing which will investigate the following:

- Typical track-set engagement geometries (up to 180 degrees of cutter engaged);
- Various cutter size and shapes in conjunction with varied rock types;
- Effects of formation being "relieved" (typical of formation ridges between track-set cutters);
- Effects of cutter being offset from its bottomhole track (restoring force); and
- Effects of cutter wearflats on forces and wear.

Security will perform the detailed data analysis of the results.

Task 4 - Cutter Force and Wear Model Enhancement

Security will complete the necessary methodology and programming to institute those things learned in Tasks 2 and 3 into a more comprehensive force and wear modeling program. Other enhancements include the modeling of an oversized hole and allowances for eccentric bit rotation.

Task 5 - Dual-Cutter Testing of Various Track-Set Configurations

Sandia will conduct these tests in a manner similar to that employed in single cutter testing. These tests will be completed to investigate the strength of the ridge of formation which is formed between cutters during track-set cutting action and its interaction with the matrix bit body. Several two-cutter track-set configurations will then be designed by Security to help identify the best method for the removal of this formation ridge. The possibility of rock prefracturing through the use of chisel-shaped cutters will also be investigated at this time. Security will perform the detailed data analysis of the results.

Task 6 - Field testing of Bits which Incorporate New Track-Set Features

Security will design and manufacture one or more track-set type bits which will incorporate design concepts developed and tested in the previous tasks. This bit will then be field tested in various rock types and strengths to establish the bit's capabilities.

These tests may also be used to check the usefulness of the new developments in the force and wear model. Amoco's Catoosa Test Facility may be used to provide this field test data.

Task 7 - Monthly and Final Report Writing

Security will write monthly letter progress reports. Sandia and Security will co-author a final report which will include the following:

- 1) Results of PDC bits in hard rock applications benchmarking;
- 2) Results of current force and wear model evaluation;
- 3) Single cutter testing procedures, results, and general evaluation of these results;
- 4) Dual-cutter testing procedures, results, and general evaluation of these results;
- 5) Results and evaluation of bit field testing.

Bit wear analysis equipment and methodology will become public information. Specific track-set configurations, and detailed analysis of cutter testing will remain proprietary to Security. Any computer code generated to utilize enhanced force and wear modeling will also not be disclosed.

3. Planned Budget

The total budgeted cost for the project is \$186k. The DOE would provide one-half the funding (\$93k), and Security would provide the remainder, \$93k. The budget is distributed among the various tasks as listed below.

**PLANNED 1993-95 BUDGET
OPTIMIZATION OF TRACK-SET CUTTING STRUCTURE
WITH SECURITY DIAMOND PRODUCTS**

	<i>Subtotal</i>	
<i>Task 1 - PDC Bit Performance Benchmarking</i>		
Data collection, analysis, and documentation	\$3,000	\$3,000
<i>Task 2 - Current Force and Wear Modeling Evaluation</i>		
Development, design, and manufacture of wear analysis device	16,000	
Data collection, analysis, and documentation	<u>4,000</u>	
	20,000	20,000
<i>Task 3 - Single Cutter Testing of Alternative Engagement Geometries *</i>		
Project management and engineering analysis	10,000	
Materials	15,000	
Travel and training	<u>2,000</u>	
	27,000	27,000
<i>Task 4 - Cutter Force and Wear Model Enhancement *</i>		
Project management and engineering analysis	28,000	28,000
<i>Task 5 - Dual-Cutter Testing of Various Track-Set Configurations *</i>		
Design and materials of dual-cutter parts	20,000	
Project management and engineering analysis	12,000	
Materials	2,000	
Travel and training	<u>3,000</u>	
	37,000	37,000
<i>Task 6 - Field Testing of Bits which Incorporate New Track-Set Features</i>		
Design and materials for bits (3 bits)	60,000	
Field testing and analysis	6,000	
Travel	<u>2,000</u>	
	68,000	68,000
<i>Task 7 - Monthly and Final Report Writing *</i>		
Monthly letter reports	900	
Final report	<u>2,100</u>	
	3,000	<u>3,000</u>
	TOTAL	\$186,000

* Work conducted by Sandia is budgeted in Section IV of this report.

4. Schedule

The schedule for this project is shown below. The number of months represent time since the start of the project, which is assumed to be September 1, 1993.

PLANNED 1993-95 SCHEDULE OPTIMIZATION OF TRACK-SET CUTTING STRUCTURE WITH SECURITY DIAMOND PRODUCTS

	MONTHS											
	2	4	6	8	10	12	14	16	18	20	22	24
Task 1	X											
Task 2	X	X	X									
Task 3		X	X	X	X							
Task 4				X	X	X	X	X				
Task 5						X	X	X	X			
Task 6										X	X	X
Task 7	X	X	X	X	X	X	X	X	X	X	X	X

C. Claw Cutter Optimization with Dennis Tool Company and DBS, a Baroid Company

1. Project Description

Dennis Tool Company and DBS will optimize the design of their patented claw cutter for hard rock drilling. This work will be done through an analytical and experimental study that evaluates various claw cutter configurations. Dennis Tool and DBS will team with Sandia to perform the following:

- Dennis Tool will design and fabricate alternative configurations of the claw cutter, including variations in the width, depth, shape, and spacing of the grooves in the tungsten carbide substrate.
- Sandia will perform numerical thermal and stress analyses to help guide the design of the alternative configurations;
- Sandia will conduct single-cutter tests to evaluate the performance and wear of the alternative configurations in hard rock;
- DBS will fabricate one or more core bits using optimized claw cutter designs and test them in the laboratory in hard rock; and
- DBS will field test full-face PDC bits incorporating the optimized claw cutter designs.

This project is a continuation of a scoping study initiated at the end of FY92. The ongoing scoping study will continue and will be augmented by Tasks 1, 3, and 7 and additional funds as outlined below.

2. Statement of Work

Task 1 - Claw-Cutter Bit Performance Benchmarking

Dennis Tool and DBS will document the current state of their technology for drilling hard rock. This will be done by selecting and documenting existing, appropriate laboratory or field case histories where a rock specimen, formation interval, or stringer was considered to be a challenging rock for existing claw-cutter bits because of rock strength. Comparative data obtained with other PDC, impregnated diamond bits, or roller bits in the same drilling environment will also be documented, if available.

Examples of data useful for benchmarking include rock type, drilled intervals, bit penetration rates, bit wear, bit life, drilling costs, and other available bit performance data. Data pertaining to the location, well, lease, operator, customer, drilling practices, and drilling depth may be considered proprietary and withheld from the

documentation, at Dennis Tool's and DBS's discretion. Field tests at Amoco's Catoosa Test Facility may be used to provide this benchmarking data.

This benchmarking data will be used for gaging improvements made in hard-rock claw-cutter bit design and, in general, for measuring the progress made in developing technology under this project.

Task 2 - Claw Cutter Fabrication

Dennis Tool will fabricate a minimum of sixty (60) PDC cutters based on the claw cutter and related concepts. The sizes and cutter configurations to be supplied will be determined in conjunction with the results of Tasks 3 and 4.

Descriptions of the configurations fabricated under this task will be detailed enough to provide a clear indication of the parameters to be varied from one configuration to the next. The fabrication process and other proprietary information related to the design and fabrication of the cutters shall remain the exclusive property of Dennis Tool and DBS.

Task 3 - Claw Cutter Stress Analysis

Sandia will perform numerical thermal and stress analyses on claw cutter designs supplied by Dennis Tool and DBS. Numerical models will be constructed that allow the pertinent features of the claw cutter to be included and varied. Parametric studies will be conducted in support of Task 2 to determine optimal designs for reducing material stresses and improving cutter life.

Task 4 - Single-Cutter Testing of Claw Cutters

Sandia will perform instrumented single-cutter tests of the cutters fabricated under Task 2. The tests will evaluate the relative cutting performance and life of each supplied cutter in hard rock at atmospheric, water-cooled conditions. Triaxial cutter forces, cutter speed, and depth-of-cut will be measured and recorded while cutting on the top face of a rock slab in a vertical lathe. Cutter wear flats will be measured and evaluated periodically to correlate cutter wear with rock removal volume, length of cut, cutter work, specific energy, and other abrasive wear parameters. Cutters will be ranked in terms of performance and wear.

Task 5 - Claw-Cutter Core Bit Design and Fabrication

The most efficient and wear-resistant cutter designs identified under Tasks 3 and 4 will be incorporated into core bits to be designed and fabricated by DBS. At least three core bits will be fabricated, with the sizes, configurations, and number of cutters to be determined in the design process.

Task 6 - Claw-Cutter Core Bit Laboratory Testing

The core bits designed and built under Task 5 will be tested by DBS in hard rock or simulated hard rock. The cutting performance and relative wear of each cutter will be evaluated to determine the most efficient and wear-resistant cutter designs.

Task 7 - Claw-Cutter Bit Field Testing

If the results of Tasks 2-6 indicate that significant improvements in hard-rock drillability have been achieved with the optimized claw cutters, DBS will design, fabricate, and field test at least one full-face bit incorporating the best cutter design(s). If appropriate and cost-effective, this field testing will be done in the same rock intervals identified by DBS in the benchmarking task of Task 1. Comparative data gathered with other bit types in the same rock formation will be obtained, if possible. Amoco's Catoosa Test Facility may be used to provide this field test data.

Task 8 - Monthly and Final Report Writing

Dennis Tool/DBS will write monthly letter progress reports. They will also co-author with Sandia a final report which contains as a minimum the following:

- 1) Results of the claw-cutter bit benchmarking task;
- 2) Descriptions of the claw cutter configurations evaluated;
- 3) Results of the thermal and stress analyses;
- 4) Single-cutter wear test results;
- 5) Descriptions of claw-cutter core bit designs;
- 6) Core-bit laboratory drilling test results; and
- 7) Field test results obtained with claw-cutter bits.

Descriptions of the configurations fabricated under this task will be detailed enough to provide a clear indication of the parameters to be varied from one configuration to the next. The fabrication process and other proprietary information related to the design and fabrication of the cutters will remain the exclusive property of Dennis Tool and DBS. Details related to the field tests that are not necessary to describe the performance of the bit will remain proprietary to the lease operator, driller, DBS, and others who may have a proprietary interest, at their discretion.

3. Planned Budget

This project will be funded by both FY92 and 1993-95 funds. The total budget is \$126,440, with \$60,000 coming from FY 92 and \$66,440 being funded with 1993-95 funds. Of the \$66,440 of new funds, Dennis Tool and DBS will provide one-half, \$33,220, and the DOE will provide the remainder, \$33,220. The budget is distributed among the various tasks as listed below.

**PLANNED 1993-95 BUDGET
CLAW CUTTER OPTIMIZATION
WITH DENNIS TOOL COMPANY AND DBS**

	<i>Subtotal</i>	
<i>Task 1 - Claw-Cutter Bit Performance Benchmarking</i> Data collection, analysis, and documentation	\$2,800	\$2,800
<i>Task 2 - Claw Cutter Fabrication</i> Claw cutter design and fabrication, 60 cutters @ \$1000 each	60,000	60,000
Task 3 - Claw Cutter Stress Analysis *		
Task 4 - Single-Cutter Testing of Claw Cutters *		
<i>Task 5 - Claw-Cutter Core Bit Design and Fabrication</i> Design and fabricate three bits @ \$5,000 each	15,000	15,000
<i>Task 6 - Claw-Cutter Core Bit Laboratory Testing</i> Procure rock and test three bits @ \$5,000 each	15,000	15,000
<i>Task 7 - Claw-Cutter Bit Field Testing</i> Design and fabricate bit, select field test site, and conduct field testing	30,000	30,000
<i>Task 8 - Monthly and Final Report Writing *</i>		
Monthly letter reports	840	
Final report	<u>2,800</u>	
	3,640	<u>3,640</u>
	TOTAL FUNDING	\$126,440
	Minus FY92 funding already provided	<u>- 60,000</u>
	TOTAL 1993-95 FUNDING	\$66,440

* Work conducted by Sandia is budgeted in Section IV of this report.

4. Schedule

The schedule for this project is shown below. The number of months represent time since the start of the project, which is assumed to be September 1, 1993. Because part of this project was actually begun at the end of FY92, some of the tasks listed below were begun before the assumed start of the project, as noted.

PLANNED 1993-95 SCHEDULE CLAW CUTTER OPTIMIZATION WITH DENNIS TOOL COMPANY AND DBS

	MONTHS											
	2	4	6	8	10	12	14	16	18	20	22	24
Task 1	X											
Task 2 *	X	X	X	X	X	X	X	X	X	X	X	
Task 3	X	X	X	X	X	X	X	X				
Task 4 **	X	X	X	X	X	X						
Task 5					X	X	X	X				
Task 6							X	X	X			
Task 7										X	X	
Task 8	X	X	X	X	X	X	X	X	X	X	X	X

* Work initiated 9/92.

** Work initiated 11/92.

D. Optimization of Impregnated Diamond Drill Bits with Hughes Christensen Company

1. Project Description

Hughes Christensen Company (HCC) will improve impregnated bit performance in hard rock by developing a methodology for matching the diamond-matrix impregnation design to the rock being drilled. HCC believes that significant increases in both penetration rate and bit life are possible with impregnated bits by applying recent advances in diamond technology. These advances are related to the coating of synthetic diamonds to enhance the retention of the diamonds in the metal matrix. These improvements have not yet been exploited in impregnated bits. A properly designed impregnation with coated diamonds should make it possible for each diamond to work longer and at greater exposure, which means greater bit life and faster penetration rates.

Under this project, HCC will:

- Develop a mechanistic drilling model for impregnated bits;
- Design and fabricate five impregnated diamond bits using advanced diamond coating technology and various impregnation designs;
- Conduct a series of drilling tests to calibrate the drilling model, and
- Use the model to develop optimal bit designs and operating recommendations for three varieties of hard rock.

Five bits will be designed and tested in three rock types to determine the effects of diamond type, size, coating, concentration; matrix type; rock characteristics; and drilling parameters such as weight on bit and rotary speed. The drilling model will guide the testing in order to minimize the number of tests necessary to calibrate the model.

2. Statement of Work

Task 1 - Impregnated Bit Performance Benchmarking

HCC will document the current state of its technology for drilling hard rock. This will be done by selecting and documenting existing, appropriate laboratory or field case histories where a rock specimen, formation interval, or stringer was considered to be a challenging rock for existing impregnated bits because of rock strength. Comparative data obtained with PDC or roller bits in the same drilling environment will also be documented, if available.

Examples of data useful for benchmarking include rock type, drilled intervals, bit penetration rates, bit wear, bit life, drilling costs, drilling practices, and other available

bit performance data. Data pertaining to the location, well, lease, operator, customer, and drilling depth may be considered proprietary and withheld from the documentation, at HCC's discretion. Field tests at Amoco's Catoosa Test Facility may be used to provide this benchmarking data.

This benchmarking data will be used for gaging improvements made in hard-rock impregnated bit design and, in general, for measuring the progress made in developing technology under this project.

Task 2 - Characterization of Laboratory Rock Types

HCC will define and characterize three rock types that are typical of extremely hard rock drilling and are usually drilled in the field with impregnated bits. Rocks will be selected that represent a wide range of properties that can affect drilling. Laboratory core analysis will be performed at HCC's direction to include the following: triaxial compression and unconfined compression testing for determination of failure envelope; tensile strength tests; Schmidt hammer tests; petrographic analysis; and physical property tests of density and porosity. Three rock blocks suitable for laboratory drilling tests will be procured and prepared for testing by HCC.

Task 3 - Laboratory Drilling Tests

HCC will design and conduct drilling experiments that will investigate the effect that impregnation mix and drilling parameters have on bit life and penetration rate. Five drill bits using different impregnation mixes and incorporating coated diamonds will be designed and fabricated. The test matrix and number of tests to be run will be determined with the aid of the mechanistic drilling model developed under Task 4.

Task 4 - Mechanistic Drilling Model Development

HCC will adapt existing mechanistic drilling models to include parameters important to the process of drilling with impregnated bits. These models consist of mathematical descriptions of the diamond cutting process that allow bit performance to be predicted as a function of bit design. Model calculations will be used to guide the experiments conducted under Task 3 and to search for combinations of bit design and operating parameters that provide optimal performance. The experimental data will be used to calibrate the model for the three rock types identified under Task 2.

Task 5 - Development of Optimal Bit Design and Operating Recommendations

Using the models developed under Task 4, HCC will develop specific bit designs and operating recommendations for each of the three rock types investigated. These designs will be fabricated and evaluated in laboratory drilling tests in each respective rock type.

Task 6 - Monthly and Final Report Writing

HCC will write monthly letter progress reports. HCC will also write a final report which contains as a minimum the following:

- 1) Results of the impregnated bit benchmarking task;
- 2) Laboratory drilling results;
- 3) Model description, including model parameter values used to achieve fit with experimental results and used to predict performance; and
- 4) General descriptions of the three impregnated bit designs for the selected rock types and recommended drilling practices for achieving optimal performance with these bits.

The exact impregnation mixtures, diamond type, diamond quality, and diamond coating technology used in these bit designs will remain proprietary to HCC.

3. Planned Budget

The total budgeted cost for this project is \$69k. HCC will provide one-half the funding, \$34.5k, and the DOE will provide the remainder, \$34.5k. The budget is distributed among the various tasks as listed below.

PLANNED 1993-95 BUDGET OPTIMIZATION OF IMPREGNATED DIAMOND DRILL BITS WITH HUGHES CHRISTENSEN COMPANY

	<i>Subtotal</i>	
Task 1 - Impregnated Bit Performance Benchmarking		
Data collection, analysis, and documentation	\$2,800	\$2,800
Task 2 - Characterization of Laboratory Rock Types		
Rock selection analysis	1,400	
Rock procurement and preparation (3 rocks @\$1,200/rock)	3,600	
Laboratory core analysis (3 rocks @ 3,000/rock)	<u>9,000</u>	
	14,000	14,000
Task 3 - Laboratory Drilling Tests		
Design experimental program and drill bits	6,000	
Perform laboratory drilling tests and analyze data	16,800	
Drill bits and other testing materials	<u>11,000</u>	
	33,800	33,800
Task 4 - Mechanistic Drilling Model Development		
Calibrate mechanistic model to experimental data	5,200	
Search for optimum drilling parameters with model	<u>4,360</u>	
	9,560	9,560

Task 5 - Development of Optimal Bit Design and Operating Recommendations

Develop optimal designs and operating recommendations	5,200	5,200
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Task 6 - Monthly and Final Report Writing

Monthly letter reports	840	
Final report	<u>2,800</u>	
	3,640	<u>3,640</u>

TOTAL	\$69,000
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4. Schedule

The schedule for this project is shown below. The number of months represent time since the start of the project, which is assumed to be September 1, 1993.

**PLANNED 1993-95 SCHEDULE
OPTIMIZATION OF IMPREGNATED DIAMOND DRILL BITS
WITH HUGHES CHRISTENSEN COMPANY**

	MONTHS											
	2	4	6	8	10	12	14	16	18	20	22	24
Task 1	X	X										
Task 2	X	X	X									
Task 3			X	X	X	X	X	X	X	X	X	X
Task 4			X	X	X	X	X	X	X	X	X	
Task 5									X	X	X	X
Task 6	X	X	X	X	X	X	X	X	X	X	X	X

E. Advanced TSP Drill Bit Development with Maurer Engineering and Slimdril International

1. Project Description

Maurer Engineering Inc. (MEI) and Slimdril International Inc. will improve the design of TSP drill bits for hard rock drilling by designing and testing several different types of TSP bits and evaluating their relative performance. Three types of 3-inch-diameter TSP drill bits will be designed and tested in hard rock:

- Optimized GRI TSP bit, a surface-set TSP bit developed by MEI under a GRI contract for medium-hard rock formations;
- TSP large cutter bit, which employs large, non-cubic TSP cutters mounted on a matrix bit body; and
- TSP-Impregnated bit, which uses TSP chips impregnated in a metal matrix that wears away to expose the chips.

Laboratory drilling tests will be conducted in hard rock (e.g., granite, basalt, or chert) at atmospheric pressure to evaluate the relative performance of the different designs. The bit that performs best in these tests will then be field tested in hard rock in one or more wells.

Sandia will contribute to this effort by conducting single-cutter tests of TSP cutters developed under this project. The objective is to evaluate the performance and wear of various cutter configurations and grades under hard-rock drilling conditions. These tests will serve as a screening tool for cutter types to be used in the various bit designs.

2. Statement of Work

Task 1 - TSP Bit Performance Benchmarking

MEI and Slimdril will document the current state of their technology for drilling hard rock. This will be done by selecting and documenting existing, appropriate laboratory or field case histories where a rock specimen, formation interval, or stringer was considered to be a challenging rock for existing TSP bits because of rock strength. Comparative data obtained with PDC or roller bits in the same drilling environment will also be documented, if available.

Examples of data useful for benchmarking include rock type, drilled intervals, bit penetration rates, bit wear, bit life, drilling costs, drilling practices, and other available bit performance data. Data pertaining to the location, well, lease, operator, customer, and drilling depth may be considered proprietary and withheld from the documentation, at MEI and Slimdril's discretion. Field tests at Amoco's Catoosa Test Facility may be used to provide this benchmarking data.

This benchmarking data will be used for gaging improvements made in hard-rock TSP bit design and, in general, for measuring the progress made in developing technology under this project.

Task 2 - Single TSP Cutter Fabrication

MEI will design and fabricate experimental TSP cutters. These cutters may consist of pie-shaped TSP segments mounted in a matrix material in a configuration similar to that of conventional PDC cutters. The objective is to develop larger cutting elements with the Thermally Stable Polycrystalline by backing the TSP segments with tungsten carbide. The experimental TSP cutters may also be cutters of different shapes (e.g. hexagonal, circular, and rectangular). These cutters will be tested by Sandia under Task 3.

MEI will also work with TSP suppliers to obtain TSP cutters of various grades (i.e., grain size, diamond type, diamond coatings). These cutters will also be tested under Task 3 to identify and characterize the wear of the best grades for hard-rock drilling.

Task 3 - Single TSP Cutter Testing

Sandia will perform instrumented single-cutter tests of the cutters fabricated under Task 2. The tests will evaluate the relative cutting performance and life of each supplied cutter in hard rock at atmospheric, water-cooled conditions. Triaxial cutter forces, cutter speed, and depth-of-cut will be measured and recorded while cutting on the top face of a rock slab in a vertical lathe. Cutter wear flats will be measured and evaluated periodically to correlate cutter wear with rock removal volume, length of cut, cutter work, specific energy, and other abrasive wear parameters. Cutters will be ranked in terms of performance and wear. These evaluations will be used to screen various cutter configurations and grades to determine the best designs to use in the bits fabricated under this project.

Task 4 - Optimized GRI TSP Bit Design, Fabrication, and Laboratory Testing

Using the results of a previous MEI project for GRI, MEI and SIlmdril will design and fabricate a 3-inch-diameter, surface-set TSP bit employing a large number of large, sharp-set TSP cubic cutters. The bit will then be tested by MEI in its Drilling Research Center. The bit will be tested at atmospheric pressure in a hard rock to be selected by MEI. Penetration rate, bit weight, and drilling torque will be recorded, and the condition of individual TSP cutters and the overall condition of the bit will be evaluated and documented at regular intervals during the drilling tests.

Task 5 - TSP Large Cutter Bit Design, Fabrication, and Laboratory Testing

Using the results of Task 3, MEI and Slimdril will design and fabricate a 3-inch-diameter drill bit that employs the best performing large, non-cubic TSP cutters. These cutters will be mounted on a matrix bit body and tested by MEI at atmospheric pressure in the same rock type employed in Task 4. Penetration rate, bit weight, and drilling torque will be recorded, and the condition of individual cutters and the overall condition of the bit will be evaluated and documented at regular intervals during the drilling tests.

Task 6 - TSP Impregnated Bit Design, Fabrication, and Laboratory Testing

MEI and Slimdril will design and fabricate a 3-inch-diameter drill bit that employs TSP chips embedded in a matrix that wears away as the bit drills, to expose the embedded chips. Different impregnation designs will be evaluated prior to selecting and fabricating the bit. The bit will be tested by MEI at atmospheric pressure in the same rock type employed in Task 4. Penetration rate, bit weight, and drilling torque will be recorded, and the condition of the bit will be evaluated and documented at regular intervals during the drilling tests.

Task 7 - Selection and Field Testing of Best-Performing TSP Bit

MEI and Slimdril will evaluate the test results obtained in Tasks 4-6 and determine which type of TSP bit offers the greatest hard-rock drilling potential. The selected bit will then be field tested at MEI's direction in one or more wells. The rock intervals to be tested will be selected by MEI in consultation with Sandia. To the extent possible, field evaluations will include comparative data obtained with other bit types, such as roller bits and PDC bits. Amoco's Catoosa Test Facility may be used to provide this field test data.

Task 8 - Monthly and Final Report Writing

MEI and Slimdril will write monthly letter progress reports. They will also co-author with Sandia a final report which contains as a minimum the following:

- 1) Results of the TSP bit benchmarking task;
- 2) Results of the single-cutter tests and cutter wear evaluations;
- 3) General descriptions of the bit designs developed under this project;
- 4) Laboratory drilling data for each bit; and
- 5) Field test results obtained with the selected TSP bit.

Detailed bit design parameters and manufacturing processes used by MEI and Slimdril in the course of this project will remain proprietary to MEI and Slimdril. Details related to the field tests that are not necessary to describe the performance of the bit will remain proprietary to the lease operator, driller, MEI, and others who may have a proprietary interest, at their discretion.

3. Planned Budget

The total budgeted cost for this project is \$160k. MEI and Slimdril would provide one-half the funding, \$80k, and the DOE would provide the remainder, \$80k. The budget is distributed among the various tasks as listed below.

PLANNED 1993 BUDGET ADVANCED TSP BIT DEVELOPMENT WITH MAURER ENGINEERING AND SLIMDRIL INTERNATIONAL

	<i>Subtotal</i>	
<i>Task 1 - TSP Bit Performance Benchmarking</i>		
Data collection, analysis, and documentation	\$4,000	\$4,000
<i>Task 2 - Single TSP Cutter Fabrication</i>		
TSP compact cutters	16,000	
TSP cutters, various shapes and grades	<u>12,000</u>	
	28,000	28,000
<i>Task 3 - Single TSP Cutter Testing</i>		
Work conducted by Sandia is budgeted in Section IV of this report.		
<i>Task 4 - Optimized GRI TSP Bit Design, Fabrication, and Laboratory Testing</i>		
Drill bit design	10,000	
Drill bit fabrication	8,000	
Laboratory testing	<u>10,000</u>	
	28,000	28,000
<i>Task 5 - TSP Compact Bit Design, Fabrication, and Laboratory Testing</i>		
Drill bit design	15,000	
Drill bit fabrication	8,000	
Laboratory testing	<u>9,000</u>	
	32,000	32,000
<i>Task 6 - TSP Impregnated Bit Design, Fabrication, and Laboratory Testing</i>		
Drill bit design	16,000	
Drill bit fabrication	8,000	
Laboratory testing	<u>9,000</u>	
	33,000	33,000

* Work conducted by Sandia is budgeted in Section IV of this report.

**Task 7- Selection and Field Testing of Best-Performing
TSP Bit**

Select best-performing TSP bit, select field test site, and conduct field tests	30,000	30,000
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Task 8 - Monthly and Final Report Writing *

Monthly letter reports	2,000	
Final report	<u>3,000</u>	
	5,000	<u>5,000</u>

TOTAL		\$160,000
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* Work conducted by Sandia is budgeted in Section IV of this report.

4. Schedule

The schedule for this project is shown below. The number of months represent time since the start of the project, which is assumed to be September 1, 1993.

**PLANNED 1993-95 SCHEDULE
ADVANCED TSP BIT DEVELOPMENT
WITH MAURER ENGINEERING AND SLIMDRIL INTERNATIONAL**

	MONTHS											
	2	4	6	8	10	12	14	16	18	20	22	24
Task 1	X											
Task 2	X	X	X	X								
Task 3		X	X	X	X	X						
Task 4				X	X	X	X					
Task 5					X	X	X	X				
Task 6				X	X	X	X	X				
Task 7									X	X	X	X
Task 8	X	X	X	X	X	X	X	X	X	X	X	X

F. Concept-Development Field Testing with Amoco Production Research

1. Project Description

Amoco Production Research will participate in the program by making available their Catoosa Test Facility (CTF) for use in evaluating concepts related to hard-rock synthetic-diamond bit design. The lithology of the test facility site is well mapped to a depth of 2600 ft, and it contains a hard-rock interval that is a challenging formation for PDC bits. The test site is, therefore, ideal for obtaining data that can be used in bit development, as well as for performance testing of bits designed for hard-rock applications.

Five field tests will be conducted at the facility during the first year, each lasting up to four days. A field-test opportunity will be offered to each participating bit company team. The concepts to be evaluated in these tests will be selected after the bit company projects begin in order to allow potential new cutter and bit design concepts to be evaluated. The types of field tests that may be conducted include:

- Instrumented drilling tests with various bit designs to quantitatively define the downhole shock environment in hard-rock drilling. This information is needed to develop laboratory test methods for simulating dynamic failure mechanisms experienced by cutters in hard-rock drilling. Such information could also be used to define or confirm the drilling characteristics associated with specific cutter and bit design concepts.
- Drilling tests with bits fitted with a variety of cutter designs. Such a test would allow promising alternative cutter materials and configurations to be evaluated simultaneously on a single bit under identical downhole conditions.
- Drilling tests of bits developed under this program to evaluate progress toward the objective of a hard-rock synthetic-diamond drill bit. The field-test task included in the bit company projects may be conducted at the CTF, as deemed appropriate by the bit company based on the targeted hard-rock commercial interest.

Selection of the concepts to be evaluated at the CTF will be made by the bit companies and Sandia. Amoco will serve in an advisory capacity by evaluating the concepts based on their extensive experience in PDC bit research and drilling at the CTF. This experience includes extensive laboratory bit testing and a significant database on PDC bit performance in the hard-rock interval at the CTF. The database may, in some cases, satisfy the benchmarking function included in each bit company project, as deemed appropriate by the bit company based on targeted hard-rock commercial interest.

2. Statement of Work

Task 1 - Evaluation of Field Test Concepts

Amoco Production Research will participate in discussions with Sandia and the bit companies regarding proposed field tests for the CTF. Amoco will evaluate each proposed field test based on the objectives of the program and Amoco's drilling experience in the laboratory, at the CTF, and in other field drilling operations (subject to confidentiality constraints). Amoco will make recommendations as to which proposed tests should be conducted at Catoosa, including any changes that may improve evaluation of the concepts to be tested.

Amoco will enter into confidentiality agreements with the bit companies and Sandia, as necessary, to protect intellectual ownership of proprietary concepts that may be proposed for testing at Catoosa.

Task 2 - Drilling Tests at the Catoosa Test Facility

Amoco will conduct drilling tests of selected concepts at the CTF. Test operations included under this task are operation of the drill rig, acquisition, recording, and analysis of standard drilling data, and photographing cutters and bits at selected drilling intervals. Standard drilling data include weight-on-bit, drilling torque, rotary speed, penetration rate, and depth versus time.

Specialized or non-standard instrumentation used in a test will be provided by Sandia or the bit company. The bit company will provide the drill bits and any non-standard downhole hardware required for a test.

Task 3 - Test Reporting

Amoco will provide two paper copies of standard drilling data obtained during each test at the CTF, one copy for Sandia and the other copy for the bit company involved with the test. Amoco will also provide copies of the data in digital form to these two parties, upon request.

Amoco will also write a letter report for each CTF test that describes the test operations, evaluates bit performance relative to that of other bits that have been run at the test site (subject to confidentiality constraints), presents photographs of the bit and cutters taken during the test, and documents any noteworthy observations related to bit performance or the testing operations.

Details related to concepts tested at the CTF will remain proprietary as specified in any confidentiality agreements that may be negotiated under Task 1. General descriptions of the concepts tested and details related to all standard and non-standard drilling data obtained at Catoosa will be published in the respective final report for each bit company project.

3. Planned Budget

The total budgeted cost for the first year of this project is \$240k. The DOE would provide one-half the funding (\$120k) to Amoco for Task 2, and Amoco would provide up to \$120k of in-kind services related to evaluation of the field-test concepts and test reporting.

PLANNED 1993-95 BUDGET CONCEPT-DEVELOPMENT FIELD TESTING WITH AMOCO PRODUCTION RESEARCH

*Task 1 - Evaluation of Field Test Concepts **

Evaluations and recommendations, value of previously-acquired drilling data, confidentiality agreements,	\$90,000
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*Task 2 - Drilling Tests at the Catoosa Field-Test Site ***

Drilling operations, standard data collection, 5 tests X 4 days/test = 20 days @ \$6,000/day	120,000
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*Task 3 - Test Reporting **

Report writing, data duplication costs, value of previously-acquired drilling data	<u>30,000</u>
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TOTAL	\$240,000
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* Costs for Tasks 1 and 3 are estimates and represent upper limits.

** DOE funding is for Task 2 only.

4. Schedule

The schedule for this project is shown below. The number of months represent time since the start of the project, which is assumed to be September 1, 1993.

PLANNED 1993-95 SCHEDULE CONCEPT-DEVELOPMENT FIELD TESTING WITH AMOCO PRODUCTION RESEARCH

	MONTHS											
	2	4	6	8	10	12	14	16	18	20	22	24
Task 1	X	X	X	X	X	X	X	X	X	X	X	X
Task 2				X		X		X		X		X
Task 3				X		X		X		X		X

IV. BUDGET SUMMARY FOR 1993-95

A. Budget for Sandia Work

Sandia will perform several tasks in support of the various projects. These include:

- Contract management of all projects, including consultation and co-authoring final reports where appropriate;
- Single-cutter testing to evaluate cutter performance and wear, in support of the Maurer/Slimdril project, the Dennis Tool/DBS project, and the Security project;
- Development of cutter test methods to simulate dynamic and abrasive wear, in support of the Smith/Megadiamond project;
- Rock property measurements in support of the Smith/Megadiamond project;
- Rock-cutter interaction studies and cutter failure testing to identify rock and cutter failure modes, in support of the Smith/Megadiamond project; and
- Numerical modeling of thermal and stress fields in cutters, in support of the Dennis Tool/DBS project.

Personnel estimates for these tasks total 3.5 person-years, at a cost of \$481k. Adding \$115k for travel, equipment, materials, and other purchases brings the total budget for the Sandia work to \$591k for 1993-95. These costs are delineated below.

**PLANNED 1993-95 BUDGET
SANDIA NATIONAL LABORATORIES SUPPORT**

Personnel Costs	<u>Person-years</u>	<u>Cost</u>
Program management and technical direction, Dept. 6111	0.6	
Single-cutter testing and evaluation, Dept. 6111	1.3	
Rock property measurements and rock-cutter interaction studies, Dept. 6117	0.6	
Thermal and stress analysis, Dept. 1561	0.4	
Dynamic testing, Dept. 2741	<u>0.6</u>	
	3.5 Person-years @	\$481,000
Travel Costs		15,000
Equipment, materials, other purchases		<u>100,000</u>
	TOTAL 1993-95 FUNDING	\$596,000

B. Summary of Total Budget for 1993-95

The total estimated cost of the program is \$1,574,440 for 1993-1995, as summarized below. Of this amount, \$596,000 would be provided by DOE to Sandia for managing the technical program and conducting several research tasks in support of the various projects. The remaining \$978,440 would fund work performed by the industry partners, with DOE contributing one-half the funds (\$489,220) and the industry partners contributing the remaining one-half (\$489,220). DOE funding for this program would be provided jointly by Fossil Energy (Office of Oil and Gas Exploration) and Conservation and Renewable Energy (Geothermal Division). Each division would contribute \$271,305 each year of the two-year period.

PLANNED 1993-95 TOTAL BUDGET SYNTHETIC-DIAMOND DRILL BIT TECHNOLOGY DEVELOPMENT PROGRAM

	<u>DOE FUNDING</u>	<u>COMPANY FUNDING</u>	<u>TOTAL</u>
Optimization of Impregnated Diamond Drill Bits with Hughes Christensen Co.	\$34,500	34,500	69,000
Advanced TSP Drill Bit Development with Maurer Engineering and Slimdril International	80,000	80,000	160,000
Advanced PDC Cutter Development and Bit Design with Smith International and Megadiamond	128,500	128,500	257,000
Claw Cutter Optimization with Dennis Tool and DBS, a Baroid Company	33,220	33,220	66,440
Optimization of Track-Set Cutting Structure with Security Diamond Products	93,000	93,000	186,000
Concept-Development Field Testing with Amoco Production Research	120,000	120,000	240,000
Sandia National Laboratories Support	<u>596,000</u>	_____	<u>596,000</u>
TOTALS	\$1,085,220	\$489,220	\$1,574,440

DOE FUNDING BREAKDOWN:	1993	1994	Total
Fossil Energy	\$271,305	\$271,305	\$542,610
Geothermal Energy	<u>271,305</u>	<u>271,305</u>	<u>542,610</u>
	\$542,610	\$542,610	\$1,085,220

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