**Deep Drilling Basic Research
VOLUME 5 — SYSTEM EVALUATIONS**

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**Final Report
November, 1988 — August, 1990**

**Maurer Engineering Inc.
University of California, Berkeley**

**Gas Research Institute
8600 West Bryn Mawr Avenue
Chicago, Illinois 60631**

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**DEEP DRILLING BASIC RESEARCH
FINAL REPORT**

VOLUME 5--SYSTEM EVALUATION

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GRI-90/0265.5

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Volume 5 – System Evaluations

Table of Contents

	Page
1. INTRODUCTION	1-1
2. TECHNICAL BASIS	2-3
2.1 CONSTRAINTS ON DRILLING CAUSED BY THE ROCK DESTRUCTION PROCESSES	2-3
2.2 CONSTRAINTS CAUSED BY THE GAS EXPLORATION AND PRODUCTION PROCESS	2-5
3. EVALUATION OF CONVENTIONAL DRILLING TECHNIQUES	3-1
3.1 LIMITS TO THE RATE OF MECHANICAL ROCK DESTRUCTION	3-4
3.1.1 Energy and Power Considerations	3-4
3.1.2 Drilling Rate Limitations	3-5
3.1.2.1 Depth of Indentation	3-5
3.1.2.2 Crater Volume	3-7
3.1.2.3 Increasing Speed and Frequency of Indentation	3-17
3.1.2.3.1 Influence of Strain Rate on Rock Destruction and Cuttings Removal	3-17
3.1.2.3.2 Materials Problems Associated With High Rotary Speeds	3-25
3.1.2.3.3 Materials Problems in Roller Cone Bits for High Speed Operation	3-26
3.1.2.3.4 Materials Problems in Drag (PDC) Bits for High Speed Operation	3-26
3.2 SUMMARY AND CONCLUSIONS	3-28
3.2.1 Indentation Depth	3-28
3.2.2 Crater Volume	3-29
3.2.3 Rate Effects	3-29
3.3 REFERENCES	3-34
4. CONVENTIONAL DEEP DRILLING COST SENSITIVITY ANALYSIS	4-1
4.1 SENSITIVITY FACTORS	4-1
4.2 DRILLING TIME PARAMETERS	4-2
4.3 CASING PARAMETERS	4-5
4.4 COMPLETIONS PARAMETERS	4-6
4.5 OTHER PARAMETERS	4-7
4.6 SUMMARY	4-7
5. EVALUATION OF THE ADVANCED MODIFICATIONS AND NOVEL DRILLING SYSTEMS	5-1
5.1 EVALUATION SUMMARY	5-1
5.2 EVALUATION PROCEDURE	5-2
5.3 PENETRATION RATE AND POWER	5-3

Table of Contents (Cont'd.)

	Page
5.3.1 Drilling Rate/Power Analysis of Advanced Modifications	5-5
5.3.2 Drilling Rate/Power Analysis of Novel Drilling Systems	5-5
5.3.2.1 Mechanical Rock Destruction Systems	5-5
5.3.2.1.1 Abrasive Jet and Cavitating Jet Drills	5-5
5.3.2.1.2 Explosive Drills	5-6
5.3.2.1.3 Spark Drills	5-6
5.3.2.2 Thermal Rock Destruction Systems	5-6
5.3.2.2.1 Laser Drills	5-7
5.3.2.2.2 Plasma and Electric Arc Drills	5-8
5.3.2.2.3 Subterrene Drill	5-8
5.3.2.2.4 Microwave, Induction, and High Frequency Drills	5-8
5.3.2.2.5 Nuclear Drill	5-8
5.3.2.2.6 Electric Disintegration Drill	5-8
5.3.2.2.7 Forced Flame and Flame Jet Drills	5-8
5.4 IMPACT ON DRILLING OPERATIONS, DEVELOPMENT RISK, AND RELIABILITY	5-9
5.4.1 Advanced Modifications	5-15
5.4.1.1 PDC/TSD Bits	5-15
5.4.1.2 Improved Roller Cone Bits	5-15
5.4.1.3 High-Pressure Jets	5-16
5.4.1.4 Top Drive	5-17
5.4.1.5 Downhole Motors	5-17
5.4.1.6 Slim-Hole Drilling Systems	5-18
5.4.1.7 Coiled Tubing	5-18
5.4.1.8 Casing While Drilling	5-19
5.4.1.9 Measurement-While-Drilling (MWD)	5-20
5.4.1.10 Automated Rig Operations	5-20
5.4.1.11 Advanced Management Techniques	5-21
5.4.2 Novel Drilling Systems	5-22
5.4.2.1 Explosive Drills	5-22
5.4.2.2 Forced Flame and Flame Jet Drills	5-22
6. CONCLUSIONS AND RECOMMENDATIONS	6-1
APPENDIX C — Cost Sensitivity Analysis of Average Regional Wells	
BIBLIOGRAPHY	

Table of Contents

LIST OF FIGURES

	Page
SECTION 3.	
Figure 3-1. Overview of Research Options for Mechanical Drilling	3-3
Figure 3-2. Bit Cutting Action	3-8
Figure 3-3. Complete Axial Stress-strain Curves for Specimens of Tennessee Marble Tested in Triaxial Compression. Numbers Adjacent to the Curves Give the Confining Stress.	3-9
Figure 3-4. Stress-Strain Curves for Berea Sandstone at Different Pore Water Pres- sures (Kbar). Below: All at 7 Kb, and 24 or 300 C., All in Compression Except Curve Marked Ext (for Extension). Above: At Confining Pres- sures (Pc) of 0.5, 1, and 2 Kb, at 24 C., At Pore Pressures (Pp) of 0, 0.5, and 1.5 Kb; All Therefore at the Same Effective Pressure of 0.5 Kb.	3-10
Figure 3-5, left and Figure 3-6, right. Effect of Bottom-Hole Pressure on Threshold Force and Crater Volume for a Single Dull Bit Tooth in Berea Sandstone	3-11
Figure 3-7. Effect of mud column pressure and formation pressure on drilling rate in Berea sandstone. Overburden pressure is 8,000 psi, bit weight 1,500 lbs., at 50 rpm.	3-12
Figure 3-8. Effect of Differential Pressure on Drilling Rate of Indiana Limestone. Overburden Pressure 6,000 psi	3-13
Figure 3-9. Penetration Rate as a Function of Pressure	3-14
Figure 3-10. Effect of Nozzle Diameter and Position on Static Holddown	3-15
Figure 3-11. Factor of Gain in Penetration Rate	3-16
Figure 3-12. Left, Effect of Solids on Drilling Performance, and Right, Effect of Solids Dispersion on Drilling Rate	3-17
Figure 3-13. Reduction In Penetration Per Revolution as a Function of Rotary Speed for Different Bit Types	3-18
Figure 3-14. Effect of Changing Rotary Speed on Rate of Penetration and Penetration Per Revolution: Data for Depths of Zero and 3,000 ft	3-19
Figure 3-15. Jets Affect Penetration in Particular When Hold Down is Accompanied By Bit Balling	3-21
Figure 3-16. Use of Jets to Reduce Bit Balling	3-21
Figure 3-17. In a Practical Range of Q and Vn, Bottom Balling is Reduced Signifi- cantly by High Nozzle Velocity and Little By High Circulation Rates	3-22
Figure 3-18. Comparison Between Perfect (Ideal) and Imperfect (Actual) Cleaning	3-24
Figure 3-19. Effect of Nozzle Extension on the Chip Removal Force	3-24
Figure 3-20. Chip Removal Force as a Function of Jet Velocity	3-25

Table of Contents

LIST OF FIGURES (CONT'D.)

	Page
Figure 3-21. Coefficients of Thermal Expansion for Materials Used in SYNDAX3 and SYNDITE PCD Products	3-27
Figure 3-22. Granite Turning Test Results. Effect of Heat on Standard PCD	3-27
Figure 3-23. Overview of Research Options for Mechanical Drilling	3-32
 SECTION 4.	
Figure 4-1. Drilling Parameter Sensitivity Analysis	4-2
Figure 4-2. 50% Reduction in Drilling Time.	4-3
Figure 4-3. Other Factors Affected by Changes in Drilling Time Parameters	4-4
Figure 4-4. Casing Parameter Sensitivity Analysis	4-5
Figure 4-5. 50% Reduction in Casing Parameters	4-6
 SECTION 5.	
Figure 5-1. Power Needed to Break Rock Thermally	5-7
Figure 5-2. Cumulative Ranking of Advanced Modifications and Novel Drilling Concepts ...	5-11
Figure 5-3. Productivity Ranking	5-12
Figure 5-4. Reliability Ranking	5-12
Figure 5-5. Impact on Drilling Operations Ranking	5-13
Figure 5-6. Impact on Environment/Safety Ranking	5-13
Figure 5-7. Development Risk Ranking	5-14
Figure 5-8. Development Cost/Time Ranking	5-14

LIST OF TABLES

SECTION 3.	
TABLE 3-I. PDC Drill Bit Performance	3-2
 SECTION 5.	
TABLE 5-I. Summary of Systems Evaluation	5-1
TABLE 5-II. Impact of Individual Drilling Parameters on Cost	5-3
TABLE 5-III. Drilling Concepts	5-4
TABLE 5-IV. Mechanical Novel Drilling Systems	5-5
TABLE 5-V. Thermal Novel Drilling Systems	5-6
TABLE 5-VI. Cumulative Ranking of Deep Drilling Alternatives	5-10

1. Introduction

Volume 2, Volume 3, and Volume 4 of this report present detailed discussions on the following subjects:

1. Deep drilling activity in the United States (Volume 2).
2. Fundamental differences between shallow and deep wellbores (Volume 3).
3. Rock/cutter interactions in deep wellbores (Volume 3).
4. Conventional, advanced, and novel drilling techniques (Volume 4).

In Volume 5, the various drilling techniques described in Volume 4 are evaluated. It begins with a general discussion of the technical basis for the analysis. In Section 2, a general description of the rock physics transformations that take place as depth increases explains the principal reasons why deep drilling ventures are exponentially more expensive than drilling to shallower targets. Each viable deep drilling concept must be able to handle the unique demands associated with the deep well environment. Also included in the technical basis section is a brief discussion of the constraints associated with drilling deep wellbores. The drilling technologies must also be able to operate within certain unavoidable constraints (such as a liquid-filled wellbore for hole stability and well control) if they are to be considered viable drilling technology alternatives.

The evaluation itself is divided into two parts. First, limitations of the mechanical rock breaking methods used with conventional drilling techniques are discussed in detail in Section 3. Included in this discussion is an organization chart detailing each of the limitations associated with the conventional drilling system, and suggested solutions that might be used to improve deep drilling techniques.

After describing the general limitations of the current state of the art, a detailed cost-sensitivity analysis of deep drilling costs when using conventional drilling techniques is presented in Section 4. The findings from this analysis are used to rank the high impact drilling parameters in the order of their influence on deep drilling costs.

The advanced modifications and novel drilling concepts are individually evaluated in Section 5 after the limitations of conventional drilling operations and the high impact cost drivers are identified. A quantitative appraisal of each system is performed using the results of the cost sensitivity analysis as a basis for evaluation. Those systems that cannot demonstrate minimum performance potential are eliminated from further evaluation during this stage of the analysis. Elimination from further evaluation in this study does not imply that a drilling concept should not be developed for other applications. However, it does indicate that the technology does not show suitable potential at this time for application in deep drilling operations.

Those systems still remaining after the quantitative analysis are evaluated and ranked qualitatively, using a set of qualitative parameters including potential productivity, reliability, impact on current deep drilling methods and the existing industry infrastructure, impact on the environment

and safety, development risk, and development time and cost. Each parameter is given a weighting factor which identifies how much impact it has on the final ranking of the drilling systems.

The sum of the qualitative parameter ratings determines the cumulative ranking for each system. Figure 5-2 (Section 5) summarizes the cumulative rankings of all the systems evaluated in the second stage of the analysis. Volume 5 concludes with recommendations for future Gas Research Institute research efforts.

2. Technical Basis

2.1 CONSTRAINTS ON DRILLING CAUSED BY THE ROCK DESTRUCTION PROCESSES

To drill a well requires that rock be removed from the space that is to become the hole. This rock can be removed in a variety of ways, all of which require either the breaking or weakening of the bonds between the atoms that form the rock minerals. This can be done mechanically (including hydraulic and thermal stress), thermally (melting or vaporization), or chemically (dissolution or weakening). In general, thermal and chemical methods involve breaking or weakening the bonds of all the atoms and therefore require large amounts of energy. For example, melting or vaporization require energy equal to the enthalpies of fusion or vaporization respectively. Typically, the enthalpy of fusion for minerals is approximately 10^9 J/m^3 and the enthalpy of vaporization even larger. At the other extreme, the formation of an ideal fracture requires only that the bonds between two layers of atoms be broken. This is the surface energy of the mineral. For minerals found in most rocks the surface energy is approximately 0.3 J/m^2 . In real rock, fracture occurs on a multiplicity of rock surfaces, even in simple tension, so the energy required to produce a fracture is actually as high as 10 to 200 J/m^2 . While rock is weakest in tension, it has not proved to be practicable to generate direct tension at the bottom of a well. In practice, compressive forces are applied and the rock fails in indirect extension or shear, depending upon the type of rock and the difference between the pore fluid pressure and the mud pressure. In uniaxial compression, most rocks fail by indirect extension, and the elastic strain energy stored in the rock at a stress equal to the strength is sufficient to break the rock into fragments. This stored strain energy is of the order of 10^5 J/m^3 , corresponding to a surface energy of about 100 J/m^2 for the fragments produced. In triaxial compression, considerably more energy is required to break rock. Indenters and drag bits used to drill wells create regions of intense triaxial compression in the region of contact between the tooth and the rock. Large amounts of energy are consumed by the processes of rock deformation and fracture. At low overbalance pressures, the region of triaxial compression is surrounded by one of induced extension that leads to the formation of chips. Higher mud overbalance pressures suppress the extension, so that the rock deforms plastically rather than forming chips. As a result, indentation (roller bits) becomes much less effective and direct shear (drag bits) may be necessary to remove rock efficiently.

Many measurements of drilling performance have shown that the energy actually required to rotate a drill bit results in a specific energy for drilling a hole that is approximately equal to the uniaxial compression strength of the rock — that is, the energy per unit volume, (MJ/m^3) equals the strength, (MN/m^2). Compressive strength of reservoir rocks are about 100 MN/m^2 . Even for a drilling rate of 10 mm/sec (120 ft/hr) in an $8 \frac{1}{2} \text{ in.}$ diameter hole, the power required is only 37 kW (50 hp), so that for mechanical drilling the limitation to drilling rates is not the amount of power that is available down the hole but rather the effectiveness with which that power is used to break rock, and the longevity of the drill bit.

It is evident that any screening process must evaluate the quantities of energy required to break the rock inherent in the destruction process itself, and that, for example, whatever improvements are brought to a process that makes hole by vaporizing the rock, it can never consume less energy than the latent heat of vaporization of that rock. The calculations above show that for mechanical rock destruction processes at least, supplying sufficient energy to the work front is not a major problem, and the rate-limiting factor appears to be the efficiency by which the energy can be transmitted across the tool-rock interface.

Another consideration that needs to be applied in any evaluation of real drilling methods is that the rock-breaking process need not be homogeneous. Even if a particular process, say, vaporization of the rock, could be excluded on energy grounds if it were applied to the excavation of the entire volume of the hole, it may be economic to apply the method to the excavation of only a part of the hole (e.g., cutting a kerf) if in so doing, the bulk of the material to be excavated is sufficiently weakened so that it can be removed with very little effort. Thus, the high expenditure of energy in cutting the kerf is "paid for" by savings realized in the rest of the excavation. A practical example of such a pay-off may well be found in the use of high-power water or mud jets in conjunction with mechanical cutters, where the jets are not capable of economically drilling the entire hole, but by weakening the rock ahead of a mechanical cutter, allow the realization of substantially greater rates of penetration.

An essential consideration is that the rock breaking process must be capable of drilling through any kind of rock that may be encountered in the well. Some rock breaking processes are extremely effective in certain kinds of rock but become virtually ineffective on a different lithology. As examples, high pressure water jets cut most porous rocks very well but are much less effective in very fine grained or crystalline rock. One of the difficulties with polycrystalline diamond bits, which are very effective in soft formations, is that they are very susceptible to damage in harder strata such as chert.

Finally, the rock-fracturing process cannot be separated from the process of removing the fractured rock from the work front. A method that only fractures the rock, (for example, one relying on thermal shock), will not be able to deepen the hole if the rock fragments remain locked in place at the bottom of the hole. Such a method would need to be combined with a chip-removal device (such as a mechanical scraper or fluid jet) to form an effective drilling system.

The evaluation will attempt to balance these factors for the various techniques examined, and will evaluate different excavation processes based on what may reasonably be expected with present or foreseeable developments in technology.

2.2 CONSTRAINTS CAUSED BY THE GAS EXPLORATION AND PRODUCTION PROCESS

Having considered the various theoretical and practical constraints which govern the choice of the rock destruction process itself, we must now see how the specific requirements of the gas producing industry affect the choice of drilling method. It is understood that the objective of the deep drilling process is to produce a hole to depths greater than 15,000 feet deep, and, typically, a few inches in diameter. The depth constraint arises because of the depths where natural gas is usually found. Hole diameter is a constraint because an adequately sized hole is necessary to produce gas in sufficient quantities to be economically worthwhile. (Note that the constraint may not arise if the objective is only exploration: in this case, any limitation on hole diameter will arise from the minimum size of the instruments that are to be used downhole, unless it is necessary to measure the producing capacity of the well by a flow test). All novel drilling methods must be capable of producing a hole of this depth and diameter to be of practical interest to the commercial gas drilling industry.

Any reservoir of natural gas (or oil) must occur in a rock formation that is both porous and permeable so that the formation fluid will flow to the well in economic quantities. This fluid will be subject to a certain natural pressure. As the borehole penetrates into the reservoir, if the pressure in the well is different from that in the formation, fluid may flow into or out of the borehole in substantial quantities. If flow into the well is not controlled, the gas or oil will escape to the surface and the well will "blow out;" if the borehole pressure is too high, the drilling fluid may be forced into the surrounding rock, and either cause fractures, or plug the pore spaces in the surrounding rock, which severely reduces permeability and the capacity to produce. Thus, it is important for safety and economic reasons to match the wellbore pressure to that of the formation even though increasing the pressure in the borehole may reduce the drilling rate.

Any candidate drilling technique must allow control of these subsurface pressures. In current practice, pressure in the borehole is adjusted by filling the hole with a water- or oil-based mud whose specific gravity is altered by adding high density solids such as powdered barite or hematite. However, the borehole may pass through several reservoirs (containing gas, water, or oil) on its way to the target depth and unfortunately, the pressures in these reservoirs may not be a linear function of depth. Thus, it becomes impossible to select any single mud density to control all the fluid pressures simultaneously. The problem is solved by inserting into the well a "casing", formed of strong steel pipe, that is run into the well and cemented in place. The casing also serves to protect the hole, by preventing collapse if the hole has traversed loose or unstable rock formations. Casing is placed in the well after drilling to a depth where the pressure at the bottom of the well requires a density of mud that would be great enough to exceed the fracture pressure of formations higher up the well. When this situation occurs, the drilling equipment is removed from the well, and the casing is run into the hole and cemented. Once the casing has been cemented, the mud density can be increased, and the drilling process continued, but only, of course, with a reduced bit diameter that will fit inside the casing. In general, the well is drilled by starting with a large diameter hole, and sequentially drilling, setting casing, and drilling again with progressively smaller diameters until the desired depth has been

reached. A typical well may be drilled using four or five concentric casings, reducing the hole diameter from 24 in. at surface to 6 in. at 15,000 feet depth.

Beyond the need to maintain control of formation pressures and to prevent collapse of the hole, there are some other constraints on the drilling process. The first is that some way must be found to remove drilled cuttings from the hole, even from very great depths. The only method that has been used successfully so far is the circulation of a fluid (water- or oil-based mud, or air) down through the hollow drill pipe and back to the surface carrying the cuttings in the annular space between the drill pipe and the hole wall (or casing). In exceptional circumstances, circulation may be reversed, with the cuttings rising inside the drill pipe. The fluid and the flow rates must be chosen not only to lift the cuttings while drilling, but also to tolerate a temporary stoppage of the circulating system. A cleaning method that carries cuttings to the surface in a gas stream, for example, must not carry such a large density of cuttings, that if the gas supply is temporarily halted, and the cuttings sediment to the bottom of the hole, they cannot be relifted when the gas stream is re-started, and jam the drilling assembly. If an oil- or water-based mud is used to remove the cuttings, it is usual to engineer a degree of thixotropy into the mud so that the cuttings will not sediment even if the flow is stopped.

The second constraint concerns the other activities that go on in the wellbore that are not strictly concerned with making the hole deeper. Most important among these are the various investigative techniques used to evaluate the geological properties of the rocks that have been penetrated, and to measure the reservoir and reservoir fluid properties. These activities, together with other measurements that determine the direction and inclination of the hole, are known collectively as well logging and must be carried out from time to time as the well is being deepened. Each candidate drilling method must allow for the periodic insertion and removal of these tools into the borehole (or otherwise incorporate them into the drilling device), and if possible, must not unduly perturb the measurement of the original properties of the reservoir and its fluids.

In summary, any novel method for drilling the well must address the following requirements:

1. It must allow the control of formation pressures at different points in the well.
2. It must deal with the question of wellbore stability.
3. A means for removing cuttings from the hole must be provided.
4. It must be possible to run logging tools in the borehole, or they must be built into the drilling equipment.

Several rock destruction processes that might otherwise be attractive could be awkward to adapt to the drilling of deep hydrocarbon wells. For example, techniques that rely on transmitting the destructive energy through a medium of low density, such as air, could place difficult demands on the borehole environment. Examples include laser devices or electron beams, that would require either that the source of energy be brought almost into contact with the rock, or that the area around the work front be filled with gas (if not a vacuum). The problems associated with maintaining a gas pressure at the work front in equilibrium with the formation pressure are substantial, and would be compounded by the problem of cuttings removal. Because of the low density of the gas in the wellbore, the entire column would have to be pressurized to reach equilibrium at the work front, and therefore would

result in substantial overpressure at points higher in the borehole. In this situation, it would be mandatory to seal the wellbore as drilling proceeds. Problems may also arise with thermal methods of rock destruction if they are to operate in the presence of a liquid pressure control/cuttings removal fluid. The high thermal conductivity and specific heat of the liquid (by comparison with a gas) may draw too much heat away from the work front for the drilling method to be effective.

Several of the problems identified above might be solved if it were possible to protect and seal the borehole as it is drilled, i.e., if the casing could be placed immediately, the hole is formed. This is an attractive prospect, and conceptually at least, could be achieved either by sliding the casing into the hole as it is drilled, or forming the casing in situ from a casing-fabricating machine situated immediately behind the bit. For the casing to be able to slide into the hole, as in the first case, there would have to be a gap between the borehole wall and the outside of the casing, and then some way would have to be found to make a sliding seal in the gap. The seal would be required to prevent communication between the drilling fluid and the different formation fluids, or between formation fluids of different types and pressures. How this could be achieved is not clear, nor is it evident how the hole could be kept open long enough to allow the slow advance of the casing over a period of, perhaps, days, until the planned casing setting depth is reached. An additional problem that is not insoluble, but would require modification to the surface equipment, is to design a method to advance the casing string, adding new sections from time to time, while simultaneously supporting the weight of the drill string inside the casing.

An alternative approach could be to form the casing in situ just behind the bit. The possibility of forming the casing in this manner is very attractive, as it would solve a whole series of problems relating to borehole stability and pressure control. The method would require using a drilling device that would drill a hole somewhat larger than its own diameter, so that it could be withdrawn through the casing after the latter is formed. This is not impossible, and, in the case of mechanical bits, designs already exist for this type of bit. The major question is what material can be fabricated in the downhole environment that is strong enough to withstand the forces of both external and internal pressure (collapse or burst) that the casing is required to support? Some progress has been made in this area but no material is yet available that approaches the properties of steel, and certainly not at such a low cost.

Turning to the constraints that exist for the surface equipment, a major consideration will be that, unless the casing can be formed in situ, a hoisting device must be provided over the well to carry the weight of the casing as it is being run into the hole. The maximum casing weight is frequently greater than the weight of the drilling equipment, and may determine the capacity of the rig required to drill a given well. Experiments have already been carried out to suspend the drilling equipment from a flexible hose umbilical, rather than from conventional drill pipe, and to run into and out of the hole by feeding the hose on and off a giant reel, but this has not eliminated the need for a conventional derrick or mast. The only savings that could probably be made would be to reduce the height of the derrick since it would no longer be so important to run tubular goods in multiples of three lengths (three times thirty feet, as is usual when tripping pipe in and out of hole).

5 Constraints on the design of the rest of the surface equipment would depend to some extent upon the nature of the drilling method. Obviously, some means would be provided to collect drilled cuttings brought to surface, and to separate them from the conveying fluid. Equally, means would be provided to shut in the well in the event of an influx of formation fluids into the borehole (blowout prevention and control), and to run and control various logging and surveying tools. Power supplies would be required, and would in all probability be similar to those used today. The only major constraints would then be in limiting the weight and area occupied by the surface equipment. A significant advantage would accrue to any new drilling method that could be operated from lighter and more compact surface equipment. It should be realized that a significant fraction of the cost of drilling wells on land goes into the preparation of the drilling site, and in remediation work afterwards, particularly in environmentally sensitive areas.

3. Evaluation of Conventional Drilling Techniques

In spite of the large range of designs and materials available, mechanical drilling bits operate in one of two basic modes. These are respectively shear, in which the tool motion is parallel with the rock surface, or indenting, in which the tool motion is normal to the rock surface. In shear (or "drag bit") cutting, a constant depth of cut can be maintained as the tool moves forward, and therefore, in principle at least, a uniform cutting action can be achieved with constant tool loads. Examples of such bits in use in the petroleum industry include natural diamond, polycrystalline diamond compact (PDC) and thermally-stable diamond compact (TSD) bits.

With an indenting action, however, because the tool cannot move forward indefinitely without encountering ever-increasing resistance from the rock, the drilling action consists of making a sequence of indentations of limited depth, and repeating the process at different points over the workfront. In practice, this is achieved either by taking a solid bit and vibrating it axially towards the workfront or by rolling a toothed cutter over the rock surface. The former drilling method, known as hammer drilling, is common in many industries, but has not yet been applied to the drilling of deep gas wells. This is primarily because of the difficulty of making an efficient down-hole hammer that will operate in drilling mud. Rolling cutter bits are exemplified by the three-cone roller bit, a design that today accounts for perhaps three quarters of the total hydrocarbon well footage drilled.

From the point of view of the mechanics of rock destruction, both shear and indenting cutters operate by first generating a volume of crushed rock under the cutter point, and then propagating cracks outward from the crushed zone that eventually allow chips to be broken away from the hole bottom. Because of the geometry of the cutting action, however, the rock broken by a shear cutter is less constrained than that under an indenting cutter, and therefore, other things being equal, cutter loads on a drag bit will be less than for an indenting bit. Further, because the drag bit sweeps forward through the volume of rock which has just been broken, it has a positive cleaning action to remove rock debris, whereas the indenting bit lifts away after forming a new crater and relies upon some other agency, for example a jet of cleaning fluid, to clean the hole bottom before the next indentation event. This lack of a positive cleaning action may become a serious limitation when attempts are made to increase the rate of penetration of indenting bits by increasing the rotary speed or depth of indentation, particularly under conditions of high bottom-hole pressure, i.e., in deep wells (see discussion below).

Thus, from the point of view of rock mechanics, drag bits are clearly to be preferred. Nonetheless, indenting (roller-cone) bits still account for the majority of footage drilled today. The reason is because the shearing action of drag bits causes much more wear to the cutter teeth than does the indenting action of roller-cone bits. This is partly because the drag bit tooth slides a greater distance under load against the rock than does the indenting tooth, and partly because the indenting tooth is regularly lifted away from the rock surface to be cooled by the drilling fluid. Thus, until the advent of really abrasion-resistant cutter materials, roller-cone bits were pre-eminent. The situation

has changed in recent years, however, with the introduction of polycrystalline diamond compact materials, and, more recently, thermally-stable diamond compacts (Volume 4). These materials have outstanding abrasion resistance, and bits using such cutting elements are now returning exceptionally high penetration rates and long bit life, at least in the softer rocks (see Table 3-I). Some problems still remain with such bits, however, in the harder and more abrasive formations, where bit life remains too low for them to be economically competitive.

TABLE 3-I. PDC Drill Bit Performance

Bit Type	Diameter (in.)	Location	Distance Drilled	ROP (ft/hr)
Hycalog DS 30	17½"	North Sea	18,016	100
Hughes B9M	12½"	North Sea	2,831	78.2
E-C King Cutter	9¾"	Gulf of Mexico	24,282	?
E-C King Cutter	17½"	North Sea	6,472	63
E-C King Cutter	12½"	Far East	6,810	97
E-C 435 S	12½"	Norway	9,660	158

* Eastman Christensen

The values in Table 3-I are remarkable both for the very long lives and for the high rates of penetration that have been achieved. Furthermore, it should be noted that the PDC bit is a relatively recent introduction, and substantial improvements in materials and operating practice are still being made. Five years ago (1984), PDC bits accounted for approximately 5% of all oil well footage drilled. Today, the figure is estimated to be 20-25%, and is continuously increasing as new applications are found.

In this report, the rate limiting mechanisms for indenting and drag type bits are described. These mechanisms are divided into three basic categories 1) indentation depth, 2) crater volume, and 3) rate effects. Figure 3-1 shows a schematic of the various factors that are considered within each of these categories. The schematic is discussed in more detail in the Summary Section.

Figure 3-1. Overview of Research Options for Mechanical Drilling

3.1 LIMITS TO THE RATE OF MECHANICAL ROCK DESTRUCTION

3.1.1 Energy and Power Considerations

At the most fundamental, the minimum energy required to produce a new section of a borehole is the energy required to separate the material inside the hole from the surrounding rock, i.e., the surface energy of the cylindrical surface. The surface energy of the minerals that make up typical rocks is of the order of 0.3 J/m^2 , and so the energy required to form one meter of new hole of diameter 250 mm ($\sim 10 \text{ in.}$) would be $\pi \times 0.25 \times 1.0 \times 0.3 = 0.24 \text{ J}$.

In reality, although the energy required to cleave a single crystal of a rock-forming mineral may be close to the surface energy, as soon as such crystals are joined together into the polycrystalline mass which is a rock, fracture proceeds by the formation, propagation, and linkage of a large number of microcracks. The resultant multiple fracture paths, hysteresis, and frictional losses all increase the energy required to finally separate the two surfaces of a growing crack in a real rock. The result is that measured fracture energies are in the range of $20 \text{ to } 200 \text{ J/m}^2$ (Cooper 1977A). Substituting even the larger of these values in the expression above yields a value of only 157 J, however, which is still very small.

The above discussion supposes that we could make our borehole by somehow inducing a cylindrical fracture at the borehole surface, and then removing the central core of rock intact to make the hole. Realizing that this would be difficult to achieve in practice, let us consider a process whereby the material to be removed is loaded to failure in some way, and the elastic energy stored at failure is used to fragment the rock. A strong rock such as granite may have a Young's modulus of 50 GN/m^2 , an unconfined uniaxial compressive strength of 200 MN/m^2 and a fracture surface energy of 200 J/m^2 . The elastic energy stored at failure will be $\frac{1}{2}\sigma\epsilon$, or $\frac{1}{2}\sigma^2/E$, where σ and ϵ are the stress and strain at failure, respectively. In the present case, the energy stored will be $4 \times 10^5 \text{ J/m}^3$. Taking the fracture energy as 200 J/m^2 , the stored energy at failure could produce $2 \times 10^3 \text{ m}^2$ of fracture surface per cubic meter of rock. This would be achieved if the rock were broken into fragments of average diameter 1.5 mm. In fact, for such small fragment sizes, 200 J/m^2 is certainly an overestimate of the rock's fracture surface energy, and therefore the average fragment size should be smaller. But even so, it is clear that if we were to input only enough energy to load the rock to failure, we would easily have sufficient energy to break the rock into fragments small enough to remove them from the borehole without difficulty.

We now compare these values with the energy consumed in the drilling of rocks by conventional means, and take as an example the laboratory drilling of a medium hard limestone (Portland limestone), at a simulated depth of 2000m. An 8 $\frac{1}{2}$ in. IADC code 1-3-6 bit in T: 0 condition was used, and this gave a rate of penetration of 16 m/h at 200 kN weight on bit and 60 rpm. The torque value recorded during drilling oscillated about 3.7 kN.m.

Under these conditions, the work done by the torque acting on the bit was 23.2 kW (31.2 HP), and the quantity of rock destroyed was $1.628 \times 10^{-4} \text{ m}^3/\text{sec}$. This yields a specific energy needed for rock destruction of $14.25 \times 10^7 \text{ J/m}^3$. This value ($142.5 \text{ MJ/m}^3 = 142.5 \text{ MN/m}^2$) is comparable to the compressive strength of the rock, which, under atmospheric conditions, is about 70 - 80 MN/m^2 .

but will be nearer to 120 MN/m^2 under the high-pressure conditions that were used for the drilling experiments (D. A. Curry, private communication). This is not an unusual finding for a variety of rocks and mechanical drilling processes (Ryhming, Cooper et al., 1980), and amounts to a requirement that to drill the rock by such a method, it will be necessary to apply a stress equal to the failure stress of the rock, and to make this stress do work equivalent to translating its point of application through the full thickness of the rock to be destroyed.

This value for the specific energy of rock destruction by the rotary drilling process, of $1.4 \times 10^8 \text{ J/m}^3$ may be compared with the estimate of energy required to load the rock to failure, found above for granite as $4 \times 10^5 \text{ J/m}^3$. The former is greater than the latter by a factor of 350 times, and this represents the order of potential improvement in efficiency for a drilling process that destroys all of the rock within the volume to be excavated. We assume, of course, that the drilling process does not break the rock down into particles smaller than 1.5 mm; if so, we shall have to provide additional energy to create the new fracture surfaces. Even greater efficiencies could be achieved theoretically if not all the rock were destroyed as, for example, by cutting around the circumference of the hole and removing a core of rock intact, but in this general discussion we do not suppose any specific type of drilling process or equipment.

The question can now be raised as to whether we need to increase the efficiency of rock destruction. The value of 32 horsepower, calculated in the example above, dissipated at the bit is not excessive, and at present it is not a problem to bring this amount of power to the workfront. Thus, even though the rock destruction process is very inefficient, neither the power nor the power density requirements appear to be limiting the drilling process.

3.1.2 Drilling Rate Limitations

If the rate of penetration is not limited by power supply constraints, the rate limiting factors must be found in the conversion process, i.e., in the amount of rock that can be broken and removed in a given time. The amount of rock that can be broken by a bit with either a drag or rolling/indenting action depends on three main factors:

- a) The depth of indentation,
- b) The volume of rock broken out from an indentation of given depth, and
- c) The number of indentations per unit area of the workfront per unit time.

Now the extent to which the drilling rate is limited by each of these factors is examined.

3.1.2.1 Depth of Indentation

The depth of penetration for either type of cutting action is, to a first approximation, proportional to the applied normal load, and therefore to the force that can be applied to the cutter. Cutters of different shapes will indent to different distances, the depth increasing, broadly, with the "sharpness" of the cutter point. Unfortunately, the sharper the cutter, the weaker and less wear-resistant it tends to be, and so a compromise must be sought in terms of sharpness, strength and wear resistance. Over many years, the bit manufacturers have produced a range of cutter

shapes for both drag and indenting cutters that reflect the best compromises that can be attained for any given rock, and for the range of cutter materials available. At present, bit teeth for soft rocks are sharply pointed, and are made of tool steel, often coated on one side with a suitable hard-facing alloy. For harder, more abrasive rocks, the bit teeth are frequently made of tungsten carbide, and, (because of the low fracture toughness of this material) are of a shorter and more rounded form. It is unlikely that a more efficient geometrical form can be designed within the strength and wear limitations of current materials, so the development of more aggressive and efficient cutter shapes will have to wait upon the development of new cutter materials.

The penetration of a cutter of any given shape may of course be increased simply by increasing the load on the cutter. In the present context, there is rarely any limit to the force that can be applied to the bit (the exception being in the drilling of top hole in hard rocks), and so the limiting factor will be found in the force that can be transmitted through the bit. This is determined by the design of the bit and the performance of the materials from which it is constructed.

In the case of roller-cone bits, simple geometrical considerations determine that the maximum cone diameter is at most about half of the bit diameter, while inside the cone there is a bearing, whose size is determined by the loads to be applied on the cone. Thus, if it is desired to increase the rate of penetration by giving the bit longer teeth and a higher weight on bit to cause the teeth to bite more deeply, there arises the double problem that to make the teeth project further, some of the cone body must be removed, but at the same time, because of the higher load requirement, the size of the bearing must be increased. This problem is well known to the bit manufacturers, and over the years designs have evolved that balance tooth length and strength with bearing requirements to give a range of bits adapted to give the best performance in any particular rock. The design of roller-cone bits has now evolved to the point where no significant further improvements can be made in their penetrating capability unless improved materials become available. Specific materials improvements that would allow increased penetration per rotation in roller-cone bits will include increasing the load-carrying capacity of the bearing (allowing more space for longer teeth), and the development of tooth materials with higher strength and toughness. The latter improvements should not be obtained at the expense of wear resistance, however, for increased ROP will then only be obtained at the cost of shorter bit life.

In a drag bit, there are no moving parts, so the only constraint to making a deeper cut is whether the cutters and bit body can stand the increased cutting loads. At present, the only drag cutter material being used is polycrystalline diamond compact (PDC), and there are limits to the size of cutter available (at this time, the maximum button diameter is 2 in. = 50 mm). This does not limit the depth of cut unduly, however, as the buttons can be mounted on studs that project out of the bit face. In rocks that are soft and not abrasive, penetration rates of 30 m/hr are not unusual at rotary speeds of 100 rpm or so, implying a depth of cut of 2.5 mm. Under these circumstances, if the rock being drilled is not abrasive, and hard bands that could break the teeth by overload are not encountered, bit lives of many thousands of feet can be attained. If the bit encounters stronger rocks, the teeth are subjected to loads that are capable of breaking either the tungsten carbide backing material of the button, or, less commonly, the material of the stud or bit body. As with the roller-

cone bits, therefore, increases in depth of penetration will be contingent on the development of stronger tooth and tooth backing materials.

3.1.2.2 Crater Volume

If increases in the depth of penetration of the bit teeth must await the arrival of superior materials, the factors that determine the relationship of indentation depth to crater volume should be examined. For a given depth of penetration and constant rock properties, crater volume depends to some extent on indenter shape, and in particular, there is an increasing ratio of crushed material to chips (in brittle rocks) as the indenter becomes blunter. For practical purposes, there is little to be done in trying to modify the indenter shape to increase the crater volume directly, as one is always led back to the finding that maximum crater volume *for a given load* is with the tooth shape that attains the greatest penetration. (A possible exception to this finding is that in very plastic rocks, such as shales, crater volume is much increased for roller-cone bits by adjusting the cone geometry so that a shearing action is generated). This line of enquiry leads back to the finding that improvements in bit performance again depend on improvements in bit construction materials.

If the drilling process is considered from the point of view of the rock, it is found that crater volume and therefore the overall rate of penetration are much affected by the mud type and the pressure environment around the bit. These are linked by the so-called "chip hold down effect" which relates reductions in ROP to increases in the differential between pore and mud pressures, and to reduced filtration rates experienced with high viscosity muds.

To understand these effects, we need briefly to review some aspects of the mechanics of rock destruction under a drill bit. The operation of either roller-cone or drag bits relies on the initial formation of a crushed zone under the bit tooth, followed by the propagation of cracks from the crushed zone out toward the surface of the rock. When the cracks reach the free surface, they liberate chips of rock that are removed by the mud flow. The rock destruction process thus includes two distinct mechanisms, the crushing of the rock under largely compressive stress, and the formation of chips by the propagation of tensile cracks running sub-parallel to the free surface of the rock, driven by the wedging action of the expanding crush zone (see Figure 3-2).

better penetration → better materials

Figure 3-2. Bit Cutting Action

It has long been recognized that drilling rates in the field decrease with increasing depth. This is partly due to the fact that deeper rocks are more compact and intrinsically stronger, because they have been buried longer, and are under greater pressure than younger, shallower rocks. However, it was also shown that field rates of penetration at depth are much lower than those obtained when the same rocks are drilled in the laboratory under atmospheric conditions. The increase in strength with pressure of a wide range of rocks has been well documented, and will not be reviewed here, except to show a typical result, for Tennessee marble, from (Wawersik and Fairhurst 1970), in Figure 3-3. Here it is noted that the yield strength of the rock increases by a factor of about two, and the rock deformation becomes progressively more ductile, as the confining pressure rises to about 50 MPa (7,250 psi, equivalent to a burial depth of about 1,750 m, or 5,700 ft.).

It is also clear, that these increases in strength and ductility depend only to a small extent on the absolute magnitudes of the applied stresses. A much more important factor is the amount by which the confining stress exceeds the pore pressure. This is the so-called "effective stress," and it has been shown that the compressive strength does not rise if increases in confining stress are matched by equal increases in the pore pressure. In other words, for constant effective stress, the stress-strain curves overlay. See Figure 3-4 from Handin, Hager et al., (1963).

Figure 3-3. Complete Axial Stress-strain Curves for Specimens of Tennessee Marble Tested in Triaxial Compression. Numbers Adjacent to the Curves Give the Confining Stress. (Wawersik and Fairhurst, 1970)

When experiments were carried out to investigate the relevance of these findings to drilling, related results were obtained. Maurer (1965) made single-tooth indentation experiments on rock samples where the rock confining stress and pore pressures could be varied independently, and where the pore fluid could be isolated from the fluid above the rock sample (the "drilling mud") if needed, by using a specially-formulated mud having essentially zero fluid loss.

Figure 3-4. Stress-strain Curves for Berea Sandstone at Different Pore Water Pressures (Kbar). Below: All at 2 Kb, and 24 or 300 C., All in Compression Except Curve Marked Ext (for Extension). Above: At Confining Pressures (P_c) of 0.5, 1, and 2 Kb, at 24 C., At Pore Pressures (P_p) of 0, 0.5, and 1.5 Kb; All Therefore at the Same Effective Pressure of 0.5 Kb. (Handin, Hager et al., 1963)

Results from these experiments showed that:

- i) The pressure necessary to cause indentation in Berea sandstone was almost independent of hydrostatic pressure when this was applied by air or clean water, but increased sharply (at 4,000 psi, to six times its "atmospheric" value) when a differential was established between pore and "borehole" pressure by use of the mud (Figure 3-5).
- ii) The crater volumes measured in these experiments showed no change as a function of pressure with air as the pressurizing medium, a reduction of about 50% at 5,000 psi using water with no differential pressure, and a reduction of about 90% at 5,000 psi with the mud (Figure 3-6).
- iii) Force, indentation curves obtained in similar experiments on Indiana limestone showed progressively greater indentation loads, and more ductile behavior with increasing differential pressure under static or dynamic loading conditions when mud was used above the rock surface. However, when water was used as the pressurizing medium the increases were only seen under dynamic

loading, and no increases at all were found when air was used to apply the pressure.

- iv) As with Berea sandstone, crater volumes in the Indiana limestone decreased sharply with pressure using mud, to a lesser extent with water, and not at all with air.

These results were paralleled by data obtained in model drilling experiments by Murray and Cunningham (1955), Eckel (1958) and Cunningham and Eenink (1959), that showed reductions in ROP (equivalent to reductions in indenter crater volume) in both Berea sandstone (Figure 3-6) and Indiana limestone (Figure 3-7) to be dependent on differential, rather than absolute pressure. Furthermore, they showed that even a material with no intrinsic strength (loose sand), could be quite difficult to drill if subjected to a sufficient differential between mud and pore pressures.

Figure 3-5, left and Figure 3-6, right. Effect of Bottom-Hole Pressure on Threshold Force and Crater Volume for a Single Dull Bit Tooth in Berea Sandstone (Maurer, 1965)

Garnier and Van Lingen (1959) made similar drilling experiments with rocks of different permeabilities, and found that whereas the permeable rocks showed reductions in ROP as a function of differential pressure when drilling with mud but not with clear water, an impermeable rock showed reductions in ROP both with water and mud. These results have been broadly confirmed more recently at full scale by Black and Green (1978) in laboratory experiments on sandstone, and in the field on shale by Viridine and Benit (1968).

Figure 3-7. Effect of Mud Column Pressure and Formation Pressure on Drilling Rate in Berea Sandstone. Overburden Pressure is 8,000 psi, Bit Weight 1,500 lbs., at 50 rpm. (Cunningham and Eenink, 1959)

The explanation of these effects is only partly related to the increase in strength of rock as a consequence of the confining stress resulting from the differential between pore and mud pressures. The increase in indentation resistance at high differential pressure reported by Maurer is similar to the increase in yield stress reported by Wawersik and Fairhurst at high confining stress. This effect alone cannot be the complete explanation for the reduction in ROP, however, as the crater volume and ROP decrease much more sharply than the rock strength increases; Maurer reported a reduction of the crater volume to one twentieth of the "unconfined" value, and similar reductions in ROP while drilling were reported by Cunningham and Eenink (1959) (Figure 3-7 and Figure 3-8).

Figure 3-8. Effect of Differential Pressure on Drilling Rate of Indiana Limestone. Overburden Pressure 6,000 psi (Cunningham and Eenink, 1959)

The dominant factor responsible for the reduction in ROP appears to be the so-called "chip hold down effect." This is the capacity of the pressure differential between the mud and pore pressures to inhibit the process of crack growth from the crush zone out to the free surface, and the subsequent lifting-off of the new chip from the bottom of the hole. Clearly, the opening of this crack and the lifting of the chip against the bottom-hole pressure will be hindered if fluid cannot flow into the growing crack to relieve the partial vacuum generated as the crack opens. This process will take time, and will depend upon how easily fluid can flow into the growing crack. One source of fluid could be the drilling mud, unless it is prevented from entering the crack by the formation of a filter cake. This explains the inhibiting effect of the drilling mud in Maurer's experiments, and the reduction of ROP reported by Cunningham and Eenink. It also explains why no reduction in crater volume was seen, even in dynamic experiments, when the indentation experiments were carried out in air, but why increases in failure load, and reductions in crater volume, were found under dynamic conditions when using water. (In addition, some decrease in crater volume, but no increase in load, was found under static conditions with water.) Evidently, the viscous losses arising from using water, rather than air, to fill the growing crack cause progressively greater problems in chip formation as the time available to grow the failure cracks decreases.

It should be noted that the fluid needed to fill growing cracks may come not only from mud filtrate, but also from pores in the rock. Therefore, other things being equal, a permeable rock should not be as susceptible to the chip hold-down effect as an impermeable one. This is indeed what was found in the experiments of Garnier and Van Lingen (1959), where it was reported that ROP was decreased in permeable rocks only when drilling with mud, but that in impermeable rocks, reductions were found with both mud and water (see Figure 3-9).

Figure 3-9. Penetration Rate as a Function of Pressure (Garnier and Van Lingen, 1959).

These observations led Garnier and Van Lingen to distinguish between what they defined as "static" or "dynamic" chip hold down. The former being the result of any nominal difference between the pore and borehole pressures, and the latter being due to the pressure reduction underneath the growing chip. Dynamic hold down can occur whether there is any static differential pressure or not. It is clear that the nominal differential between pore and borehole pressures is reduced by the filtration of mud into the formation, and so even the "static" differential pressure across the hole bottom changes as a function of mud filtration, rock permeability, and the present ROP. This distribution of pressure ahead of an advancing bit has been investigated by Young and Gray (1967), who showed that most of the pressure drop occurs within a distance of about one millimeter from the free surface of the rock, and that the pore plugging agent may be derived from either mud solids or crushed rock.

To combat the adverse effects of chip hold down, we must encourage by all means possible an equilibration between the borehole and formation pressures in both the static and dynamic senses. The first action to be taken is to reduce the static differential pressure by reducing the mud weight locally, if not throughout the length of the hole. The second action is to aid the diffusion of mud or mud filtrate into the formation and into the region of the growing cracks.

Concerning the reduction of the borehole pressure, it is well known in the field that decreasing mud weight results in increases in rate of penetration. It does increase the probability of well kicks, and therefore the risk of blowout. There is, nonetheless, the possibility that some means can be invented to reduce borehole pressure in the immediate vicinity of the workfront, while maintaining a greater and safer pressure higher up the well. Various authors have suggested ways of performing this. Van Lingen (1962) has shown how using jet nozzles only 5 mm. from the bottom of the hole increases the reduction factor for penetration rate to 0.9 from only 0.17 with conventional flushing by a large hole in the center of the drill bit; see Figure 3-10.

Figure 3-10. Effect of Nozzle Diameter and Position on Static Holddown (Van Lingen 1962)

Feenstra and Van Leeuwen (1964) presented the factor of gain in penetration rate as a function of nozzle velocity for different types of rocks; see Figure 3-11. Sutko and Myers (1971) studied the effect of number of nozzles and nozzle extension on bottom-hole pressure. They found that at constant jet velocity, use of one or two, rather than three nozzles, gave a pressure differential between the hole bottom and the formation more favorable to increased penetration rates. Bizanti (1987) has suggested that this could be achieved by the use of an upward-facing nozzle, acting as an ejector, placed just above the bit.

Figure 3-11. Factor of Gain in Penetration Rate (Feenstra and Van Leeuwen 1964)

Regarding the equilibration of pore and borehole pressures by encouraging rapid diffusion of mud filtrate into the surrounding rock, it is likely that substantial increases in ROP could be obtained by using muds with high filtration loss. However, drilling rates equal to atmospheric values will not be obtained even using pure water in the presence of a differential between pore and borehole pressures, because of the plugging effect of rock debris. Nonetheless, reduction in the solids content of the mud is clearly desirable. Papers that document changes in drilling rate with changes in the solids content include early work by Eckel (1954) and Moore (1958). Darley (1965) described the favorable results of using larger sized particles in the mud where the chip hold-down force is controlled by the presence of bridging particles. Lummus and Field (1968) showed that small increases in solids content of the mud decrease ROP and bit life, and increase total drilling time. Estes (1974) reported that colloidal particles of size less than one micron are ten times more harmful to ROP than are particles of size greater than 30 microns. In support of this observation, Lummus (1970) showed that, for the same total solids content, a dispersed mud system gives greater reductions in ROP than a non-dispersed system, at least at low solids content. By the time the total solids content reached six percent, the two muds were indistinguishable, and both gave drilling rates no better than 65% of values obtained with water. Figure 3-12 from Lummus (1970) summarizes these findings. Finally, Eckel (1967) presented results showing that it was not the presence of the suspended solids themselves that caused reductions in the rate of penetration, but the increased viscosity arising from their presence.

Figure 3-12. Left, Effect of Solids on Drilling Performance, and Right, Effect of Solids Dispersion on Drilling Rate (Lummus, 1970)

This evidence implies that the best fluid to obtain high ROP is the one that has the lowest viscosity, and therefore contains as little solid material as possible. In most cases, pure water will have the highest rate of permeation, but there are circumstances where this may not be so. Such a situation can arise, for example where the rock contains water-sensitive clays that can swell on contact with pure water, and thereby reduce the permeability of the rock independent of whether or not a filter cake is formed at the workfront itself. Such a situation has been documented in work published by Evans and Gray (1972), but is not typical. In the normal situation, one should concentrate on removing as much of the solids as possible, with a preference for removing the fine solids rather than the coarser material.

3.1.2.3 Increasing Speed and Frequency of Indentation

The third influence on the rate of penetration is the rate of indentation and the rate at which successive indentation events follow each other. Both of these are increased by increasing the rotary speed, and this increase has implications in two areas—the influence of high strain rate on the mechanics of rock deformation and cuttings removal, and the mechanical behavior of the bit.

3.1.2.3.1 Influence of Strain Rate on Rock Destruction and Cuttings Removal

Fortunately, most rocks do not increase significantly in strength as the strain rate increases (Jaeger and Cook, 1976), although substantial increases are seen in both the strength and strain to failure of shales (Wichter, 1979), (Chiu, Johnston et al., 1983) and (Swan, Cook et al., 1989). With the exception of shales, it is anticipated that by increasing the rotary speed, with the other parameters held constant, a proportionate increase in ROP will be experienced. This is

generally not so, as it is found experimentally that the penetration per revolution decreases with increasing rotary speed. The obvious explanation for the shortfall is the (dynamic) chip hold down effect, discussed above. The magnitude of the effect depends upon several factors, including the bit type. Figure 3-13, taken from Van Lingen (1962), documents this effect and shows that, at least for the limestone that was tested, there are substantial differences in performance losses as a function of rotary speed for the different bit types tested. The adverse effect of chip hold down is also expected to increase with increasing absolute pressure, i.e., depth, and indeed, this supposition is supported by the experimental work of Rowley, Howe et al., (1961) (see Figure 3-14), Garnier and Van Lingen (1959) and Van Lingen (1962). (The above findings may not be applicable to drilling shales with PDC drag bits, however, as it appears that they do not show a decreasing rate of penetration per revolution under conditions of increasing differential pressure.)

Figure 3-13. Reduction In Penetration Per Revolution as a Function of Rotary Speed for Different Bit Types (Van Lingen, 1962)

Figure 3-14. Effect of Changing Rotary Speed on Rate of Penetration and Penetration Per Revolution: Data for Depths of Zero and 3,000 ft (Rowley et al., 1961)

Notwithstanding the above observations, rate of penetration does increase with increasing rotary speed, albeit with a diminishing rate of return, and so it may be worth while to seek greater ROP by increasing rotary speed. To maintain penetration per revolution as the rotary speed is increased, we must be aware of two requirements. The first is that the volume of rock broken should not be reduced in spite of the increased strain rate and the reduced time of indentation. Here, all the recommendations made previously concerning dynamic chip hold down are relevant, i.e., we should reduce differential pressure and mud viscosity, and increase mud filtration rate as much as possible. The second requirement is that the broken rock must be cleared out of the crater and away from the workfront before the next indentation event in that area; if not, the broken rock will simply be re-crushed, and as well as shielding the hole bottom from the action of the bit, and generating excessive fines, that further reduce the ROP.

Removal of the broken rock is achieved by flow of drilling mud over the workfront, and much research has been carried out to determine how this is best accomplished, both in terms of geometrical arrangement of the bit nozzles and optimum use of hydraulic power.

As early as 1978, Pratt (1978) reported improvements in ROP by equipping roller-cone bits with extended nozzles, and there has been a steady sequence of further improvements reported since. Cholet, Abdullah et al., (1987) report the use of nozzles that are not only extended but are oriented toward the point of contact of the teeth with the rock. This resulted

in an average improvement in ROP of 20% over conventional extended nozzles. Moffitt and McGeehee (1989) report the results of laboratory full-scale drilling tests in Mancos shale using roller-cone bits with different combinations of standard and extended and/or inclined nozzles, and center jets. They found that "directed nozzles provide substantially better bit cleaning and rate of penetration than standard and short extended nozzle configurations, and slightly faster penetration rates than long extended nozzle configurations."

Work on the effects of introducing cross-flow by suppressing or reducing flow from one nozzle, and the effect of center jets was reported by Delafon and Bannerman (1989). A useful paper by White, Curry et al., (1988) gives results of combined theoretical and full-scale laboratory tests on bit hydraulics that explains some of the basis for the above-reported results.

More radical ideas on changing bit hydraulics are discussed by Hayatdavoudi, Akhigbe et al., (1984), who describe a "Vortex-generator" above the bit, and Ghalambor, Hayatdavoudi et al., (1988) who proposed the use of an intermittent mud flow to improve cuttings removal. Bizanti (1987) discussed the possibility of generating a reduced pressure in the bit region by the use of an upward-facing nozzle, and Angona (1974) has investigated the use of cavitating jets as a method of drilling rock without mechanical means. None of these four proposals has yet progressed further than field testing. There has been some interest in the use of ultra-high pressure jets to assist in the rock-destruction process. This is not a new idea, and much work has been done on this subject in the past. Two recent papers by Littleton (1987) and Maurer, McDonald et al., (1986), show that there is still an active interest in the subject.

Finally, some attention should be given to the problem of bit balling, i.e., the tendency of cuttings to stick to the bit and by interfering with the flow of mud over the bit face, reducing both cuttings removal capacity and cooling of the cutting elements. Hopkin (1967) says that concentration of cuttings in the annulus must be less than 5% to prevent balled up drill collars and stuck drill pipes. Feenstra and Van Leeuwen (1964) showed, for roller-cone bits, how jets alleviate balling by reduction of holddown and improving tooth scavenging at high bit loads where balling is accompanied by chip holddown; see Figure 3-15 and Figure 3-16. In general, a bit with large spacing between the cutting points and bit body will discourage bit balling, but this will reduce the support and hence the strength of the teeth. Similar considerations apply for PDC bits. (Warren and Armagost 1988) show that parabolic or bladed bit designs are superior to the flat face types in both ROP and resistance to bit balling in sticky formations, but they are more susceptible to damage if hard formations are encountered.

As stronger materials and better designs are found for the bit body, it may be expected that there will be an increasing tendency to employ bladed, rather than flat-face bits in the future, with the flat-face bits being reserved for harder formations (and for special applications, such as directional drilling). To the extent that they can be made strong enough, there will also be a tendency to use larger and larger diamond compacts, as these allow greater depth of cut and a less encumbered path for the removal of the cuttings.

Figure 3-15. Jets Affect Penetration in Particular When Hold Down is Accompanied By Bit Balling (Feenstra and Van Leeuwen, 1964)

Figure 3-16. Use of Jets to Reduce Bit Balling (Feenstra and Van Leeuwen 1964)

Various authors, including Chenevert (1970), Holder (1982), Holt et al., (1987), Kelly et al., (1980), Griffin (1986) etc., have performed experiments to counter the effect of bit balling using suitably altered mud. Using additives to modify drilling mud may not be

acceptable if one adheres to the strictest environmental restrictions that are increasingly coming into force. Therefore, developing a completely different method of reducing bit balling is worth looking into. A possible new approach could be the use of an electric potential at the bit surface to discourage the sticking of clay to the bit body. This proposal is based on the observation that if a potential of a few volts is established between two metal plates sandwiching a block of clay, water is liberated at the cathode plate, and this water layer prevents the clay from sticking to the metal surface. In the context of a drilling operation, the bit would be made the cathode, and the liberation of water at the bit surface would effectively discourage bit balling. Preliminary experiments carried out by the authors show that this is indeed the case.

Bottom balling, i.e., the phenomenon by which the surface layer of the hole bottom is covered by a layer of pulverized rock and mud solids compacted together is yet another aspect of deep hole drilling that demands some attention. This is more prominent on drilling a non-friable rock with an insert type bit, which has a crushing action. A large differential pressure causes the mud filter cake to act as a trap, holding the cuttings against the hole bottom, allowing regrinding to occur and effectively giving rise to bottom balling. Further, cuttings clog the pores, causing differential pressure to hold them down more firmly and giving rise to further bottom balling. Feenstra and Van Leeuwen (1964) state that most bottom balling will occur when a high circulation rate is combined with low nozzle velocity. Conversely, it can be reduced by increasing the nozzle velocity. Increasing the circulation rate is helpful but less effective (Figure 3-17).

Figure 3-17. In a Practical Range of Q and V_n , Bottom Balling is Reduced Significantly by High Nozzle Velocity and Little By High Circulation Rates (Feenstra and Van Leeuwen)

According to Maclean (1964-65), crossflow, i.e., the flow parallel to the bottom of the hole away from the area of impingement, has a greater influence, and maximizing crossflow would maximize the shear stress on the bottom and effectively keep the filter cake formed at the bottom thin and permeable. For a tricone bit, Sutko and Myers (1971) found that bottom-hole cleaning and drilling rate improved as the number of nozzles decreased and the nozzle was more extended toward the bottom of the hole. Feenstra and Zijssling (1987) discussed the formation of rock flour under different types of bits. With hard formation roller bits, the cutters truly roll over the hole bottom with minimum dragging action. This action, in combination with blunt cutters, converts particularly friable virgin rock under the cutter into rock flour, if chip hold-down is sufficiently developed. For soft formation roller bits, the dragging action of the sharp cutters helps to remove rock flour from the hole bottom, and thereby reduces bottom balling. The severe negative back rake angle present in drag type bits may also cause clogging of the rock surface. Thus, for a sharp dragging bit, in addition to intensive bottom scavenging of the hole bottom, it is a sound idea to use a minimum negative back rake angle.

Another important function of the drilling fluid is removal of cuttings from the bottom of the hole; Maurer (1962) defines perfect cleaning as the condition when all rock debris is removed between tooth impacts. He presented graphs comparing drilling rate versus rotary speed and bit weight for conditions of perfect and imperfect cleaning, i.e., for an ideal and an actual case; see Figure 3-18. Feenstra and Zijssling (1987) state that adding a fourth nozzle in the center of a large bit (up to about 10 in.) would improve its cleaning characteristics. Sutko (1973) concluded that chip size, nozzle velocity, fluid velocity and nozzle characteristics (extended or closed nozzles) are more important than fluid viscosity as far as chip removal force is concerned. Figure 3-19 and Figure 3-20 show the effect of nozzle extension and jet velocity on chip removal force.

In deep drilling, high mud overbalance pressures inhibit chip formation, resulting in much reduced rates of penetration. Most of the energy put into the bit is absorbed in plastic deformation of the rock (Maurer, 1965) and pore compaction (Suarez-Rivera et al., 1990). Under these conditions very high pressure fluid jets can be used to remove the damaged rock from the bottom of the hole and thereby improve rates of penetration.

Flow Drill has developed a proprietary system of mud cleaning, ultra high pressure pumps (34,000 psi), ultra high pressure swivels, dual tube drill string and bit nozzles. This system adds about 600 to 800 hydraulic horse power to the bottom of the hole. Initial field tests in west Texas showed 2 to 3 times improvement in rates of penetration at depths of 3000 ft to 5000 ft.

Figure 3-18. Comparison Between Perfect (Ideal) and Imperfect (Actual) Cleaning (Maurer)

Figure 3-19. Effect of Nozzle Extension on the Chip Removal Force (Sutko 1973)

Figure 3-20. Chip Removal Force as a Function of Jet Velocity (Sutko 1973)

Chips dislodged from the hole bottom have to be lifted to the surface through the annulus. Hopkin (1967) says that during slower hard rock drilling, an annular mud velocity that exceeds the slip velocity of the largest size cutting by 20-30 ft/min is usually sufficient to keep the hole clean. Slip velocity is a function of mud viscosity, constant up to a funnel viscosity of approximately 90 sec/qt, and is reduced by increasing the mud density.

3.1.2.3.2 Materials Problems Associated With High Rotary Speeds

Having established that, from the point of view of the rock destruction process, it will be worth while to increase rotary speed to increase the ROP, we need to establish the equipment and materials limitations to such an increase. First, for either roller-cone or drag bits, there are limits to rotary speed if the bit is driven by rotation of the string from surface. Problems of dynamic instability of the string are coupled with increased wear of all the string components, with the consequence that the rotary speed is effectively limited to about 200 rpm. Fortunately, the problem can be avoided by driving the bit from a down-hole motor. This may either be a relatively low speed, (100-400 rpm) high-torque, positive-displacement motor (PDM), or a turbine, which typically will operate at speeds up to 800 to 1000 rpm. Although both types of down-hole motor have had problems with reliability and wear in the past, continuous improvements are being made. Within the context of the present discussion, it is safe to assume that it will ultimately be possible to provide adequate drive power to the bit at speeds of least 1000 rpm.

3.1.2.3.3 Materials Problems in Roller-Cone Bits for High Speed Operation

Operating the bit at high rotary speeds causes different problems for roller-cone and drag bits. In the case of roller-cone bits, the major problem lies in the significantly shorter life of the bearings. Some effort has been invested in developing bearings that are adapted to high rotary speeds. Earlier developments in bearing and seal design (Deane, Doiron et al., 1984) have led to a seal with a raised "tread" pattern. The recesses in the "tread" trap pockets of oil, resulting in greater access of the oil to the sliding surfaces, and a partially hydrostatic bearing effect (Carter and Daly, 1985). This bit was found to operate satisfactorily at speeds from 300 to 700 rpm. An alternative approach suggested by Sneddon and Hall (1987B) is to retain the journal bearing design, but to make the bearing elements out of polycrystalline diamond. Sneddon states that adequately cooled diamond bearings will sustain values of PV (bearing pressure multiplied by sliding speed) of 13 million (units not defined), compared with 2 million for a lubricated ball bearing. Furthermore, because the diamond surfaces are so hard, they do not need to be protected from the drilling mud, which merely polishes the sliding surfaces. Therefore, the bearings can be conveniently cooled by allowing free access to the mud. This change has the added advantage that the contentious problem of providing an adequate seal, particularly for high temperature, high speed operation, is eliminated.

Another problem encountered at high rotary speeds is excessive wear to the gauge cutters. This is a particularly tiresome problem because, unless the hole is reamed after removal of worn bit, the next bit will be squeezed as it is run into hole, and irreparably damaged even before it has begun to drill. The recent introduction of diamond-coated tungsten carbide inserts however appears capable of solving this problem (Salesky, Swinson et al., 1983). If the manufacturing costs of introducing these improvements can be contained, it is possible that roller-cone bits capable of operating at 1000 rpm with adequate bit life will be available within the next few years.

3.1.2.3.4 Materials Problems in Drag (PDC) Bits for High Speed Operation

Two major problems associated with increasing the rotary speed when using PDC bits include excessive wear caused by frictional heating of the cutting elements, and breakage of the cutters due to high impact loads. At ambient temperatures, polycrystalline diamond compacts are mechanically damaged by cutter loading, but the rate of wear is generally low and does not cause undue problems. As temperature rises, thermal expansion mismatch between the diamonds and the cobalt catalyst filling the space between the diamonds causes significant weakening of the diamond layer. Figure 3-21 shows the difference in coefficients of thermal expansion for materials used in manufacturing PDC and TSD cutters. The problem of thermal cutter degradation is discussed at length by Sneddon and Hall (1987A), who indicate that thermal damage can occur both to the diamond layer and to the tungsten carbide support material. The hardness of the diamond portion of a PDC cutter drops linearly with temperature, and traumatic thermal-physical failure occurs at temperatures above 730°C. More importantly, the tungsten carbide support material suffers increased wear at temperatures above 350°C (Glowka and Stone, 1985) resulting in failure of both the tungsten carbide and diamond components.

Figure 3-21. Coefficients of Thermal Expansion for Materials Used in SYNDAX3 and SYNDITE PCD Products

Figure 3-22. Granite Turning Test Results. Effect of Heat on Standard PCD

In an effort to alleviate the temperature limitations of PDC bits, a range of thermally-stable diamond (TSD) cutter elements have been introduced that contain no cobalt and do not utilize a tungsten carbide substrate (Figure 3-22 compares TSD temperature stability to that for PDCs). Because of these changes, TSD cutters are capable of performing successfully at temperatures between 875 $^{\circ}\text{C}$. and 1200 $^{\circ}\text{C}$. (1200 $^{\circ}\text{C}$. in the case where oxygen is not present, 875 $^{\circ}\text{C}$ in the presence of oxygen. When using drilling fluid, the maximum temperature will be somewhere in between.) Two types of TSD manufacturing processes currently exist that drastically reduce the problem of thermal mismatch stresses. In the first process, the cobalt catalyst is removed by acid leaching, leaving a porous material that is weaker than the original metal-filled compact. In the second manufacturing process, the cobalt catalyst is replaced by silicon that has a thermal coefficient of expansion similar to that of the diamonds. The silicon improves the cutter's thermal stability, and results in a strong, nonporous TSD cutter. Although TSD technology is new, bits containing TSD cutters are currently being used to drill hard, abrasive formations that cannot be drilled effectively with PDC bits. These bits look similar to natural diamond drill bits because the TSD cutters are surface-set in a matrix body rather than pre-mounted on a tungsten carbide substrate (as are the PDC buttons). TSD bits have potential in deep drilling applications and provide numerous

opportunities for new research and development. It appears that TSD bits will find a niche between PDC and natural diamond bits for drilling hard formations in deep wells.

Although the TSD cutters have enhanced thermal capabilities, it is important to maximize cooling of both PDC and TSD cutters to improve bit life. One method of accomplishing this is to use high-power liquid jets directed at the cutter points. Another approach is to improve the wetting of the cutters by adjusting the chemistry of the flushing fluid as demonstrated during an investigation of the so-called "Rehbinder effect" by Cooper (1976 and 1977B). Here, it was shown that the addition of various organic and inorganic additives to the flushing fluid significantly reduced diamond cutter wear and increased ROP. Although these results were obtained using diamond impregnated bits, similar effects would be expected for PDC and TSD bits.

3.2 SUMMARY AND CONCLUSIONS

In conclusion, the limits to mechanical drilling can be divided into three aspects — (i) Indentation Depth, (ii) Crater Volume, and (iii) Rate Effects.

3.2.1 Indentation Depth

Depth of indentation increases with applied load and sharpness of the cutter point. Since theoretically, unlimited force can be applied to the bit, the limiting factor is found in the force that can be transmitted through the bit. The maximum value of this force depends on the design of the bit and the materials from which it is constructed. For roller-cone bits, the depth of indentation could be increased by constructing bits with longer teeth and applying high loads. Making the teeth project further implies that some of the cone body must be removed, but again the requirement of higher loads means that bearing size, and therefore the solid part of the cone, would have to be increased to accommodate it. The bit giving the best performance in a particular rock must be designed balancing tooth length and strength, with the bearing requirements. Further improvements in penetration capability can only be made by developing superior materials that allow increased load carrying capacity of the bearing and tooth materials with higher strength and toughness.

For drag bits, the only constraint to a higher bit load is the load bearing capacity of the cutters and bit body. Although the maximum button size for PDC bits to date is 2" (= 50 mm.), the depth of cut can be increased by using stud mounted buttons. Increase in penetration rate depends on the development of stronger teeth and tooth backing material. Depth of penetration increases rapidly with sharpness of the cutter point. However, the sharper the tooth, the weaker and less wear resistant it tends to be and thus a compromise has to be struck between sharpness, strength, and wear resistance. Assuming that geometric forms of bits has reached an optimum, taking into consideration the strength and wear resistance of current materials, development of better and more aggressive cutter shapes can only be possible with the development of new cutter materials.

3.2.2 Crater Volume

The formation of crater volume during a drilling process is influenced by both the tooth geometry and the behavior of the rock. As far as the tooth geometry is concerned, for a given load, crater volume would be maximum for the tool shape that has the maximum penetration. Thus the crater volume would be larger for a sharp bit than for a blunt bit that has an increased ratio of crushed materials to chips formed. Improvement in bit performance will again depend on improvement in bit construction material, to the extent that the new material allows increase in tooth sharpness without loss of strength or wear resistance.

Considering the drilling process from the point of view of rock behavior, the dominant factor is the chip hold down effect which relates reductions in ROP to increases in the differential between pore and mud pressures, and to reduced filtration rates experienced with muds of high viscosity. Drilling rates in the field decrease with increasing depth. One reason is that deeper rocks are more compact and intrinsically stronger; Figure 3-3 shows a typical result. The dominant reason is the amount by which the confining pressure exceeds the pore pressure; Figure 3-8 shows how differential pressure affects overall drilling rate. Chip hold down is related to the capacity of the pressure differential between the mud and pore pressures to inhibit the process of crack growth from the crush zone out to the free surface, and the subsequent lifting of the new chip from the hole bottom. Either the drilling fluid or the pore fluid can relieve the partial vacuum generated as the crack opens, an effect that is hindered by the use of viscous fluids; refer to Figure 3-6. This view is strengthened by the fact that crater volume and ROP decrease much more sharply than the rock strength increases as a consequence of confining stress; refer to Figure 3-5 and Figure 3-9. Rock permeability also has an effect on chip hold down effect with permeable rocks subject to chip hold down, but only when mud is used. Impermeable rocks were subject to chip hold down both with mud and with water as the drilling fluid. Thus, to combat the adverse effects of chip hold down, the borehole pressure should be kept as near equal to the formation pressure as possible. This can be achieved in two ways—reducing static differential pressure by reducing the mud weight locally, if not throughout the whole length of the hole, and/or by aiding the diffusion of mud or mud filtrate into the formation and into the region of the growing cracks. Decreasing mud weight results in increased rate of penetration, but it also increases the probability of well kicking and the risk of well blowout. However, borehole pressure could be reduced in the immediate vicinity of the workfront while maintaining a higher and safer pressure higher up in the well; refer to Figure 3-10. Rapid diffusion of filtrate into the surrounding rock can be achieved by using a low viscosity fluid containing as little solid material (particularly the finer solid particles) as possible. It is worthwhile to mention here that using pure water may not be a good idea where the rock contains water sensitive clays that swell on contact with pure water. This would reduce the permeability of the rock whether a filter cake is formed or not.

3.2.3 Rate Effects

The rate of indentation and the rate at which successive indentations follow each other has an influence on rate of penetration, and can be increased by increasing rotary speed. This has implications in two areas—the influence of high strain rate on the mechanics of rock deformation

and cutting removal, and the mechanical behavior of the bit. At high rotary speeds, penetration per revolution decreases, due to the chip hold down effect; refer to Figure 3-10 which shows the loss of performance as a function of rotary speed for the different bit types. To overcome this difficulty, the recommendations given above concerning dynamic chip hold down are relevant, i.e., the differential pressure and mud viscosity should be reduced while increasing the mud filtration rates. To prevent the regrinding of cuttings, the broken rock should be removed between successive indentations. This refers to hole cleaning and can be performed by improving bit hydraulics and the strategic placement of bit nozzles. Extended nozzles, or nozzles placed at the center of the bit are beneficial in this respect—see Figure 3-19. Cross flow, produced by suppressing or reducing the flow from one nozzle may also be used for proper cleaning of the hole bottom.

The problem of dynamic instability of the drill string coupled with increased wear of all string components at high rotary speeds has been reduced by using downhole motors operating at speeds up to 2000 rpm. At high rotary speeds, conventional roller-cone bit bearings fail in 10 to 20 hours. It may be possible to overcome this problem by using seals with a raised 'tread,' or by making the bearing elements out of polycrystalline diamond. Excessive roller bit gauge cutter wear has been prevented by using diamond-coated tungsten carbide inserts on the heel rows of the cones. The limitations of using roller-cone bits for high speed operations are tied to perfecting the use of man-made diamond bearings and diamond coated cutters at economical prices.

The main problem with drag (PDC) bits at high rotary speeds is damage to the cutter elements caused by frictional heating and by high impact loads that shatter the cutters. High alternating stresses at ambient temperatures cause some degradation problems, but the main problem is caused by the thermal expansion mismatch between the diamonds and the cobalt catalyst filling the space between the diamonds. Thermally-stable diamond (TSD) cutter elements have been used to alleviate this problem. The use of silicon in place of the cobalt enhances the strength of this material and improves its wearability under high temperature conditions. Adjusting the chemistry of the flushing fluid has also been shown to reduce diamond cutting element wear, and to maintain cutter temperatures at acceptable levels.

The above conclusions are summarized graphically in Figure 3-23, where the three possible approaches to increase the drilling rate (viz. increasing the indentation depth, crater volume or rate effects) are used as headings. Below these are outlined the specific requirements or directions in which improvements should be made, and finally in bold type, suggestions in embryo for research topics that should be addressed.

If the objective is to increase rate of penetration by increasing indentation depth, progress will depend entirely upon development of stronger, tougher, and more abrasion resistant materials (and bearing quality in roller-cone bits). Regarding the question of increasing crater volume, improvements in bit material will be beneficial, but it will also be worthwhile to investigate ways of reducing static or dynamic chip hold down, by, for example, attempting to develop muds with higher filtration rates, or by reducing the depth of cut. If increases in rate of penetration are sought by increasing rotary speed, improvements could be made in the direction of high quality seals

and bearings, or in the case of drag bits by minimizing the thermal problems, by, for example, using bits made of thermally-stable materials.

In the very long term, it is interesting to speculate whether there are inherent limitations to the design of either drag or roller-cone bits that will ultimately limit the performance of one or other of the competing concepts.

From the point of view of the rock destruction process, it would appear that the drag bit is inherently superior to the indenting bit. First of all, because loading the rock in shear is likely to require lower forces and lower overall energy consumption per unit volume of rock broken than loading the rock in compression by normal indentation. Secondly, the drag bit has a positive mechanical chip removal mechanism insofar as the cutting tool sweeps over the hole bottom and scrapes it clean of cuttings as it goes. This is in contrast to the indenting bit where chip removal depends on the jet of cleaning fluid as the indenting tool moves out of the way. Indenting tool bits are expected, and found, to be much more sensitive to poor hole cleaning hydraulics than are drag bits, and their disadvantage is likely to grow as higher rates of penetration are attained. Furthermore, the performance of indenting bits is likely to suffer as the hole depth and absolute pressure increases. This is because most rocks become more plastic with increasing confining pressure, and hence less likely to form chips under normal loading by an indenter.

By contrast, when the materials questions are considered, it is the indenting bit that seems to have the more attractive future. This is because the cutters of a drag bit continuously scrape the surface of the rock as the bit drills and are therefore subjected to a far greater frictional heating load than are the teeth of a roller-cone bit. On roller-cone bits, not only are the bit teeth pressed normally into the rock with little relative motion between tooth and rock, but the teeth are periodically removed from the workface to be completely cooled by the drilling fluid (this includes the surface that actually comes in contact with the rock). Indenting cutters are expected to run cooler than drag cutters, and, since the rate of cutter tooth wear is closely related to cutter temperature, roller-cone bits are expected to have inherently longer lives than those of a corresponding drag bit.

The argument as to whether roller-cone or drag bits have greater ultimate potential depends on whether the overall rate of penetration is limited by problems of rock mechanics and removal of cuttings, (in which case drag bits will ultimately prove superior), or whether bit performance will be limited by the materials that make up the bit. If this is so, then roller-cone bits will dominate the drilling market.

The most probable outcome is that in soft and plastic rocks, where removal of a large volume of cuttings is important and tool wear problems are not too severe, drag bits will be the most successful. When the rock becomes hard and abrasive enough to cause serious wear problems for drag bits, roller-cone bits will continue to dominate the field. The boundary of preference between the two bit types will then fluctuate as gains in material performance are balanced against advances in techniques of chip removal and hole cleaning.

Figure 3-23. Overview of Research Options for Mechanical Drilling

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4. Conventional Deep Drilling Cost Sensitivity Analysis

In Volume 2, a representative deep well was established using the average wells from seven of the eight deep drilling regions in the United States. In this section, the representative well is used to study the cost sensitivity of the following drilling parameters:

- 1) Bit life (bit usage),
- 2) Penetration rate (rotating time),
- 3) Trip time,
- 4) "Other" time,
- 5) Casing time, and
- 6) Casing materials.

These parameters were selected because they significantly influence the commonly used drilling cost equation:

$$\frac{\$}{ft} = \frac{C_b + C_r(t_b + t_c + t_t)}{D}$$

where,

- C_b = Bit Cost, \$,
- C_r = Rig Day Rate, \$/day,
- t_b = Rotating time, hours,
- t_c = Nonrotating time, hours,
- t_t = Trip time, hours,
- D = Depth drilled, feet.

For example, "other" time and casing time both effect nonrotating time, t_c , bit life has a direct affect on bit cost, C_b , etc. As described below, sensitivity factors were used to vary the magnitudes of these variables in the computer program specially designed for this analysis.

Results of the cost sensitivity analysis are needed to determine how the various drilling techniques in Volume 4 need to be evaluated. There are too many variables influencing deep drilling costs to use each one during the drilling concept evaluations. Results of the cost sensitivity analysis reveal those variables with the highest impact on deep drilling costs, permitting a more efficient drilling systems evaluation to be conducted.

4.1 SENSITIVITY FACTORS

Sensitivity factors are varied from zero (0) to one (1), depending on the magnitude of change desired (a value equal to one (1) does not change the parameter value). The sensitivity factors are strategically included in all equations influencing, and influenced by, the analyzed drilling parameter. For example, if the impact caused by doubling the rate of penetration needs to be determined, the sensitivity factor for rotating time is set at 0.5. The spreadsheet program (described in Volume 2)

then increases penetration rate, and increases or decreases the other drilling costs affected by penetration rate. The resulting dry hole costs are then calculated on the standard AFE form (presented in Volume 2). The impact of the parameter changes can then be determined by comparing the new AFE form results with the base AFE. All results presented here use dry hole costs as a basis rather than overall costs so the direct impact of drilling parameter changes on drilling costs can be shown.

A similar procedure is used to conduct cost sensitivity analyses on each of the seven average regional wells. The results from these analyses are presented in Appendix C.

4.2 DRILLING TIME PARAMETERS

The following drilling variables are used to perform the drilling time cost sensitivity analysis:

- 1) Bit life (bit usage),
- 2) Penetration rate (rotating time),
- 3) "Other" time,
- 4) Trip time, and
- 5) Rig day rate.

Bit life, which is an indicator of bit performance, design integrity, and compatibility with the formations being penetrated, is included as a time parameter because of its affect on trip time. *Penetration rate* is a measure of how quickly the bit is able to drill through the formations. *Trip time* is the time required to remove the drill bit from the wellbore and guide a new bit back to bottom. It should be noted that the trip time parameter only includes trips to change the drill bit. Trips for other purposes were not documented in the bit records and are included in the "other" time category. "Other" time is time spent on the well performing activities such as rig maintenance, fishing, lost circulation, reaming, etc. Any time not accounted for in one of the other categories is included in "other" time.

Figure 4-1. Drilling Parameter Sensitivity Analysis

Figure 4-1 shows the cost savings that can be realized by improvements in the various drilling time parameters. Increasing penetration rate (decreasing rotating time) has the greatest effect, followed by reducing rig day rate costs and increasing bit life (reducing bit usage). Reducing trip time and "other" time have significantly less effect on drilling cost.

Figure 4-2 shows that 50% reductions in the following drilling time parameters will reduce the dry hole costs by the following amounts:

Rotating Time	=	13%
Rig Day Rate	=	10%
Bit Usage	=	7.5%
"Other" Time	=	4%
Trip Time	=	3%

Figure 4-2

Increasing penetration rates can be accomplished by utilizing downhole motors, high speed bits, high-pressure jet assisted bits, PDC bits, and by optimizing drilling procedures. The feasibility of significantly increasing penetration rates has already been demonstrated with downhole motors which can drill 2 to 3 times faster than rotary rigs in many applications.

Increased bit life can be attained by improving bit designs (e.g., seal and bearing life), utilizing better bit materials, improving bit selection, and optimizing bit operating conditions (e.g., proper combinations of bit weight, rotary speed, and hydraulic horsepower). One example of increased bit life is the introduction of tungsten carbide bits in the 1950s. These bits increased bit life 5 to 10 fold in many hard formations.

Trip time can be decreased by optimizing present techniques, increasing bit life (and other downhole tool life), using lighter drill strings (aluminum or titanium pipe), and automating the tripping operation.

"Other" time can be minimized by improving the well design and by developing better monitoring/expert systems. This includes studying records from other wells drilled in the area, designing all portions of the well plan with adequate safety factors (i.e., not cutting corners to save money), and making safety a top priority.

Figure 4-3 shows the other parameters on the AFE form that change and result in a "ripple-down" cost savings when any of the drilling time parameters are changed.

Figure 4-3. Other Factors Affected by Changes in Drilling Time Parameters

4.3 CASING PARAMETERS

The following casing variables were used to perform the casing parameter cost sensitivity analysis:

- 1) Casing time, and
- 2) Casing materials.

Casing time is the time required to log, run casing, circulate cement, wait on cement, and perform any other operations before drilling resumes. *Casing materials* is the cost of all casing used to secure the wellbore, excluding tieback casing strings and tubing needed to complete the well.

CASING PARAMETER SENSITIVITY ANALYSIS REPRESENTATIVE WELL

Figure 4-4. Casing Parameter Sensitivity Analysis

Figure 4-4 shows the cost savings that can be realized by improvements in casing parameters. Decreasing the cost of casing materials has the greatest affect on dry hole costs since casing materials account for 18% of the "average" deep well total dry hole cost. Reducing casing time has about half the impact of reducing casing material costs.

Figure 4-5 shows that 50% casing parameter reductions will reduce dry hole costs by the following amounts:

CASING MATERIALS	=	9%
CASING TIME	=	5.5%.

Figure 4-5. 50% Reduction in Casing Parameters

Casing materials costs can be reduced by finding less expensive sources of presently used materials, by using alternative materials that cost less without compromising the integrity of the casing string, and by optimizing the casing string design.

Casing time can be decreased by optimizing present techniques, finding ways to decrease the weight of casing strings, and automating the casing running process. Improved coordination of the service companies involved in the casing process could also save significant time and money.

4.4 COMPLETIONS PARAMETERS

Completion costs, which account for nearly 28% of total costs for the "average" well determined in Volume 2 (see Volume 2, Figure 3-17), include the rig cost during completions operations, and the cost of casing tie back strings, surface completion equipment, cementing time and materials, coring, perforating, and stimulation procedures. Although there are areas within the completions process that could be reduced in time and/or cost, a sensitivity analysis of completion techniques is beyond the scope of this study.

4.5 OTHER PARAMETERS

Other parameters not varied in this sensitivity study include expenditures for transportation, logging, well testing, and other miscellaneous parameters. Although these parameters account for a significant percentage of total well drilling costs when summed together, they are unpredictable, making it difficult to perform a useful cost sensitivity analysis. For example, transportation expenditures can vary considerably depending on the site location, amount of equipment needed, and on how well transportation is planned for (e.g., hot-shotting equipment to the rig site at the last minute can significantly increase costs).

4.6 SUMMARY

The cost sensitivity analysis shows how doubling parameters that help decrease costs (i.e. penetration rate and bit life), and reducing by 50% those expenditures that tend to increase costs (i.e. casing materials and tripping time) affect conventional deep drilling expenditures. The analyzed drilling parameters result in the following cost savings:

Penetration rate	—	13%
Rig day rate	—	10%
Casing materials	—	9%
Bit life	—	7.5%
Casing time	—	5.5%
"Other" time	—	4%
Trip time	—	3%

what factors go in to
ROP? Effects on cost?
Time = \$ How about \$ = \$?

These seven parameters have the greatest influence on deep drilling costs. Because penetration rate has the greatest affect of all the parameters on drilling costs, it will be used to quantitatively evaluate each of the advanced modifications and novel drilling concepts in the next section.

Intangible parameters are also used in the next section to evaluate the advanced modifications and the novel drilling concepts. Some of the considerations that are examined include:

1. Productivity
2. Reliability
3. Impact on drilling operations
4. Impact on environment and safety
5. Development risk
6. Development cost and time.

Although these parameters can only be measured qualitatively, they are important issues that provide a useful means of analyzing and comparing those drilling systems that are still viable after the quantitative evaluation.

5. Evaluation of the Advanced Modifications and Novel Drilling Systems

5.1 EVALUATION SUMMARY

The results of the evaluation described in this section, and the final status of each drilling technique are summarized in Table 5-1.

TABLE 5-1. Summary of Systems Evaluation

Drilling Concept	Potential or Limitations	Status
PDC/TSD Bits	High ROP Potential	High Potential
Slim-Hole Drilling	Could Increase Productivity Extensively	
Roller-Cone Bits	Good ROP, and Long Bit Life Potential	
Down Hole Motors	Potential High ROP, Limited Reliability	
Top Drive Systems	Well Established, High Reliability	
Coiled Tubing Drilling	Good Potential to Improve Productivity	
Drilling Optimization	High Impact and Low Risk	Moderate Potential
MWD Tools	Average Potential, Limited Reliability	
Automated Rig	Ample Potential, Needs Better Reliability	
High Pressure Jets	Safety Problems, High ROP Capabilities	
Casing While Drilling	Needs Significant Development Work	
Explosive Drill	Low ROP in Plastic Formations	Low Potential
Flame Jet Drill	Inoperable In Fluid Filled Wellbores	
Forced Flame Drill		
Abrasive Jet	Insufficient Penetration Rate Potential	Eliminated From Further Consideration
Cavitating Jet		
Spark Drill		
Plasma		
Electric Arc		
Nuclear		
Laser		
Microwave		
Induction		
High Frequency		
Electric Disintegration		

The drilling concepts that have the highest potential to positively impact deep drilling operations include:

PDC/TSD Bits
Slim-Hole Drilling
Roller-Cone Bits
Down Hole Motors
Top Drive Systems, and
Coiled Tubing Drilling.

These six systems offer the best capabilities primarily because they require few changes to current drilling procedures, offer high reliability, and have the potential to significantly improve the productivity of deep drilling operations. PDC/TSD bits and roller-cone bits are included in this group because there is no negative impact on current drilling operations, the technological improvements discussed in Volume 4 are already becoming well established, and they have the potential to significantly improve penetration rate and/or bit life. Slim-hole drilling and coiled-tubing systems each have been utilized to a certain extent in the field so their reliability is good. However, these two drilling concepts are given high rankings because they have high potential to exceptionally improve the productivity of drilling operations. They can have positive impact on casing programs, penetration rates, the size and amount of equipment required, etc. Downhole motors are included in the top group because they have no negative impact on drilling operations and have the potential to yield high penetration rates because of enhanced rotary speed capabilities. Research to improve the reliability of this technology in deep drilling environments could be highly beneficial. Top drive systems can hardly be considered a new concept since they are widely used offshore. However, these systems are included in the top group of drilling technologies because they are not utilized to their full potential on land based drilling systems, and could positively enhance deep drilling procedures. This technology exhibits high reliability, and only has a moderate impact on the existing drilling infrastructure.

5.2 EVALUATION PROCEDURE

The main goal of this project is to recommend ways to improve deep drilling technology through innovative research and development projects. The first step toward determining the feasibility of developing advanced modifications and novel drilling systems is to establish the limitations of conventional deep drilling techniques. Before a valid deep drilling alternative can be recommended, it is necessary to understand the restrictions that limit conventional drilling techniques and to establish the drilling parameters that have the greatest influence on conventional deep drilling costs. Knowing what parameters have high impact on deep drilling economics helps identify the characteristics that each candidate system must possess. Because research and development funds are limited, it is essential that technological improvements enhance those deep drilling parameters having the greatest impact on cost. In this way, deep drilling research and development efforts will achieve the highest rate of return on research investments.

The conventional deep drilling cost sensitivity analysis discussed in Section 4 of this Volume indicates that when each drilling parameter is independently doubled, (or cut in half, depending on how the parameter impacts drilling costs), the parameters in Table 5-II result in the greatest percentage cost savings. Improvements to these drilling parameters are preferred since they have a substantial impact on deep drilling costs.

**TABLE 5-II. Impact of Individual Drilling Parameters on Cost
(50% Change)**

Penetration rate	—	13.0%
Rig Day Rate	—	10.0%
Casing Materials	—	9.0%
Bit Life	—	7.5%
Casing Time	—	5.5%
"Other" Time	—	4.0%
Trip Time	—	3.0%

The term next to each parameter's percentage savings indicates the driving force that influences that parameter's magnitude. Costs associated with rig day rate and casing materials are primarily driven by prevailing economic trends. Research and development efforts can significantly affect penetration rate, bit life, and trip time, but do not generally have significant effects on either rig day rate or the cost of casing materials. In this analysis, we are interested in those parameters affected primarily by research and development efforts. Of those parameters, penetration rate has the greatest impact on deep drilling costs. At a 13% reduction in costs, penetration rate has nearly twice the impact of improved bit life — the research and development parameter with the second greatest impact. Trip time and "other" time show some effect, but extreme advancements in these areas would be necessary to achieve the cost reductions that could be gained by minor improvements in drilling rate.

The following analysis is divided into stages. First, the penetration rate/power capabilities of each advanced modification and novel drilling system are evaluated. Those systems that demonstrate the ability to drill at a rate greater than or equal to conventional drilling penetration rate capabilities are considered to be viable deep drilling alternatives and advance to the second stage of the evaluation. In the second stage, qualitative considerations such as impact on current drilling procedures, system reliability and productivity, development risk and cost are evaluated. The second stage of the evaluation includes a ranking of each system based on their potential benefits and drawbacks.

5.3 PENETRATION RATE AND POWER

Penetration rate provides an excellent starting point for the screening evaluation since it is readily influenced by research and development efforts, and displays the greatest effect of all well Authorized Funding Expenditure (AFE) parameters on deep drilling costs. In this analysis, each of the drilling concepts listed in Table 5-III will be evaluated to determine their penetration rate potential. These drilling concepts are divided into three general categories:

1. Advanced Modifications
2. Mechanical Rock Breaking Novel Drilling Techniques
3. Thermal Rock Breaking Novel Drilling Techniques

TABLE 5-III. Drilling Concepts

Drilling Concept	Rock Breaking Mechanism	Category
Rotary	Mechanical	Advanced Modification
Abrasive Jet	Mechanical	Mechanical Novel
Cavitating Jet	Mechanical	Mechanical Novel
Explosive	Mechanical	Mechanical Novel
Spark	Mechanical	Mechanical Novel
Forced Flame	Spalling	Thermal Novel
Jet Piercing	Spalling	Thermal Novel
Plasma	Fusion	Thermal Novel
Electric Arc	Spalling, Fusion	Thermal Novel
Nuclear	Fusion	Thermal Novel
Laser	Spalling, Fusion, Vaporization	Thermal Novel
Microwave	Spalling	Thermal Novel
Induction	Spalling	Thermal Novel
High Frequency	Spalling	Thermal Novel
Electric Disintegration	Spalling	Thermal Novel

Drilling concepts with capabilities that do not meet minimum penetration rate criteria are eliminated from further analysis and consideration. This does not indicate that the technique is not suitable for drilling rock. However, it does indicate that the technique is not suitable for further deep drilling research and development at this time. Equation 5-1 shows the relationship between power, specific energy, and penetration rate that is used in this analysis to determine the amount of power needed by each drilling technique to deliver a benchmark drilling rate:

$$R = \frac{P}{AE} \quad (5-1)$$

where

- R = benchmark penetration rate, cm/min
- P = power transmitted to the rock, joules/min
- A = hole cross-section area, cm²
- E = specific energy, joules/cm²

Because of the importance of penetration rate, the ability to generate an adequate drilling rate is an essential attribute that each drilling concept must exhibit. All of the concepts listed in Table II

Min ROP
criterion

must be able to drill at or above the penetration rate capabilities of the conventional rotary drilling system since it is the technique currently used by the petroleum drilling industry. In the data collected for the sensitivity analysis, the highest average penetration rate using conventional rotary drilling techniques was 34 cm/min (66 ft/hr) in the Deep Tuscaloosa Trend. This drilling rate is not extraordinary, since it is not unusual for penetration rates to exceed 75 cm/min (148 ft/hr), particularly in shallower hole sections. In this analysis, 50 cm/min (98 ft/hr) penetration rates and 20 cm (8 7/8 inch) hole diameters are used as benchmark values.

5.3.1 Drilling Rate/Power Analysis of Advanced Modifications

Because advanced modifications are actually used to enhance the conventional rotary drilling system, it is reasonable to assume that any advanced modification will result in penetration rates equal to, and greater than the 50 cm/min (98 ft/hr) benchmark. No modification is going to be made to current techniques that reduces the performance of the existing system. For this reason, only those advanced modifications that satisfy the benchmark penetration rate criteria will advance to the next stage of the evaluation.

5.3.2 Drilling Rate/Power Analysis of Novel Drilling Systems

5.3.2.1 Mechanical Rock Destruction Systems

Table 5-IV displays the novel drilling concepts in Table 5-III that use some type of mechanical process to fracture and degrade rock. Also shown are the estimated specific energy ranges needed by each system to drill rock, and the magnitudes of threshold power needed (using Equation 5-1) to drill at 50 cm/min.

TABLE 5-IV. Mechanical Novel Drilling Systems

Technique	Estimated Specific Energy (joules/cm ³)	Required Threshold Power (kW)
Abrasive Jet	2000 - 4000	525 - 1050
Cavitating Jet	2000 - 4000	525 - 1050
Explosive	200 - 400	50 - 105
Spark	200 - 400	50 - 105

5.3.2.1.1 Abrasive Jet and Cavitating Jet Drills

Discussions of *Jet Drills* are found in both the advanced modifications section and the novel drilling systems section of Volume 4. In this analysis, high pressure jets are only examined as advanced modifications designed to enhance the performance of mechanical rock breaking techniques. Research has shown that using fluid jetting techniques is most productive when combined with some type of mechanical device. When used by themselves, abrasive jets and cavitating jets need unreasonably high threshold powers to achieve 50 cm/min (98 ft/hr) penetration rates. This is primarily because of the low power efficiency of high pressure jets. Because independent

application of these technologies is limited, abrasive jet and cavitating jet drills that operate without the assistance of mechanical cutters are not considered further in this analysis.

5.3.2.1.2 Explosive Drills

Although little data are available that show the maximum power generated by *Explosive Drills* at the rock face, power levels have been estimated at between 55-75 kW (75-100 HP). This falls within the threshold power range (displayed in Table 5-IV) required to penetrate at rates equal to or greater than 50 cm/min. Explosive drills are examined further in the next stage of the analysis since they show potential for producing the necessary penetration rates and power levels.

5.3.2.1.3 Spark Drills

The *Spark Drills* described in Volume 4 penetrate rock at drilling rates between 1.3 and 13 cm/min (2.5 and 25 ft/hr). Although power levels at the spark drill source can be as high as 110 to 150 kW (150 to 200 HP), the amount of power coupled directly to the rock is significantly lower. The drilling rate capabilities of this drill are well below the 50 cm/min penetration rate benchmark, and effectively eliminate this drilling technique from further consideration.

5.3.2.2 Thermal Rock Destruction Systems

Table 5-V displays the novel drilling systems in Volume 4 that use heat to fracture and degrade rock.

TABLE 5-V. Thermal Novel Drilling Systems

Novel Drilling System	Thermal Rock Removal
Forced Flame	Spalling
Jet Piercing	Spalling
Plasma	Fusion
Electric Arc	Spalling, Fusion
Nuclear	Fusion
Laser	Spalling, Fusion, Vaporization
Microwave	Spalling
Induction	Spalling
High Frequency	Spalling
Electric Disintegration	Spalling
Subterrene	Fusion

Each of these systems uses one or more thermal rock removal mechanism to break rock: spallation, fusion, or vaporization. Experimental analyses show that these thermal rock removal mechanisms require the following magnitude of specific energy to disintegrate rock:

Spallation	= 1,500 joules/cm ³
Fusion	= 5,000 joules/cm ³
Vaporization	= 12,000 joules/cm ³

Equation 5-1 is utilized to calculate power required at the rock face for each of these thermal rock removal mechanisms, using the 50 cm/min (98 ft/hr) benchmark, 20 cm (8 inch) diameter average hole size, and the specific energies listed above. The results of these calculations (shown in Figure 5-1), show that the lowest threshold power level needed to attain 50 cm/min (98 ft/hr) is 390 kW (523 hp) when using thermal spallation. Each of the systems listed in Table 5-V must be able to couple at least 390 kW of power to the rock to be legitimate replacement candidates for conventional drilling techniques. The following analysis shows that it is very difficult for any of the systems in Table 5-V to achieve penetration rates greater than or equal to 50 cm/min. As stated previously, elimination of a technique does not necessarily indicate that the system does not have potential, it only indicates that the technique does not have potential for economic utilization in deep drilling operations at this time.

Contradicts
experience
using
flame jet

Figure 5-1. Power Needed to Break Rock Thermally

5.3.2.2.1 Laser Drills

As indicated in Volume 4, *Laser Drills* built in the early 1980s had output power capabilities in the range of 20 kW (27 HP). Since that time, the U. S. Defense Department's StarWars project has developed very powerful lasers, but the large size of these lasers precludes their use in 20 cm. diameter holes. It is probably safe to speculate that even with recent advances in lasers, the technology does not exist to build the 10 to 15 cm. diameter laser needed to thermally penetrate rock at 50 cm/min. Poor laser efficiencies present additional difficulties because current lasers are only 10-15 percent power efficient thus necessitating 3,500 kW output power to couple 390 kW of

power to the rock face. Due to these power limitations, laser drills are not evaluated any further as viable alternatives to current deep drilling techniques.

5.3.2.2.2 Plasma and Electric Arc Drills

Plasma and Electric Arc Drills both have power outputs in the range of 35-75 kW (45-100 HP); significantly short of the 390 kW needed to match the drilling rate capabilities of conventional drilling techniques. Plasma and electric arc drills are hampered significantly by inefficient operation in fluid filled wellbores — a significant setback considering their efficiency in air is only 50%. Neither of these novel drilling concepts can be considered further as alternative deep drilling techniques.

5.3.2.2.3 Subterrene Drill

The *Subterrene Drill* has displayed interesting capabilities in testing at Los Alamos Scientific Laboratory (see Volume 4). However, the maximum drilling rate a Subterrene is capable of generating is approximately 1.5 cm/min (3 ft/hr) — well short of the 50 cm/min needed. Although the subterrene may prove useful in other drilling applications, it cannot be considered at this time for drilling deep oil and gas wells unless significant, new breakthroughs are made.

5.3.2.2.4 Microwave, Induction, and High Frequency Drills

The *Microwave, Induction, and High Frequency Drills* are all characterized by low power outputs and low operating efficiencies. Typical of this group is the high frequency drill which has been used successfully to spall rock, but at power outputs typically below 50 kW (67 HP). This is significantly short of the power required to match current conventional deep drilling capabilities and eliminates these techniques from further consideration.

5.3.2.2.5 Nuclear Drill

The *Nuclear Drill* is a novel drilling device that has only been considered on a theoretical basis. Estimates of the potential penetration rate capabilities vary from 2-17 cm/min (3-33 ft/hr). Because of these potential low drilling rates, this drilling concept cannot be considered further as a valid deep drilling alternative.

5.3.2.2.6 Electric Disintegration Drill

The *Electric Disintegration Drill* utilizes a spalling mechanism to thermally disintegrate the rock. Similar to the high frequency drills, the electric disintegration drill generates power outputs that are less than 50 kW (67 HP). This low power output coupled with low operating efficiency of the technique, eliminates this drill from further consideration as an alternative deep drilling system.

5.3.2.2.7 Forced Flame and Flame Jet Drills

Of all the novel systems in Table 5-V, *Forced Flame and Flame Jet Drills* are the only thermal rock destruction concepts that have capabilities comparable to those of conventional drilling techniques. A flame jet developed by Browning Engineering (see Volume 4) spalled an 8 in. diameter hole in granite at rates of 25 to 54 cm/min (50 to 106 ft/hr). Power transmitted to the

rock was 205 to 440 kW (275 to 590 HP, despite only 15-50% efficiency. Forced flame and flame jet drills are the only thermal rock destruction techniques capable of generating drilling rates greater than 50 cm/min and therefore will be considered in the next level of the evaluation.

5.4 IMPACT ON DRILLING OPERATIONS, DEVELOPMENT RISK, AND RELIABILITY

The penetration rate and power capabilities of each system have now been analyzed. Results of this evaluation indicate that all advanced modifications are capable of generating penetration rates equal to or greater than the 50 cm/min (98 ft/hr) benchmark, primarily because they modify the conventional drilling system from which the benchmark was determined. From the evaluated novel drilling techniques, only explosive, forced flame, and the flame jet drills demonstrated the potential to operate at, or above, the benchmark drilling rate. Most of the novel concepts could not produce adequate penetration rates, either because 1) they required excessive amounts of power, or 2) they could not efficiently couple available power to the rock. The evaluation described here is particularly rigorous because the deep drilling environment can be exceptionally formidable. Novel systems that failed to meet the benchmark penetration rate are not necessarily inferior rock breaking techniques that are unqualified for all drilling applications. It is simply a mandatory requirement that each system show at least a minimum level of potential since it is illogical to replace present techniques with methods that do not have adequate capabilities.

In this section, the remaining drilling concepts are evaluated using a number of considerations that are not quantitative like penetration rate, but are still very important to determining concept viability. The areas that will be appraised include:

<u>Parameter</u>		<u>Weighting Factor</u>
Weights favor current practice	Productivity	1.0
	Reliability	1.0
	→ Impact on drilling operations	0.7
	→ Impact on environment and safety	0.6
	→ Development risk, and	0.3
	→ Development cost and time.	0.2

These qualitative parameters are listed in order of importance based on their weighting factor. To determine a cumulative ranking, the individual qualitative parameter rankings are multiplied by their respective weighting factor and then summed. Productivity and reliability are the two most important considerations in this list and are given the highest weighting value. Productivity indicates how well the system will operate (Will the system save significant time and money over conventional methods?). Reliability indicates how satisfactorily the system will perform (Will the system require excessive maintenance? Will it frequently fail, resulting in costly down times?). Impact on drilling operations is given the next highest weighting factor at 0.7. This parameter indicates how easily the new technology can be incorporated into present drilling systems (Will significant changes to the existing drilling industry infrastructure be required?). Impact on environment and safety has a weighting factor of 0.6. This consideration is a very important issue in the 1990s and must be

Isn't this
already
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in ROP

carefully appraised (Are there negative environmental implications when using this concept? How safe is it for rig personnel to operate?). *Development risk* indicates the probability for successful development and is given a weighting factor of 0.3 (Will the concept work once it is designed and built?). *Development cost and time* indicates the commitment that will be required to actually get the concept utilized commercially and is given a weighting factor of 0.2 (How long, and how much money is it going to take to get industry to use this technology?). The basic premise for the weighting factors is explained using the following two examples. If a technology shows the potential to be very reliable and highly productive, issues such as development cost and time become relatively unimportant in comparison. Conversely, a system that has low potential for high productivity that is going to require massive modifications to the existing industry infrastructure is not going to be worth the required development costs and time, no matter how small.

Based on the qualitative evaluation, each of the candidate systems is given a cumulative ranking. The cumulative ranking is necessarily relative because of the unpredictable nature of the qualitative parameters. For instance, knowing what technological risks are involved when attempting to develop a new concept for commercial utilization can only be speculated. Similarly, it is difficult to forecast how much financing and time must be committed to developing a concept before it can be commercialized. The rankings were made by University of California at Berkeley and MEI engineers working on the project.

Table 5-VI displays the cumulative ranking of the advanced modifications and remaining novel drilling concepts. Figure 5-2 displays graphically the comprehensive results of the ranking procedure.

TABLE 5-VI. Cumulative Ranking of Deep Drilling Alternatives.

Drilling Concept	Cumulative Ranking	Productivity	Reliability	Impact on Operations	Impact on Environment	Development Risk	Development Cost and Time
PDC/TSD Bits	37.10	5.0	9.3	7.0	5.4	2.9	1.3
Slim Hole	30.98	9.0	7.5	5.4	5.9	2.0	1.3
Roller Cone Bits	29.58	4.0	8.8	7.0	5.4	2.9	1.3
Down Hole Motors	28.20	5.5	7.0	6.7	5.6	2.1	1.3
Top Drive	28.13	3.8	9.5	5.1	5.9	2.9	1.1
Coiled Tubing	27.70	8.3	7.0	4.2	5.0	2.1	1.2
Optimized Drilling	26.45	4.0	6.8	6.5	5.9	2.0	1.3
MWD Equipment	25.48	4.0	6.3	6.0	5.7	2.3	1.3
Automated Rig	25.70	4.8	7.0	4.0	5.6	1.6	0.3
High Pressure Jets	21.03	6.5	6.3	3.2	2.6	1.6	1.3
Casing While Drilling	18.30	5.5	4.3	2.5	4.5	0.9	0.7
Explosive Drill	13.70	3.8	2.5	3.2	2.3	1.4	0.7
Flame Jet Drill	11.53	3.8	3.0	1.6	1.8	0.8	0.7
Forced Flame Drill	11.03	3.8	2.5	1.6	1.8	0.8	0.7
Weighting Factor		1.0	1.0	0.7	0.4	0.3	0.2

Figure 5-2 shows that the advanced modifications and remaining novel drilling concepts are roughly divided into four groupings. The highest ranking group consists of slim-hole drilling, PDC/TSD bits, and improved roller-cone bits. The second group includes down-hole motors, coiled-tubing systems, optimized drilling practices, and top drive equipment. The third group contains measurement while drilling equipment, automated rigs, high-pressure jets, and casing while drilling concepts. The lowest ranking group includes explosive, flame jet, and forced flame drills.

DEEP DRILLING ALTERNATIVES RANKING Cumulative Ranking

Figure 5-2. Cumulative Ranking of Advanced Modifications and Novel Drilling Concepts

Figure 5-3 through Figure 5-8 show the individual qualitative parameters that were appraised, and how each of them influences the cumulative ranking. When studying each of these parameters, it is important to remember the associated weighting factor. Productivity and reliability have the highest impact on the cumulative ranking so concepts such as slim-hole and coiled-tubing that rank high in productivity, and top drive, PDC/TSD and roller-cone bits that rank high in reliability have higher cumulative rankings. Development cost and time has the lowest impact so even if a system ranks far above the rest of the drilling concepts in this area, the effect on the cumulative ranking will be insignificant. The following text discusses each of the advanced modifications and remaining novel drilling concepts, and how the different qualitative parameters influenced their cumulative rankings. As was done in the previous analysis, the advanced modifications will be discussed first, followed by the novel drilling concepts.

PRODUCTIVITY Weighting Factor - 1.0

Figure 5-3. Productivity Ranking

RELIABILITY Weighting Factor - 1.0

Figure 5-4. Reliability Ranking

IMPACT ON DRILLING OPERATIONS

Weighting Factor - 0.7

Figure 5-5. Impact on Drilling Operations Ranking

IMPACT ON ENVIRONMENT AND SAFETY

Weighting Factor - 0.6

Figure 5-6. Impact on Environment/Safety Ranking

DEVELOPMENT RISK Weighting Factor - 0.3

Figure 5-7. Development Risk Ranking

DEVELOPMENT COST AND TIME Weighting Factor - 0.2

Figure 5-8. Development Cost/Time Ranking

This seems
an overriding
issue

5.4.1 Advanced Modifications

The primary advantage of advanced modifications to conventional drill rigs is that they can yield significantly improved drilling performance without requiring extensive changes to the conventional drilling system. This means that they generally rank higher than the novel drilling concepts in impact on operations (see Figure 5-5). Each of the advanced modifications presented in Volume 4 is analyzed in this section of the evaluation.

5.4.1.1 PDC/TSD Bits

As mentioned in Volume 4, polycrystalline diamond cutters are classic examples of an advanced modification — mainly because extraordinary improvements in drilling performance were incorporated without drastically changing conventional drilling techniques. The same potential exists for the thermally-stable diamond products (TSD bits).

1. PDC/TSD bits rank fourth on the list for productivity. PDC/TSD bits could have a substantial impact on penetration rates in deep wellbores because of the advantages of the shearing cutting mechanism as depth increases and formations deform more plastically (see Volume 3). PDC/TSD bits may significantly improve drilling rates in deep drilling applications and penetration rate has been shown to have the greatest impact on deep drilling costs.
2. The reliability of PDC and TSD bits are ranked near the top. There is little question regarding the positive impact these bits have had on drilling shale and other soft to medium hard formations. However, there are certain aspects of PDC/TSD bit design and application that are still being resolved, as described in other areas of this final report.
3. PDC and TSD bits are given the highest ranking for impact on drilling operations because no changes are required to existing drilling systems except for the drill bit.
4. PDC/TSD bits have no impact on the environment and safety since they are used strictly as downhole tools.
5. These bits are also given the highest ranking for development risk because PDC bit technology is well established and TSD bits have shown promising capabilities in the mining industry. Above all, there is little risk associated with developing PDC and TSD bits because drill bits themselves are very conventional features of drilling systems and a better drill bit will certainly be utilized.
6. PDC/TSD bits are given the highest ranking in development cost and time, mainly because they are well established technologies, and the commitment to expanding their capabilities to the deep drilling environment will not be excessive.

PDC/TSD bits received a high cumulative ranking because of their low impact on current drilling operations, and their potential for high reliability and productivity. PDC/TSD bit technology shows exceptional potential for positive utilization in deep drilling operations.

5.4.1.2 Improved Roller-Cone Bits

Existing roller-cone bits could be significantly enhanced by improvements in seal and bearing design.

1. The productivity of roller-cone bits is ranked fairly low. Volume 3 clearly showed that in the deep drilling environment, indenting and crushing will not be as effective as PDC/TSD bits because of the increased plasticity of the formations. Improved seals and bearings in

- roller-cone bits will have greater affect on bit life and trip time than penetration rate, factors that have less impact on deep drilling costs than drilling rate.
2. The reliability of roller-cone bits is proven and will be enhanced further by changes in seal and bearing design. Seals and bearings are two primary reasons why current roller-cone bits fail.
 3. Roller-cone bits rank highest for impact on drilling operations because no modifications are required to the existing drilling system.
 4. Roller-cone bits have no impact on environment and safety because they are used strictly down hole.
 5. Because roller-cone bits are well established, there is little development risk associated with this technology. A variety of new seals and bearing concepts are already being experimented with and will eventually result in successful design improvements.
 6. Roller-cone bits rank high in the area of development costs and time. Roller-cone bits rank above PDC/TSD bits in this category because this technology is better established.

Roller-cone bits exhibit many of the same positive traits as PDC/TSD bits. Roller-cone bits are ranked slightly below PDC/TSD bits only because their potential for significantly improving the productivity of existing deep drilling procedures is not as high.

5.4.1.3 High-Pressure Jets

Using high-pressure jets in conjunction with mechanical cutters demonstrates significant potential to improve deep drilling rates. However, incorporating this technology has several drawbacks that result in a low cumulative ranking.

1. The primary area where high-pressure jets excel is in productivity. The combination of mechanical drill bits with high-pressure jets has the potential of improving productivity more than any system in the rankings except slim-hole and coiled-tubing systems. High potential penetration rates have high impact on drilling costs as shown in the cost sensitivity analysis.
2. As with any high-pressure equipment, reliability can be a problem. This is particularly true of systems that operate in harsh environments, such as drilling operations.
3. High-pressure jets rank low for impact on drilling operations because significant changes would need to be made to the circulation system. All circulating equipment including the pumps, rotary hose, swivel, and even the drill pipe, bottom-hole tools, and drill bits must be modified to operate at high pressures.
4. High-pressure jets have a low ranking for impact on environment and safety because of safety problems associated with high pressure equipment.
5. Because of the difficulty in developing the needed high-pressure components, high pressure jets represent a relatively high development risk.
6. Development cost and time are high for high-pressure jet systems, primarily because equipment costs escalate rapidly when high pressures are involved.

High-pressure jets are low on the cumulative ranking because of high impact on operations, low reliability, and considerable safety concerns.

System component

5.4.1.4 Top Drive

As noted in Volume 4, top-drive technology is already proven and currently being used in many offshore drilling operations.

1. The productivity of top drive is given the lowest ranking. Top drives increase tripping efficiency and help avoid fishing operations, but these are both low impact drilling parameters in comparison with penetration rate and bit life.
2. Top-drive systems receive a high ranking for reliability primarily because the technology is proven and being utilized.
3. Top-drive systems have an average ranking for impact on operations since they require substantial changes to the drilling system. This does not negate the technology from further consideration primarily because top-drive systems are now installed on so many drilling rigs.
4. Top drive has only a minor impact on environment and safety. This technology does present some safety concerns because it is heavy equipment used in an environment well known for its hazards.
5. Because top-drive systems are already found on many drilling rigs, there is little development risk associated with the technology. The only drawback is the high cost of the equipment — a major reason why the technology is not utilized on many land-based drilling rigs.
6. Development cost and time is given a low ranking for top-drive systems. The high cost of top-drive systems has limited their use in onshore operations.

Top drives fall in the middle of the cumulative ranking. This technology ranks high in the reliability and development risk categories, but also has the lowest ranking for productivity.

5.4.1.5 Downhole Motors

System component

As with top-drive systems, downhole motors represent a technology that is already used in a variety of different drilling operations. Downhole motor technology exhibits attributes that earn a high cumulative ranking.

1. The productivity of downhole motors is fairly high, primarily because the drill bit can be rotated at much higher speeds, generating higher penetration rates.
2. Reliability of downhole motors in the deep drilling environment is questionable and presents some challenging problems for researchers. Stability of elastomers and the durability of motor bearing packages often cause difficulties when using motors in deep drilling applications.
3. Because these motors are used exclusively downhole, this technology ranks high in impact on operations.
4. Downhole motors have no impact on environment and safety because they are used exclusively as down-hole tools.
5. The development risk associated with downhole motors is given an average ranking. Even though this technology is proven in shallow environments, utilization of downhole motors in deep hostile drilling environments is limited. The elastomers currently used have temperature limitations, and sour gas affects the life of motor components.
6. Because downhole motors are already utilized in various drilling operations, this technology ranks high in development cost and time. The basic concepts already exist — the focus now is on improving motors for deep drilling applications.

Downhole motors receive a high cumulative ranking for several reasons: they have low impact on current drilling operations, their reliability is adequate (although not outstanding), and the potential productivity of the technology is promising.

5.4.1.6 Slim-Hole Drilling Systems

During the last half century, slim-hole drilling technology has been experimented with, and even implemented in the field by drillers in the oil industry (see Volume 4). This technology has never received widespread utilization for a variety of reasons including system reliability and implementation costs. In this analysis, slim-hole drilling technology receives the highest cumulative ranking of any system, indicating that this technology should be seriously considered for deep drilling applications.

1. High productivity is the strongest incentive for this technology. Drilling a slim hole decreases site preparation costs and casing materials costs, and has the potential to improve penetration rates since the quantity of rock actually drilled is reduced.
2. The reliability of slim-hole systems can be considered fairly high because of the amount of technology that already exists. However, reliability is tempered by the limited application of slim-hole drilling to depths greater than 15,000 ft.
3. Slim-hole drilling's impact on drilling operations is significant but not prohibitive. The technology would not greatly alter existing drilling systems because much of the technology for slim-hole drilling already exists in the mining industry, and many basic procedures are shared by both industries.
4. Slim-hole drilling systems have little impact on environment and safety. In fact, one of the advantages of utilizing this technology is that drilling sites are smaller, reducing impact on environmentally sensitive areas. Safety does present a modest concern because system configuration is basically the same as conventional drilling systems, and there is a lack of experience with utilizing this technology in deep wellbores.
5. The development risk associated with utilizing slim-hole drilling systems is also significant, but not prohibitive, mainly because of the equipment and procedures that have already been developed by the mining industry. There is still risk involved because the mining industry rarely drills to depths below 10,000 ft — this is only 67% of the footage needed to qualify as a *shallow* deep well.
6. It will take substantial development cost and time to successfully implement deep slim-hole drilling technology on a large scale. However, the magnitude of the costs involved is diminished, again by the infrastructure that already exists within the mining industry. Another factor that can assist in the implementation of slim-hole drilling systems is the utilization of slim-hole drilling concepts with present drilling rigs. For instance, a "slim hole" may be defined as a section of hole drilled one inch in diameter smaller than normal.

One reason why slim-hole drilling has not experienced widespread implementation prior to this time is because reliable small diameter motors and reliable small diameter PDC/TSD bits were not developed until recently. Slim-hole drilling's high cumulative ranking in this evaluation indicates that deep drilling may provide an excellent opportunity to reintroduce the technology.

5.4.1.7 Coiled Tubing

Coiled-tubing drilling systems have been utilized to a certain extent for performing workovers but for routine drilling of oil and gas wells.

1. Similar to slim-hole drilling systems, coiled-tubing drilling systems are capable of high productivity due to extraordinary improvements in tripping efficiency, reduced casing and drill pipe wear, and enhanced penetration rates (using downhole motors).
2. If the concerns related to depth capability can be dismissed, the reliability of this technology should be moderately high. However, the stability of these materials at depth are very real concerns that cannot be overlooked.
3. Implementing coiled-tubing drilling systems will have an impact on drilling operations since the equipment associated with this technology is significantly different from the conventional configuration, indicating that a large amount of the existing infrastructure would have to be displaced.
4. Coiled tubing will not have a major impact on environment and safety, but safety is a consideration because these systems have not been used for drilling in environments that exhibit high pressures, high temperatures, and sour gas.
5. Although there is development risk associated with this technology, coiled-tubing rigs are currently being used, so the concepts are proven. The primary risk involves the capabilities of this technology at depths greater than 15,000 ft.
6. Development cost and time are moderate concerns for coiled-tubing systems. The basic concepts have already been determined and the technology is being used. Again, the capabilities of this system for deep drilling applications needs to be examined carefully.

There are a variety of questions that need to be answered concerning the depth capabilities of this technology. However, if the depth obstacles can be resolved satisfactorily, drilling deep wells using coiled-tubing systems could be an excellent alternative.

5.4.1.8 Casing-While-Drilling

Of all the advanced modifications considered here, casing-while-drilling is probably the farthest from commercial utilization. However, it does have greater potential than many of the novel drilling techniques primarily because it is a modification of existing technology.

1. The productivity of casing-while-drilling systems is low. Conceptually, they permit drilling of the entire wellbore with one bit size. This may or may not affect penetration rates. There will be savings in casing costs, but this may be offset by the added expense of 1) utilizing different casing-while-drilling materials, and 2) installing the casing-while-drilling equipment on the rig.
2. Because casing while drilling is still very experimental in nature, the reliability of this technology is questionable. A significant amount of research will be required to establish this system's capabilities and limitations.
3. Casing-while-drilling systems could have a detrimental impact on drilling operations. Although the apparatus itself is utilized downhole, changes to surface equipment would have to be incorporated. It is difficult to predict exactly what changes would be required, but they could be substantial.
4. The impact on environment and safety by casing-while-drilling systems is uncertain at best. The main concern with these systems is how well the casing system will hold in the high pressure environment often associated with deep wells. Failure of the casing could result in expensive blowouts and loss of life.
5. The development risk associated with casing-while-drilling systems could be substantial since this technology has not been used extensively and is still in the experimental stage.

Use the drill
pipe as
casing?

6. The development cost and time to achieve commercial utilization of casing-while-drilling systems is difficult to ascertain. The experimental nature of the equipment indicates that substantial obstacles must be overcome.

The cumulative ranking for casing-while-drilling systems is near the bottom. There are many questions that need to be answered regarding the concept's impact on operations and reliability, as well as questions about the actual advantages of utilizing the technology.

5.4.1.9 Measurement-While-Drilling (MWD)

MWD tools represent another example of an advanced modification that is already used extensively in conventional drilling operations. Similar to downhole motors though, MWD tools have not seen much utilization in deep well drilling because of high temperatures, high pressures, and high concentrations of sour gas.

1. The productivity associated with MWD ranks low because the only tangible savings that result from utilizing MWD tools is in the time that would otherwise be consumed by surveying and formation evaluation operations. It is possible that time savings will be offset by the high cost of using MWD.
2. The reliability of MWD tools in deep drilling applications is uncertain because of the hostile drilling environment associated with deep wells. High temperatures, sour gas environments, and the distance the signals must be transmitted all present legitimate reliability problems.
3. MWD tools have a minimal impact on drilling operations because they are used exclusively downhole.
4. MWD has no impact on environment and safety because it is used exclusively as a down-hole tool.
5. There is a certain amount of development risk associated with MWD tools because of their low utilization in deep hostile drilling environments which may make it difficult to utilize this technology.
6. Development cost and time for the MWD tools is given an average ranking. This technology has advantages since it is already used extensively in the field. At the same time the new complications presented by the deep hostile drilling environment add to development costs.

MWD is slowly becoming a standard component in drilling operations. To date, the technology has been used most for directional control in drilling operations. Because most deep wells are drilled "vertical," it may be questionable how essential MWD systems are for deep drilling operations.

5.4.1.10 Automated Rig Operations

As with the majority of concepts discussed in this evaluation, automating rig operations is a modification that has been proposed for several decades. Steps have been made to automate portions of the drilling system, but most of those efforts have received only mediocre acceptance. The majority of automation concepts can be accomplished with current technology. However, if this concept is to become commercially viable, process automations *must* be reliable, easily integrated into the conventional drilling system, and must also exhibit cost saving potential that exceeds the cost of implementing and using the technology.

1. The main impact of automated rig systems on productivity is seen in increased efficiency. Although this will tend to decrease the time required for tripping operations, the overall impact on drilling costs will not be extensive.
2. The reliability of automated rig systems is given an average ranking. The basic operations that automation equipment will be replacing are well established since they are intrinsic parts of the drilling operation. The fundamental question is: how well will the equipment perform, and for how long? Troubleshooting electronic equipment can be a tedious and difficult chore.
3. Automated rig systems are given a medium to low ranking for impact on operations. Although the basic layout of the drilling system is not modified by automation, new equipment will be needed to operate and monitor various processes independent of human control.
4. Automated rig systems have little impact on environment and safety and should result in safer drilling operations. However, any operation related to deep drilling operations, no matter how much it is automated, is going to have some danger associated with it.
5. The harsh environment generally associated with drilling operations results in a high development risk for automating rig operations. Most automation processes will require electronics equipment that is relatively fragile. Automated processes also require technicians specially trained to operate and repair the electronic equipment.
6. The development cost and time to automate a drilling rig would be significant. Some operations have been automated previously, but the main task entails splicing them all together into one cohesive system.

Automated drilling systems receive medium rankings for most of the qualitative parameters. For this reason, the cumulative ranking for this technology is only average.

5.4.1.11 Advanced Management Techniques

For evaluation purposes, this advanced modification was expanded in scope to include all drilling optimization concepts and techniques. The basic idea behind drilling optimization is to improve and optimize all the systems and techniques currently used during drilling operations without making any physical changes to the drilling rig. The major categories included in optimization techniques are hydraulics, bit selection, weight-rpm combinations, rig selection, and data acquisition.

1. Drilling optimization concepts have little impact on operations. The only reason why optimization is not given a full 100% ranking is because of instrumentation that must be added to the rig.
2. There is little development risk associated with drilling optimization. The fundamental challenge of this concept is to get engineers and drilling hands to incorporate the philosophy of optimization into daily operations. This is the main reason for only an average ranking in this area.
3. The reliability of drilling optimization is only as stable as the personnel assigned to incorporate the concept into daily operations.
4. Development cost and time required to incorporate drilling optimization techniques are minimal. The greatest expenditure will be for training personnel in how to incorporate the concepts.
5. Drilling optimization has no adverse impact on environment and safety, and may actually improve these crucial areas.

6. Considering the fact that drilling optimization concentrates only on improving existing techniques, the potential productivity of these concepts is great. Although optimization does not have the high productivity impact of slim-hole or coiled-tubing systems, it is a drilling improvement that should not be overlooked.

Drilling optimization has a cumulative ranking that falls into the second grouping of systems and modifications. These concepts have high potential at low risk and should be considered when searching for ways to decrease deep drilling costs.

5.4.2 Novel Drilling Systems

As noted previously, only three of the fifteen novel drilling techniques demonstrated the potential to operate at, or above, the benchmark drilling rate. These three systems are evaluated based on their productivity, reliability, impact on drilling operations, impact on the environment/safety, development risk, and development cost and time.

5.4.2.1 Explosive Drills

The cumulative ranking for explosive drills is very low for the following reasons:

1. The productivity of explosive drills is adequate as shown in the evaluation of penetration rate capabilities. However, the penetration rate capabilities discussed in that section of the evaluation were in for drilling in harder, brittler formations such as granite. The efficiency of explosive drills is severely limited in shales and other formations that deform plastically. Since shales represent over 50% of all footage drilled in oil and gas wells, this is a critical weakness of explosive drill systems.
2. The reliability of explosive drills is questionable. Although this concept has been tested to a certain extent in the field, there are questions about the reliability of this system when utilized continuously over a long period of time.
3. The impact on drilling operations of explosive drills has been shown by some investigators to be moderate. However, certain new pieces of equipment will be required, effecting the existing infrastructure to some extent.
4. Impact on environment and safety is a major concern with the explosive drills. The safety of any system that utilizes explosives is questionable no matter how extensive the precautions may be.
5. The development risk associated with explosive drills is very high. Explosive drills will not be quickly accepted into commercial drilling operations primarily because this concept deviates significantly from conventional drilling methods.
6. Development cost and time will be high for this concept since it has not been used on a commercial basis by the oil drilling industry. Preparing this technique for continuous operation in a deep drilling environment would be an exceptional undertaking.

The cumulative ranking for the explosive drill indicates that this concept should not be considered for deep drilling applications unless some unforeseen breakthroughs are made.

5.4.2.2 Forced Flame and Flame Jet Drills

Unless one of the casing-while-drilling techniques is soon incorporated into the drilling procedure, one fundamental condition that will remain when drilling a deep wellbore is the need to have fluid in the wellbore for hole stability and well control purposes. This requirement

effectively eliminates from further consideration any drilling system that utilizes flame to penetrate rock. The forced flame and flame jet drills rank at or near the bottom of every category for a variety of reasons. However, the fact that these drills cannot operate in a fluid-filled wellbore is the overwhelming deterrent.

6. Conclusions and Recommendations

A thorough screening and evaluate process was used to evaluate the 25 candidate deep drilling systems. A group of drills were eliminated from further consideration due to low drilling rates and the remaining candidate systems were rated according to the following parameters:

<u>PARAMETER</u>	<u>WEIGHTING FACTOR</u>
Productivity	1.0
Reliability	1.0
Impact on drilling operations	0.7
Impact on environment and safety	0.6
Development risk, and	0.3
Development cost and time	0.2

The following conclusions were reached as a result of this analysis:

1. The following group of drills were eliminated due to low potential drilling rates:

- *Abrasive Jet*
- *Cavitating Jet*
- *Spark Drill*
- *Plasma*
- *Electric Arc*
- *Nuclear*
- *Laser*
- *Microwave*
- *Induction*
- *High Frequency*
- *Electric Disintegration*

2. The following drills were rated as having *low* potential for the reasons shown:

- *Explosive Drills* (Low ROP in Plastic Formations)
- *Flame Jet Drills* (Won't Work in Drilling Mud)
- *Forced Flame Drills* (Won't Work in Drilling Mud)

3. Several drills had *moderate* potential and should be considered if technological breakthroughs are made in these areas:

- *Drilling Optimization* (Low Risk, Moderate Improvement)
- *MWD Tools* (Low Risk, Moderate Improvement)
- *Automated Rig* (Increased Tripping Speed; Drilling Optimization)
- *High-Pressure Jets* (High Drilling Rate, Safety/Reliability Problems)
- *Casing While Drilling* (Major Development Required)

4. Six drilling concepts have *high* potential for reducing deep drilling costs:

- *PDC/TSD Bits* (High ROP Potential)
- *Slim-Hole Drilling* (High ROP, Reduced Casing Costs)
- *Roller-Cone Bits* (Improved ROP, Long Life Potential)

- *Down-Hole Motors* (Potential High ROP, Improved Reliability Needed)
 - *Top-Drive Systems* (Well Established, High Reliability)
 - *Coiled-Tubing Drilling* (Fast Trips, High ROP, Slim-Hole)
5. GRI should fund work on the *high* potential advanced concepts for deep drilling applications (15,000 to 20,000 ft) because current oil-field R & D is aimed at shallower drilling applications (5,000 to 15,000 ft).
 6. Work on PDC/TSD bits and downhole motors should be undertaken because these tools have high potential for reducing deep drilling costs by increasing drilling rates and reducing drilling time, tripping costs, and casing costs.
 7. R & D on roller bits could reduce deep drilling costs by accelerating development of advanced bits utilizing diamond bearings and improved diamond-coated cutters.
 8. Improved top-drive systems for use on deep, land rigs have potential for reducing deep drilling costs since these systems allow continuous circulation during trips and drilling with longer sections of pipe, thereby reducing connection time.

Appendix C - Cost-Sensitivity Analysis of Average Regional Wells

Appendix C contains the results from the cost-sensitivity analysis performed on each of the average regional wells. The same analysis procedure performed on the representative well presented in the main text was also used for each of these wells.

C.1 THE WIND RIVER BASIN

Figures C-1 to C-3 show the results of the sensitivity analysis for the Wind River Basin. As was the condition in most of the cases, the impact of penetration rate (rotating time) was the greatest. Bit life (bit usage) was a close second because of the excessive number of bits required to reach total depth.

Figure C-1

CASING PARAMETER SENSITIVITY ANALYSIS WIND RIVER BASIN

Figure C-2

SENSITIVITY ANALYSIS - 50% REDUCTION WIND RIVER BASIN

Figure C-3

C.2 THE OVERTHRUST BELT

Figures C-4 to C-6 show the results of the sensitivity analysis performed on the Overthrust Belt well. This was the only well where penetration rate did not have the greatest affect on dry hole costs. Because bit usage comparable to that for the Wind River Basin was combined with a lower total rotating time, bit life had a greater impact on dry hole costs. Still, penetration rate had nearly as great an impact.

DRILLING PARAMETER SENSITIVITY ANALYSIS OVERTHRUST BELT

Figure C-4

CASING PARAMETER SENSITIVITY ANALYSIS OVERTHRUST BELT

Figure C-5

SENSITIVITY ANALYSIS - 50% REDUCTION OVERTHRUST BELT

Figure C-6

C.3 THE ANADARKO BASIN

Figures C-7 to C-9 show the results of the sensitivity analysis performed on the Anadarko Basin well. When bit usage drops, bit life's impact on dry hole costs decreases dramatically, as illustrated by the Anadarko Basin well. Penetration rate continues to have the greatest affect on dry hole costs followed this time by casing materials and casing time.

DRILLING PARAMETER SENSITIVITY ANALYSIS ANADARKO BASIN

Figure C-7

CASING PARAMETER SENSITIVITY ANALYSIS ANADARKO BASIN

Figure C-8

SENSITIVITY ANALYSIS - 50% REDUCTION ANADARKO BASIN

Figure C-9

C.4 THE DELAWARE BASIN

Figures C-10 to C-12 show the results of the sensitivity analysis for the Delaware Basin well. The results are very similar to those for the Anadarko Basin well with the exception that the casing time effect is not quite as prominent. Casing materials have nearly as much impact as rotating time indicating that modification to this part of the drilling program could significantly cut the total cost of the well.

DRILLING PARAMETER SENSITIVITY ANALYSIS DELAWARE BASIN

Figure C-10

CASING PARAMETER SENSITIVITY ANALYSIS DELAWARE BASIN

Figure C-11

SENSITIVITY ANALYSIS - 50% REDUCTION DELAWARE BASIN

Figure C-12

C.5 THE SMACKOVER BELT

Figures C-13 to C-15 show the results of the sensitivity analysis for the Smackover Belt. Even though 67 bits were needed to drill this well, the impact of bit life is reduced by the higher cost of the casing materials. Casing materials and bit life have almost identical impact on dry hole costs. Again, penetration rate has the greatest impact on cost.

DRILLING PARAMETER SENSITIVITY ANALYSIS SMACKOVER TREND

Figure C-13

CASING PARAMETER SENSITIVITY ANALYSIS SMACKOVER TREND

Figure C-14

SENSITIVITY ANALYSIS - 50% REDUCTION SMACKOVER TREND

Figure C-15

C.6 THE WILCOX TREND

Figures C16 to C-18 show the results of the sensitivity analysis for the Wilcox Trend. Because only 25 bits were needed to reach total depth, changing bit life has a minimal affect on dry hole costs. Penetration rate has the greatest affect, and surprisingly, casing time has nearly as much impact. The ratio of rotating time to casing time for this well was approximately 2 to 1. The ratio in most of the other wells was 5 to 1 or more. Although a small ratio between rotating time and casing time does not appear to be the trend, it should be noted that in areas where this is the case, finding ways to reduce casing time can be very attractive.

DRILLING PARAMETER SENSITIVITY ANALYSIS SOUTH TEXAS WILCOX

Figure C-16

CASING PARAMETER SENSITIVITY ANALYSIS SOUTH TEXAS WILCOX

Figure C-17

SENSITIVITY ANALYSIS - 50% REDUCTION SOUTH TEXAS WILCOX

Figure C-18

C.7 THE DEEP TUSCALOOSA TREND

Figures C-19 to C-21 show the results of the sensitivity analysis for the deep Tuscaloosa Trend. As was noted in Appendix A, penetration rates in the shallower portions of this well kept rotating time to a minimum. However, below approximately 15,000 ft, penetration rates drop off considerably. Because of the dramatic decrease in penetration rate with depth, changes in penetration rate continue to have the greatest impact on dry hole costs—almost double that of any other case. This case indicates that as the depth of the well increases, the impact of penetration rate on dry hole costs becomes greater and greater.

DRILLING PARAMETER SENSITIVITY ANALYSIS TUSCALOOSA TREND

Figure C-19

CASING PARAMETER SENSITIVITY ANALYSIS TUSCALOOSA TREND

Figure C-20

SENSITIVITY ANALYSIS - 50% REDUCTION TUSCALOOSA TREND

50% Reduction

Figure C-21

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