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Suggested Drilling Research Tasks for the Federal Government

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Suggested Drilling Research Tasks for the Federal Government

**Charles C. Carson
January 1984**

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ABSTRACT

Over the next two decades, the energy resources utilized by the U.S. and the rest of the world will gradually change. These changing resources will lead to changes in the drilling systems that are used to reach and extract them. The Federal Government can play an important role in assuring the future availability of energy by identifying key areas of drilling technology and sponsoring research and development in those areas. Projects of potential importance are identified in the general areas of improved information, enhanced permeability, drilling efficiency and new materials.

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EXECUTIVE SUMMARY

Approximately 80,000 oil and gas wells are drilled annually in the United States, and these have a total drilled footage of 389 million feet (1981 figures). This drilling far exceeds the oil and gas drilling done in the rest of the free world. In addition, roughly 700,000 water wells are drilled in the U.S. each year, with a total footage exceeding 100 million feet. Very little of this drilling for resource extraction requires state-of-the-art drilling techniques. All of the water wells and most of the petroleum wells are shallow on-shore wells in the contiguous 48 states. The wells that require high technology, and thus expensive, tools and services are the proportionately few offshore, remote or deep wells.

Future drilling for energy resources is likely to be much different from most current drilling. The United States will continue to rely heavily on oil and gas for its energy needs, but the easy-to-extract resources are finite and dwindling. They will gradually be replaced by deep, remote or alternative resources. The growing exploitation of these will place demands on current drilling systems in the areas of better information describing the drilling process, improved control of the drilling operation, the ability to operate in taxing environments, and capabilities to produce new hole orientations and geometries. The current wells that are most similar in technology requirements to these anticipated future wells are the expensive offshore or remote wells and the few wells that are currently drilled for extraction of alternative resources.

Historically, the free world's wells have been drilled by U.S. companies, people and technology. However, foreign companies and governments, especially from France, Norway and Japan, are expanding their role in developing and applying new drilling technologies. This is not surprising, since only a very small portion of the free world's reserves are in the U.S. (5%) and a much greater portion of European wells than U.S. wells are offshore (30% vs. 2%). In spite of the relatively few high technology domestic wells, new drilling tools and capabilities are being developed by numerous U.S. companies. The major service companies work continually to improve their products, and current major development areas include measurement while drilling (MWD), bits, motors, automation, and the use of computers. In the "drilling industry" no one company markets the entire drilling system; and so, technology development proceeds piecemeal, with no organization focusing on system improvements. Nonetheless, the drilling system is evolving through significant improvements to its component pieces.

The primary motivation for government involvement in drilling research is to assure adequate drilling capability for efficient exploitation of the resources that will be needed in the future. In addition, there are areas besides energy extraction that may require development of technology. These include waste isolation, defense concepts such as MX and nuclear testing. Government-sponsored development for these purposes would also provide two concurrent benefits. It would aid cheaper and more efficient extraction of current resources, and it might help U.S. companies remain competitive in drilling technology development.

In sponsoring drilling research and development to meet these goals, the government can undertake three different types of projects. It can identify and carry out those piecemeal, or evolutionary, developments that will be needed for extraction of future resources and that will not be done in the private sector. These tasks would center around improvement of current drilling systems. They might include areas such as basic research to develop knowledge and understanding or materials development to aid in dealing with severe environments. The second type of projects would be investigations of selected new drilling systems that would change the basic way that wells are drilled. These revolutionary changes to drilling technology would have to be selected carefully to ensure that they had potential for significant impact. The final type of project is traditional. The government can continue to sponsor large-scale programs that require development of new drilling technologies. Examples include: large-hole drilling for nuclear testing, drilling done to support

defense programs, scientific drilling into the earth's crust, and early support of the development of alternative resources such as geothermal, methane from coal, etc.

Several attractive research and development projects that fall in these areas are discussed in the text. These include:

1. Research, both analytical and experimental, into rock failure and rock-cutter interactions;
2. Development of sensors that "see" beyond the wellbore and, in particular, that can sense what is ahead of a drill bit;
3. Development of new materials and downhole components for high temperature, corrosive environments;
4. Development of non-damaging, fail-safe wall anchoring and bit thrusting systems; and
5. Research into novel hole lining techniques.

I. Introduction

Drilling holes into the earth's crust is a big business, both in the scale of the equipment involved and in the breadth of its applications. Drilling is an important element of a number of various operations, and in many it is a highly technical task performed with specialized, complex equipment. The tools and techniques to perform drilling have evolved for decades, and many groups and individuals continue working to further improve them. Drilling research and development is carried out by oil companies, drilling companies and tool and service companies and by government agencies and laboratories in the United States as well as in many other countries.

The U. S. Government is concerned with drilling, due in part to federal involvement in programs that require the drilling of holes -- programs such as nuclear testing, waste isolation, ballistic missile siting, scientific drilling into the earth's crust and alternative energy extraction. The government currently supports limited drilling research and development related to several of these areas, such as large-hole drilling for nuclear testing and drilling for geothermal energy extraction.

The purpose of this study, sponsored by the Department of Energy (DOE), is to identify additional project areas where government support should be applied and potentially can make a significant contribution. Several similar studies of drilling research needs have been carried out in the past, and their recommendations are summarized in Appendix A. Most of the previous studies were concerned with specific applications or resources, but all were helpful in shaping the recommendations of this study. Appendix B summarizes previous and continuing federal research and development programs in drilling. Their successes and failures are discussed, along with possible reasons for each.

This study emphasizes drilling for the extraction of energy resources. This is due to several factors: the mission of the DOE sponsor, the importance of drilling in the extraction of energy resources, and the tendency of advances to originate in the "oil patch" and then find subsequent application in other drilling. The inputs from the study came primarily from the open literature and from interactions with those in industry who are associated with drilling research. Industry leaders continually evaluate the direction in which technology must move and identify critical research tasks. Though the perspectives and emphases of government and industry are different, the thoughts and rationale of these individuals were quite helpful.

This final report for the study has three parts. Section II presents a brief summary discussion of drilling, drilling research and the role of the government in drilling research. Following this discussion, Section III lists specific research and development areas recommended for federal consideration. The technical nature of the identified tasks is emphasized. Unlike many of the previous studies, no effort is made to compile a concerted research program to meet a particular objective or to maximize the return for a certain level of funding. Such programmatic concerns are left to funding agencies. Finally, the Appendices present the factual basis for the discussion and recommendations. Numerous references are noted in the Appendices, but are not repeated in the text.

II. Discussion

The procedure for identifying promising research projects involves several considerations. One is an assessment of the state-of-the-art in drilling -- that is, what technologies are currently used to drill wells. Comparison of current capabilities with the anticipated future requirements for drilling indicates areas where improvements must occur. By considering current research emphases, both domestic and foreign, predictions can be made about technologies that will evolve to provide new capabilities. Perhaps more importantly, needed technology pieces that are unlikely to be developed by industry can be identified, and these are candidates for federally-supported research projects. The factors that affect this identification procedure are discussed in the following four points:

A. Drilling is important and will continue to be so in the foreseeable future.

Large numbers of wells are drilled in the U.S. annually, including approximately 80,000 oil and gas wells (average depth 4000' to 5000'), and approximately 700,000 water wells (average depth 100' to 200'). Significant footage is also drilled in support of mining operations but is more difficult to quantify. Many of the resources society needs would be unavailable without drilling.

Drilling accounts for a large and growing portion of energy costs. Depending on the reservoir, drilling costs account for approximately 1/6 to 1/2 the cost of oil or gas, and an even greater portion of water costs. As more expensive and more remote resources are exploited, the portion of costs due to drilling and extraction will grow. In absolute terms, in 1981 \$36 billion was spent drilling domestic oil and gas wells, while the value of the oil and gas produced was approximately \$140 billion.

In addition to well drilling, drilling technology impacts a number of other applications. These include mining shafts, transportation tunnels, waste disposal and isolation, MX siting concepts and other defense applications, and nuclear testing. The importance of these, as well as of the extraction applications, ensures the continuing importance of drilling.

B. Future resources will be different enough to present challenges to current drilling systems.

Current free-world oil and gas drilling is predominantly shallow, land drilling in the contiguous United States (Appendix C). The average well depth in the U.S. is 4600' and the median depth is less than 4000'. The preponderance of wells that are shallow is generally drilled without expensive, high technology services such as measurement while drilling (MWD), directional control and extensive logging. In fact, much of the new drilling technology has been developed specifically for application in deep or offshore wells. These wells are expensive enough to justify the cost and risk of technology development. (The dependence of well cost on depth is shown in Appendix C.) An important, related point is that a much greater portion of European drilling is offshore, (30% vs 2% for the U.S.) and so the European service companies are much more attuned to using recent-technology hardware and services than are their U.S. counterparts.

The predominance of shallow drilling will slowly fade as the resource base changes. The easy-to-extract resources are finite (Appendix D). For conventional resources, there will be growing exploitation of remote oil reservoirs and of deep (and perhaps remote as well) gas. There is continuing debate about the future of oil and gas resources and the timescale for their decline. However, there is little doubt that future resources will be more difficult to extract.

Exploitation of remote oil resources will increase the need for highly controlled and long-reach directional drilling in order to minimize production costs. The expense of production platforms accentuates the importance of maximizing horizontal reach in offshore wells. Similarly, the French are perfecting techniques for horizontal drilling to increase extraction efficiencies for land wells. Smaller and deeper oil and gas reservoirs will require better control over wellbore trajectory and more efficient drilling systems. As conventional extraction becomes expensive, more of the resource will be recovered using enhanced recovery techniques. This will also increase the demand for high-accuracy control of the trajectory and for methods of enhancing the effective permeability of the wellbore.

Utilization of alternative fossil and geothermal energy resources will place further requirements on our extraction capabilities (Appendix E). Most such resources are considered "alternative" because of an inherent difficulty in extracting them. Unconventional oil resources, such as oil shale and tar sands, are enormous--even domestic resources. Mining and surface conversion are expensive and limit the resources that can be exploited. In-situ conversion techniques are being investigated that would use numerous directionally drilled closely-controlled boreholes for controlling and monitoring the conversion process and a network of drainage holes for extracting the products. As in the case of current

tar sands drilling, the holes would not only be closely spaced, but would also be highly deviated. In addition, for efficient extraction of many resources, some means of enhancing the flow from the formation into the wellbore would be valuable.

Unconventional gas resources, such as tight gas sands and shales, geopressured gas and methane drainage from coal seams, can put even greater demands on drilling. They also comprise an enormous resource, and there is no alternative to drilling for their extraction. For the tight gas deposits, it is critical that wells penetrate small target zones and just as important that there be a means of enhancing permeability so that gas will flow into the wells. The geopressured gas will require efficient drilling in difficult environments. The exploitation of the methane in many coal seams will require carefully guided, closely spaced and perhaps highly deviated drill holes.

The unconventional utilization of coal through in-situ conversion would place similar demands on drilling systems. Solution mining through boreholes provides a viable option for obtaining needed minerals in the future, and it may also require closely controlled borehole trajectories and unique hole geometries.

The varied demands that are likely to be put on drilling systems by the extraction of future resources fall generally into the following areas (Appendix E):

1. Information during drilling. Efficient drilling of wells and exploitation of resources will require much better information than is now available during drilling. Measurement of drilling parameters, such as weight on bit, torque applied to the bit, borehole gauge and friction losses in the walls, will become more important as directional drilling applications grow. Measurement and surface indication of borehole trajectory, orientation and location, will also be important. Similarly, there will be a growing emphasis on obtaining real time information about the formation that is being drilled. In particular, sensors that "see" beyond the wellbore wall will be critical in guiding the drilling process.
2. Trajectory Control. Knowing where to drill is of little value if the drilling system cannot get there. Randomly punching holes into a reservoir is no longer acceptable for many current reservoirs. Efficient recovery of many of the future and unconventional resources will require complete control of the borehole trajectory. This is especially true for methane drainage, tight gas, geothermal and any other wells in which following a formation or intersecting a particular feature is important. Though each of these resources typically occurs in large reservoirs, the productivity of a well drilled into such a reservoir often depends on whether the wellbore intersects the right regions.
3. Permeability Enhancement. For many of the resources, methods of enhancing the flow from the formation to the wellbore are essential. This includes both avoiding or correcting formation damage done during standard drilling operations and developing new drilling and stimulation techniques. The success of current stimulation methods is often controlled by the formation. Techniques must be developed to work in all situations.
4. Hole Orientation and Geometry. Many of the future drilling applications would benefit from long-reach deviated or horizontal wells, multiply branched wells, wells that stay within a seam or reservoir, etc. Such geometries are nearly impossible to achieve with current drilling systems.
5. Extreme Environments. Drilling for many of the future resources will encounter severe environments. Drilling systems must be designed to handle extremes of temperature, corrosion, shock and stress.
6. Well Cost. Extraction of the remote, deep or unconventional resources is often uneconomical. Their exploitation can be expanded by improving drilling capabilities in the areas described above or, in the case of many, by simply reducing the cost of wells.

C. Drilling systems will evolve to meet many of the changing requirements.

As the demands on drilling systems change with changing resources, the systems will evolve in response to those demands. Some of the changes that will occur can be anticipated by considering current industrial research emphases. These include: polycrystalline diamond compact (PDC) bits and cutters, improved mud motors and turbines, measurement while drilling (MWD) systems, and automation of the rig and rig functions (Appendices F and G).

The introduction of PDC bits during the last few years has changed drilling as much as any other recent development. These bits have greatly expanded bit performance envelopes—especially through higher speeds of rotation and reduced bit weight requirements. The first generation of PDC bits is allowing manufacturers and users to learn their strengths and weaknesses. Subsequent generations using PDC or newer materials will have improved capabilities and thus, wider application.

The flexibility offered by PDC bits has made possible the expanded use of downhole mud motors and turbines, machines which convert hydraulic energy carried downhole by the drilling fluid to mechanical energy of rotation. In particular, the high rotational speeds available through motors and turbines can now be used to advantage. Motor manufacturers are developing new capabilities designed around PDC bits.

The most active area of current research is MWD. Approximately 15 companies are developing or marketing systems. MWD capabilities are rapidly expanding and MWD services are commonly used in several areas—especially offshore. To date MWD has focused on directional information, but it can also be used for improving drilling efficiency, safety and formation identification.

Moderate progress is being made in the application of automation and computers to the drilling process. Equipment manufacturers have been developing "the automated rig" for many years and several features of it are finding use—though acceptance has been slow. In addition, computers are beginning to play a role in drilling, both in data processing for safety and efficiency and, recently, in "expert systems" to aid management of the drilling process.

1. Potential Evolutionary Changes. These drilling research emphases indicate some of the directions in which drilling systems are likely to evolve to meet future needs. A current trend that will continue is the gradual improvement in the elements that affect control of the wellbore trajectory. From this trend, it is possible to extrapolate a possible evolutionary path.

MWD has made available at the surface information from downhole that previously has been unavailable—for example, real-time indications of wellbore inclination and the orientations of the hole and the bit. Operators will continue to gain competence and confidence in using this information and will identify additional information that would be beneficial. (This evolutionary path will be comprised of coupled developments in hardware and software, and the first step involves the maturation of "software" accompanying the recent MWD hardware improvements.) Once desirable data have been identified, suppliers will develop appropriate downhole tools to collect them (for example, bit weight and torque sensors and new logging tools) and controllable downhole components to take advantage of the new information (for example, controllable bent subs, controllable geometry stabilizers and turbine speed controls). By the time this occurs, the quantity of information passing up and down the transmission channel will have dictated improved data capacity and two-way communications in the channel. In addition, extensive signal processing, both uphole and downhole, will be commonplace. A later step in the evolution will be to positive, real-time, closed-loop control of the borehole trajectory. In terms of software, this will have led in one of two directions, either a high quality data channel will connect the downhole tools to the surface computer that controls them, or a downhole computer will maintain control and a "weaker" data link will connect to the surface for monitor purposes. The hardware developments required for this step include at least downhole-controllable-geometry components and perhaps non-damaging, downhole anchor and thrusting systems to allow complete control of trajectory. An interesting feature of this evolutionary path is that most of its necessary pieces have been designed and tested during the past decade.

Although such an evolutionary response to the future demands is likely, it is important to realize that just as there are wide variations among the types of wells drilled today, there will be similar variations in drilling practices in the future. The shallower or "easier" wells will not be drilled by the system that evolves to handle long-reach oil wells or deep gas wells. These cheaper wells are not likely to require complete control of the borehole trajectory, but they will benefit from the advances arising from improved control.

Drilling systems will evolve in areas other than control, as well. The rock cutting mechanism is currently changing from crushing and gouging rock with roller cone bits to shearing it with PDC bits. It is possible to extrapolate from this trend an evolutionary path that bit design may take. Similarly, the area of information collection and processing is likely to change rapidly during the next few years and a possible evolution could be defined for it. In these and other areas, drilling systems will evolve to meet the needs of the future.

2. Revolutionary Changes. Though many of the pieces necessary for the envisioned evolutionary changes will be developed, it is possible that future resources will be exploitable only with a revolutionary new drilling system that is quite different from current systems. Such a system might utilize novel or revolutionary ways of making wells. Many novel approaches to drilling wells are discussed in Appendix H. Several novel means of cutting or penetrating rock have been studied in the past, and one or more of these may find application in the future. A second part of the drilling process that presents significant potential for a new approach is the lining of the borehole once it is made. This is because the current method of casing or lining the well with steel pipe drives much of the current drilling method. Large rigs with large hoisting capacities are needed as much to line boreholes as to drill them. The costs and time arising from casing and cementing are a significant portion of well cost. The "telescoping" of the borehole is due to the requirements for casing. In most wells, a very efficient novel cutting approach would save little money if it relied on standard casing operations.

Other areas where novel approaches may find application include the means of transmitting power to the bottom of the hole and the method of removing debris. Whether these particular techniques change or not, it is possible that part of the drilling system's response to future demands will come from revolutionary rather than evolutionary changes.

D. The Government can play a role in the changing technology.

The U.S. Government has a strong interest in drilling technology development. Many of the non-extractive applications, for example, scientific drilling of the earth's crust, defense applications, waste isolation and transportation, are in areas of government responsibility. In addition, technology improvement may help insure a continuing supply of water, mineral and energy resources. There are areas in which this interest might best be served by government supported work.

1. The Opportunity. The energy industry has provided the impetus for most of the advances in drilling technology, and the structure of the industry has to some extent determined the nature of the advances. The large energy companies (and smaller independents) "own" the resources and operate the fields, but they do not drill the wells. Drilling generally is done on contract by the drilling companies, the great majority of which are quite small. Small or large, the drilling companies operate in a very competitive environment which does not allow research into new drilling methods—though the larger companies do carry out development and improvement of drilling rigs. Most of the tools and services used by the contractors in drilling wells are provided by the service companies. The leading service companies work continuously on product improvement, for example the current work on bits, motors and MWD, but few have the resources or markets to support research into advanced drilling systems. A few of the major energy companies have in the past researched novel drilling techniques, but such research is sporadic and most companies focus instead on improving current techniques and systems. In short, no company markets the entire drilling system, and none has strong motivation for developing new approaches to drilling. In fact, the structure of the industry dictates the emphasis on evolutionary improvements of the

current system to meet current needs. If a novel approach is developed, it will likely come from outside of the industry. The same is true for many evolutionary technologies that are appropriate for exploitation of alternative resources. There is no industry base for developing alternative extraction techniques.

The drilling and, to a lesser extent, the energy extraction businesses are quite cyclic, and at the current time the drilling industry is depressed (Appendix C). Research and development budgets have been cut and programs discontinued. Because this follows a recent boom, much of the capital-intensive equipment in the field is relatively new. As a result, U.S. industry is unlikely to respond rapidly to technical challenges in the near future. Furthermore, because of the cyclic nature of the industry, long-term research is seldom well supported.

2. The Challenge. Historically, it has been U.S. people, equipment and know-how that have drilled the free world's wells, but this situation is changing. A growing portion of the mobile (offshore) rigs is being built abroad—especially in the Far East. The Japanese have made significant inroads into the tubular and heavy steel markets, and the Japanese and Europeans are marketing most oil field tools and services. The Japanese in particular are working to expand their market share through purchase of American companies and agreements with U.S. partners. Drilling research and development have been emphasized in the Soviet Union for years, and in the free world, the French, with major support from their government, have provided a focus for technology development. More recently, Norway is expanding its drilling research. The Norwegian government has made drilling a "target industry" and is setting up drilling research centers funded by money derived from their offshore resources. Their plan is for Norway to become a leader in drilling technology, just as they plan to provide the rigs, ships, and people that exploit the Norwegian (and world) resource. Similarly, many projects in England are aimed at the North Sea reserves. The emphasis of foreign research and development, especially Japanese, Norwegian, and French, on longterm projects and winning a major part of the 1990's market provides an interesting contrast to the private U.S. research directed at near-term projects. The challenge to U.S. leadership is real (Appendix G), but it is tempered by the fact that the market will continue for some time to be dominated by shallow drilling in the U.S.

3. Appropriate Roles. The Government can play a significant part in U.S. technology development, as is shown by history and by the foreign examples. However, the role the U.S. Government will play will be different from that of other governments. This role will likely have three facets. First, the Government can continue to sponsor projects, such as those in alternative energy exploitation, large-hole drilling, tunnelling, and mining, that have little current commercial value but that require development and application of new drilling technology by industry. Secondly, it can keep open the possibility of an entirely new or revolutionary approach to drilling by sponsoring low-level, long-term research of novel drilling and hole-lining systems. Finally, the government can affect the speed and direction of the evolution of drilling systems by identifying the long-term, high risk projects along the likely evolutionary paths and then sponsoring or participating in work in those areas. The purpose of this work would not be to develop commercial products, but to develop materials or capabilities that are likely to be required to meet future needs and to insure that future drilling systems will be able to meet the demands placed on them by the unconventional resources. A result of government involvement in these three areas would be continued domestic emphasis of long-term drilling research projects.

III. Identification of Projects

Based on the anticipated changes in drilling systems, the current research emphases and past inclinations of industry, and an understanding of the role that government can play, it is possible to identify general areas appropriate for government sponsored drilling research and development. In addition, specific research tasks within those areas can be described. The listing below is not intended to be exhaustive but merely to include attractive, important tasks that might be considered for support.

A. Information and control during drilling.

This will be one of the most active and important areas of research in the next several years. Industry will continue to work hard in developing hardware and software to improve control over the drilling process, but there will be pieces along the evolutionary path that are appropriate for government support—especially those aspects that are important in the exploitation of unconventional resources.

Especially in this area because of its activity, but in the others as well, the line between private and appropriate public research is a fine one, and care must be taken to avoid "competition." The tasks described below are in broad and important enough areas that such conflicts can be avoided. Specific tasks include:

1. Development of "look ahead" downhole sensors. This may be a major breakthrough in the next decade. The objective of this research is to develop a sensor that can determine what is ahead of the bit and around the wellbore. Optimally, a tool would be developed that could be used during drilling to help guide and control the bit. Even a post-drilling, logging tool that could be used to find fractures, permeabilities, reservoirs, formations, etc. away from the wellbore would be extremely valuable. Several types of signals (i.e., widely varied transmission frequencies) hold promise and efficient signal processing techniques would be essential. Effective ranges of tens to hundreds of feet would be desirable. The potential payoff for such a development is obvious for safety, drilling efficiency, and optimal exploitation of a resource. A major application would come in alternative resources where control of the wellbore trajectory is critical.

2. Development of sensor systems for detailed reservoir mapping. The purpose and nature of these sensors are different from those for the "look ahead" sensor discussed above. Their ranges would necessarily be much greater and they would have no requirement for real time or rapid signal processing. It is possible, though, that one tool could be developed to achieve both purposes. The next several years will see extensive work on tools and systems for logging and geophysical measurement. Single borehole, borehole to borehole, and surface systems, complete with advanced signal processing, are needed to accurately locate and characterize the salient features of reservoirs. The efficiencies of enhanced recovery and unconventional resource extraction depend on the reliability of reservoir analyses. Inherent in this is developing an understanding of what the sensor outputs mean.

3. Development of rugged generic components for downhole instruments. Applications for downhole sensing, signal processing, and logic functions while drilling will grow rapidly in the near future. Government can sponsor development of rugged, reliable components that can be used by industry in commercial tools and systems for extreme pressure, temperature, and mechanical environments. This has been a traditional role for government in defense and space applications.

4. Research into high-data-rate and bi-directional MWD transmission links. In the near future the transmission rate for MWD data may limit system performance or application. Some rapid transmission schemes are being investigated, but government-sponsored work could aid other areas. In addition, downlinks will become as important as uplinks for improved control of wellbore trajectory. Two-directional transmission using mud pulses may prove to be difficult.

5. Research into artificial intelligence applications and development of expert systems for drilling. Well drilling provides a very good setting for applications of artificial intelligence (AI)—robotic equipment at the surface for efficiency or downhole for directional control; AI for decision making and control, both surface and downhole; and expert systems at the surface for safety, trouble avoidance, directional control, etc. Many of the applications require large computer systems and AI experience in development, making them good candidates for government sponsorship. In some of the expert systems, an industrial developer may be more limited in data sources than might a government-sponsored program.

6. Development of non-damaging wall anchors and thrusters for downhole trajectory control. Positive control of bit thrusts and advance rates and of wellbore trajectory may be an

essential part of future directional drilling systems. Several different wall-anchoring systems have been discussed, many have been patented, and a few have been tested. It is important that the system that applies thrust to the bit not damage the borehole wall. Sufficient support for research and development in this area is unlikely to come from private industry.

B. Permeability Enhancement

A key to efficient recovery of many of the unconventional resources is enhancing the flow from the formation into the wellbore. The general drilling and extraction related tasks in this area include:

1. Development of new techniques and tools for multi-legged wells. Industry has worked little with the problems of drilling, completing, and maintaining branched or "bird's foot" wells. These wells would find their primary application in unconventional resources.

2. Development of new drilling techniques to enhance permeability. It is possible that drilling tools could be used to enhance wellbore permeability, in effect to perform controlled stimulation. Techniques for underreaming or for drilling short holes out from or perpendicular to a wellbore are examples of techniques that could be investigated. This would introduce positive control into an area that currently is a "hit or miss" situation.

3. Development of new stimulation techniques. This is a general extraction technology that is important for several alternative resources. Although it is not actually drilling, it is an appropriate area for government research. Industry relies on massive hydraulic fracture, acid wash, perforation, explosive bombs and other standard techniques to improve flow into a wellbore, and development work is generally restricted to these areas. There may be other possible techniques that could be more valuable in selected situations. In addition, there are related projects, such as techniques for measurement of in-situ stresses and diagnostic methods for determining which intervals of a well to stimulate, that would also be promising research areas.

C. Drilling efficiency

In addition to projects directed toward developing new capabilities, government-sponsored work can be aimed at improving the efficiency of drilling operations. Improved drilling efficiency would expand the exploitable resource base, especially in remote and unconventional resources.

Oil field suppliers and service companies work steadily to improve existing products and capabilities. The role for government-sponsored research is in improving the drilling process with "generic" improvements, with advances in the general state of knowledge, and in areas outside of current hardware and techniques.

1. Research into the problems of long-reach and horizontal drilling. Efficient exploitation of offshore and several onshore reservoirs will require extending the horizontal reach of drilling systems to allow extraction from a larger region via a single production site. This has led industry to fund the consortium conducting the "extended reach drilling program" directed at oil resources. Long-reach and horizontal drilling technology apply to unconventional resources as well, and advancement of the state of the art would be of general benefit. Appropriate projects include: trajectory control, cuttings removal from a long highly deviated section, stuck drill pipe avoidance, hole lining, etc.

2. Research into the dynamic behavior of the drilling assembly. Efficient cutting of rock and control of hole direction and deviation depend on understanding and using the dynamics of the drill string and bottom-hole assembly. For example, dynamic response of the system can alternately lift the bit off of the hole bottom and then drive it into the formation. It is essential to understand the behavior of the system and the interaction of that system with the formation in order to understand the information collected by downhole sensors and to optimize drilling. This is a continuing, long-term project in which government sponsorship can play an important, unifying role. A first step in this direction is currently sponsored in the geothermal drilling program.

3. Research into rock failure and rock cutting mechanisms. The basic purpose of drilling is to penetrate rock, and basic research into how and why rocks fail can aid development of efficient drilling systems. This is broad, generic research in which government participation is appropriate. Related research would involve the causes of wear and potential ways to reduce it on the cutting surfaces that penetrate the rock. Research in these areas would aid in understanding the information from downhole sensors and would help in controlling the rock cutting process. Both analytical and experimental work are appropriate.

4. Development of novel hole-lining techniques. Two aspects of the motivation for this work have been discussed. The hole lining or casing operation "drives" a large portion of the cost of a well, and non-governmental support for development of novel approaches is unlikely to be strong. This is a long-term, high-risk project with a potentially large payoff.

5. Development of novel drilling techniques. Industry research and development is most likely to be in the area of rotational drilling systems, and yet other techniques could significantly increase drilling efficiency. Work on these other techniques is long-term and high-risk and is appropriate for government sponsorship.

D. New materials

In addition to new approaches to and new capabilities in drilling, there is basic work to be done in developing new materials to handle the environments and demands of future drilling. Examples include:

1. Development of materials and components to operate at elevated temperatures and pressures. The Government has played in the past (for example in the geothermal energy program) and can continue to play a significant role in developing materials for application in high temperature and pressure environments. Examples include: electronic components and systems, elastomeric components for seals and other applications, new metals, new clay-based drilling fluids, new lost circulation materials, and new explosives.

2. Corrosion resistant materials. Many of the unconventional resources are found in highly corrosive environments and special corrosion resistant materials and corrosion inhibitors may be needed. Government-sponsored research is appropriate in many cases.

3. New drilling fluid systems. Many drilling problems are caused by inadequate drilling fluids. It is possible that new fluids can be developed to perform the many functions of drilling fluids and that new systems for maintaining drilling fluids can be designed. A desirable goal would be a "prescriptive" fluid that has a spectrum of controllable, selectable characteristics and is maintained continuously rather than by batch additions.

4. New cutter materials. There is no reason to feel that the ultimate rock cutting material has been found. A material developed for another purpose may be applied to drilling, or research specifically directed toward developing new cutting materials may be carried out.

E. Resource or application related programs

By sponsoring major programs that utilize drilling, the government can provide the impetus for technology development. Examples include: nuclear waste isolation, large-hole drilling for nuclear testing, and MX missile deployment. The same thing is true in many alternative energy areas. A specific example is the drilling technology development work that DOE sponsors in support of geothermal energy development. In many of these programmatic areas there are numerous drilling-related projects that should be carried out. Though development of drilling technologies is of secondary importance in such programs, it is a definite by-product and each program plan should address drilling technology development.

Appendix A Previous Similar Assessments

Numerous studies of necessary or promising drilling research projects have been performed recently. These have been carried out by groups convened specifically for that purpose, by individual organizations, and by single analysts. Some have addressed general drilling needs while others have focused on the drilling needs arising from exploitation of particular resources. Several of the previous efforts are summarized here, in roughly descending order of relevance to this study.

Consideration of these previous studies has emphasized an interesting point. The "advanced drilling community" is small. Many of the individuals and most of the organizations that are concerned with drilling research today are the same ones that have been doing the advanced drilling studies for the last fifteen years. There are few "new players."

1. A Strategy for Developing Fossil Fuel Extraction Drilling Technology.¹

During the period from 1977 through 1979 the Division of Oil, Gas, Shale and In-Situ Technologies (replaced in the latter part of the period by the Division of Fossil Fuel Extraction) conducted an extensive series of studies and small workshops directed toward devising a plan for a federal program in drilling R&D. The work was performed, at least in part, in response to a House Appropriations Committee request to define a comprehensive federal technology development program.

Several documents were included in this effort.

The first document, titled "Drilling Technology Program", was apparently written by a contractor in late 1977.² This was followed by the "Blueprint for a Comprehensive Federal Drilling Technology Development Program" written in February 1978.³ In August 1978, a workshop involving approximately 25 government, contractor, and industry personnel met to draft the strategy document and a second, smaller meeting was held in February 1979. The second meeting resulted in the writing of "A Development Plan for Drilling Technology,"⁴ while the "Drilling R&D Strategic Plan Data Base"⁵ was compiled in March 1979. The strategy itself¹ was completed in May 1979, and other documents in this series were written as late as December 1979.⁶

The research outlined in the "strategy" document included work in four major areas: Conventional Technology Development, Advanced Concepts, Technological Interchange, and Manpower Development. The specific tasks described included:

- Computer Modeling of the Drilling Process
- Materials Research
- Fluid Dynamics Analysis
- Drilling Fluid Development
- Rock Mechanics Analysis
- Development of Data Acquisition Systems
- Instrumentation Development
- Environmental Research
- Identification and Evaluation of Advanced Concepts
- Development of New Training Programs

2. Drilling for Energy Resources⁷

The National Research Council convened a workshop in June 1975 at Park City, Utah, to consider the needs in advanced drilling research. The stated objectives of the workshop were to "assess the state-of-the-art in drilling technology; identify research and development priorities in the field; and, if appropriate, construct a framework for a national research and development strategy to improve the technology for recovering oil, natural gas, coal,

shale oil, water, nuclear fuels and geothermal energy."

The workshop participants recommended the following areas of work. (They also recommended levels of effort and funding--\$100 to \$200 million total over a five year period.)

Oil, Gas, and Geothermal

- Downhole Telemetry
- Test and Evaluation Facilities
- Downhole Motors
- Drilling Mechanics
- New Materials
- Advanced Drilling Systems
- Technical Training
- Deep Water Technology
- Deep Perma Frost Coring
- Arctic Environmental Problems
- Geothermal Equipment and Techniques

Coal, Uranium, and Oil Shale

- Improvement of Existing Drilling Methods
- Drill Materials
- Advanced Drilling Methods
- New Mining Methods

The background papers for this workshop⁸ provide a fairly comprehensive survey of drilling state-of-the-art.

3. Research Projects Needed for Expediting Development of Domestic Oil and Gas Resources Through Arctic, Offshore, and Drilling Technology⁹

The Department of Energy, through the Bartlesville Energy Technology Center, sponsored a workshop at Bartlesville in January 1981. The purpose of the workshop was to "identify those problem areas where government research could provide technology advancement that would assist industry in accelerating the discovery and development of U.S. oil and gas resources."

The workshop broke into three panels—one in each of the three areas: arctic technology, offshore technology, and advanced drilling technology. The panels developed recommendations in their separate areas, with the first two leaving recommended drilling projects for the advanced drilling panel.

Arctic

The panel on arctic technology pointed out that the majority of our oil and gas resources are in the arctic and recommended a "high national priority" be given to arctic research. Most of the specific projects recommended were related to ice behavior studies, but two were related to drilling technologies. The panel recommended work on drilling and completion techniques for penetrating gas hydrate beds and recommended research in tunneling techniques for use in subsurface, offshore production.

Offshore

The panel on offshore technology recommended several projects. Those pertinent to drilling research came in the area of deep-water completions and production.

Advanced Drilling

The advanced drilling panel recommended 34 specific research projects and development of 6 advanced drilling systems. The panel considered whether the projects should be the responsibility of industry or of government and concluded that 17 of the projects and 5 of the

advanced systems were appropriate for government research. The panel devised a weighting system and ranked the tasks by priority.

The need identified for advanced systems was to provide improved directional control and horizontal drilling. For both it was concluded that, "There is no economic incentive for development by private industry. The risk is too great." The research tasks identified were in four areas: advancing the state-of-the-art of conventional drilling, developing advanced systems, enhancing the safety of drilling operations, and mitigating the environmental effects of drilling. The research projects involved tasks in the following areas:

- Rock Mechanics Studies
- Fluid Systems Improvements
- Drilling Systems Analysis
- Materials Development
- Advanced Instrumentation Development
- Improved Component Design
- Advanced Drilling System Development
- Environmental Safeguards

4. Report of the Workshop on Advanced Geothermal Drilling and Completion Systems¹⁰

Sandia National Laboratories sponsored a workshop in January 1979 at New Orleans to help identify research and development opportunities in geothermal drilling. The purposes of the workshop were to identify new drilling and completion systems that had the potential for achieving a 50% reduction in the cost of geothermal wells and to provide recommendations to Sandia as to the research and development tasks that would be required to develop these advanced systems.

The workshop involved 40 participants who were divided into four panels: surface technology, borehole technology, rock drilling technology, and directional drilling technology. In their consideration of advanced technologies, the panels operated under two general constraints. They were to use a "systems approach" and consider the total system and not merely components that needed improvement, and they were to consider only those systems that had the potential for being implemented by 1986 within reasonable funding limitations.

Overall, 15 "advanced" systems were considered, of which three were identified that met the constraints. These were high-pressure fluid jets with mechanical augmentation, percussion drilling, and high-speed downhole motors. In addition to identifying these promising advanced systems, the panels each made recommendations of specific tasks to be performed in support of the advanced drilling system research. These recommended research areas included:

Surface Technology

- Fluid handling and conditioning systems
- Hoisting, pipe handling, and monitoring systems
- Instrumentation
- Training and well control

Borehole Technology

- Non-bentonitic clays and clay morphology
- Drill string and casing materials
- Lost circulation materials, tools, and procedures
- New cements

Rock Drilling Technology

- High-speed motor/bit system
- Percussion system

High-pressure jet system
Rock mechanics studies
Advanced studies

Directional Drilling Technology

Improved bits
Motor and turbine research
Guidance instrumentation
Improved analytical methods and training

5. Near-Term Needs in Drilling Technology¹¹

In March 1977, Dr. William Maurer testified on advanced drilling needs before the Fossil and Nuclear Energy Research, Development and Demonstration Subcommittee of the U.S. House of Representatives Committee on Science and Technology. Dr. Maurer is an expert on advanced drilling techniques and research¹² and was a participant in many of the other studies—including the four discussed above.

As is apparent from the title, this analysis dealt with a different time frame than does the current study. Dr. Maurer's emphasis was in developing concepts that would increase the capability of existing rigs in order to: 1) increase the exploration and production footage that could be drilled by the existing rig fleet; and 2) save billions of dollars in capital expense for additional rigs by expanding the potential of current ones. With this emphasis in mind, he identified 23 areas for work and then narrowed these to the most important "six areas for ERDA research which would yield near-term results." The areas were:

Downhole drilling motors
Borehole data telemetry systems
Test facilities
Improved drill bits
High-pressure jet drilling
Personnel training

6. Continental Drilling¹³

The National Science Foundation and the Department of Energy have long funded a program for drilling for scientific data. There have been several studies of the drilling technology needs for such a program. An early identification of these needs was made at a June 1974 workshop on continental drilling at Ghost Ranch, New Mexico. That workshop identified the following research and development needs in drilling technology and described tasks for each:

Improvement of drilling capabilities for crystalline rock
Improvement of drilling capabilities for high temperature rock
Improvement of drilling capability to drill controlled deviation (directional) holes
Improvement of drilling capability to drill holes below 10 km

Since the original workshop, the drilling research needs for the Continental Drilling Program (now Continental Scientific Drilling Program) have been discussed numerous times. The needs identified depend on the specific drilling targets selected for analysis. References 14, 15, and 16 discuss some of these research areas.

7. An Assessment of Directional Drilling for Fossil Energy Resources¹⁷

This report by Sandia discusses the requirements that extraction of different fossil

resources will impose on directional drilling capabilities, and from these requirements identified, 14 areas for research and development. These are:

- Bit loading at high angles (thrusting) capabilities
- Directional control from the surface
- Surveying and logging tools for high-angle holes
- Bit weight and motor speed sensors
- Computer modeling of drill string mechanics
- Reentry methods for multiple completed wells
- Water jet drilling equipment
- Methods for maintaining borehole integrity
- Study of the effects of side loads on motors
- Development of fluids for cleaning high-angle and horizontal holes
- Development of methods for making small diameter drain holes
- Testing of compatibility between PDC bits and motors
- Development of a system software model
- Study of automated and computer controlled rigs

8. Other Studies.

Several other studies make less specific or less pertinent recommendations. These include:

a. Geopressured Geothermal Drilling and Completions Technology Development Needs.¹⁸ This document discusses the needs for geopressured geothermal drilling and identifies eight general areas of technical need.

b. UGR Drilling Project.¹⁹ This document discusses the needs for directional drilling, specifically for unconventional gas resources. It outlines research in both conventional technology and advanced concepts.

c. Project MOHOLE.²⁰ This document discusses the needs identified and worked on in the pursuit of project MOHOLE for scientific deep offshore drilling (into the earth's mantle).

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Appendix B Historical Government Support of Drilling Research

During the past ten years, the government has participated in or sponsored several significant research projects in advanced drilling. Reference 1 is a valuable source book on recent research into advanced drilling techniques, and there are few approaches discussed in it that have not benefited from some level of government support. Similarly, few of the advanced drilling techniques have been investigated solely by the government. Rather, most have been studied and developed by both government agencies and private industry. The agencies that have been most active include the DOE, the Bureau of Mines, the Department of Transportation, and the Advanced Research Projects Agency of the Department of Defense, though much of the non-DOE effort has been directed toward tunnelling rather than borehole drilling.

1. Concluded Projects

Most of the recent government-supported research projects have been concluded or terminated—at varying points in the development schedule and at varying levels of success. Some of the most visible projects are summarized here. Government programs in drilling have included research or development in numerous components or analysis areas in addition to the larger scale drilling projects discussed here.

a. Clear Successes. A few of the projects resulted in products that have found widespread commercial application. Generally, these were projects in which government identified a particularly useful concept or product and funded both critical elements of its development and a portion of industry's initial use.

PDC Bits. Polycrystalline diamond compact (PDC) bits, such as Stratapax® bits, are now commonly used in certain conditions in petroleum and other drilling. The government played a large role in their introduction and gradual acceptance by industry. The DOE, through Sandia National Labs (SNL) and the Bartlesville Energy Technology Center (BETC), sponsored research into the applications and limitations of bits using the man-made diamond compact and funded several rock bit companies to design and manufacture their initial versions. Government-sponsored field tests of PDC bits and coring devices hastened their commercial viability.

Mud Pulse Telemetry. DOE support, through BETC, of the development and field testing of Teleco's initial mud pulse telemetry system aided its early success. BETC's identification and support of telemetry as a critical advanced technology hastened its commercial introduction. MWD and telemetry systems have become one of the most important of the new technologies.

b. Probable Successes. The government has played a major part in several projects that have resulted in commercial products with less widespread application. Time will show whether these products will ultimately be successful. In general, these projects involved identification of a new concept and support of early development and testing of that concept.

Cavitating Jet Nozzles. First DOE itself and then SNL funded research into the cutting effects of cavitating jet nozzles. Research into the design and performance of nozzles was funded at at least three organizations. The University of Missouri, Rolla, applied the research to mining cutting, and Daedalean Inc. developed equipment for cleaning and descaling surface and downhole geothermal equipment. Hydronautics Inc. has concentrated on putting the Cavijet® cavitating jet nozzles into commercial roller cone bits. All three applications have been successful and are likely to expand.

Terra Drill. SNL conducted the initial research into the Terra Drill concept—a drilling technique in which high velocity projectiles are fired into the rock ahead of a bit to prestress and prefracture the formation. After several years of development and testing, Sandia concluded its effort. Recently, this concept has been commercially marketed for

drilling hard formations by SNL's original contractor, who has carried the earlier feasibility work through a final design.

High-Temperature Drilling Turbine. Development of a downhole turbine for application in high temperature wells was funded by Los Alamos National Laboratories (LANL) for use in their Hot Dry Rock Program. The tool was developed to provide a capability to directionally drill holes in high temperature formations. After its development the tool became commercially available from the project's contractor.

High-Temperature Components. As part of its geothermal technology development program, SNL sponsored and conducted development of high-temperature electronic components applicable to downhole logging tools. In addition, SNL funded the development of new drilling fluids that are especially designed for geothermal application, and SNL and LANL have both funded development of high temperature elastomers for use in downhole seals. All of these components are now available commercially.

c. **Too Early to Judge Success.** Recent government-sponsored activities include several for which it is too early to determine their ultimate success. Of the four major projects discussed here, the first two projects involved modifications to current drilling methods utilizing mechanical breaking or abrasion of rock and the others utilized nonconventional approaches for removing rock.

Downhole Replaceable Cutting Surfaces. SNL investigated several means for replacing a bit's cutting surfaces without extracting the bit from the well. The concept that was carried furthest was that of a "chain drill" which relied on a cutting action similar to a standard diamond matrix bit. The cutting materials (originally diamonds and more recently PDC cutters) are imbedded in the links of a belt or chain. At any one time five links are engaging the rock and the others are stored within the bit body. When a set of links becomes worn, new ones are cycled into the cutting positions. In this way, several "bit runs" can be made by a single "bit". In certain applications, the subsequent elimination of tripping times can effect considerable cost savings. The feasibility of this concept (one of the few that has had only government support) has been demonstrated through laboratory and field tests and through analysis.

Electrodrill. BETC sponsored design and development of a concept termed "electrodrill" in which the energy required to break rock is transmitted down the hole electrically. The concept is designed around a downhole electric motor that is used just as are conventional hydraulic (mud powered) motors. This project was carried through field testing, and its initial technical feasibility was established. The power requirements for cutting rocks resulted in a fairly large electrical generating station at the surface and a large, rugged transmission line and connectors.

Spark Drill. SNL investigated the feasibility of using a high energy spark discharge to fracture and spall rocks. This concept has been studied by several organizations, both private and government, in addition to Sandia. It has been shown to be technically feasible, though problems with insulator and electrode lifetimes severely limit the applicability of this concept.

Subterrene. LANL investigated for several years the subterrene concept which uses electrical heaters to heat a probe that melts through rock. The probe can function in either of two ways. It can melt the rock and compact it into the formation around the hole (basically pushing it aside) or it can melt the rock and extrude it up through the center of the bit where it is removed by more conventional techniques. In either case, the probe leaves behind a glass-lined hole that is sealed. LANL demonstrated the feasibility of the concept with scale model, laboratory testing, and full-scale field tests.

2. Continuing Research

DOE funding for fossil drilling research has, to a great extent, been terminated, and this has ended the advanced drilling work sponsored through BETC. However, government support continues for drilling for specific alternative energy sources.

Appendix C

Drilling: State of the Art and State of the Industry

This appendix points out a few features of two separate but related topics. The first part summarizes some facets of current drilling systems, and the second presents a collection of items that help describe the current state of the drilling industry.

1. The State of the Art in Well Drilling¹

This discussion of current drilling systems is organized by apparatus and function.

a. Drilling Rig. The most visible part of a drilling system is the drilling rig. Its purpose is to lift and its size is determined by how much weight it is designed to lift. The weight on the bit (WOB) during drilling--that is, the "downward" force on the bit--is provided entirely by gravity and is controlled by increasing or decreasing the portion of the gravity load that is carried by the rig. In addition to putting tension on the top end of the drill string during drilling operations, the rig hoists the casing pipes and lowers them into the well to line and protect the hole. In many situations, it is the anticipated casing loads, not the drilling loads, that determine the required rig capacity.

b. Bit. The bit is the system component that actually penetrates the rock formation that is being drilled. There are several bit types. Roller-cone bits cut by crushing hard rocks or gouging softer ones. Diamond bits are required in very hard rocks and they cut by grinding or abrasion. Polycrystalline diamond bits cut by shearing, much as a knife or other blade would cut. For each bit type there are numerous bit designs (hundreds) for different purposes and different formations. Oil field bits of all three types cut by rotary motion, while some mining bits use impact or percussion similar to that delivered by an air hammer to fail rocks. These percussion bits are sometimes used to drill shallow petroleum wells.

c. Drill Pipe. In the simplest drilling configuration, the bit is attached to drill pipe which runs from the surface to the bit. The pipe transmits torque, tension (and, in its lower elements, compression if the bit is in contact with the formation) and fluids. The drill pipe comes in sections that usually are 30 feet long. Each time the bit drills 30 feet, the drill string (drill pipe, bit, etc.) is suspended from the surface while the rig picks up a new 30 foot "joint" of drill pipe and connects it (by threads) to the top of the drill string; and then the drilling resumes. When the bit wears out, all of the drill pipe is pulled from the hole--sometimes piece by piece, more often in "doubles" or "triples" (2 or 3 joints at a time)--so that the bit can be changed. This is called "tripping" the bit, and pulling the drill string out of the hole and then running it back in is called a "round trip."

d. Drill Collars. Drill Collars are thick-walled, heavy tubulars similar to drill pipe. They are often put in the drill string just above the bit to provide additional WOB.

e. Rotary. The rotary or rotary table converts mechanical or electrical energy from the rig's power plant to torque in the drill string. Located on the rig floor, it is the drive mechanism for rotary drilling from the surface. A few rigs, generally designed for special purposes like large-hole or slant drilling, have "top-drive" capability in which the torque is applied to the drill pipe by the hoisting mechanism at the top of the rig rather than by a rotary on the rig floor. This avoids the requirement for a sliding torque drive on the outside surface of a special length of drill pipe (the kelly). Top drive units have both advantages and disadvantages in comparison to rotary-table rigs.

f. Mud. Drilling fluid can take several forms. The most common is a water-based solution of clay minerals from which the term "mud" is drawn, but drilling muds can also be oil-based. Air is sometimes used in conjunction with or in place of mud, and other fluids are sometimes used. The type of drilling fluid that is used generally depends on the formation being drilled. The mud serves several functions in the drilling of a well. Some of the most important are to lift the cuttings from the formation face to the surface, to

balance any downhole pressures and prevent uncontrolled influx of formation fluids into the well, to protect fragile formations from chemical or physical damage, to keep the drilled hole from collapsing, and to lubricate the bit and drill string to reduce friction losses.

g. Downhole Motors. In some situations the drilling torque is applied not at the surface by the rotary table, but downhole by a downhole mud motor. When this occurs, the power is carried down the drill string in the form of hydraulic energy in the mud. It is imparted by the mud pumps on the surface and extracted by either a positive displacement motor or a turbine. The most common application for downhole motors is in directional drilling, that is, drilling in which control of the direction of the hole is attempted. Since the drill pipe need not turn when a motor is used, it can be aligned in a desired direction. (Though this can be difficult from the surface due to the effect of reactive torque on the drill string when the motor is run.) This alignment capability can be utilized by putting a bent sub, a collar with a known angle of bend, above the motor. This causes the bit to drill away from the previous center line of the hole in a known direction. Though directional work is the most common application for motors, their use in "straight" portions of the well is growing.

h. Casing. Once a portion of a hole is drilled, it must be stabilized against collapse and other possible problems. This is done by lining the hole with steel pipe, called casing. Since the different formations penetrated by a single borehole can be quite different, it is necessary to case major portions of a well as they are drilled. As a result, the normal oil or gas well "telescopes" down to its target, since sequentially smaller diameter casings must be used.

i. Cement. The casing "strings" that line the hole are set in place and grouted into the formations with cement. This protects and stabilizes the casing, and it also protects formations and aquifers by sealing them against communication of fluids between levels in a well.

j. Logging. Several times during and after the drilling of a well it may be "logged" by measurement equipment that is lowered into it. The logging tools that are used measure characteristics of the hole and the formations it penetrates.

k. MWD. A recent addition to drilling operations is measurement-while-drilling (MWD) equipment. An MWD system is built around sensors at the bottom of the drill string that measure various parameters, such as the physical orientation of the hole and the nature of the formation. The measurements are telemetered to the surface by a mud-pressure pulsing system and displayed to the driller. Because of high operating costs, MWD systems are commonly used only on the directional portions of expensive wells.

1. General. The system that includes these and several other pieces has drilled wells for decades. It has been used to drill very deep and highly deviated wells as well as simple, shallow wells. It has evolved into a fairly sophisticated system. Its primary weakness, in terms of future drilling requirements, is that control of the wellbore trajectory is an art. It is difficult to maintain positive control over deviation and trajectory.

2. The State of the Drilling Industry

Several pieces of data illustrate the "status quo" in drilling. Although individually they are common knowledge, they collectively build a picture of drilling that is surprising to many.

a. The Importance of Petroleum Products. As is shown in Table C-1, petroleum and natural gas products are quite important to the U.S. economy.² They comprise more than a third of all products produced or consumed. The importance of energy in general is also obvious. We consume 30% more (by weight) fossil fuel than everything else combined. The one "product" that is excluded from the table is water. We use roughly 650×10^9 tons/year of water of which approximately 20% is extracted from wells.³

Table C-1. Weights of Products Produced or Consumed in the United States (1979)

<u>Products</u>	<u>Annual Quantity</u> <u>(Weight, 10⁶ Tons)</u>
Non-Energy Products Produced:	
Agricultural Products (total)	714 (total)
Corn (217)	
Hay (146)	
Wheat (64)	
Soy Beans (64)	
Other (223)	
Steel and Iron	136
Aluminum	6
Copper	2
Wood Products	220
Concrete (minus cement)	457
Cement	85
Total	1620
Energy Products Consumed:	
Coal	680
Petroleum Products	945
Natural Gas	419
Firewood	95
Total	2139

b. Number of Wells Drilled. Figure C-1 displays an historical account of the number of oil and gas wells drilled annually in the U.S.⁴ As would be expected, the total number of wells has been sensitive to product prices and political constraints. The number declined until a decade ago as the U.S. grew more dependent on cheaper, imported oil. Following the oil supply crisis of 1973, the number of wells has risen dramatically. For 1983 a small decline is expected as a result of price reductions.

c. Where Domestic Wells are Drilled. Table C-2 displays the geographic distribution of U.S. well locations.⁵ Very few wells are drilled offshore (roughly 2%) and even fewer in Alaska (roughly 0.2%). The southwest and midwest dominate the drilling.

d. Depth of Drilling. Figure C-2 presents some of the most surprising data.⁶ Very few of the wells that are drilled in the U.S. are deep. The average oil well depth is about 4100 feet, the average gas well is about 5650 feet, and the combined average is about 4775 feet. As would be expected, the median depths are even shallower. Half of all oil wells are less than 3400 feet deep. For 1981, roughly 78% of the oil well footage drilled was at depths less than 5000 feet. Offshore wells are significantly deeper than onshore.

Figure C-3 shows a related fact.⁷ The average depths of oil and gas wells drilled in the U.S. have changed little over the past 20 years. Except for a move toward a larger portion of gas wells in the mid-1960s, the curves show no other trend.

e. Costs of Drilling Wells. Figure C-4 shows an interesting relationship between well depth and cost.^{8,9,10} Total cost rises very rapidly for well depths greater than 5000 feet. For well depths shallower than 5000 feet, the cost increase is nearly linear with depth. Well costs increased more rapidly than general inflation in the late 1970s, but the dramatic cost increases have disappeared during the past year when costs for several components of drilling have actually declined.

An interesting comparison is provided by Figure C-5.¹¹ Offshore drilling is much more expensive than land drilling of comparable depth.

Table C-3 presents the average cost breakdown for drilling a well.¹² The largest portion of cost is for the drilling contractor. This is basically the rig-rental cost. No other single cost is comparable to the rig cost.

f. The Impact of Independent Operators. In 1982 there were approximately 87,000 oil and gas wells drilled in the U.S. Of these, nearly 77,000 were "drilled" by independent operators, while the twenty major operators (i.e., oil companies) sponsored the drilling of the other 10,000.¹³

g. Free-World Drilling. Figure C-6 displays an interesting comparison between regions of the free world.¹⁴ North America clearly dominates the drilling. An interesting contrast to the drilling figures is provided by Figure C-7.¹⁵ It seems that the areas with the least resource are those with the most drilling. To a great extent, what is shown by the comparison is the importance of resource quality. A well in a good resource area can be 1000 times as productive as a well tapping a poor resource. For example, the average Middle East well produces 300 times as much oil as the average U.S. well.¹⁶

h. Exploitation of Offshore Resources. Figure C-8 shows the trend toward utilizing a greater portion of offshore gas resources. The data for oil reserves are quite similar.¹⁷ An interesting point is that 30% of European drilling is done offshore.¹⁸

i. Domestic Rig Count. Figure C-9 shows the recent history of the U.S. active rig count.¹⁹ It graphically displays one of the major current problems facing the industry. The rig count fell by more than 50% during the past two years, but it is now recovering.

j. Offshore Rig Count. There are approximately 675 mobile drilling rigs in the world, the great majority of which are jack-up rigs. These drill approximately 3000 offshore wells annually.²⁰ During the past two years, the rig utilization rate has fallen from nearly 100% to between 75% and 80%, leaving approximately 150 rigs idle.²¹

Figure C-1. Number of Wells Per Year (Oil, Gas & Dry Wells)

Table C-2. Locations of U.S. Drilling (1981)

<u>State</u>	<u>Wells Drilled</u>	<u>Percent of Total</u>
Texas	25,139	31%
Oklahoma	11,639	14%
Kansas	7,431	9%
Louisiana	5,619	7%
California	3,417	4%
Illinois	3,055	4%
New Mexico	2,396	3%

Figure C-2. Depth Distribution for Oil Wells

Figure C-3. Recent Average Well Depths

Figure C-4. Effect of Well
Depth on Cost for U.S.
Oil and Gas Wells

Figure C-5. Comparative Costs
for Onshore and
Offshore Wells in
1981

Table C-3. Drilling Cost Breakdown (1979)

<u>ITEM</u>	<u>PERCENT OF COST</u>
Payments to Contractors	31%
Purchased Items:	
Casing & Tubing	14.6%
Mud & Additives	7.1%
Site Preparation	5.3%
Formation Treating	4.5%
Transportation	4.1%
Tool Rentals	3.8%
Cement & Services	3.7%
Logs & Wireline Evaluation	3.1%
Other Equipment & Services	2.4%
Wellhead Equipment	2.2%
Supervision & Overhead	2.2%
Drill Bits & Reamers	1.8%
Perforation	1.6%
Wellsite Monitoring	1.5%
Fuel	1.5%
Directional Services	1.0%
Casing Hardware	0.6%
Physical Tests	0.6%
Plugging	0.4%
Miscellaneous	7.0%

Figure C-6. Free World Well Completions (Oil & Gas, 1980)

Figure C-7. Free World Oil
Reserves (1980)

Figure C-8. Portion of Gas
Produced from
Offshore

Figure C-9. Recent U.S. Rig
Count

k. Summary. Several conclusions can be drawn from these data. Free-world drilling is predominantly U.S. drilling, which in turn is predominantly shallow, land drilling. Shallow drilling is much cheaper than is deep or offshore drilling. The drilling industry is quite sensitive, in both number of wells drilled and in number of rigs active, to market forces. Though there is no apparent trend for wells to get deeper, the world is relying more heavily on offshore resources.

3. References

1. Several references discuss current drilling techniques. These include:

"A Primer of Oilwell Drilling", from the Petroleum Extension Service of the University of Texas.

and

"Drilling Manual" from the International Association of Drilling Contractors.

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• SNL. Sandia's Geothermal Technology Development Program contains many research projects directed at improved technology for drilling geothermal wells. Current projects are generally research tasks that study particular pieces of, or problems associated with, drilling systems. This is different from the projects discussed above that focused on near-commercial development of complete drilling systems. In particular, Sandia is studying the interaction between rocks and cutters, new materials for cutters, cutter wear, the dynamics of a drill string and bottom-hole assembly, new high-temperature drilling fluids, the nature and performance of Cavijet nozzles, techniques and materials for combating lost circulation, and new instrumentation for determining the nature of formations.

LANL. Just as SNL's program is directed toward geothermal drilling and completion, Los Alamos' is directed toward development of hot dry rock energy extraction systems. Thus, the drilling research conducted there is for new hardware and techniques for drilling in hot, granitic formations. The subterrene and the high-temperature turbine discussed above were developed for this purpose. Current research is directed toward modification of existing drilling hardware and techniques and investigation of the feasibility of flame jet drilling.

Continental Scientific Drilling Program. This Basic Energy Sciences program spends a portion of its funding on developing techniques and hardware for its unique drilling environments. Currently, its efforts are directed toward diagnostic systems for evaluating formations and making other downhole measurements.

Deep Sea Drilling Program. This NSF project has historically developed new techniques useful to offshore drilling. Most of the contributions have been in above-the-seabed operations, such as positioning, risers, reentry techniques, etc., and in coring. Generally, conventional drilling techniques are used.

Nuclear Waste Disposal. The waste storage programs are not conducting research in advanced borehole drilling techniques, but they have developed and evaluated systems for sinking large diameter shafts and for drilling or otherwise constructing horizontal tunnels (of both large and small diameter) for storage. The work is related more to tunnelling than to drilling.

Defense Programs. Some study of advanced drilling and tunnelling systems is being done in support of the MX basing proposals. In addition, some development of drilling systems for burial of demolition munitions may be underway.

Bureau of Mines Programs. The Bureau of Mines conducts limited research in advanced drilling methods for methane drainage from coal, leach mining, roof bolt drilling, coal and rock cutting, and rescue of trapped miners. The Bureau also conducts related research in resource mapping and evaluation, fracture location, and borehole to borehole communications.

3. References

1. *Advanced Drilling Techniques, Petroleum Publishing Company, William C. Maurer, 1980.

The reader is referred to the sponsoring agencies for information on specific technologies.

Appendix D Future Energy Supplies

This Appendix considers the resources that will be utilized to provide the world's energy for the next 20 years by summarizing the findings of several recent studies of future energy supplies. In the decade since the first oil squeeze many separate U.S., foreign, and international groups have analyzed the energy situation and predicted future energy supplies and prices. No effort is made here to duplicate or even to evaluate those efforts, merely to summarize them.

The striking conclusion that arises from surveying the various studies is that the world has plenty of energy to meet its needs, but that the sources available are neither as convenient nor as cheap as those we have relied on in the recent past. For many of the potential sources, extraction and utilization technologies must be developed or perfected before they can become viable. This fact underscores the importance of considering the future energy mix in the direction of a drilling research program. Without recognizing the characteristics of the likely future energy sources, it is difficult to describe the drilling capabilities required to utilize them.

1. Petroleum

Oil is the cornerstone of both our current energy mix and our continuing energy crisis. Roughly 45% of the energy used in the U.S. is provided by oil¹, and our demand for oil has led to a heavy reliance on imports from relatively "precarious" regions of the world. Nearly half (44%) of our oil is imported.² Furthermore, oil will continue to be our major energy source for the next 20 years and will account for 25% to 40% of our energy mix in the year 2000.^{3,4} It is ironic that we depend most heavily on our scarcest resource.

Just as with energy in general, there is an abundance of oil in place--enough to meet the foreseeable demand--and more is found daily. However, this does not mean that the oil problem has been overstated. We are rapidly exhausting the easily produced oil, the 25% that can easily be extracted from the accessible, large oil fields.^{5,6} Due to increasing difficulty in extracting oil, world-wide petroleum production is likely to peak during the 1990s and to decline by the end of the century.^{7,8} Although the different studies use different assumptions to arrive at (sometimes very) different numbers, this qualitative conclusion represents a middle ground. It is bracketed by the feeling that oil production will peak this decade⁹ and the opinion that production rates will continue to grow into the next century.¹⁰

There is general agreement that conventional oil will come from increasingly difficult environments.^{11,12} This is especially true for our domestic resources. Roughly 15% of U.S. crude oil reserves (of approximately 25×10^9 barrels) are offshore in the lower 48 states and another 30% are in Alaska.¹³ The move toward deep offshore and polar resources is apparent in other parts of the world, as well. In addition to finding oil in less hospitable surface environments, much future oil will come via enhanced recovery techniques that will increase the average percentage of oil that can be produced from a reservoir from 25% to more than 40%.

Much of the reliance on oil is caused by modern society's demands for liquid fuels, and these demands will continue even as oil production declines.¹⁴ Though unlikely to contribute much energy this century, unconventional sources of oil will supplement the more conventional sources as their production tails off. The unconventional sources discussed most frequently are oil from shales, heavy oil from tar sands, and synthetic oil from coal. These three resources are enormous. Conventional oil has a probable worldwide resource base of approximately 800×10^9 barrels, while tar sands resources are estimated to be three times as great (mostly in Canada, Venezuela, and the USSR) and shale oil resources (mostly in the U.S.) are roughly four times as great.¹⁵ The coal resource is discussed below. Though unconventional oil has been predicted to provide as much as 10% of our energy mix in 2000¹⁶, this now appears unlikely to occur until later.

2. Natural Gas

Gas resources are a natural partner of petroleum. The two are stored in the same types of geologic reservoirs and are often found together. Their uses overlap as well--though gas is more convenient for distributed systems, such as space heating, while oil is much better as a transportation fuel. Gas currently contributes more than 25% of U.S. energy.¹⁷ Worldwide reserves of gas are in much better shape than those of oil. Although the reserves for the two are roughly equal¹⁸, gas is used at a much lower rate. Furthermore, though U.S. discovery rates for new gas are declining¹⁹, worldwide discovery rates remain high.²⁰

It appears that worldwide production of gas will increase well into the next century.^{21,22} However, projections of U.S. production are less hopeful. Some of the studies find us beyond the production peak²³, while others see a production decline beginning in the middle of this decade.²⁴ Though the U.S. will likely import much more gas in 2000 than now²⁵, world production will still be limited more by transportation inadequacies than by supply.²⁶ Associated gas being produced with petroleum is even now flared in many parts of the world for lack of transportation facilities.²⁷

As was pointed out in connection with oil, the future gas resources we rely on will come from more hostile environments. In particular, gas reserves will be deeper and it is expected that a greater percentage of offshore and polar resources will be found.²⁸ Alternative sources of gas--just as "unconventional" sources of oil--comprise an enormous potential resource. The three most commonly mentioned resources are vast amounts of geopressured gas with an estimated U.S. Gulf Coast resource of at least 1000 TCF of gas, Devonian shales with an estimated U.S. resource base of 400 TCF, and tight gas sands with an estimated resource of 600 TCF in the western U.S.²⁹ These compare favorably to the approximately 190 TCF of proven reserves of conventional natural gas in the U.S.³⁰ A fourth unconventional resource is the methane gas in coal formations. It has been estimated that there is as much methane in coal within 3000 ft of the surface as in the proven natural gas reserves.³¹ In addition, in polar regions of the world, the possibility exists for vast amounts of gas hydrates.³² In the near future, the more conventional resources will provide the world's natural gas, but the deeper and unconventional sources will make significant contributions early in the 21st century. Whatever the source, gas will continue its major role in the U.S. and, to a lesser extent, the world energy mix.

Figure D-1, from the Energy Information Administration, illustrates one prediction for U.S. oil and gas production between now and 2020.³³ The changing emphasis from conventional to unconventional sources is apparent.

3. Coal

Coal is the third of the major fossil fuel resources that dominate our current energy mix. Roughly 21% of our (U.S.) energy comes from coal.³⁴ The U.S. coal resource is more than ten times greater than the combined U.S. oil and gas resources.³⁵ Worldwide the story is similar. Coal resources are vast³⁶, and in most parts of the world little effort has been made to discover more.³⁷ Major onshore and offshore discoveries are likely.³⁸

Coal use will grow through the next few decades.^{39,40} It will be a key transitional fuel that will supplement dwindling oil and gas supplies until the (inevitable?) replacement for fossil fuels appears.⁴¹ Coal is likely to provide about 30% of the U.S. energy mix in 2000.⁴² Its contribution will be limited by environmental problems, not by supply constraints.⁴³ Current technology for utilization of coal leads to severe environmental concerns, and the future use of coal (or any fossil fuel) may lead to further problems and to potentially serious climatic changes.⁴⁴ New technologies must be developed for extraction and use of coal. Two technologies commonly mentioned are remote mining and in-situ coal gasification.^{45,46}

If coal's prime virtue is its availability, its second is its potential as a source for liquid and gaseous fuels. Much of the expansion in coal production during the early part of the next century will be for conversion to "synthetic" fuels.^{47,48} The remainder of coal's expansion will be to support electricity generation. As oil and gas become less available

QUADRILLION BTU PER YEAR

Figure D-1. Comparison of Domestic Oil & Gas Production from Old and New Technologies

for this task, the tradeoff between the environmental concerns of coal and those of nuclear will dictate the path taken. At this time, it appears that coal will play a major part.

4. Nuclear Energy

Nuclear energy resources comprise a vast potential for energy use. As the International Institute for Applied Systems Analysis stated, "Nuclear energy could supply very large amounts of energy for millenia on a sustainable basis. Even within the fifty year time horizon of our study, nuclear power could contribute decisively to meeting global energy needs. The question of whether or not this potential will be used is not so much a technical question as a social and political one."⁴⁹ The ultimate answer to that political question (which divides the technical community) will determine the contribution of nuclear power to the energy mix. As was discussed, it will also determine the demands that will fall on the coal resources.

The nuclear resource is difficult to characterize, for its size depends on the specific fuel cycle that is utilized. The light water reactor (LWR), the current workhorse of the nuclear power generation industry, uses less than 1% of the energy stored in uranium.⁵⁰ Reprocessing of fuels can improve this slightly to a little more than 1%⁵¹, but breeder reactors can be 100 times more efficient than LWR technology, recovering more than half of the energy contained in the uranium.⁵² If LWRs are used, the uranium resource is roughly comparable in magnitude to that of oil and gas,⁵³ and the fuel is likely to be supply limited in this century. The limitation will be due to mining and extraction capability, not principally to a shrinking resource base.⁵⁴

Predictions of the nuclear contribution have been continuously adjusted downward over the past few years.^{55,56} At this time, it does not seem likely that the domestic capacity in 2000 will be much greater than that provided by plants currently in existence or under construction.⁵⁷ Nonetheless, roughly 1/3 of the free world's electricity in 2000 will be provided by nuclear plants.⁵⁸ In the U.S., nuclear will account for about 15% of the 2000 energy supply.⁵⁹ The damper that has descended on nuclear development arises from political and environmental concerns. For LWR technology, the concerns are primarily environmental and safety--focusing on power plant operation and waste isolation. For reprocessing plants and breeder technology, the concerns expand to include social and political ones--encompassing proliferation, terrorism, and excessive security controls. The debates surrounding these issues are not dealt with here. However, their importance to the development of nuclear fission, and consequently of coal, cannot be overstated.

5. Other Resources

The four energy sources considered above provide roughly 96% of the current U.S. energy mix.⁶⁰ Several other technologies contribute the remaining 4% and are growing in importance. However, it is unlikely that together they will contribute much more than 6% to our 2000 energy mix.⁶¹

Hydroelectric--This is the major contributor of the nonmineral energy resources. Currently it is used to generate 20% of the world's electricity.⁶² Its growth has been estimated to be between 15% and 40% over the next 20 years for the U.S.^{63,64} and roughly 200% worldwide.

Solar--Enough solar energy reaches the earth to meet the world's energy needs, and its contribution to the energy mix is growing rapidly. However, it will not play a major role until well into the next century. At this point it appears unlikely that the large "hard" solar projects, which could contribute greatly to the energy mix, will be common. More common will be the small projects, on the individual building scale, which are difficult to credit.

Geothermal--Like much of solar, this resource is being exploited by technologies that are just developing. They have been adapted from the oil field for extraction and from the utilities for utilization of the hydrothermal fluids. The energy contribution of geothermal resources is locally significant, in Iceland, New Zealand, the Phillippines, and the western

U.S. for example; but they contribute little to the worldwide energy mix. The next 30 years will see significant development and expansion of this resource.

Conservation--While not a potential source of energy that can be included in an energy supply mix, conservation has the same effect as a resource--it reduces the pressure on other sources. Conservation has already played a larger role than any of the "alternative" resources, and it is likely to do so through this century. Though its role is inherently limited, we have not determined the limits. To a certain extent, its potential is demonstrated in the gradual reduction in recent predictions of the year 2000 demand for energy.^{66,67} This reduction is at least part of the reason that a review today of the future supply of energy is likely to be much more optimistic than one from five years ago.

6. The Distant Future

This report does not attempt to predict the resources that will replace petroleum during its inevitable decline. Many different predictions have been made by different groups. These include resources from among the current list--coal, nuclear, solar, gas (abiogenic and biogenic), and unconventional liquids--and others that are current research areas. Of these, nuclear fusion is the most heavily supported. It could be contributing to the energy mix in approximately fifty years. Two others with less emphasis, but with potentially shorter development schedules, are dry geothermal resources and exploitation of the energy in shallow magma bodies. While speculation about the distant future is interesting, it sheds little light on the importance of drilling research projects.

7. Conclusions

The conclusions from this survey of future energy sources are straightforward. The energy mix for both the U.S. and the world will not change significantly over the next twenty years. Fossil fuels, especially oil and gas, will continue to provide the bulk of our energy. The use of coal will expand, in electricity generation and synthetic fuel production, to supplement oil and gas. Nuclear energy, the only nonfossil alternative that has been emphasized, is mired in political considerations and will undergo no great expansion during this century. Expansions in world energy demands will be handled by nearly proportionate expansions in the utilization of these basic resources.

The importance of these conclusions in the consideration of drilling technology comes in understanding the fossil fuel resources. Oil and gas are getting harder to extract and the bulk of their remaining resources is in unconventional forms. The future supplies will come more and more from hostile environments and from these unconventional resources. The predictions illustrated in Figure D-1 show half of the U.S.-produced oil and gas coming from unconventional sources by 2010 and nearly half of the remainder coming from Alaska. The situation in coal utilization is similar. The large portion of coal that is unmineable can be reached by drilling for methane drainage and in-situ conversion. In addition, in-situ gasification will utilize highly controlled drilling operations. Improvements in drilling capabilities and efficiencies will be required to provide sufficient energy in the foreseeable future.

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1. Source 8, Vol. II, page 7.
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5. Source 12, page 18.
6. Source 5, page 15.
7. Source 5, page 75.
8. Source 16, page 145.

Appendix E Drilling Requirements of Unconventional Energy Resources

The unconventional resources that will be exploited during the next few decades will place widely varied demands on drilling and extraction systems. These are summarized in Table E-1, which was taken from Reference 1. Many of the oil-producing resources will be mined and processed on the surface, but others will be extracted through boreholes following in-situ conversion or enhanced recovery operations. The gas-producing resources will generally be exploited through drilled boreholes, and many will require techniques that increase the effective permeability of the formation and flow into the wellbore. All forms of the geothermal resource will be exploited through drilling, often in formations and reservoirs very different from those containing oil and gas.

The "non-standard" resources that will have the largest impact on drilling technology in the foreseeable future may be the expensive, difficult to extract reserves of "conventional" resources. Heavy oil deposits, oil remaining in place after conventional recovery, very deep gas reservoirs, and remote or far offshore fields comprise these; and as seen in Appendix D, they may dominate drilling early in the next century. For these resources, the costs and capabilities of drilling systems will determine their ultimate usage.

The demands placed on drilling systems can best be seen by briefly considering the resources individually.

1. Oil Resources

a. Remote Reservoirs. Offshore production from deep or arctic waters is quite expensive. Platforms or artificial islands can cost more than a billion dollars apiece. The area that can be produced from a single platform increases with the square of the drilling radius, and so increasing horizontal drilling range can have a dramatic effect on production costs. Thus, highly deviated drilling with a long horizontal reach will find wide application in such reservoirs and is a technology being actively pursued by segments of industry. The same technology would be useful as well in remote land drilling in which surface drilling and production locations are difficult and expensive to prepare.

b. Enhanced Recovery. As is pointed out in Appendix D, conventional recovery techniques generally leave a large portion of the oil in the ground (approximately 70%). Enhanced recovery techniques are being more widely used in an attempt to decrease this figure. Both production and injection wells drilled for enhanced recovery would benefit from being precisely located and oriented in the reservoir, though more often, the wells that are used are merely poorly producing primary wells. In addition to precise location, horizontal wells have been shown in many applications to increase recovery efficiency.² Another feature, besides hole geometry, that might improve enhanced recovery capability is advanced simulation techniques that would improve flow of fluids through reservoirs. Perhaps the most critical need in enhanced recovery operations is the need for better information systems that characterize the state of a reservoir and the fluids that remain in it.

c. Heavy Oil and Tar Sands. The domestic resources of oil and tar sands are quite large, and many of the reservoirs are shallow. Efficient extraction of these resources requires closely spaced horizontal holes and has led to development of new drilling techniques (for example, those employed in the Canadian tar sands).³ In addition, techniques are being considered for gravity mining of heavy oil resources. Gravity mining might also require precisely located, highly deviated holes. Extraction of both resources would benefit greatly from new means for enhancing permeability or flow into the wellbore.

d. Oil Shale and Coal Liquefaction. Shale or coal resources that are mined and then

DIRECTIONAL DRILLING PERFORMANCE REQUIREMENTS	CONVENTIONAL OIL & GAS	UNCONVENTIONAL OIL RECOVERY			UNCONVENTIONAL GAS RECOVERY		
		HEAVY OIL	TAR SANDS	OIL SHALE	TIGHT GAS	METHANE FROM COAL	COAL CONVERSION
HOLE CONFIGURATION REQUIREMENTS							
HIGH ANGLE — LONG LATERAL	X				X		
HIGH ANGLE — SHALLOW TARGET			X			X	X
LATERAL DRAIN HOLES		X	X	X		X	X
HORIZONTAL HOLES		X	X			X	X
PRECISION VERTICAL HOLES				X	X		
LARGE DIA. SHALLOW HOLES		X	X	X			
INSTRUMENTATION REQUIREMENTS							
HIGH ACCURACY SURVEY TOOLS	X			X		X	X
RELIABLE TELEMETRY SYSTEMS	X	X	X	X	X	X	X
COAL SEAM INTERFACE SENSOR						X	X
MEASUREMENT WHILE DRILLING SYSTEMS	X				X		
DRILLING REQUIREMENTS							
MULTIPLE HOLE RE-ENTRY CAPABILITY		X	X		X	X	
THRUSTER SYSTEMS	X	X	X			X	X
BOREHOLE STABILITY TECHNOLOGY		X	X	X		X	X
CUTTINGS REMOVAL TECHNOLOGY	X	X	X			X	X
FLUIDS	X	X	X	X			
ANALYSIS AND CONTROL OF DRILLING SYSTEMS	X	X	X		X		

Table E-1. Drilling Requirements
for Future Resources

processed into liquid fuels at the surface, do require the use of boreholes for resource delineation and other mining-related functions, but their extraction puts little demand on drilling technology. In-situ conversion techniques, on the other hand, rely more heavily on drilling. The conversion process is likely to be monitored and controlled through precisely located boreholes. The oil that is extracted will probably be collected in drilled drain holes. Thus, in-situ conversion processes, like many of the other unconventional sources of oil, will require precisely controlled, deviated boreholes.

2. Gas Resources

a. Remote Reservoirs. Offshore gas shares the physical and economic constraints of offshore oil and, thus, imposes the same requirements on drilling systems for long-reach, highly deviated holes. However, gas also occurs in very deep reservoirs, both offshore and onshore, and these remote resources place additional demands on drilling systems. The high temperatures and high pressures of deep reservoirs affect drilling components and techniques. In addition, the costs of reaching and extracting them from great depths are quite high, and widespread exploitation awaits breakthroughs in drilling efficiency.⁴

b. Tight Sands and Shales. Extensive domestic resources of gas are located in tight sands and shales ("tight" denoting formations with very low permeability). Extraction of these resources requires precise drilling, to intersect and maximize exposure to lenticular formations, and advanced permeability enhancement techniques, to enable the gas to flow into the wellbore.⁵ Perhaps the greatest technical need is for improved information collection systems that help determine where to drill and where and how to stimulate.

c. Geopressured Reservoirs. Enormous potential gas resources exist in the geopressured reservoirs of the U.S. Gulf Coast. These will present challenges to drilling (and to other technologies), and several of the required improvements are outlined in Reference 5. Many of the requirements are related to the need to survive the high pressure, corrosive environment and others stem from the need for better information collection and processing in order to improve safety and efficiency.

d. Coal Gasification. The domestic coal resource is enormous, and one of the most promising means of achieving in-situ gasification of coal utilizes directional drilling to create flow paths through the coal seam.⁷ Vertical boreholes in the seam are linked by horizontal holes along the bottom of the seam. This technique, as well as others that have been suggested, would require closely controlled, highly deviated drilling.⁸

e. Methane Drainage from Coal Seams. Often when coal is mined the presence of methane in the coal seam creates a serious safety hazard, and so drain holes are drilled into the coal to allow degasification. Methane extracted in this way for safety is sometimes utilized for energy. This technique emphasizes the potential gas resource contained in the methane in unmined or unmineable coal seams. Extraction of this gas requires closely controlled, highly deviated boreholes that follow the seam.⁹ Thus, identification of formation boundaries and collection of other drilling information is essential; and permeability enhancement techniques may prove necessary to promote methane flow into the wellbore.

f. Methane Hydrates. In arctic or deep ocean sediments, the conditions can exist for the formation of gas hydrates.¹⁰ Drilling for and efficiently extracting these resources will offer significant challenges to current technology. For example, some means of changing the pressure and temperature environment will be necessary to allow the gas to escape the hydrate crystals and flow into a wellbore.

3. Geothermal Resources

All forms of the geothermal resource--dry steam, superheated water, hot dry rock and magma--require energy extraction through boreholes, and the formations that must be

drilled are harder and hotter than those generally drilled for oil and gas resources. Current utilization of geothermal resources has been limited, in part, by the high costs of drilling geothermal wells. The problems that geothermal wells introduce include: high temperatures, hard formations, corrosive fluids, severe lost circulation and well completion problems. In addition, the inability to successfully stimulate reservoirs or otherwise enhance flow of geothermal fluids into the wellbores has been another factor limiting the growth of geothermal energy applications.¹¹

The requirements that geothermal resources place on drilling systems include: obtaining better information about where to drill and stimulate; developing better control over wellbore direction in order to better intersect natural fractures; developing better stimulation systems to enhance flow into the well; developing systems and components that can survive the geothermal environments; and developing techniques to lower the cost of geothermal wells.

4. Summary

Taken as a whole, the unconventional resources will require better control over the locations and trajectories of boreholes, improved flow enhancement techniques, and better downhole sensor and information systems. As more remote and difficult to extract resources are exploited the needs will grow to include: longer horizontal reach, precise trajectory control, a capability for drilling and producing in deeper waters, the ability to handle high temperature and pressure, the ability to "see" beyond the wellbore, and simply, lower drilling costs.

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Appendix F. Domestic Research Emphases

The companies that supply drilling services and equipment work constantly to improve their products. This effort has provided the impetus for the evolutionary improvements that have taken place in drilling technology. Several of the current research and development efforts are briefly discussed here, in roughly descending order of effort. An interesting point to note is that the bulk of domestic work is short-term, product oriented development. Recently several industrial organizations, including many of the major operators, formed the Drilling Engineering Association to jointly sponsor drilling research. This action indicates an interest in research as well as a recognition of the need for more of it.

1. Measurement While Drilling (MWD)

MWD systems have become commercially available during the last five years, with widespread availability only during the last two to three. There currently are between 150 and 200 complete systems available for use throughout the world, and these are provided by five major suppliers. Numerous other companies, both in the U.S. and abroad, are developing their own systems that should reach the marketplace in the next few years. MWD systems are finding expanding markets as they demonstrate their reliability and usefulness. They have proven quite valuable in helping control directional drilling and hole deviation, especially in off-shore drilling. In the near future they will also be used to aid formation evaluation and drilling safety and efficiency, though these are not currently emphasized.¹

Three basic subsystems make up an MWD system: 1) a downhole sensor and signal conditioning package, 2) a means for transmitting information from downhole to the surface, and 3) surface equipment for receiving, interpreting, and displaying the transmitted information. Development is proceeding in all three areas.

Very active research and development is being conducted in the area of new sensors. Systems are now available to measure hole inclination and azimuth, tool-face orientation during periods of nonrotation of drill pipe, formation properties via gamma ray and resistivity tools, weight on bit (WOB), torque, and annulus temperature and pressure—though seldom are all measurements included in a single package. Work is proceeding to expand the suite of available measurements to include, for example, fluid-influx measurements, a turbine RPM indicator and additional formation evaluation tools. Data-rate limitations of the transmission system will limit the number of sensors in use at any time, but the list of available sensors will expand as the market and the number of suppliers expand. The package employed for any particular portion of a well will be determined by the desired measurements.

The companies that are developing new MWD systems, as well as those that currently market systems, are working hard to include downhole computers for signal processing and signal conditioning to partially overcome the limitations of the transmission link. By downhole processing and creative message coding it is possible to increase the number of sensors for which an MWD system can give timely information.

Signal transmission for all of the existing systems and for nearly all of those under development is done by "mud-pulse telemetry," i.e., sending pressure signals through the drilling mud inside the drill pipe. In the different MWD systems, this is accomplished with three very different kinds of signals, a "positive" pulse generated by the sudden restriction of a valve in the mud stream to generate an increased pressure that propagates to the surface at the acoustic velocity of the mud, a "negative" pulse generated by opening a valve that reduces pressure in the mud system by allowing bypass of the motor/bit pressure drops, and a "siren" that generates a constant, continuous frequency signal and transmits data by changing phases. Other, non-mud-pulse, transmission methods have been investigated in the past, and work continues on electromagnetic transmission through the earth, acoustic transmission through the drill pipe, and hardwire transmission via an electrical conductor in the drill pipe. Guaranteed signal propagation is the concern for the first two of these, and expense and the possible impact on standard rig operations are concerns for the third.

The final subsystem of MWD systems is the surface equipment for receiving and processing the signals from downhole. Each MWD company develops its own decoding and display system based on its sensors, downhole processing, and transmission mode. Though much effort is devoted to developing useful and meaningful displays, this is not the critical area of research and development that the downhole sensors and transmission means are.

2. Drill Bits

Research and development for new bits rivals the MWD work as the most active current effort. The PDC bit (a bit with cutters made of polycrystalline diamond compacts—a man made material) is rapidly growing in use in a wide variety of formations.² Estimates have been made that 50% or more of the drilling in 1990 will be done by PDC bits. At the height of the drilling activity two years ago, more than 20 companies marketed PDC bits, but now the major bit companies are beginning to take control of the PDC bit market, as well as the roller-cone and diamond bit markets. These companies are working to improve all three types of bits.

The PDC work is important in part because PDC bits cause rock to fail in a different way than either roller-cone or diamond bits. PDC bits are drag bits that cut or shear rock rather than crushing or grinding it. Through their experience with PDC bits, the bit companies are learning to optimize the design of shear bits, the generic name for bits of the PDC type. The next generations will use greatly improved man-made diamond materials in different shapes to further improve their performances. One attractive feature of shear bits is their lack of moving parts, and another is that aggressive bits basically machine the rock and are more likely to provide control of the drilling process. The weaknesses of the early PDC bits—poor materials control, poor bonding of the cutter to the bit, and inadequate hydraulics—are being overcome, though the hydraulics of shear bits will continue to limit them in the foreseeable future.

In addition to the improvements in shear bits, new materials work is improving roller-cone bits. New cutting materials—to supplement tungsten carbide—are under development, as are new materials to improve the bit life and reliability of bearings and seals. Even though use of shear bits will grow rapidly, roller-cone bits will continue to play a significant, if not dominant, role in the foreseeable future.

Some of the most interesting work in bit development is in hybrid, or mixed-mode, bits. Many companies combine natural diamonds, PDC cutters, or tungsten carbide buttons, using each for the function they do best. Similarly, companies are investigating the impact of including hydraulic jet cutters with mechanical cutters. A problem with jet cutting is that there are rocks that are not susceptible to hydraulic cutting. Combining the two cutting modes avoids this problem.

3. Downhole Motors

The successes of shear bits and MWD have fueled growing use of downhole mud motors, both positive displacement motors (PDM) of the Moineau type and turbines. The shear bits have greatly expanded bit performance envelopes, allowing higher rotational speeds and lower WOB—both conducive to success for motors. MWD has provided more control over WOB and hole deviation, allowing better use of motors. However, the expanding use of motors is also due to basic improvements in motors themselves, and research and development of motors continues at a significant level.³

Downhole motors have a basic advantage over rotary drilling in their ability to concentrate the drilling energy on the rock and, as a result, to drill faster. Another advantage is that they obviate the need to rotate the drill pipe, and thus, they reduce pipe wear and pipe failure problems. However, in the past their use has been limited by efficiency problems. In particular, bearing weaknesses have limited the thrust carrying capability and reduced the lifetime of PDMs. Similarly elastomeric stators have limited lifetimes and restricted high temperature applications. Significant advances have recently been made in these areas (motor lifetimes of a hundred hours are expected and 200-hour lifetimes are common). Current work emphasizes materials development, for seals and stators, and new designs, for motors and bearings, to achieve even longer life and wider performance

parameters in order to better utilize shear bits. The goal for motor applications is to achieve a motor/bit system that can drill rapidly and efficiently from casing point to casing point without having to trip—to replace either motor or bit.

Current development work in mud-driven turbines has similar goals. Turbines have inherently higher speeds than do PDMS, and so they suffered even more from the lack of a high speed bit. The success of the shear bits has rekindled interest in turbines, and because of their ability to function at high temperatures, many feel they have a brighter future than PDMS. Current research is directed toward solving the problems associated with speed control and thrust limitations. Depending on the load conditions, turbines can "run away" or stall. This sensitivity of performance to load is a major current limitation.

4. Directional Tools and Capabilities

MWD and downhole motors have contributed greatly to the ability to control direction of a wellbore, but other tools and capabilities are being developed for this purpose as well. In particular, new surveying and steering tools are being developed, both for use alone or with MWD. These will provide greater accuracy, reliability and timeliness, and many will require significantly shorter delays to the drilling process in order to run a directional survey or take other data. The instruments under development cover the spectrum of capabilities, from new "single shot" or "multi-shot" tools to complete inertial packages for wellbore mapping.⁴

In addition, new downhole components are being developed and marketed that will aid in the physical control of wellbore trajectory. Bent subs and bent motor housings have been used for some time, but downhole controllable-angle bent subs are beginning to find use. In addition, new concepts in the use of eccentric collars and stabilizers are being tried for directional control.

Perhaps the largest efforts, both past and current, in improving directional control have been in connection with major programs. Historically, many techniques were developed for the THUMS drilling in Long Beach; and today much work is being carried out for North Sea drilling and in the Extended Reach Drilling Program run by Mobil Oil for a consortium of companies. These programs develop directional drilling hardware as well as solutions to specific problems, such as cuttings removal, differential sticking, and casing and cementing in highly deviated wells.

5. Automated Rig Functions

Automation for drilling rigs has been "just around the corner" for two decades and is slowly being accepted.⁵ Many companies have developed and now market automatic pipe racking and handling systems, and they are beginning to find application, especially offshore. "Iron Roughnecks®" automated pipe make-up and break-out systems, are becoming more common. Even complete "automated rigs" are being used—the Extended Reach Drilling Program, for example, drilled the top portion of their current hole with National Supply's Automated Drilling Machine.TM Such rigs can basically be run by a single operator.

6. Drilling Information—Computers

The "information revolution" is slowly beginning to impact the drilling industry. Research and development is proceeding in three areas: computer-program assisted drilling supervision, expert machines to help in real-time oversight of drilling operations, and telemetry and remote monitoring of drilling performance.⁷

Several of the major oil companies have developed libraries of drilling analysis programs supported by extensive data bases. These are designed to help specify mud systems, casing programs, bottom-hole assemblies, directional programs, and other aspects of the planning and drilling of a well. In addition, they are used to advantage in drilling training programs. Many of the companies are developing these programs for implementation on minicomputers to make them available at the rig. When this is done, many other functions, such as inventory control and ordering, can be handled by computer.^{8,9}

A related application is the recent introduction and continuing development of "expert systems" to aid in drilling. Currently being developed for trouble shooting and problem avoidance during drilling, such systems simulate the experienced expert and provide capable guidance at the rig site.¹⁰ Development of such systems will accelerate in the near future.

A few companies have developed information systems that relay drilling rig data back to a central location for monitoring and data storage.¹¹ Some of the systems relay real-time information, while others relay the information a few times a day. Those that relay infrequently use the data for filing daily reports and for building a data base that can be used for drilling analysis. Those that relay real-time rig measurements and data provide continuous monitoring of the drilling activity by experienced people in order to help avoid trouble or solve problems.

7. Miscellaneous Downhole Tools and Drilling Systems

The companies that supply downhole tools are continually improving their products, in areas such as hole openers, reamers, drill collars, drill pipe, casing and cementing equipment, and formation evaluation. Though such work is significant and will have a large impact on the evolution of the drilling system, it does not reflect a current "emphasis" of drilling research. Similarly, investigation of new drilling methods and systems has gone on throughout recent years, but the current work on four new techniques makes this a minor emphasis worthy of discussion.

A recent development that has received much attention is the Robot Drill,TM a system for drilling controlled trajectory, highly deviated holes.¹² The system is built around an electric-hydraulic motor that is anchored to the borehole wall and receives its thrust by "pushing" against its anchor pads. The anchoring system uses two sets of "feet" that sequentially hold and release to allow advance. The system is suspended on a rather simple umbilical hose and cable.

Similar development is being conducted by at least three companies on thermal spallation systems built around flame jets.¹³ Basically, each of these systems uses a downhole rocket engine to heat the rock, causing small flakes to spall off of the rock face. In this way, the borehole is advanced. This system is suspended by a fairly complicated set of hoses to carry fuel, oxygen, and cooling water. Several problems must be solved before spallation drilling will find wide application.

A third "new" system is a water jet system built around cavitating nozzles.¹⁴ If high enough system pressures can be supplied, water jets can mechanically break rock and the borehole can be advanced. The effect of cavitating nozzles is to reduce the pressure requirements. In addition, research is being conducted into the design of a downhole intensifier to provide the required pressures. Nonetheless, several development steps are required before such a system is fielded.

The fourth alternative drilling system being investigated is the Terra Drill that augments a conventional cutting head with a system that fires projectiles into the rock ahead of the bit.¹⁵ The projectiles pre-fracture hard rocks, making them easier to drill. Because this technique would rely on the existing drilling system for its implementation, it is probably the most mature of the "new" technologies.

8. Drilling Fluids

Significant effort is being directed toward improvements in drilling fluids and mud systems. Use of oil-based muds is growing, and research into cheaper and environmentally benign oil muds, such as paraffinic-based mineral oil muds, is important. Research is also being directed toward new additives for water-based muds that will help control sensitivity to temperature. In addition, formation damage is a concern for all mud systems, and research continues for additives that will help control damage. Finally, industry is developing new systems for effective processing of muds, as solids control is critical for maximizing rate of penetration, hole stability, and pump life.

9. Source 2, page 16.
10. Source 1.
11. Source 12, page 18.
12. Source 15, pages 40 & 178.
13. Source 13, page 7.
14. Source 15, page 141.
15. Source 12, pages 17-119
16. Source 7.
17. Source 8, Vol. II, page 7.
18. Source 12, page 21.
19. Source 5, page 25.
20. Source 15, page 38.
21. Source 15, page 38.
22. Source 15, page 50.
23. Source 5, page 27.
24. Source 16, page 164
25. Source 16, page 161
26. Source 16, page 55
27. Source 15, page 38
28. Source 18, page 57
29. Source 18, page 58
30. Source 11.
31. Source 18, page 58
32. Source 12, page 22
33. Source 8, Vol. III, page 175
34. Source 8, Vol. II, page 7
35. Source 8, Vol. III, page 95
36. Source 12, page 36
37. Source 15, page 31
38. Source 16, page 173
39. Source 12, page 27
40. Source 9, page 7-3
41. Source 9, page 7-1
42. Source 7.
43. Source 3, page 25.
44. Source 12, page 28.
45. Source 12, page 28.
46. Source 14, page 69.
47. Source 3, page 245.
48. Source 8, Vol. III, page 169
49. Source 15, page 43.
50. Source 3, page 33.
51. Source 2, page 193
52. Source 3, page 33
53. Source 2, page 193
54. Source 14, page 123.
55. Source 4, page 35
56. Source 12, page 34
57. Source 5, page 35
58. Source 12, page 34
59. Source 7
60. Source 8, Vol. II, page 7
61. Source 7.
62. Source 14, page 89
63. Source 9, page 9-4
64. Source 5, page 39
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Appendix G

Foreign Drilling Research

Summarizing the drilling research that is done abroad is difficult, and it is likely that this appendix overlooks several important research activities. Its purpose, though, is to indicate major trends, not to be complete. Several considerations dictate this emphasis on trends. Drilling is done throughout the world, and drilling techniques and hardware are improved at nearly every drillsite. Detailing these efforts would be impossible and so this survey must focus on formal drilling research programs. Similarly, the lines between exploration or production research and drilling research are blurred, and so "pure" drilling research is emphasized. Finally, the nature of multinational corporations complicates the distinction between domestic and foreign research. For example, important research is done in England by both American and French service companies and so the identification of research by nation is not especially meaningful. In spite of these difficulties, two trends are apparent from the survey. First, much of the extensive European research is directed toward extraction of North Sea resources; and secondly, considerable world-wide development is directed toward the emerging market in third world drilling. Most of the information for this summary is from direct contact with the individuals conducting the research.^{1,2}

1. Participants

The general nature of the efforts in several nations are summarized here. In Section 2, specific research areas are discussed. The focus in both sections is on technologies that will affect world-wide drilling.

a. France. The French have been active in drilling research for several years. The French Government has emphasized general scientific and technological development, both in their nationalized industries and in the private sector.³ In drilling, France has been at the forefront in several areas. They have been quite active in offshore drilling and currently hold the water depth record for oil and gas drilling. Similarly, the French have been active in development of tools and techniques for horizontal drilling and have pioneered the use of horizontal sections in producing formations to enhance well productivity. Specific technological developments that have come out of the French program are improved mud motors, flexible drill pipe, downhole controllable components and the systems to control them, and advanced logging instrumentation.

An important factor in French technology development has been the government's policy of sponsoring research which, if successful, is given off to a specially formed nationalized company for development and marketing. Several products have been brought to market in this fashion. As much as any other national group, the French have identified and are pursuing the potential export market for drilling technologies.⁴

b. Norway. The Norwegians, relative latecomers to oil field technology development, have followed their North Sea resources to the forefront of drilling technology. Norway has emphasized domestic exploitation of the North Sea, and the same emphasis is applied to petroleum-related research and development as well. Two new, major facilities have been constructed for drilling research, one in Rogaland and the other in Trondheim. A full-scale drilling rig has been constructed for hardware and systems tests, and work is proceeding in a number of areas, including: rig design and automation, downhole instrumentation, problems of inclined and deviated well bores, development of drilling muds, cements and lost circulation materials, and optimization and control of the drilling process.⁵ Much of the funding for this work has come by requiring that oil companies operating in the Norwegian North Sea re-invest some of their income in domestic drilling research.

c. Japan. Like Norway, Japan is a latecomer to drilling research and development and like both France and Norway, the Japanese efforts benefit from a national policy that is

quite supportive. Japan's response to near total reliance on imported energy was to step up efforts to develop alternative supplies. Their work on geothermal energy under the "Sunshine Project" has led them into development of drilling technologies.⁶ Furthermore, the alternative energy technologies have been identified as potential areas of Japanese technical domination, similar to electronics and autos.⁷ In particular, the Japanese have been supplying heavy steel products - rigs, tubulars and valves - to the oil industry for some time.⁸ Recently they have been marketing bits and other tools and attempting to enter the downhole motor market. These and their recent efforts to license, buy or duplicate various pieces of American technology indicate their intention to compete, especially in Asian and other third world markets.

d. Soviet Union. Russian drilling technology has paralleled the U.S. technology for decades. They have a very active drilling and production program. They have drilled, and are continuing to drill, the world's deepest well⁹ and they drill roughly one-third as much footage as is drilled in the U.S., considerably more than anyone else. The Soviet Union conducts a large program in drilling research and development.¹⁰ Several research organizations function under the Ministry of Petroleum. The primary ones for drilling research appear to be the All Union Research Institute for Drilling and the several development centers at the various regional, reservoir-based headquarters. One of the most pervasive of the Soviet developments is downhole motors, both positive displacement motors and turbines. The Russians continue to lead the world in many aspects of motor technology and their designs have been widely marketed and copied.

e. England. The research and development being carried out in England is more difficult to characterize than in some other European countries, for it is done primarily in private facilities where it is kept proprietary. Perhaps typical of these facilities is Schlumberger's new drilling research facility at Cambridge. Both the building and staff are being designed around advanced drilling research tasks. Other companies maintain research facilities in the United Kingdom and most are directed towards developing hardware and techniques for North Sea drilling.

f. Other European Countries. Research is being conducted in several other countries, among them The Netherlands, Germany, Austria, Belgium, Italy, and Switzerland. Generally, the work is done by operating companies, such as the important work being done by Shell at The Hague, or by service companies working on product improvement. Much of the research is motivated by particular drilling environments, for example the North Sea drilling, the deep drilling done in Austria and the high temperature geothermal drilling done in Italy.

g. Canada. Canadian companies and the Canadian Government sponsor several drilling research and development activities. Several of the operating companies have formed the Canadian Drilling Research Association which sponsors projects of mutual interest. Activities have included testing of Russian turbines, work in MWD, bit development, and solids removal. In addition, individual companies have developed techniques for drilling shallow tar sands; and the Alberta Provincial Government has formed the Alberta Oil Sands Technology and Research Authority, which has investigated new extraction techniques.¹² Finally, like their European and U.S. counterparts, the Canadian service companies work steadily to improve their tools and services.

h. Latin American Countries. The Latin American Countries and their national oil companies work on technologies for extracting their domestic resources. The work often is focused on exploration and production rather than drilling and little of it is directed toward export of technology.

i. Middle Eastern Countries. Like the Latin American Countries, the Middle Eastern Countries focus their research and development efforts on production questions. In such a productive environment, there is little premium on efficient drilling.

2. Research Emphases

Many of the areas of emphasis for foreign research are the same as for domestic research.

a. Drilling Motors. One of the foremost areas of foreign development is that of down-hole drilling motors. The Soviets and the Europeans have historically utilized motors to a much greater extent than have U.S. drillers. The Russians have long built and used both turbines, or turbodrills, which are used in their very deep wells and several designs of positive displacement motors, variants of which are marketed throughout the world. The French Company, Neyrfor, has marketed very similar motors for years and the European divisions of Christensen, an "American" service company, develop and market many of the motors used in the North Sea. It is fair to say that the foreign suppliers are working as hard as the U.S. motor manufacturers and it is unclear where major breakthroughs will occur. Also, as was pointed out above, the Japanese are making a significant effort to enter the market through both acquisition and development of technology.

b. Bits and Rock Cutting. The understanding and improvement of bits is another area of European emphasis. The Soviets have an extensive program of bit design and rock cutting research, but the bits that they use most widely are copies of Western designs. Some of the best work in rock failure and cutting technology is done in the Netherlands by Shell. The Norwegians are beginning to study rock failure and French laboratories have used high-speed photographic techniques to study rock and cutter interactions for years. The English and Belgian laboratories, too, have programs studying bit improvements. The bit companies throughout Europe work constantly to improve their bits on a scale comparable to American efforts.

c. Rigs and Platforms. The Japanese, and other Asian shipbuilders, and the Norwegians, and other European shipbuilders, have become quite active in the design and building of offshore drilling and production facilities. Furthermore, the rigs used in land drilling in Europe are designed and built in Europe. The markets that will be the focus for competition in this area are the growing third world and offshore drilling efforts.

d. Measurement While Drilling (MWD). Although the U.S. companies are working very hard on new MWD systems, no one company or country has a corner on MWD research. Significant efforts are also being made in France and England. It is interesting to note that of the three most widely used MWD systems, two are marketed by French companies and the third was developed in Canada. Since the most active current market for MWD systems is the North Sea, it is not surprising to find research and development programs in those companies and countries that service the fields there.

e. Drilling Mechanics. The Norwegians, the English and the French all have active ongoing efforts to understand the bottomhole environment and the behavior of the drilling system. The focus of much of this work is improved understanding and capabilities in directional and horizontal drilling. Both will be critical in extracting future resources.

f. Tubular Goods. During the recent U.S. drilling boom, a shortage of American-supplied tubulars - drillpipe and casing - allowed Japanese suppliers to enter the market. Very rapidly they developed a reputation for having the highest quality tubular goods and they have retained a significant portion of the market. Similarly, German suppliers have earned a reputation for quality. This oil-field experience is little different from the experiences in the general steel marketplace.

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Appendix H Novel Drilling Methods and Other Revolutionary Changes

It is possible that the improvements that take place in drilling will be revolutionary in nature--that is, they will not be incremental improvements to standard rotary drilling. It is, by their very nature, difficult to predict revolutionary improvements, but it is possible to identify areas where such changes might take place.¹

Potential revolutionary changes can be better discussed in the context of the basic function of a drilling system--to create a conduit from a reservoir to the surface--than in reference to existing drilling methods. This basic function has several subfunctions, seven of which are identified below. These subfunctions provide a framework for considering novel approaches to drilling. They also emphasize an important, and often overlooked, point--that a system for achieving one of the subfunctions must also deal with the others. For example, there are several novel ways to break rock identified below, but a drilling system must do more than break rock. It must also remove the rock debris and stabilize the resulting hole. This necessity to perform all of the functions is the failing of many novel approaches. The same point is true in considering cost reductions. An advanced method for penetrating rock that relies on current methods for casing and completing wells is unlikely to effect significant cost savings. The drilling cost breakdown in Appendix C shows that on the average, more than half the cost of a well comes from items that are not related to the cutting process and that are not time-related costs. Thus, speeding the cutting process alone is limited in its cost-savings potential.

Nonetheless, it is helpful to consider novel approaches to each of the subfunctions. When this is done, some of the most promising advanced techniques can be identified, keeping in mind the requirement that a system achieve all of the subfunctions involved in providing the desired conduit. The most attractive of the novel techniques are identified in the summary.

1. Penetrate Rock

Reference 2 is a standard review of advanced drilling techniques that summarizes the work that has been done on more than twenty drilling techniques. Most that are discussed are listed in Table H-1. Drilling systems generally penetrate rock using one of four methods: mechanical breakage, thermal spallation, melting and vaporization, and chemical reaction. Research and development has been carried out on systems that utilize each of these means.

The most intensely investigated, and perhaps the most promising, advanced technique is water-jet drilling. Pure water jets, cavitating jets and abrasive-laden jets have all been studied extensively. Jets are currently used to augment mechanical cutters in drilling and to cut rock by themselves in several mining applications. Water-jet drilling remains the most commonly discussed advanced rock penetration mechanism.

Other novel techniques (and their proponents) abound. Many are especially appropriate for certain types of rocks (e.g., the spallation concepts) and others are optimal for specific depth horizons or specified fluids (e.g., laser systems that need a vapor-filled hole). None stands out as the obvious replacement for rotary drilling, and none, other than water jet cutting, seems deserving of serious development effort at this time.

2. Transmit Power

Alternative ways of transmitting power have not been as widely studied as ways of penetrating rocks. Many times they are considered as part of the rock penetration system. (For example, the power for explosive drilling is carried to the bottom of the hole chemically in the explosives.) However, a few have been given independent consideration.

a. Flexible Drill Pipe. Both coiled steel tubing units and steel-reinforced

Table H-1. Novel Rock Penetration Schemes

Replaceable Cutter Head Drills
Abrasive Jet Drills
Cavitating Jet Drills
High Pressure Jet Drills
Flame Jet Drills
Rocket Exhaust Drills
Electric-Arc and Plasma Drills
Electron Beam Drills
Laser Drills
Electric Disintegration Drills
Spark Drills
Implosion Drills
Explosive Drills
Projectile Drills
Thermomechanical Drills
Subterrene Drill
Thermocorer Drill

elastomeric tubing systems have been used as drill pipe, to suspend the rock cutting apparatus and to carry fluids to the bottom of the well. Due to torque carrying limitations, such systems are used with downhole motors. Their advantages include faster tripping and the possibility of hardwire communications between surface and downhole equipment.

b. Electric Cables. The transmission of electric power for use by a downhole electric motor has been investigated both in the U.S. and abroad. A downhole electric motor offers advantages in control, and transmission by cable allows two-way, high data rate communications systems.

c. Downhole Fluid-Pressure Intensifier. Transmission of hydraulic energy via the mud is a standard means of getting power downhole, but combining this with a downhole, fluid-driven, high-pressure pump is not. Water jets and other advanced cutting systems may require large downhole pressures. In many cases these may be most efficiently and most safely generated downhole in an intensifier that trades high flow rates for high pressures.

One of these, or some other method, may prove to be the most attractive way to transmit the necessary rock-breaking power to the bottom of the hole. It appears likely that an advanced drilling system would use some means other than 30 foot lengths of drill pipe to transmit torque.

3. Remove Debris

The current method for removing cuttings from a wellbore is to lift them with a fluid (mud, air, mist, etc.). It is possible that they can be removed in some other, more efficient manner. For example, in one of its modes, the subterranean drilling system melted the rocks it penetrated and stored them (densified) along the walls of the borehole. Other possibilities are to utilize staged mechanical removal, as is currently done with wireline cores, or continuous mechanical removal, such as with an auger or a buoyancy-based system utilizing a dense fluid.

4. Line Borehole

Casing the borehole after it is drilled is one of the most demanding and expensive of the current operations. It is demanding in the sense that it requires large hoisting capacities in rigs, it requires drilling a well that decreases in diameter with increasing depth in order to accommodate multiple casing strings, and it necessitates the cementing operations. Lining a long-reach or horizontal borehole may, in fact, be more difficult than drilling it. Casing's expense is shown by the cost breakdown of Appendix C. The casing hardware and cement account for more than 20% of the total well cost, and this does not include the time-related costs for casing and cementing operations. Several alternative means for casing a hole have been considered.

a. Case-While-Drilling Systems. Several methods for advancing "standard" steel casing during the drilling operation have been proposed. Achieving this would aid in stabilization of the borehole and would save the operational time currently required for casing.

b. Formed-in-Place Liners. Several new materials and processes have been discussed for use in lining a wellbore. Downhole mixing of multicomponent cement, epoxy or plastic that is squeezed into the formation and sets up has had limited investigation. Weaving or forming a steel "pipe" downhole has been discussed. For either, the concept is to have a "casing maker" that closely follows the bit and forms a smooth, stable borehole wall. While it is desirable for this lining to be permanent, one that lasted through the drilling process and then was reinforced with a single-sized, bottom-to-top permanent liner installed after drilling may also be beneficial.

c. Expandable Casing. Casing materials that can be lowered through an undersized hole then expanded would remove the necessity of telescoping the well. These could be installed in individual pieces or in fairly long strings.

d. Melted and Densified Rock Liners. One of the most attractive features of the

subterranean drilling system was its method for lining the hole. Because it penetrated by melting, it was able to use the melted material for hole lining. This provided a smooth, impervious skin that performed many of the functions of casing. The same lining technique could be used with many different rock penetration methods.

5. Determine Downhole Conditions

In the last three subfunctions, beginning with this one, the distinction between evolutionary improvements and revolutionary changes narrows significantly. Regardless of the mechanism that is used to make or line a well, improved information and control of the trajectory will be essential--even if the mechanism is centered around a current drilling system. The measurements that will be taken to indicate downhole conditions will include: those that indicate the condition of the rock cutting operation and apparatus (e.g., stresses, temperatures, wear, etc.) in order to allow efficient removal of rock; those that indicate formation characteristics immediately ahead of the cutter face in order to optimize cutting efficiency; and those that indicate the characteristics of the formation surrounding the well in order to determine where to drill to optimize either extraction or drilling efficiency. Novel sensors and downhole computers may be developed to make and interpret these measurements.

6. Monitor and Control Wellbore Trajectory

Instrumentation and hardware may be developed to allow the monitoring and positive control of the wellbore trajectory. Possibilities include: inertial navigation units, downhole guidance computers, wall anchor and thrusting systems, and automatic bit advance systems. One novel approach would be to input the desired trajectory and allow the computer-controlled drilling mechanism to produce it. Another would be to input the desired target resource or formation characteristics and to let the sensors find it, the computer optimize the trajectory to it, and the control system reach it. Any advanced drilling system will most likely maintain control globally over its trajectory and locally over the formation-cutter interface parameters.

7. Enhance Productivity

The sensors that help determine downhole conditions can be used to enhance the productivity of the well by helping guide the wellbore to the "best" location. Other developments may come about as well. These include: new hole geometries, such as long horizontal portions, to optimize the intersection or offshoot wells in the producing zone; underreaming techniques to increase flow or intersect fractures; and new stimulation techniques. It is likely that an advanced drilling system will use some method of enhancing wellbore productivity.

8. Summary

These basic functions for a drilling system are the likely areas in which revolutionary breakthroughs will change the way wells are drilled. The particular developments that appear most promising include: water-jet cutting, rock cutting with a downhole electric motor, use of a continuous tubing to replace drill pipe, developing an alternative to standard casing, sensors that see far out from the wellbore, downhole guidance and control computers, wall anchor and thrusting systems, and development of new stimulation techniques.

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