SANDIA REPORT

SAND97–2903 • UC–1243
Unlimited Release
Printed December 1997

Recommendations of the Workshop on Advanced Geothermal Drilling Systems

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Distribution
Category UC-1243

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RECOMMENDATIONS OF THE WORKSHOP ON ADVANCED GEOTHERMAL DRILLING SYSTEMS

April 15-16, 1997
Berkeley, California

Summarized by

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ABSTRACT

At the request of the U.S. Department of Energy, Office of Geothermal Technologies, Sandia National Laboratories convened a group of drilling experts in Berkeley, CA, on April 15-16, 1997, to discuss advanced geothermal drilling systems. The objective of the workshop was to develop one or more conceptual designs for an advanced geothermal drilling system that meets all of the criteria necessary to drill a model geothermal well. The drilling process was divided into ten essential functions. Each function was examined, and discussions were held on the conventional methods used to accomplish each function and the problems commonly encountered. Alternative methods of performing each function were then listed and evaluated by the group. Alternative methods considered feasible or at least worth further investigation were identified, while methods considered impractical or not potentially cost-saving were eliminated from further discussion.

This report summarizes the recommendations of the workshop participants. For each of the ten functions, the conventional methods, common problems, and recommended alternative technologies and methods are listed. Each recommended alternative is discussed, and a description is given of the process by which this information will be used by the U. S. DOE to develop an advanced geothermal drilling research program.

This work was sponsored by the U.S. Department of Energy, Office of Geothermal Technologies. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

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EXECUTIVE SUMMARY

At the request of the U.S. Department of Energy, Office of Geothermal Technologies, a group of sixteen experts was convened in Berkeley, California, on April 15-16, 1997, to discuss advanced geothermal drilling systems. The objective of the workshop was to develop one or more conceptual designs for an advanced geothermal drilling system that meets all of the following criteria:

1) the system would perform all the necessary functions for drilling a model geothermal well;
2) the system would reduce the cost or economic risk of drilling a geothermal well and/or improve the lifetime productivity of the well, thereby reducing well cost/unit heat; and
3) the system contains one or more key components that do not currently exist but might be developed with DOE funding.

During the workshop, the process of constructing a model geothermal well was examined in detail. To make the discussion process more manageable, the drilling process was divided into ten essential functions. Each function was examined, and discussions were held on the conventional methods of accomplishing each function and the problems commonly encountered. Alternative methods of performing each function were then listed and evaluated by the group. Alternative methods considered feasible or at least worth further investigation were identified, while methods considered impractical or not potentially cost-saving were eliminated from further discussion. In general, the recommendations were made with the consensus of all the workshop participants.

Several recommendations were of a general or systems nature. They are:

1. *Any viable drill bit for cutting hard rock requires the use of mechanical cutters to cut a round hole and maintain gage.*

2. *More extensive use of software should be made in the geothermal drilling process.*

3. *The use of robotics in geothermal drilling should be undertaken where possible.*

4. *The use of very large upper-well sections with multiple lower legs (i.e., multi-lateral completions) should be considered as a way to reduce the number of times that upper-hole problems need to be addressed in a given field.*

5. *The industry needs to develop better ways to analyze and handle the risk of putting expensive tools downhole.*

6. *The industry needs to better follow technological advances in other fields (e.g., robotics, microelectronics, materials, and oil and gas drilling).*

7. *Institutional and logistical constraints should be addressed in order to reduce well costs.*

The recommended alternative methods for accomplishing the ten essential functions of the geothermal well construction process are listed below. The numbering associated with each list is provided for convenience only and does not imply any priority.

Rock Reduction

1. *Drag bits using synthetic diamond or other advanced materials.*
2. *Low-pressure waterjet-enhanced drill bits.*
3. *High-pressure waterjet-enhanced drill bits.*
4. *Percussive hammer bits.*
5. *Disk-cutter bits.*
6. *Large-diameter wireline core bits.*
7. *Casing-while-drilling with a retrievable motor and bit.*
8. *Replaceable-cutter bits.*
9. *Rock machining at ultra-high RPM.*
10. *Hybrid rotary-coring.*
11. *Hard-rock underreaming.*

Downhole Energy Transfer

1. *High-temperature fluid motors.*
2. *Coiled tubing.*
3. *Downhole electric motors.*
4. *Composite drill pipe or tubing.*
5. *Insulated drill pipe.*
6. *Aluminum drill pipe.*
7. *Downhole pressure intensifier for high-pressure waterjet drilling.*
8. *Percussive mud hammer.*
9. *Compact rigs and automated pipe handling.*
10. *High-temperature pipe recovery tools.*
11. *Diesel exhaust scrubbing for use as a non-corrosive drilling fluid.*

Rock Removal

1. *High-temperature drilling fluids, including temperature-stable drilling foams.*
2. *Large-diameter wireline coring.*

Borehole Stabilization and Fluid Containment

1. *Advanced wellbore lining techniques for achieving mechanical integrity and outflow sealing.*
2. *Open-hole packers for improved lost-circulation cementing efficiency.*
3. *Alternative cements for lost circulation control.*
4. *Polymer foam for lost circulation control.*
5. *Removable production-zone plugs.*
6. *Improved underbalanced drilling techniques.*
7. *Lightweight drilling muds.*

Control of Formation Pore Fluids

1. *Advanced wellbore lining techniques for achieving inflow sealing.*
2. *Improved underbalanced drilling techniques.*
3. *Removable production-zone plugs.*

Permanent Borehole Preservation

1. *Advanced wellbore lining techniques for permanent borehole preservation.*
2. *Cement-lined casing.*
3. *Alternative casing materials.*
4. *Casing-while-drilling.*
5. *Improved methods of emplacing production liners.*
6. *Latex and other advanced cements for corrosive environments.*
7. *Robotics system for running hot liners.*

Sensing, Communication, and Process Control

1. *Temperature-hardened logging tools.*
2. *High-temperature MWD/LWD systems.*
3. *Advanced rig instrumentation and software.*
4. *Better target definition.*

Directional Drilling and Control

1. *High-temperature downhole motors.*
2. *High-temperature variable-angle bent sub.*
3. *Directional thrusters/retractors/directors.*
4. *Steerable percussion hammer.*

Production Stimulation

1. *Wellbore designs that maximize flow from the reservoir.*
2. *Advanced fracture stimulation methods.*
3. *High-temperature downhole motors for multi-leg completions.*
4. *Hard-rock underreaming.*
5. *High-temperature perforators.*
6. *Thermal-shock fracturing with cold water.*

Well Maintenance and Workover

1. *Ultrasonic scale removal.*
2. *Electromagnetic scale control/removal.*
3. *Tornado frac to rubblize scale.*
4. *Chemical additives to reduce silica scaling.*

These recommendations will be used by the DOE to form a strategy for developing advanced geothermal drilling technology. This strategy will include:

- an evaluation of the current state of the art in each recommended technology area;

- estimation of the cost-saving potential of each technology;
- development of system and component specifications;
- prioritization of projects;
- solicitation and funding of project proposals for developing the recommended technologies; and
- technology transfer to the U.S. geothermal industry.

I. Purpose and Need for the Workshop

The DOE Geothermal Drilling Technology Program

The U.S. Department of Energy, Office of Geothermal Technologies, is striving to reduce the cost of accessing and using geothermal energy in order to foster the use of this environmentally favorable resource. Geothermal well costs represent a significant (35-50%) portion of the capital investment required for a typical geothermal power plant. Well cost reduction is thus a major thrust of the DOE technology development effort.

DOE has recently divided its geothermal drilling R&D program into two elements: *conventional technology development* and *advanced technology development.*

Conventional drilling technology development refers to incremental changes in conventional drilling equipment and procedures that, taken together, should reduce geothermal well costs by 25%. In responding to the pressing needs of the geothermal industry, the DOE-sponsored drilling R&D program at Sandia National Laboratories has evolved to carry out that role.

Advanced drilling technology development refers to the development of drilling components and systems that are fundamentally different from conventional equipment and techniques used today. It is envisioned that this program element will contain longer-term and more fundamental applied research than the conventional technology program. DOE plans to fund this research at the organizations where the ideas and basic research originate. Sandia will provide technical assistance, where appropriate, in testing, analyzing, and commercializing the resulting technology.

Defining a Program on Advanced Geothermal Drilling Technology

There is no clear delineation of potential R&D projects into either the conventional or advanced category. Rather, there is a continuum of projects, ranging from minor modifications of a conventional tool or technique to major changes in the drill rig and the entire drilling process.

Furthermore, there is no clear definition of what constitutes advanced drilling technology. Advanced techniques could include everything from existing, state-of-the-art coiled tubing drill rigs to fanciful devices that might be seen in science fiction movies. Funding scenarios for technology development programs could be imagined that range from a few hundred thousand dollars to millions of dollars per year.

It was, therefore, recognized by DOE that the structure and content of a new program to develop advanced geothermal drilling technology must be carefully designed with the agility to respond to a variety of influencing factors and potential opportunities. It was also recognized that clear, unambiguous advice from industry was needed as a starting point so that industry expectations could ultimately be met in this endeavor.

Workshop Objectives

This workshop was DOE's first step in developing a meaningful and effective R&D program in "advanced" geothermal drilling technology. By convening a panel of experts in geothermal drilling and advanced drilling systems, it was anticipated that a clear definition would emerge of what "advanced geothermal drilling technology development" means to the industry, which problems can and should be addressed, which alternative techniques are feasible, and which techniques should be developed with public funding.

Specifically, the stated objective of the workshop was to develop one or more conceptual designs for an advanced geothermal drilling system that meets all of the following criteria:

1) the system would perform all the necessary functions for drilling a model geothermal well;

2) the system would reduce the cost or economic risk of drilling a geothermal well and/or improve the lifetime productivity of the well, thereby reducing well cost/unit heat; and

3) the system contains one or more key components that do not currently exist but might be developed with DOE funding.

Thanks to the active participation of all workshop attendees, these objectives were substantially met. The results and recommendations of the workshop are outlined in this document. As outlined in Section V, these recommendations will be used in the continuing process of defining a Department of Energy R&D program to develop advanced geothermal drilling technology.

II. Workshop Participants

Workshop participants were selected by Sandia to represent a wide cross-section of the geothermal and drilling industry. The participants, listed below, represent: geothermal operating companies; oil and gas operating companies; drilling consultants; geothermal consultants; geothermal and petroleum service companies; and private, university, government, and national-laboratory drilling researchers.

M. E. (Mike) Akins, Chevron Petroleum Technology Company, Houston, TX

Louis E. Capuano, Jr., ThermaSource, Inc., Santa Rosa, CA

Elwood Champness, Drill Cool Systems, Inc., Bakersfield, CA

Jim Combs, Geo Hills Associates, Los Altos Hills, CA

George A. Cooper, University of California, Berkeley, CA

John T. Finger, Sandia National Laboratories, Albuquerque, NM

David A. Glowka, Sandia National Laboratories, Albuquerque, NM

Paul E. Grabowski, U.S. Department of Energy, Washington, DC

Eduardo E. Granados, GeothermEx, Inc., Richmond, CA

Gerald W. Huttrer, Geothermal Management Company, Inc., Frisco, CO

B. J. Livesay, Livesay Consultants, Encinitas, CA

William C. Maurer, Maurer Engineering, Inc., Houston, TX

Kenneth G. Pierce, Sandia National Laboratories, Albuquerque, NM

Lew W. Pratsch, U.S. Department of Energy, Washington, DC

Roger Rinaldi, Resource Technology, Inc., Tulsa, OK

Michael E. Utt, Unocal Corporation, Sugar Land, TX

CalEnergy, Ridgecrest and Calipatria, CA (by conference call)

Navy Geothermal Project Office, Ridgecrest, CA (by conference call)

III. Workshop Structure and Approach

The workshop took place over a day and a half on April 15-16, 1997. In order to take advantage of a systems approach and structure the workshop to cover all relevant topics, the discussions were organized in the following manner.

An ideal geothermal well with maximized productivity and minimized cost was postulated and discussed in some detail. The purpose was to reach agreement on the salient features of such a well, features that must be deliverable by any process used to construct the well.

The process of actually constructing a model geothermal well was then examined. To make the discussion process more manageable, the drilling process was divided into ten functions. These functions are defined below.

Rock Reduction: Reduction of the rock at the bottom of the borehole into pieces that are small enough to be transported to the surface. Normally accomplished with a rock drill bit.

Downhole Energy Transfer: Transfer of mechanical, electrical, hydraulic, chemical, or other energy required to reduce the rock. Normally accomplished with drill pipe, both with and without downhole motors.

Rock Removal: Removal of the reduced rock from the bottom of the borehole to the surface. Normally accomplished with drilling fluids such as drilling mud, aerated muds, mist, and air.

Borehole Stabilization and Fluid Containment: Maintaining a stable borehole wall that does not slough, cave in, or collapse; and containing the wellbore fluid within the wellbore, thereby preventing lost circulation. Normally accomplished with cements and drilling fluids treated with density, viscosity, and fluid-loss additives.

Control of Formation Pore Fluids: Prevention or control of the entry of formation fluids into the wellbore during the drilling and completion process. Normally accomplished with weighted drilling fluids or underbalanced drilling with air.

Permanent Borehole Preservation: Providing permanent structural support and sealing of formations penetrated by the borehole. Normally accomplished with steel casing and cement.

Sensing, Communication, and Process Control: Use of data from the drilling process to help control the process and maximize drilling efficiency. Normally accomplished with the driller's natural feedback from the drilling process (senses of sight, hearing, and touch), measured parameters such as WOB and RPM, and, (in some drilling applications) measurement-while-drilling (MWD) and logging-while-drilling (LWD) systems.

Directional Drilling and Control: Tools and techniques for determining and controlling the direction of a borehole. Normally accomplished with single-shot surveys, downhole motors, bent subs, and (in some drilling applications) MWD systems.

Production Stimulation: Techniques and treatments for increasing the productivity of a well. Normally accomplished with acid soaks, acid stimulation, and, in many oil and gas applications, massive hydraulic fracturing and high-energy gas fracturing.

Well Maintenance and Workover: Techniques and tools for maintaining the productivity of a well after it goes into production. Normally accomplished with high-pressure waterjets (hydroblasting) and drilling with workover rigs to remove scaling and repair corrosion damage.

The conventional method of accomplishing each function and common problems associated with those methods were examined. Alternative methods for accomplishing each function were then identified and, in many cases, discussed in detail. A general consensus was reached on the viability of the alternative methods for each function, and the feasibility of developing viable drilling systems based on these alternative methods was considered.

Alternative methods considered to be feasible by the workshop participants remained on the list that was developed for each function. Alternative methods considered impractical or of little cost-saving potential were eliminated from further discussion. The result is a list of alternative geothermal drilling technologies that are considered feasible or have significant potential. The remainder of this document identifies and describes these technologies.

In addition to a structured brainstorming session for each group of functions discussed, a general, unfettered brainstorm was also held for about two hours on the second day. The purpose of that session was to generate ideas for what might be considered ultra-advanced geothermal drilling systems. This session generated its own list of ideas, which are presented in the appendix and are incorporated below into the discussions where appropriate.

IV. Workshop Recommendations

The recommendations of the workshop participants are presented here in the same framework in which the topics were examined at the workshop. A model geothermal well is first discussed, followed by general recommendations related to drilling system issues. The bulk of the remaining discussion then relates to the alternative drilling techniques and tools recommended for accomplishing each of the ten functions in the well construction process.

A Model Geothermal Well

The well shown in Figure 1 was postulated as a "model" geothermal well, meaning it contains all of the features of a typical well but with specific dimensions shown (e.g., depths, casing diameters, kick-off angles). This model well is a multiple-leg well, shown with the first leg already completed and the second leg being drilled. The purpose of defining such a well is to use it as a baseline design with which to judge advanced drilling concepts and related improvements in well design and construction.

In general, there was agreement that the model well design represents a baseline conceptual model of a typical "good" geothermal well, but it was noted that wide variations in specific design details are possible. The details shown in Figure 1 represent typical dimensions for wells in parts of The Geysers, but they do not accurately represent wells in other fields. It was agreed by the participants that specific details related to depths, casing program, and multiple-leg design are field-dependent. There does not exist a single model well then, but rather a model well for each geothermal reservoir encountered.

It was, therefore, agreed that advanced geothermal drilling technology should be evaluated with flexible model well designs in mind. Sandia will consult with workshop participants and others to better define the range of variables that should be considered in the design of model geothermal wells for various reservoirs. This information will allow prospective advanced drilling systems to be evaluated in terms of their ability to construct ideal geothermal wells under a wide variety of conditions.

It should also be noted that it was generally agreed that the need for capabilities for constructing horizontal wells in geothermal reservoirs is not particularly significant. Whereas horizontal drilling allows producing sedimentary formations to be followed in oil and gas drilling, geothermal formations do not have planar, horizontal structures. It is more important in geothermal drilling to be able to kick the well at more modest angles, 20-60°, in order to target a general region or fracture direction.

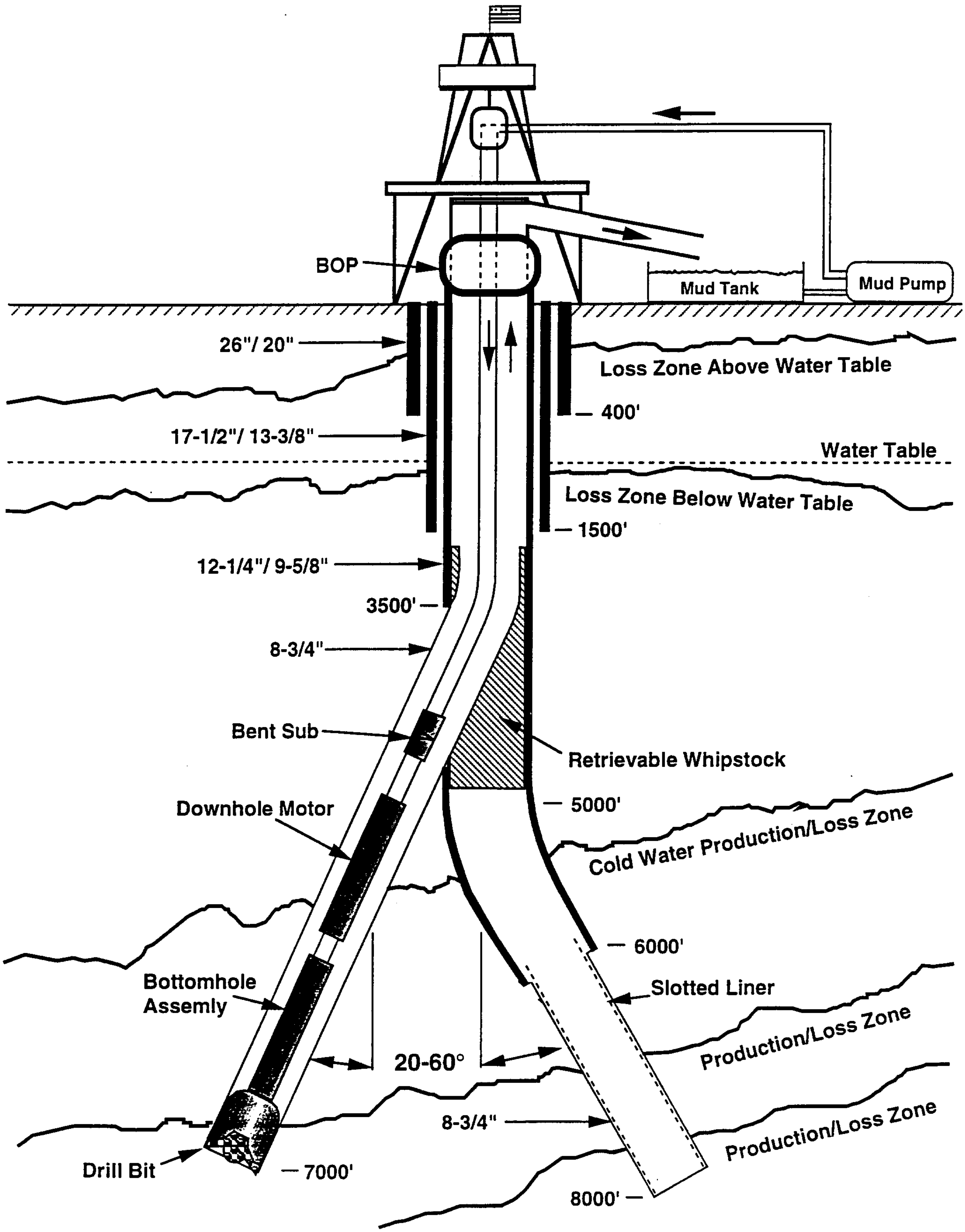

Figure 1 - A Model Geothermal Well

Drilling System Considerations

The following recommendations relate to drilling system issues that are of a general nature:

1. *Any viable drill bit for cutting hard rock requires the use of mechanical cutters to cut a round hole and maintain gage.* This conclusion had implications with respect to the type of rock reduction techniques that were considered feasible by the workshop participants.

2. *More extensive use of software should be made in the geothermal drilling process.* Better systems analysis, planning tools, and real-time data analysis and expert systems are needed for designing drilling and casing programs and for dealing with expected and unexpected problems.

3. *The use of robotics in geothermal drilling should be undertaken where possible.* In most cases, this is regarded more as a safety measure than a cost-saving one. Removing people from the high-risk tasks, such as handling drill pipe, should result in fewer injuries. These tasks, however, probably cannot be done any faster with automated mechanical systems than with a well-trained crew.

4. *The use of very large upper-well sections with multiple lower legs should be considered as a way to reduce the number of times that upper-hole problems need to be addressed in a given field.* This approach would also reduce the number of wellheads and therefore the surface impact and related site preparation costs. It requires major advances in directional drilling capabilities at high temperatures.

5. *The industry needs to develop better ways to analyze and handle the risk of putting expensive tools downhole.* Reluctance to risk the possible loss of expensive tools limits the available technology that can be used in geothermal wells.

6. *The industry needs to better follow technological advances in other fields (e.g., robotics, microelectronics, materials, and oil and gas drilling).* Technologies developed for other industries could have significant impact when applied to geothermal drilling. Identifying, evaluating, and assisting in the transfer of this technology to the geothermal industry is a legitimate and valued role of the DOE drilling technology program.

7. *Institutional and logistical constraints should be addressed in order to reduce well costs.* Conventional drilling done properly was cited as a sure way to reduce geothermal drilling costs. A shortage of trained rig hands often hampers geothermal drilling operations. The possibility of establishing a geothermal drilling training program should be considered by the Geothermal Energy Association (GEA) and/or the Geothermal Resources Council (GRC). DOE assistance in meeting the technology needs of such a training program may be helpful. This assistance would include providing geothermal drilling simulators for the various crew levels needed, from rig hand to driller and drilling engineer. The state of the art in drilling simulators should

be evaluated and, where necessary, advanced specifically for geothermal drilling to make simulators available to the industry. Other logistical constraints should be examined to determine where technology development could play a role.

Rock Reduction

Conventional Methods

1. *Tungsten-carbide-insert tricone roller bits remain the only viable alternative for most geothermal drilling.* Although polycrystalline diamond compact (PDC) bits have found extensive use in softer rock formations, they have not been proven capable of drilling the hard, fractured rock typically found near geothermal resources. Diamond enhancement of the cutting structure of roller bits is a relatively new development that is still gaining acceptance as a cost-saving approach in the drilling industry.

Common Problems

1. *Low rate-of-penetration (ROP) because of hard-rock conditions.* Penetration rates below 15 ft/hr are typical in geothermal drilling, and rates below 10 ft/hr are very common. Well cost studies indicate that well costs are very sensitive to penetration rates up to 30 ft/hr. Achieving such a penetration rate on a routine basis would save about 10-15% of the total cost of a typical geothermal well.

2. *Short bit life because of hard, fractured, abrasive, and high-temperature rock conditions.* Bit life as low as 24 hr, or 200-400 ft, is common. Doubling bit life would save up to 5% of the cost of a typical geothermal well.

Feasible Alternative Methods

It was the consensus of the workshop participants that mechanical cutters are required in any type of drill bit used in rock in order to ensure that a round hole of a relatively constant diameter is drilled. This eliminated a number of novel drilling techniques from further discussion, including concepts such as flame-jet drilling and pure-waterjet bits. The energy-intensive nature of other novel techniques, such as rock melters, was also discussed and found to be a concern more from the standpoint of delivering the energy to the drill site and downhole than from the standpoint of actual energy usage.

The following methods were considered by the workshop participants to be feasible alternatives to the tungsten-carbide-insert tricone roller bit. It was widely recognized, however, that these alternatives would generally cost more than roller bits and must, therefore, exhibit significantly improved performance in order to reduce overall drilling costs.

1. *Drag bits using synthetic diamond or other advanced materials.* Although the inherent limitations of drag cutters in hard rock were recognized, workshop participants generally agreed that improvements in hard-material technology should be encouraged. There is currently an abundance of interest and an explosion of materials research projects in this country aimed at hard-rock drilling. With DOE funding, Sandia is assisting the industry by providing cutter performance and wear testing services and has recently been inundated with requests to test new materials.

Thermally stable polycrystalline (TSP) diamond cutters, in particular, have demonstrated a good potential for hard-rock drilling. Several projects are currently under way to bond TSP material to a tungsten carbide cylinder, thereby creating a cutter similar in size and shape to conventional PDC cutters. When combined with a high-speed downhole motor and a rock machining approach (see below) TSP cutters may be able to cost-effectively drill hard rock.

Many of these new materials have a potential for use in locations on downhole tools other than drag cutters. Sliding valves, bearing surfaces, and fluid flow pathways all have a need for improved, high-temperature, hard-surfacing technology.

2. *Low-pressure waterjet-enhanced drill bits.* "Low pressure" is taken to be pressures at or near the pressure capability of conventional mud pumps. The current limitation is about 5,000 psi. Higher pressures are possible but are not often used. Pump maintenance costs increase dramatically at pressures above 3,000 psi.

   Numerous laboratory tests have indicated that a low-pressure (<5,000-psi) waterjet can dramatically reduce the forces on a drag cutter if the jet is directed at the cutter-rock interface. This effect is thought to result from improved cleaning of the interface, thereby increasing contact stresses between the cutter and the rock, and hydraulic extension of the microfractures created in the rock by the mechanical cutter. By using waterjet assistance, it may be possible to improve the performance of both roller cone and drag bits in hard rock drilling.

   At least two projects are currently under way to implement this concept into a fieldable drill bit. Novatek, Inc., and the University of Missouri-Rolla are designing a waterjet-enhanced rotary percussive drilling system under a Small Business Innovative Research (SBIR) grant. Sandia Labs, Security DBS, Dynaflow, Inc., and Terra Tek are designing and testing a mudjet-augmented PDC bit with funding from the National Advanced Drilling and Excavation Technology (NADET) Institute. If proven feasible, these efforts should be funded for further development and commercialization.

3. *High-pressure waterjet-enhanced drill bits.* High-pressure (>5,000 psi) waterjets will cut rock unassisted, but mechanical cutters are still needed to keep the hole diameter from changing as different rock strata are penetrated. Very high pressures (>15,000 psi) are required in order to cut all rock types encountered, and the ability of the waterjet to cut rock diminishes as the depth of the borehole increases. Nevertheless, this concept has been proven to work in the field, and workshop participants endorsed further study and development, particularly if new technologies such as downhole intensifiers and coiled tubing can be used to deliver the needed pressures downhole (see discussion under the Downhole Energy Transfer section below).

   At least one project is now under way in this area. FlowDril Corporation is developing a downhole pressure intensifier (see the Downhole Energy Transfer section below) that will produce 35,000-psi mudjets. The jets are directed at the rock surface, but not at the cutter-rock interface. Thus, the PDC bit used so far with this system depends more on a kerfing action to weaken the rock surface rather than direct waterjet assistance to individual cutters. The Gas Research Institute (GRI) and the DOE Morgantown Energy Technology Center (METC) are providing funding to FlowDril.

4. *Percussive hammer bits.* There is continuing and growing interest in percussive hammer bits, driven partially by the recent successful use of air hammers in drilling low-pressure gas wells. Drilling with liquid or mud hammers has had more variable success. Mud hammers are more susceptible to downhole failures and plugging, and the effect of the hydrostatic head on the rock surface is to make it less susceptible to percussive disintegration. Directional drilling is difficult with percussive hammers, and it is difficult to maintain bit gage in hard rock. Nevertheless, these problems can be solved, this concept continues to show significant potential for many types of geothermal drilling, and its further development should be supported.

   Both solid-head and roller cone bits have been used for percussive drilling. Solid-head bits perform better in many cases, but roller bits will continue to drill when less brittle rock is encountered that does not respond well to percussion. Synthetic-diamond enhancement of both bit types has significantly improved maintenance of hole gage, which has historically been a problem with percussive drilling in hard-rock environments. The percussive hammers themselves are discussed under the below section on Downhole Energy Transfer.

5. *Disk-cutter bits.* This type of bit is used successfully in hard-rock tunnel-boring machines. The concept is similar to that of a tricone roller bit except that instead of the discontinuous point contact between the rock and the teeth on a tricone bit, the disk cutter sees continuous rolling contact along a line traveled by the disk. This has some wear advantages in hard rock drilling, at least on the scale of bits used in tunnel boring machines. Also, with the depths-of-cut used in tunnel boring, there is considerable interaction between adjacent disk cutters, which increases the overall efficiency of the drilling head.

   Development of a disk-cutter drill bit has been under way at the Colorado School of Mines for several years. An ongoing study funded by NADET is exploring the feasibility of a disk-cutter bit for geothermal drilling. If the desired penetration-rate or bit-life advantages can be proven, further support of this development work would be warranted.

6. *Large-diameter wireline core bits.* This concept was a recommendation of the Geothermal Energy Association (GEA) workshop in April, 1996. Although not defined in any detail, the concept as reported is to drill with a large-diameter (e.g., 12-1/4 inch) core bit so that large rock cores can be retrieved with a wireline. Although this concept was recognized in the present workshop to have serious deficiencies (e.g., the need to handle very large-diameter drill pipe), it was considered to have some potential for use in a casing-while-drilling system (see below).

   From the standpoint of the bit, there is probably no inherent difficulty in scaling up conventional wireline coring designs. Impregnated-diamond core bits of 12-1/4 inch outer diameter are entirely feasible, but expected penetration rates are very low. A more aggressive core bit design, perhaps incorporating hard-rock PDC or TSP cutters, would be needed to make penetration rates economically competitive with conventional rotary drilling. More discussion of this concept is provided in the Rock Removal section below.

7. *Casing-while-drilling with a retrievable motor and bit.* This concept is attractive where borehole wall stability is a problem. Being able to protect the hole with the casing as it is drilled would alleviate many problems with drilling through rubblized zones. It may cause other problems, such as the risk of committing the steel to the hole up front. On the other hand, common wireline coring is essentially a casing-while-drilling concept in that the drill rod is occasionally left in place as casing (though usually unintentionally).

   Casing-while-drilling could be accomplished by either rotating the casing from the surface or using a wireline retrievable motor and bit. The bit would either have to be a bi-center bit, which drills a hole larger than the bit body, or it would require a retracting mechanism to allow it to be withdrawn through the casing. A sacrificial bit that would remain downhole at the bottom of the casing would not be practical unless it could be guaranteed that the bit would drill the entire casing interval, something that would be difficult to do.

   In any event, if a viable casing-while-drilling concept is ever developed, it is clear that a specialized bit will also be needed. Bi-center PDC bits have been used successfully in many soft-rock formations. A bi-center roller bit would require development but may be feasible. Retracting bits have been built both in the U.S. and in Russia, so they are known to be technically feasible.

8. *Replaceable-cutter bits.* The concept of replaceable-cutter bits is economically valid only if the time required to trip a bit is a significant portion of the drilling time. This occurs either when the hole is very deep or the bit life is low. If a conventional bit lasts only 24 hours, and it requires 8 hours to trip, then a replaceable-cutter bit might make sense if it is robust and performs as well as a conventional tricone bit. If a conventional bit lasts 80 hours, however, an 8-hour trip may not be excessive for changing the bit; and the bit is often pulled after such a long time for some other reason anyway, such as surveying, logging, downhole tool wear or reaching a casing point.

   A more compelling reason for replaceable-cutter bits may be an ability to change the cutter type downhole as the formation type changes. The ability to switch from roller-cone to PDC cutters and back again, for example, might make it possible to efficiently drill interbedded soft and hard formations with the same bit.

   Replaceable-cutter bits have been successfully built both in the U.S. and in Russia. These bits functioned properly in changing cutters downhole, but it was found difficult to design such a bit that would drill as fast as a solid-body bit. The economic feasibility of replaceable-cutter bits is therefore still waiting to be proven.

9. *Rock machining at ultra-high RPM.* This concept would employ drag bits rotating at ultra-high rotary speeds with very small depths-of-cut. This would be one way to control and minimize the high impact forces imposed on drag bits drilling at conventional rotary speeds in hard rock. Because of the greater amount of frictional heat generated at higher speeds, however, this concept would require the development of cutter materials that are more temperature-resistant than conventional PDC cutters.

   At least one project was undertaken (and aborted) to develop a borehole machining system. Amoco and Smith Tool/Dynadril considered a 3,000-RPM system using PDC or TSP cutters together with rate-of-advance control. At the time that project was conducted (the mid-1980's), cutter materials that could handle those speeds were not available. Bonded-TSP and other synthetic materials may, however, make this concept feasible in the near future.

10. *Hybrid rotary-coring.* A concept that captures the salient features of many of the above methods is a hybrid drill that employs a coring bit nested within a larger rotary drill bit. The core bit could be situated on a telescoping section of drillstring that would allow the bit to drill ahead of the stationary bit to capture rock core and encounter loss zones with a smaller-diameter penetration. This would allow the loss zones to be sealed more easily. The core bit could be mounted along with a downhole motor on the core tube and retrieved with a wireline periodically to recover core and replace the bit and motor, if necessary. This would also leave the center of the larger drillstring open, allowing cement to be pumped downhole for lost circulation control without first tripping the drillstring. This concept could have significant merit if the economics of the entire drilling process are favorable.

11. *Hard-rock underreaming.* Underreaming the production interval of a geothermal well could significantly increase or restore its productivity by increasing wellbore diameter and removing scale or drilling fluid damage from the near-wellbore region. Underreaming is routinely done in softer formations but has not been routinely accomplished in harder geothermal formations. If developed for hard-rock applications, underreaming bits would probably find immediate use.

    Several types of underreaming bits are possible. Bi-center bits, as previously discussed, are feasible and have been developed for softer formations. Both roller-type and drag-type cutters could also be employed in bits with underreaming arms that extend and retract, again similar to but more robust than underreamers used in softer formations. Waterjet assistance may provide the performance boost needed. When combined with a downhole intensifier to provide the high-pressure fluid, such a tool may appear feasible.

Downhole Energy Transfer

Conventional Methods

1. *Rigid drill pipe rotated from the surface, drilling with 30-ft joints, tripping with 90-ft triples.* The top drive system appears to be superior to the rotary-table drive system, but top drive is not as widely used because it is more expensive and the rotary table has been around longer. The top drive permits pumping when pulling out of or running into the hole or when working stuck pipe. It also allows drilling connections to be made in doubles or triples, depending on the derrick.

2. *Downhole motor converting drilling fluid power delivered through rigid drill pipe.* Downhole motors have made directional drilling possible, and they are widely used in geothermal drilling. Most geothermal wells are directionally drilled to reach a specified target. Directional work (i.e., turning the well) is generally done above the reservoir, followed by conventional rotary drilling (without the downhole motor) to maintain the new wellbore direction. Measurement-while-drilling (MWD) systems make directional drilling a true real-time process.

Common Problems

1. *Slow tripping.* Pulling the drillstring out of the hole, changing the bit, and putting the bit back on bottom typically takes 45 minutes to one hour per thousand feet of depth and requires a drilling crew of five. Some degree of automation is being used in offshore oil and gas drilling, but it improves safety more than it speeds up the process.

2. *Temperature limitations on downhole motors.* The maximum operating temperature for most positive-displacement motors (PDMs) is only about 125°C because of the elastomeric stator. Recent developments indicate this limit may be increasing to 200°C with improved elastomers. Still higher-temperature capability is needed if motors are to survive soak temperatures in the lower portions of geothermal wells.

3. *Drill pipe corrosion.* Corrosion of the drill pipe is a significant problem, particularly when drilling with air or aerated mud. The high temperatures, low pH, and surface erosion caused by the high-velocity, particle-laden flow make for a highly active corrosion cell. Most of the additives used in past years to retard corrosion contain chrome and are no longer used.

Feasible Alternative Methods

The following methods were considered by the workshop participants to be feasible alternatives to the conventional methods currently used to deliver power downhole.

1. *High-temperature fluid motors.* PDMs are needed with the capability to operate at higher temperatures and with air or two-phase fluid (aerated mud, foam, or mist). This would allow more directional work to be done in the lower portion of the well,

which may have a significant advantage in certain cases. High-temperature motors are currently a high-priority development item within several service companies.

Air turbines were also deemed feasible if used with speed reducers to reduce rotary speed and increase torque output. Speed reducers have been built in both the U.S. and Russia, but they are not yet commercially available in this country.

Insulated drill pipe (see below) may be quite effective in reducing downhole temperatures sufficiently to allow conventional PDMs to be used in lower wellbore sections. Insulated drill pipe would not only deliver cooler fluid to the motor, it would also cool the well so that longer soak times could be tolerated.

2. *Coiled tubing.* The use of coiled tubing instead of rigid pipe is attractive from several standpoints. Rapid tripping, the capability of running continuous electrical power or signal cables down the tubing, and the capability of pumping high pressure fluids without joint-sealing problems are three advantages. In the oil and gas industry, the use of downhole fluid motors on coiled tubing is a rapidly-developing, state-of-the-art directional drilling technique. Coiled tubing is also used in the geothermal industry, but primarily in well-cleanout or workover operations. Coiled tubing undergoes significant plastic deformation during use, and this could lead to abnormally high-corrosion rates in geothermal wells than encounter low-pH fluids.

   Most coiled tubing can handle 5,000-10,000 psi. Higher pressures are possible, but it is not apparent what the upper limit would be. It is difficult to conceive of 30,000-psi tubing being flexible enough to coil. Concentric coiled tubing is also possible to manufacture, which opens the possibility for insulated coiled tubing and dual-flow drilling with high-pressure waterjets and low-pressure flushing.

   Coiled tubing is most common in the 1-1/4 inch diameter, with some availability in the 2-3/8 and 2-7/8 inch diameters. This is rather small for geothermal well sizes and the high drilling fluid flow rates usually required. Larger tubing is available, but fatigue life is reduced as tubing diameter increases. Another disadvantage of coiled-tubing drilling is the necessity of always using a downhole motor to turn the bit, which can significantly increased drilling costs.

   In addition to the limited fatigue life, larger-diameter tubing requires larger tubing reels. Very large and heavy tubing loads are often hard to deliver to remote geothermal sites. There is a real need for a field-applicable tubing joint so that the full length of tubing required for drilling can be delivered in more than one load and joined at the drill site.

   The possibility also exists for using concentric coiled tubing to make insulated drill pipe. The advantages of drilling with insulated drill pipe are discussed below.

3. *Downhole electric motors.* Electric motors may have real advantages over fluid motors in temperature capability and have been used for drilling by the Russians since the 1960s. The Russian electro-drill uses a two-conductor power line run down the

inside of rigid, jointed drill pipe, with a power connector at each joint of pipe. Speed reducers are used to reduce rotary speeds to a few hundred RPM.

The use of electric motors on coiled tubing was considered to be particularly feasible and probably on the horizon within several years in oil and gas drilling. The capability of running a single power line down the coiled tubing to transmit high-speed data as well as power along the line opens up a wide range of possibilities for MWD and LWD systems.

4. *Composite drill pipe or tubing.* Flexible composite tubing, similar to the Coflexip drilling hose develop by Elf in France, has an appeal in that it is not as susceptible to fatigue life limitations as conventional coiled tubing. Coflexip was essentially a flexible hose that acquired torque-carrying capability through a special imbedded-wire weave. Several projects are also under way in the U.S. to develop lightweight, rigid composite tubing for drilling. Composites may be more resistant to corrosion, and their lightweight nature would make the use of compact rigs more feasible for deep geothermal drilling. One concern with composite tubing is its limited capability to withstand torque.

5. *Insulated drill pipe.* Downhole fluid temperatures can be significantly reduced if even a small amount of insulation is added to the wall of the drill pipe. This is because less of the heat in the fluid flowing out of the well is transferred through the drill pipe to the downflowing fluid. More heat is thereby removed from the well, making the downhole environment less hostile for downhole motors, instruments such as MWD systems, and the drilling fluid itself.

   Drill Cool Systems, Inc., is developing insulated drill pipe in a GDO project that has been recently initiated. Sandia is assisting in the analysis and testing of the design. It is anticipated that an insulated drill string will be available for field testing in early 1998.

6. *Aluminum drill pipe.* Aluminum drill pipe has applications in high-angle drilling, where the reduced weight helps overcome sliding friction. It requires steel tool joints and is not suitable to highly abrasive wear conditions, but it may be of use in compact-rig applications because of its light weight. Aluminum drill pipe is commercially available in Russia. If heat-treated, aluminum pipe may over-age and weaken in high-temperature geothermal wells.

7. *Downhole pressure intensifier for high-pressure waterjet drilling.* FlowDril is developing a downhole pressure intensifier that will take part of the low-pressure mud flow downhole and produce 35,000-psi mudjets. The device is basically a differential piston device that uses valving to reciprocate the piston, and it produces a small volume of high-pressure fluid. FlowDril has completed several successful field tests and is still working to improve the life of the device. The Gas Research Institute (GRI) and the DOE Morgantown Energy Technology Center (METC) are providing funding assistance to FlowDril to develop this tool. Additional funding is needed to harden the tool for geothermal drilling applications.

Maurer Engineering also worked on the development of a downhole pressure intensifier, this one using a centrifugal-pump approach. By using multiple vanes, the output pressure of the pump was pushed over 15,000 psi, without the use of seals. Although Gas Research Institute (GRI) funding for this project was terminated, this approach merits further investigation.

8. *Percussive mud hammer.* As noted under the Rock Reduction section above, percussive hammer development is of high current interest in the industry. Under a GDO project with Sandia, CalEnergy, Unocal, and Amoco, Novatek is developing a mud hammer based on their patented non-plugging design. The hammer design does not include any elastomeric parts or critical springs, so it does not have any inherent high-temperature limitations. Both a 7-3/4 inch and a 12-1/4 inch tool will be built and tested under this project. If successful, a need will exist to further optimize the hammer by matching the hammer and rock impedances to improve penetration rates.

9. *Compact rigs and automated pipe handling.* Compact rigs are drill rigs with a smaller footprint than conventional rigs that are capable of drilling to the same depth. Compact rigs have been available for some time now, but the latest generation of rigs offers modern automation and controls not previously available. An ongoing study by Geothermal Management Company under contract to Sandia is documenting the current state of the art. Automated pipe handling systems are already used in high-dollar oil and gas drilling operations offshore. Top drives also offer distinct advantages, as previously noted, and should be incorporated into more geothermal drilling operations. As new rigs are built, attention should be paid to building the rigs for easy maintainability and coordinated operation.

10. *High-temperature pipe recovery tools.* Downhole tools for freeing stuck pipe are needed that will operate at high temperatures. One suggestion was that a downhole vibrator might be driven by drilling mud flow to fluidize and remove the debris sticking the pipe. The entire ensemble of common low-temperature fishing tools, back-offs, and jars should be examined to determine what should and can be temperature-hardened to work better in the geothermal environment.

11. *Diesel exhaust scrubbing for use as a non-corrosive drilling fluid.* Drill pipe and casing corrosion can be very extreme when drilling with air in some geothermal fields. The use of an inert gas, such as nitrogen, has been tried and found to be effective but very costly. As an alternative, a Sandia study conducted about 15 years ago investigated the use of catalytic converters on the drill rig's diesel generators to scrub the exhaust for use as an inert drilling fluid. The study concluded that the process is feasible, but it was never commercialized. This technology should be re-examined for use in both drilling and workover operations in geothermal fields.

Rock Removal

Conventional Methods

1. *Drilling mud pumped downhole with solids removal equipment and mud chillers at the surface when required.* A wide variety of chemical and other additives are available to control the properties of the mud, such as density, viscosity, pH, gelling, fluid-loss, and bridging-particle characteristics. Modern surface equipment for removing solids is effective but costly. Mud chillers are available on a rental basis and are effective in reducing the temperature of the mud pumped back downhole. Use of this equipment, however, is not compatible with many lost circulation materials (LCMs) used to reduce drilling fluid loss to small fractures and porous rock.

2. *Two-phase fluid (air mixed with water or mud) pumped downhole.* When underbalanced conditions are encountered, it is often necessary to drill with a low-density drilling fluid in order to clean the hole of rock chips. Large air compressors are usually brought in and used with a small amount of drilling mud or water and foaming agents to provide anything in the continuum from aerated drilling mud to mist. This practice will grow in importance as underbalanced drilling techniques are further developed and used.

3. *Small-diameter wireline coring.* In addition to a small amount of rock chips removed with the drilling fluid, a core of rock is recovered (often intact) in wireline coring operations. The rock core is received by a core tube latched in place above the core bit. When a prescribed length is drilled (5-30 ft), a wireline in dropped down the drill pipe, where it latches onto and retrieves the core tube with its captured rock. The tube is unloaded and dropped back downhole where it latches in place, and the cycle repeats.

Common Problems

1. *High mud flow rates required in large-diameter wells.* The high flow-rate requirements for cleaning a large-diameter well mean that large volumes of expensive drilling fluid are consumed if lost circulation occurs.

2. *Mud viscosity control at high temperatures.* Bentonite and polymer muds both experience degradation at high temperatures. Viscosity can either increase or decrease at high temperatures, so it is difficult to achieve an optimal viscosity at all points along the flow path. Mud engineering and additive costs can become significant when extremely high downhole temperatures are encountered.

3. *Mud cleaning and cuttings removal costs.* With increased costs associated with the disposal of drilling mud and rock cuttings, it is becoming more important to clean, reclaim, and re-use drilling mud. More and more sophisticated mud-cleaning systems are being used in geothermal drilling, and this represents an essentially new, or certainly increased, on-site cost.

Feasible Alternative Methods

Workshop participants considered the following technologies to be worth further investigation for improving rock removal:

1. *High-temperature drilling fluids, including temperature-stable drilling foams.* Drilling muds and additives for extremely high temperatures will be needed as hotter geothermal resources are discovered and tapped. Muds capable of drilling to 500°C and even higher will be needed within the next few years. Temperature-stable drilling foams are also needed for underbalanced drilling.

2. *Large-diameter wireline coring.* The concept of drilling with large-diameter (e.g., 12-1/4 inch) wireline coring equipment has some appeal. The relatively small amount of rock that is reduced downhole implies an improved drilling efficiency and fewer rock chips to plug production zones. The ability to drill blind (with no fluid returns), producing fine cuttings that could be carried out of the wellbore into the loss zone would also be advantageous. This concept is similar in effect to the casing-while-drilling concept in that the drill rod is much closer in diameter to the diameter of the wellbore, and in fact could be left in place to serve as the casing. Disadvantages of such a system would be the difficulty of tripping the large-diameter drill rod that would be required, the relatively low penetration rate of most impregnated-diamond core bits, the time associated with retrieving the core, the weight of the rock core if retrieved in reasonable lengths, the cost of the large-diameter core pipe, and the risk of getting it stuck in the well. Nevertheless, the concept does merit a study of its feasibility. Of particular interest are improved-performance core bits and the capability of retrieving the core while at the same time drilling ahead.

Borehole Stabilization and Fluid Containment

Conventional Methods

1. *Weighted and unweighted drilling muds with filter-cake, fluid-loss, and formation-stabilizing additives for maintaining borehole stability.* Because of the underpressured nature of most geothermal formations, unweighted muds are almost always used. In some cases, such as Dixie Valley, NV, the fracture gradient is such that a full wellbore of drilling fluid will often exceed the bottomhole pressure required to hydraulically fracture the formation.

2. *Lost circulation materials (LCMs) for minor lost circulation, and cement pumped through open-end drill pipe for major loss zones.* LCMs such as cottonseed hulls and shredded paper are often successfully used to plug minor fractures and pores in lower-temperature portions of a well.

3. *Two-phase fluid (air mixed with water or mud) to reduce borehole pressure and fluid loss.* Induced lost circulation (i.e., lost circulation caused by hydraulically fracturing the rock formation with drilling mud) is common in geothermal drilling. Drilling mud is also capable of significantly degrading the permeability of production zones. Consequently, aeration of the mud to one degree or another to produce a lightweight drilling fluid is already commonly done, and this practice will increase in use as underbalanced drilling techniques are further developed and implemented.

4. *Multiple casing strings.* A typical geothermal well is drilled with at least three or four casing strings, all usually tied back and cemented all the way to the surface. The various strings protect and segregate penetrated aquifers, stabilize the wellbore, and in many cases, allow drilling to proceed by permanently preserving the part of the hole already made.

Common Problems

1. *Lost circulation and related problems, such as stuck pipe, twistoffs, and casing cementing failures.* Lost circulation is very pervasive in geothermal drilling, accounting for 10-20% of the cost of a typical well. The inability to bring rock chips out of the hole under lost circulation conditions can cause the chips to accumulate in the wellbore or become packed into a surrounding loss zone. It is not uncommon for the chips to fall around and stick the drill pipe in the hole, which can lead to a twistoff and an expensive fishing or sidetracking operation. Cementing casing in place through a loss zone is often difficult unless the loss zone is sealed first. Sealing a single loss zone can often require multiple cement plugs. Finally, because geothermal production zones are often lost circulation zones when the wellbore is full of drilling mud, permanently sealing off such zones is not an option if the well is expected to produce geothermal fluids. Production-zone damage also occurs from the intrusion of drilling mud and rock chips into the zone during drilling.

2. *Wellbore sloughing and collapse.* Soft or interbedded formations are often encountered that are not competent to withstand the stresses created by the hole being drilled. Sloughing and collapse of the wellbore wall occurs, particularly in high-angle sections of the hole. Wellbore instability of this nature is usually addressed by isolating the formation behind casing. This can limit choices on casing depths and diameters as well as hole trajectory.

3. *Lateral well displacement due to pressure-induced fault slippage.* Some evidence exists that localized fault movement can be triggered when a borehole crosses a fault and provides hydrostatic pressure and lubrication to reduce frictional forces between the two rock faces. Although this movement may only be on the order of an inch or less, this can cause drag problems that can lead to stuck pipe when tripping the drillstring.

4. *Reduction in hole size due to the need for multiple casing strings.* With each additional casing string run in the hole to maintain stability or contain fluid, the eventual bottomhole diameter is reduced. Consequently, in order to achieve an adequate bottomhole diameter, very large-diameter holes are initiated at the surface. Many of the costs associated with geothermal drilling can be attributed to the large hole diameters required in the upper portions of the wells.

<u>Feasible Alternative Methods</u>

The following technologies were considered by the workshop participants to be potentially cost-saving alternatives to the conventional methods for achieving wellbore stability and fluid containment:

1. *Advanced wellbore lining techniques for achieving mechanical integrity and outflow sealing.* It was generally agreed by workshop participants that alternative tools and techniques for lining a wellbore are needed if major reductions in well costs are to be achieved. If the wellbore wall could be sealed as the hole is drilled, both lost circulation and wellbore stability problems could be eliminated. In addition, such a technique could permit a monobore well design, where the diameter of the hole is constant from the bottom of the surface casing to the top of the reservoir.

   A number of schemes were discussed, including: an epoxy or polymer skin sprayed or extruded in-place; a mechanical skin, such as a metallic patch, composite material, expandable slotted liner, the Shell cladding system, and assemble/expand-in-place casing; a ceramic skin built in-place with the addition of flux and heat; and hyper-thixotropic fluids. It was suggested that alternative liners could be considered temporary until drilling is complete and could then be cased over with one long production string. Some techniques may satisfy all the requirements for permanent wellbore sealing and preservation and would simply replace conventional casing. Finally, some techniques may be more suitable for stabilizing production zones, while some may be more applicable to non-producing zones.

A study to evaluate alternative wellbore lining concepts is currently under way by Livesay Consultants and Sandia with NADET funding. This one-year study will examine novel wellbore lining concepts that have been proposed in the past as well as new ideas to develop a strategy for developing one or more promising concepts.

2. *Open-hole packers for improved lost-circulation cementing efficiency.* Proper placement of a cement plug is essential for sealing a lost circulation zone. If a loss zone is not located on bottom, it is often difficult in large-diameter wellbores to set a "balanced" cement plug that will remain in a location in the wellbore where it can seal the zone. Channeling of the cement toward the bottom of the hole is common, requiring more cement volume for effective plugging of the zone itself. In foam cement jobs, control of cement movement is required in order to prevent the lightweight cement from rising to the top of the wellbore. The continued development and use of open-hole packers for controlling cement movement was, therefore, considered to be important.

   A drillable straddle packer has been developed by Sandia and is undergoing large-scale demonstration tests in Sandia's Engineered-Lithology Test Facility (ELTF). Tests thus far indicate that the packer is capable of effectively isolating a loss zone and controlling the flow of cement into the zone. After successful conclusion of the remaining tests, a field test opportunity will be sought in 1998.

   Retrievable casing packers have been successfully used in foam cement jobs, where the foam cement was set in loss zones just below the casing shoe. Improved open-hole packers are needed in order to improve the placement flexibility of foam cement plugs. Sandia's drillable straddle packer may not have sufficient pressure capability for this purpose. A retrievable open-hole packer should be adapted or developed for this application.

3. *Alternative cements for lost circulation control.* Conventional Portland cement with high concentrations of silica is normally used for lost circulation control in geothermal drilling. Alternative cement formulations offer various potential advantages and should continue to be investigated. Nitrogen-foamed cement has recently been used with outstanding results in several geothermal wells. The lightweight, expanding nature of this cement allows it to more effectively cement lost circulation zones if a packer can be set above the plug to contain it. Cementitious muds that are rapid setting and more chemically compatible with drilling mud have also been formulated and field tested. Lightweight, CO_2-resistant cements have been formulated that show potential for use in highly corrosive environments.

   Field evaluation of these alternative cements is currently under way in a GDO project involving Sandia, CalEnergy, Halliburton, the Resource Group, and Brookhaven National Laboratory. Field tests under closely monitored and recorded conditions are being conducted to evaluate the character of the loss zones encountered, the effectiveness of the cements in sealing the zones, and the cost savings that result. Extensive surface and downhole logging is being conducted to provide solid evidence of performance. In general, the workshop participants agreed that alternative cement research and testing should be vigorously encouraged and supported.

4. *Polymer foam for lost circulation control.* Expanding, fast-setting polymer foam was considered to be worth further investigation as a lost circulation and formation-consolidation treatment. A GDO project about ten years ago concluded that polyurethane foam may be viable at relatively shallow depths if correctly deployed. Its characteristics make it ideal for sealing and consolidating porous rubble zones and fractures. Two delivery concepts have emerged as potentially viable: pumping a large volume of one- or two-component chemical foam downhole through flexible hoses; or delivering a fixed volume of chemicals downhole in a tool and dispensing them into a flexible, porous bag to prevent jet-mixing with the water and thereby maximize foam expansion.

   Sandia is currently studying the feasibility of the first technique. Working with an industry partner that manufactures foam pumping and delivery systems, Sandia will design, build, and test a shallow-hole system that can be deployed in slimholes. The porous bag approach has also been studied by Sandia in the past, but that project has been idle for several years because of other high-priority projects and manpower limitations.

5. *Removable production-zone plugs.* A method to temporarily cover or seal a section of borehole passing through a prospective production zone would be useful. It would allow drilling to continue in some cases where otherwise not possible in order to reach additional production zones. While this method could be considered a sub-set of the above method on advanced wellbore lining techniques, removable production plugs would be applied only in specific borehole sections, not in a continuous fashion as with perhaps most of the advanced lining techniques.

   Potential methods of temporarily sealing a potential production/loss zone include: various types of setting fluids (e.g., polymers and cements) that can be removed with chemicals (e.g., acid) or which degrade over time with exposure to temperature; and mechanical patches such as low-strength casing that can be temporarily sealed in place and removed in one piece, milled, or dissolved to regain the full open-hole diameter.

6. *Improved underbalanced drilling techniques.* An improved capability of drilling slightly underbalanced under a wide variety of conditions would be very useful to the geothermal industry. By slightly producing the permeable zones during drilling, lost circulation is avoided and permeability damage of the production zones is prevented. On the other hand, high fluid production rates are not desirable from the standpoints of safety and the cost of dealing with large volumes of produced fluid at the surface. Drilling at the balance point is somewhat difficult and requires further technology development to become more widely used in a routine manner in geothermal wells.

   Hardware, software, and technique development are all needed for improved underbalanced drilling. Ways to overcome the corrosion and erosion experienced with air drilling, such as the previously mentioned catalytic converter for inert gas generation, would be useful. Downhole hardware, such as jet subs and parasite aeration strings, and techniques for using this hardware should be further evaluated and developed for this application. Software for calculating underbalanced drilling parameters and for controlling fluid density and flow rates is needed to allow underbalanced drilling to be optimized and fully utilized in a safe manner.

Software development for underbalanced drilling has been under way at Maurer Engineering, Inc., for the oil and gas drilling industry as part of a Drilling Engineering Association (DEA) project. Sandia has recently funded Maurer to upgrade the software for geothermal drilling applications. The resulting software will essentially be a Windows-based replacement for the Geotemp program Sandia developed in the early 1980s and which has been widely used by the geoscience community to calculate downhole well temperatures under flowing conditions. The new software will include the capability of simulating drilling with air, drilling mud, or any two-phase mixture of the two, as well as multiple production and loss zones.

7. *Lightweight drilling muds.* Techniques for reducing drilling mud density without gas are also of significant interest. Maurer Engineering has recently completed a study of drilling muds loaded with glass microspheres. Mud densities as low as 5 ppg have been achieved with no crushing of the microspheres as they are pumped through the mud drilling system. Further investigation of this technology for geothermal applications is warranted.

Control of Formation Pore Fluids

Conventional Methods

1. *Weighted and unweighted drilling muds to maintain wellbore hydrostatic pressure above pore-fluid pressure; and a rotating head and choke/blow-out-preventer system to control steam and gas kicks that enter the wellbore.*

2. *Drilling slightly underbalanced with two-phase fluid (mist, foam, or aerated mud) such that formation pore fluids are produced at a low, controllable rate.*

3. *Multiple casing strings.* Casing is used to seal off permeable zones that produce fluid which is not wanted in the wellbore because of its low temperature or hostile chemistry.

Common Problems

1. *Drilling underbalanced with confidence.* Drilling under conditions of a controlled blow-out, as underbalanced drilling is often called, is not a simple matter, and it is probably not for the feint of heart. Safety and fluid-disposal cost considerations become paramount when large volumes of hot pore fluid are produced. More diagnostic hardware and software are needed to help the driller and the drilling engineer safely drill underbalanced.

2. *Permeability damage to production zones by over-controlling pore fluids.* As previously discussed, maintaining absolute control over pore fluids by using conventional drilling mud often leads to lost circulation and partial plugging of permeable zones. This plugging may not be reversible: drilling mud contains clay particles that can bake into a solid precipitate that cannot be easily eroded, dissolved, or chemically etched.

3. *Downhole blowouts (simultaneous production and lost circulation).* This is a particularly difficult and costly problem to correct. It underscores the need for developing better wellbore lining and sealing technology for hostile conditions.

4. *Sealing unwanted flows.* It is sometimes difficult to seal unwanted flows from entering the wellbore. This is especially true of flows that become undesirable over time due to declining temperature or increasing corrosivity, because the option of casing through the zone is not usually viable after the drill rig is moved off-site. Alternative wellbore lining and sealing technologies that could be deployed with workover rigs as well as drill rigs would be helpful.

5. *Reduction in hole size due to the need for multiple casing strings.* See previous discussion under Maintenance of Borehole Stability and Fluid Containment section.

Feasible Alternative Methods

The feasible alternative methods recommended by the workshop participants were previously discussed under the Borehole Stabilization and Fluid Containment section. These methods are listed again below for completeness.

1. *Advanced wellbore lining techniques for achieving inflow sealing.* These are essentially the same methods previously discussed for borehole stabilization and fluid containment within the wellbore. In this case, however, the emphasis is on sealing fluids against *entering* the wellbore, rather than leaving it. Any viable wellbore lining method must effectively seal against both fluid inflows and outflows.

2. *Improved underbalanced drilling techniques.* See previous discussion under Borehole Stabilization and Fluid Containment section.

3. *Removable production-zone plugs.* See previous discussion under Borehole Stabilization and Fluid Containment section.

Permanent Borehole Preservation

Conventional Methods

1. *Casing joined and installed from the surface.* Although carbon-steel casing is normally used, high-alloy metallic casing and liners, such as titanium, and cement-lined casing and liners are sometimes used to reduce corrosion and scaling. Casing sections are normally screwed or welded together as the casing is installed into the well with the drill rig. The drill rig is often sized according to the weight of the casing it must hang in the hole.

2. *Production liners in the producing zones.* Slotted or perforated liners are usually used. Downhole perforation is usually not economical due to the large number of perforations that would be required over the long production intervals often found. Production screens and gravel packs are also used in completing geothermal wells.

Common Problems

1. *Casing cementing problems.* It is imperative that the full length of a casing string be cemented to the wellbore wall because of thermal expansion and possible buckling if the casing is not fully supported. Yet this is not always easy to achieve because of: (i) lost circulation zones, which steal cement as well as drilling fluid and can require costly top-cement jobs and perf-and-squeeze operations to correct; and (ii) failure of casing stage collars at high temperatures, which can also require costly remedial cementing operations in order to recover the use of the well.

2. *Liner insertion problems.* It is not uncommon for debris and unstable wellbore walls to prevent easy installation of a liner after the drillstring has been removed. If a slotted liner is installed in a production interval without removing the debris, it is likely to clog the liner slots and reduce wellbore productivity. "Hot lining", or installing a slotted liner in the production interval while allowing the well to produce slightly to clear out the debris, has been accomplished successfully in some fields to maximize wellbore productivity. It is, however, a hazardous operation for drilling crew members on the rig floor because of the flowing steam at the wellhead and the increased risk of an uncontrolled steam kick or blowout.

3. *Casing, liner, and wellhead corrosion.* Corrosion of the tubulars in a geothermal well is often a problem. Casing corrosion limits the useful life of a well and necessitates assessment of the tradeoff between higher-cost, corrosion-resistant casing materials and more frequent replacement of the well. New approaches for analyzing and dealing with casing corrosion are needed.

4. *Large rig size required to run conventional steel casing.* Because of the extreme weight of conventional steel casing used in geothermal wells, very large drill rigs are generally required to run it. Such rigs have high site-preparation, mobilization, and operating costs. Casing alternatives that lead to reduced casing weight would reduce these costs.

Feasible Alternative Methods

The following alternatives were considered to be worth further investigation for their cost-saving potential in completing geothermal wells:

1. *Advanced wellbore lining techniques for permanent borehole preservation.* These are essentially the same methods previously discussed for borehole stabilization and fluid containment within the wellbore. In this case, however, the emphasis is on *long-term*, permanent preservation of the wellbore rather than temporary lining. Some of the concepts discussed are more suited to one application or the other. One requirement for long-term casing that may not be applicable to temporary lining is the requirement for effectively sealing the casing/liner to the wellbore wall and preventing annular groundwater flows. See the previous description for examples of the alternative ideas discussed at the workshop. The idea of emplacing an expandable slotted liner in an underreamed production zone was of significant interest at the workshop.

2. *Cement-lined casing.* Cement-lined pipes are used in several applications where corrosive fluids are handled, including surface pipelines in geothermal fields. Cement-lined casing has a good potential for mitigating casing corrosion costs, but past attempts failed at the pipe joints. A design that employs joint seals or some method for lining the casing in place was considered worth investigating. Methods for repairing cracked or chipped cement lining may also be needed.

3. *Alternative casing materials.* Composite casing materials could have a distinct weight advantage over steel casing if they could be proven capable of the severe service required. Polymer-, epoxy-, or metallic-coated casing materials may also have potential for corrosion resistance.

4. *Casing-while-drilling.* This concept is attractive where borehole wall stability is a problem. It was discussed previously for the case where a retractable bit would be used on the lower end of conventional steel casing. Another concept considered worthy of study was an extruded or formed-in-place, non-metallic casing that would be installed directly behind the bit. Again, the economics of such a system almost dictate that significantly degraded drilling performance could not be tolerated if it is to compete with conventional drilling and casing techniques.

5. *Improved methods of emplacing production liners.* Alternative techniques for washing or drilling liners into place in the production interval are needed. Several potential methods were discussed, including the Baker duplex shoe, a method devised by Louis Capuano, and schemes similar to casing-while-drilling concepts. Underreaming bits may also be useful for this application. Robotics systems to safely perform "hot lining" of geothermal wells may be worth developing.

6. *Latex and other advanced cements for corrosive environments.* New cements are needed for conventional and advanced wellbore casing operations in highly corrosive wells. Conventional Portland cement degrades severely under such conditions, leading

to accelerated corrosion of the casing itself and annular fluid flows between permeable zones. Latex and other corrosion-resistant cements, such as Brookhaven National Laboratory's CO_2-resistant cement, should be further developed and tested in these applications.

7. *Robotics system for running hot liners.* A need exists for an automated pipe handling system for installing slotted liners while slightly producing a geothermal well. Such a system would allow the well to be safely cleaned out while installing the liner, thereby maximizing productivity of the well.

Sensing, Communication, and Process Control

Conventional Methods

1. *Conventional rig instrumentation.* This refers to surface instrumentation transducers commonly employed in geothermal drilling, including those for measuring: weight-on-bit (WOB); rotary speed (RPM); rotary torque; kelley height; mud inflow (pump-stroke counters); mud outflow (paddlemeter); standpipe pressure; inflow/outflow temperatures; and mud pit levels. This information is used by the driller, drilling engineer, and geologist to control the drilling process and infer downhole conditions from the data.

2. *Well logging tools.* The well logging tools commonly used in geothermal drilling include directional surveys (e.g., single-shot surveys) as well as pressure/temperature/spinner (PTS), sonic, gamma ray, formation microscan imaging, and borehole televiewer logs. This information is used by the driller to directionally orient the well and by the geologist and reservoir engineer to evaluate the geothermal resource.

3. *Drilling by "feel".* The driller uses the senses of sight, hearing, and touch to gather continuous data on the status of the drilling process. A good driller utilizes this information to adjust drilling parameters and optimize performance. Improving the training and real-time information available to the driller are vital to the goal of reducing geothermal drilling costs.

Common Problems

1. *Temperature limitations on downhole instrumentation.* The entire suite of downhole information gathering and transmission systems available to the oil and gas drilling industry are of limited use in geothermal drilling because of temperature limitations. Commercial MWD/LWD systems employ electronics that do not survive downhole soak temperatures encountered in the deeper portions of geothermal wells during drilling. Even higher temperatures are encountered when the well is producing geothermal fluid; thus logging tools and wirelines available in oil and gas drilling are not applicable to geothermal logging without costly temperature hardening.

2. *Data-rate limitations of existing telemetry methods.* Current mud-pulse telemetry methods for commercial MWD systems are capable of baud rates of only about 10 bits/second. This severely limits the amount of data that can be transferred back and forth. If the transmission rate could be increased significantly, real-time data such as downhole accelerations could be acquired to help optimize and smooth the drilling process.

3. *Unreliability of surface instrumentation.* Rig instrumentation is generally rugged and reliable, but it is not always very accurate. This is particularly true of the inflow and outflow meters used by the industry. Pump-stroke counters measure the pumping rate but not necessarily the drilling fluid flow rate, because of uncertainties in the pump efficiency. Paddlemeters are notorious for providing only a very a rough indication of

drilling fluid outflow rates. Improved flow rate measurements are needed in order to optimize the drilling process and to detect and quantify problems such as lost circulation and steam kicks. Software to help analyze incoming rig data in real time would also be extremely helpful.

Feasible Alternative Methods

The workshop participants enthusiastically acknowledged the advantages of improved data gathering and process control in geothermal drilling. The following technologies should be evaluated:

1. *Temperature-hardened logging tools.* There is a great need to continue development work to increase the temperature capabilities of well logging tools. One successful approach taken by Sandia and others has been to develop dewared (heat-shielded) memory logging tools that do not require electrically-conducting wirelines. Such tools can be run on lower-cost and more corrosion-resistant "slicklines" available on most drill rigs. Sandia has developed and is working to commercialize four memory logging tools that operate to 400°C for up to 10 hours: a PTS tools (in cooperation with Pruett Industries); a spectral gamma tool; a downhole steam sampler (in cooperation with Unocal and Thermochem); and a core-tube data logger (in cooperation with Tonto Drilling and Boart Longyear).

   Sandia is also investigating the feasibility of designing logging tools with electronic components based on a new high-temperature silicon-on-insulator chip technology that is expected to become commercially available within the next 2 years. This technology, originally developed for weapons applications, has the potential for creating logging tools that would function to 300°C unshielded. Sandia is also evaluating the use of thermal batteries, which operate at temperatures exceeding 300°C, for high-temperature logging applications.

2. *High-temperature MWD/LWD systems.* Although MWD systems are not widely used in geothermal drilling today, it was the general consensus of the workshop participants that increased use of MWD would help reduce geothermal drilling costs. One concept that had appeal was a "poor-man's" MWD system that is reliable, cheap, fast, and dumb, meaning that is collects and transmits data at a high rate to the surface, so that the analysis can be done uphole instead of downhole. This contrasts with high-cost systems where data analysis must be done downhole because data transmission is too slow to send anything but analyzed results to the surface.

   As a first step along the path toward achieving such a system, a temperature-hardened mud-pulse telemetry system should be examined. The market for such a system, however, should be determined before significant effort is made on temperature hardening any one package. Other improvements that would make the system more geothermal specific may need to be addressed first.

   For example, increasing the transmission speed of an MWD system should be a top priority. Advanced mud pulse, short-hop electromagnetic, acoustic, and electrical systems have all been or are still being studied. If higher transmission rates become available, the ability to transmit real-time data to and from multiple downhole transducers and controllers could significantly improve drilling equipment and practices. For example, real-time downhole acceleration data could allow the driller to adjust WOB and RPM to reduce bit vibrations and improve hard-rock drilling capabilities and bit life.

Advanced drilling sensors of interest in geothermal drilling include: downhole accelerometers, navigational/directional sensors, bit and annular pressure transducers, and temperature probes inside and outside the drillstring, in bit bearings, and in drag cutters. Knowing the bit pressure drop, annular fluid level, borehole direction, and bit accelerations and temperatures would help the driller achieve levels of system performance not currently attainable.

Other advanced sensors that qualify more as LWD components include: near-bit imaging, near-bit seismic, and other fracture detection and geological characterization sensors. Such sensors could be incorporated into an MWD system or deployed as a wireline-deployable package periodically during drilling, perhaps down the drillstring.

Advanced software is also needed to interpret incoming downhole data in real time. Rapid analysis of data will allow the geologist and the driller to optimize the well to maximize the resources it accesses.

The Morgantown Energy Technology Center (METC) of DOE has recently issued a solicitation for projects to develop high-temperature MWD systems, primarily for oil and gas drilling. Because of its applicability to geothermal drilling, Sandia has offered to assist the funded companies in their development and testing efforts.

3. *Advanced rig instrumentation and software.* Improved rig instrumentation is needed to increase the accuracy of certain parameter measurements. Inflow and outflow rates, in particular, are extremely useful parameters to know accurately, yet they are difficult to accurately measure for a variety of reasons. Sandia has been working on this problem for several years, developing a rolling float meter for outflow measurements and evaluating a commercial Doppler flow meter (made by Peek Measurements) for inflow rate measurements. These projects are almost completed, with commercialization hopefully near.

   The myriad of rig instrumentation sensors typically sending data to the driller and drilling engineer is already almost too complex. An abnormal reading in one or more of the many readings displayed on the video screen at the driller's station and in the drilling engineer's office is not unusual. It is often difficult to ascertain what is happening on the rig and in the hole based on the displayed data. Expert system software that analyzes the data and helps in its interpretation would be extremely useful.

   Such an expert system is under development as a GDO project at Tracor, Inc., under contract to Sandia. Tracor is developing a neural-net model that organizes the incoming data, analyzes the probability of several possible events, and determines the most probable status of the drilling process. The system is robust in that it is capable of detecting probable transducer and other measurement errors and displaying conclusions about the drilling process with a high degree of confidence. For example, using inflow- and outflow-rate measurements along with other rig parameters, the system is able to determine whether an abnormal hydraulic condition is caused by lost circulation, a steam kick, pumping problems, or transducer error. The system will be expanded to include early detection and analysis of other rig parameters and problems such as impending stuck pipe, bit failure, and drillstring twistoffs.

Advanced software, in general, should be further developed and utilized in geothermal drilling. Because of the small market, it is not reasonable to expect that sophisticated geothermal drilling software that can fully utilize the computing power of modern desktop PCs will be developed solely with private funding. Maurer Engineering, Inc., with funding from several DEA-member companies, has developed an integrated suite of drilling software modules for oil and gas wells that have significant cost-saving benefits when used properly. Modifying those software modules for geothermal drilling and implementing their use throughout the industry could help reduce geothermal well costs significantly.

4. *Better target definition.* It was noted that improved definition of the target for a directional hole could save considerable costs, particularly if tolerances were better defined. A wider range of options for reaching the target could then be considered and, with better drilling engineering software, minimum-cost well designs and trajectories could be found.

Directional Drilling and Control

Conventional Methods

1. *Standard rotary tools with a whipstock.* Whipstocks are in-hole anchors that allow a well to be "kicked-off" in a certain direction to sidetrack hardware stuck in the hole or to drill a lateral leg in an existing hole. Smith Drilling and Completions has recently completed a GDO project to develop a retrievable whipstock for geothermal wells.

2. *Mud motor with a bent sub or bent housing.* The standard technique for drilling the directional part of the hole, i.e., the portion of the hole where it turns, is with a bent sub or motor housing that cocks the bit in a selectable direction and a motor below the bend that rotates the bit to drill.

3. *Specific bottom-hole-assembly (BHA) designs.* The design of the bottomhole assembly can be varied relative to factors such as stabilizer placement, drill collar size, and length, to make the bit "walk" right or left, up or down, or to maintain a straight trajectory.

4. *Directional measurement, typically done with single-shot surveys taken with a tool deployed down the drillstring.* Conventional steering tools that employ electronic components are always at risk of thermal damage in geothermal wells.

Common Problems

1. *Cost and difficulty of setting hole direction.* Directional drilling is a highly specialized service. Most of the bits and tools for directional drilling were developed for the oil and gas industry, where the average rock is softer. In hard-rock drilling, it is often difficult and costly (in terms of time spent) to achieve the direction desired.

2. *Cost and difficulty of controlling deviation and maintaining intended direction.* Hard-rock drilling requires high weight-on-bit. A high bit weight typically causes the bit to deviate from drilling a straight hole unless proper attention is given to BHA design.

3. *Temperature limitations on downhole motors.* These limitations (see previous discussion) limit the ability to turn the hole at depth, so most directional work is done in the upper sections of the hole.

Feasible Alternative Methods

The workshop participants identified the following technology areas needing work to improve directional drilling and control:

1. *High-temperature downhole motors.* Improving the temperature capability of downhole motors above the current 200°C would allow directional drilling to be done lower in the well, thereby increasing the flexibility of well design and resource access.

See the previous discussion of high-temperature downhole fluid and electric motors in the above section on Downhole Energy Transfer.

2. *High-temperature variable-angle bent sub.* A variable-angle bent sub that could operate at higher temperatures than currently available tools would be useful in drilling multi-lateral wells, particularly in the lower sections of a well.

3. *Directional thrusters/retractors/directors.* It was the consensus of workshop participants that an effective thruster/retractor/director would be needed in geothermal drilling only if high-angle wells were to be drilled with coiled tubing. Technology development in this area will occur for horizontal drilling in the oil and gas industry, and temperature hardening for geothermal conditions could follow if the practice demonstrates significant potential for geothermal drilling. Consensus was not reached, however, on the need for horizontal or even ultra-high-angle drilling in geothermal fields.

4. *Steerable percussion hammer.* The feasibility of steering a well with a steerable percussion hammer was considered possible given the mechanics of the percussive drilling process. The feasibility, however, first depends on developing a reliable percussive hammer for geothermal conditions. See the discussion on percussive hammers and bits under the Rock Reduction and Downhole Energy Transfer sections.

Production Stimulation

Conventional Methods

1. *Drill another well.* When insufficient production is achieved after drilling a geothermal well, the only feasible alternative in most cases is to drill another well. Make-up wells are often drilled to augment the production of existing wells after a field has declined in productivity.

2. *Re-drill portion or extend well.* In some cases, the lower portion of a non-productive well can be re-drilled or deepened to reach a different, more permeable or higher-temperature fracture.

3. *Multi-leg or forked completion.* The productivity of a given well can often be enhanced by drilling multiple productive legs from the same wellhead. This is commonly referred to as a crow's-foot, multi-lateral, multi-leg, forked, or branched completion.

4. *Fracture stimulation.* Fracture stimulation includes acid stimulation, massive hydraulic fracturing, and gas fracturing. These methods of enhancing well productivity are more commonly used in oil and gas reservoirs rather than geothermal reservoirs. This is because of the difference in permeability scales between the two types of well. Matrix permeabilities in oil and gas formations are typically several hundred *millidarcies*, while fracture permeabilities are often several hundred *darcies* in successful geothermal fields. Acid stimulation is the most common type of treatment performed in geothermal wells, primarily as a way to help restore damaged permeability.

Common Problems

1. *Conventional stimulation methods are costly and often ineffective in geothermal wells.* A basic problem is that a stimulated hydraulic fracture is likely to run parallel to the most permeable natural fracture set in the reservoir. Unless a significant natural fracture is intersected by the stimulated fracture, increasing the well's effective permeability by several hundred darcies is not probable. Even if the current formation stress state is such that intersecting natural fractures is possible, it is still costly to create the frac-fluid flow rates necessary to achieve new permeabilities of that magnitude. Gas fracturing has typically not produced the fracture lengths required to connect with surrounding fracture systems in geothermal formations. Acid stimulations are often effective in removing drilling mud from producing fractures, but typical geothermal rock types are not very susceptible to acid etching. Consequently, acid treatments do not generally create new permeability where none previously existed.

2. *Temperature limitations on downhole motors.* These limitations impair the ability to drill multiple legs in a well at depth (see previous discussion).

3. *Temperature limitations on perforators.* The explosives or charges used in casing perforators do not operate predictably at temperatures encountered in geothermal wells. Premature detonation is often experienced. Consequently, this method of connecting the wellbore with a permeable zone that is behind the casing is not reliable in high-temperature geothermal wells.

Feasible Alternative Methods

The following methods were considered to be potentially feasible alternatives for stimulating geothermal well production:

1. *Wellbore designs that maximize flow from the reservoir.* Geothermal wellbore flow models need to be further developed and verified so they can be used to design wellbores to achieve maximum flow from the reservoir. The optimal diameter at any given depth depends on the thermodynamic characteristics and permeability of the reservoir. Improved wellbore design could improve well productivity and reduce costs in many cases.

2. *Advanced fracture stimulation methods.* An extensive field testing program was sponsored by DOE in the late 1970s to evaluate several types of fracture stimulation treatments in geothermal wells. The tests were largely unsuccessful in making good producers out of dry holes, but there was evidence of improvement in some marginal producers. Given the advancements in fracture stimulation technology in the past 20 years, it may be time to re-examine the potential for using some such technique to improve geothermal well productivity.

3. *High-temperature downhole motors for multi-leg completions.* Improving the temperature capability of downhole motors above the current 200°C would allow multi-leg completions to be done lower in the well, thereby improving the well productivity. See the previous discussion of high-temperature downhole fluid and electric motors in the above section on Downhole Energy Transfer.

4. *Hard-rock underreaming.* Underreaming the production interval of a geothermal well could significantly increase or regain its productivity by increasing wellbore diameter and removing scale or drilling fluid damage from the near-wellbore region. See the previous discussion under the Rock Reduction section.

5. *High-temperature perforators.* Improving the temperature capability of perforators would make this option available for more geothermal conditions, allowing more flexibility in perf-and-squeeze operations for casing repair and for placement of casing perforations in production zones.

6. *Thermal-shock fracturing with cold water.* It may be possible to increase near-wellbore permeability by flooding the wellbore with cold water and thermally shocking the surrounding rock formation. If the thermal-shock stresses are sufficient to fracture the rock, increased permeability may result, but the fractures may also tend to remain

closed. Previous field tests of this method indicated some promise, and the technique should be further evaluated.

Well Maintenance and Workover

Conventional Methods

1. *Scale prevention with chemical additives.* Chemicals are often pumped downhole to inhibit scale formation in the upper portions of a geothermal well.

2. *Scale removal.* Geothermal fluids are often high in total dissolved content (up to 250,000 parts per million in the Salton Sea geothermal field). Scale removal is often part of the routine workover that is done to geothermal wells in certain fields. Scale can be removed with a drill bit on a workover rig, high-pressure waterjets, and/or an acid treatment. A flowing cleanout is sometimes done, where the well production is maintained while the scale is removed. This prevents the scale debris from remaining in the wellbore or getting into the production zone.

3. *Casing and liner repair.* Damage to the casing can sometimes occur during workover operations to remove scale. Corrosion of the casing may also lead to a need to repair it. Perf-and-squeeze cement treatments are used where possible to repair casing cement jobs. Scale removal is the primary type of repair needed in production liners. This can be done in place, though drilling damage is more of a risk in liners than in casing. Liners can sometimes be removed from the wellbore to facilitate cleaning, repair, or replacement.

Common Problems

1. *Scale removal, casing repair, and other workover procedures are costly.* More cost-effective well maintenance technology is needed.

2. *Workover drilling with air to protect the production zone accelerates casing and drill pipe corrosion.* New technology is needed for inert gas drilling.

3. *Thermal cycling of the well to conduct workover operations is sometimes detrimental to the stability and productivity of the well.*

4. *Chemical scale inhibitors and removers exist for calcium scales but not for silica scales.*

Feasible Alternative Methods

The following methods were considered to be worth studying for use in geothermal well maintenance and workover:

1. *Ultrasonic scale removal.* This concept is similar to that used in other ultrasonic cleaning tools. High-frequency sound waves traveling in the fluid bounce off the surface to be cleaned, creating cavitation bubbles that scavenge the surface. GRI reportedly funded the development of a prototype tool for this application. The potential of this concept in geothermal well scale removal should be explored.

2. *Electromagnetic scale control/removal.* Scale control using electromagnetics is a concept that is currently highly touted in the plumbing industry. The concept should be explored to determine its validity and its applicability to scale control in geothermal wells.

3. *Tornado frac to rubblize scale.* The 70-grain tornado frac is a tool that essentially sets off a series of small explosions downhole to break up the scale for removal. This could be effective in geothermal wells, though some concern exists about its effect on the casing-cement bond.

4. *Chemical additives to reduce silica scaling.* Chemical scale inhibitors and removers for silica scales would be useful if the cost were reasonable.

V. Continuing the Process

The recommendations of the Workshop on Advanced Geothermal Drilling Systems represent the first step in an ongoing process to define and implement a new DOE program to develop advanced geothermal drilling technology. The following steps outline the approach that will be used in this process:

1. *Geothermal Energy Association endorsement.* These recommendations will be submitted to the GEA for endorsement. This trade group represents the U.S. geothermal industry, and its endorsement of these recommendations would lend additional credence to their validity.

2. *Evaluation of the state of the art of the recommended technologies.* The recommendations of this workshop will be evaluated by Sandia to determine the state of the art in each technology area. Based on the results of this survey, an approach to developing and implementing the recommended technologies will be formulated.

3. *Analysis of cost-reduction potentials.* The potential for reducing geothermal well costs by implementing the recommended technologies will be examined by Sandia using a well-cost model for typical geothermal wells. Because workshop participants concluded that a different model well design probably exists for each geothermal reservoir encountered, several well-cost models may be needed to fully evaluate the cost-saving potentials of the various technologies. Only those technologies that have a significant cost-saving potential will be further evaluated.

4. *Development of component and system specifications.* For each recommended cost-saving technology, Sandia will develop specifications for drilling components and systems that can be used to solicit proposals for developing the related technologies. Required dimensions, methods of operation, environmental constraints, and performance criteria will be specified for each component or system.

5. *DOE solicitation of proposals.* Based on the specifications developed above, the DOE Office of Geothermal Technologies will write and implement one or more solicitations for proposals to develop the recommended technologies. These solicitations will be targeted at U.S. industry, university, and other domestic R&D organizations. Proposals will be evaluated for their feasibility and potential for reducing geothermal well costs. Proposals will be funded in accordance with the budget available for advanced geothermal drilling research.

6. *Technology development and implementation.* Technology developed by the funded projects will be laboratory- and field-tested, and successful developments will be transferred to the U.S. geothermal industry. With DOE funding, Sandia will assist in the technology transfer process by providing laboratory and field testing assistance and by serving as an interface with the geothermal community where needed.

VI. Acknowledgments

The assistance of the workshop participants in addressing the important issues examined in this workshop is gratefully acknowledged. The assistance of Bill Livesay in documenting the workshop recommendations is also appreciated. Thanks to the following people for providing helpful comments on the draft report: Louis Capuano, Jim Combs, George Cooper, Bill Livesay, Ken Pierce, Mike Utt, Mark Walters, Jack Wise, and John Rowley.

This work was sponsored by the U.S. Department of Energy, Office of Geothermal Technologies. Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

Appendix

Brainstorming Ideas for Ultra-Advanced Geothermal Drilling

The following ideas were generated during a two-hour brainstorming session to consider ultra-advanced geothermal drilling systems. Where there was general approval or significant interest in an idea, it has been incorporated into the recommended technologies discussed in the body of this report. Many of these ideas have been studied in the past.

Rock "eating" system
Rock melters
Flame-jet drilling
Abrasive waterjet drilling
Chemical drill with encapsulated chemicals; drill and line simultaneously
Biological rock destruction
Projectile drilling
Vibration rock destruction
Sonic rock destruction with or without resonance
Laser drill
Laser-waterjet drill
E-beam drill
Plasma-waterjet drilling and coring
Ultra-high RPM, small depth-of-cut drills; with high-pressure downhole motors
Cryogenic drilling with mechanical assist
Explosive drilling
China-syndrome nuclear drill
Waterjet underreamer
Raise-boring underreaming
Large-diameter wireline coring
Hybrid rotary-coring drilling
- pilot drilling to identify problems
- core recovery
- coring with hole opening
- telescoping/nested core bits
- with lost circulation fixes along the way

Electro-potential bit protection
Coflexip-type drilling hose
Coiled tubing with field joining capability
Insulated, dual-wall coiled tubing for high-temperature workovers and slimhole drilling
Catalytic converter for inert gas drilling
Hydrostatic pressure reducer for enhanced drilling
Remotely-operated jet subs
Downhole pump for reverse circulation or dual-pipe drilling
Conventional drilling done right
Casing-while-drilling
- using foam/epoxy drilling fluid to form temporary lining and anti-stick pipe

  - using downhole chemicals sprayed on the wall
  - sealing with guar-gum sealing
  - sealing with hyper-thixotropic fluid

Continuous lining systems, temporary and permanent

Downhole power production
  - thermoelectric
  - US Army fuel cell
  - downhole steam conversion

Improved logistics

Improved training
  - DOE/GEA/GRC-sponsored
  - geothermal drilling simulator for rig hands and engineers
  - encourage some type of temporary employment services for geothermal drillers

Joint drilling research and development program with the Japanese through NEDO

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