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# POTENTIAL IMPACTS OF ARTIFICIAL INTELLIGENCE/EXPERT SYSTEMS ON GEOTHERMAL WELL DRILLING COSTS

#### FINAL REPORT

#### Prepared for:

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#### **ABSTRACT**

The Geothermal Research Program of the U.S. Department of Energy (DOE) has as one of its goals to reduce the cost of drilling geothermal wells by 25 To attain this goal, DOE continuously evaluates new technologies to determine their potential in contributing to the Program. One such technology is artificial intelligence (AI), a branch of computer science that, in recent years, has begun to impact the marketplace in a number of fields. Two subsets of AI with potential application to geothermal drilling are expert systems and intelligent machines. Expert systems techniques can (and in some cases, already have) been applied to develop computer-based "advisors" to assist drilling personnel in areas such as designing mud systems, casing plans, and cement programs, optimizing drill bit selection and bottom hole assembly (BHA) design, and alleviating lost circulation, stuck pipe, fishing, and cement Intelligent machines with sensor and/or robotics directly linked to AI systems, have potential applications in areas of bit control, rig hydraulics, pipe handling, and pipe inspection. Using a well costing spreadsheet, the potential savings that could be attributed to each of these systems was calculated for three base cases: a dry steam well at The Geysers, a medium-depth Imperial Valley well, and a deep Imperial Valley well. The calculations incorporated costs associated with drilling problems, and assumed that each AI system evaluated would succeed in attaining specific efficiency goals. Based on the average potential savings to be realized, expert systems for handling lost circulation problems and for BHA design are the most likely to produce significant results. Other expert systems, specifically for bit optimization and mud design, would also yield significant savings but will likely be available (or already are) from the oil and gas drilling industry. Effort should concentrate on extending these existing systems to geothermal applications. Automated bit control and rig hydraulics also exhibit high potential savings, but these savings are extremely sensitive to the assumptions of improved drilling efficiency and the cost of these systems at the rig.

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#### CHAPTER 1: INTRODUCTION

#### 1.1 Rationale and Objectives

Expanded use of this nation's vast geothermal resources will depend on the resolution of technical problems in exploiting this resource and its cost competitiveness with other fuel types. Existing geothermal system costs compare favorably with conventional energy systems, however, the cost of extracting geothermal energy from harsher, more remote, or deeper resources precludes its full-scale development in today's market. Reducing these development costs would have a major impact on the magnitude of geothermal energy use.

A major cost component for geothermal energy is the cost to drill and complete wells for extracting the hot brines. The U.S. Department of Energy, Geothermal Technology Division (DOE/GTD) considers drilling and completion research to be a high priority and conducts related R&D efforts through its Hard Rock Penetration Research activity. As part of its strategic R&D program planning process, GTD continually evaluates the potential of new R&D areas in geothermal research. One such area is the field of artificial intelligence (AI).

The pace of development and application of AI systems in industry has accelerated greatly in the past few years. At the present time, intensive R&D is underway in the U.S. oil and gas industry to adapt and utilize AI technology in well drilling and completion (Weeden, 1987). Successful development and application of such systems could significantly enhance the economics of well drilling operations by reducing down-time, increasing the safety of the drilling operations, and optimizing the drilling and production design of wells. The benefits of the R&D would also be directly applicable to

geothermal resource development, where well drilling, in some cases, can account for over half of total power plant costs (Brówn and others, 1981)

The overall goal of this report is to provide DOE program planners with the information and data they need to determine the appropriateness of DOE R&D funding of AI research pertaining to geothermal drilling, and to focus this research in the areas where the greatest benefit can be realized. It is hoped that this report will also be useful to the private sector: both to AI system developers seeking new applications and potential markets, and to the drilling industry in its efforts to cut costs and increase efficiency.

The objective of this study is to identify and assess the specific aspects of geothermal drilling and completion that could be impacted by AI technology and to determine the extent of this impact in economic terms. The need for quantitatively estimating economic impacts is founded in the goal of GTD's drilling research effort: to achieve a 25 percent reduction in hydrothermal drilling costs through R&D (U.S. DOE, 1987). The results presented in this report allow DOE to assess whether research in the area of AI for geothermal drilling is appropriate in terms of its research mandate.

#### 1.2 Definitions and Scope

#### 1.2.1 Artificial Intelligence

The problem of explicitly defining AI has plagued researchers in the field since the term "artificial intelligence" was first coined in 1956 (Kurzweil, 1985). One fairly well-known definition is that a computer exhibits artificial intelligence if it exhibits characteristics normally associated with human behavior (e.g., understanding, language, learning, reasoning, problem solving, etc.) (Barr and Feigenbaum, 1981). The problem with this definition is that it presents a "moving target." As computers become more and more commonplace, the domain of typical computer tasks

increases in the public perception. What might have been considered "intelligent" behavior 20 years ago may be considered commonplace for today's computers. For the purposes of this study, artificial intelligence will be loosely defined as a computer application that exhibits at least three of the five following qualities.

- o The program, without explicit human intervention, can compare many alternatives and select an optimal path.
- o The program can identify when it has insufficient information and can then attempt to obtain more complete data, either by querying the user or through direct sensor input.
- o The program can handle uncertain, approximate, or missing data and still make a choice, perhaps qualified by a "certainty factor."
- o The program can "learn," i.e., information and experience gained in one application can be applied to future applications.
- o The program is written using generally recognized AI or expert system programming languages or techniques.

The field of AI can be subdivided into numerous topics. The two groups most likely to have application in the geothermal drilling process are expert systems and intelligent machines.

#### 1.2.2 Expert Systems

Based on early studies of AI, it was determined that it was not possible to build a machine that could universally solve any problem based on general knowledge and reasoning principles (Teknowledge, 1984). Studies began to focus on the way humans approached and solved specific problems, resulting in the concept of an expert system: a system whose knowledge and intelligence are restricted to a single, narrowly defined subject.

Expert systems are computer programs designed to make decisions or solve problems much in the same way that a human expert would. The knowledge, methods, and heuristics ("rules of thumb") that a human expert uses to approach and solve problems are built into a computer program, called an

expert system. The expert system is thus an intermediary between a human expert who places information in the system and the human user who consults it for assistance in making decisions based on that information.

An in-depth discussion of expert systems is beyond the scope of this report. The basic principles and components of expert systems are summarized here; for more detailed information, the reader should consult one of the numerous available texts dedicated to the subject.

There are three key issues in designing and building an expert system: knowledge representation, inference, and control.

#### **Knowledge Representation**

As a basis for its operation, an expert system must have a knowledge base. The knowledge base incorporates general knowledge about the specific topic for which the expert system is designed as well as heuristics that are used to generate new knowledge and solve a problem. The knowledge in an expert system is stored symbolically; meanings are assigned to symbols (much the way that humans assign meanings to words, which are spoken or written symbols) and to relationships between symbols. Three principal ways of knowledge representation in an expert system are logic-based, rule-based, or frame-based.

Logic based systems use formal logical principles to define the relationships available between symbols. Rule-based systems are similar to logic-based systems and they are composed entirely of if-then statements. The individual rules can also be assigned a measure of probability or certainty of being true. Frame-based systems associate a number of attributes with each object, and all of the objects represented in the system fit the same type of frame. Of these three types of knowledge representation, rule-based is the most commonly used in expert systems.

#### Inference

Inference is the mechanism that the computer uses to derive new information from existing information. The part of the computer program that performs this function is called the "inference engine." Two typical inference mechanisms are modus ponens and inheritance. Given the two statements, "if A then B" and "A is true," modus ponens allows the deduction that "B is true." Inheritance uses the concept of classification, where each level in a classification possesses certain qualities. Any item contained in the classification then also "inherits" the qualities of the higher level objects to which it is associated. As an example, given that "all A's are B's" and "C is a B," inheritance allows the deduction that "C is also an A."

#### Control

Control is the automated direction of the search strategy to rapidly arrive at the conclusion for a specific problem. The two categories of control methods are goal-directed and data-directed. In goal-directed reasoning, a likely solution is hypothesized and further evidence is sought to support or deny this hypothesis. The additional evidence may come from facts, derived facts, or further interrogation of the system user by the program. The use of goal-directed reasoning with rule-based systems and modus ponens inference is referred to as a backward-chaining system. This is most applicable in situations where there is a finite and relatively restricted set of possible outcomes.

Data-directed control systems examine the patterns of facts and conditions and follow all possible solution paths that are warranted. As new information becomes available, certain paths may be eliminated, eventually resulting in a final recommendation(s). When combined with rule-based systems, these are known as forward-chaining. They are most useful where

occurrences of new facts are important in driving the system and where those facts must be considered as soon as they occur.

In selecting and designing control systems, important questions that need to be addressed are the choice of which potential solution is to be examined first, the point at which a line of reasoning should be abandoned, and whether solutions should be pursued in parallel or one at a time (Scown, 1985).

#### 1.2.3 Intelligent Machines

Intelligent machines is a field gaining widespread industrial and military application. Many authors, particularly in the AI industry, equate intelligent machines with robotics. However, devices widely known as robots exist in industry without the use of AI. The Robotics Institute of America, in 1979, defined an industrial robot as a "reprogrammable multifunction manipulator designed to move materials, parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks." Reprogrammable does not necessarily imply the use of AI.

In this study, we define intelligent machines as systems coupling AI directly to physical devices, including but not limited to sensors and/or robots. As such, the area of intelligent machines is an intersection of the two sets (robotics and AI) incorporating elements from both. Facets of AI that can apply to intelligent machines include symbolic reasoning, signal processing, and interpretation (including vision), and expert systems.

The design and use of intelligent machines is an active area of current research. Particular topics under investigation include: signal processing and interpretation, optimizing task planning and arm movement, dexterity and coordination, tactile sensing, dynamic control using force feedback, and the man-machine interface (Gevarter, 1985).

#### 1.2.4 Geothermal Drilling

Geothermal drilling is the process of constructing wells to tap the hot geothermal fluids trapped in underground reservoirs. The purpose of this brief section is to delimit the scope of the study by defining what is to be considered as part of the geothermal drilling process. Many aspects to the drilling process are described in detail in Chapters 2 and 3.

Consider drilling to be a black box as shown in Figure 1-1. Going into the box is specific information defining the well and funds to pay for it. This information does not limit how the well is to be drilled, but instead defines the well in terms of the desired result. Parameters included are:

- o Location
- o Depth
- o Drilling deviation and orientation
- o Type of well (exploration, production, injection, etc.)
- o Expected flow volumes

This information (along with the necessary funds) goes into the black box. Inside the black box is the equipment, manpower, and expertise to perform details such as specific well design, formulation of the drilling plan, and the actual drilling of the well. Coming out of the black box is a drilled well satisfying the initial specifications.

Some services, although excluded from the black box, are typically conducted during the drilling process, such as well logging and testing for reservoir evaluation. These processes, in effect, modify the inputs to the black box in midstream. Included in the black box is well logging done specifically to evaluate the drilling of the well (e.g., directional surveying) or to determine the mechanical competency of the well (e.g., cement bond logging).

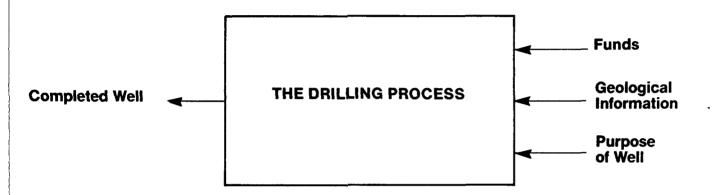


Figure 1-1
REPRESENTATION OF THE DRILLING PROCESS

#### 1.3 Methodology

The goal of this study is to determine the potential savings that could result from the development of AI applications in geothermal drilling. Having defined the scope of the study in the previous section in terms of AI and drilling, this section describes the methodology used to approach the problem.

- Characterize the U.S. geothermal drilling market. Review historical geothermal drilling activity in the U.S., and group past drilling activity by depth and geographic region. Project future drilling activity, based on anticipated power-on-line, to determine the areas of most significance in the near- and long-term. The value of new drilling technologies varies according to the particular drilling conditions at various sites, therefore it is more likely that new techniques would be developed if they have widespread application.
- explore the link between geothermal drilling and (the much more widespread) oil and gas drilling for potential implications in technology transfer. In some cases, it is possible that AI applications already existed in the oil and gas industry can be extended to geothermal drilling with minimal effort. Also, the commercialization and overall cost effectiveness of an AI application developed for geothermal drilling may be significantly enhanced by the existence of a huge potential market in the oil field.
- Review the geothermal drilling process to identify potential applications of artificial intelligence. Include all phases of the drilling operation, i.e., well design and planning, rig operation during trouble-free drilling, and the occurrence of drilling mishaps. Survey the current state-of-the-art in industry and any on-going research efforts.
- Evaluate the identified AI topic areas to estimate the potential cost savings in geothermal drilling that could be realized if the systems were developed and implemented. Define optimistic savings goals for the effect that the particular AI application could have on the geothermal drilling process. The following examples illustrate the types of goals included: (1) X percent increase in rate-of-penetration; (2) X percent reduction in occurrence of lost circulation problems; (3) X percent reduction in pipe tripping time; and (4) X percent reduction in time associated with solving stuck pipe problems. Also estimate the marginal cost to the field developer (where appropriate) of using each AI system.
- o Construct base case geothermal wells, including average cost allowances for drilling problems. Using a drilling costing spreadsheet, calculate the average cost of these wells. Apply estimated savings goals to the base case wells to estimate the impacts of AI R&D.

- o Rank AI applications based on potential impact. Conduct sensitivity analyses on R&D improvements. Select the most promising R&D applications given potential savings and the results of the sensitivity analysis.
- o For the selected applications, discuss the role of industry and DOE R&D, and recommend actions to be taken.

#### CHAPTER 2: DRILLING OVERVIEW

The purpose of this section is to give an overview of the process of drilling a geothermal well and to discuss the various facets of drilling costs. This discussion is primarily for the benefit of readers unfamiliar with geothermal drilling, and therefore is fairly general. Readers already familiar with geothermal drilling should proceed directly to Chapter 3.

#### 2.1 Overview of the Drilling Process

Geothermal drilling technology has evolved over the years from oil and gas drilling. Similar but unique techniques and equipment have been developed to handle the special conditions associated with geothermal drilling, such as:

- o Well design to allow for large flow volumes
- o Materials and sensors to survive high temperatures
- o Materials to resist highly corrosive brines

Drilling a geothermal well is accomplished with a drill bit at the end of a string of drill pipe. The bit is rotated either from the surface by turning the entire drill string or just above the bit using a downhole drilling motor. This rotation, coupled with weight applied to the bit, serves to crush or grind the rock at the bit face. Drilling fluid (mud or air) circulates down the center of the drill pipe and is ejected through jets in the bit. The fluid returns to the surface in the annulus between the drill pipe and the borehole wall, carrying with it the drill cutting from the bottom of the hole. Drilling fluid also serves to cool the drill bit and to pressurize the hole to prevent the intrusion of unwanted fluids.

A geothermal well is drilled in stages. Drilling proceeds with a particular size drill bit until a predetermined depth is reached. The drill string is then withdrawn and steel piping, called casing, is run into the

well. The annular space between the outside of the casing is then filled with cement; either circulated into place (like the drilling fluid) or poured in from the top of the annulus.

The cement and casing serve to: (1) prevent the borehole from caving in on the well in less-consolidated formations; (2) isolate various fluid-bearing zones penetrated by the well from one another; and (3) convey the geothermal fluids from the production zone to the surface. In geothermal wells in particular, the cement is critical in that it supports the casing against axial expansion and contraction caused by thermal cycling, which has been known to cause buckling in geothermal wells (Snyder, 1979).

After the casing is cemented in place, a smaller drill bit is selected and the well is deepened by drilling out the bottom of the casing. The completed well will be made up of a number of telescoping holes, the last of which is frequently not cased (Figure 2-1). The various casing strings and the purposes they serve are:

- o Conductor Casing: The conductor casing is a short string of large diameter pipe used to keep the top of the wellbore open and to act as a fluid return pipe for deeper drilling. It is usually 26 to 30 inches in diameter and 20 to 100 feet deep.
- o Surface Casing: The surface casing (typically 20 inches in diameter) is set inside the conductor casing from the surface to a depth in the range of 300 to 800 feet, depending on the local geology. Surface casing isolates the well from near-surface ground water zones and supports the hole against shallow, less-consolidated formations.
- o Intermediate Casing: The intermediate casing supplies added structural support and may be used to isolate and retain troublesome formations such as sloughing shales and over- or under-pressured zones. The casing is typically 13 3/8 inches in diameter and is set from the surface to 1800 to 2800 feet. Shallow geothermal wells may omit the intermediate string.
- o Production Casing: The bottom of the production casing is usually set just above the top of the production zone. In some areas, the casing is set to the bottom of the well, and production screens are used in the well opposite from the production zone. Sizes for production casing are typically 9-5/8 or 10-3/4 inches in diameter. The production casing may initially be set as a "liner" (i.e., not run all

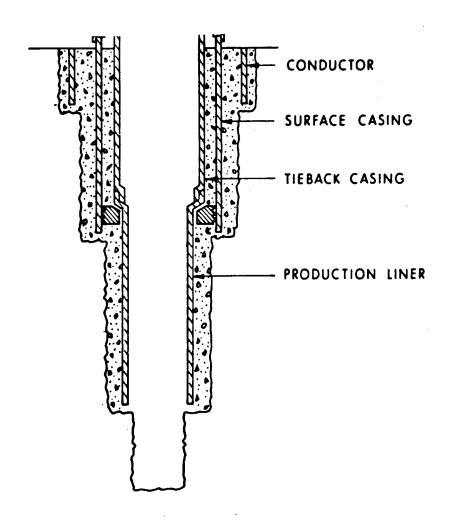


Figure 2-1 SCHEMATIC OF A TYPICAL GEOTHERMAL WELL

SOURCE: Nicholson and Snyder, 1982

the way to surface) and then later "tied back" to surface as illustrated in Figure 2-1.

The hole for the production casing (typically drilled with a 12-1/4 inch bit) may be drilled directionally if called for in the well plan. It may also be drilled with either air or mud, depending on the reservoir conditions. From the bottom of the production casing or liner, the well will be drilled into the production zone, either to a predetermined depth or until adequate fluid production is attained.

The drilling process does not run uninterrupted from surface to total depth (TD). Other than breaks to set and cement casing, there are many instances where the drilling process will halt during the normal course of operations, including:

- o Replacing worn drill bits
- o Conducting well logging operations
- o Reservoir testing
- o Rig maintenance

Furthermore, drilling may be halted by the occurrence of a drilling accident such as a well blowout, lost circulation, stuck drill pipe, or the loss of equipment in the well.

#### 2.2 Geothermal Drilling Costs

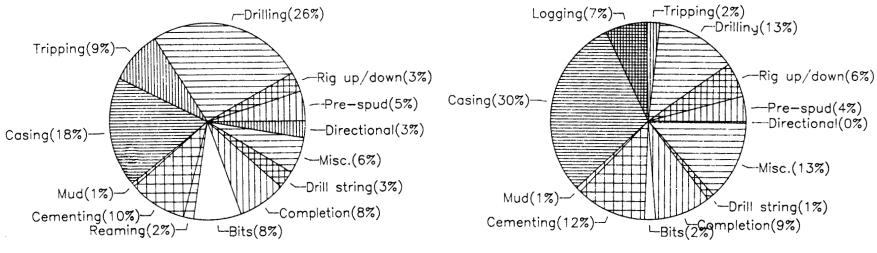
The cost of drilling a geothermal well can ultimately be attributed to three interrelated factors: time, equipment, and information.

The charge for using much of the equipment in well drilling is based on the amount of time it is used or on site; therefore the longer it takes to drill a well, the more it will cost. Factors that increase the amount of time it takes to drill a well include the depth and diameter of the well, special operations (well logs, well tests, coring), and the occurrence of drilling problems.

Equipment costs reflect those items that are bought and consumed during the drilling process. These items include drill bits, casing, fuel, cement, and completion and production hardware. Costs for this equipment depend on the amounts of equipment required and the extent to which the equipment must be "hardened" to resist high temperatures and hostile brines. Therefore, equipment costs will tend to rise with increasing depth, hostile conditions, and the frequency of drilling accidents.

Throughout the process of drilling a well, the geothermal operator (the company owning the well) incurs substantial charges for services provided by expert consultants and service companies. These services can be related to special operations such as well logging or testing, cementing, or for problem-related activities such as fishing or lost circulation. Essentially, the geothermal operator is paying for information, either in the form of expert advice or of measurements of well and formation parameters.

Determining accurate and up-to-date costs for geothermal drilling is a very difficult exercise. Historical data are often inaccurate and may not represent current practice. In addition, industry is reluctant to release cost information, which it considers highly proprietary. Costs of wells with government participation do not represent typical industry costs because of the scientific emphasis placed on the drilling operation. To circumvent this, Carson and others (1983) compiled detailed cost data for drilling materials and services and applied these costs to "typical" drilling scenarios to estimate overall well costs. Although the prices used in that study no longer apply, the distribution of costs has probably not changed significantly. Figure 2-2 shows the division of cost by source for trouble-free wells at The Geysers and for various fields within the Imperial Valley.



The Geysers-8000' Well



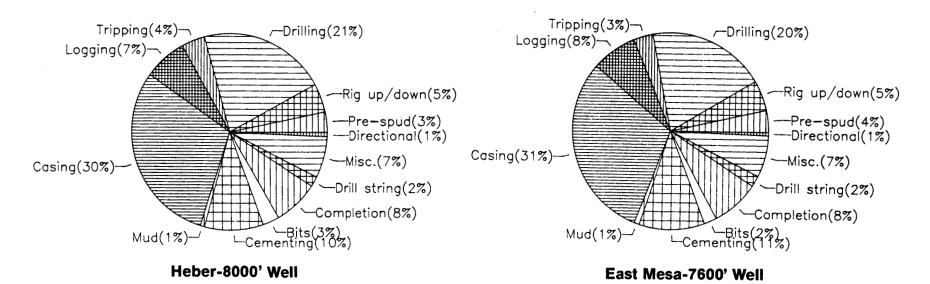


Figure 2-2
DRILLING COSTS BY ACTIVITY FOR FOUR GEOTHERMAL AREAS

SOURCE: Carson and others (1983)

#### CHAPTER 3: CHARACTERIZATION OF U.S. GEOTHERMAL DRILLING

#### 3.1 The Drilling Industries

Drilling for geothermal development has many ties to the other sectors of the drilling industry: oil and gas, water, mineral exploration, and scientific drilling. In particular:

- o Direct-use geothermal drilling, typically characterized by shallow depths and low to moderate temperatures, has much in common with water well drilling.
- o Drilling for geothermal electric power development is very similar to oil and gas drilling, except that it is characterized by a much more hostile environment.
- o Mineral exploration and scientific drilling can exhibit some of the typical characteristics of geothermal drilling -- abrasive rock formations and high temperatures (for deep scientific wells). These wells are often drilled to gather geologic and geophysical information and tend to be smaller in diameter and less susceptible to the economic constraints of geothermal wells.

This close relationship to other sectors of the drilling industry has had advantages and disadvantages for the geothermal industry. To its benefit, the technology base and extensive industry infrastructure have made geothermal drilling possible; without the existing drilling industries, it would have never been cost-effective or economic to develop a geothermal drilling capability. To its detriment, however, the geothermal industry is strongly overshadowed by the other types of drilling. Approximate magnitudes of the number of wells drilled per year are 500,000 water wells; 50,000 oil and gas wells; 5,000 mineral exploration wells, and 50 to 100 geothermal wells. Companies in oil and gas drilling often cannot justify development of specialized hardware and services needed to handle the hostile environment associated with geothermal reservoirs.

Table 3-1 provides approximate comparisons among the various drilling technologies. Of these, oil and gas drilling is the most important in

Drilling Technology	Wells/ Year (U.S.)	Depth (ft) Typical Range Maximum	Maximum Temp. (F)	Rig Types
Oil and Gas	50,000 <u>+</u>	2,000 to 20,000 30,000	400 <sup>0</sup>	Rotary, Turbodrill
Water	500,000 <u>+</u>	20 to 200 1,000	80°	Cable, Rotary
Geothermal	80 <u>+</u>	500 to 10,000 12,000	700 <sup>o</sup>	Rotary, Turbodrill
Mining	5,000 <u>+</u>	50 to 2,000 5,000	150°	Rotary, Coring
Scientific	<5	1,000 to 10,000 50,000	?	Rotary, Turbodrill, Coring

Table 3-1
COMPARISON OF DRILLING TECHNOLOGIES

ensuring the availability of the technology to drill geothermal wells. Water well drilling does not require the extent of high technology needed in oil and gas and hight-temperature geothermal drilling. Scientific drilling, while it may lead to the development of specific hardware applicable to geothermal wells, is not a generously funded area of drilling research at the present time. Drilling for mineral exploration, while often using sophisticated coring technology, is limited to shallow depths and low temperatures.

Drilling for high temperature geothermal resources uses much the same equipment, technology, and techniques as oil and gas drilling. Generally, the geothermal drilling service and supply industry is the same set of companies as the oil and gas drilling industry. This sector includes drilling contractors, mud and cement companies, drill bit manufacturers, tubuler suppliers, logging companies, etc. In addition, many of the key field developers in the geothermal industry are subsidiaries or divisions of large oil companies (e.g., Unocal, Chevron, Sante Fe, and formerly Phillips and Shell).

The high temperature, abrasive rock, and hostile brines result in a geothermal well being 2 to 4 times as expensive as an oil or gas well of comparable depth (Kelsey, 1982). Since drilling in some cases represents approximately 50 percent of the cost of building geothermal power plants (Brown and others, 1981), reducing drilling costs has been a major objective of research efforts, both in government and industry. Because of the overwhelming number of oil and gas wells drilled with respect to geothermal, and the fact that many of the key geothermal companies are also oil companies, applicable research is generally conducted by industry only when there is potential application for the technology in oil and gas drilling. Therefore, a key factor in this study is the belief that potential development of AI applications for geothermal drilling must always be considered in the context

of the oil and gas drilling industry.

#### 3.2 Geothermal Drilling Activity Overview

In this section, the history of geothermal drilling activity in the United States is reviewed from its earliest practice to the present time, leading to qualitative projections of future drilling activity. The background information illustrates the links between geothermal and the other drilling industry sectors, and shows the regional trends of drilling activity.

#### 3.2.1 Historical Overview

In 1892, the Boise (Idaho) Warm Springs Water District drilled two 400 foot wells to provide hot water for a geothermal district heating system (Trembley, 1979). These are probably the first wells drilled in the United States explicitly for geothermal development. Although available references do not describe the drilling technology used for these particular wells, it is likely they were drilled using cable tools, the prevalent technique at the time for water well drilling. Cable tool drilling is still widely used for direct-use wells today (Storey, 1974).

The first three known wells at The Geysers, California (1922 to 1924), were also drilled using a cable tool rig; the deepest reaching a depth of 318 feet. It soon became apparent that this technique was inadequate, since the "tools . . . were altogether too light, and impractical in other ways, for the volumes and pressures of steam encountered" (Siegfried, 1925). Five more wells were drilled at The Geysers from 1924 to 1926 using a rotary drilling rig. This rig was similar to those used for oil drilling at the time, modified slightly to control the steam pressure by circulating water in the borehole (Grant, 1927). The deepest of the early wells reached a depth of 640 feet. After the first eight wells, drilling at The Geysers was abandoned

until Magma Power Company drilled six successful geothermal steam wells in 1955.

Other areas drilled for geothermal energy in the early part of the twentieth century include Steamboat Springs, Nevada (1920s); the Salton Sea, California (1927); and Coso Hot Springs, California (1930s).

Nineteen fifty-five, the year Magma began drilling at The Geysers, can be considered the beginning of the modern period of geothermal drilling. By 1960, when the first 125 MW power plant came on-line at The Geysers, 11 wells had been drilled in the area (Stevovich, 1975). Other locations subject to exploratory drilling during this time were the Salton Sea (including an oil wildcat in 1957) and Casa Diablo (in western Long Valley) in California; and Brady Hot Springs and Beowawe in Nevada.

Nationwide, detailed geothermal drilling statistics prior to 1973 have not been published, although Stevovich (1975) reports that by 1970, over 200 wells had been drilled in the United States exploring for geothermal energy; 75 of these at The Geysers. It is likely that the balance of the 200 wells includes many shallow thermal gradient and scientific holes, which would not necessarily be considered geothermal wells.

Detailed statistics for geothermal drilling after 1973 have been published (Gerstein and Entingh, 1981; U.S. DOE, 1986). The number of wells and total footage drilled for various regions in the U.S. from 1980 to 1986 are presented in Table 3-2. Figure 3-1 shows a breakdown by depth category of the number of wells drilled at The Geysers, Imperial Valley, California, and elsewhere.

## 3.2.2 Present and Future Drilling Activity

As indicated in Table 3-2 and Figure 3-1, drilling activity to date has concentrated in The Geysers and the Imperial Valley of California, with

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	198		198		198		198		198		ì			
Region or State	Wells	Footage	Wells	Footage	Wells	Footage	Wells	Footage	Wells	<u> Footage</u>	Wells	Footage	MELIZ	Footage
The Geysers	37	284701	41	317648	49	377162	39	324958	52	358957	44	337763	41	312603
Imperial Valley	9	86043	16	90617	11	88003	1	9785	43	239538	14	66807	6	46524
Other California	7	22344	2	5800	12	19616	9	17396	15	37892	16	21671	1	6450
Nevada	15	77389	17	98067	12	37205	7	19232	6	36457	6	22821	3	14113
New Mexico	4	25663	11	55693	3	10835	3	850			1	7001	4	1040
Oregon	6	16025	4	10319			2	5900	1	4000	1	4000	6	19059
Other Areas	15	50222	12	42888	16	50890	7	12448	2	4165	3	6315		
TOTALS	93	562387	103	621032	103	583711	68	390569	119	681009	85	466378	61	399789

NOTE: Statistics based on date drilling was completed.

Data includes production, injection, and wildcat wells for electric power and direct use.

Also included are temperature gradient and other wells 1000' or deeper.

Table 3-2
GEOTHERMAL DRILLING ACTIVITY: 1980 to 1986

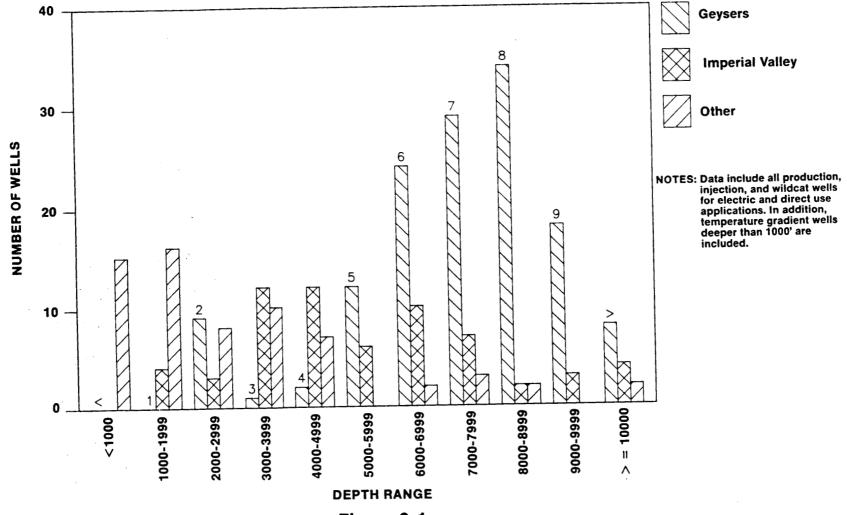


Figure 3-1 GEOTHERMAL DRILLING BY DEPTH: 1984 to 1986

Sources: Petroleum Information, U.S. Department of Energy

significantly less activity in other regions. In the future, the level and distribution of geothermal drilling will depend on future trends in energy prices, needs for additional power on-line, and regulatory issues that can promote or impede the exploration and development process. Although precise projections, in light of these uncertainties, are futile, it is possible to qualitatively predict the regional trends of geothermal drilling activity in the near- and long-term.

Mansure and Brown (1982) conducted a study to project future drilling activity by location based on estimated reserves and site-specific power-online growth scenarios. Table 3-3 illustrates their predictions for power online and total wells drilled from 1981 through 2000. Also shown are actual figures for 1981 through 1986. Mansure and Brown accurately predicted the level of activity at The Geysers through 1986. Power-on-line and drilling activity in the Imperial Valley has lagged slightly from their projected levels, while drilling in Nevada has occurred sooner than anticipated. The almost total lack of activity in the Valles Caldera, New Mexico, was not predicted (it should be noted that Mansure and Brown based their prediction of development in the Valles Caldera on DOE's plans -- since aborted -- to build a 50 MW demonstration project at Baca).

In the near-term (O to 5 years), geothermal drilling will likely be characterized as it is today -- the plurality of wells will be drilled at The Geysers; drilling in the Imperial Valley will become more active, approaching the level of activity at The Geysers; and the balance of geothermal activity will be scattered throughout California, Nevada, and Utah.

In the mid- and long-term (5 to 20 years), geothermal development will approach the limits of capacity of The Geysers field, although it will continue to be an area of active drilling due to the need for replacement wells. Based on current power-on-line predictions (Kruger, 1987) the Imperial

REGION	MWe On-line 1981	Wells Drilled 1981-85 (2)	MWe On-line 1986	Wells Drilled 1986-90	MWe On-line 1991	Wells Drilled 1991-95	MWe On-line 1996	Wells Drilled 1996-00	MWe On-line 2000
GEYSERS									
Predicted	900	220	1820	158	2321	136	2450	127	2510
Actual	909	217	1788						
MPERIAL VALLEY					<u>.</u>		<del></del>		
Predicted	0	118	200	351	520	754	1300	1225	2420
Actual	22	74	151						
ALLES CALDERA									
Predicted	0	37	50	73	90	87	250	77	340
Actual	0	4	0						
IEVADA		·							
Predicted(1)	. 0	0	0	63	100	114	240	137	480
Actual	0	26	14						
ROOSEVELT HOT SPRINGS									
Predicted	0	0	0	56	70	73	210	70	310
Actual	0	2	20						
OTHER			- <u>-</u>				· · · · · · · · · · · · · · · · · · ·		
Predicted	0	70	0	115	0	208	0	327	0
Actual	0	37	33						

SOURCES: Mansure and Brown, 1982; DiPippo; 1986; Petroleum Information

**Table 3-3** COMPARISON OF HISTORICAL AND PREDICTED POWER-ON-LINE AND **DRILLING ACTIVITY** 

NOTES: (1) Measure and Brown presented data for "Northern Nevada".
(2) Wells drilled include production, injection, and wildcat wells for electric power development only.

Valley and other areas of California, Nevada, Utah, and possibly the Pacific Northwest will become active geothermal areas. Current evidence supports the conclusion of Mansure and Brown (1982) that the Imperial Valley will be the focus of geothermal development in this time-frame.

#### 3.3 Typical Geothermal Wells

Since The Geysers and the Imperial Valley are likely to be the two major areas of geothermal drilling in the near and long-term, this study has evaluated the impacts of artificial intelligence developments on drilling using these two particular areas as base case scenarios. Obviously there are numerous other areas of current and likely geothermal development, but to characterize each of them would require substantial effort and would be severely limited by the paucity of data. The Geysers and the Imperial Valley represent radically different geothermal drilling regimes. It is hoped that, by studying AI applications in the context of these two important geothermal systems, an overall perspective of the value of artificial intelligence to geothermal drilling in general can be gained.

#### CHAPTER 4: OVERVIEW OF POTENTIAL AI APPLICATIONS

Artificial intelligence (AI) has numerous potential applications in geothermal drilling. Expert systems may be used to plan and design a well, optimize drilling parameters, and provide guidance in problem areas. Robotics or automation could be applied in most areas of rig operation. In some instances, AI applications already exist in oil and gas drilling. Others are under current development, and still more are at the conceptual stage.

In this study, AI applications were divided into areas of expert systems and intelligent machines. The following sections describe the potential uses of these areas in geothermal drilling and review their current status in industry. In Chapter 5, the potential savings to be realized from implementing these systems are calculated.

In order to calculate the impact of AI applications on geothermal drilling costs, the potential benefits and approximate costs of each system were estimated. For each AI system, savings "goals" were established in discussions with drilling experts to form an optimistic estimate of the impacts that each system could have. The sensitivity analysis in Section 5.3.2 permits the reader to vary these goal assumptions should he disagree with those used in this analysis.

It is assumed that all costs evaluated in this study represent the cost to the geothermal developer. Given this consideration, it is necessary to account for not only potential savings from AI systems, but also the cost per well that would be incurred by using these systems.

For expert systems, this cost is assumed to be negligible. The geothermal developer will incur an "investment cost" for developing or purchasing the expert system, but his marginal cost for using it on one

additional well will be very small.

For intelligent machine applications, it is likely that substantial associated costs will arise due in part to the traditional structure of the drilling industry. Unlike expert systems, where the developer usually owns and operates the system, service companies and/or drilling contractors would offer applications using intelligent machines. These companies would charge the geothermal developer for the use of the hardware and any personnel needed to operate it. The cost will be based on: (1) actual operating expenses and overhead costs incurred by the service company; (2) charges to recoup R&D investment by the service company; and (3) what the service company perceives the developer is willing to pay.

# 4.1 Expert System Applications to Geothermal Drilling

Expert systems have applications to geothermal drilling in areas of well design and planning, drilling optimization, and prevention and resolution of drilling problems. In these applications, the expert system would be accessed either in the office (for pre-drilling planning) or from the well site (for applications during the drilling process). Depending on the complexity of the problem, expert systems can be developed for stand-alone micro- and minicomputers and for mainframe computers accessed from remote terminals.

# 4.1.1 Well Planning and Drilling Optimization

Well planning is the process of optimizing the design of a well using the criteria of minimizing cost and the likelihood of accidents and problems, and maximizing the ultimate production value of the well. This process begins long before the well is spudded and continues through final well completion.

Included in this category are the design of the well plan prior to drilling, any modifications made to it during the drilling process, and the design and optimization of parameters directly affecting drilling efficiency,

such as mud properties and bit selection and operation. This category is differentiated from the next section, drilling problem analysis, by the lack of a real sense of urgency in conducting the analyses. In general, the expert system could be run off-site, and the resultant decisions, although they may improve the drilling efficiency, are not mandated by immediate needs.

Since many of these operations require balancing numerous factors against one another, some with varying degrees of certainty, expert systems can and have been applied to these cases. Five of the more significant areas of well design and drilling optimization are described below, including the types of information required in each and a qualitative discussion of the potential benefits that could be attained with better designs. Existing expert systems for each area of well design and drilling optimization are mentioned in the paragraph and described in further detail in Section 4.1.3.

# Casing Program

Casing itself represents a significant portion of the total cost of a geothermal well, typically 20 to 30 percent (Nicholson, 1984). The geology of the site determines the number of casing strings and the optimal setting depths. Normally, general practice in the region and the best interpretation of the specific geological conditions decide the drilling plan. As drilling proceeds, circumstances may dictate necessary modifications to the casing program. Size of casing is balanced between increasing the flow area available and the higher costs of drilling a larger diameter well. Optimizing a casing program could save money by: (1) avoiding the purchase of unneeded casing; (2) allowing drilling of larger diameter hole only to the depth necessary; and (3) reducing the risks of lost circulation or blowouts.

For the purposes of establishing goals, the casing program can not be treated solely as a cost reduction or efficiency improving parameter. It is

possible that the optimal casing program for a particular well would be a larger diameter casing than would normally be used. This means that a larger well must be drilled, a larger rig might be necessary, and the casing would be more expensive. This will increase the cost of drilling the well. The optimized casing will allow more production from the well, reduce the number of wells required to develop the field, and reduce the overall development cost. Therefore, any well cost savings from an idealized casing program could only be calculated by projecting increased production rates dependant on the reservoir itself.

In this study, we estimate the magnitude of potential savings that could be seen from a casing design expert system by assuming that at a given well, the casing has been over-designed. The casing design expert system recommends trimming 200 feet off the intermediate casing, and concludes that a lighter weight or different grade of production casing will not sacrifice safety or durability (and will save \$5.00 per foot of casing).

Elf Aquitane reportedly has a fully developed expert system, called CASES, that designs casing strings to meet geological constraints, specifications, and local regulations (Marion and others, 1985).

## Cement Design

In geothermal wells, all casing strings are cemented back to surface; therefore, the casing program largely dictates the cement requirements. A potential application of expert system exists in the design and planning of the actual cement job--how much cement is needed, at what rate should it be pumped, what properties should the cement have (density, thickening time and temperature), and whether stage-cementing should be used. Better design of cement slurries could be accomplished with more accurate predictions of downhole temperatures and reservoir conditions (Shryock and Smith, 1981). In

most cases, better cement jobs will result in savings later in the life of the well by preventing or postponing the need for workovers to repair casing.

Occasionally, the need for recementing during drilling may be avoided.

The expert system for casing design would not materially impact the cost or amount of time for cementing. Its most likely area of impact on drilling costs would be in preventing and minimizing some of the problems that might occur. Many of the problems that occur during cementing are mechanical in nature (pump failures, leaking seals, etc.) and would not be affected by an expert system for designing cement jobs. An optimistic goal for the impact of a cement design expert system on geothermal drilling would be circumventing 50 percent of the problems that occur while cementing. Once a problem occurred, the expert system would not have any effect on the amount of time required to solve the problem.

ARCO reportedly has developed a PC-based expert system for designing cement slurries for oil and gas wells (Oil and Gas Journal, 1987).

## Bit Program

Factors incorporated into the design of a bit program to optimize the rate of penetration on a particular well include: choice of drill bit, weight on bit while drilling, rotational speed, hydraulics and fluid properties, and formation properties (Hawkes, 1985). Bit optimization techniques correlate formation parameters, bit characteristics, and bit histories in the region and formations where the well is to be drilled. Potential savings can result from faster penetration rates and reduced wear on drill bits (which means fewer drill bits and fewer pipe trips to replace worn bits).

Adams (1985) estimates that bit selection through comparison of offset wells can save 10 to 30 percent in drilling cost per foot for oil and gas wells. For this study, a savings of 20 percent is the assumed goal for a bit

design expert system. It is likely that many geothermal operators use offset bit records to drill their wells, but this is at least a reasonable, optimistic value for potential savings from a drill bit expert system.

Rotating cost can be expressed as (Adams, 1985):

# Rotating Cost = Bit Cost + Rig Time Cost x (Trip Time + Rotating Time) ROP \* Rotating Time

In reality, optimizing bit parameters to reduce drilling cost per foot by 20 percent would involve changes in all or some of bit cost, rotating time, and rate-of-penetration (ROP). For the purposes of this analysis, it is easiest to simulate a 20 percent reduction in drilling cost per foot by assuming no change in bit cost and rotating time, and an increase of 25 percent in rate of penetration. In calculating estimated savings, this increase in rate of penetration is assumed to occur only below the conductor casing.

Drill-Right, Inc., offers an expert system, "Bit Expert", that analyzes dull bits and recommends changes in bit types or operating conditions (Simpson, 1986).

## Mud Program

The drilling mud serves a number of purposes in well drilling. It cools the drill bit, lubricates the drill string, removes cuttings, prevents influx of fluids from the formation, and aids hole stability. The drilling mud is formulated based on requirements dictated by geology, reservoir characteristics, temperature, and the drilling plan. Variables include density, viscosity, resistance to fluid loss, and chemistry. An optimized mud program can result in savings due to prevention of mud-related problems, including lost circulation, stuck pipe, and formation sloughing, and can

increase drilling efficiency. For this analysis, the goals for the impact of a geothermal drilling fluid expert system are: increase rate of penetration by 10 percent below the conductor casing, reduce lost circulation occurences by 50 percent, prevent hole sloughing, and reduce stuck pipe instances by 50 percent.

NL Baroid probably has the most famous drilling application of an expert system in its MUDMAN, designed to aid in diagnosis and control of drilling mud problems (Stark and Bergen, 1985). Drill-Right, Inc., offers three expert systems for drilling muds: "The Well Planner" calculates formation fracture gradients, kick tolerances, and required mud weights; "Drilling Fluid Analyzer" provides a solids content analysis of the drilling mud and recommends treatment; and "Mud Doctor" generates mud treatment recommendations based on specific mud problems (Simpson, 1986).

# Bottom Hole Assembly (BHA) Design

The bottom hole assembly makes up the lower part of the drill string from the drill bit to the top of the drill collars. Components include some or all of the following: (1) the bit; (2) the bit sub connecting the bit to remainder of the drill string; (3) drill collars used to control the weight applied at the bit; (4) reamers for opening the hole; (5) stabilizers for reducing vibration and increasing directional control; and (6) directional tools including bent subs and downhole motors or turbines. The selection of BHA is a function of well depth, well geometry, geology, drill bit characteristics, and existing or desired well deviation.

Optimizing BHA design can increase bit life and/or rate of penetration, improve directional control, and reduce drill string vibration (thereby potentially reducing the failure rate of downhole components). Goals for an expert system for BHA design used in this study are: increase rate of

penetration by 10 percent below the conductor casing; reduce side tracking by 25 percent; reduce twist offs by 25 percent, and reduce fishing occurences by 25 percent.

#### 4.1.2 Accident Prevention and Cure

Drilling experts are frequently called upon to assist operators in handling problems that occur during drilling. These problems are almost always unexpected; interrupting the normal drilling operation and requiring immediate action. Carson and Lin (1982) estimated that drilling problems increase the cost of an average well by 15 percent and, in certain wells, can result in a 100 percent increase over the cost of a trouble-free well.

Applicability of expert systems to drilling problems depends on the complexity of the problem and the number of different alternatives and amount of information that must be considered. Expert systems may have application to many of the problems that occur in drilling; such as lost circulation and well control, fishing, stuck pipe, and cement problems. Each is discussed in the following paragraphs, including the cause and severity of the problem, potential applications for expert systems, and existing expert systems. Existing expert systems are mentioned briefly in each paragraph and discussed in detail in Section 4.1.3.

## Lost Circulation and Well Control

Overall, lost circulation is the most serious problem in geothermal drilling (Caskey and others, 1985). It occurs when the well encounters a formation zone with lower pressure than in the wellbore. When this happens, the wellbore fluid leaves the well and enters the formation. Other than the expense of the lost fluid, lost circulation can lead to stuck pipe, cement problems, and loss of well control. In many cases, drilling is halted until the lost circulation problem can be solved. Various bridging agents, or lost

circulation materials (LCMs), are added to the mud in hopes of blocking the loss zone. When this does not work, the zone is cemented. If it can not be successfully cemented, it may be necessary to sidetrack or abandon the well. In some instances, the drop in fluid level due to lost circulation will lead to a well kick, and the operator must find the balance between losing circulation and a well blowout.

Potential applications for expert systems include: prevention, diagnosis of location and type of lost circulation, selection of LCM, and application of cures (Satrape, 1987). In certain instances, the lost circulation expert system will overlap with the mud expert system (as described in Section 4.1.1) but the lost circulation system will be designed as a very specialized, indepth system requiring less effort to develop than the complete mud expert system. Goals for savings that could be realized from a lost circulation expert system in this study are a 50 percent reduction in of lost circulation occurrences, and a 50 percent reduction in the average time to solve lost circulation once it occurs (no reduction in the direct cost of solving lost circulation is assumed, i.e., what is gained in efficiency is lost because it is more expensive). In addition, a 50 percent reduction in stuck pipe incidents is also assumed, since a common cause of stuck pipe is differential sticking due to lost circulation (Courteille and others, 1986).

Sandia National Laboratories has developed a preliminary prototype expert system, named GEOTHERM, for solving lost circulation problems in geothermal wells. For the related problem of well control, Hydrocarbon Technologies, Inc. (Houston, Texas), has developed an expert system for oil and gas applications, called WELLSAFE, to control kicks and kill a well.

# Fishing

Fishing is the process of retrieving debris or equipment from the well

where it prevents or inhibits further drilling. Probably the most common situation in fishing is retrieving drill pipe that has either twisted off or stuck in the well. Other "fish" include cones and bearings from drill bits, parts of stabilizers or centralizers, wireline, or tools dropped from the surface. There is a large array of "fishing tools" for these situations, including overshots to retrieve stuck pipe, spears for wireline, magnets and baskets for debris, etc.

An expert system could help the rig personnel to select and operate the proper fishing tools. Such an expert system would not reduce the need for fishing, but could reduce the associated time and costs. In this analysis, the goals of an expert system for fishing are assumed to be: 50 percent reduction in operational cost; 50 percent reduction in time; and 25 percent reduction in the time needed to solve other fishing-related problems (stuck pipe, twist off, and sloughed hole).

# Stuck Pipe

During drilling and pipe tripping operations, drill pipe often becomes stuck in the well. This can be caused by differential pressure (as in a lost circulation zone), by wearing a key seat on one side of the borehole, by sloughing or expanding formations above the drill bit, etc. Once stuck, there are numerous procedures that can be applied to free the drill pipe. Simply working the drill pipe can often pull it free. In other cases, pumping a lubricant down the wellbore can loosen it. In more difficult situations, it is necessary to "back-off" the drill pipe: a free-point tool is run to determine where the drill pipe is stuck; an explosive device is positioned above the free point and detonated to back off the drill pipe. After backing off, the drill string is run back into the hole with fishing jars to attempt to loosen the stuck pipe. Sometimes, it may be necessary to wash over the

fish to displace fill that may be causing it to stick. In the worst case scenario, it may be necessary to abandon the pipe in the well and cement and sidetrack.

An expert system designed for stuck pipe would attempt to prevent its occurrence, diagnose the problem, and recommend procedures to solve it. For this case, the analysis assumes goals of a 50 percent reduction in the occurrence of stuck pipe, a 25 percent reduction in average problem-solving time, and a 25 percent reduction in direct costs. In addition, the time to solve the related problems of lost circulation and hole sloughing is assumed to be reduced by 25 percent due to this expert system.

One of the first expert systems developed for the drilling industry was built to prevent, diagnose, and solve stuck pipe problems. This system is called SECOFOR (formerly known as The Drilling Advisor) and was built by Teknowledge, Inc., for Elf Aquitane (France).

#### Cement Problems

Problems that can occur during well cementing include channeling of cement behind the casing, contamination of cement by drilling or formation fluids, insufficient cement volume, or mechanical problems during cement pumping that result in less than total displacement (Smith, 1976). The first step in troubleshooting is to diagnose a cement problem. The best indicator is monitoring returns during the cement job. If returns are less than expected and/or do not come all the way to the surface, cement may have been lost to the formation, or washouts in the wellbore may have resulted in a greater borehole volume than anticipated. If more cement comes to the surface than expected, it is possible that large channels of uncemented casing exist. These problems can result in serious trouble later in the life of the well; therefore, it is usually necessary to take remedial action as soon as

possible. If a poor cement job is suspected, the operator may run a cement bond log (an acoustic measurement of cement behind casing) or he may perform remedial cement "squeezes" to fill gaps behind the casing.

This expert system would be designed to help solve cementing problems once they occur--as opposed to a cement design system that would design cement slurries to prevent cementing problems. For the cement problem expert system, the goal is to develop an expert system that would reduce by 50 percent the time required (average) to solve cement problems.

# 4.1.3 Existing Expert Systems for Well Drilling

This section describes in more detail the existing expert systems mentioned in the previous two sections. These expert systems are summarized in Table 4.1. The following paragraphs give a brief description of each system and discuss its application to geothermal well drilling. With the exception of GEOTHERM (Sandia), all of these systems were developed for oil and gas drilling and may not apply directly to geothermal. Judgements of applicability to geothermal drilling are based on descriptions of the programs available in the literature and in promotional material. For more detailed information, the reader should consult the references listed or the companies themselves.

#### MUDMAN

MUDMAN (Stark and Bergen, 1985) was created by NL Baroid to aid in diagnosing and controlling drilling mud problems. In addition, it assists in rig inventory control, report preparation, and engineering calculations. In its diagnosis, MUDMAN can incorporate unknown or uncertain information. The knowledge base contains data on the properties of various muds and history for the well in question; in a given consultation it has access to histories of

EXPERT SYSTEM	APPLICATION	OWNER (DEVELOPER)	STATUS	REFERENCE
MUDMAN	Drilling fluids	NL Baroid (Carnegie-Mellon U.)	Available .	Stark and Bergen, 1985
SECOFOR	Stuck drill pipe	Elf Aquitane (Teknowledge)	Proprietary	Courteille and others, 1986
GEOTHERM	Lost circulation	Sandia Nat. Lab.	Preliminary prototype	Satrape, 1987
The Drilling Expert System	Various drilling aspects	Drill-Right, Inc.	Available	Simpson, 1986
WELLSAFE	Well control	Hydrocarbon Technologies, Inc.	Available	Hydrocarbon Technologies, Inc.,1987
Cement Advisor	Cementing	ARCO .	Proprietary	Oil and Gas Journal, 1987
CASES	Casing design	Elf Aquitane (unknown)	Proprietary	Marion and others, 1985

Table 4-1
SUMMARY OF EXISTING EXPERT SYSTEMS FOR DRILLING

nearby wells for which the operator has obtained rights to information. In all cases, security of data from different operators is maintained. The program is maintained at Baroid's central office and is accessed by remote terminals from the well site.

Currently, Baroid is using MUDMAN successfully and plans to install it on smaller computers for operation at remote sites.

Although MUDMAN was designed for oil and gas applications, it probably has direct applications to geothermal drilling. Since it is offered through a company active in geothermal (and a member of the Geothermal Drilling Organization, the DOE industry cost-shared drilling research group) it is conceivable that MUDMAN will be applied to geothermal. Additions to the knowledge base would be needed to handle the muds used in geothermal drilling. It also may be possible to modify MUDMAN to act as an expert in drilling fluid related problems in geothermal wells, such as lost circulation.

#### **SECOFOR**

Teknowledge, Inc., developed SECOFOR (originally called the Drilling Advisor) for Elf Aquitane (France) to diagnose incidents of stuck drill pipe in oil and gas wells (Courteille and others, 1986). Based on information provided by the user, SECOFOR determines likely causes of pipe sticking and provides a set of treatment recommendations designed to solve the problem and prevent it in the future.

As of 1986, there were over 400 rules in the system and its operation had been verified by comparison with experts' recommendations for particular sets of problems (Courteille and others, 1986). The program had not yet been installed in the field. Planned refinements for the system include: increasing the use of historical data, incorporating other incidents (fluid loss or gain, well swabbing), integrating with on-line sensors, using it as a

training aid, and extending the ability of the system to use certainty factors.

In order to apply SECOFOR to geothermal drilling, slight enhancements to incorporate geothermal pipe sticking historical data would probably be necessary. Other factors that may be unique to geothermal drilling could include mud types and the ability of certain tools (i.e., free points, back offs, etc.) to operate in the hostile geothermal environment. Elf Aquitane is not an active geothermal operator and would be unlikely to extend SECOFOR for geothermal applications. Another company would probably have to obtain a license from Elf Aquitane to work with SECOFOR.

#### **GEOTHERM**

GEOTHERM is a prototype version of an expert system developed in 1986 by Sandia National Laboratories to control lost circulation in geothermal wells. In its current state, it is not a commercial package but a "framework" for a useful system, providing a base that could be expanded in discrete modules, ultimately resulting in a complete system. In order for GEOTHERM to be a useful tool in the field, a much greater sophistication is needed than that exhibited in the initial prototype. Specific areas for further effort include locating loss zones, diagnosing types of lost circulation, use of available data from other wells, and LCM selection (Satrape, 1987).

## The Drilling Expert System

The Drilling Expert System is a set of five expert systems developed and marketed by Drill-Right, Inc. (Simpson, 1986). The expert systems are based on general drilling guidelines and algorithms published by established experts or drilling institutions. The five systems are: (1) Well Planner, which calculates formation fracture gradients, kick tolerance, and required mud weights to prevent wellbore collapse; (2) Drilling Fluid Analyzer, which

generates a drilling fluid evaluation and treatment recommendations with data from the abbreviated mud form; (3) Mud Doctor, which suggests general cures to eight major drilling fluid trouble categories from the IADC Drilling Manual; (4) Bit Expert, which supplies expert analysis of milled tooth and insert bit dull condition and recommends changes in bit type or operating parameters; and (5) Drilling Expert, which gives a detailed analysis of morning reports or real time drilling data from an abbreviated report form.

Based on promotional material and published reports (Simpson, 1986), The Drilling Expert System is a large collection of well-known analysis techniques and operational guidelines for all aspects of oil and gas drilling. Similar guidelines could probably be assembled for geothermal drilling.

#### WELLSAFE

WELLSAFE is an expert system developed by Hydrocarbon Technologies, Inc. (1987), to advise rig supervisory personnel when encountering a kick, well control, or potential blowout situation. The program operates on either Apollo or Sun work stations and can be easily installed on any minicomputer or mainframe.

WELLSAFE is probably directly applicable to geothermal drilling, although well kicks are a much less serious problem in geothermal than the opposite condition, lost circulation.

# ARCO Cement Advisor

ARCO's cementing expert system was developed using the knowledge of a leading expert in oil-well cementing. The system aids in the design of cement formulations and spacers (Oil & Gas Journal, 1987). It assists the user in designing a base cement then selects additives necessary to achieve the specific property requirements. The system can also critique a submitted

design. The system has 2000 rules and operates on an IBM PC-AT.

To be applicable to geothermal drilling, it is likely that significant rules would have to be added to incorporate geothermal cementing practices and account for the properties of geothermal cements. The framework of the system would probably not need much alteration. As in the case of SECOFOR, the system is proprietary in nature and a licensing agreement would have to be obtained before geothermal commercialization.

#### CASES

CASES is an expert system developed by Elf Aquitane to design casing configurations in oil and gas wells (Marin and others, 1985). CASES was built using information from field experience, accepted design guidelines, and analytical computer programs. It can account for geological constraints, regulations, and use of specified tubing.

CASES could probably apply to geothermal casing design with an addition of rules describing practices in geothermal drilling. The proprietary nature of the program would once again be a major stumbling block.

# 4.2 Intelligent Machine Applications to Geothermal Drilling

Automation has slowly penetrated the oil and gas drilling industry over the past several decades. A drilling rig with an automated pipe-handling system was developed by Automatic Drilling Machines (ADM), Inc. and successfully tested in the late 1960's and early 70's (Kennedy, 1971). The ADM rig was never widely accepted. Currently, some degree of automation exists in mud systems, pipe racking (especially on drill ships and semisubmersibles), and other aspects of the drilling operation.

Many measurements are also taken in modern drilling practice, including mud properties, drilling parameters, pipe inspection, downhole measurements (i.e., measurement while drilling or MWD), directional measurements, etc.

These measurements generally assist the drilling engineers in monitoring the progress of the well and provide information to help optimize and maintain the safety of the drilling process.

The combined application of AI and robotics in well drilling will connect the automation aspect with the sensors (to monitor the progress of the well) and with a control system for optimizing drilling performance. The AI process should be able to operate without supervision during normal operation, and it should be able to detect a problem when it occurs. Upon detection of the problem, the system would set off an alarm to notify rig personnel, and it would be able to take the first steps to handle the problem. For example, if the well were to kick while drilling, the system would stop drilling and circulate the well, preparing to build mud weight. The fact that the system could take the initial steps would give the rig personnel time to evaluate the problem and plan a course of action.

Figure 4-1 shows a general block diagram of a possible robotic rig operated using AI systems. It is not likely that a completely unmanned drilling rig could have applications in drilling, with the possible exception of planetary expeditions and sampling in contaminated areas. However, the proposed rig would still have substantial personnel requirements. Intelligeng machine applications would primarily be in the area of maximizing the efficiency of the drilling process. Specific areas for which automation is not considered are: rig maintenance and repair, stocking and inventory of supplies, and resolving drilling problems beyond the initial reaction stage.

Several of the systems composing the "intelligent" drilling rig could be implemented separately. These are: well hydraulics, pipe handling, pipe inspection, and drill bit control. Each is discussed in the following sections.

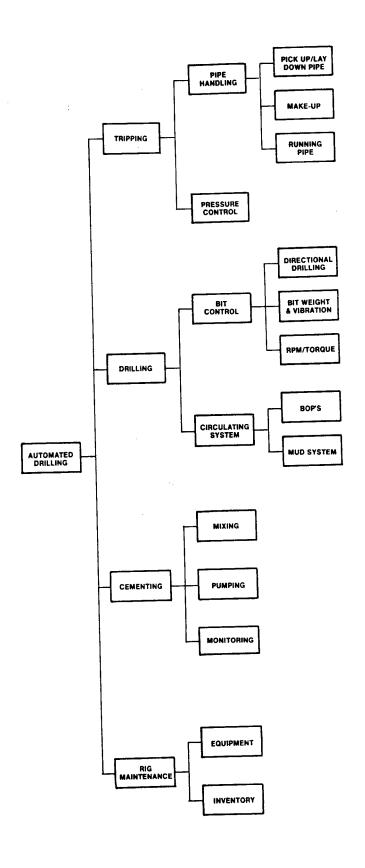


Figure 4-1
BLOCK DIAGRAM OF ROBOTIC DRILLING RIG

#### Drill Bit Control

Ultimately, the purpose of a drilling rig is to drill a well, and the drill bit at the end of the drill string is the one part performing this task. All other systems and components merely enable the drill bit to fulfill its task. It follows that control of the drill bit is a primary target for optimization with AI.

There are actually two related but separate components of bit control: penetration and direction. Not only must the bit deepen the hole, but it must drill in the direction specified by the well planner, be that straight or deviated. Both tasks could be addressed by an intelligent bit control system.

Figure 4-2 shows a block diagram of such a bit control system.

Measurements are made of drilling parameters both on the surface and downhole. These measurements would be interpreted by an AI system similar to expert systems (except designed for machine control instead of human interface) to determine if drilling is proceeding as planned and if the well is correctly deviated. Based on measurements of formation parameters and drilling progress, and knowledge of the bit and drill string characteristics, the system could optimize drilling parameters. Other possibilities would be to monitor drill bit wear to modify drilling parameters for optimizing the trade offs between bit life and penetration rate. Drilling accidents such as sticking and twist off could also be prevented in certain cases—it is possible that drill string vibration and torque may yield information of impending problems in this area. If applicable, it would also be interfacing with other possible AI systems such as the mud system.

The AI system would then send signals to a controller to modify drilling parameters per instruction. In theory, measurement, interpretation, and control could occur either at the surface or downhole, or both. Depending on the amount of data transfer likely, significant research may be needed on high

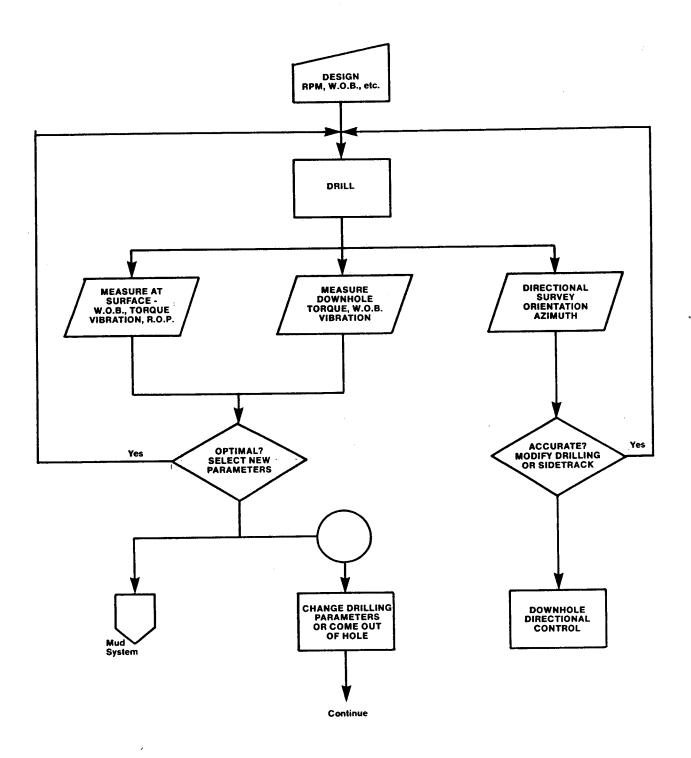


Figure 4-2
ROBOTIC DRILL BIT CONTROL SYSTEM

data rate transmission during drilling. Another possibility would be an entire downhole system including mud motor, thrusters, bit, sensors, and computer, as proposed by Carson (1984).

Many of the individual components that would make up intelligent bit control already exist in one form or another and others could be developed with existing technology. Surface sensors already exist to monitor many of the important drilling parameters. Downhole sensors are incorporated into today's measurement while drilling (MWD) systems that can measure and transmit to the surface data relating to directional control, drilling, and formation parameters.

The potential advantages that could be realized from an intelligent drilling system include: faster penetration rate, enhanced drill bit life, improved directional control, and possible early detection of stuck pipe and twist off. For the purpose of evaluating potential impacts of developing this AI system, the following goals for such a system are assumed in the analysis: 50 percent savings in rotating costs below the conductor casing (modeled using a 100 percent increase in rate-of-penetration and no change in bit life or cost); and 50 percent reduction in occurrences of stuck pipe, twist off, and side-tracking.

It is reasonable to assume that the implementation of such a system would result in a significant increase in rig operating rates. Using typical costs for an MWD system as a guide, this analysis assumes use of a downhole drilling system would result in doubling geothermal rig rental rates.

#### Pipe Handling

The pipe handling system handles the pipe from the pipe rack to the well. It would move pipe from the pipe rack to the V-door and into the derrick. It would also trip pipe into and out of the well, and add joints to the drill

string as needed while drilling. Measurements would include hook load, travelling block position, and trip tank volume. The system would also receive input from other rig systems, specifically the bit control and rig hydraulics.

The AI system would interpret measurements to identify tight spots, obstructions, well swabbing, kicks, and other things that could occur during drilling. If immediate action were necessary, the system would determine what action to take and implement it.

Many of the components of an intelligent pipe handling system, shown in Figure 4-3, already exist in the drilling industry. An automated pipe-handling system was developed over 25 years ago (Kennedy, 1971). Peltier (1987) discusses a system used by Elf Aquitane for on-line measurement and processing of information during pipe tripping. Since most of the components are within the realm of existing technology, the primary lack is the AI controller that link them.

An intelligent pipe handling system would improve the efficiency and speed of tripping pipe into the well, although the savings here are limited to reducing the amount of time needed to make a connection. The actual speed of raising and lowering the drill pipe is not limited by equipment, but rather is set to prevent swabbing the well. The pipe handling system could also detect and take immediate action to prevent some stuck pipe incidents. Twist offs may also be prevented since the torque used in making pipe connections on the rig floor would be better controlled. For the purposes of this analysis, the goal for reduction in tripping time is 50 percent. Other savings assumed are a 25 percent reduction in instances of stuck pipe and twist off. It is assumed that the robotic pipe handling system would result in a 10 percent increase in rig rental rates. This figure is a result of higher equipment

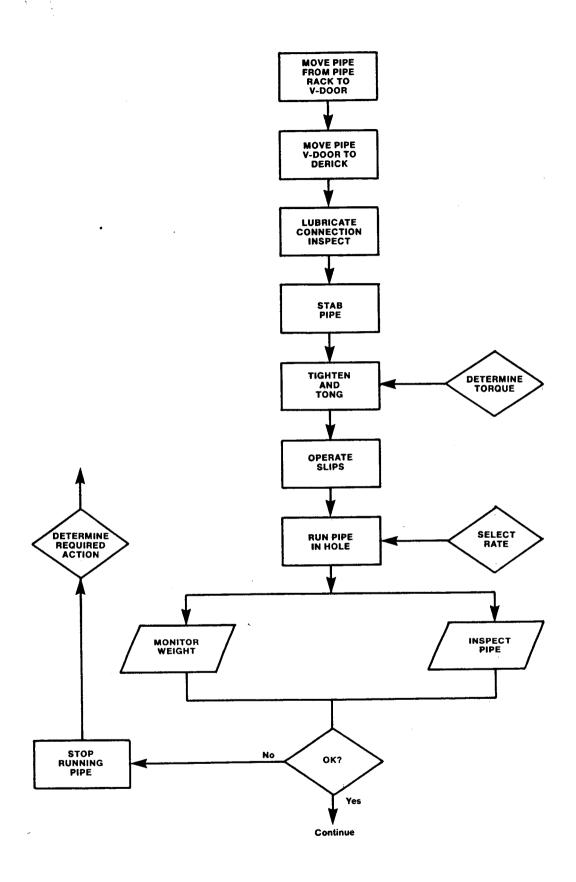


Figure 4-3
ROBOTIC PIPE HANDLING SYSTEM

costs but potentially significant reductions in labor and insurance costs.

# Pipe Inspection

Drill pipe failure, leading to twisting off of pipe in the well, is a serious problem in geothermal drilling. A twist off usually occurs at a tool joint that has weakened, possibly due to incorrect make-up torque or hostile well conditions. Current practice is to flux test drill collars and tool joints on the surface of the well when a problem is suspected (often after a twist off has occurred).

Kahil and Logan (1986) describe an electromagnetic tubing inspection device that tests pipe as it passes through the wellhead. This system, the Wellhead Scanalog (offered by Baker Tubular Services), has the capability to inspect 2-3/8 and 2-7/8 inch tubing for mechanical wear and corrosion. The device measures the wall thickness of the pipe and a computer identifies areas of non-uniform wall thickness.

For geothermal applications, a system capable of handling 5- to 6-inch drill pipe and drill collars would be necessary. In addition, the possibility of measuring parameters other than wall thickness, such as internal defects, would be useful. These measurements could be made as the pipe was tripped into or out of the well, and a computer would evaluate the "signature" of the pipe and identify joints where defects existed.

An optimistic goal for the impact of such a system would be to reduce the occurrences of twist off by 90 percent. It is anticipated that this system would be used primarily in the drilling of the production zone, and would result in a 25 percent increase in rig rental rates in the production zone. It should be noted that the operating cost of this type of system will depend strongly on whether the system is operated by service companies or by rig personnel.

#### Well Hydraulics

The hydraulics system is controls the circulation of the drilling mud during the drilling operation. The properties of the mud (i.e., viscosity, density, solids, chemistry) must be maintained within certain ranges, otherwise drilling performance can suffer.

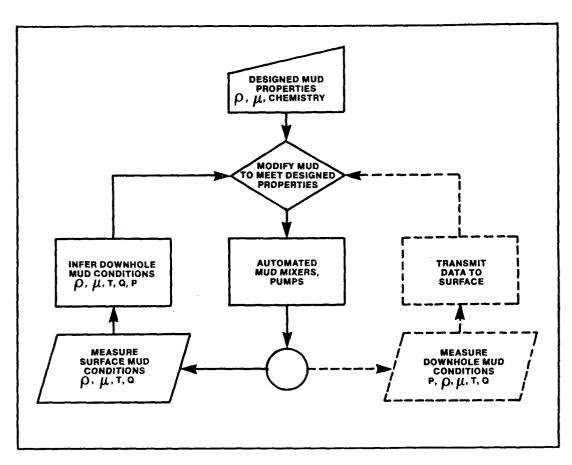
The components of the hydraulics system include:

- o Mud Pump provides the energy to pump the mud down the drill pipe and return it up the annulus
- o Mud Pits serve as storage area for extra mud not in the well
- o Shale Shaker screens out cuttings from the returned mud

  Many geothermal rigs also use a mud cooling system once high temperature
  geothermal zones are encountered.

Potential applications of AI to mud systems would incorporate sensors to monitor mud conditions and current drilling status, and would include a data base of formation properties and previous drilling history where available. An "intelligent" controller would take the above information, select the correct course of action, and send signals to an automated system for mixing mud and adding ingredients as necessary to attain the selected properties. In addition, a system for identifying problem conditions and setting off alarms would be incorporated. One possible configuration of such a system is shown in Figure 4-4.

Most of the components of this intelligent drilling mud system already exist in the marketplace. Computerized mud loggers measure properties (both electrical and rheological) of drilling fluids for analysis. Automated mud mixing systems (with manual control) have been available in the industry since the late 1960s (Halliburton Services, 1969). NL Baroid's MUDMAN, described in Section 4.1.3, is a software version of a program that would monitor mud properties and recommend steps of action.



ho: Density; ho: viscosity; T: Temperature; P: Pressure; Q: Flow rate

Figure 4-4 ROBOTIC MUD SYSTEM

Potential savings from an intelligent mud system could include improved drilling efficiency, reduction in mud-related well problems, and savings on drilling mud costs. Such a system could also be developed with the capability to monitor cementing operations, thereby identifying related problems early in the operation. Since the system would be able to respond to problems more quickly than a human operator, it would probably be more effective in preventing drilling accidents. Therefore, the following savings goals for an automated mud system are assumed in this analysis: 10 percent increase in rate of penetration below the conductor casing, no hole sloughing, and 50 percent reduction in lost circulation and stuck pipe. In addition, since the automated hydraulic system could be used to monitor cementing operations, thereby identifying problems sooner than otherwise, a reduction of 50 percent in the time and cost of cementing problems is also assumed. To account for the additional expense of automating the mud system, a 100 percent increase in daily mud maintenance costs is assumed.

#### Well Pressure Control

Well pressure control equipment is used to control the well in the instances of a well kick or blowout. Although this is an integral part of the rig hydraulics system, it is treated as a separate entity because it would be possible to develop an automated system for blowout control, independent of the mud hydraulics system.

The components of an intelligent well pressure control system would include sensors for monitoring well pressure and fluid density, algorithms for recognizing when conditions are unsafe, and controls to operate blowout preventers and weight mud as (Figure 4-5). All of these components, with the exception of the control mechanism, already have been developed. One expert system (WELLSAFE) has been developed for controlling well kicks.

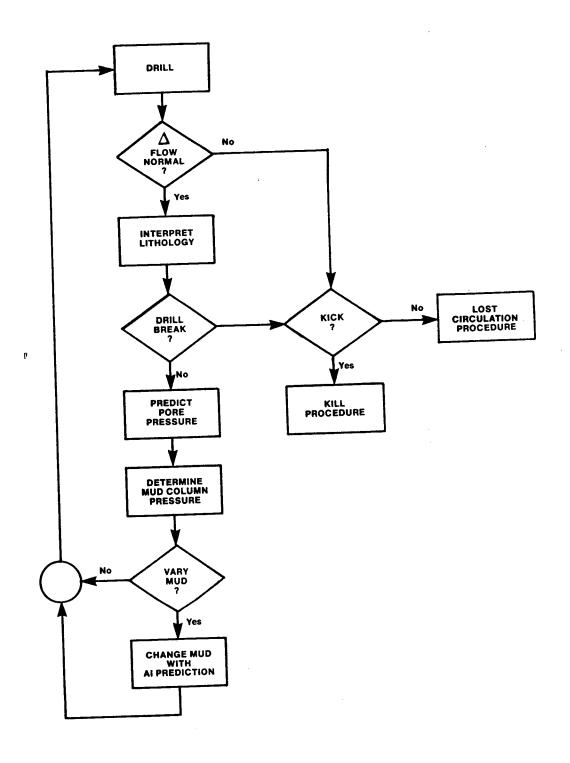


Figure 4-5
ROBOTIC WELL CONTROL SYSTEM

SOURCE: Oil And Gas Journal (1987)

Potential savings from intelligent well pressure control would be realized from cost reductions associated with well kicks and blowouts. As this problem is much more serious in oil and gas drilling, limited application for such a system would exist in geothermal drilling. For this reason, the potential cost savings of such a system are not calculated.

# CHAPTER 5: CALCULATION OF POTENTIAL SAVINGS

# 5.1 Method of Drilling Cost Calculation

Calculation of drilling costs in this analysis was accomplished with the use of DRILTAC, a public-domain well design and costing spreadsheet developed by Resource Technology, Inc., of Tulsa. A description of DRILTAC is included in Appendix A. In developing DRILTAC, Resource Technology conducted extensive research to obtain drilling equipment and services costs (circa mid-1985) that are included in the DRILTAC user's manual (Resource Technology, Inc., 1986). These data were used to calculate drilling costs in this study.

Minor modifications to DRILTAC were necessary, specifically to enable the spreadsheet to account for eight categories of drilling problems. These problems were included in the drilling cost calculation by applying estimates of average time and cost per problem occurrence, adjusted for the probable number of occurences per well. With this technique, drilling problems manifested themselves as a direct increase in drilling time plus cost increases due to both the direct cost of the problem and the indirect cost of rental for "down" time.

#### 5.2 Base Case Scenarios

To calculate a representative estimate of geothermal drilling cost savings, three base case scenarios were assembled: a steam well at The Geysers, a 6,000-foot hot water well in the Imperial Valley, and a 10,500-foot Imperial Valley well. These base cases are not ideal, instead they have been devised to represent the characteristics of an average or typical well of each type. The well descriptions are based on interpretations of published reports, open-file well records from the California Division of Oil and Gas, and other publicly available drilling summaries.

# 5.2.1 Geysers Well

The Geysers geothermal reservoir is a dry steam field where water exists in the reservoir at high temperature and below saturation pressures. The geothermal reservoir formation is primarily highly fractured Franciscan graywacke, interlayered with basaltic volcanic rocks and serpentine (McLaughlin and Stanley, 1975). The fractures serve as conduits for the geothermal steam which convects heat from a deep heat source toward the surface. A successful geothermal well at The Geysers is determined by whether it intersects enough fractures to supply adequate steam production.

Geothermal wells at The Geysers are usually drilled directionally, with multiple wells drilled from a single pad. The use of multiple well platforms reduces surface environmental damage and eases access into the mountainous terrain. Directional drilling, if normal to the preferred fracture orientation, is also more likely to intersect fractures.

Wells at The Geysers are usually mud drilled to 4,000 to 6,000 feet (often with downhole mud motors) to the top of the geothermal reservoir, then conventionally air drilled the final 3,000 to 4,000 feet (Capuano, 1982). Difficulties encountered in drilling include lost circulation, stuck pipe, drill pipe corrosion, and the high temperature and abrasiveness of the formations.

The base case Geysers well was derived from published reports (Carson and others, 1983; Capuano, 1982) and from well records on file at the office of the California Division of Oil and Gas in Sacramento. Figure 5-1 shows the basic design of the well. The input data to DRILTAC and the cost assumptions are included in Appendix B. The assumed frequency and associated time and costs of drilling problems, presented in Table 5-1, were derived by interpreting data presented in Carson and Lin (1982).

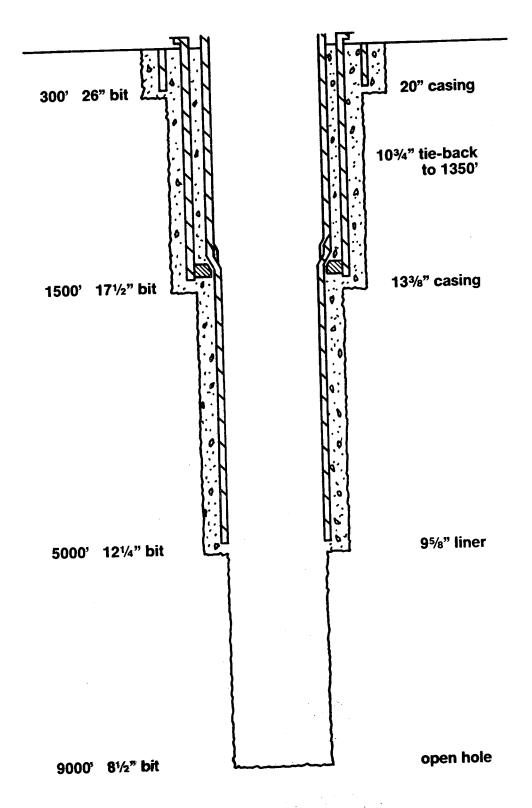


Figure 5-1
DESIGN FOR GEYSERS BASE CASE WELL

DRILLING PROBLEMS		Hours lost	Direct cost
Problem Type		/occurrence	/occurrence (1)
Lost Circulation Casing Cementing Fishing Side Tracking Twist Off Stuck Pipe Sloughed Hole	0.92 0.10 0.54 0.26 0.26 0.24 0.49 0.16	54.00 42.00 48.00 72.00 96.00 114.00 78.00 54.00	2000.00 10000.00 20000.00 5000.00 40000.00 30000.00 30000.00

NOTE:

(1) Direct cost excludes hourly costs for rig rental and other charges not directly associated with the problem. Examples of direct charges are: service company experts to solve the problem, lost drilling fluid, LCM, additional cement materials, replacement casing hardware, and replacements for drill pipe and other hardware lost in the hole.

Table 5-1
ASSUMED FREQUENCY AND AVERAGE COST OF DRILLING PROBLEMS FOR
THE GEYSERS BASE CASE WELL

The summary time and cost analysis from DRILTAC for the base case Geysers well, excluding drilling problems, is shown in Table 5-2. Table 5-3 shows the base case well with drilling problems. For the base case with problems, a 9,000-foot well (using mid-1985 costs) costs approximately \$1.5 million and requires 56 days to drill. Drilling problems account for 8 1/4 days and about \$200,000 (14 percent) of the total cost.

# 5.2.2 Imperial Valley Wells

The Imperial Valley of California lies within the Salton Trough, the northern extension of the Gulf of California and a result of a continental spreading center. At the southern end of the Salton Trough is Cerro Prieto, and large Mexican geothermal development. The Imperial Valley contains a number of geothermal fields under active exploration and development (Figure 5-2).

The geothermal fields of the Imperial Valley exhibit similar geologic parameters although they may vary in depth, temperature, and brine chemistry. The properties of the various Imperial Valley geothermal fields are listed in Table 5-4. The geothermal reservoirs in the Imperial Valley are primarily sandstone, exhibiting a combination of matrix and fracture permeability. Overlaying the geothermal reservoirs is an impermeable clay cap, below which the clay content gradually decreases to the middle of the reservoir. At the bottom of the reservoir, formation permeability decreases sharply. Based on drilling in Cerro Prieto and the Salton Sea Scientific Drilling Program well (Aguirre and Garcia, 1981; Harper and Rabb, 1986), wells that penetrate below the normal production wells encounter zones of fracture-dominated permeability and low pressure. Since almost all of the drilling conducted in the Imperial Valley has been done recently by private industry, detailed public information on the drilling problems is not available. In the Cerro Prieto geothermal

CALCULATION AREA 4.		INDIVIDUAL OPERATION Time and Cost Analy		
Operation	Oper. Total Time (Hrs.)	Percent Total Time (%)	Oper. Total Cost (\$)	Percent total Cost (%)

	1		(%)
0 755 19	0.00% 65.82% 1.66%	63550.00 487205.00 95054.00	5.05% 38.68% 7.55%
70 63 <b>4</b> 5 0	6.10% 5.49% 3.92% 0.00%	45493.00 38066.00 31918.00 77350.00	3.61% 3.02% 2.53% 6.14%
64 131 0	5.58% 11.42% 0.00%	216905.00 152855.00 0.00	17.22% 12.14% 0.00% 0.00%
0 0 1147	0.00%	51200.00 \$1,259,596.00	4.06%
	755 19 70 63 45 0 64 131 0	755 65.82% 19 1.66% 70 6.10% 63 5.49% 45 3.92% 0 0.00% 64 5.58% 131 11.42% 0 0.00% 0 0.00% 0 0.00%	755         65.82%         487205.00           19         1.66%         95054.00           70         6.10%         45493.00           63         5.49%         38066.00           45         3.92%         31918.00           0         0.00%         77350.00           64         5.58%         216905.00           131         11.42%         152855.00           0         0.00%         0.00           0         0.00%         0.00           0         0.00%         51200.00

# Table 5-2 CALCULATED TIME AND COST ANALYSIS FOR TROUBLE-FREE **GEYSERS WELL**

CALCULATION AREA 4.	INDIVIDUAL OPERATION	
	Time and Cost Analysis	

Operation 0	per. Total Time (Hrs.)	Percent Total Time (%)	Oper. Total Cost (\$)	Percent total Cost (%)
8 Road and Site Prep.	0	0.00%	63550.00	4.35%
9 Drilling Operations	755	56.13%	487205.00	33.38%
10 Bits/Cutters	19	1.41%	95054.00	6.51%
11 BHA	70	5.20%	45493.00	3.12%
12 Tripping Operations	63	4.68%	38066.00	2.61%
13 Auxiliary Operations (1	) 163	12.12%	140006.00	9.59%
14 Drilling Fluids (2)	0	0.00%	105062.00	7.20%
15 Casing Operations (3)	68	5.06%	220663.00	15.12%
16 Cementing Operations (4	) 157	11.67%	180679.00	12.38%
17 Maintenance	. 0	0.00%	0.00	0.00%
18 Drilling Problem (5)	50	3.72%	32630.00	2.24%
19 Other	. 0	0.00%	51200.00	3.51%
20				· [
21 Total Program 22	1345	100.00%	\$1,459.608.00	100.00%

NOTES:

Due to the manner in which DRILTAC was designed, it was necessary to modify it to handle drilling problems. Therefore, problems have been incorporated into the various drilling operations as described in the notes.

- (1) Includes time and direct costs for fishing, side tracking, twist off, stuck pipe, and sloughed hole.
- (2) Includes direct costs for lost circulation.
- (3) Includes time and direct costs for casing problems.
- (4) Includes time and direct costs for cementing problems.
- (5) Includes time for lost circulation.

# Table 5-3 **CALCULATED TIME AND COST ANALYSIS FOR "AVERAGE" GEYSERS WELL**

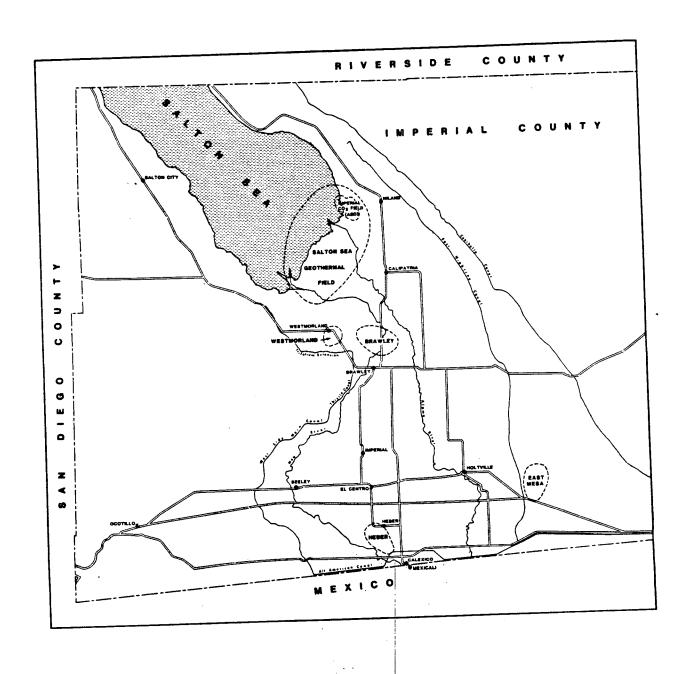


Figure 5-2
MAP OF IMPERIAL VALLEY GEOTHERMAL AREAS

SOURCE: Carson and others (1983)

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Geothermal Area	Existing Plant Capacity (MWe net)	Approximate Capacity Under Construction (MWe net)	Estimated Capacity (MWe for 30 years)	Approx. Temp. (F)	Typical Well Depths (feet)	Approximate Salinity (TD - ppm)
Brawley	-	-	640	500	7,000-14,000	70,000-200,000
East Mesa	12.5	78	360	360	5,000-8,500	14,000-20,000
Heber	92	-	650	370	5,000-11,000	2,000-50,000
Salton Sea	44.5	104	3,400	550	3,000-10,000	250,000-350,000
Westmoreland	-	-	1,710	400	10,000+	?

SOURCES: U.S. Geological Survey (Circular 790)
Petroleum Information, National Geothermal Service
Bookhaven National Laboratory

Table 5-4 **CHARACTERISTICS OF IMPERIAL VALLEY GEOTHERMAL FIELDS** 

field to the south, the most serious problems are lost circulation, cementing, and temperature-related failures (Aguirre and Garcia, 1981).

#### Medium-Depth Imperial Valley Well

The well design for the base case, medium-depth Imperial Valley well was based loosely on the Imperial Valley model wells presented by Carson and others (1983) with input from private sources. The well design is presented in Figure 5-3 and the detailed inputs to the DRILTAC costing spreadsheet are included in Appendix B. The assumed drilling problems summary for the Imperial Valley well is shown in Table 5-5. This information was partially based on data presented by Carson and Lin (1982), but generally was estimated with the understanding that geothermal drilling in the Imperial Valley is relatively trouble-free when compared to other areas.

Summary time and cost analyses are presented in Tables 5-6 and 5-7. Including the average effects of drilling problems, the base case Imperial Valley well to 6,000 feet costs approximately \$840,000 and requires 24 1/2 days to drill. Of this, approximately \$85,000 (10 percent) in direct and indirect costs and four days can be attributed to drilling problems.

#### Deep Imperial Valley Well

The well design for the base case, deep Imperial Valley well, is shown in Figure 5-4. This well is based loosely on the Salton Sea Scientific Drilling Project (SSSDP) well drilled by the U.S. Department of Energy in 1985-86 (Nicholson, 1986). Every effort was made to factor out the scientific aspects of the drilling operation used in the SSSDP well in order to simulate, as closely as possible, a commercial well drilled to tap the same resource. The details of the well plan used in the DRILTAC calculations are included in Appendix B. The assumed drilling problem summary is shown in Table 5-8. This

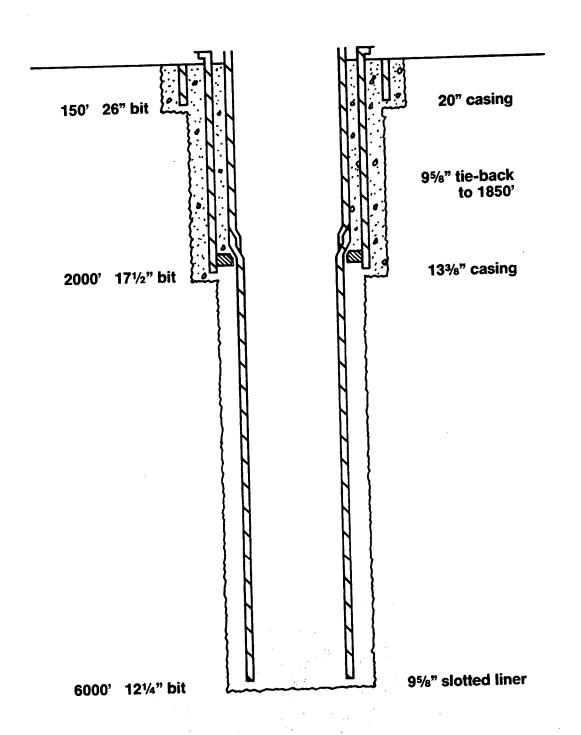


Figure 5-3
DESIGN FOR MEDIUM DEPTH IMPERIAL VALLEY BASE CASE WELL

DRILLING PROBLEMS	RILLING PROBLEMS Occurrences per well			
Lost Circulation Casing Cementing Fishing Side Tracking Twist Off Stuck Pipe Sloughed Hole	0.20 0.10 0.30 0.20 0.05 0.20 0.30 0.05	30.00 42.00 48.00 72.00 96.00 114.00 78.00 54.00	20000.00 10000.00 20000.00 5000.00 40000.00 30000.00 5000.00	

NOTE:

(1) Direct cost excludes hourly costs for rig rental and other charges not directly associated with the problem. Examples of direct charges are: service company experts to solve the problem, lost drilling fluid, LCM, additional cement materials, replacement casing hardware, and replacements for drill pipe and other hardware lost in the hole.

# Table 5-5 ASSUMED FREQUENCY AND AVERAGE COST OF DRILLING PROBLEMS FOR MEDIUM-DEPTH IMPERIAL VALLEY BASE CASE WELL

CALCULATION AREA 4.

#### INDIVIDUAL OPERATION Time and Cost Analysis

Operation	Oper. Total Time		Oper. Total Cost	Percent Total Cost
	(Hrs.)	(%)	(\$)	(%)
Road and Site Prep.	0	0.00	24800.00	3.30%
Drilling Operations	249	50.40%	135590.00	18.05%
10 Bits/Cutters	8	1,62%	53667.00	7.15%
I1 BHA	25	5.06%	13650.00	1.82%
12 Tripping Operations	23	4.66%	12247.00	1.63%
13 Auxiliary Operations	30	6.07%	46380.00	6.18%
14 Drilling Fluids	Ö	0.00%	33915.00	4.52%
15 Casing Operations	76	15.38%	306615.00	40.83%
16 Cementing Operations	83	16.80%	87448.00	11.64%
7 Maintenance	Ō	0.00	0.00	0.00%
18 Drilling Problems	Ŏ	0.00%	0.00	0.00%
9 Other	Ō	0.00%	36700.00	4.89%
20	-		Ì	
l Total Program	494	100.00%	\$751,012.00	100.00%

#### Table 5-6 CALCULATED TIME AND COST ANALYSIS FOR TROUBLE-FREE MEDIUM DEPTH IMPERIAL VALLEY WELL

CALCULATION AREA 4. INDIVIDUAL OPERATION Time and Cost Analysis

Operation Ope	r. Total Time (Hrs)	Percent Total Tim (%)	e Oper. Total Cost (\$)	Percent Total Cost (%)
8 Road and Site Prep.	0	0.00%	24800.00	2.96%
9 Drilling Operations	249	42.35%	135590.00	16.21%
10 Bits/Cutters	8	1.36%	53667.00	6.42%
11_BHA	25	4.25%	13650.00	1.63%
12+Tripping Operations	23	3.91%	12247.00	1.46%
13 Auxiliary Operations (1)	99	16.84%	101813.00	12.17%
14 Drilling Fluids (2)	Ŏ	0.00%	43477.00	5.20%
15 Casing Operations (3)	80	13.61%	309908.00	37.05%
16 Cementing Operations (4)	98	16.67%	101311.00	12.11%
17 Maintenance	Õ	0.00%	0.00	0.00%
18 Drilling Problems (5)	6	1.02%	3276.00	0.39%
19 Other	ŏ	0.00%	36700.00	4.39%
20	j			
21 Total Program	588	100.00%	\$836,439.00	100.00%

NOTES:

Due to the manner in which DRILTAC was designed, it was necessary to modify it to handle drilling problems. Therefore, problems have been incorporated into the various drilling operations as described in the notes.

- (1) Includes time and direct costs for fishing, side tracking, twist off, stuck pipe, and sloughed hole.
- Includes direct costs for lost circulation.
- (3) Includes time and direct costs for casing problems
- (4) Includes time and direct costs for cementing problems(5) Includes time for lost circulation.

#### Table 5-7 **CALCULATED TIME AND COST ANALYSIS FOR "AVERAGE" MEDIUM-DEPTH IMPERIAL VALLEY WELL**

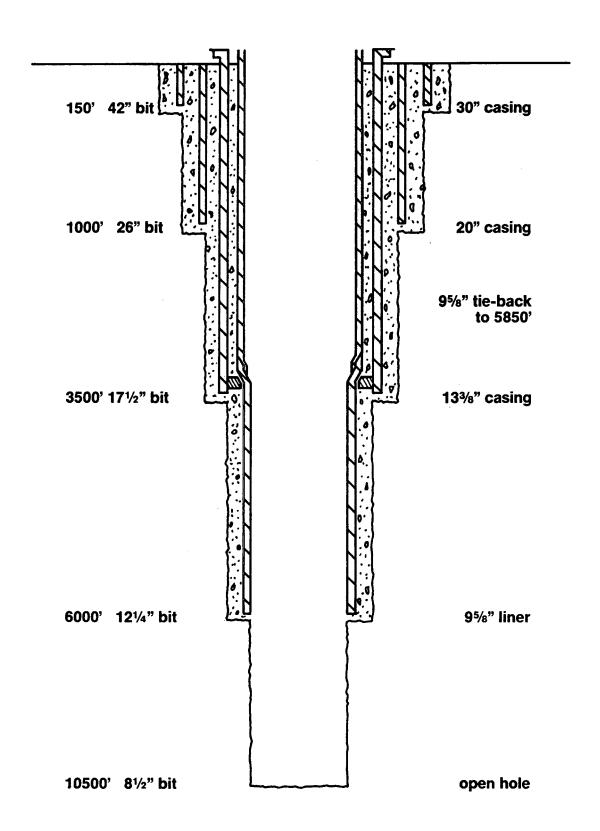


Figure 5-4
DESIGN FOR DEEP IMPERIAL VALLEY BASE CASE WELL

DRILLING PROBLEMS	Occurrences	Hours lost	Direct Cost
Problem Type	per well	/occurrence	/occurrence(1)
Lost Circulation Casing Cementing Fishing Side Tracking Twist Off Stuck Pipe Sloughed Hole	3.00 0.15 0.60 0.40 0.15 0.40 0.75 0.05	54.00 42.00 48.00 72.00 96.00 114.00 78.00 54.00	20000.00 10000.00 20000.00 5000.00 40000.00 30000.00 5000.00

NOTE:

(1) Direct cost excludes hourly costs for rig rental and other charges not directly associated with the problem. Examples of direct charges are: service company experts to solve the problem, lost drilling fluid, LCM, additional cement materials, replacement casing hardware, and replacements for drill pipe and other hardware lost in the hole.

Table 5-8
ASSUMED FREQUENCY AND AVERAGE COST OF DRILLING PROBLEMS FOR
THE DEEP IMPERIAL VALLEY BASE CASE WELL

data was loosely derived from experiences in the SSSDP and generalized information on drilling in the Imperial Valley.

The calculated cost summaries for a deep Imperial Valley well, without and with problems, are shown in Tables 5-9 and 5-10, respectively. The 10,500-foot base case well costs about \$2.0 million and requires over 69 days to drill. Of these totals, drilling problems account for approximately \$350,000 in direct and indirect costs (17.5 percent) and 14 1/2 days of added time on location.

#### 5.3 Calculations

#### 5.3.1 Summary of Cost Savings

The 13 AI systems and their projected goals for cost savings (described in Chapter 4 and summarized in Table 5-11) were applied to the three base case geothermal well scenarios to calculate the savings in overall drilling costs for the base case wells. The individual results were then combined based on potential near- and long-term impacts.

Near-term impacts were defined as those that could have an impact within three years. Because of the lead time needed to design and develop hardware systems, it is likely that only the expert systems could be commercialized within this time frame. To calculate overall average impacts of near-term projects, the following weighting system was used to average the savings of the three base case scenarios: 50 percent for The Geysers well, 25 percent for the Imperial Valley medium-depth well, and 25 percent for the deep Imperial Valley well. These weights were chosen in light of the projected drilling activity described in Chapter 3.

All projects were included in the category of possible long-term impacts. Since it is expected that the Imperial Valley will begin to play a larger role in geothermal development toward the end of this century, different weightings

CALCULATION AREA 4.

### INDIVIDUAL OPERATION Time and Cost Analysis

Operation	Oper. Total Time			Percent Total Cost
	(Hrs.)	(%)	(\$)	(%)
8 Road and Site Prep.	0	0.00	34750.00	2.13%
9 Drilling Operations	707	53.68%	441518.00	27.10%
10 Bits/Cutters	31	2.35%	168283.00	10.33%
11 BHA	60	4.56%	37500.00	2.30%
12 Tripping Operations	184	13.97%	112261.00	6.89%
13 Auxiliary Operations	41	3.11%	33125.00	2.03%
14 Drilling Fluids	l o	0.00%	88765.00	5.45%
15 Casing Operations	118	8.96%	438238.00	26.90%
16 Cementing Operations	176	13.36%	211379.00	12.98%
17 Maintenance	1 0	0.00	0.00	0.00%
18 Drilling Problems	ا ٥	0.00%	0.00	0.00%
19 Other	ا أ	0.00%	63200.00	3,88%
20		]		
21 Total Program	1317	100.00%	\$1,629,019.00	100.00%
	]			

## Table 5-9 CALCULATED TIME AND COST ANALYSIS FOR TROUBLE-FREE DEEP IMPERIAL VALLEY WELL

CALCULATION AREA 4.

### INDIVIDUAL OPERATION Time and Cost Analysis

Operation	Oper. Total Time	Percent Total Time		Percent Total Cost
·	(Hrs.)	(%)	(\$)	(%)
8 Road and Site Prep.	0	0.00	34750.00	1.76%
9 Drilling Operations	707	42.49%	441518.00	22.37%
10 Bits/Cutters	31	1.86%	168283.00	8.53%
11 BHA	60	3.61%	37500.00	1.90%
12 Tripping Operations	184	11.06%	112261.00	5.69%
13 Auxiliary Operations(1)	191	11.48%	169625.00	8.59%
14 Drilling Fluids (2)	0	0.00%	160390.00	8.13%
15 Casing Operations (3)	124	7.45%	443676.00	22.48%
16 Cementing Operations (4)	205	12.32%	241379.00	12.23%
17 Maintenance	0	0.00%	0.00	0.00%
18 Drilling Problems (5)	162	9.74%	101250.00	5.13%
19 Other	0	0.00%	63200.00	3.20%
20				100 000
21 Total Program	1664	100.00%	\$1,973,832.00	100.00%
·		,		

NOTES:

Due to the manner in which DRILTAC was designed, it was necessary to modify it to handle drilling problems. Therefore, problems have been incorporated into the various drilling operations as described in the notes.

- (1) Includes time and direct costs for fishing, side tracking, twist off, stuck pipe, and sloughed hole.
- (2) Includes direct costs for lost circulation.
- (3) Includes time and direct costs for casing problems.
- (4) Includes time and direct costs for cementing problems.
- (5) Includes time for lost circulation.

## Table 5-10 CALCULATED TIME AND COST ANALYSIS FOR "AVERAGE" DEEP IMPERIAL VALLEY WELL

Change in Drilling Parameter	Bit Optimiz. ES	Mud Optimiz. ES	BHA Design ES	Lost Circ. ES	Casing Design ES	Stuck Pipe ES	Fishing ES	Cement Design ES	Cement Problem ES	Robotic Bit System	Robotic Rig Hydraul.	Robotic Pipe Handling	Robotic Pipe Inspect.
Increase Mud Maint. Cost								, , , , , ,			100%		
Increase Rig Rental										100%		10%	
<pre>Increase Rig Rental (Prod.Zone)</pre>													25%
Increase ROP	25%	10%	10%							100%	10%		
Reduce Cement Prob. Occurrence			<del></del>					50%					
Reduce Cement Prob. Cost											50%		
Reduce Cement Prob. Time									50%		50%		
Reduce Fishing Occurance			25%										
Reduce Fishing Cost							50%						
Reduce Fishing Time							50%						
Reduce Hole Sloughing Occurrence	•	100%									100%		
Reduce Intermed. Hole Depth					200 ft								
Reduce Lost Circul. Occurrence	. 1/1 1/11	50%		50%							50%	····	
Reduce Lost Circul. Time				50%		25%							
Reduce Prod. Casing Cost					\$500/1	00'							
Reduce Side Track Occurrence			25%							50%			
Reduce Sloughed Hole Time		<del></del>	****			25%	25%		,				
Reduce Stuck Pipe Occurrence		50%		50%		50%				50%	50%	25%	
Reduce Stuck Pipe Cost						25%							
Reduce Stuck Pipe Time						25%	25%						
Reduce Trip Time				<u> </u>								50%	
Reduce Twist Off Occurrence			25%							50%		25%	90%
Reduce Twist Off Time							25%						

Table 5-11
SUMMARY OF ASSUMED GOALS FOR ARTIFICIAL INTELLIGENCE APPLICATIONS

were used to calculate average impacts on overall drilling cost. For longterm effects all base case scenarios were weighted equally, resulting in the Imperial Valley as a whole being twice as important as The Geysers.

Table 5-12 presents the result of the individual costing runs for each base case and AI application along with the weighted average potential savings for the near- and long-term. Savings are expressed both as weighted-average percent and dollars.

#### 5.3.2 Sensitivity of the Results

The potential savings attributed to each AI application are merely a reasonable goal that could be used in planning the R&D for that project. There is a large degree of uncertainty in defining these goals, and any individual would probably have developed a different set of estimates. To allow the reader to apply different goals for AI systems, sensitivity studies were run on most of the areas of savings to show the specific impact of each (refer to Figures 5-5 to 5-10). By comparing the impact for the case assumed in this study to a different reasonable value, the reader could modify the predicted savings in drilling costs based on different reasonable savings goals.

For example, the intelligent bit control system has, as a goal, to increase rate of penetration by 100 percent. A 100 percent increase in rate of penetration, by itself, yields a weighted savings of about 16 percent in the long-term (from Figure 5-7). From Figure 5-7, a 50 percent reduction in rate of penetration would result in long-term weighted savings of 11 percent, a drop in savings of 5 percent. To get an idea of the effect of substituting 50 percent increase in rate of penetration for the 100 percent assumed in the analysis, merely subtract the 5 percent marginal savings from the overall predicted savings of 4.6 percent, for a resultant <u>decrease</u> in drilling costs

	PERCENT DEC	T FROM BASE WELL	AVERAGE SAVINGS					
SYSTEM DESCRIPTION	GEYSERS	SSSDP	IMPERIAL VALLEY	SHORT TERM W	\$/WELL	LONG TERM WE PERCENT	\$/WELL	
BIT OPTIMIZATION ES	7.98	7.25	4.80	7.00	104054	6.68	99911	
MUD OPTIMIZATION ES	7.25	9.08	4.24	6.96	106585	6.86	106838	
BHA DESIGN ES	4.80	4.32	3.22	4.29	63083	4.11	60756	
LOST CIRCULATION ES	3.71	6.95	1.92	4.07	65387	4.19	69132	
CASING DESIGN ES	2.36	1.78	4.34	2.71	35083	2.83	35295	
STUCK PIPE ES	2.42	. 3.29	1.89	2.51	37849	2.53	38691	
FISHING ES	1.36	1.48	1.48	1.42	20324	1.44	20481	
CEMENT DESIGN ES	1.01	.80	.88	.93	13159	.90	12631	
CEMENT PROBLEMS ES	.64	.50	.52	.58	8226	. 55	7854	
AUTOMATED BIT CONTROL	5.59	5.86	2.35	N/A	N/A	4.60	72306	
AUTOMATED RIG HYDRAULICS	3.14	5.51	1.18	N/A	N/A	3.28	54821	
AUTOMATED PIPE HANDLING	.30	2.49	.50	N/A	N/A	1.10	19237	
AUTOMATED PIPE INSPECTION	.17	23	.23	N/A	N/A	10	-1459	
-								

Table 5-12 SUMMARY OF PREDICTED SAVINGS FROM AI SYSTEMS

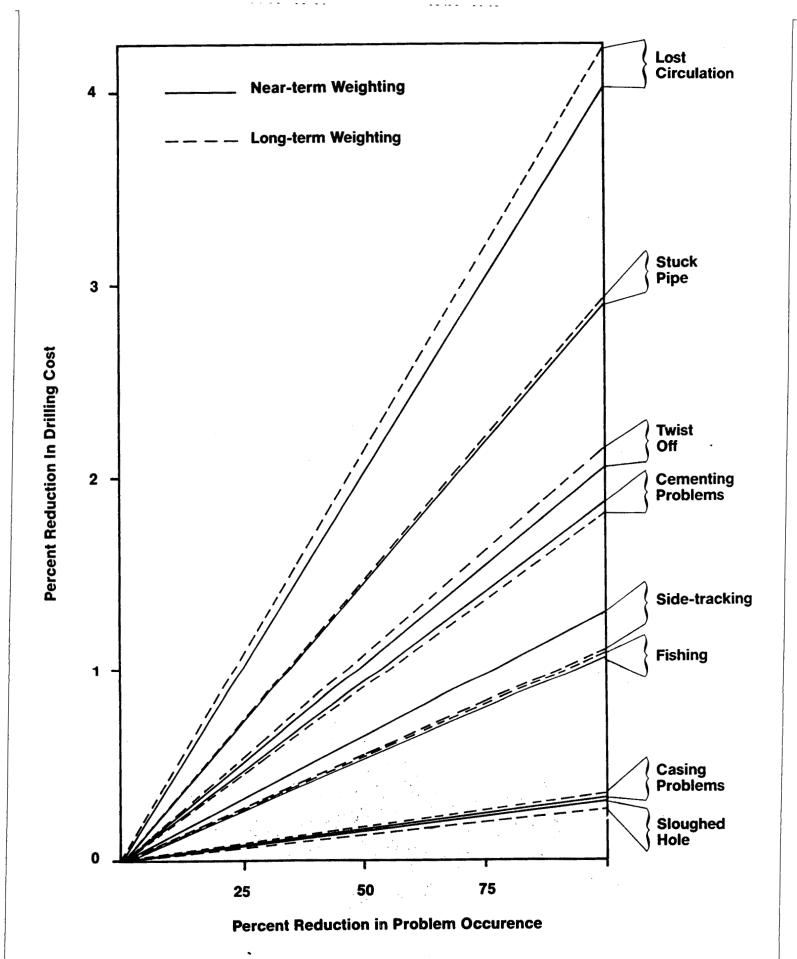


Figure 5-5
SENSITIVITY OF DRILLING COSTS TO PROBLEM OCCURRENCES

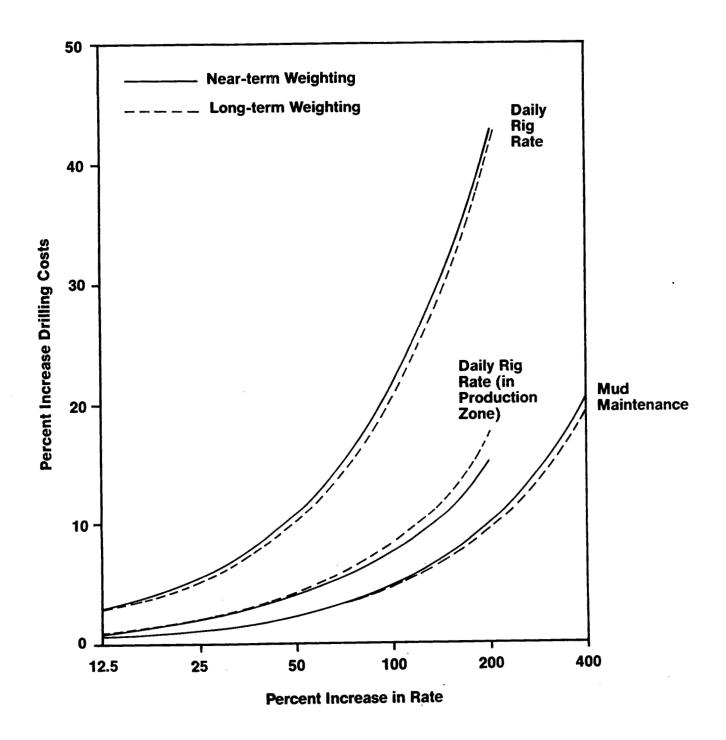


Figure 5-6
SENSITIVITY OF DRILLING COSTS TO RIG CHARGES

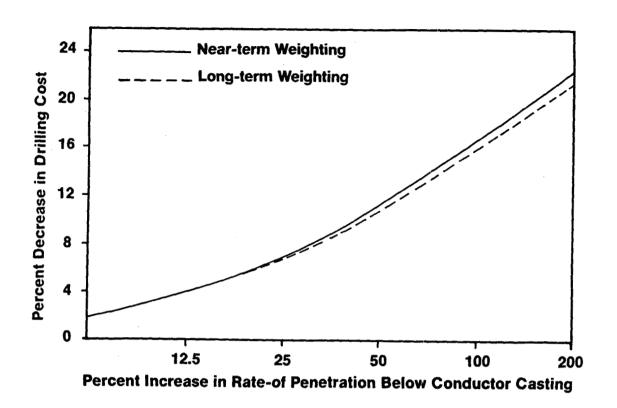


Figure 5-7
SENSITIVITY OF DRILLING COSTS TO RATE OF PENETRATION

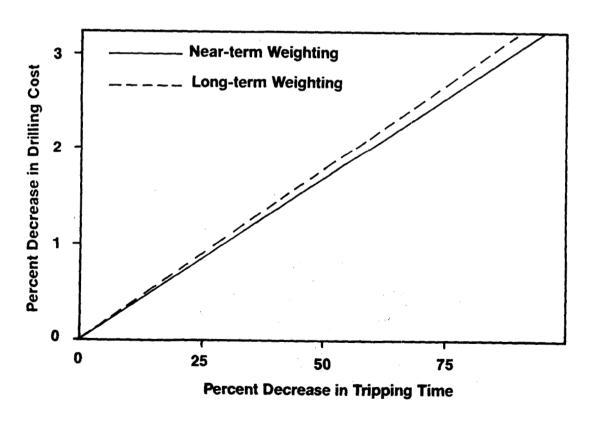


Figure 5-8
SENSITIVITY OF DRILLING COSTS TO TRIPPING RATE

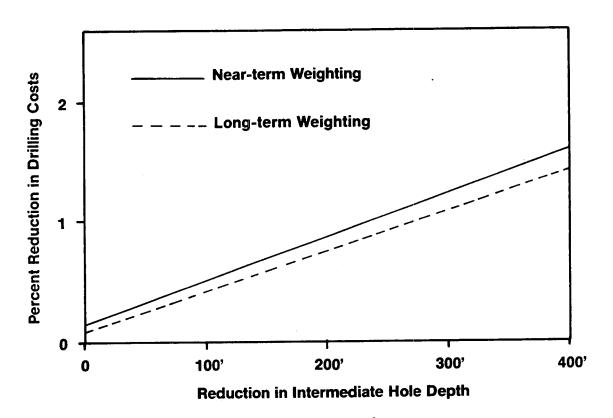


Figure 5-9
SENSITIVITY OF DRILLING COSTS TO INTERMEDIATE HOLE DEPTH

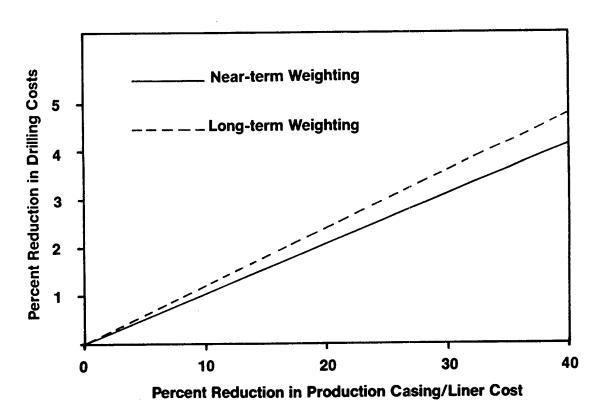


Figure 5-10
SENSITIVITY OF DRILLING COSTS TO PRODUCTION CASING/LINER COSTS

of 0.4 percent. It should be noted that this is only an approximation of what savings would occur under the new assumptions. For AI systems with savings predicted in more than one area, the savings may not be independent, and the effect of changing one goal may increase or decrease the impact of the other goals.

Within the ranges of savings predicted for each AI system the most sensitive parameters are the rig rental rate and the rate of penetration (as can be seen from Figures 5-5 to 5-10). Predictions of savings based on assumed changes in these parameters must be used with care.

#### CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

#### 6.1 Summary of Results

Table 6-1 summarizes the near- and long-term potential savings that could be realized from the particular artificial intelligence systems, assuming the attainment of the performance goals specified for each in Chapter 4. Savings for each are divided into low (less than 2 percent), medium (between 2 and 4 percent) and high (greater than 4 percent).

#### 6.2 Discussion of Specific Systems

The AI systems evaluated in this report are reviewed in this section in order of decreasing predicted savings. Specific matters discussed for each, where appropriate, are the reliability of the assumptions used in determining the savings, the current status of AI systems in the particular area, and the research needed to extend the system to geothermal applications.

#### 6.2.1 AI Systems for Near Term Cost Reduction

#### Expert System for Drill Bit Optimization

The expert system for drill bit optimization scored the highest of all systems evaluated in this study with an estimated cost savings of 7 percent using near-term weighting. This is based on an assumption that the expert system would lead to a 25 percent decrease in rotating costs. Since drilling costs per foot are a major factor in overall drilling costs, the true savings that could be realized from an expert system for bit control may be substantially lower or higher than calculated in this analysis.

In the oil industry, well-recognized techniques based on offset drilling records exist for optimizing drill bit selection and operation. It is likely that these techniques apply directly to geothermal drilling. Although no

=======================================	=======================================	
SAVINGS	NEAR-TERM WEIGHTING	LONG-TERM WEIGHTING
HIGH >4%	Bit Optimization ES Mud Optimization ES BHA Design ES Lost Circulation ES	Mud Optimization ES Bit Optimization ES Robotic Bit Control Lost Circulation ES BHA Design ES
MEDIUM <4% >2%	Casing Design ES Stuck Pipe ES	Robotic Rig Hydraulics Casing Design ES Stuck Pipe ES
LOW <2%	Fishing ES Cement Design ES Cement Problems ES	Fishing ES Robotic Pipe Handling Cement Design ES Cement Problems ES Robotic Pipe Inspect.

## Table 6-1 SAVINGS OF ARTIFICIAL INTELLIGENCE SYSTEMS

expert system for bit optimization was identified in this study, based on the potential savings to be realized it is likely that either: (1) proprietary systems have been developed; (2) no system exists, but manual methods are adequate and the use of an expert system is not necessary; or (3) the potential savings predicted in this study (based on Adams, 1985) are too optimistic. RECOMMENDATION: Let the oil industry develop this system and transfer it to geothermal if appropriate.

#### Expert System for Mud Optimization

The potential savings from an expert system for mud optimization are almost as high as those described above under bit optimization (6.96 versus 7.00 percent). Important assumptions for this system are the 10 percent increase in rate-of-penetration and the fact that there was no increase in charges for implementation of the system.

At least one widely offered expert system exists for mud optimization in oil and gas drilling--NL Baroid's MUDMAN. To develop such a system for geothermal applications, the most obvious method would be to extend the capabilities of an existing system (be it MUDMAN or another) to include data for geothermal drilling fluids and reservoir conditions. Including air as a drilling fluid in the system would also be a benefit to the geothermal drilling industry. RECOMMENDATION: If an existing expert system for mud design and monitoring could be customized for geothermal drilling, including air drilling, it would be a worthwhile project.

#### Expert System for Bottom Hole Assembly Design

The assumptions used as goals in calculating potential savings for this system are fairly reasonable. If such a system were developed for oil and gas drilling, it would probably be readily applicable to geothermal drilling in the Imperial Valley. However, the conditions at The Geysers--highly abrasive

rock, high-speed turbodrilling, and air drilling--are not typical of oil and gas applications.

An expert system could be developed that would couple a knowledge base with a dynamic drill string model (such as Sandia's GEODYN (Baird and others, 1984)) to optimize the BHA design for efficient drilling while minimizing the frequent problem of severe vibrations. RECOMMENDATION: An expert system for BHA design is an attractive possibility for R&D.

#### Expert System for Lost Circulation

The expert system for lost circulation scored the highest of all proposed AI systems which addressed drilling problems. This is appropriate since lost circulation is generally accepted as the overall most serious problem in geothermal drilling. GEOTHERM, the preliminary prototype expert system developed by Sandia National Laboratories, is at present not field worthy. It needs significant expansion of its capabilities for diagnosing lost circulation, selecting lost circulation materials (LCMs) based on well and formation characteristics, and preventing lost circulation (Satrape, 1987). While lost circulation is also a serious problem in the oil industry (Messenger, 1981), an expert system developed to handle lost circulation in oil and gas wells would not be readily applicable to geothermal drilling due to the very different conditions associated with geothermal wells (i.e., lowpressured reservoirs, widespread fractured formations, and high temperatures). RECOMMENDATION: The possibility of expanding GEOTHERM to handle diagnosis, prevention, and selection of LCM based on conditions in the well should be considered.

#### Casing Design Expert System

The assumptions used to calculate the potential of a casing design expert

system were that, for the particular cases studied, the system would recommend a different well design (200 feet shallower intermediate hole, less expensive production casing). These were conditions set to determine potential savings that could be realized if a well were over-designed. In reality, the savings associated with a casing design expert system would be more associated with overall field development--larger, more productive wells would be more expensive but would reduce the number of wells needed. RECOMMENDATION:

Before developing an expert system for casing design, a detailed analysis should be conducted considering field development practices and costs and the possible areas for improvement.

#### Expert System for Stuck Pipe

An expert system to handle and prevent stuck pipe problems may have moderate impact on the overall cost of geothermal drilling. Teknowledge has developed SECOFOR for oil and gas applications, and Elf Aquitane, the project sponsor, obviously believes that the potential savings were worth the cost of development. Such a system may be applicable to geothermal applications without significant additional effort. RECOMMENDATION: An expert system for handling stuck pipe problems is likely to be a worthwhile development; before embarking on such a project, the possibility of obtaining license to SECOFOR should be explored.

#### Other Systems

Expert systems for fishing, cement design, and cement problems show potential savings significantly less than the other systems evaluated in the study. RECOMMENDATION: Unless data available at a later time indicates that greater savings could be realized from these systems, they should not be developed at the expense of those systems with greater potential.

#### 6.2.2 AI Systems for Long-Term Cost Reduction

#### Expert System for Mud Optimization

See discussion in Section 6.2.1.

#### Expert System for Bit Optimization

See discussion in Section 6.2.1.

#### Intelligent Bit Control

Based on the assumptions used in this analysis, a system for robotic bit control has the potential to reduce overall drilling costs by 4.6 percent. However, this estimate is very sensitive to the assumptions for reduced rotating costs and increased rig rental rate. Because of the likely high development cost, this system will probably only be developed for application in expensive offshore and remote environments. RECOMMENDATION: Before embarking on an expensive R&D project to develop an automated bit control system, a detailed analysis of costs and benefits of the system is warranted.

#### Expert System for Casing Design

See discussion in Section 6.2.1.

#### Expert System for Bottom Hole Assemble Design

See discussion in Section 6.2.1.

#### Intelligent Rig Hydraulics System

Based on the savings assumed in this analysis, a robotic rig hydraulics system would result in average drilling cost savings of about 3.3 percent per well. As for the case of the robotic bit control system, these savings could be markedly different depending on the costs of implementing such a system. On the positive side, it should be noted that many of the components for this system already exist in the drilling industry today, including an automatic

mixing system, continuous measurement of mud properties, and expert systems for mud monitoring and design. Missing is a system that would link all of these and operate at the rig site. RECOMMENDATION: A thorough evaluation of costs and benefits of this system is in order before substantial funds should be spent on R&D.

#### Expert System for Casing Design

See discussion in Section 6.2.1.

#### Expert System for Stuck Pipe

See discussion in Section 6.2.1.

#### Other Systems

Unless revised cost and/or savings assumptions are warranted, the development of intelligent pipe handling and pipe inspection systems will not result in significant savings in drilling geothermal wells and is not recommended. The assumed cost of using these systems outweighs the likely benefits that could accrue.

#### 6.3 Recommendations

#### 6.3.1 Development of AI Systems

Based on the results of the analysis conducted in this study and described elsewhere in this report, expert systems for bottom-hole assembly design and lost circulation control could result in significant savings in geothermal drilling and should be considered for R&D funding. Expert systems for bit optimization, mud optimization, and stuck pipe are also worthwhile projects, but R&D funding should wait until these systems can be transferred from the oil drilling industry where they either exist or are likely to be developed in the near future. Detailed analysis, emphasizing both potential savings and likely costs, is recommended before funding projects to develop an

intelligent bit control system, an intelligent mud system, and an expert system for casing design. Development of other systems evaluated in this study is not recommended at this time.

#### 6.3.2 Other Recommendations

Much of the analysis in this study was based on reasonable assumptions and very limited hard data. The reliability of the base case models, in particular the drilling problems assumptions, could be greatly improved if more data (and more recent data) on actual wells were available. This is especially true for the Imperial Valley wells.

DRILTAC, the well design and costing spreadsheet used in this analysis, was indispensable in calculating the potential savings from the various AI applications. Its value as a R&D strategy and planning tool would be greatly enhanced with the following modifications:

- o The spreadsheet should be modified to handle various types of drilling problems. In its current state, lost time for all drilling problems is lumped together under a single input in each casing zone and there is no straightforward means to account for direct costs associated with drilling problems.
- o The default values in the program and much of the data in the user's manual seem to be geared for oil and gas drilling. These should be extended to include geothermal drilling.
- o The spreadsheet appears to calculate cement volumes based on the difference between casing O.D. and bit size, and the length of the cemented zone. This is inaccurate in the case of a tie-back string run inside of intermediate casing. This "bug" should be corrected.

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### APPENDIX A:

DESCRIPTION OF DRILTAC

Excerpted from:
DRILTAC User's Manual

#### USER'S MANUAL

#### DRILTAC

(DRILLING TIME AND COST EVALUATION)

By

Resource Technology, Incorporated 4555 South Harvard Avenue Tulsa, Oklahoma 74135 (918) 743-2985 This Work Was Supported By The U.S. Department of Energy,

Sandia National Laboratories,

Under Contract DE-AC04-76DP00789

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#### A. INTRODUCTION

A number of computer programs have been developed to assist in the analysis of well design procedures. They relate to casing design, mud hydraulics, total well cost, etc. None, however, are available in the public domain that simultaneously evaluate the time and cost factors of the drilling equipment, the operational activities, the purchased components, and the inherent interrelationships of these elements. DRILTAC meets this need. This program is designed for use on a conventional personal computer (P.C.) with 640K of internal memory. It is easy to use and extremely versatile. The program utilizes LOTUS 1-2-3 for the program software. LOTUS 1-2-3 is a spreadsheet-type program that displays the traditional grid of columns and rows.

DRILTAC has the ability to develop and analyze a model of a hypothetical well and a model of the drilling system that will be used to drill the well. The program allows the user to change the geological environment of the well and the well design to any configuration desired. In addition, the user can change the various drilling parameters such as the mud program, the casing program, trip times, bottom hole assemblies, etc. Time and cost factors of every element of the drilling system and the drilling operation can also be changed as desired. Because of this flexibility, the program is extremely useful for testing the sensitivity of the total time and cost of drilling a well against individual system components, well design elements, or drilling operations time and/or cost change(s). Multiple changes can also be tested and evaluated by use of sensitivity analysis techniques.

#### B. PROGRAM CONCEPT

#### 1. The Program

DRILTAC is a spreadsheet oriented program that allows the user to theoretically design and drill a well of any configuration, determine the total time and cost of drilling the well and then evaluate the incremental time and cost factors attributed to each element of the drilling operation and/or its associated drilling system components. The program is based on LOTUS 1-2-3 software and consists of two input data bases, and four calculation display areas. data bases consist of a well design file that allows the user to design any type of well, and an operations time and cost file that allows the user to input time and cost factors such as trip time and casing cost. The four calculation display areas are: 1) Operation Variable Cost Calculation, 2) Time and Cost Analysis, Day Rate, 3) Time and Cost Analysis, Footage Rate, 4) Individual Operation, Time and Cost Analysis. Varying the input data will change the calculation display area data, thereby allowing the operator to evaluate the effects on time and cost of changing the well design or the drilling operation. Application of sensitivity analysis techniques allows the evaluation and/or comparison of the effects of multiple changes and the time value involved.

#### 2. Program Methodology

The designing of a well and the establishment of the drilling instructions can be divided into a series of functions. These functions, as noted in Figure 1, can be combined into a <u>simplified</u> logic diagram that displays the order in which each function must be accomplished, and the interrelationships involved.

As noted, the functions of geology (geologic understanding) and downhole equipment requirements are considered first and are combined to determine the casing program which in turn defines the well design. Having established this design, the drilling methods can then be determined. Drilling methods refers to the types of drilling procedures such as air drilling, mud drilling, coring, etc., that will be used to make hole. Bit programs, fluid programs, and cementing programs are determined next. Special drilling instructions such as bottom hole assembly changes, number of surveys and logging trips, and special tool requirements must also be defined.

WELL DESIGN AND DRILLING INSTRUCTIONS LOGIC DIAGRAM (Abbreviated)

Figure 1

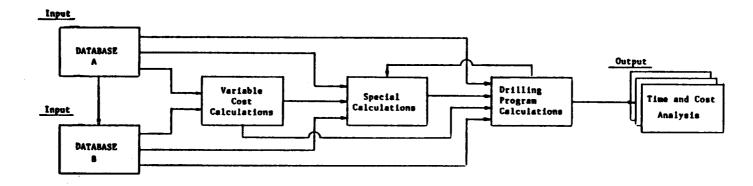
In reality, when all of the above functions have been completed, a drilling contract would normally be obtained, which in turn would define the type of rig used to drill the well. This contract would also establish day rates or footage rates, and other cost factors such as who pays for the pipe or the fuel. In this program, the type of rig, the payment schedule, other cost factors, etc., are selected by the program user.

The DRILTAC program allows the user to logically determine or perform all of the above functions, to vary the time and cost factors involved in each and to evaluate the resulting drilling program. DRILTAC performs the above operations by means of the logic design noted in Figure 2. This design requires the operator to input data of his choice into DATABASE A and B. This data is then combined in Calculation Area 1 to determine the individual variable cost increments associated with the different drilling operations. It also is combined in a special calculation area, into a series of equations that are used throughout the entire program. These equations automatically compute data such as depth drilled or trip time.

Values from DATABASE A and B, the variable cost data, and the special calculations, are then combined in the drilling program calculation area to determine the drilling program values. These calculations are then evaluated to develop the three remaining calculation display areas.

Because of the nature of the operating sequences, they can be combined into a computer spreadsheet program. LOTUS 1-2-3 software is used for this purpose. The spreadsheet is divided into seven main areas. DATABASE A defines the well design and the drilling instructions. It establishes the actual well configuration and casing program, the drilling techniques to be used, the bit program, the drilling fluids program and the cement program. It also defines the type of rig to be used and any auxiliary operations that may be required. The data required for Database A must be input by the model operator.

1 -



DRILTAC PROGRAM LOGIC DIAGRAM

Figure 2

DATABASE B incorporates the operation time and cost required by the various drilling and auxiliary operations. It includes transportation costs, rig operating rates, bit change time, etc. Some of this data is automatically entered by the computer program and some must be entered by the operator.

The input data for both DATABASE A and B can be obtained from Appendix A and/or B of this document. These Appendices define the requirements of each of the subsections in DATABASE A and B. They also provide numerous tables and charts from which the required data can be obtained.

Calculation areas 1, 2, 3 and 4 perform the necessary computations to determine the output displays of the program. Calculation area 1 displays the Variable Cost data. Calculation area 2 displays the time and cost factors associated with each drilling operation, and the cumulative time and cost as each operation takes place. These calculations are based on Day Rate costs. Calculation display 3 illustrates the time and cost of the drilling program in terms of a Footage Rate. Calculation area 4 displays the cumulative time and cost of each of the drilling operations, and certain key items such as total bit cost. The percent (%) of each of these costs with regard to the total cost is also shown.

#### NOTE:

- DATA CAN ONLY BE ENTERED IN DATABASE A AND DATABASE B AND ONLY IN THOSE CELLS THAT ARE UNDERLINED.
- IN CALCULATION AREAS 1 THROUGH 4 DATA WILL ONLY APPEAR IN THOSE CELLS NOT CONTAINING A DASHED LINE.

# DATABASE A

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# APPENDIX B:

INPUT DATA FOR

BASE CASE WELL SCENARIOS

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GEYSERS INPUT DATA

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86	Other	i	1	1	1	1	1.	J
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88	Additives (Types)	1	1	1	1	<b>!</b>	_!	
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92	Cement Type	:6+SILICA	16+SILICA	16+S+RET	IG+S+RET	1	.1	1
93	Annulus Fill Ht. (Ft.)	1 300.00	1500.00	3650.00	1350.66		!	<b>!</b>
94	Unit Cost (\$/Cu. Ft.)	7.00	7.60	7.60	7.66	!	_	!
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9B 1.9 Auxiliary Operations	!		i				!		!		!			
99 Surveying (No. of Runs)	ļ		-i.					3.56	<u>.</u>		i		i	
188 Logging (No. of Runs) 181 Other (No. of runs)	ļ		-,		-	<b>1.</b>			.' !		ا د - خ		' 17 ·	
162	;		- ¦	1.91	;			un-is-				r-nano	; ;	ng
183 1.10 Bottombole Assembly (BHA) Changes	i		. ;	1.6ē	i	7.00	-	11ing 6.88	) 	ob rein	¦		· 	
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14 Mebilizati	DN	: 6.6	: 15600.00 :	
15		1 1	1	
16 2.4 Rin Operation	o Rates	1	1	
17 Day Rate (	\$/Hr.)	1	1	
18 Standby/	Mondrilling	1	160.02 :	
19 Rig With	Fipe	<b>t</b> 1	260.00	
29 Rig With	out Pipe	!	!!	
21 Other		}	1	
22 Footage Ra	ites (\$/Ft.)	1		
23		1	!!	
24 2.5 Fuel Consump	tion (Gal./Hr.)	1	1	
25 Standby/No	ndrilling	1	1	15.7
26 Drilling		1	! !	62.7
27 Tripping		1	! !	
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33 30000-50	695,	:	:	9.6
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	ore Drilling - Conv.		<u> </u>	
51 Other - Co	re Drilling - Wireline	}	!!	

TABASE B.  OPERATION TIME AND COS	T DATA		
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2 Other - Other			!
2 Beller - Deller 3	1 !	<b>'</b>	! !
4 2.10 Supervision Cost (\$/Hr.)		62.00	!
5			!
6 2.11 Condition Brilling Fluids (Avg. Hrs.)	1 1.5		}
7	1		
B 2.12 Water Cost (Total \$)	1	}	:
9 Furchase Cost	;	1650.00	)
ß Disposal Cost	1	959.66	:
1	1	<b>!</b>	{
2 2.13 Bit Change (Avg. Hrs.)	1 1.5	1	1
3	1	}	! 1
4 2.14 Bottomhole Assembly (BHA) Change (Avg. Hrs.)	1 5.€	<b>;</b>	1
5	:	l	<b>;</b>
6	1	<b>!</b>	:
7 2.15 Drilling Penetration Rates (Ft./Hr.)			<b>;</b>
8 Ione A		<b>.</b>	<b>.</b>
9 Rotary DrlaAir	:	<b>.</b>	! <del></del>
B Rotary DrigMud	1		1 18.6
i Downhole Mtr. Brlo.			! 
Core Brillino - Conventional		i	<u>'</u>
Core Drilling - Wireline	i	i ,	i
4 Other	i	i 1	i
5 Ione B	i 1	i •	i I
6 Rotary DrigAir 7 Rotary DrigMud	1	1 1	15.0
7 Fotary DrigMud B Downhole Mtr. Drig.	•	! !	
Core Drilling - Conventional	;	) !	i !
G Core Drilling - Conventional		! !	' :
1 Other	1	!	·
2 Zone C	1		· 
Rotary DrlgAir	1	· }	ł
4 Rotary DrigMud	1		18.6
5 Downhole Mtr. Drlg.	;	,	18.6
6 Core Drilling - Conventional	1	1	1
7 Core Drilling - Wireline	1	l.	1
B Other	1	1	
7 Zone D	;	•	 
A Rotary DrloAir	1	<b>!</b>	29.5
fotary DrlgMud		!	l
2 Downhole Mtr. Drla.	ï	ŀ	
Core Drilling - Conventional	;	1	
4 Core Drilling - Wireline	ł	1	1
5 Other	;		

VATÁ	BASE B. OPERATION TIME AN	D COST DATA		
	Operation		(Oper. Cost)  . (\$)	
96	Zone E	!	<u>'</u>	<del></del>
97	Rotary BrloAir	;	: :	
98	Rotary DrimMud	1	_	
99	Downhole Mir. Drla.	ł	: :	
186	Core Brillino - Conventional	1	:	
61	Core Drilling - Wireline	ł	1 1	
192	Other	1	1	
<b>£</b> 3	Zone F	:	;	
184	Rotary DrloAir	1	1	
85	Rotary DrloMud	1	1	
18è	Downhole Mtr. Drla.	1	1	
<b>#</b> 7	Core Drilling - Conventional	İ	: :	
128	Core Drillino - Wireline		1	
45	Other	ŀ	1	
119	Ione 6	1	1	ł
111	Retary DrluAir	i	;	
112	Rotary DrlgMud	ł	1	!
113	Downhole Mtr. Drlg.	;	:	
114	Core Brilling - Conventional	1	1	
115	Core Drilling - Wireline	1	:	
116	Other	!	1	
117		1	1	
118	2.16 Reaming Operations	1	1	l
19	Reseing Rates (Ft./Hr.)	ŀ	1 1	
12₽	Zone A	: 5.6	1	<b>!</b>
21	Zone B	: 5.€	1	
122	Zone C	¦ 5. <i>€</i>	1	1
23	Zone D	: 5.₽		
124	Zone E	: 6.0		ł
125	Zone F	. 9.6	-	
126	Zone 6	. 6.8	1	i
127		i.		-
128	2.17 Pipe Handling Operations	!		i
129	Round Trip (Avg. Hrs./Round Trip)	!	:	-
130	6-4999'	1 3.0		i
131	5###-9999'	1 4.9		
132	18996-149997	1 12.5		•
133	15008-19999	1 21.0		
134	26686-24999'	; 31.5		i
135	25688-29999'	1 44.0		1
136	3999-34997	1 58.5		i
137	35994-39999	1 75.0		
138	4 <i>0080-4</i> 4999'	1 93.5	i	i

MEDIUM-DEPTH IMPERIAL VALLEY INPUT DATA

i datab I	OPERATION TIME AND COS	T DATA				
; }					i Misc.	
		(Hrs.)	1	(\$)	1 !	
149		!	!		· · · · · · · · · · · · · · · · · · ·	
	2.1B Auxiliary Operations - Surv. (Avg. Hrs./Run)	!	;			
142	6-4979'	3.6				
143	5446-9999	: 3.5				
144		1 5.4				
145	15269-19999	7.0			, , , ,	
146	26666-24799'	9.6			, ,	
147	25666-299999	1 11.0			1 1	
148		113.5			, ,	
	3666-3499°				1 1	
149	35999-39999`	1 16.4			1 i	
156	4000-4499°	1 19.6			i i	
151	45@@#-5@@@@?	21.5	i		i i	
152	AF Aug 191 - Barrellan - Lauria	•	i		i i	
	2.19 Auxiliary Operations - Looging	i .	i ,		i i	
154	Loc. Time (Avo. Hrs./Run) & Cost (\$/Run)		i		i i	
155		7.00	101	.00.20	i i	
156	5#8#~9999	ļ	ļ		1	
157	10000-14999	ļ			1 1	
156	15#90-19799'	¦			1	
159	28262-24999'				: :	
169	25###-29999"	1			1	
161	3 <del>6£6£</del> -34999'	!	l		1	
162	<b>35###-</b> 39999°	1	1			
163	46669-4479 <b>9</b> *	1	!		1	
164	45@@@~5@@@@*	1			;	
165		· ·	;		1	
166 2	2.28 Auxiliary Operations - Other	1	:		! !	
167	Operation Time Per Run (Avg. Hrs./Run)	117.9	ł		:This ac	counts for average lost
168	Operation Cost Per Run (Avg. \$/Run)	:	1 3			d cost for problems (exc
69		!	!		:lost ai	rc, casing, and cement)
179 2	2.21 Coring Operations	i	:		1 1	
171	Core Drilling - Conventional	!	!		: :	
172	Coring Operation Charges (\$/Hr.)	1	1	55.00	!!	
173	Change Drilling Tools (Avg. Hrs.)	5.9	!		: :	
174	Core Barrel Length (Ft.)	!	1	,		
175	Trip In/Out (Avg. Hrs.)		!			
176	£-4999°	3.5	1		: :	
177	5486-9999°	4.6			1	
178	19986-14999	1 11.6	,		1 1	
179	15000-19999'	17.6				
189	24787-25779	1 28.€			1	
181	38226-56280'	57.₽				
182		1	•			
83			í			

DATA	ABASE B. OPERATION TIME AND	COST DATA		; !
	Operation	Op Time  (Hrs.)	Oper. Cost	;   Misc.   
184		1	<del> </del>	
185		ì	:	<b>!</b>
196	Core Drilling - Wireline	:	<b>;</b>	1
187	Coring Operation Charges (\$/Hr.)	1	50.00	1
188	Rig Up/Bown (Ava. Hrs.)	1 2.€		<b>!</b>
189	Change Drilling Tools (Avg. Hrs.)	5.6	:	<b>!</b>
190	Core Barrel Length (Ft.)	i	!	lI
191	Trip In/Dut (Avg. Hrs.)	<b>†</b>	<b>(</b>	1
192	₽-4999°	1.5	!	1
193	5#f#-9999'	1 1.3		! !
194	18888-14999'	1 1.5	:	
195	15486-19799'	1 2.5		l
196	28888-299997	1 4.₽	1	1 1
197	3 <b>2662-56662</b> '	1 9.9	}	<b>!</b>
198		1	:	1 1
199		<b>;</b>	•	<b>!</b>
2 <b>8</b> £		;	1	<b>!</b>
261		1	1	t t
<b>2@</b> 2	2.22 Casing Operations	i	ł	1
203	Rig Up (Avg. Hrs.)	: 2. <del>0</del>	! !	<b>!</b>
2₿4	Rig Down (Avg. Hrs.)	: 2.#	1	l l
2₽5	Prepare to Run Casing (Avg. Hrs.)	1 6.₽		<b>!</b>
206	Other (Avo. Hrs.& Total Cost \$)	!		!
2€7		1		<b>!</b>
298	Zone A	i	•	<b>!</b>
269	Casing Run Time (Avg.Hrs./1000°)	: 3.5		<b>!</b>
21€	Tools & Services (Total Cost #)	i	3500.00	l l
211	Other (Avg. Hrs. & Total Cost \$)	<b>!</b>		<b>!</b>
212	Zone B		1	
213	Casing Run Time (Avg. Hrs./1889')	3.9		
214	Tools & Services (Total Cost \$)		1 7886.88	
215	Other (Avg. Hrs. & Total Cost \$)			
216	Ione C		<b>.</b>	
217	Casing Run Time (Avg.Hrs./1808')	3.6		•
218	Tools & Services (Total Cost \$)		5000.00	· · · · •
219	Other (Avo. Hrs. & Total Cost \$)	1 4.20	. 1 <i>965.86</i> 1	Accounts for average casi
220	Ione B	i	<b>i</b>	problems
221	Casing Run Time (Avg.Hrs./1000')	2.5		i 1
222	Tools & Services (Total Cost \$)	i	: 5 <b>488.8</b> 8	i i
223	Other (Avo. Hrs. & Total Cost \$)			i 1
224	Zone E	1 8 4	i	i. i
225	Casing Run Time (Avg.Hrs./1666')	6.0		i
22 <del>6</del>	Tools & Services (Total Cost \$) Other (Avg. Hrs. & Total Cost \$)	i	: <b>8.5</b> 6	i i

(DATA	BASE B. OFERATION TIME AND				  -  -
   	Operation	10o Time: (Hrs.)	(\$)		1 
122B	Zone F	!		<u> </u>	1 
227				ŀ	!
239		1	. 0.00	<b>!</b>	1
231				:	!
232	Zone 6	1	1	1	•
233	Casing Run Time (Avg. Hrs. /1690')	: 0.0	†	;	!
234	Tools & Services (Total Cost \$)	1	<b>9.6</b> 9	!	1
235	Other (Avg. Hrs. & Total Cost \$)	1		;	l
236		1	1	:	1
237	2.23 Cementing Operations	<b>;</b>	<b>!</b>	;	<b>!</b>
238	Rio Up (Avo. Hrs.)	: 2.€	:	:	1
239	Rig Down (Avg. Hrs.)	1 2.9		<b>!</b>	1
248	W.B.C./Test (Avg. Hrs.)	; 4.€	:	ł	1
241	Other (Avg. Hrs. & Total Cost \$)	;	\ \	:	1
242		1	!	ł	1
243	Zone A	:	}	1	!
244		: 3.#	!	1	1
245		;	1268.68	;	i
246	Other (Avo. Hrs. & Total Cost \$)	1	!	1	1
247	Ione B	!	<b>!</b>	1	1
248	Cementing Time (Ava. Hrs.)	i 3. <i>6</i>		!	1
249	Tools & Services (Total Cost #)	1	1200.00	1	1
25₽	Other (Avg. Hrs. & Total Cost \$)	1	·	1.	1
251	Zone C	1	}	;	1
252	Cementing Time (Avg. Hrs.)	i 7.£		1	1
253	Tools & Services (Total Cost \$)				!
254	Other (Avo. Hrs. & Total Cost \$)	1 25.92	19899.99	<b>!</b> Accour	ots for "average" cementing
255	Ione D	1	l	proble	ms.
1256	Cementing Time (Avo. Hrs.)	1 7.6	1	<b>!</b>	
257	Tools & Services (Total Cost \$)			<b>i</b>	
258	Other (Avg. Hrs. & Total Cost \$)	1	İ	!	
259	lone E				
26F	Cementing Time (Avg. Hrs.)	6.0			1
261	Tools & Services (Total Cost \$)		6.66		
1262	Other (Avg. Hrs. & Total Cost \$)		!		<b>.</b>
263	Zone F			}	
264	Cementing Time (Avg. Hrs.)	1 6.6			
265	Tools & Services (Total Cost \$)		9.99	i	i .
266	Other (Avg. Hrs. & Total Cost \$)		·	;	I .
267	Zone 6		i	<b>i</b>	
268	Cementing Time (Avg. Hrs.)	. 6.9		<b>.</b>	
269	Tools & Services (Total Cost \$)		6.85	<b>.</b>	1
276	Other (Avo. Hrs. & Total Cost \$)	١	·	1	i

:DATA	DASE B.  OPERATION TIME AND CO	ST DATA			• 
;	Operation	Op Time	lOper. Cost	! Misc.	<b>.</b>
:		(Hrs.)	<b>{                                    </b>	!	1
1272	2.24 Wellhead Equipment and Installation	 	!	; {	<b>.</b> <b>!</b>
1273	Install Time & Equip. Cost (Tot. Hrs. & \$	) }	1	1	ł
1274	Zone A		: 6500.00	!	<i>f</i>
1275	Zone B	1 26.9	7500.00	<b>!</b>	1
1276	Zone C	1 26.6	1 4999.99	1	! !
1277	Zone D	1 2€.€	14588.88	1	
1278	Zone E	. 6.6	. 9.66	1	f 1
:279	Zone F	8.6	6.96	1	
1286	Zone G	6.6	6.55	1	<u> </u>
1281			:	1	
1282		:	1	!	i i
1283	2.25 Maintenance and Drilling Problems	t	1	1	
1284	Percent Jone Time (%)	1	1	!	1
1285	Ione A	!	1	;	}
1285	Maintenance	ł	!		! •
1297	Drilling Problem	ł	1	1	<b>.</b>
1288	Zone B	:	1	1	!
:289	Maintenance	1	1	1	}
1299	Drilling Problem	1	1	1	! !
1291	Ione C	1	1	;	l <u>_ ,                                     </u>
1292	Haintenance	<b>t</b>	1	1	Time associated with
1293	Drilling Problem	1	1	8.6	Lost Circulation
1294	Zone D	;	!	i	! !
1295	Maintenance	1	1	1	1
1296	Drilling Problem	1	1	!	<u> </u>
1297	Zone E	:	}	1	
1298	Maintenance	1	:	1	1
1299	Drilling Problem	:	1	1	
1300	Zone F	1	1	l	!
1301	Maintenance	i	!	!	
1392	Drilling Problem	1	:	!	I
1303	, Zone 6	1	1	1	
1394	Maintenance	1	1	1	i .
1345	Orilling Problem	1	1		}
1396		1	1	1	l

•

DATABAS		WELL DESIG	ON AND DRIL	LING INSTR	UCTIONS			¦ 
	Requirement	Zone i		Zone :		Zone   E	Ione   F	Zone :
В 1	.1 Geologic Evaluation	!	!		   	!	1	1
9	Classification Number	1 1	2 :	3 ;				<u>-</u>
i e		<b>.</b>	!	1	1	!		
11 1	.2 Well Geometry	1				}		
12	Hole Depth From Surface (Ft.)		2066.88			!	-!	i
13	Hole Diam. (In.)	26.99	17.5 <del>2</del> 1	12.25				
14		!	:				1	i •
15 1	.3 Casing Program						DRILTAC	
16	•						ihers.an	
17	Casing/Liner Diam. (In.)		13.38				.the_ca	
18	Unit Cost (\$/14%')	1 5200.00	3648.66	3914.99	:_simula	ted as	_a_sing]	e_strin
19	· ·			}	•		i.	i :
29 1	.4 Drilling Techniques & Equip. Used	i	ł	:	:		1	i
21	Drilling Method (% Time)	;			;	:	1	<b>!</b>
22	Rotary Brilling-Air		1	·	l		-	
23	Air Comp. & Aux. Equip.						.	
24	Air Hammers	<b>!</b>	1		!	1	_1	·
25	Pownhole Motors	·				¦	.	
26	Other	l					_	
27	Rotary Drilling-Mud	100.00	150.50	166.66		1	_!	1
28	Telemetry Systems	1					_	
29	Other	!	!		i	!	.	
3 <del>ř</del>	Downhole Motor-Mud	1	1		1	1	_!	
31	Downhole Motors	1	1		!	1	_	
32	Deviation Sub & Tools		!	!	!	1	.	.
33	Telemetry Systems	!	1	}	i	1	_!	!
34	Other	1	!	1		!	_1	
35	Core Drilling-Conventional	1	1	i	!	1	_	1
36	Downhole Motors				_			.1
37	Beviation Subs \$ Tools	1		_	١		.'	1
38	Telemetry Systems	1	1	1	1	.1	1	
39	Other						_!	
4#	Core Drilling-Wireline							
41	Downhole Motors						_!	
42	Deviation Subs & Tools	1	1					
43	Telemetry Systems	1					.1	
44	Other	1	I	1				.
45	Other	1		1	1	<b>!</b>	_	
46	Reaming (Ft.)		1	200.00	<b>!</b>			.1
47	•	}	1	1	!	1	1	1
	1.5 Rig Selection	1	;	1 1	1	1	1	;
49	•	t	}	1	1	1	•	1
	1.6 Bit Program		1	1		.		
51	Rotary Drilling-Air	!			1		1	:

DATABASE A.	WELL DESIG	ON AND DRIL	LING INSTR	UCTIONS		*****	
Requirement	! Zone i					Zone   F	
52 Bit Selection	1	·					
53 Bit Cost (\$/Bit)	1					;	
54 Bit Life (Avg. Hrs.)	1	·		<b>!</b> :			
55 Rotary Drilling-Mud	:		<b>:</b>			i	
56 Bit Selection				! <u> </u>			
57 Bit Cost (\$/Bit)						i	
58 Bit Life (Avg. Hrs.)	39.09	39.56	39.66	·	!		
59 Downhole Notor - Mud	•	1		i .	•		
66 Bit Selection				·			
61 Bit Cost (\$/Bit)	. 1	1					
62 Bit Life (Avp. Hrs.)	;	!	1				
63 Core Drilling - Conventional	1	ł	1			į	
64 Bit Selection	1	1	1				
65 Bit Cost (\$/Bit)				!!		i	
66 Bit Life (Avg. Hrs.)	1		!				'
67 Core Drilling - Wireline	1	1	!	!			
66 Bit Selection			1				; 
69 Bit Cost (\$/Bit)	1	!	!				
75 Bit Life (Ava. Hrs.)	1	1	!				·
71 Other	1	:	!	1 1			
72 Cutter Selection	1		1	1			İ
73 Cost (\$)				·;			
74 Cutter Life (Avg. Hrs.)	1	1					!
75	i	!	1	; ;	1		
76 1.7 Drilling Fluids Program	1	!	1	1		i	:
77 Surface System Build Up	1	1	1	; ;			<b>;</b>
78 Surface Svs. Vol. (BBLS.)	360.66	1	!	1	1	ł	:
79 Additives (Types)	BENT/LIME		1	1 1			
BG Total Unit Cost (\$/160 BBLS.	236.66	1	1	1	}	1	<u>:</u>
81 Additional Volume	1	I	1	i :		•	i
82 Additives (Types)	IB.L.CG	1B, L, C6	IB.A		i	i	·
83 Total Add. Cost (\$/100 BBLS.	1 236.66	238.00	250.00				<u>'</u>
84 Daily Maintenance	1	1	4	1	<b>.</b>	i	i
85			1500.00				`
86 Other	1		1	1	i . Tan	; *	i 
87 Equipment Cost (\$)	1	<u> </u>	1 4969.00	Lost C	<u>irculat</u>	<u>ינט עטר</u>	e <u>ct</u>
88 Additives (Types)				Costs.	·		i
89 Unit Cost (\$/Cu.Ft. of Hole)		İ				·	·
98	1	1	1	1	i	<b>i</b>	i
91 1.8 Cement Program	i	Ī	1	i	i	i	i
92 Cement Type	IR-MIX	16+SILICA	1		1		.i
93 Annulus Fill Ht. (Ft.)	1 150.06	1 2000.00				·	i
94 Unit Cost (%/Cu. Ft.)	: 3. <b>4</b> 6	7.00	1				
95		i .	1	1	i	:	!

				AND DE	. L.L			10 1 1 G M 2						
Pequirement	; ;			Zone B			:	Zone D	!	Zone E		Zone   F		Zone 6
ç <sub>ò</sub>	1		 !		:		!		 !			· !		
97	;		;		i		i		:					
9B 1.9 Auxiliary Operations	1		ŀ		ĺ		•		ì				i	
99 Surveying (No. of Runs)	!		.:	1.68	;	3.60	!_		1_		}	!	. 1	
160 Logging (No. of Runs)	;		_;	1.55	į	2.99			. 1_	~~~~				
161 Other (No. of runs)	ļ		-!-		. :	1.00	10	ther	ŗu	n 15	ŋ	eeded	- p	)
182 183 1.18 Bottomhole Assembly (BHA) Changes	;	1.68	;	1.59	; ;	3.99		imula						
DRILLING PROBLEMS	! T i	<b>2</b> 05	!!!	ours	!0	arstian				~				
Problem Type		iell				ost Ost	1							
	·¦		-:-		¦		1							
Lost Circulation	:	€.29	i	30.00	12	5666.66	!							
Casing	!	<b>9.</b> 18	!	42.00	116	989.99	i							
Cementino	i	ø. 3£		48.66	12	996.98	1							
Fishing	!	9.29	•			950.00	-							
Side Tracking	:	9.95	-			966.96	•							
Twist Off Stuck Pine	i	Ø.20 Ø.30	-	114.66										
	•	4 (4	•	79 A4	. 7/	928.28	•							

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 	BASE B.  OPERATION TIME AND	COST DATA		
	Operation	10p Time {(Hrs.)	Doer. Cost    (\$)	Misc.
9	2.1 Road Location and Site Prep. (Total \$)	:		ŀ
16	2.2 Initiation (Total \$ & Hole Depth. Ft.)	; ;	13000.00	50.0
12	2.3 Ris Movement (Avg. Hrs. & Total \$)		1	1
13	Demobilization		12360.00	
14	Mobilization		: 9869. <b>66</b>	
15		!	!	-
	2.4 Rig Operating Rates	i	•	i
	Day Rate (\$/Hr.)			
	Standby/Nondrilling		149.66	
19	Rig With Fipe		246.66	
	Ria Without Pipe		·	
	Other	;		
22 23	Footage Rates (\$/Ft.)	:	!	
	2.5 Fuel Consumption (Gal./Hr.)	1	:	1
25	Standby/Nondrilling	1		6.5
	Drilling			13.1
	Tripping			
2ó	<b>⊕-4</b> 999°			19.6
29	Trippino 9-4999* 5888-9999'			26.2
36	16666-14999	1		8.6
31	15###-19999			6.6
32	2000-29995			6.6
33	30000-50000			6.6
34		,		
35	2.6 Fuel Cost (\$/Gal.)	. 1	1.66	
36		,		!
37	2.7 Transportation and Mist. Cost (\$/Hr.)		89.66	
38		1		
39	2.8 Rental Cost (\$/Hr.)	: :	150.00 1	
48		ţ		}
41	2.9 Special Tool Cost (\$/Hr.)	1		•
42	Air Compressors & Aux. Equip.	1		
43	Air Hammers	1 1	!	
44	Downhole Motors	1		
45	Deviation Subs & Tools	1		
46	Telemetry Systems	1	**********	
47	Other - Rotary Drilling - Air	!		
4B	Other - Rotary Drilling - Mud	1		١.
49	Other - Downhole Motor - Mud			' · .
54	Other - Core Drilling - Conv.		<sup>1</sup>	
51	Other - Core Drilling - Wireline		''	'
	menter mente mittitud mit ettilk		'	

DATAB	ASE D. OPERATION TIME AND COS	ST DATA		
	Operation		Oper. Cost    (\$)	
52	Other - Other	1		1
53		1	1	
54	2.1# Supervision Cost (\$/Hr.)	!	62.55	:
55		1	i i	
	2.11 Condition Drilling Fluids (Avg. Hrs.)	1 1.5	i J	•
57 50	2.12 Water Cost (Total \$)	1	!	, !
58 : 59	Purchase Cost	:	786.66	• }
•	Disposal Cost	1	786.88	
61	D1300201 C031	i	1	
	2.13 Bit Change (Avg. Hrs.)	1 1.6	!	:
63		:	!	}
64	2.14 Bottomhole Assembly (BHA) Chance (Avg. Hrs.	): 5.£	;	1
65		1	1	i
66			!	<b>!</b>
_	2.15 Drillino Fenetration Rates (Ft./Hr.)	1	1	<b>.</b>
éB	Zane A		i	i
69	Rotary DrlgAir	i	i	19.9
7£	Rotary DrigMud	i	i 1	1 19.0
	Downhole Mtr. Drla.	1	1	•
	Core Brilling - Conventional	!	•	i {
73 74	Core Drillino - Wireline Other	!	;	' !
7 <del>4</del> 75	Zone B		i	·
76	Rotary DrigAir	1	1	
. –	Rotary DrigMud	1	1	30.6
	Downhole Mtr. Drlg.	ŀ	<b>!</b>	!
79	Core Drilling - Conventional	1	1	1
86	Core Drilling - Wireline	1	1	1
81	Other	1	!	!
<b>B</b> 2	Zone C	1	1	
<b>B</b> 3	Rotary DrlgAir		i	
84	Rotary DrigHud		i	1 25.6
85	Downhole Htr. Drlg.	í	i.	1
Bò	Core Drilling - Conventional	i	i I	i
87	Core Drilling - Wireline	!	!	!
88	Other Zone D	1	!	'
99 98	Rotary DrioAir	!	•	1
91 91	Rotary DrigMid	i		
92	Downhole Mtr. Drla.	1	1	1
93	Core Drilling - Conventional	1	1	<b>!</b>
94	Core Drilling - Wireline	ţ	•	(
95	Other	1	1	1

	OPERATION TIME AN	NE COST DATA		
	Operation	•	per. Cost: (\$)	Misc.
9ċ	Ione E	1 1	;	
97	Rotary DrloAir	1 1	Ι.	
98	Rotary DrloMud	1 1	1	
99	Downhole Mtr. Drlg.	1 1	1	
199	Core Drilling - Conventional	1 1	1	
le1	Core Drilling - Wireline	: :	1	
192	Other	1 1	1	
<b>. 6</b> 3	Ione F	1 1	1	
164	Rotary DrlaAir	1 1	1	
105	Rotary DrlgMud	1 1		
196	Downhole Mir. Drla.	1 1		
197	Core Drilling - Conventional	: :	•	
168	Core Drilling - Wireline	1 1		
199	Other	1 1		
110	Zone 6	1 1		
111	Rotary BrlgAir	iii	1	
112	Rotary DrlgMud	1 1		
113	Downhole Mtr. Drla.	iii		
114	Core Drilling - Conventional	ii		
115	Core Drilling - Wireline	i		
116	Other	1 1	ì	
117	o circi	i	i	
	2.16 Reasing Operations	iii		
119	Reaming Rates (Ft./Hr.)	1 1		
129	Zone A	: 36.0 :	ì	
121	Ione B	1 15.0		
122	Zone C	1 12.0		
123	Zone D	1 8.6 1		
124	Ione E	1 6.6 1		
124 125	Ione E	. 6.6	:	
126	Zone 6	1 6.6 1		
127		; ;	i	
	2.17 Pipe Handling Operations	1 1		
129	Round Trip (Ava. Hrs./Round Trip)	ii		
130	<b>4-4999</b>	1 3.6 1		
131	5888-9999	1 4.6		
132	10000-14999'	1 12.5 1	,	
133	15446-19999'	1 21.8	į	
134	2003-17777	1 31.5 1	•	
135	25 <del>464</del> -29599'	1 44.6 1	1	
136	30936-34799'	1 58.5 1	•	
136 137	35###-39999°	1 75.9	,	
		1 93.5 1	. ,	
138 139	40000-44797' 45000-50000'	1 113.6 1		

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DEEP IMPERIAL VALLEY INPUT DATA

I DATAI	SASE B. OPERATION TIME AND COS	T DAT	·A					1
	Operation	10s T	ime!	Oper	. Cost	. H	isc. i	<b>i</b>
}		! (Hrs	5.) (	(	(\$)	1		<b>!</b>
14 <u>ë</u>		 !	 ¦				;	<b>.</b>
	2.18 Auxiliary Operations - Surv. (Avg. Hrs./Run)	:	!			1	ł	
142	6-4997'		3.0	}		1		<b> </b>
143	5888-9999		3.5			1		1
144	19799-14799'		5.6			ŧ		1
145	15###-19999		7.0 :			;	:	1
146	2000-24779		9.#			1		<b>!</b>
147	25000-29999					1	;	1
148	38889-34999'		3.5			1		<b>!</b>
149	35228-39999		6.0			1		1
150	40000-44999		9.0			!		!
151	45866-56660'		1.5			;		1
152	*****	1		ŀ		;		1
	2.19 Auxiliary Operations - Looping	ì	ţ	1		!		1
154	Log. Time (Ava. Hrs./Run) & Cost (\$/Run)	1		:		1		1
155	8-4999'		. #ø :	102	166. <b>66</b>	ì		
156	5000-9779				866.66			1
157	10000-14999		_			1		1
158	15000-19997					-		:
159	20000-24999					1		1
166	2500ñ-29995°					- 1		:
161	30000-34999'			:				1
162	35@@@-39999'					٠.		1
163	46066-44999'	,				-		1
164	45000-50000	1				-		<b>:</b>
165	10002 00001			' : 		-		<b>;</b>
	2.2# Auxiliary Operations - Other	1				1		1
167	Operation Time Per Run (Avg. Hrs./Run)	1 6	B. 1			i		1
168	Operation Cost Per Run (Avg. \$/Run)	1			825 <b>0.</b> 0	ITI	nis a	ccounts for average lost ti
169	Dati detail abot it i han in a vinan	i	1					st for problems (except los
17#	2.21 Coring Operations	ł		ŀ		E.	ircul	ation, casing and cement).
171	Core Drilling - Conventional	;	1	ì		:		1
172	Coring Operation Charges (\$/Hr.)	ŀ		!	55.60	1		1
173	Change Drilling Tools (Avg. Hrs.)	1	5.#	:		1		1
174	Core Barrel Lenoth (Ft.)	1		1		1_		1
175	Trip In/Out (Avg. Hrs.)	1		ŀ		-;		•
176	£-4799	;	3.₽	!		ł		1
177	5868-5999		4.6			1		•
1178	1 <del>8</del> 665-14997		1.5			ŧ		1
179	15666-1999?		7.₽			;		1
189	2644-29999		8.€			1		1
181	39969-50960'		7.0			i		1
182		ţ		:		:		1
183		1		1		ŧ		1

IDATA	ABASE B.  OPERATION TIME AND	COST DATA		******
	Operation	(On Time)	Oper. Cost ( (\$)	Misc.
1184		1	 	:
1185		1 1		:
1186	Core Drillino - Wireline	1 1	l	1
1187	Corino Operation Charges (\$/Hr.)		56.60	;
1188	Rig Up/Down (Avg. Hrs.)	1 2.5		:
1189	Change Drilling Tools (Avg. Hrs.)	1 5.0 1		ŀ
1199	Core Barrel Lenoth (Ft.)		}	1
1191	Trip In/Out (Avo. Hrs.)	1 1		
1192		1.0		<b>:</b>
1193		1.3		
1194	1988-14999	1.5		<u> </u>
1195	15888-19999	1 2.5 1		
1196	28888-29997	1 4.0		i
1197	36469-58966'	! 9.€ :		
1198		i i		;
1199 1200		i i		i
1201		i i	i	i
	2.22 Casing Operations	i i	i ·	i <i>1</i>
1203	Rio Up (Avo. Hrs.)	2.6	1	•
	Ria Down (Ava. Hrs.)	1 2.8		i I
1205	Prepare to Run Casino (Avo. Hrs.)	1 12.6		<b>!</b> !
1296	Other (Avo. Hrs.& Total Cost \$)	! 12.17 1	(	! !
1207	prince tutés in 214 fores cost 43	''		<b>.</b> !
1268	Zone A	!!!	7	' !
1269	Casino Run Time (Avo.Hrs./1888')	1 3.5 1	!	• !
1216	Tools & Services (Total Cost \$)		3500.00	!
1211	Other (Avg. Hrs. & Total Cost \$)	i i		•
1212	Ione I			!
1213	Casino Run Time (Avo.Hrs./1606)	3.21	1	•
1214	Tools & Services (Total Cost \$)	1 1	5000.00	į.
1215	Other (Avg. Hrs. & Iptal Epst \$)	!!	!	
1216	Zone C	1 1		ł
1217	Casino Run Time (Avo.Hrs./1888')	. 1 3.8 1	:	
1218	Tools & Services (Total Cost \$)	1 1	7608.88	<b>;</b>
1219	Other (Avg. Hrs. & Tutal Cost \$)	1 4.26 1	1969.86	Accour
122€	Zone D	1 1		1
1221	Casino Run Time (Avg.Hrs./1660')	: 6.6 :	;	
1222	Tools & Services (Total Cost \$)	1 1	9.66	!
1223	Diher (Avg. Hrs. & Total Cost \$)	11		
1224	Ione E	1		1
1225	Casing Rum Time (Avg.Hrs./1888')	1 6.6 1	:	
1226	Tools & Services (Total Cost #)		6.55	ł
1227	Other (Avg. Hrs. & Total Cost \$)	11		

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DATA	ABASE B. OFERATION TIME AND	COST DATA		!			
	Operation		(\$)				
228	Ione F	1	;	! !			
229	Casing Run Time (Avg.Hrs./1888')	: 0.0	1	1			
230	•	1	. 9.99				
231	Other (Avo. Hrs. & Total Cost \$)	1	ţ	1			
232	<u>•</u>	1	!	: !			
33		9.6	1	1			
234	Tools & Services (Total Cost \$)	1	. 6.66	: :			
35	Other (Avo. Hrs. & Total Cost \$)	i	1				
236	Senzi Miles III 2 (See See See See See See See See See Se	!	!	1			
	2.23 Cementing Operations	1	1	!			
238		1 2.0	1				
235	·	1 2.6					
24 <u>ë</u>		1 6.9					
241							
242		!	1				
243		į					
244		3.6					
45	lools & Services (Total Cost \$)		1200.00				
245		i	!	!			
247	•		' !				
248		1 3.6	•				
49			1 1269.66	! !			
25Ø					ts for	"average"	cement
251	Zone C		!			average	o cinicii o
252		•	•	!			
253			. <b>'</b> !	 ! !			
254		•	'	, , !			
255		,	. '	, . !!			
256		. 6.6	•	 !			
236 257	Cementing Time (Avg. Hrs.) Tools & Services (Total Cost \$)	1 2.5		; ;			
258				}			
259	Ione E						
268		: 8.6	1				
261	· · · · · · · · · · · · · · · · · · ·		6.60	· ·			
262			1				
263	· ·		· '				
264		9.4	•				
265			9.00				
265 265		•	1				
267		'					
26B		6.6	•	. , ; !			
269		!	6.00	. , ! !			
279 279		!	!	, , ! !			
271 271	Dince luth, mrs. & inter cost at	;	. '				

•

I DATA	BASE B. OPERATION TIME AND COST	T DATA			1
 		•	Oper. Cost		:  
:		(Hrs.)	(\$)	1	;
 1272	2.24 Wellhead Equipment and Installation	<del></del>	 !	!	
273	Instell Time & Equip. Cost (Tot. Hrs. & \$)	:	<b>;</b>	:	:
1274	•		: 6500.00	1	1
275		26.€	7000.00	;	1
1276		: 20.€	19488.88	1	1
277	Zone D	. 5.6	8.96	<b>;</b>	:
127B	Zoné É	. 6.6	6.60	1	1
279	Ione F	8.6	6.20	<b>;</b>	i
286	Zone 6	: 6.£	6.66	:	1
281		1	ŀ	1	:
1282		1	1	1	1
283	2.25 Maintenance and Drilling Problems	1	:	1	:
1284	Percent Zone Time (%)	;	!	1	1
285	Ione A	!	1	1	<b>:</b>
286	Maintenance	:	ł	1	.1
287	Drilling Problem	1	!	1	.1
288	Ione B	1	1	1	i
289	Maintenance	1	;	1	.1
290	Drilling Problem	;	1	1	_1
291	Zone C	1	;	1	1
292	Maintenance	1	ł	1	<b>_\</b> .
293	Drilling Problem	:	i	1.7	Time associated with lost
1294	Ione D	ls.	:	1	circulation.
295	Maintenance	1	!	1	.1
296	Drilling Problem	1	1	1	_1
297	Zone E	1	;	1	1
295	Maintenance	1	!	1	_1
299	Drilling Problem	ł	1	1	_1
399	Ione F	1	1	ł	1
361	Maintenance	i	1	1	.1
1392	Drilling Problem	ł	ŀ	1	- 1
363	Ione 6	ł	1	1	1
1394	Maintenance	;	1		_
395	Drilling Problem	}	1		.1
1366		1	i	1	i

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		WELL DESI	EN	AND DRIL	L	ING INSTR	UC	TIONS					
	***************************************	l Zone l A	-			Ione :			1		! Zo		Zone ! 6
? 1	1.1 Beologic Evaluation	<u> </u>	<u></u>		 ¦	 ;	 				!		:
i	Classification Number	1	;	1 !	!	3 !		3	}	5	1	;	
ī		1	i		ŀ	;	1		:		:		:
1	1.2 Well Geometry	ł	ŀ	!	}	:		:	}		1	i	!
:	Hole Depth From Surface (Ft.)	150.00	1	1000.00	;	35 <b>66.0</b> 6 1	6	882.88	1165	66.68	!		! !
	Hole Diam. (In.)	42.66	l	26.f9	}	17.50 :	i	12.25	ľ	8.54			
·"		ŀ	ļ		;	1	ľ		1		1		:
1	1.3 Casing Program	<b>!</b>	ł	;	!	;		;	}		t	;	
,		150.00	ł	1869.86	!	3566.66	6	664.68	1	6.68	NOT	E: .	Since_
	Casing/Liner Diam. (In.)	38.68	ļ	20.00 :	!	13.38 :		9.63	}				does
j	Unit Cost (\$/100')	1 7546.44	!	5266.66	ļ	3448.46	3	814.66	1	9.00	not	cor	rectly
		}	)	;	}	ł		;	}				ie-bac
1	1.4 Drilling Techniques & Equip. Used	;	1		i	;	!		1		cas.	ings	, the
	Drilling Method (2 Time)			:	!	;	l	1					nd tie
)	Rotary Drilling-Air	!	!		!		!		!				<u>re run</u>
		`	`- !		-				` <b></b> -		bne	str	ina.
,	Air Hanners	' 											
		'   											
1	Other	' !	<u>'</u> -	'	' !	·'	·						;
		126.88	'- !	188 88 1	'-	144 44 !	<b>'-</b> -	160 66	1	46.64	' !		'
1	Telemetry Systems		•	11.0.20									
,	Other	'   	!	'!	<b>'</b> -	' <sub>!</sub>	'		'		' !		' !
;	Downhole Motor-Mud												
•	Downhole Motors	!											
	Deviation Sub & Tools												
	Telemetry Systems												
	Other												
	Core Drilling-Conventional												
,	Downhole Motors		_		_								
•	Deviation Subs \$ Tools												
		 	۱ <u>-</u>				,		4		+		' !
1	Telemetry Systems Other :	' !	¦-		_	'							' !
)	Core Brilling-Wireline		_										
		 											_
	Deviation Subs & Tools	!											
													_
	Other	!			_								
	Other	,			-					AA 20	·	i	
	Reaming (Ft.)		į		٠-	!	i		i 4	PP. 99	.i		
		i	:			;		i			i	i	
	1.5 Rio Selection	2	ï		i	;	1		i				i
	·	1	}	1		i		1			1	:	-
1	1.6 Bit Program		١_	;	-				<b> </b>				
1	1.6 Bit Program Rotary Brilling-Air		 	 }	-	! ;		 ;			i 		

		WELL DESI	en and DKI	LLING INST	KOLIIUMS			
	Requirement	l Zone l A		l Zone l C		! Zone ! E	l Zone	
52	Bit Selection	1		1				
53	Bit Cost (\$/Bit)	1	1	1	!		1	
54	Bit Life (Avg. Hrs.)	1	1	.			1	·
55	Rotary Drilling-Mud	!	1	1	:	i .	:	
56	Bit Selection				:TCRB-12		1	¦
57	Bit Cost (\$/Bit)	1 4945.00						
58	Bit Life (Avg. Hrs.)	24.45	1 24.6€	1 24.66	29.00	29.99		<b>!</b> _
59	Downhole Motor - Mud	!	1	1	ł	!	:	!
60	Bit Selection	1		.		İ		!
61	Bit Cost (\$/Bit)	1	1	i	1	!		
62	Bit Life (Avg. Hrs.)	1		.		1	1	!
ė3	Core Drilling - Conventional	}	!	ł	1	i	:	
64	Bit Selection	1		.1		1		¦
65	Bit Cost (#/Bit)	!	1	1	!			
ćó	Bit Life (Avo. Hrs.)	1	1	1		!	1	·
ė?	Core Drilling - Wireline	!	!	i i	1	}	!	
68	Bit Selection	!	1	1	!	1	1	i
69	Bit Cost (\$/Bit)	1		}		!	1	
ĨĒ	Bit Life (Ava. Hrs.)	1	1				1	
71	Other	1	1	!	1	:	:	
72	Cutter Selection	1	1	!	1	!	<b>!</b>	<b> </b>
73	Cost (\$)		!	;	¦	¦	1	
74	Cutter Life (Avg. Hrs.)	1	1	!	!	!		<b> </b>
75	•	!	!	`	}	<b>;</b>		
76	1.7 Drilling Fluids Program	:	!	1	1	1	!	<b>!</b>
77	Surface System Build Up	1	!	1	!	<b>:</b>	:	
7B		1 468.88	1	<b>!</b>	1	1	1	<b>!</b>
79	·	BENT/LIME	!	;	!	<b>;</b>	;	
86	Total Unit Cost (\$/100 BBLS.)	: 230.40	;	:	1	:	1	i
81	Additional Volume	1	}	1	1	ł	<b>:</b>	
82	Additives (Types)	1B.L.C6	IB,L,CG	IB,A	1			
83	Total Add. Cost (\$/1## BBLS.)	230.05	230.60	250.00	259.56	258.88	1	
84	Daily Maintenance	1	l	1	:	1		1
85	Cost (\$/Day)	1 1500.00	1500.00	1566.96	1569.66	1580.88		
86	Other	:	1	1	1	ŀ	1	:
87	Equipment Cost (\$)		- 	1	1	160000.00	Lost_Ci	rculat
88	Additives (Types)					I	direct-	costs
89	Unit Cost (\$/Cu.Ft. of Hole)		1					
96					1			1
91	1.8 Cement Program	1	<b>!</b>	<b>!</b>	†	:	:	1
92		(R-MI)	16+SILICA	16+S+RET	IB+S+RET		1	
93		1 150.00	1000.60	: 3540.68	: 6000.00	6.00	1	
94	Unit Cost (\$/Cu. Ft.)	: 3.60					}	

Denvise and	,	7	,	7	1	7		7	1	7	1	7		7
Requirement	i !	Zone A	;	Zone B	!	Zone C	!	Zone D	•	Zone E	•	Ione F	1	Ione R
9ó	ŀ		i		ľ		ł		ł		:		1	
97	ŀ		ţ		;		1		!		ł		1	
98 1.9 Auxiliary Operations	:		ł		1		ł		1		i		ł	
99 Surveying (No. of Runs)	1_		۱_	1.26	!	2.99	;	3.88		3.00			ا۔	:
188 Lagging (No. of Runs)	1_		_	1.88	1	1.66	!	3.69				ther		
191 Other (No. of runs)	1_		_!	(1.63)	+_		7.		.!.	<u>`]`o`O</u>				o simu
192	i		;		1		i		ł				_	prob
1#3 1.1# Bottomhole Assembly (BHA) Changes	<b>!</b> _		١.		.!	3.99	1	3.00	;	6.99	١.		-	
DRILLING PROBLEMS	 ! T	 i <b>s</b> es		lours	: n	peration	 :							
Problem Type						ost	!							
	-	~~~~~	- ; -		-									
Lost Circulation	;	3. <b>9</b> £	1	54.66	12	9929.99	1							
Casing	ŀ	Ø.15	ŧ,	42.66	111	8050.00	ļ							
Cementing	i	9.69	i	48.66	12	0060.0 <b>0</b>	1							
Fishing	¦	6.46	ŀ	72.00	! !	5000.00	1							
Side Tracking	ŀ	Ø.15	1	96.99	14	0960.0£	ł							
Twist Off	ŀ	€.4€	i	114.66	13	90.8506	:							
Stuck Pipe	1	€.75	1	78.99	13	8286. <b>6</b> 6	1							

DATA!	PASE B.  OPERATION TIME AND	COST DATA		
	Operation	•	Oper. Cost:	
<b>e</b> 9	2.1 Road Location and Site Prep. (Total \$)	   	: 34750.00	
1# 11	2.2 Initiation (Total \$ & Hole Depth, Ft.)	! !	1 25006.00	50.0
12	2.3 Rig Movement (Avg. Hrs. & Total \$)	.	!	ł
13	Demobilization	. 9.6	: 20600.00 :	
14	Mobilization	: 0.0	15660.00	
15		1.	!!	
16	2.4 Rip Operatino Rates	1	1	l
17	Day Rate (\$/Hr.)	1	<b>;</b>	
18	Standby/Nondrilling		1 160.00	
14	Rig With Pipe	1	269.66	
2ê	Rig Without Pipe	<b>;</b>		:
21	Other	;		
<b>2</b> 2	Footage Rates (\$/Ft.)	i	1	
23	-	;		
24	2.5 Fuel Consumption (Gal./Hr.)		!	i
25	Standby/Nondrilling	!		15.7
2ò	Drilling	:	1	62.7
27	Tripping	1		
26	<del>5</del> −4979°	!	!	26.7
29	5664-9999'	1	: :	62.7
36	10000-14999	:	:	94.1
31	15286-19999	1	: :	8.6
32	24006-29999'	1.	•	9.9
33	30266-50660'	1		6.6
34			·	
35	2.6 Fuel Cost (\$/Gal.)	1	1.66	
36		1		<b> </b>
37	2.7 Transportation and Misc. Cost (\$/Hr.)	1.	85.00	
3B	•	ł	:	i
39	2.8 Rental Cost (\$/Hr.)	1	155.60	
46		•	<b>:</b>	}
41	2.9 Special Tool Cost (\$/Hr.)	1 .		
42	Air Compressors & Aux. Equip.		[	}
43	Air Hanners	1		
44	Downhole Motors		1	}
45	Deviation Subs & Tools	1 1		
46	Telemetry Systems		1	}
47	Other - Rotary Drilling - Air			
48	Other - Rotary Drilling - Mud	1		}
49	Other - Downhole Hotor - Mud	:		. •
59	Other - Core Drilling - Conv.			
51	Other - Core Drilling - Wireline		` 	

: DATA	BASE B.  OPERATION TIME AND COS			
;		Op Time   (Hrs.)	Oper. Cost	l Misc. I
52 53		;		; }
54	2.1# Supervision Cost (\$/Hr.)		62. <b>6</b> 2	 !
56 57	2.11 Condition Drilling Fluids (Avg. Hrs.)	1.6	<b>!</b>	 
: 57 : 58 : 59	2.12 Water Cost (Total \$) Purchase Cost	1	: : : 1050.86	!
1 66 1 61	Disposal Cost		1 956.60	
63	2.13 Bit Change (Avg. Hrs.)	1.6	}	: {
65	2.14 Bottomhole Assembly (BHA) Change (Avp. Hrs.	)1 5.#		1 1 1
67	2.15 Drilling Penetration Rates (Ft./Hr.) Zone A	1	! !	; ;
69 79	Rotary DrlgAir Rotary DrlgHud	!		16.6
71 72	Downhole Mtr. Drlg.  Core Drilling - Conventional	:	i <b>!</b>	
73	Core Drilling - Wireline Other	1	, ; ,	
75	Zone B Rotary BrigAir	· · · · · · · · · · · · · · · · · · ·	; <b>;</b> ;	36.6
177 178	Rotarv DrlgMud Downhole Mtr. Drlg. Core Drilling - Conventional	;	<b>.</b> !	1
1 79 1 88 1 81	Core Drilling - Wireline Other	; ;	: !	\ \ \
82	Zone C Rotary DrlgAir	1		
84	Rotary DrigMud Downhole Mtr. Drig.	1	<b>.</b>	25.0
1 86 1 87	Core Drilling - Conventional Core Drilling - Wireline	:	1 1	
89	Other Zone D	1	 	
9 <del>2</del> 91	Rotary DrlgAir Rotary DrlgHud	1	<b>:</b>	15.6
! 92 ! 93	Downhole Mtr. Drlg. Core Drilling - Conventional	1	<b>!</b>	
1 94 1 95	Care Drilling - Wireline Other	!	: !	

l DATA	PASE B.  OPERATION TIME A	ND COST DATA		
:   	Operation		elOper. Cost	
96	Zone E	;	¦	!
97	Rotary DrlgAir	1	1	
98	Rotary DrloMud	:	,	14.6
99	<del>-</del>	1	1	
100		:	1	<b></b>
101		:	1	
102	<del>-</del>	1		!
163		1	1	
164		1	1	1
165	Rotary DrlgHud	i		`
196	· · ·	1		1
167		i	i	
108		ì	•	¦
159	Other	į	· ·	·
119				' !
111		į	•	
112	<u>-</u>	•		' 
113	• •	•	•	'   
114	•	,	•	
115	·	;	, ,	!
	Core Drilling - Wireline	,	1 3	
lić.	Other	,	•	¹
117	O. 41 December Decembers	١	1	! •
	2.16 Reaming Operations	i	i 1 1	i
19	Reaming Rates (Ft./Hr.)	i . 70 <i>i</i>	i i	i •
129	Ione A	32.4		i
121	Zone B	: 3 <b>9.0</b>		
122	Zone C	1 12.6	•	i
123	Zone D	1 12.6	•	•
124	Zone E	1 5.6		j I
125	Zone F	. 6.6		•
126	Zone 6	i 9.6	7 (	•
127	O 47 Disa Handlina Danadina	i	i i	i 1
	2.17 Pipe Handling Operations	i	i	i
129	Round Trip (Avg. Hrs./Round Trip)	í	i i	i
130	<b>g-</b> 4999'	1 4.6		i
131	5000-9999'	: 8.9		i •
132	10006-14999'	1 12.5		i
133	15206-19999	1 21.0		
134	24944-24999'	1 31.5		i
135	25 <del>000</del> -29999'	1 44.6		
136	3 <b>0</b> 900-34999'	1 58.5		l
137	350PP-39999'	1 75.9		
138	<del>4<u>864.5</u>-449</del> 99'	1 93.5		<b>!</b>
39	45968-56966*	1 113.6	! !	

1 <i>DH</i> 11 	ABASE B.  OPERATION TIME AND CO				) } !
;·		!Op Time	Doer. Cost	l Misc.	
) 		(NFS.)	1 (7/	! 	-{
140		}	:	1	i
141	2.18 Auxiliary Operations - Surv. (Avg. Hrs./Run)	<b>)</b> :	!	:	1
142	g-4999°	: 3.£	!	;	<b>!</b>
143	5 <i>088-9</i> 999°	1 3.5	!	:	!
144	1888-14999	: 5.€	!	:	1
145	15000-19999	1 7.0	ł	:	1
146	24688-24999'	1 9.5	!	i	1
147	25efg-29999°	1 11.0	l	1	1
148	30909-34999	13.5	!	i	1
149	35464-39999	1 16.2	1	:	;
156	40030-44979	1 19.5	1	ł	1
151	45888-58888'	1 21.5	1	<b>!</b>	1
152		1	1	1	1
153	2.15 Auxiliary Operations - Logging	1	1	!	1
154	Log. Time (Avg. Hrs./Run) & Cost (\$/Run)	1	!	;	1
155	8-4999°	1 6.55	10000.00	:	1
156	549£-9999'	1 6.82	1 10000.00	1	1
157	16262-14999'	1	1	1	•
158	15000-19999'	1	1	•	1
159	26863-24999°		\	}	:
160	25886-29999"	1	1	1	1
161	3000-34999	1		1	
162	35###-39999°	1	1	1	1
163	4000°-44999°		1		:
164	45666-58686'	1	1	1	1
165		!	1	!	<b>;</b>
166	2.26 Auxiliary Operations - Other	1	:	1	1
167	Operation Time Per Run (Avg. Hrs./Run)	158.0	!	1	1
168	Operation Cost Per Run (Avg. \$/Run)	1	1 42758.8	This a	accounts for average lost
169		1	†	1	and cost for problems excep
170	2.21 Coring Operations	1	1	i me	and cost for problems excep
171	Core Drilling - Conventional	1	1	Lost	chrc.,casing, and cement.
172	Coring Operation Charges (\$/Hr.)		55.00	i	1
173	Change Drilling Tools (Avg. Hrs.)	₹ 5.#	!	ŀ	1
174	Core Barrel Lenoth (Ft.)	1	1	1	_1
175	Trip In/But (Avg. Hrs.)	;	t in	1	· <del>V</del>
17á	<b>£-4</b> 999°	3.6		1	:
177	5464-5999'	1 4.9		1	1
178	14566-14999°	11.0		i .	1
179	15#6#-19999'	17.0		1	1
189	2 <b>8589-</b> 29999'	28.6		!	1
181	30000-50000°	1 57.0	:	1	1
182		ł	1	ŀ	1
B3 .		;	<b>:</b>	:	i

DATA	ABASE B.  OFERATION TIME AND	COST DATA		;
	Operation	:Op Time !(Hrs.)	¦Oper. Cost ¦ (∳)	Misc.
184			!	
185		ł	1	1
186	Core Drillino - Wireline	ł	!	1
187	Coring Operation Charges (\$/Hr.)	1	50.00	1
188		: 2.€	!	1 1
189				: :
198	Core Barrel Length (Ft.)	:		1
191			·	
192	<i>6-</i> 4999'	1 1.6	!	1
193		1 1.3		
194		1 1.5	1	1 1
195			•	i i
196				· · · · · · · · · · · · · · · · · · ·
197		9.9		
198	JITTE JETTE	!	, !	, , , , , , , , , , , , , , , , , , ,
199		1	) )	, ,
200 200		,	) 	
		1	' '	1 1
201	2 22 Coming Downskinson	i	i	i i
	2.22 Casing Operations	1 2 4	i	i i
293	Rig Up (Avg. Hrs.)	2.6		i i
	Rio Down (Avg. Hrs.)	1 2.6		i i
	Prepare to Run Casino (Avg. Hrs.)		i ,	i i
200	Other (Avg. Hrs.& Total Cost \$)	į	i	
207	• 4		i •	i i
298	Zone A			<u>.</u>
269	Casing Run Time (Avg.Hrs./1060')	3.5		<u>.</u>
218	Tools & Services (Total Cost *)		3500.00	3
211	Other (Avg. Hrs. & Total Cost \$)			1
212	Zone B			1
213	Casing Run Time (Avg. Hrs./1800')			
214	Tools & Services (Total Cost \$)	1	3500.00	1 1
215	Other (Avg. Hrs. & Total Cost \$)	1		1
216	Zone C	. !	ŀ	1
217	Casing Run Time (Avg.Hrs./1000')	3.4		!
218	Tools & Services (Total Cost \$)	ŀ	7000.00	1 1
219	Other (Avg. Hrs. & Total Cost \$)	!		1 1
22 <del>8</del>	Zone D	1	ŀ	1
221	Casing Run Time (Avg.Hrs./1908')	1 3.€ 1		1
222	Tools & Services (Total Cost \$)	1	10000.00	1
23	Other (Avg. Hrs. & Total Cost \$)	1 6.39	1500.00	Accounts for average casi
224	Ione E	1	)  -	problems.
25	Casing Run Time (Avg.Hrs./1008°)	: 6.6 :		1
22£	Tools & Services (Total Cost \$)	1	8.60	1
27	Other (Avg. Hrs. & Total Cost \$)		<del>-</del>	1

IDATA:	BASE B. OFERATION TIME AND			! !
;	Oper ation	(Op Time ((Hrs.)	Oper. Cost	I Misc. I
1228	Zone F			
1229	Casing Run Time (Avg.Hrs./1868')	1 6.6	;	;
1230	Tools & Services (Total Cost \$)	1	9.66	
1231				
1232		1	:	
1233		1 5.5	;	:
1234			9.99	1 1
1235	Other (Avg. Hrs. & Total Cost \$)		}	1
1236	•	;	!	`I
	2.23 Cementing Operations	ł	:	1
		1 2.€	i	1
		1 2.6	}	1
1246		1 12.€	1	1
1241	Other (Avg. Hrs. & Total Cost \$)	ì	:	;
1242	·	;		1
1243	Ione A	1	<b>;</b>	1
1244	Cementing Time (Avg. Hrs.)	1 3.0	1	1
1245	Tools & Services (Total Cost #)	:	1200.00	1
1246	Other (Avg. Hrs. & Total Cost \$)		t .	1 1
1247	Zone B	}	;	
1248	Cementing Time (Ave. Hrs.)	1 3.6		
1249	Tools & Services (Total Cost \$)	1	1268.66	
1256	Other (Avg. Hrs. & Total Cost \$)	1	1	1
1251	Zone C		·	
1252	Cementing Time (Avg. Hrs.)	: 3.0		1
1253	Cementing Time (Avg. Hrs.) Tools & Services (Total Cost 9)	1	1266.69	i i
1254	Other (Avg. Hrs. & Total Cost \$)	1	!	1
255	Zone D	1	`   	i i
1256	Cementing Time (Avg. Hrs.)	1 7.6	!	1
1257	Tools & Services (Total Cost \$)	1	1766.66	1
1258	Other (Avg. Hrs. & Total Cost \$)	1 28.86	12000.00	Accounts for average cementing
1259	Zone E	1 1	!	iproblems.
1260	Cementing Time (Avg. Hrs.)	1 9.6		
1261	Tools & Services (Total Cost \$)	1 1		1
1262	Other (Avg. Hrs. & Total Cost \$)	1	!	1
1263	Inne F	;		1
1264	Cementing Time (Avg. Hrs.)	6.6	į	
1265	Tools & Services (Total Cost \$)	1	4.06	1
1266	Other (Avg. Hrs. & Total Cost \$)		1	1
267	Zone 6	}		•
1268	Cementing Time (Avg. Hrs.)	6.6	1	
1269	Tools & Services (Total Cost *)		8.45	
1279	Other (Avo. Hrs. & Total Cost \$)		;	
1271 ·	Print Hilliam III at a lagar anne 41			

l DAT	ABASE B.			٥		1
¦ •	OPERATION TIME AND COS					! !
, 	•		Oper. Co			İ
ł		!(Hrs.)	(\$)	1		
777	2.24 Wellhead Equipment and Installation	 !	!	 !		! !
273	Install Time & Equip. Cost (Tot. Hrs. & \$)			į		į
274	Ione A		: 6500.:	68 :		!
275	Zone B	20.0				
276	Zone C	26.6				1
277	Ione D		1 18468.6			 
278	Zone E	6.6		66 :		1
279	lone F	6.6	_	76 I		1 1
282	Zone 6	6.0		99 i		<b>;</b>
281		!	t	1	1	<b>!</b>
282		!	1	1		1
	2.25 Maintenance and Brilling Problems	ł	ł	:		<b>!</b>
284	Percent Zone Time (%)	ţ.	:	1		1
285	Zone A	1	:	1		1 1
286	Maintenance	!	;	;		1
287	Drilling Problem	!	:	H		ı t
288	Zone B	1	1	ŀ		:
289	Maintenance	<b>!</b>	1	- 1		<b>1</b>
29#	Drilling Problem	1	;	:		1
291	Zone C	<b>!</b>	1	i	;	1
292	Maintenance	ļ	1	1		1
293	Drilling Problem	1	!	- 1		ł
294	Zone D	1	}	l		1
295	Maintenance	i	:	1		1
296	Drilling Problem	!	1	1		1
297	Zone E	;	:	ł		1
298	Maintenance	:	1	ţ		<b>i</b>
299	Drilling Problem	!	t	;	26.0	Time associated wit
300	Zone F	1	!	ŀ		lost circulation.
3#1	Maintenance		1	ł		
302	Drilling Problem	!				1
3 <b>#</b> 3	Zone 6		i	1		<b>i</b>
394	Maintenance	i	i			i
3 <b>#</b> 5	Drilling Problem		i .			<b>i</b>
300		i	i	- 1	i .	i