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Technical and Cost Analysis of Rock-Melting Systems for Producing Geothermal Wells

by

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TECHNICAL AND COST ANALYSIS OF ROCK-MELTING SYSTEMS FOR PRODUCING GEOTHERMAL WELLS

by

John H. Altseimer

ABSTRACT

The drilling of wells makes up a large fraction of the costs of geothermal energy-extraction plants, and billions of dollars for wells will be needed before geothermal energy is nationally significant. Technical and economic system studies are summarized regarding the application of the Subterrene concept, i.e., excavating and penetrating rocks or soils by melting, to the production of deep wells such as may be used for dry hot rock or geopressurized geothermal energy-extraction systems. Technically, it was found that Subterrene features are compatible with those of current rotary drilling practices. In fact, some special features could lead to improved well production techniques. These include the buildup of a glass lining along the borehole wall which provides structural resistance to collapse; close control of hole geometry; the existence of a barrier between the drilling fluids and the formations being penetrated; nonrotation; potentially better bit life; and faster rates of penetration in deep, hard rock. A typical optimum-cost well would be rotary-drilled in the upper regions and then rock-melted to total depth. Indicated cost savings are significant: a 30% or 3.9 million dollar (1975 \$) reduction from rotary-drilled well costs are estimated for a 10-km depth well with a bottom hole temperature of 673 K. Even for relatively cool normal geothermal gradient conditions, the savings for the 10-km well are estimated as 23% or 2.1 million dollars.

I. INTRODUCTION

A. Objectives

The objectives of this program are:

- to study the application of the Subterrene concept to the production of deep wells such as may be used for dry hot rock or geopressurized geothermal energy-extraction systems and
- to make technical and economic comparisons with rotary drilling techniques and systems.

B. Background Information

A previous study¹ of geothermal wells made with rotary drilling techniques concluded that the drilling of conventional hot-water or steam-dominated wells was both technically difficult and costly, compared to typical U.S. oil and gas wells of comparable depths. Costs of two to four times higher

than those of average oil or gas wells were indicated. No one part of the rotary drilling process could be singled out as being responsible for this situation. Rather, a number of interrelated problems are at play, many of which are directly or indirectly related to high downhole temperatures. High temperatures contribute to elastomer and metallurgical failures in drilling bits; downhole measurement devices are severely affected or made inoperable; mud and circulation systems become more difficult to handle and more costly; cements must be made resistant to much higher temperatures than in the case of oil and gas wells and require special installation techniques; and tubular goods plus all other exposed

equipment are more susceptible to corrosion and chemical attack. Erosion of tubular goods can also be severe, especially in steam-dominated wells where cuttings may be carried out of the hole at high velocities. Due to the very nature of geothermal fields, the formations being drilled are often hard and badly fractured, which puts additional stresses and fatigue cycles on the downhole rotating equipment and the rig structure itself. Finally, the surface terrain in geothermal fields is often difficult, leading to high surface and site costs.

Improvements in geothermal well drilling technology would be beneficial in light of the fact that a significant part of the cost of a geothermal energy-extraction facility are the wells. In terms of dollars these costs could be many tens or hundreds of billion dollars depending on the extent of geothermal energy-extraction development. If the so-called dry hot rock (DHR) extraction system² is demonstrated to be feasible by the research now under way at the Los Alamos Scientific Laboratory (LASL) and geopressurized systems³ also are developed, then geothermal energy could become very important indeed as a national energy source. According to estimates made by White and Williams⁴ the geothermal energy resource available to DHR and geopressurized systems in the regional conductive environments (depths down to 10 km, not including any methane contribution) is $\sim 33\,500\,000 \times 10^{18}$ J ($8\,000\,000 \times 10^{18}$ cal = $31\,800 \times 10^{18}$ Btu). This is 2600 times their estimated value for conventional steam and hot water geothermal energy resources and 440 000 times the total U.S. energy consumption in 1972 of 75.9×10^{18} J.

Both DHR and geopressurized wells can be difficult to produce. Dry hot rock wells are intentionally made in solid and preferably very hot basement rock, hence their name, whereas geopressurized wells are 2 or 3 km deep or greater in highly pressurized (approaching lithostatic) and difficult-to-drill formations. Thus, the models used in this study are meant to simulate difficult-to-drill wells such as the above.

The rock-melting Subterrene excavation concept has been described extensively for various applications.^{1,5,6,7,8,9} Briefly, it is a system of excavating and penetrating rocks or soil by melting, simultaneously providing the three major elements of a conventional excavation process: rock fracturing,

debris removal, and wall stabilization. The element that makes innovative solutions in these three areas possible is the liquid rock melt produced. The melt can be formed into a glass lining to seal and support the walls of the borehole; it also binds loose soil materials effectively into a stabilized liner; and it can be solidified into particulate debris for convenient removal.

An 84-mm-diam melting bit that was designed to operate in hard dense rock, such as basalt, is shown in Fig. 1. The holes in the fluted part of the bit are melt-removal ports through which the melt flows to be solidified by a stream of gaseous coolant in a debris-formation chamber. The solid debris is then transported out of the borehole by the coolant. Many melting bits for many rock types have been tested in LASL's rock laboratory, and a number of small-scale field operations have been successfully conducted. For the most ambitious field test to date, the Experimental Field Unit (EFU) shown in Fig. 2 has been used to form an 84-mm hole in solid basalt to a depth of 30 m.

II. SYSTEM MODEL

A. GEOWELL Program

A computer program called GEOWELL has been assembled to analyze the critical technical and economic aspects of a Subterrene well-production system. This program is written in FORTRAN IV and is run on a CDC-6600 computer. System assumptions and the various technical and cost elements that make up the model are presented in the following discussions. Because both rotary and rock-melting systems are cost-optimized for producing different parts of a well, the program contains both rotary and rock-melting prediction capabilities for deep geothermal wells. For future studies and as more geothermal well data become available, the program's capabilities will be expanded to include a complete spectrum of geothermal well types.

B. Beneficial Use of Rotary Techniques and Equipment

In one of our studies evaluating the usefulness of current rotary drilling equipment to projected rock-melting, we concluded that most of the equipment could be used directly or easily modified to handle the new requirements. Also, more often than not in the upper intervals, rotary drills progress faster and cheaper than rock-melting bits. We estimated and subsequently assumed in the system model that, typically, rotary drills would be economically best to

Fig. 1. Subterranean 84-mm (3.31-in.)-diam extruder bit, of type used to make 30-m-deep bore-hole in solid basalt at LASL field test site.

drill the conductor and surface holes and that, thereafter, the large variety of rotary tools and techniques would be on standby availability if needed. This assumes that the upper 2- or 3-km intervals are sedimentary and relatively easy to penetrate with rotary drills, whereas, the deeper intervals are much more difficult. Because Subterranean does not require rotation, ultimate utilization of Subterranean devices may, in some cases, depending upon the specific site geology, eliminate the fairly substantial rotary components altogether. A favorable current trend in rig design appears to be toward the use of all-electric rigs, in which case the equipment is even more compatible with the electric powered rock-melting bits.

C. Well Designs Selected for Study

Two exploratory gas wells of recent years, drilled under difficult conditions and to record depths, represent the use of some of the best rotary drilling technology available today: (1) E. R. Baden No. 1 drilled to 9158 m (30 050 ft), and (2) Bertha Rogers No. 1 drilled to 9583 m (31 441 ft), both drilled in the Anadarko Basin in Western Oklahoma by Lone Star Producing Co. of Oklahoma City. After reviewing well designs used in many other wells both in the U.S. and abroad we selected the designs of the above two wells as guidelines for GEOWELL. Figure 3 shows the well design for a total depth of 10 km drilled completely by rotary bits. Moderate formation and fracture pressures, i.e., approximately

Fig. 2. Experimental Field Unit at LASL field test site used for basalt penetration tests.

hydrostatic, are assumed in the upper 4300 m. High pressures, i.e., approaching lithostatic, are assumed from 4300 to 7000 m. Thereafter, to total depth, it is assumed that pressures are moderate again. Hole sizes range from 914 mm (36 in.) to 200 mm (7-7/8 in.). Casings are heavy and mostly of high-grade steel as indicated in the figure. The production-string hole size was 103 mm (4.044 in.) at total depth. Cementing is as illustrated.

Figure 4 shows the well design when rock-melting bits are used below the 660-mm (26-in.) hole section. As stated previously, we assumed that the 914- and 660-mm holes are always rotary drilled. Below the 660-mm hole, rotary drills are used until it is desired to start rock melting. The top of the rock-melted hole is assumed to be drilled variably so that the proportions of rotary and melted holes corresponding to minimum total costs can be computed. The size of the hole at total depth in this well is identical to that shown for the all-rotary case. However, note that intermediate hole and casing sizes are smaller due to the advantageous use of the rock glass liner. It is assumed that the thickness of the glass liner is controllable and that structurally the liner is capable of withstanding compressive loading, but not tension. In the upper section to 4300 m, high internal pressure is imposed on the hole casing and lining while the hole from 4300 to 7000 m is formed. This pressure is due to the use of heavy

Fig. 3. Well design for the all-rotary drilled well.

mud needed to counteract the high *in situ* pressures in the 4300- to 7000-m interval. The steel casing must be heavy enough to withstand high tensile stresses and no benefit from the glass lining is assumed. In the 4300- to 7000-m interval the glass lining is made heavy so as to withstand the collapsing pressures occurring after this interval is formed, and mud weights are decreased for work on the intervals below 7000 m. Between 7000 and 10 000 m the collapse strength of the glass liner might again be used to advantage and the wall thickness of the steel casing could be reduced. However, to be conservative, this advantage is not assumed and a steel-casing wall thickness comparable to that shown in Fig. 3 for the 7000- to 10 000-m section is used.

For well depths less than 10 000 m the casing wall thicknesses are reduced in proportion to the ratio of well target depth to the base line depth of 10 000 m, except for some variations as defined in Table I.

D. Surface Equipment

Surface-equipment requirements for a combined rotary and rock-melting system are similar to those for an all-rotary project. Because it is anticipated that rotary drills will be most economical to produce the conductor and surface holes, the initial

Fig. 4. Well design for combined rotary drilled and rock-melted wells.

rig setup will include a complete rotary system, which will remain on the rig for the job duration and be available for later use if needed. Conventional pipe-handling techniques will be applicable to the Subterrene system, with a few new operational procedures anticipated, such as rapid electric circuit continuity checks at each joint. If cables are used instead of pipe for power circuits and these cables are reeled into and out of the hole in long lengths, new cable-handling drums, drives, and related equipment will be necessary.

For the mud system, the use of rock-melting bits offers three benefits:

- The need for special chemical compositions that are compatible with the formations is reduced because the mud is sealed from the penetrated formations by the rock-glass lining.
- The hole size will be much more precise than with rotary drills and therefore mud volumes will be significantly smaller.
- The sealing action of the glass lining will greatly reduce lost-circulation problems.

These advantages will lead to wellhead mud systems that are smaller and, perhaps, simpler than with rotary systems.

The power levels required for rock melting are compatible with those already required on rotary

TABLE I
HOLE AND CASING DIMENSIONS IN METERS FOR
ROTARY/ROCK-MELTED WELLS

Definitions: $DC = \frac{EL}{10\ 000}$

EL = target depth

i = designation of Elements 1 to 7
as defined in Fig. 3 or 4.

DNHi = hole diameter

DODi = casing outer diameter

DIDi = casing inner diameter

DUi = depth of upper end of casing

DLi = depth of lower end of casing

Diameters:

DNH1 = 0.914, DNH2 = 0.660, DNH3 = 0.406,
DNH4 = 0.311, DNH5 = 0.200.

DOD1 = 0.762, DID1 = $0.724 \times DC + 0.762 \times (1-DC)$

DOD2 = 0.508, DID2 = $0.476 \times DC + 0.508 \times (1-DC)$

DOD3 = 0.340, DID3 = $0.303 \times DC + 0.340 \times (1-DC)$

DOD4 = 0.219, DID4 = 0.206

DOD5 = 0.127, DID5 = $0.103 \times DC + 0.127 \times (1-DC)$

DOD7 = 0.178, DID7 = $0.141 \times DC + 0.178 \times (1-DC)$

Lengths:

DL1 = 30 (IF EL < 3773: DL1 = 0)

DL2 = $-800 + 11/50 \times EL$, (IF DL2 < 30: DL2 = 30)

DL3 = $4300 \times DC$, DL4 = $7000 \times DC$, DL5 = $10\ 000$
 $\times DC$, DL6 = $6100 \times DC$

DL7 = $3900 + 39/50 \times EL$ (IF DL7 < 0: DL7 = 0)

DU4 = $4100 \times DC$, DU5 = DL6, DU6 = DL7

deep-well rigs, e.g., up to 3000 hp. Diesel engines could be switchable from rotary drilling to rock-melting to drive electric generators. Also, the trend toward and increasing use of all-electric rigs should make it even easier to meet equipment requirements to provide melting power. Other new surface operational requirements will be generated by the need to monitor downhole power, penetration rate, bit thrust and debris removal.

A primary surface cost item is the cost of the drilling contractor who supplies the rig, the supporting equipment, and the crew. It was assumed that the rock-melting surface requirements are sufficiently similar to those for rotary drilling so as to base daily drilling contractor costs on oil and gas practice. In GEOWELL, the drilling

contractor cost is divided into rig (CRIG) and drill-pipe (CPIPE) costs. For these estimates 1973 oil and gas data were compiled from the open literature and then upgraded to 1975. Using EL as the total target depth in meters, the resultant curve fit equations used in the program are:

$$CRIG = 1453 + 0.2022 (EL) + 10.19 \times 10^{-6} (EL)^2, \$/d$$

$$CPIPE = 106.8 - 0.0419 [EL] + 20.55 \times 10^{-6} (EL)^2, \$/d.$$

The above CPIPE is used when an all-rotary-drilled well is made. When Subterrene is combined with rotary, a method of proportioning the rotary and Subterrene drill pipe costs is employed.

E. Drill Pipe

1. Coaxial Aluminum. Design studies produced a Subterrene drill pipe capable of carrying both electric current and the downflow of drilling fluid. The pipe is shown in Fig. 5 and consists of two concentric 7075 aluminum tubes separated by a 2-mm-thick layer of material that bonds the tubes structurally together and acts as an electric insulator. A conventional tool joint on the outer tube serves as the structural connection with adjacent pipe. The current in the outer tube flows across the threaded contact surfaces, the smooth metal contact, and the sealing surface at the joint leading edge. The inner tube has a tight sliding fit at the joint for electric contact, but no axial forces can be transmitted. Handling and operational characteristics of this pipe are similar to those of conventional drill pipe. The initial cost is approximately three times higher but this disadvantage is reduced by an enhanced

Fig. 5. Subterrene aluminum drill pipe concept. Pipe is sized to meet stress and power transmission criteria in a 10 000-m total-depth well.

operating lifetime for the Subterrene pipe due to the fact that Subterrene pipe does not rotate and is not exposed to the usual rotary pipe fatigue stresses and frictional wear. The above described aluminum pipe is used for both technical and cost analyses in GEOWELL.

A pipe with an outside diameter of 140 mm (5.51 in.) fits well into all sections of the borehole being studied and was therefore selected as a standard in the GEOWELL analysis. The outside diameter is maintained at 140 mm, whereas the other dimensions are varied to meet power transmission and load criteria. The basic power criterion is that the total transmission and melting power shall not exceed 2000 kW. The structural criterion is that the pipe stress shall never exceed 0.75 times the aluminum (Type 7075) room-temperature yield stress. The loads considered include pipe weight, buoyancy, penetrator thrust, and pipe breakaway. Figure 5 shows typical drill-pipe dimensions for Subterrene use in a 10 000-m well with a 50-K/km geothermal temperature gradient, in combination with a bit capable of a penetration rate of 1.0 mm/s in rock at 283 K. The latter parameter is specified because it establishes the bit melting-power level that is used in the check of the pipe power transmission criterion. Costs are calculated on the basis of these dimensions to arrive at a basic material and fabrication cost. Other estimates are made, e.g., delivered pipe cost, pipe lifetime, and drilling contractors profit to finally arrive at a Subterrene drill-pipe cost in dollars per day.

2. Steel and Aluminum Pipe Plus Electric Cables.

Rather than putting the melting bit at the end of many thousand meters of coaxial aluminum stem, a promising approach to cost savings in labor would be to affix the melting bit to the end of standard drill pipe and to supply the bit with electric power by means of a drop-in cable. The cable, made up of a number of standard length sections and fitted with suitable connectors, would cut tripping time because once the connectors are assembled they need not be disassembled but simply rolled up on the cable drum when the cable is withdrawn. This eliminates the time wasted disassembling, cleaning, and reassembling connectors. Of course, for the concept of a detachable and retrievable melting bit (to be

discussed later) the cable concept is a necessity because it provides the means of withdrawing the bit as well as powering it.

The concept of a drop-in cable operation has been used, for example, in powering downhole electric motors and is proven technology. Cable used for drop-in Subterrene applications would, admittedly, not be standard. It must have high strength and the insulation must be capable of withstanding high temperatures. A conceptual diagram of such a cable is shown in Fig. 6. The members of the conductor/load-carrying cable and the brazed-on end fittings are made of beryllium-copper alloy with a yield strength of 1100 MPa (160 000 psi). The captive compression nuts are nickel-steel. Cable insulation consists of silicone rubber and the connector insulation is mica-filled epoxy.

The joining of cable lengths is a simple procedure: (1) the two center conductor studs are joined by a threaded collar which brings the standard and reverse-threaded studs together; (2) the two half-cylinder spacers are filled with silicone grease and pushed into place around the collar; and (3) the outside captive compression nuts are screwed together to seal and complete the junction. Although each junction represents a wide spot in the cable, the diameter of 83 mm allows essentially unimpeded circulation of drilling fluids in the annulus between it and the inside diameter of the drill pipe.

Figure 7 illustrates how the cable might be used on the job. The cable is capable of being wrapped on a hoist drum with a winding diameter of 2 m, a width of 2.2 m, and a flange diameter of 2.6 m. On

Fig. 6. Conceptual cable connection.

Fig. 7. Conceptual melting-power cable handling system.

such a drum a 10 000-m cable will form 19 overlapping layers. A suitable drive and brake system will be supplied. The snatch block could be 1.5 m in diameter. The drill-pipe system will consist of a limited length of the previously described coaxial aluminum pipe and a long length of conventional steel pipe. The cable will be installed inside the steel pipe and lowered in one piece to the bottom of the steel pipe where an electric connection to the bit is made under remote control. At the surface the cable top will be connected to a sub that makes the structural connection between the aluminum and steel pipe and also electrically connects the cable to the aluminum pipe. Aluminum pipe will be added as the bit progresses until the bit has to be tripped. To trip, the aluminum pipe, cable, and steel pipe are withdrawn in that order.

F. Rock Melting Bits

Subterrene melting-bit design descriptions and

their development status are readily available in the literature.⁵⁻⁹ The bit needed for producing wells is the melt-extruder type that uses either gas or liquid as the drilling fluid. Inside the bit the molten rock from the excavation face is ducted to intersect a stream of coolant, and the resultant small rock-glass particles and rock-wool-like debris are then transported up the annulus out of the well. An example of a melt-extruder type bit used for field tests at LASL is given in the Appendix.

Enough technical data are available to allow engineering assumptions for bit life and rate of penetration. A bit life of up to 100 h has been obtained with experimental bits. Relatively little effort has been expended to improve this performance by developing new corrosion- and wear-resistant surfaces, but bit lifetimes of at least several hundred hours should be within reach. Rates of penetration achieved to date are low, averaging only ~ 0.2 mm/s, primarily in igneous materials. A top priority effort of the Subterrene program is therefore directed toward increasing the rate to 1 mm/s (11.8 ft/h) in igneous rock. To accomplish this goal, better methods of delivering energy to the rock at the bit leading edge are needed. The most promising is the use of melt-heating, i.e., running electric current directly through the molten rock boundary layer at the bit leading edge. Small scale tests of this technique have been encouraging. In GEOWELL the assumed performance of the design-point bit was as follows: a lifetime of 300 h and a rate of penetration (ROP) of 1 mm/s (11.8 ft/h) at a rock temperature of 283 K. Note that rock temperature is specified because ROP varies with rock temperature.

Besides penetration rate, a major bit design problem may be that of obtaining sufficient clearance between the glass former (located immediately behind the melting face) and the hole so as to facilitate bit travel during trips. As will be discussed later in the section on tripping, a clearance of several millimeters on the radius is desirable to prevent bit damage or high pressure drops across the bit during fast trips. Several design approaches appear possible (1) use an expendable glass former that is forcefully worn down to a smaller diameter when initially retracted, (2) vary the diameter as needed by mechanical or thermal means, (3) use a rock-melting broach with a controllable diameter behind the primary bit to slightly enlarge the hole (this will

be discussed later in more detail), (4) continuously enlarge the hole slightly behind the glass former with a rotating cutter driven by a downhole mud motor, and (5) use a mechanical broach to enlarge sections of the hole behind the bit. Indeed, while making a 30-m-deep hole into solid basalt at Los Alamos in December 1974, a simple broaching tool was used to allow easy insertion of the bit for completion to final depth. It appears that various engineering solutions to the clearance problem are available and a practical solution will be developed. No attempt to forecast its exact nature is made in this report.

In GEOWELL, the rock-melting bit costs in 1975 dollars, PENC, are based on Subterrene Program experience and are defined by the following equation, where DPEN is penetrator diameter in meters:

$$PENC = 1286 + 20556 (DPEN) + 69053 (DPEN)^2, \text{ \$/bit.}$$

With bit life in meters/bit, hole diameter, and corresponding hole length as inputs, the program calculates the number of bits required. These are multiplied by the cost from the above equation to predict total costs for bits of any size, thus accumulating the bit costs in this way for the entire hole length.

G. Rotary Bits

The rotary bit rate of penetration and the bit life in meters per bit were estimated on the basis of conversations with people in the drilling industry, on many cases cited in the open literature, and partially on the results of a national conference on deep drilling held at Ghost Ranch, NM.¹⁰ The bit performance is described by the following equations:

$$ROTEL = ELEV(J) + \frac{DL}{2},$$

$$RROP(J) = 591.62(ROTEL)^{-0.6739}.$$

When $ROTEL < 1440$ m:

$$BITM(J) = 884.0 - 0.553(ROTEL).$$

When $ROTEL > 1440$ m:

$$BITM(J) = 97.0 - 0.0033(ROTEL),$$

where

ROTEL = average depth (m) of computational interval "DL" below depth "J",

RROP(J) = rate of penetration (m/h) at depth ROTEL,

BITM(J) = bit meterage (m/bit).

In the 660-mm (26-in.)-diam hole interval it is assumed that a 660-m hole opener is used to enlarge either a 444-mm (17.5-in.)-or a 406-mm (16-in.)-diam hole. The hole opener is assumed to have the same ROP as defined above, but only one-half the meterage.

Because the wells being simulated are being made in formations that are relatively difficult to drill, it is assumed that high-grade carbide-insert journal-bearing bits are used. Costs for such bits were obtained from 1975 industrial catalogs and are as given below:

$$BITC = 1677.0 - 9604(BITD) + 51680(BITD)^2$$

$$HOCST = 7628,$$

where

BITC = cost of rotary bits (\$/bit),

BITD = diameter of rotary bits (m),

HOCST = cost of 660-mm-diam hole opener (\$/bit).

H. Electric Power Transmission and Generation

The transmission lines assumed for GEOWELL are the two tubes making up the coaxial aluminum drill pipe already described and illustrated in Fig. 5. The operating temperature of the pipe vs depth is calculated and the resultant temperature effect on electric resistance is taken into account. From Subterrene experience, the typical resistance of the heating elements in the melting bit was estimated to be 1 Ω . This bit resistance value is used in all cases. The bit power is obtained by calculating and summing the power needed to melt the rock face and the borehole liner, as well as the power lost by conduction to the rock surrounding the bit. The size of the aluminum pipe, needed to calculate pipe resistance, is controlled by the following two criteria: (1) stress, as previously discussed, and (2) the total electric power fed downhole, which shall not exceed 2000 kW. This power limit is arbitrary and was selected because it is consistent with power levels found on large rotary drilling rigs. In all cases studied, the pipe was sized by Criterion (1). Knowing the power needed at the bit, it was convenient to establish equations using the ratios of circuit resistance to bit resistance to arrive at values for power consumed in the aluminum circuits. The type of current, whether dc or ac, need not be specified but if ac current is used, its frequency is assumed to be less than 400 Hz.

An additional estimate assumes that the joint resistance is zero. As part of the study of transmission-line efficiencies, we investigated the resistance of butt and sliding transmission-line joints. Such joints are necessary between sections of drop-in cable and sections of coaxial aluminum drill pipe. Several references, including the Alcoa Bus Conductor Handbook,¹¹ and our own experience with Subterrene drilling operations point to the conclusion that as long as reasonable cleanliness is maintained when making such threaded, sliding and butt joints between similar conductors, the contact resistance is negligible compared to the resistance of the parent material.

To estimate the cost of the power required to operate the melting bit, we assumed diesel-generator sets would be used just for generating that power. An overall generating efficiency of 30% and diesel fuel costs of 0.40 \$/gal are used. Capital equipment costs are amortized over a ten year lifetime, and a 20% return to the drilling contractor on his investment are also included.

I. Drilling Fluids

1. Functions of a Drilling Fluid. The drilling fluid for a rock-melting system has to perform the following functions.

a. Form solid debris. The molten rock is channeled from the excavation face of the bit to a debris-formation section where the fluid chills the melt into a form suitable for ejection out of the borehole.

b. Cool glass liner. Immediately behind the bit melting surfaces is a glass-liner-former and cooling section that is cooled by circulating drilling fluid. While the cooling requirements are not severe, the fluid must not clog the flow channels, suffer thermal degradation, or corrode the surfaces being cooled.

c. Control formation pressures and prevent caving. Similar to rotary drilling, the drilling fluid can keep formation fluids out of the hole by maintaining positive pressures on the wall. The positive pressure also helps prevent caving of wall material into the hole. Another consideration requires that the mud have a low filtration rate or lose little water to the surrounding formation; this should prevent excessive caking on the wall and

possible dangerous swelling of hydrating minerals in the formation. Rock-melting will materially help the drilling fluid to perform this function because the melting process maintains the inherent structural integrity of the surrounding rock and the glass liner provides additional strength. Further, the liner seals the borehole thus isolating the formation from the drilling fluid.

d. Carry out debris. The drilling fluid has to carry the excavation debris up the annulus and out of the hole.

e. Hold solid additives in suspension under stagnant flow conditions. Using conventional techniques, the fluid will be stagnant while trips are made or when certain other nondrilling jobs are in progress and the solids are normally kept in suspension. For a very hot hole it may be necessary to change the operating techniques so that circulation is maintained at all times. In that case, this function may no longer be essential.

f. Reduce corrosion. Corrosion can be inhibited or checked somewhat with an appropriate mud composition. However, a new corrosion problem is introduced at the melting surfaces when the bit is initially brought to temperature and is surrounded by fluid in direct contact with the melting surfaces. This problem may best be solved by using a protective coating on the hot surfaces.

g. Lubricate moving pipe or casing. With rotating drills, lubrication is a very important requirement. For the nonrotating Subterrene, lubrication is only required for axial movements of tubular goods into or out of the hole.

2. Fluid Selection. It has already been demonstrated experimentally that Functions a and b can be performed very well with gas because all bits tested to date have used either nitrogen or air except for one 114-mm-diam consolidating coring bit with a water-cooled stem and glass former. For Function c, lack of high formation pressures or fluid intrusions would allow the use of a gaseous drilling fluid. In steam-dominated geothermal wells, the use of air as a rotary drilling fluid is often advantageous. At The Geysers, CA, air is used routinely in ~2-km deep wells because of mud lost-circulation problems caused by low formation pressures. Air solves lost circulation, but the subsequent intrusion of steam

into the annulus results in high gas and debris velocities and extreme erosion of the casing, drill pipe, and surface equipment. With a hole sealed by glass, both steam intrusion and erosion would be reduced.

Function d could cause equipment, operational, and surface-safety problems if the hole is deep and very high inlet gas pressures are required. A recent analysis by R. D. McFarland¹² of LASL shows that nitrogen gas can be used satisfactorily in a 3-km-deep, 150-mm-diam hole melted in formations having a geothermal gradient of 70 K/km. The analysis indicates, however, that greater depths would lead to undesirably high gas inlet pressures at the well head. Function e would not be applicable to gas; Function f, corrosion inhibition, could be accomplished with gas; but Function g, lubrication, could not be accomplished.

Study of the above requirements shows that under certain conditions a gas might be a satisfactory drilling fluid. However, for the well models selected for this study, gas could not perform Function c. Also, the high inlet pressures required for depths down to 10 km would be impractical. Thus, the use of a liquid-based drilling fluid appears to be mandatory. Based on rotary experience, liquid drilling fluids like water, water-based muds, or oil-based muds could perform Function c through g. It is estimated that Functions a and b could also be handled even though this has not yet been demonstrated experimentally. In GEOWELL, an average or typical mud is postulated as will be defined later in Section K.

3. Effects of High Temperatures. In hot geothermal wells, and especially when Subterrene is used, muds will have to be resistant to chemical or physical thermal degradation. Muds will be in continuous contact with elevated geothermal temperatures. Also, on startup of melting bits, mud can be in direct contact for short times with melting surfaces at ~ 2000 K. An example of a possible thermal degradation problem follows. Barite (BaSO_4) is a commonly used mud-weighting material that can be dissociated by heat:

Now, BaO has a melting point of 2170 K and an accumulation of such material in front of the melting surfaces may stop the normal progress of the bit. Also, the SO_3 can break down to SO_2 , and this can combine with water to form sulfuric acid that is highly corrosive to hot bits. New muds may have to be developed to overcome problems of this nature.

4. Mud Cost Estimates. Mud costs are frequently broken out as separate items in the open literature making it possible to compile such data for oil and gas wells; these data are used in GEOWELL to represent wells drilled into normal geothermal gradient formations. The resultant total mud costs in 1975 dollars, CMUD, (neglecting the very shallow wells for this study) are:

$$\text{EL} > 1354 \text{ m: CMUD} = 21912 - 28.64 (\text{EL}) + 0.0108 (\text{EL})^2, \$.$$

For Subterrene mud costs, the beneficial effects of precise hole size control with rock melters compared to rotary and glass lining of the borehole, i.e., isolation of the mud from surrounding formations, resulted in an estimate that costs are ~ 0.75 times the above rotary costs. Some further estimates are:

$$\text{ROTMUD} = \text{CMUD} \frac{\text{ELR}}{\text{EL}}, \$$$

$$\text{SUBMUD} = \text{FMUD}(\text{CMUD} - \text{ROTMUD}), \$,$$

where

ROTMUD = mud costs chargeable to rotary drilling,

ELR = depth of hole made by rotary drill,

EL = total hole depth,

SUBMUD = mud cost chargeable to Subterrene, and

FMUD = rotary-to-Subterrene adjustment factor equal to 0.75.

J. Borehole Liners

1. Early Experience With Glass Liners. Holes have been melted and rock-glass liners formed in a variety of rock materials. These include igneous materials like biotite coarse-grained granite, granitic gneiss of high quartz content, Dresser and local olivine basalts, Bandelier tuff, latite, orthoclase, and rhyolite. Sedimentary materials include Green River and a local red shale; a siliceous limestone; soft to moderately hard limey sandstones from Tuzigoot National Monument, AZ; alluviums from the Santa Fe formation and the Nevada Test Site; a compacted alluvium-containing basaltic gravel from Hanford, WA; and a special frozen water-saturated alluvium that simulated arctic permafrost. The

thicknesses of the glass liners vary with the type of penetrators, rocks, or soil. For example, Fig. 8 shows a thin liner of < 4 -mm thickness in granite made with an extruding penetrator. Figure 9 shows a liner of ~ 15 -mm thickness made in tuff with a consolidating penetrator. Figure 10 shows another interesting wall formation that is made up of unmelted Green River shale rubble and its rock glass. Similarly favorable results have been obtained with a variety of other materials.

Characterization tests of glass liners¹³ were conducted at LASL to establish their permeability and strength characteristics. The liners were measured to be much more permeable than dense granite but much tighter than the parent rocks. For example, at low pressures and with nitrogen gas, a Bandelier tuff glass specimen had a permeability of 8 millidarcys which was three orders of magnitude less than the parent rock. Local olivine basalt varied, depending on the selected sample, from 0.5 to 10 millidarcys, whereas the corresponding rock-glass permeabilities were too low to be detected.

Crush strength test results were encouraging. A parent basalt rock had a crush strength of 44 MPa (6400 psi), whereas its rock glass measured 108 MPa (15 700 psi). Parent Bandelier tuff was measured at 2.8 MPa (400 psi) and a specimen of tuff glass taken from a 51-mm-diam hole wall had a tangential crush strength of 36 MPa (5200 psi). Another tuff-

glass specimen taken from a 114-mm-diam hole wall had a tangential strength of 132 MPa (19 000 psi). Thus, the tuff-glass tangential strengths were 13 to 47 times greater than those of the parent material.

2. Most Recent Characterization Tests of Glass Liners. Terra Tek, Inc., in Salt Lake City performed more comprehensive tests of glass-liner properties.¹⁴ The test series were made on Bandelier-tuff parent rock and on glass samples taken from LASL penetration

Fig. 9. Hole melted in tuff rock specimen. Note heavy consolidated rock glass lining on borehole wall.

Fig. 8. Hole melted in granite specimen with extruding penetrator. Note debris.

Fig. 10. Hole and liner formed by Subterrene in Green River shale rubble.

test specimens. They found that liner permeability decreases rapidly with confining pressure. For example, a permeability of 8 millidarcys at 1 MPa confining pressure, using air as the test fluid, decreased to 200 microdarcys at 50 MPa. It appears that small flaws were forced closed at the higher confining pressures. It was also shown that the radial compressive strength decreases with radial distance from the hole centerline. Axial and transverse strengths are approximately equal. It was possible to test glass-liner and parent-material composite cylinders for collapse strengths. The rock-glass cylinders failed at a calculated inner-surface stress of 129 MPa (18 700 psi). The glass cylinders were 2.6 to 18 times stronger in collapse than dry and wet parent-tuff cylinders, respectively. The composite specimen, made up of an inner cylinder of tuff glass surrounded and bonded to parent tuff, was tested without failure to the pressure limits of the test setup: ~ 1.5 times the failure pressures for the all-glass cylinders. These results indicate favorable behavior for actual downhole liner configurations, i.e., glass liners structurally bonded to the surrounding rock. In all cases, tensile strengths were low at only ~ 1 MPa (140 psi). Terra Tek, Inc., conclude that glass-lined holes are obviously much more competent than unlined holes and present new possibilities for engineering applications.

3. Conceptual Methods for Forming Thick Glass Liners. For discussion purposes, let us categorize liner thicknesses and define "thin" as < 6 -mm, "intermediate" as 6 to 20 mm and "thick" as > 20 -mm. Thin liners are those that one might form with extruding penetrators in structurally sound and dense rock. In some cases, the liner might be "stripped" off completely as the penetrator progresses. Intermediate thicknesses have been attained frequently in the Subterrene experimental program, especially when using consolidating-type penetrators. Thick liners are of interest for high-pressure zones of wells such as those modeled in this report. One of the most intriguing potentials for the Subterrene melting process is that of sealing and structurally stabilizing a hole with the solidified melt material. An ultimate benefit could be the elimination of steel casing and conventional cement, at least in

the very hot lower sections of a geothermal well. Thus, a brief discussion of potential methods of forming thick glass liners follows.

a. Use of Long Conduction Heating Sections.

This approach is a logical extension of today's bit designs and is conceptually illustrated in Fig. 11: use of a leading face of high heat flux is followed by a conduction-heating section long enough to produce a thick melt, followed by a glass-former section. Two interesting experiments were recently conducted that apply to this discussion. A 60-mm-diam consolidating penetrator was tested successfully in basalt samples that contained a predrilled 32-mm-diam hole. The tests were made to verify the predicted advance rates of a heated conical surface in basalt when no leading edge was present to affect the rate. The penetrator achieved a steady rate of 0.5 mm/s at a surface temperature of 1690 K, and of 0.85 mm/s at a surface temperature of 1770 K. These relatively

Fig. 11. Downhole assembly concept with long melt section and high penetration rate face.

high rates suggest a penetrator design with a conical surface doing most of the melting by use of conventional Subterrene conduction and radiation heat transfer techniques. However, a different and more efficient melting concept would be employed at the leading edge. For example, preliminary research studies indicate that it may be feasible to significantly increase the rate of energy deposition into the rock at the excavation face by causing an electric-heating current to flow directly through the rock melt layer.

This concept would produce the hole and thick lining simultaneously -- with significant time, cost, and operational advantages. Another advantage stems from the fact that the liner is made without a reduction in hole size. Disadvantages are (1) bit costs increase because of the long additional refractory heating components behind the forward face section; (2) power transmission requirements and costs increase; (3) for the glass liner, one is forced to use whatever material happens to exist in the formations being penetrated; and (4) if large fissures are encountered it may be difficult to accumulate enough melt locally to effectively seal them.

b. Installation of Thick Liners After Hole is Made.

A different design concept for making thick glass liners is shown in Fig. 12. This concept would have the hole made beforehand with a high advance rate bit that only produces a minimal liner. This bit would then be tripped and the thick-liner tool would be lowered to the maximum depth of the section requiring the thick liner. A metal packer would then be actuated to seal the annulus at the bottom end of the tool. The liner material would consist of pellets of predetermined size which would be fed into the annulus and packed around the tool by a reverse mud flow technique. Melting power would be turned on to melt the pellets and then the tool would be pulled up at a constant rate to form the liner. In known fissure zones the tool could be slowed to allow the melt to flow out to seal the hole properly. Mud would circulate at a low rate to perform two functions: (1) cool the glass former section and, (2) slightly fluidize the unmelted pellets to facilitate their movement to the melt zone. Equal peripheral wall thicknesses would be

Fig. 12. Conceptual elements of a thick-liner emplacement tool.

controlled by centering devices as indicated.

Favorable features of the above concept are (1) liner materials and properties are controllable, (2) the use of liner materials with moderate melting temperatures may allow the use of less costly melting-surface materials like stainless steels, (3) large local cracks can be sealed because the quantity of liner material fed to the melter is controllable, and (4) although more total melting energy per hole is required, the additional costs of this energy would not be significant. Disadvantages are (1) additional time is needed, comparable to that

required to place and cement steel casing, and (2) the hole size is reduced by the liner thickness and bit size would have to be stepped in a manner similar to that used in steel cased wells. Thus, compared to the first concept, the average overall well hole size would be increased and a cost penalty incurred.

Obviously, numerous variations of the above two concepts are possible but will not be further discussed except to note that the idea of installing a liner by a melting process also has some application to rotary drilling. Indeed, such a special tool has been of interest to the Subterrene Program for some time, but time and funding limitations have prevented its development.

4. Assumptions Made for GEOWELL. The following glass-liner characteristics are assumed: (1) the solidified melt will seal the hole effectively, (2) liner collapse strength, working in conjunction with the surrounding rock, is high, (3) liner wall thicknesses are controllable, and (4) liner tensile strengths are negligible. The melting-power variations required to accommodate variable liner thicknesses with depth were not programmed into the present analysis because melting-power cost is relatively low. Also, more detailed breakdowns of estimates regarding the melting penetration rate would not affect the final conclusions of the study significantly.

An estimate of melting power is included that assumes the use of a diesel generator set. Cost of diesel fuel is included as well as the contractor's charges to cover a 10-year equipment lifetime and a 20% contractor's return on his investment.

For steel casing, it is assumed that the conductor and surface casing would be made of the low cost K-55 grade steel and all the remainder would have to be of a higher grade such as P-110. Typical costs for casing delivered to the well site were obtained from industrial catalogs and run from 0.55 to 0.57 \$/kg for K-55 grade steel casing and from 1.23 to 1.45 \$/kg for the higher-grade steels. The program calculates the casing volumes and weights and multiplies the weights by the appropriate cost in dollars per kilograms. The steel casing is cemented into the holes as illustrated in Figs. 3 and 4. The volume of cement is calculated and multiplied by the appropriate dollars per cubic meter. The unit-volume estimates were partly derived from cost

experience gained at LASL's GT-2 geothermal test well and run from ~ 220 \$/m³ at a depth of 1 km to 540 \$/m³ at 10 km. A linear variation between these two depths is assumed to account for increasing difficulties due to increasing temperature and greater depths.

K. Thermal and Hydraulic Conditions

Equations for the thermal and hydraulic conditions in rock-melted boreholes were set up to facilitate the evaluation of rock-melting, and the corresponding equations for rotary drilling were not included. However, rotary conditions could be easily simulated in future expansions of the program. The following assumptions are incorporated into this part of the Program:

- Geothermal temperatures increase linearly with depth.
- A typical drilling mud, based on water properties as a function of temperature and pressure is assumed, with multipliers of 1.5, 30.0, and 0.77 on density, viscosity, and heat capacity, respectively.
- The flow rate of the drilling fluid is based on upper annulus dimensions and is calculated to be sufficient to move the excavation debris (assumed as spherical particles) upward at a velocity equal to the terminal velocity of the particles multiplied by 1.5.
- Maximum particle diameter is 10 mm with a density of 2700 kg/m³.
- Friction factors for the pipe and annulus are based on absolute roughnesses of 4.57×10^{-5} and 3.05×10^{-4} m, respectively.
- Tool-joint pressure losses are zero inside the drill pipe because of flush design. Outer-joint losses are estimated.
- Heat transfer through the wall of the coaxial aluminum pipe illustrated in Fig. 5 is included.
- Heat transfer to or from the surrounding rock is included, based on transient heat conduction in a semi-infinite slab as a function of drilling time.
- Heat addition to the drilling fluid from the debris and cooling of the glass lining is included as a lump sum at the penetration location.

- Heat addition along the length of the stem due to power-transmission losses is included.

L. Tripping

The tripping parameter important to GEOWELL is the average rate. For Subterrene systems it is assumed that the rate could be at least equal to that achieved by a well-performing rotary crew. An empirical rule for moderate depths in the drilling industry appears to be that a trip can be made at a round trip rate of ~ 0.7 h/300 m (0.7 h/1000 ft) of hole. This is equivalent to setting aside 31.7 stands (~ 27.4 m or 90 ft per stand) of pipe per hour. Data for the very deep E. R. Baden No. 1 well drilled to 9158 m were published by Patterson et al. in a report¹⁵ on deep drilling. A linear fit through these data resulted in a round trip rate of 0.79 h/300 m, which is equivalent to ~ 28 stands per hour, and this is the rate selected for use in GEOWELL.

M. Time for Casing, Cementing, and Standby Operations.

The times required to drill and trip are calculated, based on program input data for bit-penetration rates, bit lifetimes, and average tripping rates. Two secondary time estimates are also needed: (1) time for casing and cementing, and (2) standby times to take care of the usual undesirable and unplanned delays associated with any large construction project. The times, in hours, estimated for casing and cementing are

$$\text{CCT1} = 120 + 0.024(\text{DL1})$$

$$\text{CCT2} = 120 + 0.024(\text{DL2})$$

$$\text{CCT3} = 120 + 0.024(\text{DL3})$$

$$\text{CCT4} = 120 + 0.024(\text{DL4})$$

$$\text{CCT5} = 120 + 0.024(\text{DL5})$$

$$\text{CCT} = \text{CCT1} + \text{CCT2} + \text{CCT3} + \text{CCT4} + \text{CCT5},$$

where

CCTi (i = 1 through 5) are times to install and cement each of the casing indicated in Figs. 3 and 4;

CCT is the cumulative casing and cementing time for the completed well; and DLi are lower depths of each i-th casing.

Average standby time is estimated as 15% of the total well production time, which equals 0.176 times the sum of the times to drill, trip, case, and cement.

N. All Other Costs

There are costs that are essentially independent

of whether rotary or Subterrene systems are used. To arrive at these costs in a simple and direct manner, we used the following procedure. First, well cost data reported by the American Petroleum Institute¹⁶ for all 1973 U.S. oil and gas wells (onshore, excluding Alaska) were curve-fit in terms of total depth and then upgraded to 1975 dollars by a factor of 1.20. The latter factor was derived from discussions with a member of the Cost Study Committee of the Independent Petroleum Association of America (IPAA) and from a review of the IPAA Cost Study Report.¹⁷ The resultant equation is

$$\begin{aligned} \text{OTHER} = & 10481 + 38.7(\text{EL}) - 7841(10^{-6})(\text{EL}^2) \\ & + 9.157(10^{-6})(\text{EL}^3), \$ \end{aligned}$$

where

EL is the total depth in meters.

Then, all other costs, TOTHER, are obtained from

$$\text{TOTHER} = 0.284(\text{OTHER}), \$$$

The factor of 0.284 was derived from a standard-well cost-breakdown table in the above-referenced IPAA report by selecting what were considered pertinent cost items for this study. (The table was developed in 1969 but the most recent five-year update by IPAA does not show any significant changes.) The selected cost items and their percentage of the total cost are

Purchased Items	Weight (% of Total Well Cost)
• Road and site preparation	6.8
• Transportation	2.9
• Fuel	0.9*
• Well site logging and/or monitoring system	1.3
• All other physical tests	0.8
• Logs and wireline evaluation services	3.0
• Special tool rentals	2.4
• Wellhead equipment	2.4
• Other equipment and supplies	2.0
• Supervision and overhead	2.2
• All other expenditures	3.7
TOTAL	28.4

* Increased 225% over IPAA value to account for recent large fuel-cost increases.

III. TECHNICAL STUDY RESULTS

A. Thermal and Hydraulic Conditions

Calculations were made for both a normal geothermal gradient of 25 K/km and a high gradient of 75 K/km to determine the influence of geothermal temperatures on the various parameters. The drilling fluid is mud, as previously defined. Figure 13 shows the mass flow rate required to lift the debris in the upper annulus plotted as a function of debris diameter. The above two geothermal gradients had little influence on flow-rate requirements. The maximum typical-mud flow rate required to remove the largest particles (10-mm-diam) is 46.1 kg/s. Figure 14 shows how maximum mud temperature varies with the particle diameter and geothermal gradients. At the flow rate required to remove 10-mm particles the maximum mud temperature is only 312.6 K. Even if the flow rate were reduced to half, the temperature would only rise to 336 K. Thus, the particle removal criterion establishes the mud flow rate and the temperature never reaches a high level even in the case of a high geothermal gradient where the bottom-hole rock temperature is up to 1033 K. The latter is, of course, only true when adequate circulation is maintained. In a stagnant condition the temperature would rapidly approach the rock temperature and would require new systems that would permit continuous circulation even during bit-tripping operations.

A plot of depth vs mud temperature is shown in Fig. 15. The temperature gradually rises as the mud flows downward inside the drill pipe and heat is transferred from the warmer mud flowing up the annulus. A small temperature increase occurs at and near the bit where fluid cools the bit and the molten rock. The temperature then gradually increases due to heat transfer from the hot rock surrounding the hole to reach a maximum value before the heat transfer into the drill pipe and down-flowing fluid causes a gradual decrease thereafter. Figure 16 shows the drilling-fluid velocities in the drill-pipe and annulus channels vs location in a 10 000-m-deep well.

Analyses of pressure drops from well inlet to outlet and of the pump hydraulic horsepower required, do not indicate any unusual pump equipment problems for rock-melted systems. The pump hydraulic horse-

power required from the well inlet to the outlet vs debris particle diameter for the 10-km-deep well case is plotted in Fig. 17. For the maximum requirement case of a particle diameter of 10 mm, this requirement ranges from 716 to 723 hp. Note that geothermal gradients do not change the requirements very much. Taking into account surface inlet pressure drops and motor efficiencies, the actual pump-drive power requirement might be ~ 25% higher than the above value, or ~ 900 hp. This is reasonable and well within the range of motor power levels on current drilling rigs.

Fig. 13. Mud flow rate vs particle diameter in a well of 10 000-m total depth

Fig. 14. Maximum mud temperature vs particle diameter in a well of 10 000-m total depth.

Fig. 15. Depth vs mud temperature in a 10 000-m total depth well.

Fig. 17. Mud hydraulic power vs particle diameter in a well of 10 000-m total depth.

Absolute pressures involved in the 10-km-deep well are plotted as a function of depth in Fig. 18. The total drop between the drill pipe and annulus flow channels is 18.04 MPa (2620 psi) of which 11.56 MPa (1680 psi) is in the drill pipe and 6.48 MPa (940 psi) is in the annulus. Note that in contrast to the normally high drops across rotary bits, the drop indicated across the rock-melting bit is negligible. This is because it is very easy to cool the bit, the wall, and the debris with a low coolant velocity because the mass flow rate is relatively high and the heat transfer into the liquid is very favorable.

Some additional pump horsepower data are shown in Fig. 19 where pump horsepower vs total depth is plotted.

B. Drill Pipe Stresses

By using the assumed electrical resistance of 1Ω for the bit we found that the stress criterion dictated the design of the drill pipe and not the total power criterion. In fact, the load that makes up $\sim 2/3$ and more of the critical design load is the pipe breakaway load of 0.700 MN (157 000 lb). This value may be conservatively high but it is based on information that up to ~ 0.890 MN might be encountered in oil or gas wells.¹⁸ The most severe loading conditions occur at the maximum depth of 10 000 m. For such a well (with a geothermal gradient of

Fig. 16. Mud velocities vs depth in a well of 10 000-m total depth.

Fig. 18. Depth vs mud absolute pressure.

25 K/km, a nominal melting rate of 1 mm/s, a maximum debris size of 10 mm, and using mud as drilling fluid) the calculated axial stress in the aluminum drill pipe (see Fig. 5) at the wellhead is only 121.5 MPa (17 600 psi) during normal operation. The comparable stress at start of hoist and with the breakaway load applied is 364.0 MPa (52 700 psi) or 0.75 times the allowable yield stress. As was already indicated in Fig. 5, pipes that meet these conditions have reasonable and practical configurations.

Note the following important operational consideration for aluminum pipe in hot wells: If, for some reason, the circulation is stopped long enough for the stagnant mud and pipe to approach local rock temperatures, then the strength of the aluminum would be reduced and, depending on the particular conditions, a pipe tensile failure could occur. This problem may be solved by revising the downhole assembly and operation to provide continuous circulation.

C. Tripping

Major factors to be considered during tripping are pipe stress, surface handling, and downhole pressure effects that could upset the hole stability.

Fig. 19. Mud hydraulic power vs total depth.

The pipe-stress problems can be controlled by operating a properly designed string at low acceleration or deceleration rates. Rates of movement are dictated more by downhole pressure considerations and will be discussed further below. Surface handling of the stands has been well developed over the years, and it is estimated that Subterrene operations would be similar to rotary with regard to structural and handling considerations. The major part of the following discussion deals with pressure effects due to moving a drill-pipe string up or down a hole. These results were not obtained with GEOWELL but were calculated separately.

Moore¹⁹ describes the importance of surge and swab pressure controls. Surge pressures are associated with fluid flow caused by running equipment into a hole and swab pressures are those caused by pulling equipment out of the hole. Moore itemizes the problems: (1) More than 25% of blowouts are due to swabbing, (2) surging causes lost circulation both during drilling operations and running casing, (3) pipe movements that produce alternating surge and swab pressures can cause hole sloughing and other detrimental effects, and (4) swabbing can result in unwanted intrusions of formation fluids. Just running a clean pipe into or out of a hole filled with mud can easily produce significant surge or swab pressure effects amounting to 1000 to 3000 kPa (145 to 435 psi). This has been amply verified in the field.

For the assumed rock-melting systems, the downhole pressure problems due to pipe will not be different from present ones. What is different is the

bit and its fit in a hole that is made to close dimensions. An evaluation was made, therefore, of melting-bit clearances and pressure drops across the bit. At LASL, Hanold²⁰ has studied the case of Couette fluid flow within two relatively closely spaced walls with one wall moving and with pressure increasing in the direction of motion -- an analysis applicable to a cylindrical bit or pipe being moved within a borehole. It was assumed that the annular gap is small enough so that circumferential effects can be neglected. Figure 20 shows the configuration analyzed. The calculation terms are defined as follows:

V = pipe velocity, m/s

μ = viscosity of drilling fluid, Pa·s

$\frac{dp}{dx}$ = pressure gradient, Pa/m

h = thickness of annulus, m

λ^* = velocity-splitting streamline location, m

V_1 avg = average velocity in + x direction, m/s

Q_1 = volumetric flow rate in + x direction, m³/s

$$a = \frac{2\mu V}{\frac{dp}{dx}}, m^2$$

c = circumference of hole, m

The basic derived equations are

$$\lambda^* = h - \frac{a}{h}$$

$$V_1 \text{ avg} = V \left[-\frac{a}{6h^2} + \frac{1}{3} - \frac{h^2}{6a} \right]$$

$$Q_1 = cV \left[\frac{a^2}{6h^3} - \frac{a}{2h} - \frac{h^3}{6a} - \frac{h}{2} \right]$$

The drilling fluid is assumed to range from water to thick muds. Water has a viscosity of 0.001 Pa·s. A mud of median weight might be represented by a vis-

cosity of 0.03 Pa·s, as is done in GEOWELL, and a heavy mud by 0.06 Pa·s.

Let us examine the dynamics of the tripping operation. Neglect friction of the pipe in the hole and buoyancy effects. A minimal 3% increase in hoist loads can be allowed to provide acceleration forces, and identical start and stop pipe velocity-vs-time characteristics can be assumed. It can also be assumed that the rig has good trip-rate controls and that the velocity is constant between the start and stop acceleration periods. A final estimation assumes that joints can be made or unmade in 60 s. Two overall rates are of interest (1) 28 stands/h, which is a reasonable state-of-the-art value and is used in GEOWELL, and (2) 35 stands/h, which is 20% higher and might be feasible with future operational improvements.

The performances for these two cases are listed below:

	28 stands/h	35 stands/h
Overall average velocity, (m/s)	0.21	0.27
Stand length, (m)	27.40	27.40
Cycle time, (s)	128.00	102.00
Stationary time, (s)	60.00	60.00
Moving time, (s)	68.00	42.00
Acceleration (m/s ²)	0.29	0.29
Acceleration time, (s)	1.40	2.35
Maximum velocity, (m/s)	0.41	0.69

To be conservative, the 35-stands/h rate condition of 0.69 m/s was used to calculate the pressure drop across bits used to make 0.20-, 0.25-, and 0.30-m-diam holes. It was estimated that the effective bit-and-glass former length amounted to 0.75 x bit diameter. The results are shown in Fig. 21 for the three fluids with different viscosities. There are an infinite number of possible operating conditions; also, additional pressure changes of even greater magnitudes can simultaneously occur due to movement of long pipe itself. It can be seen that for each fluid plotted there is a rapid increase in pressure drop when the annular gap decreases below a certain dimension. For water this gap is ~ 0.75 to 1.0 mm. For the average mud this gap is ~ 3 mm and for thick mud, ~ 4 mm.

Fig. 20. Configuration used for tripping ΔP analysis.

Fig. 21. ΔP across bit while tripping vs radial clearance, withdrawal rate = 0.69 m/s.

For Subterrene bits, a radial clearance of 0.75 to 1 mm for a 300-mm-diam bit would appear to be attainable although there are no experimental data to support this statement. However, a 3- or 4-mm clearance would probably require new, more complex glass-former designs or other new concepts to meet the requirements.

D. Times Required for Major Tasks

Typical percentages of total well-production times required for the major tasks are summarized graphically in Figs. 22 and 23. Figure 22 shows the GEOWELL predictions for the all-rotary drilled well cases, using the best-estimate values for component performances, whereas Fig. 23 shows the combined rotary and rock-melting system cases. For the latter data, the depths of the rotary-drilled well sections above the rock-melted sections were optimized for minimum overall well costs. The rock-melting nominal rate of penetration is 1 mm/s and the geothermal temperature gradient is 25 K/km.

The figures show that, percentage-wise, the rock-melting system has only a very small increase in drilling and penetration time over the all-rotary case. The range of percentages of time used to "make hole" is from ~ 50 to 57%. Tripping takes a

much greater fraction of total all-rotary time than does rock melting. In fact, tripping becomes almost negligible for the latter case. For example, in 10 000-m-deep wells the bit tripping percentages are 19 and 3% for the all-rotary and the rotary rock-melting cases, respectively. The favorable performance of the Subterrene system is due to the enhanced rate of penetration of the melting bit as the rock temperature increases with depth and the fact that no degradation of the melting bit life need be assumed because of high *in situ* temperatures.

The time fractions required to install and to cement the casing is significant in both cases. Thus, the future development of new and continuous rock-glass liner-emplacment capabilities is indicated as being worthwhile.

Fig. 22. Time distribution by task vs well depth for rotary drilled wells.

Fig. 23. Time distribution by task vs well depth for rotary/Subterrene wells.

E. Power Transmission

1. GEOWELL Predictions. The GEOWELL program calculates the various downhole losses, total power, and the transmission efficiency. Assuming that the coaxial aluminum drill pipe is used, Fig. 24 shows the losses vs total depth calculated for the highest power case, i.e., assuming a 1-mm/s nominal penetration rate in a 25 K/km geothermal gradient. Total power required ranges from 580 to 740 kW at depths of 5000 and 10 000 m, respectively. The corresponding fraction of useful-to-total power ratio is shown in Fig. 25. The transmission efficiency is reasonably high ranging from 50 to 39% for depths of 5000 and 10 000 m, respectively. The 10 000-m efficiency tends to remain high compared to the 5000-m values because of the beneficial effects of higher rock temperatures on the melting process. Figure 26 provides more information on total power requirements

Fig. 24. Typical distribution of melting power at total depth.

Fig. 25. Useful-to-total power ratio vs total depth.

Fig. 26. Total power downhole vs total depth.

for cases with various nominal penetration rates from 0.2 to 1.0 mm/s. None of the above predictions indicates any particular power-transmission problems to depths as great as 10 000 m. The only other problems that may develop are chemical corrosion and dirty contact joints, and these are assumed to be preventable.

2. Choice of Power. A study of the type of electric power to be used, whether ac or dc, indicated that ac is the better choice because of the considerations discussed below.

In a system development program, it would be initially cheaper to generate 60-Hz alternating-current power. Diesel-electric generators of several hundred kilowatts capacity are readily available, and such power units operate more efficiently and controllably if they produce ac rather than dc. Moreover, if dc is really desired, solid-state units are available which can easily convert the current from ac to dc.

However, other considerations rule against the transmission of dc power to the melting penetrator.

The first and most important of these is corrosion. The environment within the geothermal bore is a drilling mud which consists of a water solution containing many corrosive ions and a suspension of particulates. The presence of dc electric power flowing along a conductor immersed in this mud would enhance the production of corrosion cells due to the potential gradient along the conductor. Such corrosion would be particularly detrimental around any conductor anomaly such as a threaded joint. By its inability to establish and to support such corrosion cells, ac has a distinct advantage.

A second consideration is impedance-matching. For example, to supply 200 kW to the bit at 5 km it is estimated that a dc power source of 1564 V and 477 A would be required. At 10 km, the power source would be 2905 V and 477 A. Direct-current equipment capable of a continuous voltage change over a range like this would be costly, bulky, and difficult to control. However, such voltage requirements could be easily met by the combination of an ac power source and transformer or saturable reactor.

The use of ac also has some disadvantages such as inefficiencies due to hysteresis, dielectric losses, and changing power factors. However, with proper design, the small losses remaining in the transmission circuit and in other related equipment are acceptable.

3. Power Conditioning. Downhole transformers have been investigated because they could result in power savings by lowering transmission-line currents. However, while a reduction in current is desirable, the corresponding increase in voltage is not easy to handle because voltages of, e.g., nearly 3 kV are already anticipated at depths of 10 km. The prospect of additional insulation requirements for higher voltages is quite formidable; especially because the expected ambient temperatures of the deep bore are well into the range that degrades electrical insulation.

Moreover, a study of best transformer core materials shows a power-saturation level of 0.233 W/mm^2 . A transformer core designed to pass 200 kW would have a total core area of 0.836 m^2 ; far too large to have a reasonable form factor for use in a 200-mm-diam borehole.

F. Hole Control

No evaluation of a well production system would be complete without a discussion on hole control relating to unexpected encounters with abnormal high-pressure fluids, where normal pressure is defined as approximately hydrostatic. The consequences of lack of control during such encounters are well known and may include, e.g., blowout, cratering around the rig, severe hole damage, violent ejection of drill pipe, other loss of expensive equipment, loss of human lives, and hole abandonment. While geothermal wells like hot dry rock might not often encounter abnormal pressures because of the type of formations being sought, the possibilities still exist and the drilling system must be able to cope with the problem.

Abnormal pressures are not uncommon in the oil and gas industry according to Thomeer and Bottema.²¹ They describe practical examples from widely scattered areas such as northern Germany, Netherlands New Guinea, and West Pakistan where pressures approaching lithostatic have been encountered. Another area known for high pressures up to ~90% of lithostatic is an 80-km-wide belt on the Gulf Coast of Louisiana. Dickinson's²² studies show that the rate of pressure increase with depth, once the abnormal pressure zone is encountered, can be very high although many wells have shown only a gradual rate. The encounters occur at depths of ~2.5 to 3 km. Of six examples of typical wells, one well showed an initial rate at the initial encounter with the abnormal of 622 kPa/m (27.5 psi/ft) over a pressure rise of 10 300 kPa (1500 psi). Other rates ranged from 20.4 kPa/m (0.90 psi/ft) to 146 kPa/m (6.5 psi/ft) and overall pressure level increases with depth were ~34 500 kPa (5000 psi). Thus, during serious encounters with abnormal zones the pressure level can increase abruptly and substantially.

According to rotary drilling literature, the first step is to detect that a pressure increase is being encountered. This is done by heeding such indicators as an increase of fluid in the mud pits, a sudden increase in penetration rate usually accompanying a downhole loss of overbalance, large gas bubbles expanding as they rise causing a rapid unloading of the mud and producing gas kicks, a change in circulation pressure because of mud dilution, the development of gas-cut mud due to small gas bubbles,

direct shows of the intrusion fluid, and a flow of mud from the well. The second step is to close the blowout-prevention (BOP) valves. Third, shut-in pressures are measured; these data will provide a measure of the encountered pressure and an estimate of the fluid intrusion into the annulus. Fourth, knowing the bottom pressure from Step 3, a gradual change in mud weight is made by a controlled circulation process and the intruding fluid is circulated out. Fifth, if the formation fracture pressures at intermediate depths are too low to withstand subsequent mud weights and no casing is in place, steps are taken to install casing to take high mud-weight bursting loads. Sixth, the drilling continues by using overbalancing mud weights in the abnormal pressure zone.

All the abnormal pressure indicators discussed above apply with melting bits except that the penetration rate for a fixed bit-weighting condition will decrease as pressure increases rather than increase as is the case with rotary bits. There are three indicators that may be better than those available to rotary drillers. First, the appearance of the rock-glass debris can change with the introduction of intrusion fluids. Undoubtedly, the debris will be continuously monitored as part of the melting operation, and intrusion may therefore be detected by this method. Second, a sudden high face pressure on the melt could cause erratic flow conditions through the melt bleedoff channels or at least could change the bit operating characteristics. Third, a very rapid indicator should be a change in the bit thrust loading required to maintain a penetration rate, due to a change in the face pressure pushing upward on the bit. The thrust on the melting face is generated by the local mud pressure, by the thrust loading from the weight of drill collars and pipe, by the buoyancy effects, and by in situ pressures being encountered. A thrust load cell mounted directly behind the bit may be especially useful to obtain the fastest reading of thrust deviations and indications of in situ pressure changes for hole-control purposes.

With rotary, the intrusion into a bare hole will be relatively unrestricted. This may enable the driller to detect it rapidly before his bit progresses too far into the abnormal formation and to prevent a disastrous blowout because of the rapid

inflow. With melting, a thin and somewhat porous liner laid down along the bore would somewhat restrict the intrusion flow and thus give the driller more time for corrective actions. Also, the wall would tend to be structurally stabilized by the glass liner and not slough in due to the inflow. These are advantages for the melter. However, if a thick impervious liner is laid down it is conceivable that it might stand up to the high pressure for some time until the underpressure condition would lead to a sudden wall collapse, blowout, and a trapped pipe and downhole assembly. The latter failure should never occur except under unusual circumstances. If a thick liner is being laid down it must be assumed that it is part of an operational plan and that some knowledge of downhole pressure had been obtained beforehand by means such as thrust monitoring. The wall thickness will be selected to withstand a potential underbalance and, further; the mud weight should be adjusted to prevent any hazardous underbalance condition.

The use of heavy muds dictated by abnormal pressures can lead to a swabbing problem where the adhesion of the thick, viscous mud to a tripping pipe results in a pressure drop at hole bottom. If the initial overbalance is not large enough then the hole becomes underbalanced and fluids might intrude to give trouble. Here, again, the capability to form a good collapse-resistant glass liner along the hole would be very advantageous because the liner could absorb the temporary underbalance as the pipe is pulled. This would increase the operational flexibility and safety of the job.

Another difference between rotary and melting systems might be noted. Considering the above swabbing-underbalance problem, the rotary solution would be to use a heavier mud so as to obtain a sufficient overbalance margin. However, a greater overbalance would reduce the rotary rate of penetration somewhat and therefore constitute a system performance penalty. No similar penalty appears to exist for melting bits.

All the above considerations lead to the conclusion that hole control with rock-melting systems is no more difficult than it is with rotary drills. Indeed, it would appear that any change in melting penetration performance caused by a rapid change in formation fluid pressure could be detected very

rapidly. Also, a measured change in the thrust being applied on the bit would provide a good estimate of the pressure change downhole. This presents the interesting possibility for developing a pressure detection system that would give the driller more time to take corrective action and also more positive data on the pressures being encountered.

G. Penetration Into Very Hot Rocks

Let us look at the well production performance plotted in Fig. 27 for cases where rocks at very high temperatures (up to magma) are being penetrated. The figure also includes two "cool" wells for comparison purposes. The rotary drilled well is assumed to be drilled into rock at the approximately normal geothermal gradient of 25 K/km that results in a 10 000-m bottom hole temperature of 433 K. The case was run on GEOWELL using best-estimate component performances. All the rock-melting cases assume that the nominal bit penetration rate is 1.0 mm/s in rock at 283 K. The cool-rock-melted well also assumes a 25 K/km gradient. One of the hot wells is assumed to be in a 100-K/km gradient that results in a 10 000-m bottom temperature of 1283 K. The other hot well simulates an encounter with a magma chamber where a gradient of 50 K/km is assumed to a depth of 6560 m and of 500 K/km thereafter to 8200 m where penetration is stopped at 1431 K.

Figure 27 illustrates that the difference in overall production time between the three rock-melting cases is not large, the cool well requiring 4400 h to reach total depth or 19% more than the 3700 h for the 100 K/km case. On the other hand,

Fig. 27. Depth vs production time for various geothermal temperature conditions.

the rotary drilled well requires more than twice the time for any of the rock-melted cases. The overall average rates of penetration from spudding-in to total depth, not including the time to put in the final casing, are:

Case	Total Depth (m)	Average Overall ROP (m/h)
All rotary, 25 K/km	10 000	1.10
Melted, 25 K/km	10 000	2.27
Melted, 100 K/km	10 000	2.70
Melted, 50 and 500 K/km, to 1431 K	8 200	2.46

The penetration rates vs depth for the above cases are plotted in Fig. 28 to graphically illustrate that the enhancement of ROP due to increasing rock temperatures is small in a normal geothermal gradient well but becomes quite significant in high gradients. No significant performance data was found for rotary bits used to drill in very hot rocks such as are being considered here, except for some small and shallow holes through Hawaiian lava-lake crusts where very high cooling-water flow rates were used during lava penetration. Certainly, rotary bits would have to be kept very cool to prevent rapid material deterioration and loss of useful life.

Fig. 28. Depth vs melting rate of penetration for various geothermal temperature conditions.

A word of caution about the above GEOWELL predictions for operations at very high rock temperatures: the program has not been set up to cope with all the problems related to very hot rocks. Rather, the modus operandi has been patterned quite closely after those for conventional rotary drilling. The predictions for penetration rates should be reasonable and the above discussions, therefore, still apply. However, other problems are not addressed, e.g., casing and cementing to total depth in very-high-temperature surroundings. Also, if normal tripping techniques are used, downhole assemblies would have adequate time to approach the surrounding rock temperatures, and problems of high-temperature corrosion and other material degradations would be introduced. Long periods of noncirculation would allow the downhole drilling fluids to heat up and possibly deteriorate or be hard to handle when circulation is reinstated. Both rotary and Subterrene systems would encounter variations of these problems and continuous circulation at all times for both systems is therefore mandatory for operation in very hot rocks. From our observations of drilling difficulties and our knowledge of costs involved with rotary drilling of conventional geothermal wells we estimate that the lower limit of rock temperature requiring continuous circulation may be ~ 650 K, especially for deep to ultradeep wells.

New downhole assemblies and techniques for both rotary and Subterrene systems are needed to effectively cope with very high hole temperatures. The Subterrene concept opens the way to some interesting new designs, because the bit itself is inherently suited to operation at rock-melting temperatures. For example, Fig. 29 illustrates a design that could be compatible with a very hot borehole because it would include the following capabilities:

- Almost continuous circulation at all times.
- Casing, if required, is always in place behind the bit while hole is being made.
- Bit trip times will be short because the bits are reeled-in or deployed on long electric power cables.
- Thick rock-glass liners can be produced continuously by proper selection of melting techniques and surfaces.

The design concept is as follows: the drill pipe, which can also become the final casing, is made as

Fig. 29. Retrievable bit downhole assembly concept.

large as possible to just allow room for debris removal through the annulus. Because the debris is formed from molten rock, the Subterrene provides some flexibility and control of the size and shape of the debris. Flush pipe joints, such as are currently available, would be used. The melting bit is attached to the drill pipe by means of a remote latching mechanism. Electric power is supplied through a centrally located beryllium-copper cable. To unlatch the bit a force is applied to the cable, which lifts the drill collars a short distance from the bit, leading to an unlatching sequence. The collars and bit are then reeled rapidly to the surface in a similar manner as already suggested in Section II, E, 2, while the drill pipe remains in place. Reverse circulation can be used to assist

bit movement. A reverse sequence is used to trip a new bit downhole. All the while, the drill pipe remains in the hole allowing circulation to continue and avoiding stagnant overheated fluid in the borehole. It is estimated that the glass former will have a much longer lifetime than the hot melting bit, but eventually the glass former will have to be replaced. At that time the bit and cable assemblies will be tripped, and a central coolant line will be lowered into the hole to maintain circulation while the glass former is tripped and replaced. Admittedly, the latter pipe tripping operation is more complicated than normal but it can be done. However, it may not be necessary to pull the pipe at all depending on the length of the final section that can be produced in very hot rocks or magma.

IV. COST STUDY RESULTS

A. Rotary Drilled Wells

1. Comparison of Predicted and Actual Well Costs. Because of the paucity of data for hot geothermal wells, the cost data for our model essentially represent drilling in normal geothermal temperature gradient conditions. Therefore, the model can be checked by comparing its predictions directly with actual oil and gas-well data. Figure 30 shows typical oil and gas well costs vs total depth. The solid dots are average total costs for all U.S. wells drilled in 1974 by state or drilling district, excluding Alaska and offshore wells, and published in the Joint Association Survey.²³ All costs were upgraded to 1975 dollars by using inflation factors derived from a cost study of the Independent Petroleum Association of America (IPAA) and from direct communications with the IPAA staff.¹⁷ The three circled deep-well costs were obtained from the open literature. The solid line is obtained from GEOWELL by using the component performances (best estimate) described in Section II. The predictions appear to be reasonably matched to actual well costs and trends. If anything, the predictions are conservatively low considering that the model is meant to simulate wells that are above average in drilling difficulty.

2. Major Rotary Cost Items. The major cost items in deep rotary drilled wells simulated by GEOWELL are itemized in Table II. Wells are difficult to generalize and the costs shown obviously reflect

TABLE II
MAJOR COST ITEMS FOR ROTARY-DRILLED DEEP WELLS IN NORMAL GEOTHERMAL GRADIENTS

Cost Items	Total Depth (m)							
	10 000		8500		7000		5000	
	Cost (M\$)	Fraction of Total	Cost (M\$)	Fraction of Total	Cost (M\$)	Fraction of Total	Cost (M\$)	Fraction of Total
Drill pipe (D. P.)	0.6875		0.3741		0.1835		0.0564	
Drilling contractor (w/o D.P.)	1.7728		1.1836		0.7533		0.3729	
Drilling contractor (with D.P.)	2.4603	0.28	1.5577	0.26	0.9368	0.25	0.4293	0.25
Mud	0.8155	0.09	0.5588	0.09	0.3506	0.09	0.1487	0.08
Casing	2.1917	0.25	1.5607	0.26	1.0301	0.28	0.4858	0.28
Cement	0.3917	0.04	0.3292	0.06	0.2654	0.07	0.1783	0.10
Bits	0.4990	0.06	0.4059	0.07	0.2992	0.08	0.1726	0.10
"Other", common to all systems	2.4911	0.28	1.5329	0.26	0.8630	0.23	0.3275	0.19
TOTAL WELL COSTS	8.8493		5.9452		3.7451		1.7422	

the site-specific assumptions used to set up the model. However, let us compare the GEOWELL results with those published annually by the Cost Study Committee of the IPAA. In using the IPAA cost breakdown, note that the wells reported by IPAA are typically oil and gas and not hot, geothermal types, and their average onshore depth is only ~1.6 km which is shallow when compared with those being studied here.

The IPAA studies show 36% of total costs for the drilling contractor. GEOWELL predicts 25 to 28%. This decrease is probably mainly due to the fairly optimistic overall average drilling rates which decrease the total time that the contractor has to be on site. IPAA lists mud as 7% compared to GEOWELL's 9% - a reasonable increase considering the size of hole and the high temperatures. IPAA lists casing and cement as 22% compared to GEOWELL's 29 to 38%. The casing program in GEOWELL addresses very difficult high-pressure conditions that require above-average hole protection, which explains the high GEOWELL cost. Also, the 38% value refers to a 5000-m well and further adjustments in well design might reduce casing and cementing costs, remembering that the model is essentially set up for deeper wells, i.e., 7 to 10 km. IPAA lists bit costs at 1.4% compared to GEOWELL's 5 to 10%. This deviation is explained by the use of expensive carbide bits throughout the modeled wells and by the relatively large sizes required for the deep wells. The item listed as "other"

Fig. 30. Well costs, typical oil and gas wells and GEOWELL normal gradient predictions.

ranges from 28 to 19%. The modeling for "other" was based on the IPAA cost breakdown where it amounted to 28%. This is a major cost item assumed to be common to both rotary and Subterrene systems and its exact magnitude is not overly important for comparing the two systems.

3. Effects of Rotary Bit Performance Variations. To obtain an indication of the economic importance of rates of penetration and bit life (expressed as meterages or total meters of penetration before the bits must be tripped), program runs were made with multiplying factors ranging from 0.5 to 8.0 applied to equations for ROP and meterages. The results are shown in Figs. 31 and 32 for 5000- and 10 000-m-deep rotary drilled wells. In Fig. 31, the maximum savings range from ~12 to 15% for 5000- and 10 000-m depths, respectively, with most of the savings realized before the multiplying factor reaches five. A promising advance rotary drilling technique that has been extensively researched for a number of years is the high-pressure jet bit concept. Maurer²⁴ states that jet bits operating at 100 000 kPa (~15 000 psi) can drill oil wells two to three times faster than conventional bits. Neglecting the substantial cost for additional high-pressure components, an improvement factor of 3 shows cost savings of only 9 to 12%. This savings would, of course, be markedly higher for other types of wells, e.g., offshore, where the daily rig costs are much higher than is assumed in GEOWELL.

Looking at the effects of meterage we see in Fig. 32 that the maximum possible savings would be

~11% using an eightfold improvement. Such improvements may be possible, e.g., through the chain bit concept now being researched at the Sandia Laboratories.²⁵ However, the additional bit costs will have to be included in any future study to determine whether a net saving would result.

What is concluded from the above study results is that the estimates for ROP and meterage used in GEOWELL could be changed substantially without changing the total well costs enough to seriously detract from a comparison of Subterrene and rotary system costs.

4. Optimum Rotary and Melting Depth Combinations. For rock melting applications, let us first examine what the upper rotary drilled depth, ROTEL, should be to achieve minimum well costs. The interactions of ROTEL and nominal melting-penetration rates with well costs are shown in Figs. 33 through 36 for four total depths. For both rotary and melting operations, the GEOWELL component performance estimates are as described in Sec. II. The geothermal gradient is 25 K/km. In each figure the loci of optimum ROTEL and minimum costs are indicated. The depth, DL2, of the 660-mm (26-in.)-diam hole, which is assumed to be always made by rotary drills, is also indicated.

For depths from 7000 to 10 000 m and between nominal melting rates of 0.4 to 1.0 mm/s, DL2 is close to the optimum depth and therefore the initial assumption to use melting bits only below DL2 does not cause any analysis problems. At the state-of-the-art rate of 0.2 mm/s, the optimum ROTEL moves down to ~4000 m.

Fig. 31. Rotary drilled wells, effect of rate of penetration on total costs.

Fig. 32. Rotary drill wells, effect of bit life on total costs.

Fig. 33. Costs vs rotary depths, 5000-m rotary/
Subterrene normal gradient wells.

Fig. 34. Costs vs rotary depths, 7000-m rotary/
Subterrene normal gradient wells.

Fig. 35. Costs vs rotary depths, 8500-m rotary/
Subterrene normal gradient wells.

Fig. 36. Costs vs rotary depths, 10 000-m rotary/
Subterrene normal gradient wells.

5. Effects of Melting Bit Performance Variations. The effects of melting rate of penetration and bit life variations on well costs were determined for normal geothermal gradient wells. Figure 37 shows the effect of bit life on costs, using 1 mm/s as the nominal ROP and a depth of 8500 m. The ordinate is the ratio of cost for any selected life to a base cost. The base cost corresponds to a 300-h life, which is the best-estimate value in GEOWELL, and bit life ranges from 100 to 800 h. It can be seen that cost changes only by $\sim 7\%$ over the whole range and that at 300 h, the cost savings is 5% compared to the state-of-the-art life of 100 h.

Fig. 37. Effect of melting bit life on rotary/Subterrene well costs.

Fig. 38. Effect of melting rate of penetration on rotary/Subterrene well costs.

Thus, bit life does not strongly affect well costs.

Figure 38 is similar to Fig. 37 with cost ratio as the ordinate but with nominal ROP as the abscissa over a range of 0.2 to 1.4 mm/s. Base ROP is 1 mm/s, the Subterrene R&D program target, and bit life is fixed at 300 h. The figure shows that ROP is a more important parameter than bit life. Just doubling the state-of-the-art value to 0.4 mm/s saves 25% in well costs and at 0.6 mm/s the savings is 33%. However, from ~ 0.6 mm/s and up the cost savings become increasingly less significant. As a program target, the 1 mm/s appears satisfactory.

6. Comparison of Rotary and Subterrene Costs.

Figure 39 shows both rotary and Subterrene cost predictions vs total depth. The Subterrene wells use optimum ROTEL depths and the geothermal gradient is 25 K/km. For these wells the state-of-the-art nominal melting rate of 0.2 mm/s is not cost-competitive with rotary. The rates required for the melted wells

Fig. 39. Well costs vs total depths in cool wells, geothermal gradient: 25 K/km.

to equal the rotary drilled well costs range from 0.24 to 0.42 mm/s for 10 000- and 5000-m-deep wells, respectively. However, at 0.6 mm/s the cost savings of melted over rotary wells range from 18 to 8% for 10 000- and 5000-m-deep wells, respectively, and at the program target rate of 1.0 mm/s the corresponding savings are 23 to 16%. Remember that these savings are for wells being made under relatively cool, normal-gradient conditions.

7. Major Subterrene Cost Items. Table III is similar to Table II that tabulated absolute and fractional GEOWELL cost predictions for rotary drilled wells. On a percentage basis, the cost distribution for melted wells is considerably different from that for rotary wells and comparisons on an absolute cost basis may be more instructive. Table IV therefore shows the ratios of Subterrene-to-rotary absolute costs. Table IV shows that Subterrene drill-pipe costs are only 0.41 to 1.0 times those of rotary pipe for 10 000- and 5000-m-deep wells, respectively, even though the delivered price for the Subterrene is approximately three times that of conventional steel pipe. These low costs are due to the expected

long life of the Subterrene pipe because it is not subject to the normal wear and tear of rotation. The drilling-contractor Subterrene-to-rotary cost ratios are 0.48 to 0.82, also very favorable, and due partly to the drill pipe but mainly to decreased time on site. Mud benefits are derived from precise geometry control and some isolation from the formations by the glass linings in the boreholes. Casing is benefited by the use of the glass liners to perform some of the casing structural functions. Bits show a Subterrene-to-rotary cost ratio of only 0.39 even with the high unit price of the refractory metal melting bits. This low ratio is due to the 300-h life of the melting bits and partly to the use of expensive rotary carbide insert bits in the rotary drill wells. However, the bit assumptions could be changed considerably and the predictions would still indicate that melting-bit costs are not a big factor in overall well costs. Finally, going back to Table III, the cost to melt rock in the borehole is represented by the sum of the listed fuel and generating-equipment costs. These costs are not significant, being only ~ 1% of the total Subterrene well costs.

TABLE III
MAJOR COST ITEMS FOR ROTARY/SUBTERRENE WELLS IN NORMAL GEOTHERMAL GRADIENTS

Cost Items	Total Depth (m)							
	10 000		8500		7000		5000	
	Cost (M\$)	Fraction of Total	Cost (M\$)	Fraction of total	Cost (M\$)	Fraction of total	Cost (M\$)	Fraction of total
Drilling Contractor:								
Rotary Drill Pipe (D.P.)	0.0201		0.0130		0.0080		0.0024	
Rotary Rig w/o D.P.	0.1840		0.1263		0.0845		0.0394	
Subterrene D.P.	0.2637		0.1833		0.1209		0.0590	
Subterrene Rig w/o D.P.	0.7083		0.5371		0.3940		0.2526	
Total Drilling Contractor	1.1761	0.17	0.8597	0.18	0.6074	0.20	0.3534	0.24
Mud, Rotary + Subterrene	0.6422	0.10	0.4400	0.09	0.2761	0.09	0.1153	0.08
Casing	1.8496	0.27	1.3266	0.28	0.8852	0.29	0.4292	0.29
Cementing	0.3812	0.06	0.3178	0.07	0.2535	0.08	0.1661	0.11
Bits, Rotary	0.0964	0.01	0.0658	0.01	0.0429	0.01	0.0099	0.01
Bits, Subterrene	0.1004	0.01	0.0863	0.02	0.0718	0.02	0.0569	0.04
Melting Fuel	0.0480	0.01	0.0393	0.01	0.0306	0.01	0.0207	0.01
Melting Power Gen. Equipment	0.0094	--	0.0077	--	0.0060	--	0.0040	--
"Other", common to all systems	2.4911	0.37	1.5329	0.33	0.8630	0.28	0.3275	0.22
TOTAL WELL COST	6.7944		4.6761		3.0365		1.4830	

TABLE IV
RATIOS OF SUBTERRENE TO ROTARY COSTS

Item	Total Depth (m)	
	10 000	5000
Drill pipe	0.41	1.00
Drilling contractor with drill pipe	0.48	0.82
Mud	0.78	0.78
Casing	0.84	0.88
Cement	0.97	0.93
Bits	0.39	0.39

B. High Gradient Wells

1. Extrapolation Assumptions. The cost predictions so far have all been for normal geothermal gradients and should be reasonably valid. Now the remaining task is to extrapolate the predictions from normal to high gradients. However, only a few statistics are available because (1) not many very hot geothermal wells have been drilled and (2) little detailed data have been released by the companies drilling the wells. Nevertheless, estimates will allow us to compare Subterrene and rotary systems. The simple procedure used here is to apply multiplication factors to the appropriate cost equations in GEOWELL. The factors used are explained below.

Our definition of a hot well is one that has a bottom-hole temperature of 673 K (751 F). In a rotary drilled well, it is predictable that for such a hot well, costs will be higher than for a typical normal gradient well due to; (1) decreased bit life, (2) decreased drill-pipe life or the need to switch to more expensive pipe to reduce high-temperature corrosion or other material degradations, (3) expensive cement and much more difficult cement-emplacement problems, (4) expensive casing with better high-temperature strength and corrosion resistance, and (5) considerably more mud-handling and well-control problems plus more expensive muds that are stable at the higher temperatures. Reasonable and conservative multiplication factors to represent the above problems are shown below. These factors are easy to change in the program as more information becomes available.

Cost Item	Factor
Bit life	0.75
Drill pipe	1.5
Cement	3.0
Casing	1.5
Mud	3.0

The Subterrene systems are not affected by temperature as much as rotary are. There is no bit-life degradation and mud costs should be benefited even more by the isolation from the formations afforded by the glass lining on the borehole wall. The other three items above will impact Subterrene about the same as rotary. Therefore the factors selected for Subterrene hot wells are:

Drill pipe	1.5
Cement	3.0
Casing	1.5
Mud	2.0

2. Costs. The rotary and Subterrene GEOWELL predictions for hot wells as defined above are shown in Fig. 40. Because all bottom-hole temperatures are assumed to be 673 K, the geothermal gradients vary with depth, but across the range of data plotted all gradients are above normal. It can be seen that with the state-of-the-art nominal melting rate of 0.2 mm/s, the Subterrene well cost is not much different from that for rotary drilling. At 0.6 mm/s, midway between current and program target rates, the cost savings are significant (26 and 17% for 10 000- and 5000-m depths, respectively), and also greater than for comparable depth normal gradient wells. At 1 mm/s the Subterrene cost is indicated as being clearly superior over rotary, being 30 and 21% less than rotary for 10 000- and 5000-m depths, respectively.

Figure 41 shows basically the same hot well predictions that were shown in Fig. 40 but also relates the predictions to various geothermal gradients from 25 to 70 K/km.

Figure 42 shows the cost results in still another way. The 9750- and 6500-m depths correspond to 40 and 60 K/km gradients, respectively, and to 673 K bottom temperatures. Costs for the approximate normal gradient of 25 K/km are also shown. Even at the 0.2-mm/s rate, savings of 8% over rotary are indicated for the 9750-m-deep hot well. At 1 mm/s

Fig. 40. Well costs vs total depths in hot wells with various melting bit performances. Rock temperatures increase linearly to 673 K (751 F) at total depth for all wells.

Fig. 41. Well costs vs total depths for geothermal gradients of 25 to 70 K/km.

the savings are 29% at 9750 m and in a 6500-m well they are 25%; even down to a rate of ~ 0.5 mm/s the predictions are strongly in favor of Subterrene.

V. CONCLUSIONS

The study conclusions are:

- The GEOWELL computer program is a good simulation of deep and difficult wells of the type defined, allowing the evaluation of major technical or cost items. Other well models could be specified and the program adjusted accordingly for further studies.
- The Subterrene concept can be combined with conventional drilling operations without major operational perturbations. However, for very hot boreholes, a change in system design and operation is indicated to develop the capability of maintaining continuous, or nearly continuous circulation while working in the hot part of the borehole. This applies to both rotary and Subterrene systems.

Fig. 42. Subterrene well to rotary well cost ratio vs nominal melting bit rate of penetration.

- Subterrene performance of ~ 0.2 -mm/s penetration rate and 100-h bit life, can in some cases, provide marginal cost savings. However, if the Subterrene Program achieves the target performances, i.e., 1.0-mm/s penetration rate and 300-h bit life, then Subterrene-produced wells would be significantly less expensive than rotary. In hot wells (673 K bottom temperature) the savings of 30 and 21% are predicted for depths of 10 000 m and 5000 m, respectively. Even in cool, normal-gradient conditions, the savings are favorable, ranging from 23 to 16% for depths of 10 000 m and 5000 m, respectively.

- All other potential Subterrene design or operational problems that were studied appear to have viable solutions.

- The most interesting feature of the drilling by melting concept is to form rock-glass liners on the borehole wall. These liners offer opportunities to solve well-production problems associated with, e.g., hole control, lost circulation, casing design, cementing, and high-pressure packers to the innovative designer or operator.

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APPENDIX

EXAMPLE OF AN EXTRUDER MELTING-PENETRATOR DESIGN

Two mechanical assembly drawings are shown to illustrate the design of the 84-mm (3.31 in.)-diam extruding-type penetrator. This penetrator was used successfully in a field demonstration near Los Alamos, NM to form a 30-m-deep vertical borehole in solid basalt. In the main body of this report, Fig. 1 is a photograph of one of these bits and Fig. 2 shows the Experimental Field Unit on site.

Drawing 59Y-32755 shows the bit assembly and details of the molybdenum face-melting body; melt

extrusion-channels and heaters can also be seen. Drawing 59Y-32753 shows the stem or drill-pipe assembly. Besides supporting the bit, the stem was used to flow nitrogen gas acting as coolant and drilling fluid to the bit and transmit the electric power for melting. The debris was carried out of the borehole through the central hole in the stem and was collected in storage bags on the surface for further studies.

BILL OF MATERIAL				BILL OF MATERIAL				BILL OF MATERIAL				BILL OF MATERIAL			
ITEM	QUANTITY	UNIT	DESCRIPTION	ITEM	QUANTITY	UNIT	DESCRIPTION	ITEM	QUANTITY	UNIT	DESCRIPTION	ITEM	QUANTITY	UNIT	DESCRIPTION
51	1	QTY	P/N 2755-51 RETAINER	36	2	QTY	P/N 2755-36 MOLY PIN	21	2	QTY	"B-32UNC x .500 LG. SOC. HD SET SCR.	100	1	P/N	P/N 2755-100 OUTER GAS NOZZLE SUB-ASS'Y
52	1	"	P/N 2755-52 THURST COLLAR	37	1	"	P/N 2755-37 PYRO WASHER	22	1	"	P/N 2755-22 COVER PLATE	200	1	"	P/N 2755-200 INNER TUBE SUB-ASS'Y
53	1	"	P/N 2755-53 FLOW DIRECTOR	38	3	"	P/N 2755-38 HEATER TRANSITION	23	2	"	P/N 2755-23 MOLY PIN				
54	1	"	P/N 2755-54 OUTER TUBE	39	3	"	P/N 2755-39 TOP HEATER (OPTIONAL)	24	1	"	P/N 2755-24 BN SEAL RING	1	1	"	P/N 2755-1 BODY
55	1	"	P/N 2755-55 TOP HOLEFORMER	40	3	"	P/N 2755-40 TOP HEATER	25	1	"	P/N 2755-25 PYRO WASHER	2	1	"	P/N 2755-2 EXTRACTOR
56	1	"	P/N 2755-56 LOWER PYRO RING	41	3	"	P/N 2755-41 RECEPTOR	26	3	"	P/N 2755-26 ELECTRODE	3	1	"	P/N 2755-3 AFTERBODY
57	4	"	[4-.40UNC x .78LG] SOC. HD SET SCR. STEEL	42	12	"	P/N 2755-42 DUMMY HEATER	27	5	"	RETAINING RING FOR [250] SHAFT * HF-2025	4	1	"	P/N 2755-4 TOP INSULATOR
58	2	"	P/N 2755-58 LOCK PIN	43	15	"	P/N 2724-25 HEATER SHT C21	28	3	"	P/N 2755-28 SPRING SLEEVE	5	4	"	[250-.20UNC x .312] LG. SOC HD SET SCREW
59	2	"	P/N 2755-59 LOCK PIN	44	3	"	P/N 2724-47 HIGH POWER HEATER SHTC43	29	3	"	P/N 2755-29 ELECTRODE SPRING	6	2	"	RETAINING RING FOR [187] SHAFT * HF-2024
60	1	"	P/N 2755-60 TOP GLASS FORMER (OPTIONAL)	45	3	"	P/N 2755-45 SPRING KEEPER	30	3	"	P/N 2755-30 KEEPER SLEEVE	7	4	"	[312-.24UNC x .250] LG. BUTTON HD. SOC. SCR.
61	1	"	P/N 2755-61 MIDDLE GLASS FORMER (OPT.)	46	3	"	P/N 2724-34 HEATER TIP SHT C20	31	1	"	P/N 2755-31 WASHER	8	1	"	P/N 2755-8 PURGE TUBE
62	1	"	P/N 2755-62 BOTTOM GLASS FORMER (OPT.)	47	1	"	P/N 2755-47 THURST WASHER	32	3	"	P/N 2755-32 ELECTRODE INSULATOR	9	1	"	P/N 2755-9 THERMAL SHIELD
63	1	"	P/N 2755-63 PYRO RING	48	1	"	P/N 2755-48 COUPLING	33	3	"	P/N 2755-33 TUNGSTEN ELECTRODE	10	1	"	P/N 2755-10 TRANSITION BLOCK COVER
64	1	"	P/N 2755-64 MIDDLE HOLEFORMER	49	1	"	P/N 2755-49 SCREEN	34	1	"	P/N 2755-34 INNER GAS NOZZLE	11	1	"	P/N 2755-11 TRANSITION BLOCK
65	1	"	P/N 2755-65 GRAPHITE HOLEFORMER	50	1	"	P/N 2755-50 SPLIT COLLAR	35	1	"	P/N 2755-35 PYRO WASHER	2	1	"	P/N 2755-12 INNER TRANSITION SLEEVE
66	7	"	P/N 2755-66 MOLY WASHER									13	1	"	P/N 2755-13 OUTER TRANSITION SLEEVE
67	1	"	P/N 2755-67 BOTTOM HOLEFORMER									14	1	"	P/N 2755-14 SPRING KEEPER

+0.08 -0.15
4.75" x 6.3 DEEP 2 HOLES
DO NOT BREAK THRU

4.75 ϕ x 5 DEEP 2 HOLES EQ. 5F
DO NOT BREAK THEM

VIEW A

[illegible]