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THE SUBTERRENE ROCK-MELTING CONCEPT APPLIED TO THE PRODUCTION OF DEEP GEOTHERMAL WELLS*

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Abstract

The drilling of wells comprises 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 cost studies were made of the application of the Subterrene concept, i.e., excavating and penetrating rocks or soils by melting, to deep wells such as may be used for dry-hot-rock or geopressure geothermal energy extraction systems. Technically, it was found that Subterrene requirements are compatible with those of current rotary drilling practices. Certain features of the rock-melting concept such as the glass lining on the borehole wall, and nonrotation, provide opportunities for the development of better well production techniques in hot wells. 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 33% or 4.5 million dollars reduction from rotary drilled well costs are estimated for a 10 km depth well with bottom hole temperatures of 673 K. Even for normal geothermal gradient conditions, the savings for the 10 km depth is estimated as 23% or 2 million dollars.

INTRODUCTION

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

Subterrene Program. The rock-melting concept, called Subterrene at the Los Alamos Scientific Laboratory (LASL), had its beginning in the early 1960's when a device known as the electric drill was tested, but it was not until 1972 when funding from the Atomic Energy Commission and later from the National Science Foundation made it possible to conduct a significant study and research program. After a thorough survey of national excavation needs the research was directed toward horizontal tunneling and utility emplacements. With the establishment of the Energy Research and Development Administration (ERDA) the sponsorship of the program was transferred to the ERDA Division of Geothermal Energy with the objective of developing a viable system for producing geothermal wells in deep, hot geologic formations.

The melting excavation concept has been described extensively for various applications (see Altseimer, Hanold, Neudecker, Rowley or Sims [1-9]). Briefly, it is a system of excavating and penetrating rocks or soil by melting, sumultaneously 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. The melt can be formed into a glass lining to seal and support the walls of the borehole. The rock melt also binds loose soil materials effectively into a stabilized liner. Excess liquid melt can either be used in the liner or 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 Figure 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 coolant in a debris formation chamber. The solid debris is then transported out of the bore hole 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 conducted successfully. The most ambitious field rig, shown in Figure 2, has been used to form an 84-mm hole in solid basalt to a depth of 30 m.

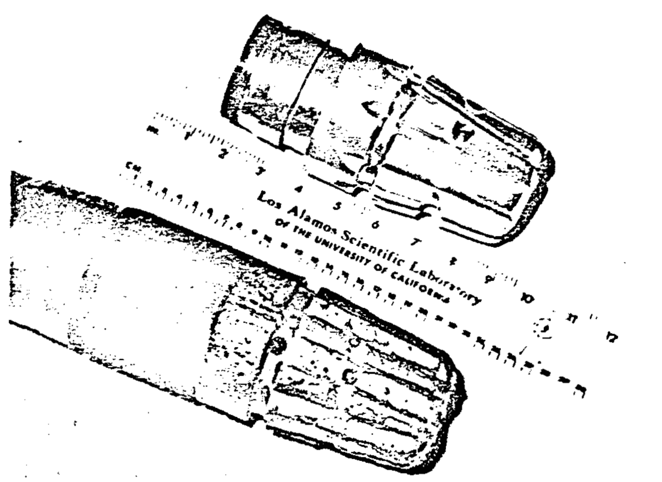

Figure 1. Subterrene extruder bit.

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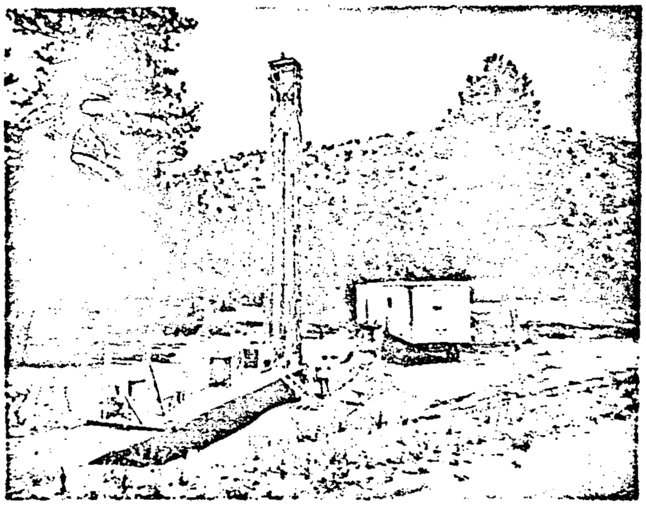

Figure 2. Field rig at basalt test site.

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. 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.

Magnitude of the Geothermal Resource. One is justified to question whether the geothermal energy resource is large enough to warrant large R&D expenditures for improved well production systems. A recent Geological Survey report by White and Williams [10] presents estimates; total heat contents include identified plus estimations of undiscovered resources. For hydrothermal convection systems (conventional steam and hot water to 3 km) the heat content is 12,800 x 10^{18} J (3050 x 10^{18} cal = 12.1 x 10^{18} Btu) whereas the heat content of igneous systems (molten rock plus crystallized parts and hot margins) is 419,000 x 10^{18} J (100,000 x 10^{18} cal = 400 x 10^{18} or 33 times higher than that of conventional hydrothermal resources. For regional conductive environments (0 to 10 km under all states of the union and not including a methane contribution) the estimated value is ~ 33,500,000 x 10^{18} J (8,000,000 x 10^{18} cal = 31,900 x 10^{18} Btu) or 2600 times conventional hydrothermal values. Geopressure and DHR systems would exploit the latter category. Compared to the U.S. total energy consumption in 1972 of 75.9 x 10^{18} J (18.1 x 10^{18} cal = 0.072 x 10^{18} Btu), Report to 94th Congress [11], the above resource is immense, and efforts towards extraction, conversion, and utilization should be very worthwhile indeed!

THE SYSTEM MODEL

The computer model developed for the studies reported herein is called GEOWELL. The major technical and cost items used in GEOWELL are summarized below.

Well Designs. Two exploratory gas wells of recent years, drilled under difficult conditions and to record depths, used 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) 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 hydrostatic, were assumed in the upper 4300 m. High pressures, i.e., approaching lithostatic, were assumed from 4300 to 7000 m. Thereafter, to total depth, it was assumed that pressures were moderate again.

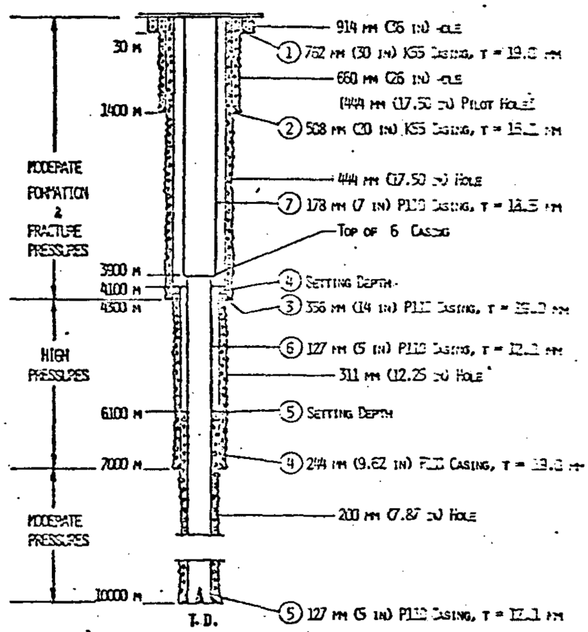

Figure 3. Well design for the all-rotary drilled well.

Figure 4 shows the well design when rock-melting bits are used below the 660-mm (26-in.) hole section. It was assumed that the 914- and 660-mm holes would always be made by rotary drilling. Below the bottom of the 660-mm hole, rotary drills would continue to be used until it was desired to start rock-melting. 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.

Surface Equipment. Surface equipment requirements for a combined rotary/rock melting system are similar to those now used for all-rotary projects. Because it is anticipated that it will be most economical to use rotary drill to produce the conductor and surface holes the initial 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. Also, the power levels required for rock melting are compatible with those already required on rotary deep well rigs, e.g., up to 3000 hp.

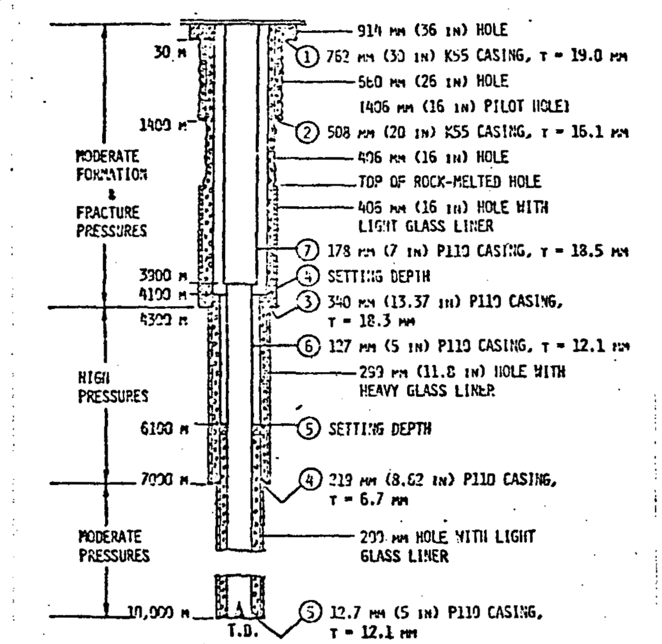

Figure 4. Well design for rotary/rock-melted well.

In GEOWELL, the drilling contractor's 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:

$$CRIG = 1453 + 0.1184\ (EL) + 1019 \times 10^{-6}\ (EL)^2,\ \$$$

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

Drill Pipe. Design studies produced a Subterrene drill pipe capable of carrying both electric current and the downflow of drilling fluid. The pipe is shown in Figure 5 and consists of two concentric 7075 aluminum tubes separated by a 2-mm-thick layer of material that structurally bonds the tubes 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 thread contact surfaces and the smooth metal contact and 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 very similar to those of conventional drill pipe. The initial cost is approximately three times higher but this disadvantage is reduced by an enhanced 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.

A pipe with an o.d. of 140 mm (5.51 in.) was found to fit well in all sections of the borehole being studied and was therefore selected as a standard. Thus, in the GEOWELL analysis the o.d. is maintained at 140 mm, whereas the other dimensions are varied to meet current and load criteria. 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

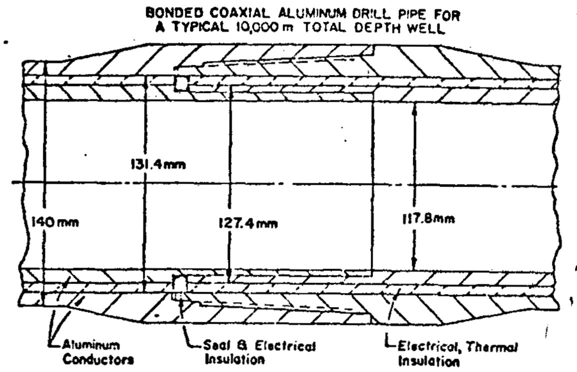

Figure 5. Subterrene aluminum drill-pipe concept.

a penetration rate of 1.0 mm/s in rock at 283 K. Costs are calculated on the basis of these dimensions to arrive at a basic material and fabrication cost. Other estimates are made as to delivered pipe cost, pipe lifetime, drilling contractors profit, etc., to finally arrive at a Subterrene drill-pipe cost in dollars per day.

Bits. Subterrene melting-bit design descriptions and their development status are readily available in the Subterrene literature. The bit needed for producing wells is the melt-extruder type using 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 is then transported up the annulus out of the well. In GEOWELL the assumed design-point bit performances are 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. For example, using GEOWELL estimates, the above 1-mm/s or 3.6-m/h ROP increases to 17.65 m/h in magma at 1431 K.

Attaining and demonstrating longer lifetime and higher ROP remain development problems for melting bits. Another problem is that obtaining sufficient clearance between the glass former (located immediately behind the melting face) and the hole so as to facilitate bit travel during trips. A clearance of several millimeters on the radius is desirable to prevent bit damage or high-pressure drops across the bit during fast trips. At least five approaches to solving this problem have been identified, but will not be further discussed. Practical solutions are under study and will be developed.

GEOWELL also included rotary-bit performance estimates. Field performances vary widely depending on site and operating conditions. In GEOWELL an attempt was made to simulate relatively easy rotary drilling in the sedimentary upper formations and harder drilling in the deeper, more crystalline formations. The equations defining performance vs depth used in the program are for rotary penetration rate, RROP, at any rotary depth, ROTEL, in meters:

$$RROP = 591.62 \times (ROTEL)^{-0.6739},\ m/h$$

and for bit meterage:

$ROTEL < 1440$ m: $BITM = 884.0 - 0.553\ (ROTEL)$, m/bit
$ROTEL > 1440$ m: $BITM = 97.0 - 0.0033\ (ROTEL)$, m/bit

Some additional performance variations are included to account for multiple operations like pilot holes followed by hole-opener operations. The above equations give a range of ROP from 592 m/h at spudding-in to 1.2 m/h at 10,000 m depth. Meterage ranges from 884 m initially to 64 m at 10,000 m depth.

For rotary bits we used catalog data for carbide bits. The rock-melting bit costs, PENC, are based on Subterrene Program experience and are defined by the following equations, where DPEN is penetrator diameter in meters:

$$PENC = 1286 + 20556\ (DPEN) + 69053\ (DPEN)^2,\ 1975\$$$

Electric Power Generation and Transmission. A summary discussion of rock-melting power requirements follows. First, ac is the better choice over dc for several important reasons, the most important one being corrosion. The presence of dc electric power flowing in a conductor immersed in mud or drilling fluid would enhance 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 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 met easily by the combination of ac power source and transformer or saturable reactor.

The use of ac has also 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 other related equipment are acceptable.

For power-cost estimates, GEOWELL includes calculations for the costs of diesel electric generators amortized over 10 years as well as diesel fuel costs.

Drilling Fluids. The drilling fluid for a rock-melting system has to perform the following functions: (a) form solid debris, (b) cool the glass-former section, (c) control formation pressures and prevent caving, (d) carry out debris, (e) hold solid additives in suspension under stagnant flow conditions, (f) reduce corrosion, and (g) lubricate moving pipe or casing.

Based on rotary drilling experience, drilling fluids like water, water-based muds, oil-based muds, etc., could perform Functions (c) through (g). It is estimated that Functions (a) and (b) could also be handled even though this capability has not yet been demonstrated experimentally. For the well models set up for this study in which high formations pressures are postulated, muds are deemed essential to carry out Function (c).

Open-literature data for mud costs in oil and gas wells were used to estimate the mud costs for the rotary well model. For normal geothermal gradients, the total mud costs, CMUD, are:

$EL < 1354$ m: $CMUD = 2903$, 1975\$

$EL > 1354$ m: $CMUD = 21912-28.64\ (EL)+0.0108(EL)^2$, 1975\$.

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

Hole Support. The following glass-liner characteristics were assumed: (1) the solidified melt seals the hole effectively; (2) the collapse strength of the rock-glass lined wall is high; (3) liner wall thicknesses are controllable; and (4) liner tensile strengths are negligible.

For the steel casing used in the modeled wells, the conductor and surface casing are made of low-cost K-55 grade steel, whereas the remainder is made from a higher grade such as P-110. Casing costs were obtained from industrial catalogs. Cementing costs in dollars per cubic volume are mainly based on our DHR drilling experience. With the input dimensions, the program calculates the weight of the casing and the delivered-casing costs. For cement costs, the total volume of delivered cement is calculated for the well model being considered, and this volume is multiplied by the appropriate cost in dollars per cubic meter.

Other Assumptions Relating to Thermal and Hydraulic Analyses. In addition to the various assumptions described above, the program includes the following assumptions for an analysis of thermal and hydraulic conditions during Subterrene operation:

- 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, 0.77 on density, viscosity, and heat capacity, respectively.
- The flow rate of the drilling fluid is based on terminal velocity of spherical particles in the upper annulus multiplied by 1.5.
- Maximum particle diameter is 10 mm with a density of 2700 kg/m^3.
- Friction factors of pipe and annulus are based on absolute roughnesses of 4.57×10^{-5} and 3.05×10^{-4} meters, 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 Figure 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.

STUDY RESULTS

Hole Control. No evaluation of an advanced drilling system would be complete without a study of hole-control methods.

Early detection of a downhole pressure increase is critically important. According to rotary-drilling literature, 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. All these indicators of abnormal pressure apply also to melting bits except that the penetration rate will decrease rather than increase when face pressure increases to upset the thrust condition. Two indicators exist which may be superior to those available to rotary drillers. First, sudden high face pressures on the melt could cause erratic flow through the melt bleedoff channels or at least could change the bit operating characteristics. Second, a very rapid indicator would be any change in bit thrust loading required to maintain a penetration rate, due to a change in face pressure pushing upward on the bit. For the most rapid reading of thrust deviations and indications of *in situ* pressure changes, a thrust load cell mounted directly behind the bit would be especially useful.

The use of heavy muds necessitated by abnormal pressures can lead to a swabbing problem where the thick, viscous mud adhering to a tripping pipe causes the pressure at hole bottom to drop. If the initial overbalance is not large enough the hole becomes underbalanced and intruding fluids might cause trouble. Here, a good collapse-resistant glass liner would be advantageous because the liner could counteract the temporary underbalance as the pipe is pulled. This capability would add additional operational flexibility and safety to the job.

It is concluded that hole control with rock-melting systems is not more difficult than with rotary drills. Indeed, it seems that any change in melting-penetration performance caused by a rapid change in formation-fluid pressure could be detected very rapidly. Also, a measurement of the change in thrust being applied to the bit would result in a good estimate of the pressure change downhole. These indications offer opportunity of developing a pressure-detection system that would give the driller more time for corrective action and also provide more positive data on the pressures being encountered.

Technical Analysis. The GEOWELL analytical results given below for thermal hydraulic, and stress conditions in the well are limited to the most severe technical condition, i.e., a rock-melting bit operating at the bottom of a 10,000-m deep well at a penetration rate of 1 mm/s in rock of 283 K. Results are given for both a normal geothermal temperature gradient of 25 K/km and a high gradient of 75 K/km.

Figure 6 plots the mass flow rate required to lift the debris in the annulus as a function of debris diameter. For the maximum particle size of 10 mm, the required mud flow rate is 46.1 kg/s. Figure 7 shows the mud temperature throughout the borehole at the 46.1-kg/s rate while exposed to a 75-K/km geothermal gradient. The maximum temperature is only 312.6 K. If the maximum particle size, and, hence, flow rate is reduced then the corresponding increase in maximum mud temperature is as shown in Figure 8. Even if the flow rate is halved to 23 kg/s, corresponding to a particle size of 2.5 mm, the maximum mud temperature would still be a reasonable 336.5, even at the high geothermal gradient with a rock temperature of 1033 K at total depth. Thus, the mud flow rate is established by the particle-removal criterion and not by the mud temperature.

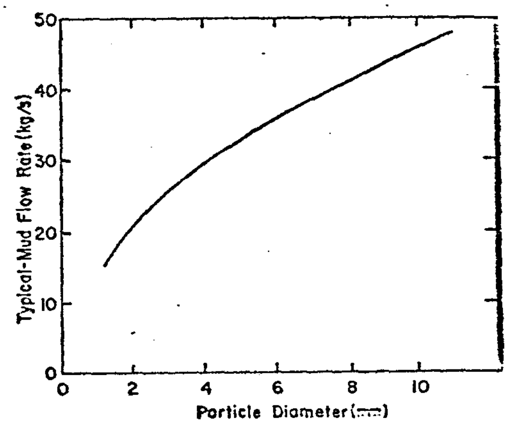

Figure 6. Typical mud flow rate vs debris particle diameter.

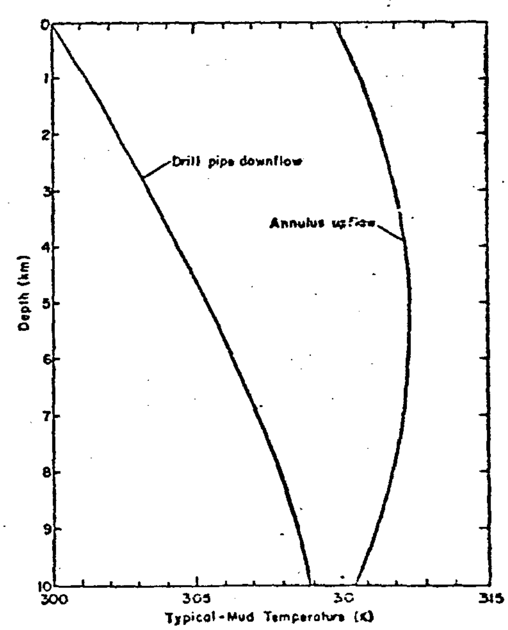

Figure 7. Mud temperature for the 10 mm particle diameter condition.

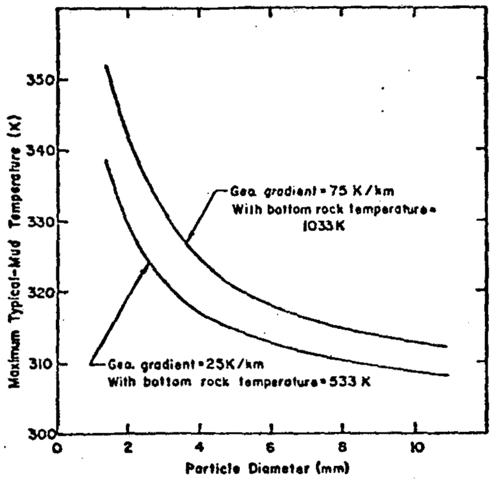

Figure 8. Maximum typical mud temperatures.

For a particle diameter of 10 mm the horsepower required from the well inlet to the outlet is ~ 720 hp. Taking into account surface inlet pressure drops and motor inefficiencies, the actual pump power might have to be as high as ~ 900 hp -- well within the range of power levels on current drilling rigs. The total pressure drop between the drill pipe and the 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. In contrast to the normally high drops across rotary bits, the drop across the rock-melting bit is negligible.

Using the coaxial aluminum pipe considered in Figure 5 for a 10-km well and including an allowance for a 650,000-N (146,000 lb) breakaway load, the maximum stress in the aluminum pipe is 364,000 kPa (52,700 psi) at a yield-to-load safety factor of 1.33. Under normal operating conditions at this depth the maximum stress is only 170,900 kPa (24,800 psi). Thus, no severe stress problems are indicated.

Cost Analysis. For the following cases, in which rotary and rock-melting techniques are both used in each well, the depth of well drilled by rotary methods is chosen so as to minimize overall well cost. In most cases the rotary-drilled portion could have been shorter but this possibility was restrained by the decision that the 0.914- and 0.660-m-diam holes at the top of the well will always be made by rotary drills. The melting ROP is nominally 1 mm/s at 283 K rock temperature.

Figure 9 shows the total well costs for wells made in a geothermal gradient of 25 K/km, which is approximately normal. The model is most accurate for the very deep cases, e.g., 8 to 10 km. The cost savings compared to rotary drilled holes are significant; 23% or approximately 2 million dollars per well for 10 km depths. At 6 km, for the well model analyzed, the savings is 18%. The crossover point at 2.9 km is caused by the increasingly higher ROP of the rotary drill in the upper formations compared to Subterrene.

Figure 10 summarizes the cost predictions for wells with much higher downhole temperatures. The solid lines correspond to cases having 673 K bottom temperatures. The dashed lines indicate constant geothermal gradient conditions. With rotary systems, the high temperatures result in increased costs for bits, drill pipe, casing, cement, and muds. With Subterrene systems, cost penalties also occur for casing, cement and muds but some savings are experienced because of improved bit performance in hotter rock. The net result is to the advantage of the Subterrene. At 10 km depth savings over rotary drilled wells is 33% or 4.5 million dollars. At 6 km depth the saving is 28% or 1.2 million dollars.

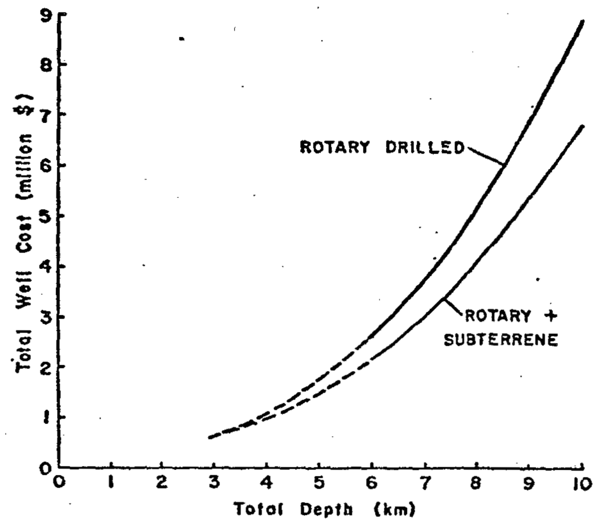

Figure 9. Costs of deep wells produced in 25 K/km geothermal gradient.

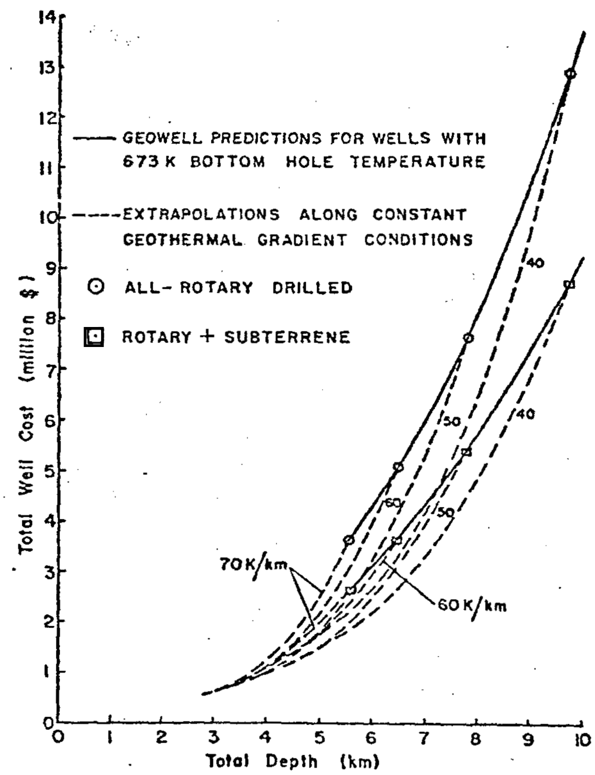

Figure 10. Costs of deep wells produced in high geothermal gradients and with bottom hole temperatures of 673 K.

A bottom hole temperature of 673 K in deep wells such as are being discussed here has never been encountered in oil and gas wells. Using present technology, rotary drillers could not push much beyond this temperature limit without excessive costs in time and money. However, the Subterrene concept opens up new opportunities to push into ever higher temperatures. Casing is a major cost item and it can be minimized by further development and use of glass liners. The glass liners also help solve the mud problem, allowing simpler muds or drilling fluids to be used. Drill pipe strength and corrosion problems can be solved by developing continuous circulation systems. The nonrotating Subterrene pipe should be an important advantage here. Cements per se, cannot be helped much by Subterrene except that the glass liner use can minimize the amount of cement needed and facilitate its installation.

A melting bit lifetime range of 100 to 1000 h was surveyed to determine the influence of lifetime on overall well costs. Cost changes only ~ 7% over the above range. As shown in Figure 11; an increase in lifetime from 100 to 300 h provides a cost savings of 5% or most of the possible savings. Thus, lifetime does not affect overall costs significantly.

Assuming an average bit lifetime of 300 h, the program was run over a melting ROP range of 0.2 to 1.4 mm/s. Figure 12 shows that ROP is a more important parameter than lifetime. Increasing the rate to only 0.4 mm/s, which is twice the state-of-the-art value, saves 25% in well costs and at 0.6 mm/s the savings is 33%. However, beyond 0.6 mm/s the savings become increasingly less significant. For a Subterrene program target, the 1 mm/s rates appears to be satisfactory. From the figure one can also deduce that at 0.3 mm/s in normal gradient wells, the costs of rotary and Subterrene produced wells will be nearly equal.

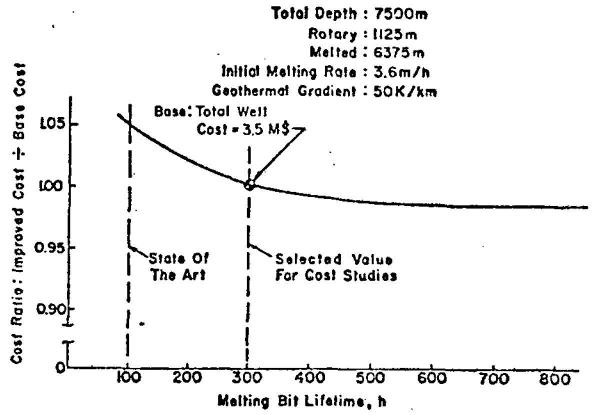

Figure 11. Effect of bit lifetime on total well costs.

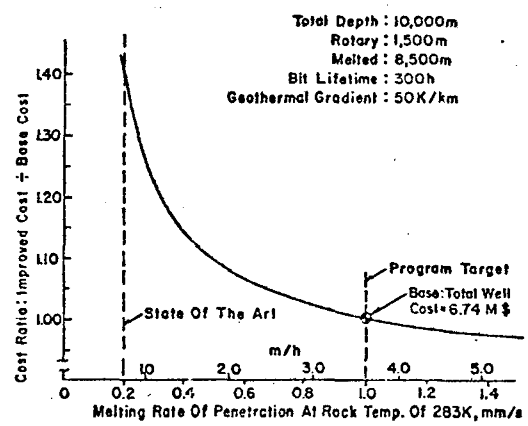

Figure 12. Effect of melting rate of penetration on total well costs.

CONCLUSIONS

A detailed evaluation of the Subterrene rock-melting concept applied to the production of deep geothermal wells indicated that no insurmountable technical impediments exist. It is recommended that rotary and melting techniques be combined to realize minimum overall well costs. The current bit-penetration rate has to be increased from 0.2 mm/s (nominal) to at least 0.3 mm/s to match the cost of the modeled rotary drilled well in a normal geothermal gradient. Bit lifetime does not have as large an effect on overall well cost as penetration rate. At a nominal rate of 1.0 mm/s the Subterrene shows a 23% savings over a rotary drilled 10 km well at normal gradients. At 6 km, the savings is 18%. For wells in higher geothermal gradients, the savings increases to 33% for 10 km and 28% for 6 km, i.e., 4.5 and 1.2 million dollars per well, respectively. Using the rock-melting concept, the potential for innovative technical improvements allowing deep penetration into increasingly higher temperatures, e.g., > 673 K, appears promising.

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