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PRELIMINARY WELL DESIGNS AND COSTS
FOR MAGMA ENERGY EXTRACTION WELLS

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ABSTRACT

An evaluation of the economics to drill and complete wells into magma chambers for power production required cost estimates for the wells. These cost estimates involved investigating the capability of high temperature drilling technology, technology of tubular materials and capability of developing technology for penetrating the magma. A number of various well diameters were costed for systems where well fluid not exposed to magma (closed) and well fluid is exposed to magma (open). These wells were costed for only a single temperature and geologic area. The basic conclusion is that wells can technically be drilled into the magma if hot, high pressure formation fluids from large systems are not encountered.

The well profiles presented here have not undergone detailed engineering design. They are for preliminary costing only. Actual designs may be far more complex based on further geologic and operating information.

Introduction

A preliminary investigation to determine whether or not drilling and extracting energy from shallow magma bodies could be technically and economically feasible was conducted by Well Production Testing, Inc. under a contract issued by Sandia National Laboratories. The project was conducted in four stages. The preliminary designs were costed, the power output at the wellhead was calculated based on the well design, and the resulting electrical power output was estimated and then an economic model applied.

In light of the many unknowns, assumptions were necessary for this study. However the primary results indicate that technology to drill the wells exist and that cost ranges of the wells are reasonable. However, the one drilling condition which cannot be handled with present technology is drilling through extensive formations containing hot, high pressure fluids. If such a condition is encountered, any well would have to be abandoned based on our present capability of continued drilling into such a regime.

The study assumes the site of the wells to be Long Valley, California where rhyolitic magma is predicted to be approximately 5335 meters below the surface. Three wells of various diameters were preliminarily design and costed for two extraction systems. The closed extraction assumes that the working fluid is contained within the well piping and is not permitted to come in contact with the magma. The open loop alternative assumes that the power plant working fluid flows through the magma which is subsequently cooled and fractured. The working fluid is then collected and transmitted to the surface.

In all cases considered, a well completion with a production tube within the wellbore allowed for counter current flow of the working fluid. Insulation was used between the center and annular flow where the well diameter was large enough to accommodate the additional thickness. The open system with dual wells (injector plus producer) was costed; however, the power extraction system and economics were not analyzed.

The following describes the present status of high temperature drilling technology. Of particular importance are the materials for tubulars and methodology of magma penetration. It should be stressed that detailed engineering of the tubular stresses, installation procedures and well operating conditions have not been done. The well profiles shown here are for cost estimating purposes only.

*References appear at end of text.*
High Temperature Drilling Technology

The technical capability of drilling into the magma regime is unknown. Deep wells have been successfully drilled to temperatures of 400°C. In Hawaii, shallow wells have been drilled in magma by Sandia. However, the technology of deep magma wells drilled and completed for long term production can only be speculative at this time.

Presently, with respect to temperature, drilling technology can be categorized as shown in Table 1. This table is a generalization. However, it points out the technical areas which need to be better understood for successful completion and production of magma wells. Because of these unknowns, the total well costs can only be preliminary.

Certainly the depth ranges of 5487 to 9146 meters can be obtained. However, the extreme temperatures, potential high formation pressures, and corrosive nature of the fluids are severe limitations on the technology. Also, the capability to significantly penetrate the magma may either prove extremely difficult or very easy.

Of all potential problems, high formation pressures at temperatures greater than 250°C create an impossible drilling condition with presently known technology. New drilling fluids (or methodologies) will be needed to make drilling successful and safe.

For costing of drilling and completion of any magma wells, the following general criteria were established:

1. All casing wetted by fluid exposed to reservoir fluids will be High Chromium.
2. All casing inserted into the magma will be nickel alloy.
3. All seals required above 300°C will be metal to metal probably using some type of threaded connection.
4. Cementing, as presently known, will be limited to temperature regimes of 310°C or less. This limitation applies to jobs requiring more than 150 sacks or to crucial seals. Cementing is allowed up to 400°C for small jobs where short pumping times and hole cooling can be employed, and where cement is only for support.
5. Surface or intermediate casing would normally be set below all known zones of permeability greater than 1.0 Darcy, or below any zones of potential loss circulation.

Well Designs

The well design used in this study was based on the temperature profile shown in Figure 1. The casing setting depths were controlled by both geologic and temperature considerations. The wellbore sizes were those presently in common use in the petroleum and geothermal industries as shown in Figures 2 through 4.

In addition to the criteria above, the following ones for one well completion schemes were used:

1. Carbon steel wetted by uncontaminated fluids would be used for casing up to 450°C.
2. Normal or slightly subnormal formation pressures were assumed.
3. Drilling above the magma was assumed to be with standard, or slightly modified, equipment and methods in present use.
4. Rigorous casing design was not done.

The basic method of penetrating the magma in all cases assumed that the tube extending into the magma would be used also as the penetrating instrument. This tube would remain in the magma. The remaining well completion would require development of the reservoir in the open system and then running the double-walled, insulated tubing string. The closed system would require the development of the reservoir system.

Drilling times were estimated based on trouble free drilling based on the experience of drilling similar wells in geothermal environments to 13,000 feet (however, not to such great temperatures). The base bore well drilling time curve estimate is shown in Figure 5. There were three basic well sizes which were costed. Schematics of these well profiles are shown in Figures 2 through 4.

Materials for Tubulars

There are a number of materials suitable for tubulars for temperatures up to 1600°C in natural atmospheres. In addition, several types are suitable for special parts such as gamma prime nickel, dispersion hardened nickel, tungsten, etc. Metal technology of 800°C and above is mostly a result of work on jet engines, rocket engines and gas cooled nuclear reactors. The primary concern for magma energy extraction wells is the corrosion effects of
gases such as H$_2$S and CO$_2$ at high temperature (and potentially high concentrations).

The petroleum and geothermal industry experience with respect to temperature can be summarized as follows:

a) -50°C to 340°C - Work is through, complete, excellent and even quite redundant.

b) 340°C to 565°C - Some excellent work but scattered coverage.

c) Above 565°C - Almost non-existent.

Most candidate materials that have been extensively tested for many types of corrosion resistance throughout their temperatures of utility. Unfortunately, utility has meant the load bearing capability, as well as corrosion resistance at temperatures above maximum use temperatures as dictated by mechanical strengths. Data generated by employing corrosive media in either a gaseous or liquid state. Magma is so complex that tests for magma should be done with magma. The candidate materials need to be tested for corrosion for temperatures above 870°C. Special testing is needed for the 565°C to 870°C regime.

Corrosion tests under load for the first phase are not required. For the first phase, testing is to determine a) relative merit, b) predictable lifetime and c) type of corrosion.

One needs to categorize the materials as follows:

1) RT - 450°C Carbon steel
2) 450°C - 980°C Nickel base alloy
3) 925°C - 1100°C NiCo base alloy
4) 1065°C - 1200°C Molybdenum substrate clad with NiCo base alloy
5) 1200°C - 1600°C SiC, ZrO$_2$, Al$_2$O$_3$

The overlap is intentional; testing will select one or the other.

Somewhere above 1200°C, one has to use ceramics. Benefits are outstanding. Corrosion resistance is superb. Upper temperature of use approximates 1600°C. Flexural strengths are good-20,000 psi at RT. Even at 1200°C, flexural strength will have dropped only 50 to 67%. There are three candidate ceramics: SiC, Al$_2$O$_3$ and ZrO$_2$. All show sufficient promise to be available as engineering materials, as well as tubulars.

Unfortunately, it takes care to handle ceramics in the field and great skill to design load bearing hardware of ceramics. The problems are twofold: low toughness and brittleness. Ceramics have been improved to the point of achieving a toughness in impact testing of 7 ft-lbs. This is a thousandfold better than the very best ceramics commonly encountered as insulators. However, 20 ft-lbs is considered as the lower limit for routine design.

**Magma Penetration**

Drilling above the depth and temperature where formations become plastic, i.e. flowing, the formations should remain stable. However, the behavior of high temperature rock types under various confining stresses have been initially studied. One interesting conclusion is that confined specimens heated to 900°C and ducromed at 25°C are at least as strong as those that have not been preheated. Thus, sufficiently cooling and keeping the formations cool (the degree of cooling is yet to be determined) may well allow drilling conventionally to within the melt zone.

Once the melt zone has been sufficiently penetrated, the wellbore may be stabilized long enough to insert the completion casing. Stabilization is envisioned to take place by cooling out radially to a sufficient distance so that stability will be retained for some time. The wellbore may become extremely enlarged due to thermal fracturing, which is fine, as long as the wellbore remains at a sufficient diameter to get the production casing down to the liquidous rock.

These types of drilling techniques have proven successful in drilling unstable, flowing salt sections, obviously, at lower temperatures. Whether or not such techniques will be successful through the transition from solid to molten rock is yet to be determined.

Once the bottom of the completion casing is inserted into the melt zone, drilling may not be extremely difficult. The drilling technique is envisioned to be similar to that conducted by the Sandia scientists on Hawaii. That is drilling will take place by jetting high pressure water to fracture and remelt 25°C of formation below the bit which would be installed on the bottom of the production tube. Progress may be slow because hole stability above the bit may have to be maintained by keeping these zones sufficiently cooled. It may be required to actually force fluid into the formation for sufficient cooling as more and more pipe is inserted into the magma chamber. Cooling by injecting (at lower pressures and temperatures) is much more dramatic than cooling by circulation. Numerous variations and techniques for
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magma drilling (actually "magma penetration" is more descriptive than "drilling") can be envisioned.

Thus, the metal tubular inserted into the magma will remain as the permanent installation. As presented above, several materials are candidates for these tubulars.

During non-cooling periods, the strength and material of the production tube would need to withstand the magma chamber environment. Defining this environment will be crucial to the tube design.

Well Cost Estimates

A number of well types were costed for the Long Valley temperature profile (Figure 1). This profile allows drilling the well down to about 9000 feet at only a 200°C temperature and then to about 14,500 feet at 300°C. Drilling technology is adequate to drill these sections without too many serious impediments.

It is considered that drilling problems may begin deep in the transition zone. Then, penetrating deep into the magma chamber itself maybe very difficult or very easy. At this time, this capability is only a guess. Economics are highly dependant upon the depth penetrated into the magma chamber.

For costing it was assumed that drilling into the magma was reasonably well developed. That is, technology existed for industry drilling and producing power.

The types of wells and their costs are shown in Table 2. Tables 3 and 4 show the breakdown of individual cost categories for the base bore - open system. The percentage breakdown is about what is expected in any deep well except that the bits, drillstring, etc. are slightly higher. No special drillstring steels were used because it was assumed that sufficient cooling would take place while drilling down to the magma (liquid rock) to sufficiently cool the drillstring to at least 425°C.

Conclusions

Based on this preliminary investigation of drilling and completing wells into magma, the following activities are recommended:

1. Investigation of drilling fluids (may not be liquids in present use) and other methods to control potential high pressure, high temperature corrosive gases.

2. Theoretical and laboratory research into methods of penetrating great depths (up to 3000 meters) into the magma chamber. This includes material, rock mechanics and methodology.

3. Development of wellbore heat and mass transfer codes to model these downhole super temperatures during drilling and completion operations.

4. The results of the above should be applied to liquid and solid behavior at the predicted temperatures for drilling and completion materials and equipment selection and design.

5. Corrosion testing, starting with a detailed survey of the combustion for power generation industry, of metals under various anticipated downhole conditions. This is required for well life predictions.

6. Design of casing strings and development of materials, equipment or methodology for installation of casing strings to withstand the thermal cycling and stresses which may be encountered.

7. Interpretation of geological data as it reflects conditions which will be encountered in drilling.

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References


FIGURE 2.

BASE WELL, OPEN SYSTEM.

FIGURE 3.

FIGURE 4.

FIGURE 5.

FIGURE 5.

DRILL 26" HOLE TO 2100'

DRILL 17 1/2" HOLE TO 13,000'

SMALL BORE WELL, CLOSED SYSTEM.

BIG BORE WELL, OPEN SYSTEM.

DRILLING CURVE FOR LV-CIR-1 - BASE WELL

DEPTI IN FEET (1,000)