"DRILLING FLUID TEMPERATURES IN A MAGMA - PENETRATING WELLBORE"

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ABSTRACT

This paper describes the numerical modeling of the drilling fluid temperatures in a deep well that penetrates a magma body. The basic assumptions for the model are listed, the importance of the fluid temperature is considered, and the effect of changing the model parameters is assessed. The stratigraphy and formation temperature profile assumed for this hypothetical well are similar to Long Valley, CA, where a relatively shallow magma body is believed to exist. A major result of this modeling is demonstration of the benefit of insulated drillpipe.

INTRODUCTION

Sandia National Laboratories manages a DOE-funded program to investigate the engineering feasibility of extracting energy from magma. Our activities include geophysics, geochemistry, energy extraction technology, and drilling, all with an underlying framework of system integration. The eventual goal is to drill an experimental well that can be used to learn, in detail, about the process of energy extraction from magma. As a preliminary step in planning this well, I have investigated the variation in drilling fluid temperatures when certain drilling conditions are changed.

BASIC CONDITIONS

The formation temperature for the well is shown in Figure 1 and is a simplified version of the postulated profile in Long Valley, CA. The vertical (isothermal) parts of the curve above 15,000 feet represent permeable zones where groundwater convection keeps temperatures near-constant. The top of the magma body is at 17,000 feet and the wellbore extends approximately 1 kilometer into the liquid rock. The wellbore below 17,000 feet exists in a peninsula of solidified rock (Figure 2) which has been chilled by the circulation of drilling fluid as the bit drills ahead. Drilling rate in the model is assumed to be 250 ft/day down to 17,000 feet and 100 ft/day between 17,000 and 20,000 feet.

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NUMERICAL MODEL

This modeling was done with a thermal simulator code, called GEOTEMP2,[1] which calculates the temperatures in the drillpipe, in the annulus, and in the rock surrounding the wellbore. The code treats natural and forced convection and conduction within the wellbore, as well as conduction in the rock surrounding the wellbore. Physical properties of fluids, tubulars, and rock are user-defined for any given run; flow rate, drilling rate, and circulation time can be varied during the run. The code does, however, impose certain restrictions.[1] The most important deviations from realism are the requirements that all casing strings run to the surface (i.e., no liners, and, therefore, no flow area changes) and that the wellbore be a constant diameter from surface to total depth. I have examined limiting cases for both of these variables, however, and their effect on the fluid temperature profiles is surprisingly small.

BASE CASE WELL

Calculation of the fluid temperatures in a "normal" well shows that (Figure 1) the maximum temperature is very high and that the temperatures in the drillpipe and annulus are never very different. The conditions for this well are:

Wellbore - 12 1/4 inch diameter to 20,000 feet
Casing - 9 5/8 inch diameter to 17,000 feet
Drillpipe - 5 inch OD
Fluid - water
Flow Rate - 350 gpm

Since many drilling fluid components or additives are unusable at such high temperatures, the effect of adding 3/8-inch-thick insulation with a thermal conductivity equal to asbestos to the outside of the drillpipe was calculated. As Figure 1 shows, the bottomhole and maximum temperatures are much lower with insulation, but the fluid returns to the surface hot enough to present a problem.

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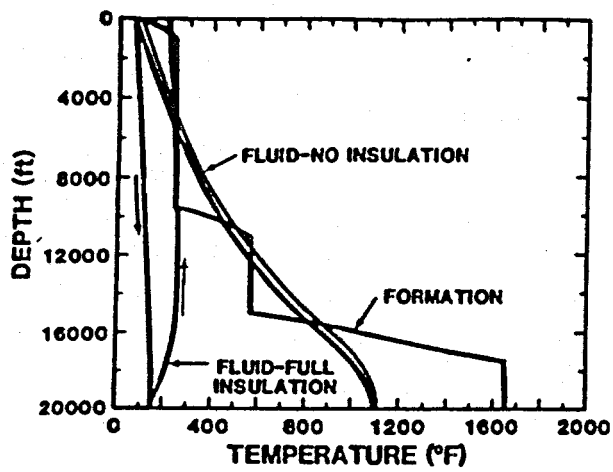

Figure 1. "Fluid and Formation Temperatures in a Magma Well"

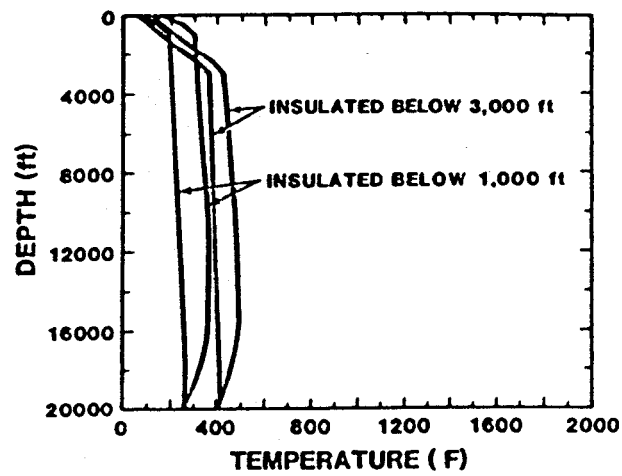

Figure 3. "Change in Fluid Temperature with Increase in Uninsulated Length"

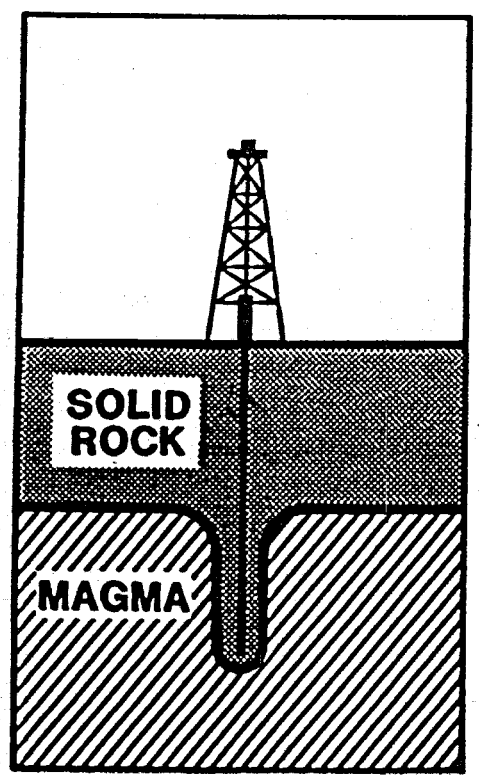

Figure 2. "Wellbore Penetrating a Magma Chamber"

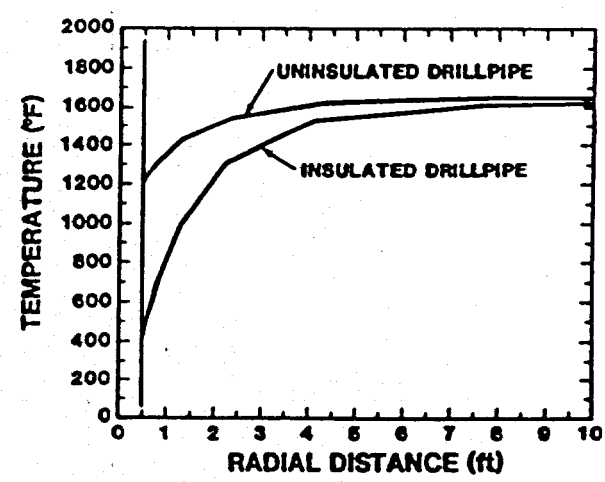

Figure 4. "Radial Formation Temperatures at 20,000 ft Depth"

If the upper part of the drillpipe is not insulated, then it can cool the returns to an acceptable temperature while keeping the downhole temperatures relatively low. By varying the uninsulated length, this tradeoff can be moved in either direction (Figure 3). An uninsulated length of 1000 feet is the base case, and succeeding changes in temperature profiles are referred to this.

SIGNIFICANCE OF FLUID TEMPERATURE

When drilling a well into a hot target, the fluid temperature is important because it affects so many other aspects of the well design. Some of the key factors influenced by temperature are:

1) Fluid selection - Many fluids are unsuitable for use at high temperatures either because a property (such as viscosity) changes reversibly to an extent that the fluid is unusable in the hot regime or because the fluid, or its additives, are permanently degraded by the heat. This problem obviously becomes more acute as the number of required additives increases.

2) Tubular selection - Casing and drillpipe can be significantly affected by high temperature for at least two reasons. Strengths of the various steels not only drop as they get hotter, but sometimes have a time-dependent strength loss. There is also geochemical evidence that corrosion will be a severe problem in a magma well. Since a common rule of thumb in chemical kinetics is that reaction rates double for every "x" increase in temperature (where "x" can be as small as 10 degrees C), it is clear that a relatively modest increase in temperature can aggravate the corrosion problem by several orders of magnitude.

3) Bit cooling - We do not know yet what type of bit will be used to drill each section of a magma well, but it is hard to imagine a situation in which high temperature would not degrade bit life. Roller cone bits would suffer probable bearing failure and increased wear on the softened body and cutting structure, while diamond bits (natural or synthetic) need maximum possible cooling to maintain low temperatures in the diamonds. Since bit life becomes a more important cost factor as depth increases, bit cooling could have a very significant economic effect in the deep, hot parts of the hole.

4) Hole stability - When drilling has reached a magma chamber, the circulation of the drilling fluid must cool the magma enough to provide a solid wellbore wall and a partly (at least) solidified hole bottom for the bit to attack. The radius of the solidified rind around the wellbore will depend on the temperature of the drilling fluid and the length of time that it has been circulated at the specified depth. If a pump malfunction or a trip causes a break in circulation, then the peninsula of solid rock will begin reheating and there will be a critical time by which circulation must be re-established if wellbore integrity is to be maintained. Radial temperature profiles in the magma around wellbores with insulated and uninsulated drillpipe are shown in Figure 4. It can be seen that, for example, the temperature at a 2.0-foot radius is about 1230°F for the insulated case and about 1510°F for the uninsulated case. Since, for many rocks, this temperature change corresponds to a nearly complete loss of strength, the benefits of cooler drilling fluid may be crucial to hole stability.

If we assume that the drillpipe will be insulated, there are still several variables to be considered. Reasonable ranges for these have been used in the code and a brief summary of these results follows:

TABLE 1

Temperature Variation With Changes in Drilling Conditions

CONDITION	BOTTOM HOLE TEMP	MAX TEMP	RETURNS TEMP
Uninsulated	1100	1104	93
Full Insulation	149	257	208
Base Case	264	360	169
Flow--200 gpm	390	521	166
Flow--500 gpm	198	278	159
Insulation--1/8 inch	349	422	158
Insulation--3/4 inch	239	348	172
Mud	223	318	175
16,000 ft--Uninsulated	532	535	91
16,000 ft--Full Insulation	101	157	145

(a) Flow rate (200 and 500 gpm) - These calculations indicate that 200 gpm is too low (this is probably true from other flow considerations) and that there is little incentive to increase the flow rate past 350 gpm.

(b) Insulation thickness (1/8 and 3/4 inch) - There is a notable difference when increasing from 1/8 to 3/8 inch, but little additional

improvement from going on to 3/4 inch.

(c) Viscosity - The properties of a 10 ppg mud with 15 cp plastic viscosity and 5 lbf/100 sq ft yield point were used to represent a typical drilling fluid. The slightly lower temperatures with mud are primarily caused by the viscosity, which lowers the heat transfer coefficient of the mud compared to water.

(d) Casing and wellbore size - A number of different casing and wellbore size combinations with flow areas varying by a factor of three were tried. The detailed results are not given but in no case did the maximum or bottomhole temperatures vary from the base case by more than a few tens of degrees.

(e) Shallower Wells - To assess the importance of insulated pipe in drilling the upper part of the hypothetical magma well, I calculated the temperature profiles in a well that had only been drilled to 16,000 feet in the same geothermal gradient. The uninsulated case is not too different from conventional geothermal drilling, while the insulated pipe provides an almost benign environment that never exceeds 200 degrees F.

In general, there were no major surprises in the ways that changing the well parameters changed the temperatures. Some of the variables had less effect than might have been expected, but none of them had an especially sensitive threshold.

Finally, it is necessary to think about how insulated drillpipe might actually be made. I have assumed that the worst (i.e., most expensive) case would be to use commercial concentric drillpipe and fill the annulus with insulation (or perhaps just leave it empty). Concentric pipe usually costs about 3 times as much as normal drillpipe, but its requirement of a dual flow path in the drill string would not apply if we only want insulation around a single flow path.

We should also remember that special alloys needed for the temperatures of uninsulated drilling are more expensive than conventional steels and may even be more than insulated pipe. There are also several possibilities for coating conventional drillpipe with insulation. If erosion, bonding, and thermal expansion problems can be overcome it is possible that insulated pipe could be less than 150 percent of the cost of conventional.

BOREHOLE STABILITY

There are two major stability problems when the wellbore has penetrated a magma body where the lithostatic pressure in the magma is higher than the wellbore pressure. One is the reheating of the solidified rind when there is a break in circulation. This happens fairly quickly, as shown in Figure 5, and can cause wellbore collapse and loss of the hole. The other problem is creep of the hot rock, which tends to make the wellbore squeeze in behind the bit even while normal drilling is in progress. Both of these situations are considered in the worst case; that is, water drilling fluid gives the minimum wellbore pressure and the maximum pressure difference with the assumed lithostatic head in the magma. The interruption in circulation also is assumed to occur as soon as drilling is ended; if circulation continues after the end of drilling, then a later interruption will have a longer reheating time.

Radial displacements of the wellbore wall for both of these conditions were calculated with a finite element code used in other rock mechanics analyses at Sandia. Values for the high temperature strength and creep coefficients were taken from a report by Friedman, et al.[3] The results were generally encouraging; the displacement of the wellbore wall while drilling was a few millimeters, and the displacements as a function of time after circulation has stopped are shown in Figure 6. These curves show that there is at least one day available to re-start circulation before the wellbore walls have moved significantly.

CONCLUSION

The calculations described here have given a very strong indication that insulated drillpipe will be nearly indispensable when drilling into a magma body and will be useful in less demanding holes drilled toward a hot target. The improvement in performance with insulated pipe is relatively insensitive to changes in most of the flow conditions, as long as certain threshold values are maintained. The apparent value of this technology justifies further development, including prototype hardware.

ACKNOWLEDGEMENTS

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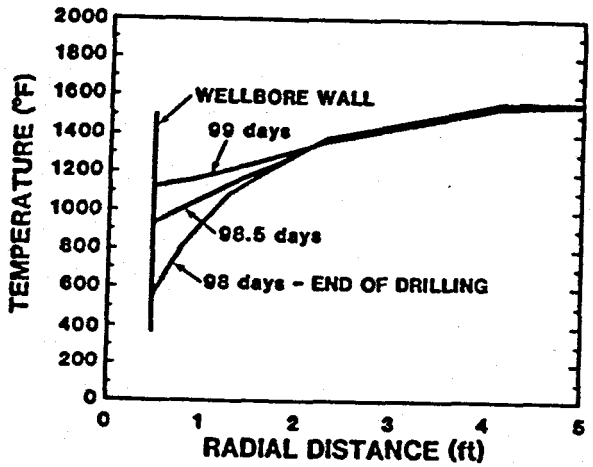

Figure 5. "Temperature Increase if Circulation Stops at end of Drilling"

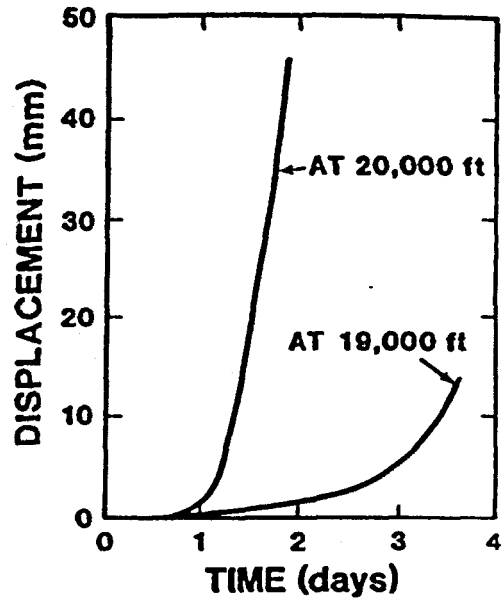

Figure 6. "Displacement of Wellbore Wall after Circulation Break"

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