ROCK MELTING: A SPECIALTY DRILLING SYSTEM FOR IMPROVED HOLE STABILITY IN GEOTHERMAL WELLS

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Keywords: Specialized drilling, rock melting, stabilized well bore, glass lining.

ABSTRACT

A Los Alamos National Laboratory team is actively reevaluating a drilling system that uses electrically-heated graphite, or molybdenum penetrators to melt a hole as it is slowly pushed through rock. The primary result of a rock melting penetrator is to form molten material that consolidates into a rugged glass lining, thus preventing hole collapse and minimizing the potential for cross-flow and lost circulation. Drilling fluid requirements are reduced or eliminated, and the penetrator does not rotate.

Laboratory bench tests are being coupled with time-dependent thermomechanical models to understand the physics of the process and adapt rock melting to a variety of field environments.

The potential geothermal drilling applications include a wellbore seal in lieu of intermediate casing particularly in areas of lost circulation or borehole wall collapse. Additionally, by modifying the penetrator tool, the system could be designed to melt through a stuck pipe or bit, thereby eliminating cementing and redrilling. Modification of the rock melting drill to allow injection of reagents and thinners into the melt to increase penetration rates, and enhance glass liner properties is also under investigation.

INTRODUCTION

In response to the perceived needs of US. industry, Los Alamos National Laboratory is developing a unique energy-related technology with a potential for high payoff. This technology involves rock melting, and utilizes a modularized mobile rock-melting drilling to produce and stabilize boreholes in rock. This represents an innovative technological develop-ment which has the potential to provide a solution to geothermal drilling problems involving hole stabilization and borehole sealing.

The concept of rock melting, was first invented at Los Alamos National Laboratory in the early 1960's (Armstrong et al., 1962). In an attempt to meet the demand for new cost-efficient drilling in geothermal environments, a three year rock melting program sponsored by the U.S. National Science Foundation, and named *Subterrene,* was initiated at LANL in 1973 (Hanold et al., 1977). The thrust of this program was two-fold:

(1) To serve as a proof of concept experiment and demonstrate that a rock melting tool was capable of forming boreholes in a variety of rock types.

(2) To demonstrate the feasibility and competiveness of the method in relation to common mechanical drilling techniques.

The program was successful in both instances. By the end of 1976, over twenty horizontal and vertical field holes, 2.5 cm to 10 cm in diameter and up to 30 m in length, were drilled in a variety of rock types, ranging from granites, basalts, tuffs to unconsolidated sediments and soils. The maximum penetration rate obtained however was 1.0 mh^{-1}, and this rate was not deemed competitive with average mechanical drilling rates (3.0 to 6.0 mh^{-1}).

Although rock melting still cannot compete with conventional drilling techniques in terms of penetration rates, it offers one major advantage which is now more fully appreciated: the molten rock layer which forms around the borehole during penetration, consolidates in-situ into an impermeable, potentially strong glass lining that promises to alleviate hole collapse and isolate the well bore from permeable zones. In addition, several recent technological advances combined with strategic energy requirements, have led us to seriously reconsider the rock melting program as a viable drilling technology or borehole lining tool.

The high costs incurred by conventional rotary drilling in the exploration of new geothermal areas and the monitoring of existing reservoirs have compelled some drilling operators to consider miniaturized drill systems and use slim holes (<10 cm diameter boreholes) instead of larger boreholes (Garg and Combs, 1994). The introduction of coiled tubing technologies and improved power cable systems help minimize the use of conventional down hole wet connects. This allows electrical power to be supplied via a down hole electric unit, and may therefore lend itself to the use of rock melting technology to otherwise inaccessible depths.

Large cost overruns associated with borehole stabilization and encasement of directional holes suggest that there exists important niches in which drilling costs are high using conventional drilling methods. Because wellbore and formation conditions are hot and corrosive in geothermal environments, there exist major difficulties in the cementing operations. These arise principally from high temperatures, lost circulation zones and the contamination of cement slurries with conventional drill fluids. Rock melting does not involve fluids and is most efficient at higher temperatures, such that this technique could help alleviate many complexities associated with the use of cements. The technology may therefore be economically viable in spite of the slower penetration rates, if used to eliminate intermediate casing and cementing requirements for primary sealing in fragile formation intervals and lost circulation areas.

METHODS, TECHNIQUES AND MATERIALS

The rock melting concept is based on the use of refractory metal and/or ceramic penetrators designed to pierce rock and soil by progressive melting rather than by chipping, abrading, or spalling. Several relatively small 5 cm to 15 cm diameter refractory metal and ceramic penetrators have been designed and tested at Los Alamos since 1973.

These prototypes fall into two categories:

(1) Melting-consolidating penetrators that are used for penetrating unconsolidated and porous consolidated rocks, but that do not allow sample recovery.

(2) "Universal" melting-extruding penetrators, that are adapted for all rock types including dense, hard rocks (porosity <0.20). These have a central extrusion hole through which the rock is recovered as chilled discrete glass particles or glass lined cores.

Both designs produce dense glass linings on the hole left in their passage. The experimental program at Los Alamos, is designed to predict the relationships between thrust, power, surface temperature, penetration rate and glass lining properties for a wide variety of rock types and soils.

Figure l a shows a compacting penetrator tested on a soil sample. The molybdenum penetrator is heated to high temperatures (≥1500°C) using a stack of oriented pyrolytic-graphite disks held in a graphite cavity within the bit. As the penetrator is thrust into the rock or soil, the substrate melts at the tip and along the sides *of* the bit and cools and solidifies into a glass lining behind the penetrator, which is insulated from the drill stem by a ceramic insulator (Figure 1b).

Previous basic research on rock melting has allowed us to identify melting and solid-state compaction (plastic deformation) as the two major coupled high temperature mechanisms controling the advancement rate of the molybdenum penetrator through the rock, and the formation of the lining. Affecting these processes are the compositional and textural variables of the rock substrate, such as its thermal properties (heat capacity, thermal diffusivity, melting temperatures), bulk chemistry, modal mineralogy, porosity, and melt viscosity.

At present, the GeoEngineering Group at LANL is testing drilling equipment built by Morrison-Knudsen, based on earlier Los Alamos designs. This includes a portable, field-tested multi-directional drilling rig, five $MoSi_2$-coated Molybdenum penetrators and associated hardware. Laboratory tests involving the use of a planar array of 30 thermocouples emplaced in rock samples, and distributed along the pathway of the drilling, are used to monitor the development of the time dependent thermal distribution around the moving penetrator. An optical pyrometer focused on the molybdenum surface through a port in the rock, is employed to directly measure the penetrator temperature at the beginning of each experiment. A Wheatstone bridge on the drill column is used to monitor the stress/load on the penetrator tip. *LABVIEW* PC software is used to acquire our real-time data base.

RESULTS

Examples of glass linings using melting-extruding and compacting-type penetrators have been tested. The most significant feature, shown in Figure 2, is the dense glass lining formed in all rocks drilled using the rock melting technique. Hard, dense granite-gneiss (Fig. 2a) and Bandelier tuff with approximately 40% porosity (Fig. 2b), were both pierced using a melting-extruding penetrator and melting-compacting penetrator respectively. The gneiss sample was melted in the laboratory. The tuff sample represents a field test in undisturbed volcanic rock, drilled to a depth of 25 m, using the electric power (3.5-4.0 kW), stem-cooling, and instrumentation developed in the laboratory. Even though the penetration rates (≈1 mh^{-1}) and temperatures (≈1500°C) were similar in both cases, the lining thicknesses are variable, mostly due to the different porosities of these rocks.

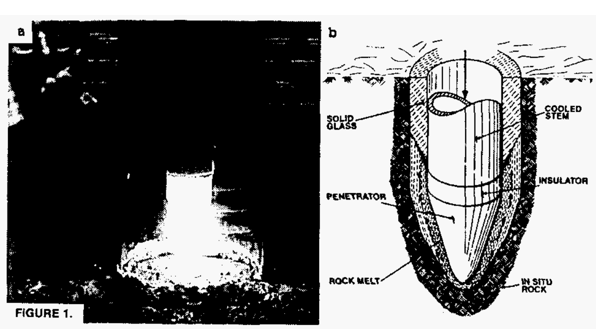

Figure 1. Melting consolidating penetrator entering unconsolidated rock (la) and schematic representation of penetrator (**1b).**

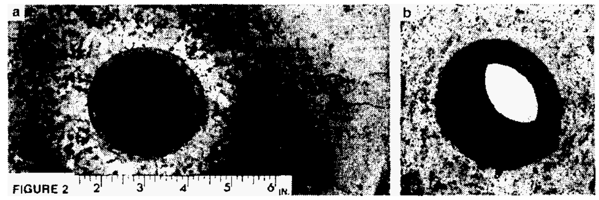

Figure 2. Holes and glass linings in granite-gneiss (2a) and Bandelier tuff (2b), made with a universal-extruding and consolidating penetrator respectively.

At present, the relatively low penetration rates represent the major draw back to this technology. The present penetration rates in unconsolidated and porous-consolidated rocks vary from 1 mh^{-1} to 0.3 mh^{-1} based on rock melting laboratory and field tests. In water-saturated rocks, penetration rates may be slower due to phase change and mass transport of heat in H_2O. While this rate is not competitive with conventional drilling rates under "normal" drilling conditions (10 mh^{-1} to 3 mh^{-1}), it may be highly cost effective in areas where traditional drilling fluids cannot be used, such as in deeper geothermal environments and problem areas involving environmental restoration and waste management.

A typical example of the temperature distribution around the penetrator is illustrated in Figure 3, which represents results from a finite element time-dependent thermal model.

The 5 cm diameter penetrator is in white, and the drill pipe is represented by the grid (which is also the 1 cm grid spacing used in the model). The rock type is Berea sandstone (20% porosity), the penetration rate is 0.3 mhr^{-1} and the penetrator temperature, distributed uniformly at the surface is at 1500°C. Clearly visible is the extent of the thermal perturbation associated with rock melting. The 100°C isotherm does not extend beyond 20 cm from the hole. The melting interface responsible for the formation of the glass lining, is mostly restricted to the vicinity of the penetrator. For a melting-consolidating penetrator, the ratio of outer radius to inner radius of the glass lining is simply (Gido, 1973),

$$R = r_m/r_p = (1/\varnothing)^{1/2} \quad (1)$$

where r_m is the outer radius of the glass lining, r_p is the radius of the penetrator or inner glass lining, and O is the porosity of the rock. The maximum velocity limit for a compacting penetrator, increases linearly with the heated length and decreases as the square of the radius of the melting interface (Cort, 1973).

From these results, one may conclude that compacting penetrators require large volumes of rock to be melted to form a hole by simple consolidation. For geothermal environments, where dense, low porosity rocks represent the norm, reasonable penetration rates can only be obtained using an extruding penetrator design. In this case however, the penetration rate will increase as the temperature increases at depth. A laboratory experiment, conducted in two identical blocks of basalt, one at 25°C and the other pre-heated at

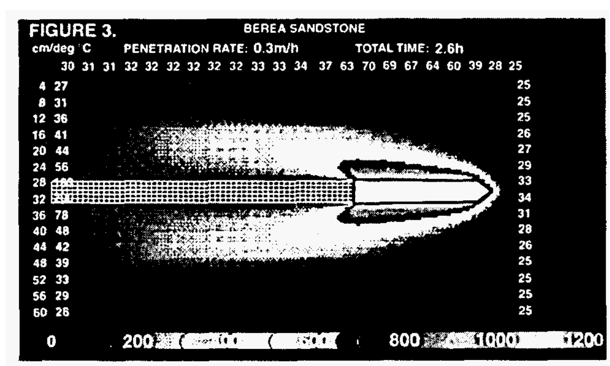

Figure 3. Finite element simulation *of* rock melting penetrator and stem melting through Berea sandstone at 0.3 mh^{-1}.

360°C, resulted in a 25% increase in melting penetration rate for the pre-heated block, even though the operating conditions were the same.

DISCUSSION

High temperature environments associated with geothermal sites, render conventional drilling difficult and costly, principally due to the corrosion and oxidation of diamond drill bits and drill stem. Oxygen corrosion rates are drastically increased due to the use of air drilling methods. Because rock melting is a nominally "dry" drilling technique, rendered more effective at high temperatures, it is well suited for such adverse drilling environments, which inhibit drilling fluid circulation. Potential geothermal drilling applications may include a wellbore seal in lieu of casing, particularly in areas of borehole collapse and loss of circulation. Cementing casing in geothermal wells in under pressured areas has been a problem throughout the industry. This technique could help alleviate problems associated with cementing and sealing geothermal wells, as cements are unstable at high temperatures and strength retrogression of cements with time is common.

A modified penetrator tool could also be designed to melt through a stuck pipe or bit, thereby eliminating the frequent down hole cementing and redrilling operations used in geothermal sites today. The cool temperatures behind the penetrator also allow the use of guidance systems and borehole measuring devices behind the drill head, making it adaptable to directional drilling.

In addition, it has applications in angled and horizontal directional drilling, in subsurface environments that involve porous and loosely consolidated materials, which are susceptible to borehole collapse. With the exception of cryogenic methods, rock melting is the only technique which can produce linings during drilling, with the potential to immediately stabilize horizontal boreholes.

CONCLUSION

The rock melting specialty system offers several major advantages for potential geothermal applications, over conventional drilling technology:

(1) It does not involve the use of conventional fluid lubricants or muds.

(2) The molten rock layer which forms around the borehole during penetration, consolidates in-situ into a strong impermeable glass lining. Borehole sealing and stabilization is immediate and may defer or preclude the need for cemented-in-casing.

(3) Because of the thermal characteristics of most rocks (e.g. low thermal conductivity), temperature gradients in the vicinity of the borehole are high, and the rock substrate remains unaffected by the drilling technique within ten to twenty centimeters from the borehole.

The primary task at Los Alamos, is to understand and develop glass linings in rocks with known physical and chemical properties, so as to engineer glass casings with predictable properties and characteristics. The determination of the mechanical properties of the glass linings obtained from field tests and laboratory bench tests, is a key to understanding the long- and short- term borehole stabilization properties. Because of the possible leaching of the glass liners over time by ground waters, we plan to assess the chemical integrity, and the weathering resistivity of the glass linings by performing leaching experiments.

Three avenues of research are being pursued at Los Alamos:

(1) Experimental laboratory tests coupled with simple finite element modeling, designed to quantify the variables and the mechanisms responsible for rock penetration and lining formation. Model systems include volcanic, igneous and sedimentary rocks such as basalts, tuffs, granites, shales, sandstones and unconsolidated sediments that serve to test rocks with different textural (density, porosity) and compositional (melting temperatures, liquid viscosities) characteristics.

(2) Experimental and numerical tests, to optimize existing penetrator designs, in order to improve lining quality and penetrator performance. This involves the determination of glass lining strengths and resistance of the linings to chemical degradation, chemical remobilization and weathering. Incompatible, compatible, and volatile element tracers are employed to quantify the chemical remobilization during melting and assess the permeability properties of the glass linings in the presence of various fluids.

(3) Field tests aimed to adapt the penetrator to existing borehole technologies and problems (coiled tubing, slim hole stabilization etc...), and to implement an effective, compliant technology for geothermal operations.

Acknowledgments

The authors gratefully acknowledge the assistance of Aaron Dick, Adrianna Sparks and rock melting team members. We would like to acknowledge Jim Albright for his constructive criticisms. In addition, we are indebted to John Blyler from Morrison-Knudsen.

References

Armstrong, D.E., Coleman, J.S., McInteer, B.B., Potter, R.M. and Robinson, E.S. (1962). Rock Melting ***as*** *a* Drilling Technology. Los Alamos National Laboratory Report, LA-3243.

Cort, G.E. (1973). *Rock* Heat-Loss Shape Factors For Subterrene Penetrators, Los Alamos National Laboratory Report, LA-5204-MS.

Garg, S.K. and Combs, J. (1994). Slim holes for geothermal exploration and reservoir assess-ment in Japan. *GRC* Bull., Vol.23, pp.89-96.

Gido, R.G. (1973). Subterrene Penetration Rate: Melting-Power Relationship. Los Alamos National Laboratory Report, LA-5204-MS.

Hanold, R.J., Altseimer, J.H., Armstrong, P.E., Fischer, H.N., and Krupka, M.C., (1977). Rapid *Excavation By* Rock Melting, The LASL Subterrene Program, Los Alamos National Laboratory Report, LA-5979-SR.