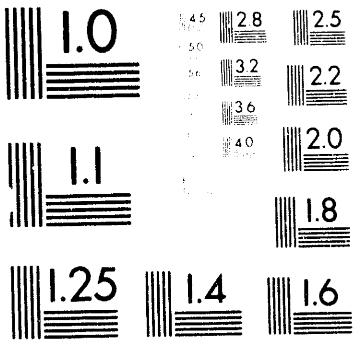
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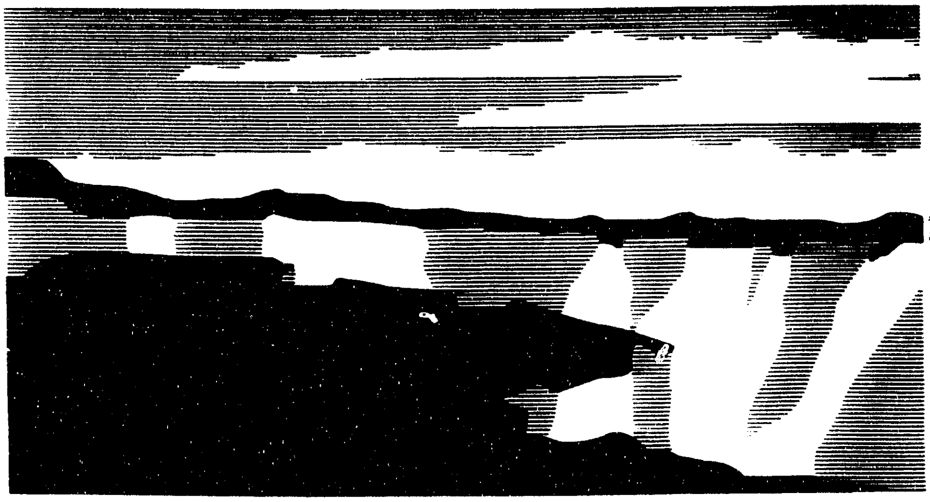

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Proposed paper for 1994 Drilling Technology Symposium

THE ROCK MELTING APPROACH TO DRILLING

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ABSTRACT (LA-UR-93-2851)

During the early and mid-1970's the Los Alamos National Laboratory demonstrated practical applications of drilling and coring using an electrically-heated graphite, tungsten, or molybdenum penetrator that melts a hole as it is slowly pushed through the rock or soil. The molten material consolidates into a rugged glass lining that prevents hole collapse; minimizes the potential for cross-flow, lost circulation, or the release of hazardous materials without casing operations; and produces no cuttings in porous or low density (<1.7 g/cc) formations. Because there are no drilling fluids required, the rock melting approach reduces waste handling, treatment and disposal. Drilling by rock melting has been demonstrated to depths up to 30 m in caliche, clay, alluvium, cobbles, sand, basalt, granite, and other materials. Penetrating large cobbles without debris removal was achieved by thermal stress fracturing and lateral extrusion of portions of the rock melt into the resulting cracks. Both horizontal and vertical holes in a variety of diameters were drilled in these materials using modular, self-contained field units that operate in remote areas. Because the penetrator does not need to rotate, steering by several simple approaches is considered quite feasible. Melting is ideal for obtaining core samples in alluvium and other poorly consolidated soils since the formed-in-place glass liner stabilizes the hole, encapsulates volatile or hazardous material, and recovers an undisturbed core. Because of the relatively low thermal conductivity of rock and soil materials, the heat-affected zone beyond the melt layer is very small, <1 inch thick. Los Alamos has begun to update the technology and this paper will report on the current status of applications and designs for improved drills.

INTRODUCTION

The Subterrene is a system invented and patented by scientists and engineers at the Los Alamos National Laboratory (LANL) for making vertical, horizontal, or inclined holes in the ground by melting rocks and soils. Rock melting is a novel rock destruction mechanism available to the industry in special circumstances where mechanical stress methods may have difficulty; it is not expected to replace conventional drilling. The three essential steps of excavation - rock fracturing, debris removal, and wall stabilization - are accomplished in a single integrated operation by the Subterrene. 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 binds loose soil materials effectively into a stabilized liner; it can be solidified into particulate debris for convenient removal. This paper describes current rock melting technology, mentions some potential applications, and outlines directions for improvements to the technology.

SUBTERRENE CONCEPTS

The Subterrene makes holes in rocks and soils by progressive melting instead of mechanical chipping or abrading. The smooth-faced penetrator (Fig. 1) or "drill bit" is made of a refractory metal such as tungsten or molybdenum and some of their alloys. The rock surrounding the hot penetrator is melted as it is thrust into the formation. Pressure created by this downward thrust forces the liquid rock-melt to flow outward around the sides of the penetrator and stem. The steel stem is thermally insulated from the bit and cooled by recirculating air or water through its interior. The melt freezes on the cooled exterior to form a dense vitreous lining for the hole, an example of casing-while -drilling. This lining is useful to prevent sidewall collapse in loose, unconsolidated formations and it provides a perfectly round, smooth, in-gage borehole. The operation just described is that of the "melting-consolidating" type of Subterrene, designed for making holes in porous rock or soft ground. Figure 2 is a photograph of a melting-

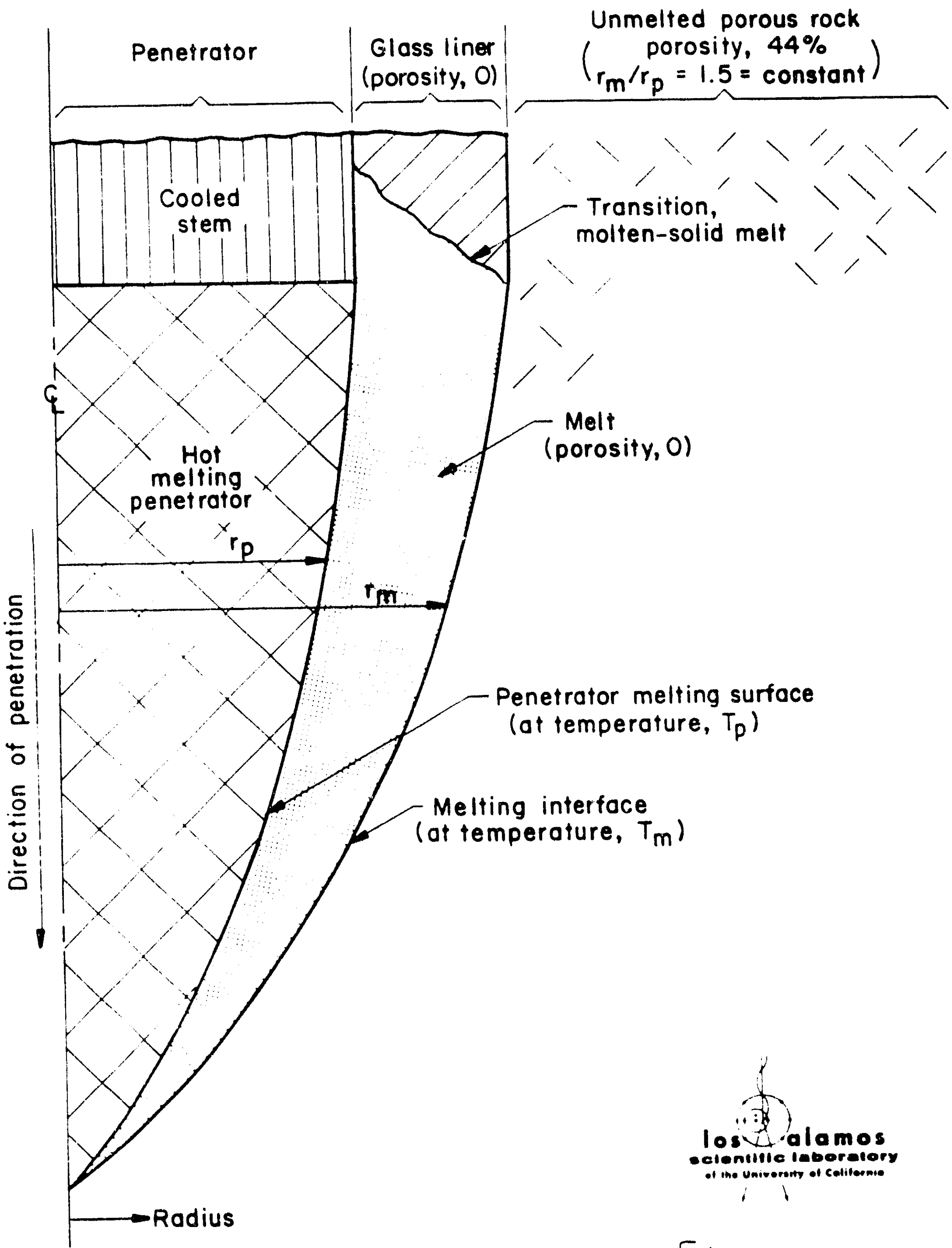

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Fig 1

Fig 2

consolidating penetrator entering the surface of porous rock. The "glass" lining formed when the rock melt cools is more dense and occupies a smaller volume than did the original porous rock so the molten debris can be entirely consolidated in the dense glass lining, completely eliminating the need to remove debris.

For rocks with a higher density (> 1.8 g/cm^3) or to make a thinner hole lining in porous rock, a portion of the molten rock is continuously removed from the borehole by extruding it through a central nozzle in an annular melting face. The glass lining's thickness can be adjusted by penetrator design and operating parameters. The debris extruded in the form of low-density "popcorn" or "glass wool" is carried to the surface by the stem coolant flow. A close-up photograph of a 50-mm diameter hole melted in high quartz-content granite gneiss by a universal-extruding penetrator is shown in Fig. 3. The word "universal" is added to the extruding penetrator's name because it is capable of penetrating nearly all rock and soil types.

For geophysical prospecting it is desirable to extract a relatively undisturbed core sample to identify the rock layers at various depths. A continuously coring penetrator has a toroidal or ring-shaped melting bit with a large central hole for forming and extracting core samples. It can be used in any rock or soil by melting an annular passage, with a glass lining on both the central core and the sides of the hole. Although there is a small (typically < 1 inch thick) heat-affected zone around the core, it is mechanically undisturbed and the lining keeps unconsolidated material in place. This is the best way to make larger shafts and tunnels, by melting an annular "kerf", after which the central region is easier to fracture and remove. The central core is expected to be mechanically fractured by thermal stress which may be all that is required to facilitate its removal. All of these Subterrene concepts have been demonstrated in the field in a variety of rocks and soils (Hanold, 1977).

OPERATING EXPERIENCE

The Subterrene has been tested at Los Alamos in diameters from 2.5 to 10 cm and depths to 30 m, in a variety of rock types including dense rock and loose formations and the holes created are dimensionally stable and straight. Both horizontal and vertical holes have been drilled. For high-angle drilling, hole cleaning problems should be alleviated because some (or all) debris is consolidated into the hole lining and the remainder is in the form of low density material.

Rock types and formations that were melted by prototype Subterrene devices include both igneous and sedimentary listed in Table I.

Table I
Rock Types and Formations Melted by Prototype Subterrene Devices

Igneous
Basalt, olivine, dense
Granite, biotite, coarse-grained
Rhyolite
Latite
Orthoclase
Tuff, Bandelier, nonwelded to semiwelded.

Sedimentary
Limestone, siliceous
Shale, red


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Alluvium, Santa Fe formation, semiconsolidated silt to large pebbles, dry and wet (≈15 wt. % water)
Alluvium (soil from Nevada test Site, dry semiconsolidated)

The Russian St. Petersburg Mining Institute has experimented with drilling by melting in tuff, basalt, rock salt, alluvium, gravel, sand, loam and so forth (Kudryashov, et al., 1991). They have demonstrated some impressive performance with improved penetrator bit materials up to 12 cm in diameter made of ceramics and sintered oxides (in addition to refractory metals) at temperatures to 1800 °C.

The ability of Subterrene penetrators to produce stable holes through a variety of difficult, variable, and broken rock samples was verified by extensive testing. One example illustrated in Fig. 4 (*NEED TO GET FIG 4 - it is Fig II-2 in Hanold)* is a conglomerate of Hanford alluvium containing basaltic gravel and large cobbles. Penetration of the largest cobble (8-10" diameter) without debris removal was achieved by thermal stress fracturing and lateral extrusion of portions of the rock melt into the resulting cracks. The ability to provide a continuous vitreous lining across nonhomogeneous samples was demonstrated in tests in which layers of alluvium, shales, and tuff were penetrated. The vitreous lining that stabilizes the hole is smooth and competent and can be annealed using optimally-cooled forming regions directly behind the penetrator. Experiments designed to evaluate and optimize rock-glass properties were used to establish it as an in-situ structural element for hole support during penetration. Laboratory experiments confirmed a considerable increase in crush strength and decrease in permeability for rock-glass liners compared to the parent rock. NOTE: In this paper, we have used the words "vitreous" and "glass" interchangeably for variety in writing style, but technically the solidified melt material is not a true glass.

ROCK-MELTING FUNDAMENTALS

Most rocks melt at relatively low temperatures because they are mixtures of individual minerals and solid solutions. Magma, from which many rocks are derived, is primarily a molten silicate solution defined chemically in terms of metal oxides. Analysis has shown that eleven of these oxides are sufficient to chemically describe 99% of the rocks that form the earth's crust. Silicon dioxide and aluminum oxide constitute 75% of these by weight, according to Krupka, 1973. The oxide mixture causes the phase transformation to occur over a broad range of depressed temperatures depending on constituents and impurities. This contrasts to the sharp melting point of a pure substance. The temperature interval over which most rocks melt at atmospheric pressure is 1250 to 1500 Kelvin (1790 - 2240 °F). These observations imply the following: (a) melting is relatively insensitive to the type of rock. (b) the physical hardness of the rock is of no concern., and (c) refractory metals, alloys, and ceramics are available whose melting points and structurally useful temperature limits are considerably higher.

Two rock types which are more difficult to penetrate by melting (Lundberg, 1975 and Krupka, 1973) are quartzite veins and some pure-grade sedimentary formations like limestone and dolomite. The calcite ($CaCO_3$) in these decomposes to both volatile (CO_2) and high-melting components (CaO) but not to liquid phases. Naturally-occurring impurities in limestone, such as water and silica tend to improve the melting behavior of calcite and the lowest-melting point eutectic of the calcite/silica system melts at only 1437 °C. Small particles of high-melting material such as quartz (SiO_2) in inhomogeneous rocks and soils cause relatively few problems. Bandelier tuff is an example of a material that starts the melting process by forming a very fluid liquid containing large quartz crystals which begin to dissolve as melting progresses.

The total energy required to melt rocks of various types is nearly the same within reasonably narrow limits (Krupka, 1973). For an 89 mm (3.5 inch) diameter hole the electrical power supplied to the melting bit is approximately 7 kW-hr per foot of hole. Existing systems capable of drilling 5 to 10 cm diameter holes are powered with ≈85 to ≈330 Amp DC current feed to pyrolytic-graphite heater elements. The energy required to melt rock is considerably greater than that required to mechanically destruct it, 5000 Joules/ cm^3 to melt versus 100 Joules/ cm^3 for a rotary bit, according to Maurer (1968). This disadvantage is offset by the fact that the energy cost is still a negligible fraction of the total cost of drilling and by the fact that melting has other advantages (Table II).

Table II
Advantages of Rock Melting

- Predictable advance rate relatively independent of formation.
- Rock penetration, debris removal, and wall stabilization in one system.
- In many drilling situations requirements for drilling fluids are reduced or eliminated.
- Mechanical forces, on the bit and stem are less than rotary drilling, leading to lighter more portable equipment.
- Bit does not contact solid rock so wear is minimal.
- Smaller equipment and fewer fluid requirements lead to smaller drill pad footprint.
- Environmental advantages include absent or less toxic drilling fluids, silent, vibration and dust-free operation, and compact drill pad.
- Case-while-drilling feature reduces interzonal cross flow.
- Potential advantages in deep drilling operations:
  - Increased temperature at depth facilitates rock melting (contrast with problems at 250 to 300°C in conventional drilling).
  - Extended bit life with fewer bit trips.
  - Non-rotating system with reduced wear on drill stem.
  - Improved bore stability and well control.

APPLICATIONS FOR ROCK MELTING

The St. Petersburg Mining Institute (Kudryashov, et al., 1991) has designed a melting-consolidating penetrator for reinforcing the foundations of ancient buildings built on unstable soils. This seems to be a very realistic and economical application of rock melting, particularly in St. Petersburg which is a very old city built on a group of marshy islands. They also envision applications for reinforcing unstable intervals of shafts with easily melted packing materials, for reinforcing landslides, edging open-pit mines, and drilling shafts in geothermal and salt deposits.

We believe that specialty applications offer the greatest potential for immediate use of rock melting technology. For example, the non-rotating bit with relatively low thrust loads can probably be steered easily and precisely, although this has not been demonstrated. Steering through unconsolidated material containing boulders should be more easily accomplished for these reasons in combination with the uniform, smooth, in-gage borehole which helps keep the stem centralized precisely. Schiuh (1993) believes that the share of U.S. rigs devoted to horizontal and directional drilling is likely to increase to 50% within the next decade or so. He also says that the two primary needs are to improve well completions and targeting accuracy. The potential for continuous sampling while drilling and accurate positioning data is enhanced because of the electrical leads in place and the fact that impacts and vibrations are minimal. Quiet, dust-free operation without liquid effluent are other desirable characteristics.

The Subterrene has not been demonstrated in diameters larger than 10 cm and capital costs and other factors lead to considering small-diameter applications initially. These characteristics make utility emplacement in congested areas and river crossings the most likely early uses. The name "micro tunneling" has been coined to describe such applications and the following quotation from Ozdemir and Friant (1993) illustrates the potential: "Micro tunneling is an area which has been undergoing very rapid growth worldwide. In the US, the micro tunneling industry has been growing at an annual rate of about 30 percent as more owners become aware of the capabilities of this technology. Micro tunneling is a very attractive option for construction of small diameter tunnels as it eliminates the surface disruption associated with trenching. To date, micro tunneling has primarily concentrated on soft ground due to limitations of the technique to excavate hard rock or soft ground mixed with hard boulders. It is strongly believed that significant improvements can be made in the micro tunneling technology through technology transfer from the TBM industry both for hard rock and soft ground. To effectively accomplish this transfer, research is needed to fully understand the needs and requirements of the micro tunneling industry, as well as to develop small, efficient cutting tools that can be efficiently utilized on micro tunneling machines. If micro tunneling machines are developed for hard rock excavation, this is expected to open up large new markets for utility tunnels, highway and river crossings, and sewer projects. Another area needing further development is the machine guidance system to allow construction of longer tunnels with the required alignment tolerances."

A second potential application is installing ground-coupled heat pumps (GHPs), the ideal heating/cooling system for the 1990s with benefits for the consumer, the utility and the environment. High installation cost of GHPs is the primary barrier to more widespread use because of the high cost of drilling to the required depth of approximately 200 feet to install the heat transfer loops. For the reasons mentioned above the rock melting technology may help reduce drilling costs and speed the introduction of GHPs.

Another small-diameter, relatively shallow application that takes advantage of the Subterrene's unique characteristics is drilling characterization boreholes in or near contaminated zones such as hazardous landfills or buried storage tanks. No contaminated cuttings are brought to the surface in typical low density formations at landfills. As the molten region expands outward and downward from the penetrator, it will encompass the contaminated soil and incorporate non-volatile contaminants into the solidified glass liner. Organic components would be destroyed in the melt by pyrolysis. The pyrolyzed products could migrate to the surface where they would oxidize in air, or they might diffuse radially into the contaminated formation. Although it may contain micro-cracks that would prevent its use as an impervious barrier, the vitreous lining will help to minimize the escape of hazardous gases and liquids. The smooth, uniform surface of the liner will facilitate in-situ sampling and it can be penetrated by conventional means if necessary to obtain samples. Because of the low thermal conductivity of rock and soil materials, the heat- affected zone is small, only a fraction of an inch beyond the outside of the melted layer. Beyond this thin zone, experience shows that there is no change in the character and concentration of materials. The melt layer returns to ambient temperature in a few days. If a universal-extruding penetrator design is used to drill into a hazardous waste site, the solid debris is easily collected by filtering the contaminated coolant air stream. Drilling by rock melting is compatible with proposals to stabilize buried waste by in-situ vitrification (Koegler, 1992).

There is potential for the rock-melting technology to install impervious barriers to encapsulate hazardous waste in-situ by forming a long, narrow trench around and under the waste. The penetrator can be knife-shaped because it does not rotate, and it can be moved horizontally to create a narrow slot without removing debris which might contain contaminants. The properties of the glass lining can be improved by design of an annealing section that follows the melting bit and chemical additives can also be incorporated into the glass in the molten state. The narrow trench can be backfilled with an impervious liner, or if the glass barrier is deemed sufficient, the trench can be left open for monitoring.

Small-scale applications that are totally undeveloped include low-cost (i.e. hardware-store) disposable silicon carbide-coated graphite penetrator bits for household and farms to use, for example, installing fence posts and underground lawn sprinklers.

A rock-melting bit can be used as an adjunct in conventional (vertical, slant, or horizontal) drilling operations, stored on the drill pad to be attached to the bottom of the drill string whenever the situation calls for it. Some design adaptations will be required in order to facilitate an efficient switch, but there is no fundamental reason why this concept should not work. Potential drilling situations (Azar, 1993 and Mock, 1993) where rock melting is viewed as a time and money saving adjunct are listed in Table III.

Table III
Rock-Melting Adjuncts to Conventional Drilling

- Sealing the well bore in lieu of casing operations.
- Penetrating a stuck pipe or bit (the refractory-metal bits can melt steel) in lieu of cementing and redrilling a new section.
- Getting past lost circulation zones, washouts, or borehole wall cave-ins.
- Drilling hard rock.
- Drilling hot rock (>250-300°C), particularly for geothermal wells. A significant increase in penetration rate when drilling hot rock has been demonstrated.
- Drilling deep to superdeep (4.5 to 7.5 km) where the non-contact melting penetrator can last longer and reduce the number of trips required.
- High-angle slant drilling where hole cleaning problems can be alleviated with a combination of melt consolidation (reducing the total amount of cuttings produced) and melt extrusion with tailored particle size and density to enhance removal. The debris character can be modified by controlling the geometry of the extruding nozzle combined with temperatures and coolant flow velocity in the region where debris is created.
- Directional drilling where the non-rotating, low-thrust bit combined with accurate centering in a smooth uniform hole can enhance accuracy.
- Continuous coring for mineral exploration oil and gas sampling, or scientific drilling.
- To obtain improved downhole instrumentation.
- To avoid problems with corrosive formation fluids.
- To help meet environmental constraints on conventional drilling.

Rosen (1991) points out that the frontier in earth science lies in boreholes from 4.5 to greater than 10 km deep. Most commercial drilling is relatively shallow at 1400 meters for the average exploratory well and only a very few exceed 4.5 kilometers. Deep to superdeep drilling will yield information to refine seismic surveys, chart the evolution of sedimentary basins and shield volcanoes, and uncover important clues on the origin and migration of mantle-derived oil and gas. He lists primary technical obstacles to such drilling as excessive trip time to change bits, difficulty in maintaining a straight vertical hole, and high temperatures at depth. Although it is not without its own set of technical problems, the rock-melting Subterrene has many advantages that address or solve all of those listed difficulties

Los Alamos is interested in exploring these and other potential applications for rock melting technology in cooperative arrangements with industry. Inquiries are invited.

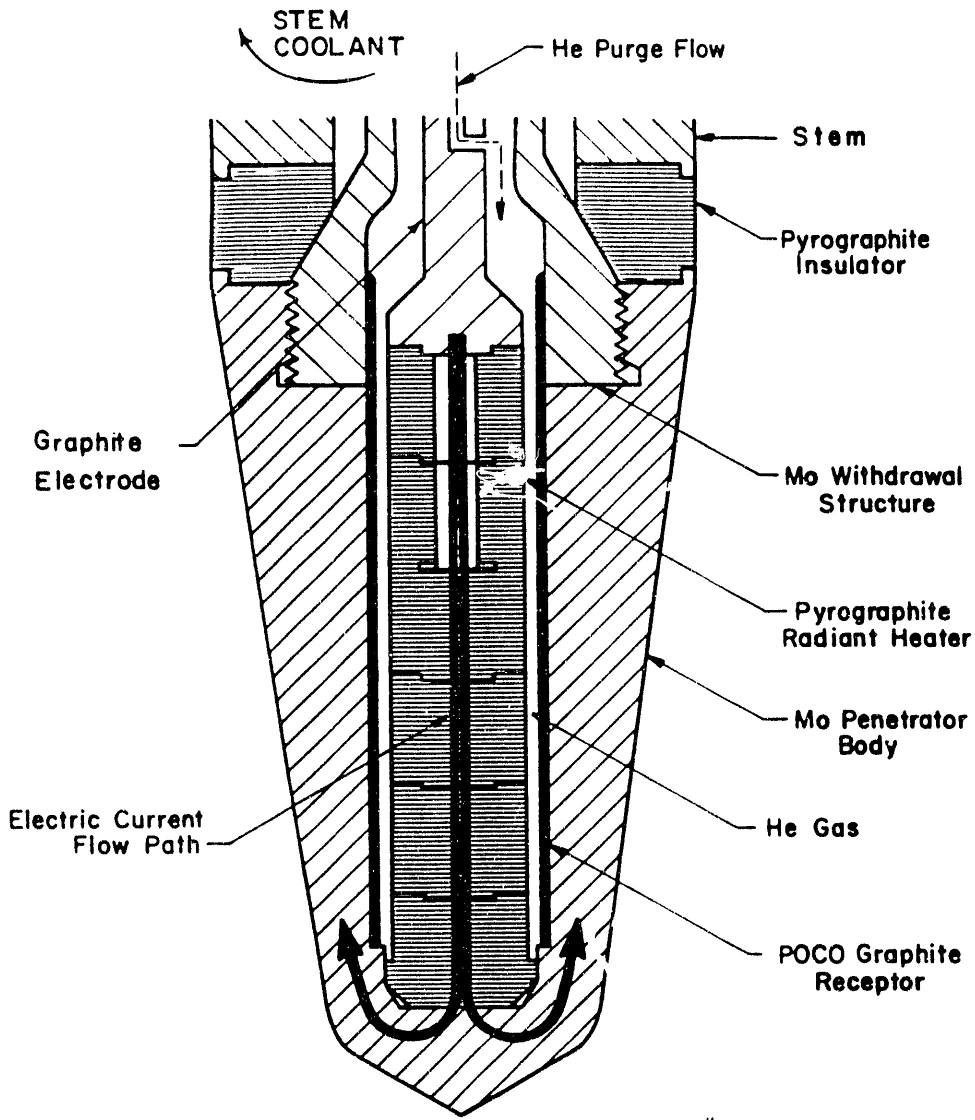
POTENTIAL IMPROVEMENTS TO SUBTERRENE DEVICES

The Subterrene rock melting technology is proven but it dates from the 1970s, and there are many potential improvements that could be applied. To meet all of the above drilling applications there must be demonstrations and technology developments in several areas:

- Larger diameter and deeper holes should be demonstrated in the field.
- Faster penetration rates are desirable for some applications. This can be achieved with more efficient heat transfer to the rock by several mechanisms (see below).
- Directional and slant drilling should be demonstrated.
- For deep drilling particularly, the electrical resistance heaters should be modified to increase electrical resistance and cause it to increase with temperature.
- Stem connections and adaptations to conventional rigs need to be ruggedized and improved.
- Specialized bits and (in some cases) complete tools need to be designed and tested.

In the Subterrene, (Fig. 5) direct current electrical energy heats a pyrolytic- graphite resistive element in a central cavity inside the refractory metal bit. The heat is carried by conduction and radiation across the cavity and by conduction through the body of the bit into the rock. Other methods based on applying thermal energy (as opposed to mechanical breaking) to penetrate rock include electric arc and plasma drills, electron beam drills, electric disintegration drills, flame jet drills, laser drills, rocket exhaust drills, a thermocorer drill, and thermal - mechanical drills (Maurer, 1980). High-power microwaves, improved lasers, and neutrally-charged particle beams are recent developments that can be added to this list. High capital costs and unproven design for rock melting applications will eliminate many from the list so this paper concentrated on the Subterrene. All thermal methods (as well as most other novel drills) require more energy to remove rock than mechanical rock fracturing methods (Maurer, 1980).

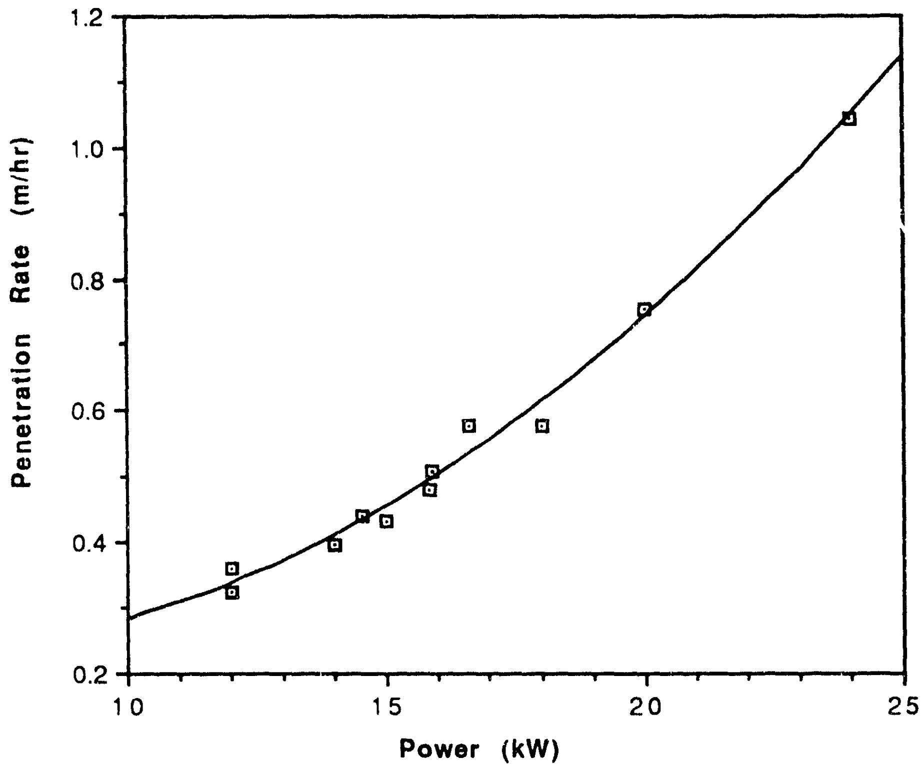
Figure 6 shows the relationship between penetration rate and electrical power supplied to the melting bit. The Subterrene design used to obtain this data is an 89 mm (3.5 inch) diameter High Advance Rate Extruder (HARE) that was used in laboratory experiments to drill hard rocks and compacted alluvium (density 2.1 $g.cm^3$).



STEM
COOLANT
He Purge Flow
Stem
Pyrographite
Insulator
Graphite
Electrode
Mo Withdrawal
Structure
Pyrographite
Radiant Heater
Mo Penetrator
Body
Electric Current
Flow Path
He Gas
POCO Graphite
Receptor

Fig 5

Figure 6 Penetration Rate for HARE Universal-Extruding Penetrator in Basalt



The concave upward slope of the fitted curve indicates that significantly higher penetration rates can be achieved by running the penetrator at higher power, i.e. hotter temperatures to increase the rate of heat transfer to the unmelted rock. However, the molybdenum refractory alloy in the bit is approaching its practical temperature limits at the upper end of this range when operating at 1550 - 1650 °C. Research completed in the program of the 1970s (Hanold, 1977) showed that the practical limitation in penetration rate is the inability to transfer heat from the leading edge to the unmelted rock through the thin melt layer at the tip. The combination of low thermal conductivity in the melt and geometric limitations in the restricted space available for heater and structure at the tip will always constrain the leading edge heat flux. To increase the leading edge heat flux, new penetrator materials capable of hotter temperatures can be employed, or more direct methods of heating the rock without thermal conduction through the melt can be used.

Russian researchers have shown (Kudryashov, et al., 1991 and Rowley, 1993) ceramic oxide materials capable of ≈2400 °C without degradation in air. These or other ceramics and composites, although not yet demonstrated in rock melting may be ideal solutions to increase penetration rates. The Russians may have demonstrated it, but their reporting is not entirely clear on whether higher penetration rates were achieved (Rowley, 1993). Our research in high temperature materials shows other advantages for ceramics such as high electrical resistivity and high structural strength at temperature. Simpler structural design and improved electrical characteristics, i.e. higher voltage and lower current power transmission to the bit, are expected benefits. Los Alamos is beginning to address the materials issues in some internally-funded research and we are interested in forming partnerships with industry.

A departure from the internally-heated bit is to generate heat directly in the rock. We mentioned some of these methods, such as high-power microwaves, in a previous section. Direct melt heating by arranging the electrical circuit of a penetrator so that current passes through the melt layer and deposits most of its power adjacent to the melting interface has been recognized as a possibility for a long time (Hanold, 1977). This is possible because the electrical resistivity of most minerals decreases with increasing temperature in both the liquid and the solid phases. Also, the electrical resistivity of molten rocks is many orders of magnitude lower than that of the parent solids. We investigated the feasibility of directly heating the rock in laboratory "desk top" experiments and found 3.6 m/hr could be achieved without special effort (nearly 4 times the rate achieved for conventional Subterrenes). The simple experiment had potential for up to ten times this penetration rate if heat losses that occur in small scale were absent. We used tuff, basalt and granite for the experiments, but work was halted before a complete database and practical penetrator designs could be developed. Because these results are a strong indication that much higher penetration rates can be achieved, Maurer (1980) recommends that future work be directed at the melt-heating concept.

Energy consumption and penetration rate are probably not the most useful standards of comparison for drilling methods. The total cost to drill to required depth, including the costs of meeting environmental regulations should be the yardstick. Advance rate, which accounts for trips and other stoppages, is a more useful standard than penetration rate. Here, the fact that thermal drilling is likely to require fewer bit trips and is less susceptible to formation variables such as lost circulation zones, as well as making fewer demands on mud systems can tip the balance. Add to this the advantages of a lighter weight system, with smaller footprint on the drill pad, with no noise, dust, or rotating machinery, and the total cost comparison can easily shift away from conventional methods.

SUMMARY

We think that rock-melting technology deserves another look, in light of today's technology, environmental concerns, and drilling needs. The Subterrene has demonstrated many of the capabilities and potential necessary to achieve desired ends and solve existing problems. It only needs development along a specific direction which Los Alamos is committed to support. Hanold (1977) summarizes the significant results and achievements through June 1976 in the Subterrene program that was sponsored by the National Science Foundation, Research Applied to National Needs (NSF-RANN) and by the US Energy Research and Development Administration, Division of Geothermal Energy. It is proposed to make use of this approximately $5 million (in 1970's dollars) investment. We invite your questions and inquires.

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