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AUTHOR(S): John H. Altseimer

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los alamos scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

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THE UTILIZATION OF MELTING TECHNIQUES FOR BOREHOLE WALL STABILIZATION*

John H. Altseimer
University of California
Los Alamos Scientific Laboratory
P.O. Box 1663, Los Alamos, NM 87545

ABSTRACT

The Los Alamos Scientific Laboratory has recently completed a research program on the Subterrene concept based on excavation by melting. Theoretical and experimental studies were made for a broad range of applications. Most recently, a study of Subterrene deep geothermal well production systems predicted that, compared to rotary-drilled wells, significant cost savings are possible, e.g., 2 and 4 million dollars for 10-km-deep wells and geothermal gradients of 25 and 40 K/km, respectively. It was also concluded that for most wells the rate of penetration of the melting bits should be increased several times over that attained in the Subterrene tests. Ideas exist for accomplishing this but they await a new R&D program. However, other improvements in the field of borehole sealing and stabilization may be easier to achieve and would be applicable to any type well. Subterrene melting penetration tests showed that borehole glass liners can be formed in a wide variety of materials and structural characterization tests showed that tuff glass cylinders can be many times stronger in compression than the parent material. Also, the tests showed that the rock-glass liner permeability decreases rapidly with confining pressure. New melting devices are conceivable that could line rotary-drilled boreholes with rock glass or other materials with resultant improvements in well costs. With emphasis on borehole liners, this paper presents an overview of interesting Subterrene program results, data on rock-glass liners, and suggestions on how molten materials might be applied to the borehole wall as part of a rotary drilling operation.

I. Introduction

The Los Alamos Scientific Laboratory (LASL) has recently completed a research program on the Subterrene concept. Those not familiar with the concept may refer to the final status report, Hanold (1976), for a summary of the program and its accomplishments. Basically, the concept is a means for excavating rocks or soil by melting, stabilizing the excavation with a rock-glass liner, and removing excess material in the form of solidified rock-glass debris. Early in the 1960s, it was demonstrated that

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electrically heated devices can penetrate most types of rock or soil. However, it was not until early 1973 that a substantial research program was initiated. This program continued until October 1976 when a termination of federal funding ended LASL's Subterrene research and studies.

Along with the basic research work, many potential applications of rock melting were studied, some of which will be discussed in this paper. Main emphasis, however, will be given to the use of rock glass liners for borehole stabilization. Some important and pertinent Subterrene application studies will be summarized, followed by a discussion on rock-glass liners. The paper will conclude with several suggestions on how the liners might be installed in deep rotary-drilled boreholes.

II. Subterrene Application Studies

A. Water Drain Holes

The use of rock melting devices to produce sewer, water, and other utility tunnels was studied, which led to a request by the National Park Service that the Subterrene be used to make water drain holes in ancient Indian ruins at the Bandelier National Monument, NM. The requirement was for a drilling system that would not vibrate or be otherwise damaging to the fragile ruins. LASL technicians made three successful vertical drainage holes and the National Park Service personnel took over to produce five more, Williams and Griggs (1973).

B. Large Tunneling Machines

Another study involved the use of Subterrene for the production of large tunnels by melting a kerf in the desired tunnel configuration and excavating the main face by means other than melting. Diameters up to 12 m were studied using a nuclear reactor system to supply the thermal energy to the kerf rock-melting surfaces. Heat pipes were assumed to carry the heat from the reactor to the melters. Analyses indicated that tunnel costs could be reduced significantly by using such tunneling machines. This conclusion was fairly well corroborated by an independent cost study made by the A. A. Mathews Co., applying industrial cost-estimating techniques, Bledsoe (1975). Their study assumed that Subterrene tunnelers would be used to produce three large tunnels that had, in fact, been produced by conventional machines and for which the costs were known. Two of the three comparisons showed cost savings when Subterrene machines were used.

To demonstrate the stabilizing effect of a rock-glass liner on a tunnel wall, a small tunnel was constructed in a man-made bunker of soil. The dimensions are 1 m wide x 2 m high x 2 m deep, with the floor flat and the roof arched. It was a successful demonstration and the tunnel still stands at one of the LASL experimental sites.

C. Coring Devices

The tunneling studies also included the detailed design of a Geoprospector, Neudecker (1974). This is a 300-mm (1-ft.)-diam device for taking core samples ahead of a proposed tunnel route. An annular melting surface forms a centrally located glass-encased core that could be withdrawn by wireline techniques. Preliminary tests of such coring techniques were made with the 114-mm (4.5-in.)-diam corer, Murphy (1976). Successful cores were made in both tuff and alluvium. Figure 1 shows an end view of one of the tuff cores.

D. Geothermal Wells

The most recently contemplated application was the production of hot geothermal wells because it appeared that the melting concept should be inherently compatible with hot rock or even magma. The fact that the melting penetration rate would be

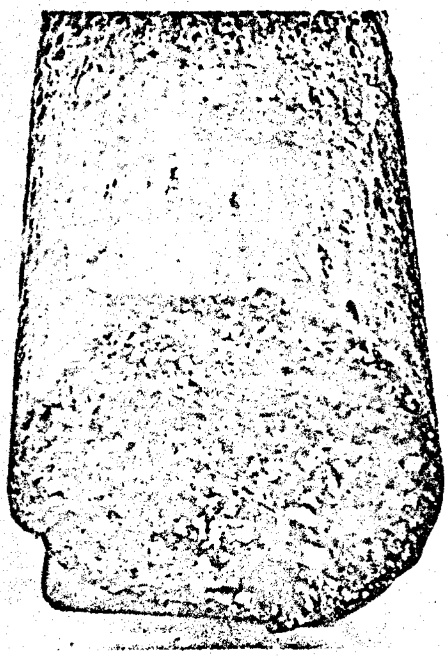

Fig. 1.
Subterrene-produced core in Bandelier tuff, 64-mm diam.

enhanced in hot rock was demonstrated in a laboratory test in which a Subterrene bit penetrated a block of Dresser basalt preheated to 650 K (647F). Theoretically, the penetration rate was expected to increase at least 25%. This expectation was confirmed by the test.

The deepest borehole attained in the experimental program, 30 m, was produced with a bit of 84 mm (3.3 in.) diameter. This hole was made in a thick layer of Jemez basalt near Los Alamos, NM. The demonstration depth was selected primarily because of cost and not because of technical restraint considerations.

III. Deep Well System Studies

A. The GEOWELL Computer Model

Based on experimental and theoretical results obtained in the Subterrene program, a Subterrene system for producing deep geothermal wells was conceptualized and assembled into a computer model called GEOWELL. The technical and operational characteristics of the system were then evaluated, and well production costs were predicted and compared with those of rotary drilled wells, Altseimer (1976). Difficult well-production conditions were assumed in addition to well depths ranging from 5 to 10 km. A combination of rotary and Subterrene operations was considered necessary, in which the initial intervals were always rotary drilled. For any specific case being studied, the rotary-to-total depth ratio was selected to optimize the overall well cost. The rotary bit life and its rate of penetration (ROP) were modeled on the basis of empirical drilling data for many wells, compiled from the open literature. The rock-melting bit life was assumed to be 300 h, and its ROP ranged from a state-of-the-art value of 0.2 mm/s (2.4 ft/h) to a program target of 1.0 mm/s (11.8 ft/h) into rock at 283 K. The melting ROP was continuously corrected for temperature increases beyond the 283 K nominal temperature. The most important system-study results are summarized below.

B. Surface Equipment

Rotary drills were found to be the correct choice for the upper intervals primarily because of their favorable bit life and ROP in the typically easy-to-drill upper sedimentary formations. Thus, the surface equipment should include a complete rotary system, which could remain on the rig for the job duration and be available for later use if needed. In general, it was concluded that conventional drilling technology and equipment should be readily transferable to a new Subterrene system. In fact, the trend toward an increasing use of all-electric rigs should make it even easier to meet equipment requirements to provide melting power.

C. Subterrene Drill Pipe

Design studies produced a Subterrene drill pipe design capable of carrying both electric current and the downflow of drilling fluid. The pipe is shown in Fig. 2 and consists of two concentric 7075 aluminum tubes separated by a 2-mm-thick layer of material that bonds the tubes structurally together and acts as an electric insulator. A conventional tool joint on the outer tube serves as the structural connection with

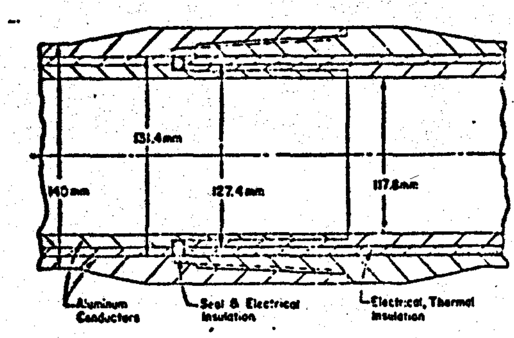

Fig. 2.
Subterrene aluminum drill pipe concept. Pipe is sized to meet stress and power transmission criteria in a 10 000-m total-depth well.

adjacent pipe. The inner tube has a tight sliding fit at the joint for electric contact. Handling and operational characteristics of this pipe are similar to those of conventional drill pipe but the initial cost is about three times higher. In the GEOWELL analysis, the outside diameter was maintained at 140 mm, whereas the other dimensions were varied to meet power transmission and load criteria. Figure 2 shows typical drill-pipe dimensions for Subterrene use in a 10 000-m deep well.

D. Melting Power Requirements

The downhole power required by the melting bits studied ranged from 120 to 750 kW. An ac system was chosen as the most feasible for two main reasons. First, it would not establish and support corrosion cells like dc would. Second, handling a wide operating voltage range with dc is not as easy as with ac. Some ac disadvantages such as hysteresis, dielectric losses, and changing power factors do exist but are taken care of with relative ease.

E. Continuous Power Cables

An alternative to the coaxial aluminum pipe previously described would be a melting bit affixed to the end of standard drill pipe and supplied with electric power by means of a drop-in cable. The cable, made up of a number of standard length sections and fitted with suitable connectors, would cut tripping time because, the connectors once assembled, would not have to be disassembled but could simply be rolled up on the cable drum when the cable is withdrawn. The time wasted disassembling, cleaning, and reassembling connectors could thus be eliminated. Cable used for downhole melting would, admittedly, not be standard. A conceptual diagram of such a cable is shown in Fig. 3. The members of the conductor/load-carrying cable and the brazed-on end fittings are made of beryllium-copper alloy with a yield strength of 1100 MPa (160 000 psi); the captive compression nuts are nickel-steel; cable insulation consists of silicone rubber, and the connector insulation is mica-filled epoxy.

Figure 4 illustrates how such a cable might be used. The drill-pipe system would consist of a short length of coaxial aluminum pipe as previously described and of a long conventional steel pipe. The cable would be installed inside the steel pipe and lowered in one piece to the bottom of the steel pipe where an electric connection to the bit would be made under remote control. At the surface the cable top would be connected to a sub that structurally connects the aluminum and steel pipes and electrically connects the cable to the aluminum pipe. Aluminum pipe would be added as the bit progresses until the bit has to be tripped. To trip, one would withdraw the aluminum pipe, cable, and steel pipe, in that order.

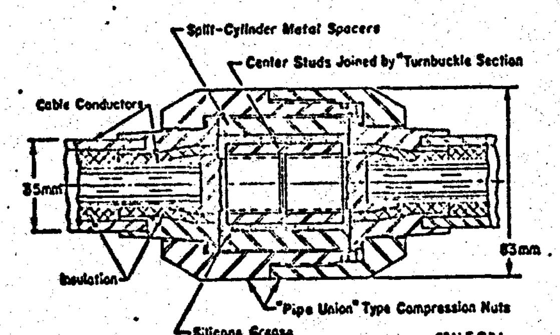

Fig. 3.
Conceptual cable design.

F. Melting Bit Performance

Technical data are available 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

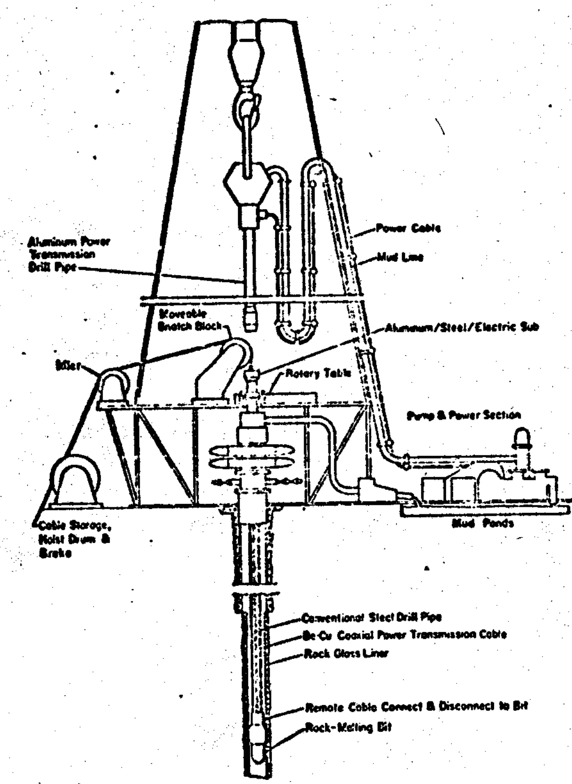

Fig. 4.
Conceptual melting-power cable handling system.

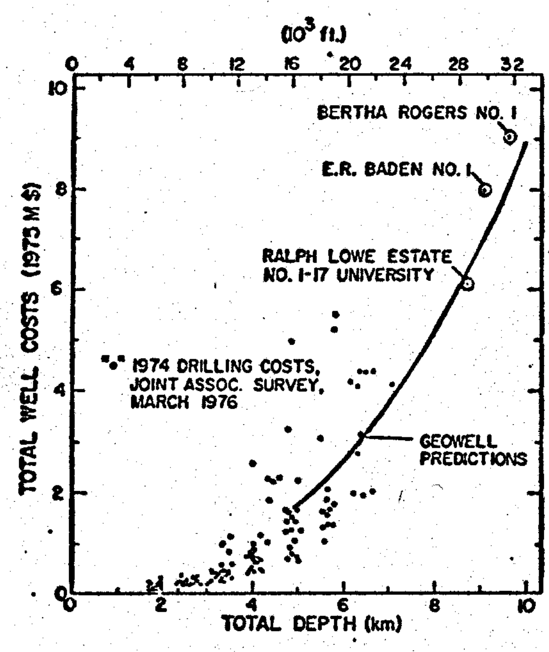

Fig. 5.
Well costs, typical oil and gas wells and GEOWELL normal gradient predictions.

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, primarily in igneous materials. A top priority effort of the Subterrene program was therefore directed toward increasing the rate to 1 mm/s (11.8 ft/h) in igneous rock. To accomplish this goal, better methods of delivering energy to the rock at the bit leading edge. Small-scale tests of this technique have been encouraging, but a considerable R&D effort will be required before such a concept is ready for practical application.

Away from the leading edge of a melting bit a conical melting body can significantly enhance the melting process. A test demonstrated this mechanism very convincingly. A basalt test specimen was predrilled to remove the rock that would normally be melted by the leading edge of a conical penetrator. With the penetrator body temperature below the operating maximum, sustained rates of just under 1 mm/s were attained--a four- to five-fold increase over that expected if the leading edge heat flux were controlling the rate.

G. Cost Study Results

The GEOWELL program predicts total production costs per well and produces the corresponding cost breakdowns for major parts of the production project. A comparison, Fig. 5, of the all-rotary-drilled well cost predictions with actual oil or gas well costs shows that the program results are credible. All costs are in 1975 dollars and drilling conditions are for the normal geothermal gradient of 25 K/km. If anything, GEOWELL underestimates the cost somewhat because the tripping rate in the model is quite optimistic. Also, the ROP and possibly the allowances for unscheduled downtime are slightly optimistic. However, these characteristics were left in the program because it was assumed that rotary drilling techniques would improve, and because, for comparisons with future production techniques like Subterrene, the rotary system should be defined optimistically.

Table 1 shows typical cost breakdowns for 8500-m-deep wells. For the all-rotary-drilled case, 26% of total costs for drilling contractor may be optimistic, as is discussed above. The 7% for bits

TABLE 1

MAJOR COST ITEMS FOR 8500 M DEEP WELLS IN NORMAL GEOTHERMAL GRADIENTS

Cost Items	Rotary-Drilled Cost (M$)	Rotary-Drilled Fraction of Total	Rotary/Subterrene Cost (M$)	Rotary/Subterrene Fraction of Total
Total Drilling Contractor	1.56	0.26	0.86	0.18
Mud	0.56	0.09	0.44	0.09
Casing	1.56	0.26	1.33	0.28
Cementing	0.33	0.06	0.32	0.07
Bits, Rotary	0.41	0.07	0.07	0.02
Bits, Subterrene	--	--	0.09	0.02
Melting Fuel	--	--	0.04	0.01
Melting Power Gen. Equipment	--	--	0.01	--
"Other," common to all systems	1.53	0.26	1.53	0.33
TOTAL WELL COST	5.95		4.69	

may be high, but costly carbide bits are used extensively. Because we are emphasizing borehole stabilization in this paper, the items that should be especially noted are the costs for mud, casing, and cement: together they account for 41% of the total. For the Subterrene case these three items add up to 44%; but, in absolute values, their cost is 2.45 M$ for the rotary-drilled well compared to 2.08 M$, or $370,000 less, for the Subterrene-produced well. Note that the melting-bit cost is not large and that the cost of fuel and electric generating equipment needed to provide the melting power is not significant--less than 1%.

Estimated effects of high geothermal gradients on costs are summarized in Fig. 6. The curves labeled cool are for wells in gradients of 25 K/km whereas the two hot wells are at gradients of 60 and 40 K/km for 6.50 and 9.75-km-deep wells, respectively, both with the same bottom-hole temperature of 673 K (751°F). For the cool wells, the melting ROP should be ~ 0.4 to 0.6 mm/s (~ 4.7 to 7.1 ft/h) to begin to show significant savings, i.e., savings of ≥ 10%. For the hot wells, the required ROP is ~ 0.2 to 0.4 mm/s (~ 2.4 to 4.7 ft/h). Thus, the nominal state-of-the-art ROP of 0.2 mm/s might only be economically worthwhile for very deep and hot wells. However, if the target ROP of 1.0 mm/s were achieved, the benefits would be substantial: savings could range up to ~ 30% or 3.9 M$ for the hot 9.75 km deep well.

IV. Rock Glass Borehole Liners

A. Experience in Forming Liners

Rock-glass liners have been formed in a variety of rocks including igneous materials like biotite coarse-grained granite, granitic gneiss of high quartz content, Dresser and local olivine basalts, Bandelier tuff, latite, orthoclase, and rhyoline. Sedimentary materials include Green River and a local red shale; a siliceous limestone; soft or moderately hard limy sandstones from Tuzigood National Monument, AZ; alluviums from the Santa Fe formation and the Nevada Test Site; a compacted alluvium-containing basaltic gravel from Hanford, WA; and a special frozen water-saturated alluvium that simulated arctic permafrost. Dense and thick, composite, and dimensionally accurate liners have been produced depending on the particular test conditions. For example, Fig. 7 shows a dense liner of ~ 15-mm thickness made in tuff; Fig. 8

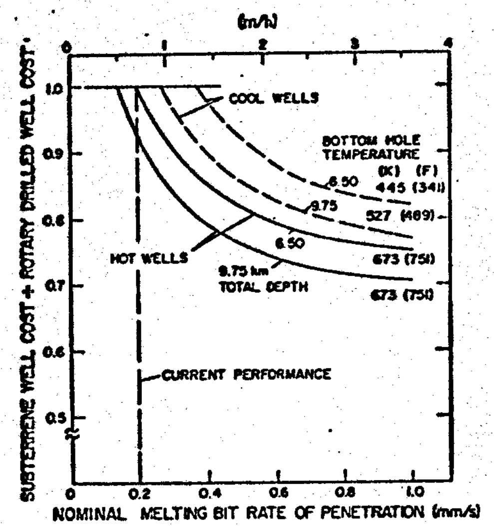

Fig. 6.
Subterrene well to rotary well cost ratio vs nominal melting bit rate of penetration.

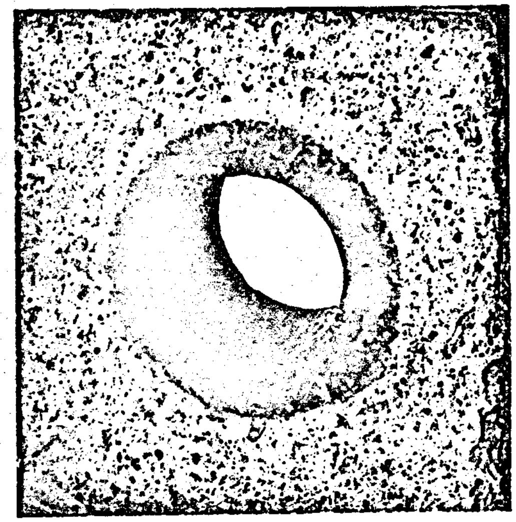

Fig. 7.
Hole melted in tuff with heavy glass liner, 50 mm (2 in.) diam.

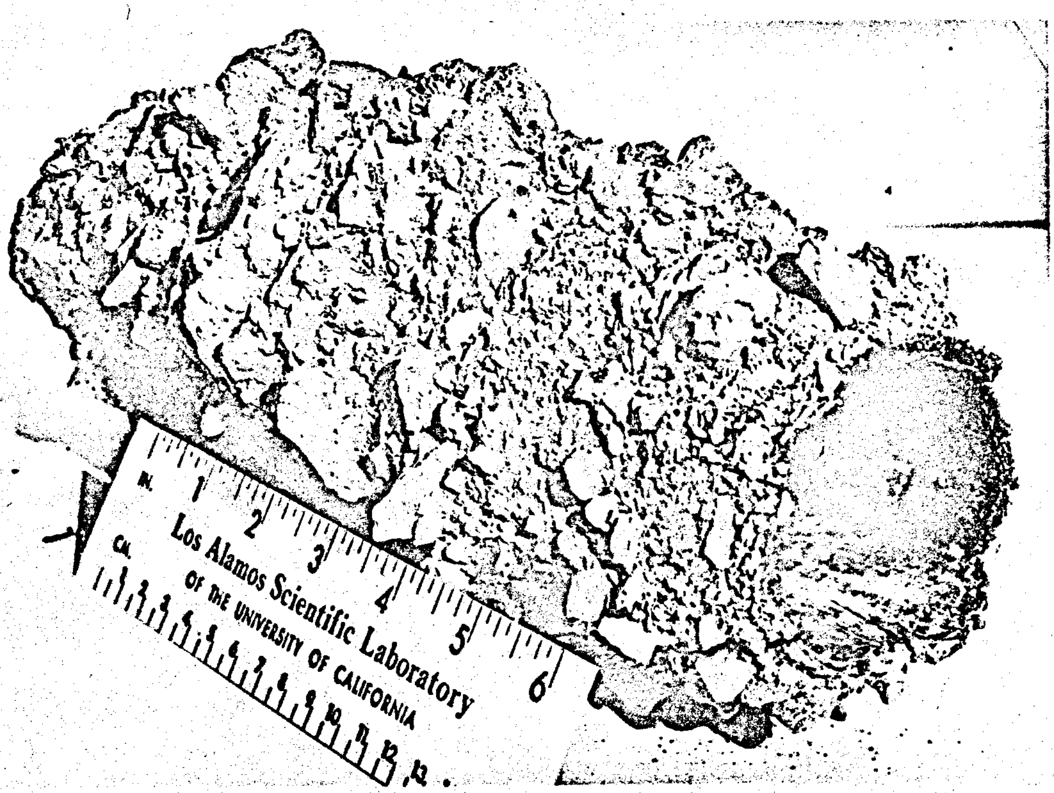

Fig. 8.
Hole formed by Subterrene in Green River shale rubble.

shows a composite liner made up of unmelted Green River shale rubble cemented together by its rock glass; Fig. 9 illustrates dimensional precision. The hole in Fig. 9 is one of two 13-m long holes in Bandelier tuff, one vertical, and the other horizontal. The holes were both straight to within several millimeters and the wall was smooth and cylindrical as can be seen. (This photograph was the result of a sequence of exposures made as a light source was moved along the base.) Similarly favorable results with liners were consistently obtained in the other Subterrene tests.

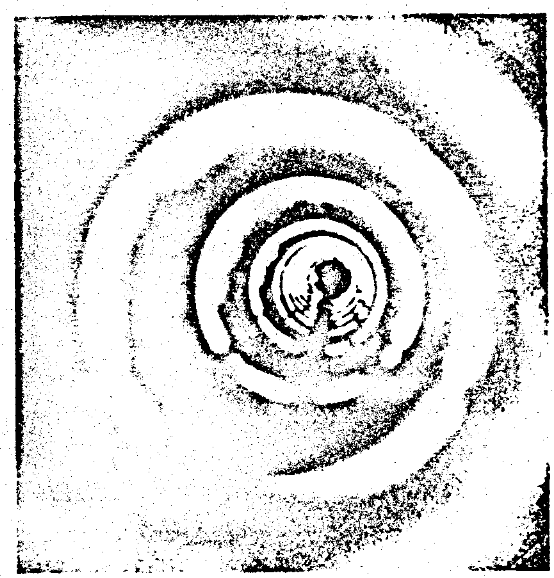

Fig. 9.
Glass-lined bore in tuff demonstrating straightness over 13 m length. Diameter is 50 mm (2 in.)

The early Subterrene penetrators tested in low-density rock and soil used graphite glass-former sections. Graphite was selected because it minimized the tendency for the cooling glass to stick or adhere to its surface during the solidification process. Initial experiments with penetrators in dense rock employed a segmented graphite glass-forming section based on the earlier penetrator experience. While capable of producing dense glass linings in hard rock, the relatively soft graphite used in the early systems was easily scored by irregularities in the liner during extraction, leading to frequent replacement of the forming sections. This problem was addressed by designing more rugged, abrasion-resistant assemblies that employed refractory metal segments in place of the all-graphite segments. An initial design used a molybdenum forming ring followed by a graphite release ring to minimize rock glass sticking during the critical cooling-temperature range. In the cold condition, the diameter of the graphite ring is smaller than that of the molybdenum so that the abrasion from the hole wall is borne by the metal parts.

B. LASL Liner Characterization Tests

Characterization tests of glass liners, Lundberg (1975), were conducted at LASL to establish their permeability and strength. The liners were found to be much more permeable than dense granite but much tighter than the parent rocks. For example, at low pressures and with nitrogen gas, a Bandelier tuff-glass specimen had a permeability of 8 millidarcy--three orders of magnitude less than the parent rock. The permeability of local olivine basalt varied, depending on the selected sample, from 0.5 to 10 millidarcy, and the corresponding rock-glass permeabilities were too low to be detected.

Crush-strength test results were encouraging. A parent basalt rock had a crush strength of 44 MPa (6 400 psi), whereas its rock glass measured 108 MPa (15 700 psi). Parent Bandelier tuff was measured at 2.8 MPa (400 psi) and a specimen of tuff glass taken from a 51-mm-diam hole wall had a tangential crush strength of 36 MPa (5200 psi). Another tuff-glass specimen taken from a 114-mm-diam hole wall had a tangential strength of 132 MPa (19 000 psi). Thus, the tuff-glass tangential strengths were 13 to 47 times greater than those of the parent material.

C. Terra Tek Liner Characterization Tests

Terra Tek, Inc., of Salt Lake City, UT, performed more comprehensive tests of glass-liner properties, Nielsen et al (1975). The test series were made on Bandelier tuff parent rock and on glass samples taken from LASL penetration test specimens. They found that liner permeability decreases rapidly with confining pressure. For example, a permeability of 8 millidarcy at 1 MPa confining pressure, using air as the test fluid, decreased to 200 microdarcy at 50 MPa. Small porous flaws were apparently forced to close at the higher confining pressures. Also, the radial compressive strength decreased with radial distance from the hole center line. Axial and transverse strengths are approximately equal. Glass-liner and parent-material composite cylinders were tested for collapse strengths with the following results: the rock-glass cylinders failed at a calculated inner-surface stress of 129 MPa (18 700 psi); they were 2.6 to 18 times more resistant to collapse than dry and wet parent-tuff cylinders, respectively. A composite specimen, made up of an inner cylinder of tuff glass surrounded and bonded to parent tuff, was tested without failure to the pressure limits of the test setup: ~ 1.5 times the failure pressures for the all-glass cylinders. In all cases, tensile strengths were low, only ~ 1 MPa (140 psi). The Terra Tek researchers concluded that glass-lined holes are obviously structurally much sounder than unlined holes and present new possibilities for engineering applications.

D. Installation of Thick Liners in a Borehole

Aside from producing a complete borehole, probably the next most intriguing application of the rock-melting process is the creation of a glass liner to stabilize rotary-drilled boreholes. We have shown earlier that, for rotary-drilled wells of the type modeled, the costs for mud, casing, and cement are high, i.e., 41% of the total well cost. All three of these cost items could be reduced significantly by using rock-glass liners that are formed either continuously or at frequent intervals as the well is being produced. Ideally, the well would be made with a conventional conductor and a short surface casing, followed by a constant-diameter glass-lined borehole to total depth. Hole stabilization would then be completed by running-in a steel casing of constant diameter to any depth considered necessary. The combination of steel casing plus cement plus heavy rock-glass liner would form a solid composite structure.

To achieve the type of system I am suggesting, a variety of approaches are possible that are limited only by the ingenuity of the designer. One concept offered here for purposes of discussion, is illustrated in Fig. 10. Assuming that rotary drills are being used, the rotary bit would be tripped out and the tool shown in Fig. 10 would be lowered to the maximum depth of the section requiring the thick liner. A packer would then be actuated to seal the annulus at the bottom end of the tool. The liner material would consist of pellets of predetermined size, which would be fed into the annulus and packed around the tool by a reverse mud-flow technique. Power would be turned on to melt the pellets and the tool would be pulled up at a controlled rate to form the liner. In fissured or sloughed zones the tool could be slowed down to allow

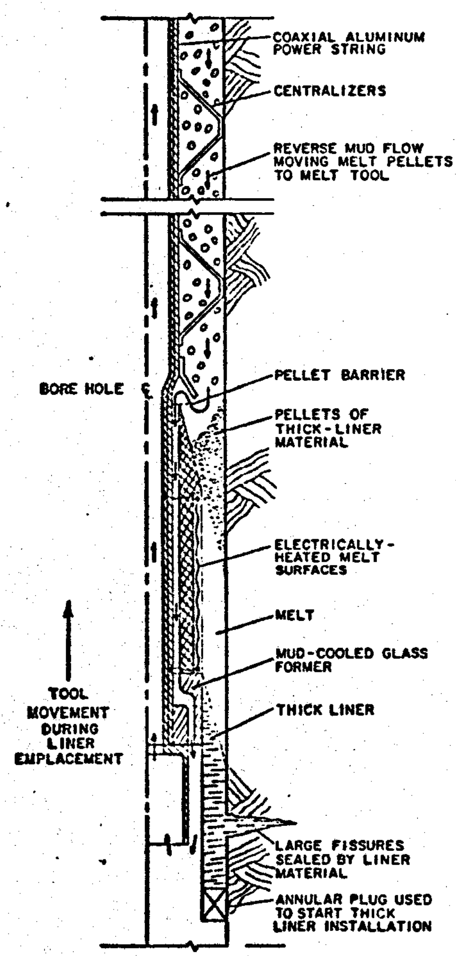

Fig. 10.
Concept of a thick-liner emplacement tool.

the melt to flow out to seal the hole properly. Mud would circulate at a low rate to cool the glass-former section and to slightly fluidize the unmelted pellets to facilitate their movement to the melt zone. Peripheral wall thicknesses would be equalized by centering devices.

This concept offers the following advantages: (1) liner materials and properties are controllable, (2) the use of liner materials with moderate melting temperatures will enhance the life of the melting surfaces, (3) large local cracks can be sealed because the quantity of liner material fed to the melter is controllable, and (4) although melting energy is required, the additional costs of this energy would not be significant. Among the disadvantages we list the following: (1) additional time is needed, comparable to that required to place and cement steel casing, and (2) the hole size is reduced by the liner thickness, and bit size would have to be stepped in a manner similar to that used in steel-cased wells.

The second disadvantage listed above might be eliminated by using a dual rotary-bit arrangement in the downhole assembly. The bottom bit could be conventional and of the size planned for the final borehole; whereas the second bit would be of a hole-opener type that could be remotely expanded downhole. Thus, when the assembly is tripped below the thickly glass-lined interval, the hole-opener would be expanded and rotary drilling would recommence until deemed desirable to install another section of glass lining. The hole opener would then be contracted, the assembly tripped out, and the glass-liner tool lowered to install more glass lining. The above concepts would permit the production of a glass-lined borehole with a constant diameter throughout its length. Based on Subterrene program experience, the melting tool suggested above could probably be developed within a reasonable length of time.

V. Conclusions

- The rock-melting concepts offer opportunities for basic improvements of excavation techniques.
- For deep wells, the rate of penetration of the melting bit must be increased about threefold over the laboratory rates, although even current bit performance could show cost savings, especially in hard-to-drill and hot wells.
- Rock-glass borehole liners can be many times stronger in compression than the parent material and can be relatively impermeable. Also, the melt can cement loose materials together in a structurally effective manner. However, the tensile strengths of the liners are very low.
- Practical devices for installing thick rock-glass liners in rotary-drilled boreholes may be possible. Potentially, the installation of rock-glass liners could improve hole stabilization, eliminate lost circulation, and minimize mud contamination of the formations being penetrated. In addition, cost savings for casing, cement, and muds could be achieved.
- Based on research results from the Subterrene Program, the application of rock-glass liners in boreholes could be a near-term extension of the melting concept.

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