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INFORMAL REPORT

A Versatile Rock-Melting System for the Formation of Small-Diameter Horizontal Glass-Lined Holes

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

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by

D. L. Sims

Work supported in part by a grant from the National Science Foundation, Research Applied to National Needs (RANN).

CONTENTS

APPENDIX

A VERSATILE ROCK-MELTING SYSTEM FOR THE FORMATION OF SMALL-DIAMETER HORIZONTAL GLASS-LINED HOLES

by

D. L. Sims

ABSTRACT

Rock-melting penetrators with diameters ranging from 50 mm (2 in.) to 76 mm (3 in.) have reached a stage of development at the Los Alamos Scientific Laboratory (LASL) which suggests that these devices are ready for practical application. Prototype refractory metal penetrators have formed glass-cased vertical holes of 26 m (82 ft) in a single run, and horizontal holes with diameters up to 127 mm (5 in.) are expected in the near future. These small horizontal holes can be used for underground utility conduits; for high-explosive shot emplacement; and as drainage holes to stabilize road cuts or embankments.

Design concepts and preliminary specifications are described for a Subterrene system that forms small-diameter horizontal holes in rock by melting and simultaneously lines the hole with glassy rock melt. Most components of the system are commercially available. Deviation sensors and alignment-control units can be added to ensure that the holes are straight. The design and operation of this Subterrene system are described and proposed development approaches for the hole-forming assembly are discussed.

I. INTRODUCTION

A. Program History

Rock-melting penetrators (Subterrenes) are under development at the Los Alamos Scientific Laboratory (LASL) to produce self-supporting glass-lined holes in rock and soil (Fig. 1) by progressive melting rather than by chipping, abrading, or spalling.[1] Rocks and soils melt at temperatures that are relatively high: common igneous rocks at ∿ 1500 K, almost at the melting temperature of steel (1500 to 1800 K). Thus, the melting penetrators must utilize refractory metals such as molybdenum (Mo) and tungsten (W), which melt at 2880 and 3650 K, respectively, and which, in addition, have low creep rates at the rock-melting temperatures.

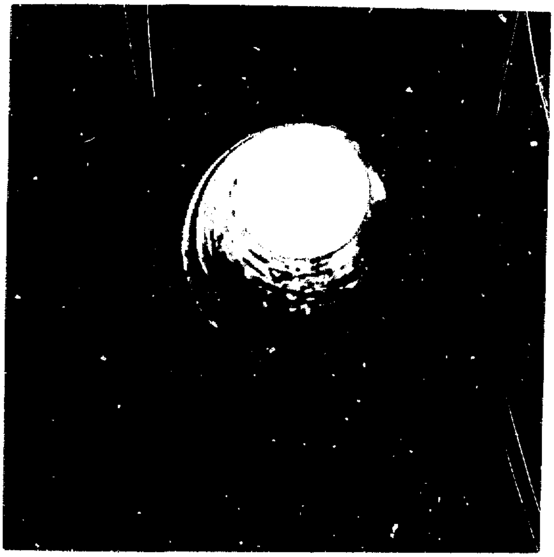

Fig. 1. Glass-lined hole melted in laboratory specimen of tuff.

Excavation by rock- and soil-melting offers potentially new and novel solutions to the three major areas of the excavation process:

- Making the hole or breaking up the rock.
- Providing structural support for the bore hole.
- Removing or displacing the debris or cuttings.

The liquid form of the rock- and soil-melt produced by a heated penetrator introduces new solution concepts into the latter two areas:

- The liquid melt can be formed into a glass lining to seal or support the walls of the bore hole, and
- Any excess liquid melt can be chilled and formed into glass rods, glass pellets, or rock wool (Figs. 2 and 3); or used to form a glass-cased core that can be removed by present wire-line methods.

The liquid melt produced by soil- and rock-melting techniques offers the potential of a complete systems approach to the processes of hole making, tunneling, and excavation. The LASL development program in rock- and soil-melting techniques has already demonstrated in laboratory and field tests an attractive advancement in practical excavation technology for the production of short, horizontal, small-diameter holes. This experience has been partially developed through the extensive testing of melting-consolidating penetrators[2] (MCPs). The tests consisted of:

- Melting 50-mm (2-in.)-diam, glass-lined drain holes in Indian ruins[3] at Bandelier National Monument (Fig. 4).
- Melting a 50-mm (2-in.)-diam glass-lined vertical hole in Los Alamos volcanic tuff to a depth of 26 m (82 ft) in a single run.[4]
- Melting a 50-mm (2-in.)-diam glass-lined horizontal hole in Los Alamos volcanic tuff to a length of 16 m (50 ft) (Figs. 5 and 6).
- Melting a sequence of 76-mm (3-in.)-diam glass-lined holes in volcanic tuff in the laboratory (Fig. 7).

Fig. 2. Hole melted in granite specimen with an extruding penetrator. Note debris.

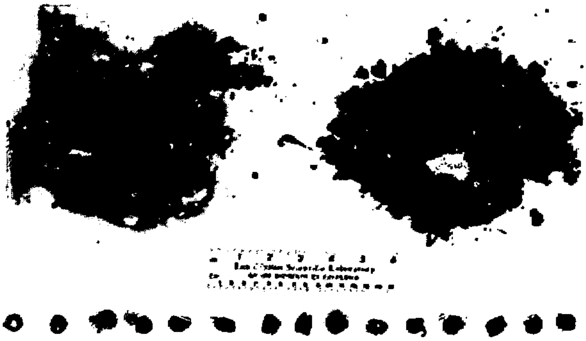

Fig. 3. Rock-wool and black glass debris from holes melted by extruding penetrator.

Fig. 4. Modular Subterrene field demonstration unit melting drain holes at Bandelier National Monument.

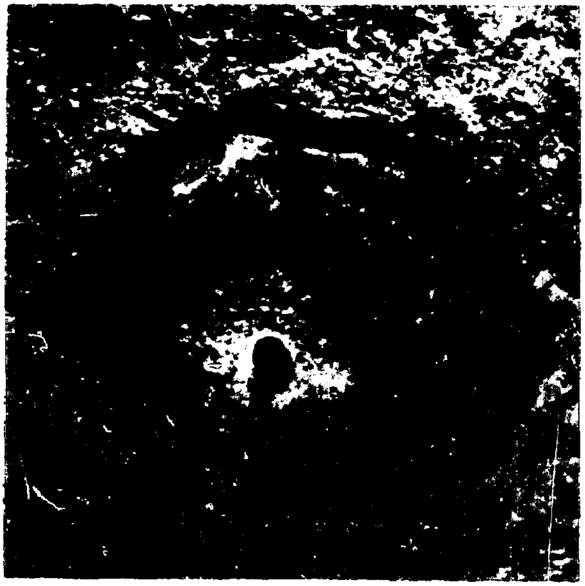

Fig. 5. Consolidating Subterrene Penetrator "holing through" a 16-m (50-ft)-long horizontal hole.

Fig. 6. Stem and service head in position to melt a 50-mm (2-in.)-diam horizontal hole.

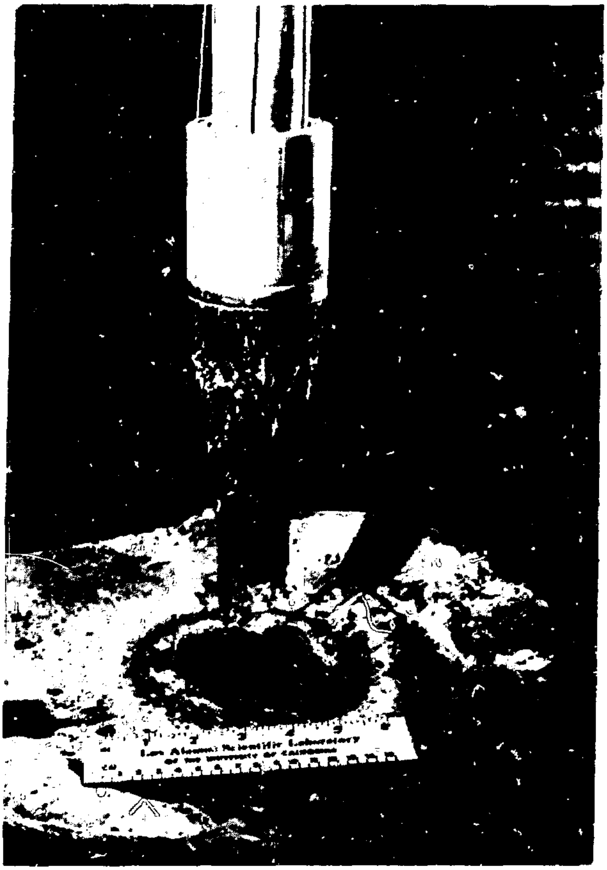

Fig. 7. Consolidating penetrator after melting a 76-mm (3-in.)-diam hole in Los Alamos tuff.

- Melting stable, 50-mm-diam glass-cased holes in shales, adobe, and alluvium (Fig. 8).

In addition, the prototype test program has developed a universal extruding penetrator (UEP) designed for hard, dense rock.[5] Tests with this unit have:

- Melted 66-mm (2.5-in.)-diam holes in basalt and granite (Fig. 2).
- Demonstrated the capability of tailoring debris for different applications to meet varying debris-return systems (Fig. 3).

A modularized, mobile field-test and demonstration unit[6] (Fig. 4) has been constructed, and was used successfully for melting glass-lined drainage holes in the floor of Indian ruins at Bandelier National Monument. This test rig will be used for additional field tests and for demonstrations of improved consolidating and extruding penetrators.

In addition, LASL is currently developing a 114-mm (4.5-in.)-diam, consolidating, coring penetrator that will produce a 63-mm (2.5-in.)-diam glass-encased core.

B. Small-Diameter Horizontal Subterrene System

The coring capability for the Subterrene, together with the commercial needs for horizontal holes for underground power lines[7,8] and a review of requests for information on the rock-melting Subterrene, has prompted the preparation of preliminary design concepts and specifications for a horizontal Subterrene capable of melting glass-lined, 76-mm (3-in.)-diam holes to lengths of ∿ 50 m (165 ft) with sufficient accuracy for most commercial applications. Horizontal glass-lined holes of this diameter and length could be useful as:

- Glass-lined drain holes for subsided mines.
- Glass-lined drain holes through diked areas to accelerate drainage after flooding.
- Injection holes for burning mines.
- Sealed, glass-lined inspection holes in mine faces or in dam abutments.
- Sealed, glass-lined inspection holes in suspected pollution areas.
- Underground utility conduits for telephone, gas, water, and television lines.
- Glass-lined holes for high-explosive shot emplacement.
- Drainage holes to stabilize road cuts and embankments.

System descriptions, preliminary design concepts, and detail component descriptions are presented in the following sections, along with indications of additional development programs required to provide subsystems that are not yet available for this versatile horizontal hole-melting device. Such a device will also

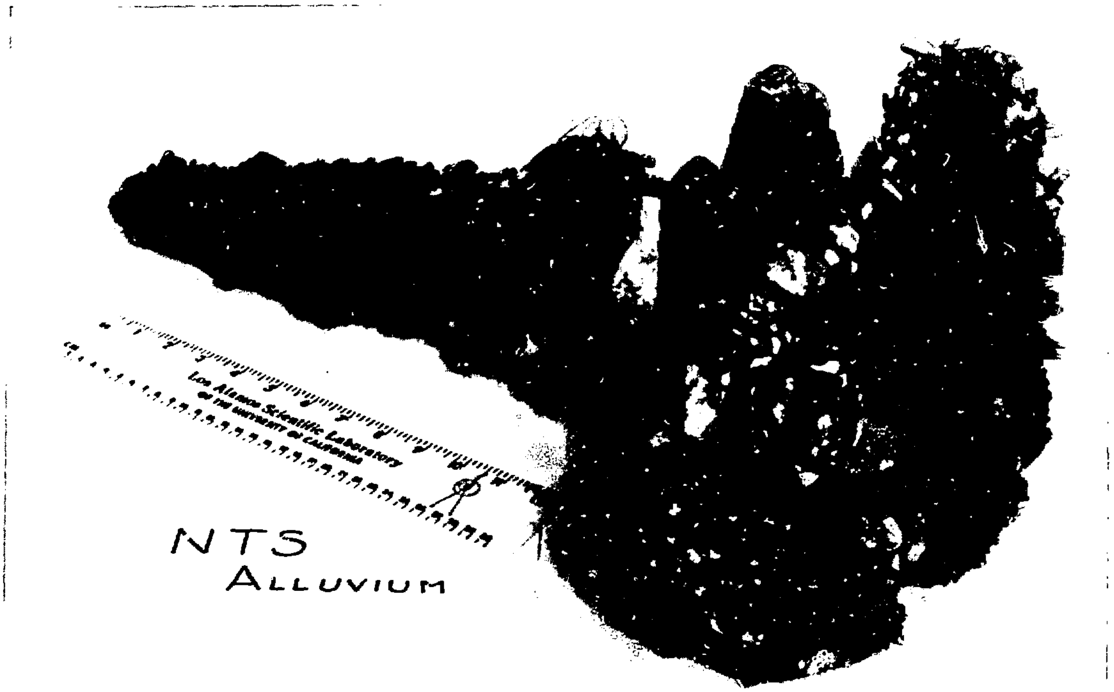

Fig. 8. External surface of glass-lined hole melted in dry alluvium.

provide necessary and valuable information for the development of the Geoprospector system.*

II. SYSTEM DESCRIPTION

The components of the proposed small-diameter horizontal Subterrene system, depicted in Fig. 9, are similar to those of the modularized rock-melting Subterrene demonstration unit shown in Fig. 4. These components include:

- A stem advancer, Fig. 10, that will continuously advance the stem by use of two independent hydraulic cylinders and remotely operated stem clamps.
- A dual-tube stem consisting of a flush outer steel tube, coupled in sections, and an insulated inner copper tube. These tubes provide the electric-power conductors to the heated penetrator, circulate coolant to the hole-forming assembly (HFA), and provide a force path to transfer the thrust to the advancing melting penetrator.
- Circulating, compressed-air coolant, to cool the stem, chill the glass-hole lining, and form small glass pellets (or rock wool) from the excess melt produced by a UEP. This excess melt debris is carried to the surface and ducted through the service head into a separating and collecting station. The return coolant from a consolidating penetrator is ducted directly into the ambient air.
- A quick-disconnect service head, Fig. 11, that connects the operational lines to the stem (i.e., electric power for the penetrator, coolant air for glass-forming and debris removal, and sensor and instrumentation leads).
- The HFA (hole-forming assembly), Figs. 12 and 13, which is selected to fit the job requirement, can be assembled interchangeably from the following subcomponents:

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*See Ref. 7, p. 19, for a brief description of this continuously coring tunnel prospecting device.

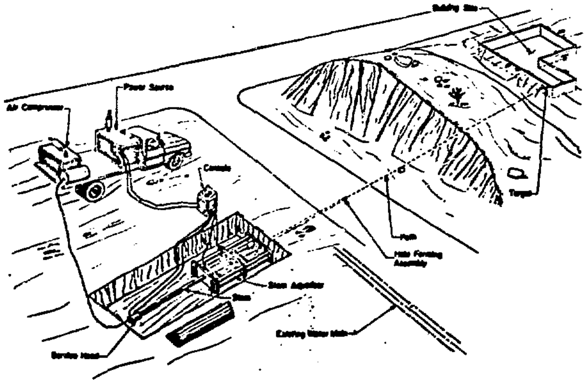

Fig. 9. Horizontal Subterrene melting a water service hole.

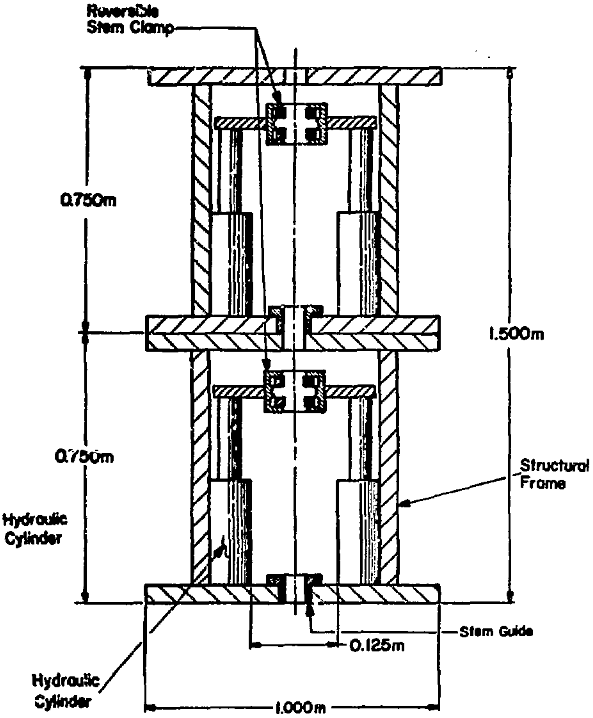

Fig. 10. Small-diameter horizontal Subterrene stem advancer.

- **A heated penetrator**, to melt rock or soil: A melting consolidating penetrator (MCP)[2], Fig. 14, is used in loose soils, alluvium, and low-density rock, and forms a glass lining; whereas a universal extruding penetrator (UEP)[5], Fig. 15, is used in dense or hard rock and produces rock debris.

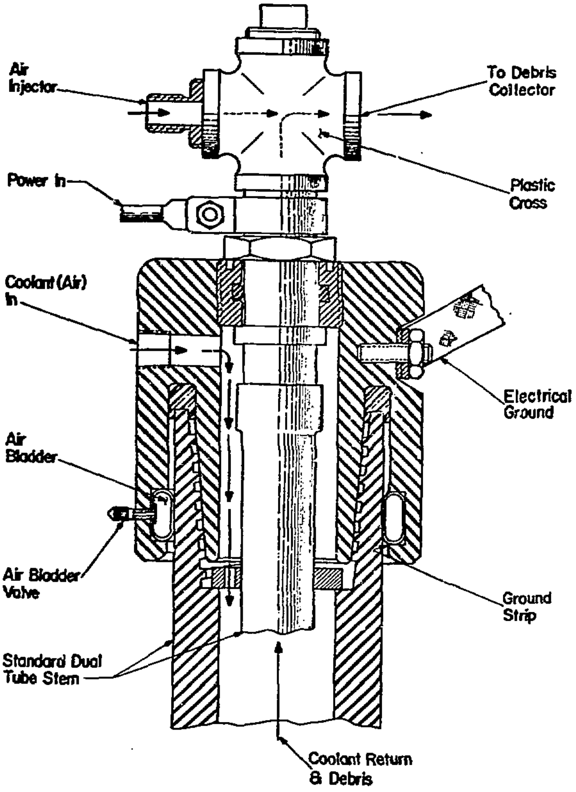

Fig. 11. Quick-disconnect service head.

- **A glass former**, attached directly to the penetrator, chills and forms the glass hole lining from the liquid melt. For the extruding penetrator, this unit also contains the components to chill the extrudate and to process the excess melt into removable debris.

- **A centralizer**, to hold the HFA on course.

- **An alignment control section (ACS)**, to return the HFA to course when deviation is detected. The controlling force is oriented and applied from the surface control console.

- **A deviation sensor (DS) or deviation indicator (DI)**, detects deviation of the HFA from the projected center line of the hole. Signals from the DS or DI are processed and displayed on the control console. The HFA can be made up in a variety of

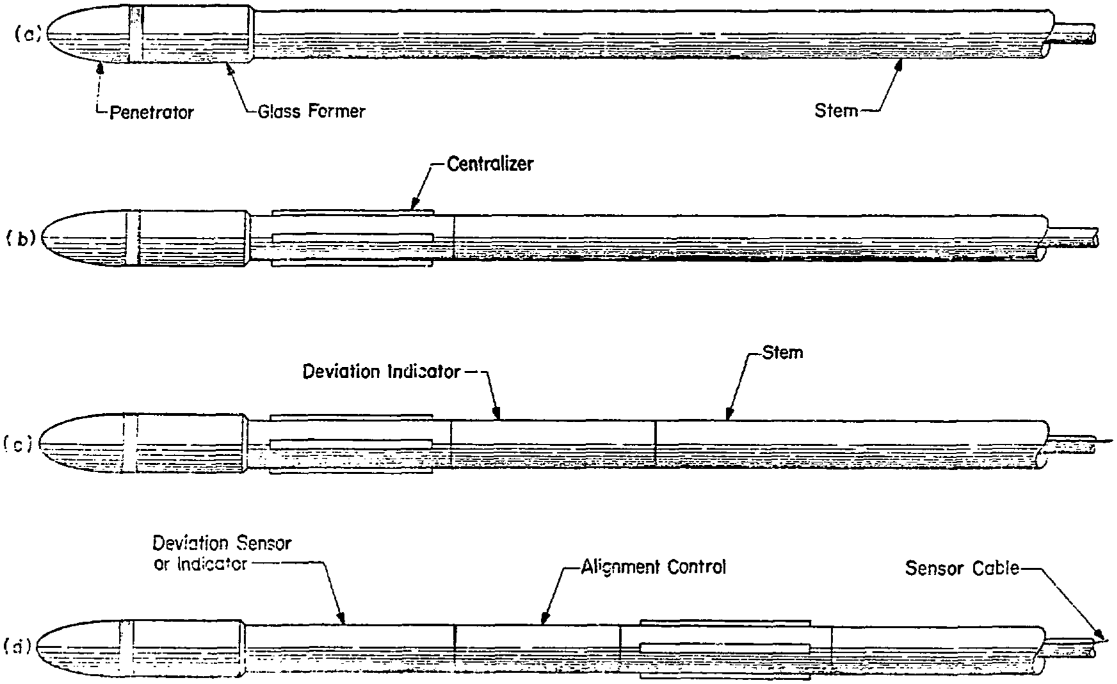

Fig. 12. Hole-forming assemblies: (a) simplest HFA-penetrator, glass former, and stem; (b) addition of centralizer; (c) additional deviation indicator; (d) complete assembly with alignment control.

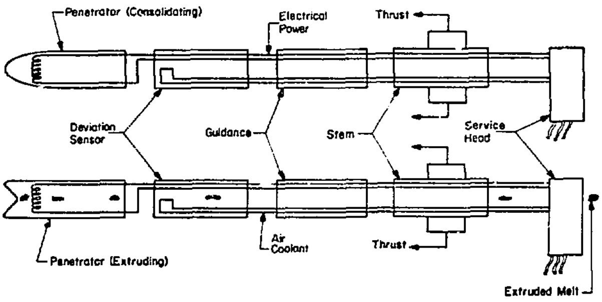

Fig. 13. System schematic for a horizontal consolidating and horizontal extruding Subterrene showing the required functions of the components.

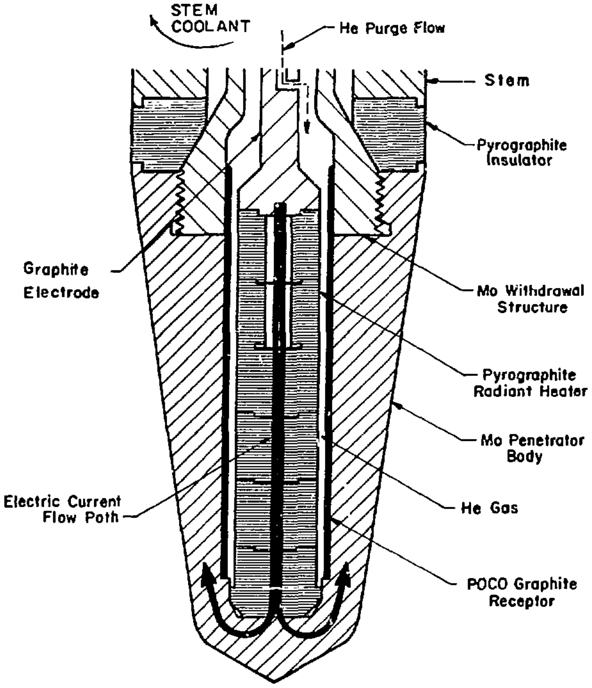

Fig. 14. Consolidating penetrator for loose soil and low-density rock.

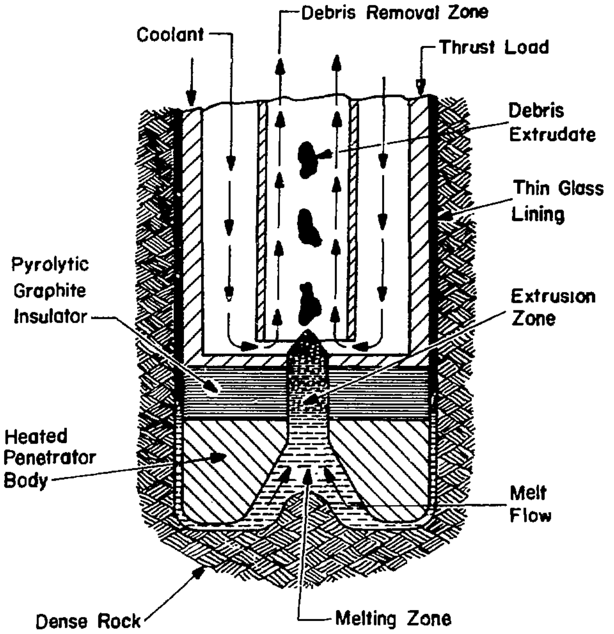

Fig. 15. Extruding penetrator for dense rock.

configurations, as indicated in Fig. 12, to achieve the needed straightness for a given job.

- A complement of service units are needed to furnish electric power to the penetrators, sensors, and instrumentation; coolant air to the stem and glass-former; and hydraulic power to the stem advancer and stem clamps (Fig. 16). The coolant-air supply also powers an air-oil intensifier for emergency stem advance and retraction.

- A single control and instrumentation console will be provided for the necessary electric power, hydraulic and air controls, and for displays. Sensor displays and alignment-correction indications will also be shown on the console so that one operator can supervise the melting of a straight hole.

Note that the proposed horizontal rock-melting excavation system which forms the glass-lined holes in place can be assembled from various subcomponents to produce holes of varying straightness. For example, the hole-forming assembly can:

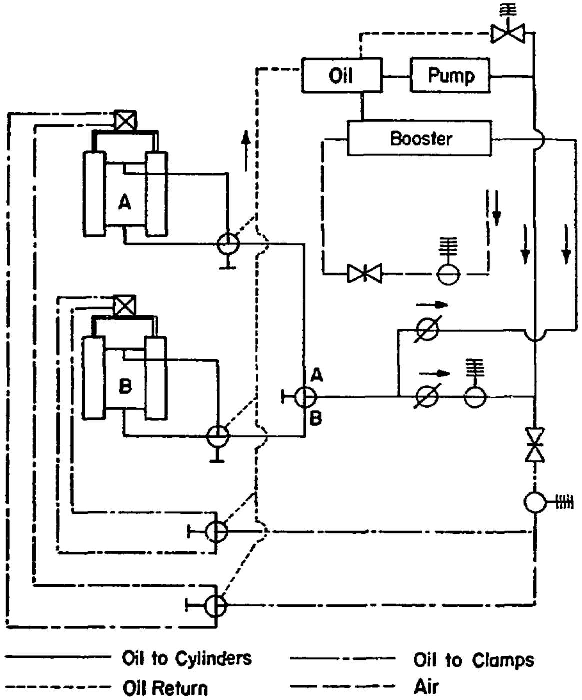

Fig. 16. Hydraulic and air-control circuits for operation of horizontal stem advancer.

- Melt an accessible, glass-lined hole under obstructions or structures such as roads, highways, railroads, and canals where hole straightness is not a major factor. This can be accomplished with a simple HFA consisting of only a penetrator, glass former, and stem, as indicated in Fig. 12(a).

- Melt a very straight, accessible, glass-lined hole from an established point to intersect a target point with a maximum terminal deviation of two hole diameters or less. This will require a HFA equipped with a deviation sensor, a surface-operated alignment-control unit, and a sensor signal that can be displayed on and monitored from the control console by the operator [Fig. 12(d)].

The proposed system concepts, components, and specifications are detailed in the following sections.

III. SUMMARY OF SYSTEM SPECIFICATIONS

The following list summarizes the preliminary specifications for a horizontal hole-melting Subterrene system:

- Inside diameter of the glass lined hole, 76 mm (3 in.).
- Hole-length capability, 50 m (164 ft).
- Rate of penetration,
  - For a melt-consolidating penetrator (MCP) in loose alluvial soil up to 0.84 mm/s (2 in./min).
  - For a universal extruding penetrator (UEP) up to 0.42 mm/s (1 in./min).
- The two penetrator types are interchangeable, are electrically powered, and use circulating air for cooling and debris removal.
- The glass formers and hole sizers are integral parts of the penetrators.
- The maximum hole deviation is less than two diameters, but the system can be assembled in a simple version for less accurate operation.
- Deviation of the HFA from the projected hole center line is detected by the deviation sensor, and the amount of deviation is displayed on the control console.
- Directional control of the HFA is provided by a differential cooling system whose operation is regulated at the control console for high accuracy. Lesser straightness will be controlled by simple stem rotation.
- The hydraulic stem advancer-retractor is capable of continuous motion and is provided with remotely operated stem clamps. Hole alignment can be set within the range of ± 0.25 rad (15 deg) from the horizontal.
- The advancing stem will be a dual tube to transmit power and coolant and for debris removal when required. The stem will be flush externally and of sectioned lengths for ease of handling.
- Melting power is estimated at 15 kW, and total available power should be ∿ 25 kW.
- A quick-disconnect service head is included.
- The single control console will incorporate controls for air supply, hydraulic and electrical power; HFA deviation and amount of applied directional control; and instrumentation displays.
- The service units to be included are:
  - Air compressor.
  - Alternating-current generator, engine-driven.
  - Alternating current-to-direct current converter.
  - Hydraulic pump, motor-driven.
  - Air-oil hydraulic booster.
  - Light truck for mobility.
- Service leads and hoses are supplied as required.

IV. DESCRIPTION OF LASL-DEVELOPED AND COMMERCIALLY AVAILABLE SUBCOMPONENTS

A. General

This section describes components of the system that are either already developed or can be designed and assembled in a straightforward manner from commercially available products. The demonstration rig for 50-mm (2-in.)-diam penetrators has had excellent results in initial runs. Much of this simple, inexpensive modular rig (Fig. 4), can be used as the design base for the 76-mm (3-in.)-diam horizontal Subterrene. Other components have been thoroughly tested both in the laboratory and in field-test rigs. The alignment accuracy of the demonstration rig is sufficient for many anticipated uses of horizontal, glass-lined holes. In fact, by intermittently rotating the stem and the HFA of 50-mm (2-in.)-diam Subterrenes while melting vertical (Fig. 17) and horizontal (Fig. 18) holes, bores were produced that were straight to considerably better than two hole diameters in 16 m of hole length.

B. Description of Components

Specifically, the proposed small-diameter horizontal Subterrene system would consist of the components detailed below.

1. Stem Advancer

The stem advancer (Fig. 10) will advance the stem continuously with two independent, twin hydraulic-cylinder units and remotely operated stem clamps.

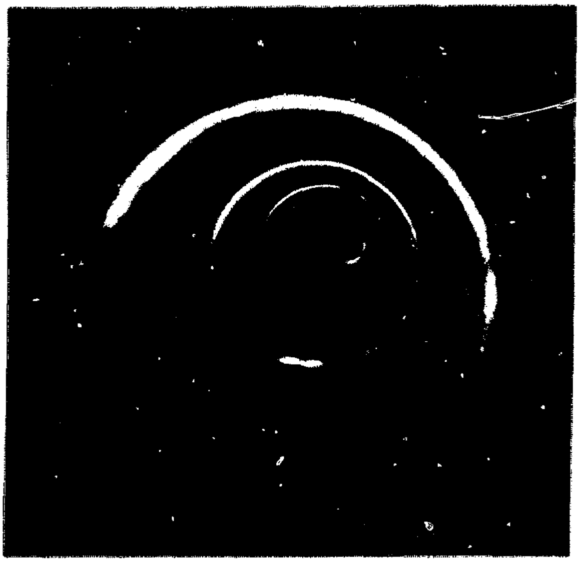

Fig. 17. Photograph showing degree of straightness in a glass-lined vertical hole.

Fig. 18. Photograph showing degree of straightness in a glass-lined horizontal hole.

- Normal operating pressure will be 6.9 MPa (1000 psi) for an advancing load per cylinder pair of 20000 N (4550 lb_f) and a retracting pull of 28000 N (6350 lb_f).

- Emergency operation will use four cylinders with a maximum of 13.8 MPa (2000 psi).

- The frame (head and base of each cylinder pair) will be adapted for fastening to anchor posts, and will be rigid at the above loads.

- Retraction time of a cylinder pair, with normal operating pressure using the hydraulic pump only, will be 20 ± 5 s.

2. Advancing Stem

- The dual-tube advancing stem (Figs. 11 and 12) will be similar to that used on the modularized, mobile rock-melting Subterrene demonstration unit.[6]

- The stem will be flush externally and slightly smaller in diameter than the HFA. The inner copper tube will have an inside diameter of ∿ 27.5 mm ($1\frac{1}{16}$ in.).

- The operating temperatures of the stem are estimated to be less than 600 K. Materials used in stem construction near the HFA will have an operating life of 3000 h at this temperature. Additional stem sections will be constructed of conventional materials (low-carbon steel) and will operate at lower temperatures (400 K).

- The stem will be assembled in lengths of 1.5 m (5 ft) and 3 m (10 ft).

3. Service Head

The service head (Fig. 11) will provide a quick disconnect (and connect) of the surface supply lines to the stem (electric power, coolant, instrumentation, and debris removal).

4. Hole-Forming Assembly (HFA)

The hole-forming assembly (Fig. 12) for the simplified small-diameter horizontal Subterrene system would be assembled from the following.

- A heated penetrator will be selected for the anticipated rock or soil to be encountered. Melting-consolidating penetrators 76 mm (3 in.) in diameter (Fig. 14) will be used for melting glass-lined holes in alluvium and low-density rock, and will be similar in design to the consolidating penetrators that have been developed. Universal extruding penetrators, which are interchangeable with melting-consolidating penetrators in the HFA, are used for melting in dense or hard rock. The design and construction of this type penetrator is also well advanced. Both penetrators will produce glass-lined holes of the same diameter.

- A glass former and hole sizer is attached directly to the penetrator. Because the melt is processed differently by the two types of penetrators, the glass former and hole sizer must be changed when the penetrator types are changed. The outside diameter varies with penetrator design, but is normally 0.15 mm (0.005 in.) larger than the penetrator diameter (at operating conditions).

- A centralizer -- essentially a section of advancing stem with longitudinal ribs built up to within 0.25 to 0.40 mm (0.010 to 0.015 in.) of the inside diameter of the finished glass lining -- is placed between the glass former-and-hole sizer and the forward end of the advancing stem.

5. Service Units

The service units required to operate the small-diameter horizontal Subterrene are:

- A skid-mounted air compressor rated at 200 ℓ/s (44 cfm) at 825 kPa (120 psi).

- A trailer-mounted, diesel-powered ac generator rated at 25 kW, with 60-cycle outputs of 17 kW at 220 V and 8 kW at 110 V.

- A solid-state ac-to-dc converter with 15 kW capacity, remotely controlled from the operator's console and powered by 60-cycle 220 V.

- The hydraulic supply is a constant-volume vane pump with a 3.8-kW (5 hp) 220-V 60-cycle motor. The output is 0.15 ℓ/s (2.4 gal/min) at 14 MPa (2000 psi) delivery pressure.

- The emergency hydraulic supply is furnished by an air-oil booster that provides 0.25 ℓ (16 in.^{3}) with a 300-mm (12-in.) stroke. The hydraulic pressure is 13.8 MPa (2000 psi) from the 55-kPa (80-psi) air supply.

- Power, coolant, and hydraulic leads are of conventional field-service weight to hook up the separate units.

6. Control Console

The electric, hydraulic, and air controls needed to operate the small-diameter Subterrene system will be grouped on the console (Fig. 16), so that a seated operator can control all operations. Instrument displays on the control console will include:

- The advancing or retracting load on the stem, reading in Pa and lbf/in.^{2}
- The hydraulic pressure available for advancing or retracting, reading in Pa and lbf/in.^{2}
- The hydraulic pressure on the stem clamps reading in Pa and lbf/in.^{2}
- The air pressure in use for cooling and debris removal, and the pressure available for the air-oil booster, reading in Pa and lbf/in.^{2}
- The advance rate of the stem, reading in mm/s and in./min.
- The accumulated advance, reading in m and ft.
- The amperage, voltage, and wattage of the heater circuit, and the heater resistance.

7. Mobilizing and Transport

The mobile small-diameter horizontal Subterrene system is transported on a one-ton truck.

The maximum length of a small-diameter glass-lined hole that can be successfully bored with this minimum system has not yet been determined. When increased hole length and accuracy are required, a deviation sensor (DS) and an alignment-control section (ACS) will have to be added to the HFA. Development of these units is discussed in the next section.

V. DEVELOPMENT PROGRAM

A. Versatility of Hole-Forming Assembly

The subsystems (see Section III) of the small-diameter horizontal Subterrene system are, with three exceptions, either already in use or are commercially available. The three exceptions are:

- A deviation indicator,
- A deviation sensor,
- An alignment-control section.

The deviation indicators and deviation sensor subsystems can be adapted from available instrumentation and electronics, but the alignment-control unit will require a development program and is unique to the proposed horizontal hole-forming system.

These additional subsystems allow a planned programming of hole-forming assemblies (HFAs) for jobs requiring varying levels of hole straightness and completion accuracy. Desired levels of performance can be achieved by assembling HFAs in the following configurations:

Assembly A. A heated consolidating or extruding penetrator (depending on geology and density of the formation) is used with an advancing stem [Fig. 12(a)] to melt, e.g., horizontal, shallow surface drain holes; equipment-placement holes; and utility conduits having moderate tolerances for installation misalignment. The course of the melted hole is controlled by periodic partial rotation of the advancing stem to equalize deviations caused by eccentricity of the assembly.

Assembly B. A heated penetrator, centralizer, and advancing stem [Fig. 12(b)] can be used to extend the length of holes melted with alignment requirements similar to those of Assembly A. The centralizer holds the heated penetrator on course, allowing higher stem loads, increased penetration rates, and longer controlled penetration. Periodic partial rotation is again used to equalize deviations due to assembly eccentricity. The centralizer assists in the control of penetrators over longer and more accurate runs such as utility conduits for high-voltage supply and gravity-sewer connectors.

Assembly C. This system consists of a heated penetrator, centralizer, deviation indicator[*], operator signals, and advancing stem [Fig. 12(c)]. In addition to providing the increased hole-alignment capability of Assembly B, the operator is alerted whenever the HFA deviates by a preset amount from the proposed hole center line. By indicating to the operator the quadrant of deviation (viewed down the hole) the operator may initiate a course correction by quadrant rotation of the advancing stem rather than by periodic partial stem rotation. Continued quadrant deviation would signal a mechanical cause, either a change in geologic formation (boulders) or stem deformations.

Assembly D. A heated penetrator, deviation sensor (or deviation indicator), alignment-control section, centralizer, operator signals, and advancing stem [Fig. 12(d)] are assembled. This unit can track the deviation of the HFA assembly from the projected center line of the hole in terms of azimuth and bearing, and display this information on the control console. The alignment-control section allows the operator to turn the HFA toward the projected hole center line. This assembly also allows the operator to follow and to control the HFA in a predetermined deviated path. Such positive control of the hole-forming assembly will increase the capacity of the small-diameter horizontal Subterrene system for

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[*] The deviation indicator is used for quadrant deviation signal and control.

following critical paths or intersecting small targets.

B. Development of Attitude-Control Sensors

Several approaches to the development of sensors, deviation indicators, and alignment-control systems are being investigated. The deviation indicator (DI) shown conceptually in Fig. 19 will flash a light on the control console to alert the operator that the hole-forming assembly has deviated a predetermined amount in a given quadrant (viewed from the stem-advancer end). The signal is generated when the cantilevered section of the inner tube is contacted by the outer housing after a predetermined deflection. This approach is similar to that of a simple torque-wrench indicator.

The development of a deviation sensor (DS) can choose among several possibilities:

- Laser optical systems are currently in use for aligning tunnel-boring machines; however, although the HFA will probably deviate more than one diameter in a guidance-control cycle and although the use of a laser is therefore questionable, these systems will be reviewed for possible adaptation of the HFA.

- Inertial guidance systems are widely used for navigation and attitude-control systems. These systems will also be reviewed.

- Gyrostabilizers are extensively used for navigation, attitude control, and bore-hole surveying.[9-11] They will be reviewed for possible application for inclusion in the HFA. A preliminary review indicates that hole size and length of time to melt a hole may restrict their use to attitude and directional control.

- Surface triangulation of a seismic source in the HFA may be a method to determine hole deviation. Results to date have not been promising, but a state-of-the-art review should reveal whether sufficient progress has been made to accurately track an HFA.

- Triaxial dc magnetometers are in use for attitude-sensing and navigation. In one current application[12,13] the device is following the path of a directional drilling tool and signals any deviations of a bore hole in conventional oil, gas, and water drilling, or in guiding the drilling of life-support holes to trapped miners. A review of this system will determine its adaptability for HFA use.

C. Examples of Deviation Sensors

Two possibilities discussed above are used to illustrate the sensor section of the HFA, the surface display, and the operator's use of the display to initiate corrective action (see Figs. 19, 20, and 21). An open-loop sensing and control system is considered adequate for the length of hole specified in Section III.

The relatively simple deviation indicator shown in Fig. 19 can alert the operator if the HFA is deviating in a given quadrant. A section of the inner tube is built as an independent cantilever beam by using a flexible bellows connection. Four contacts are placed around the inner tube with a small initial standoff clearance from the tube. Deflection of the outer housing, forced by hole deviation, will cause contact between the inner tube and one of the four contacts. Closing of the contact will light up a corresponding signal on the control console. Corrective action can then be initiated either by rotating the advancing stem to equalize mechanical alignment, or by using an alignment-control section in the HFA. Physical orientation of the advancing stem is maintained by aligning and clamping fiducial protractors that are attached to the stem section at the stem advancer.

A triaxial magnetometer sensor can detect rotation of its axes relative to an initial orientation. Figure 20 shows schematically the use of a triaxial magnetometer as the deviation sensor for a

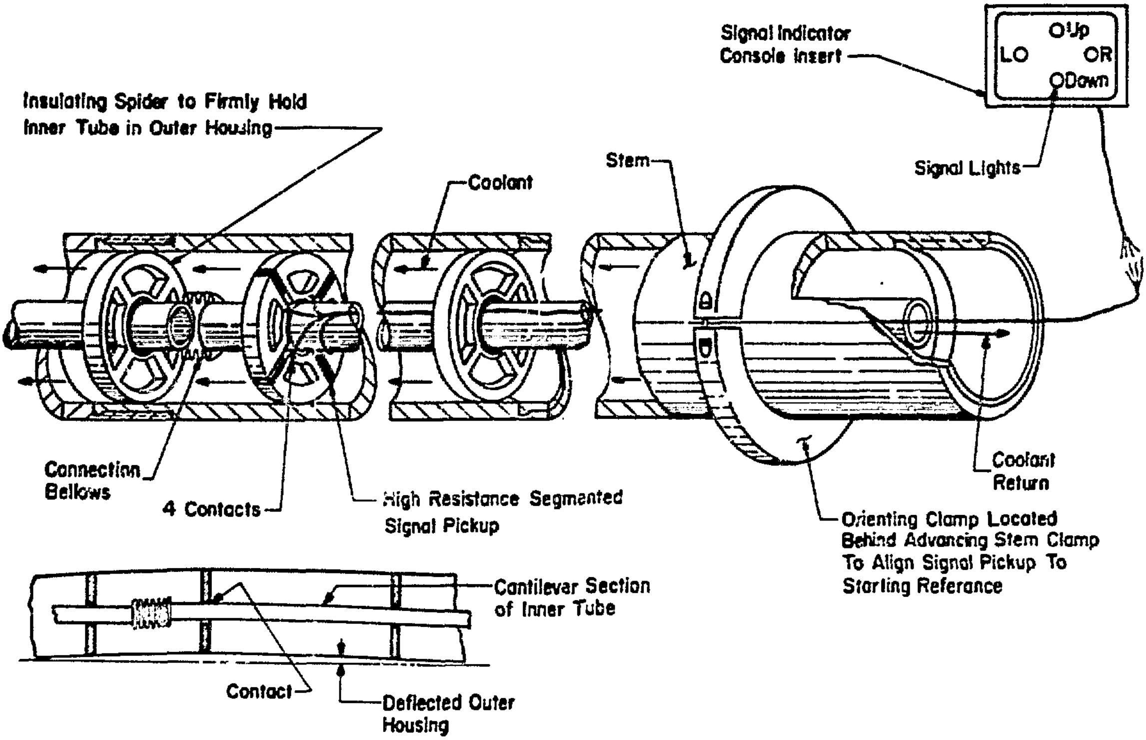


Fig. 19. HFA deviation indicator.

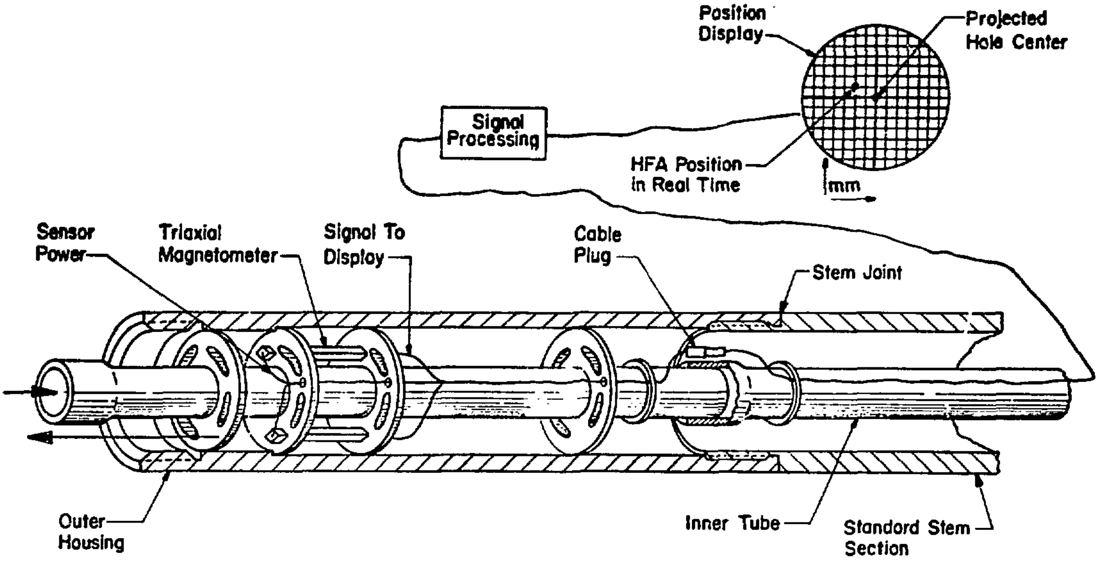
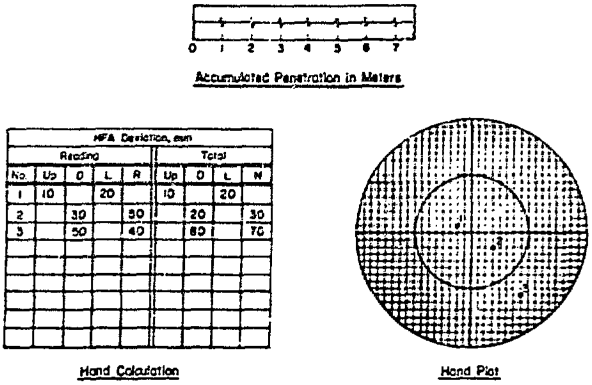


Fig. 20. Triaxial magnetometer deviation sensor.

small-diameter horizontal Subterrene. The power to the sensor and the return signals is carried in a multiple-channel cable to a signal processor. After processing, the change in position of the HFA is displayed on an oscilloscope screen in the control console. A computer can be used to plot continuously the excursions of the HFA from the hole center. However, penetration rates are sufficiently slow to determine HFA excursions by hand-calculation (Fig. 21), eliminating computers and plotters.

D. Alignment Control Section (ACS)

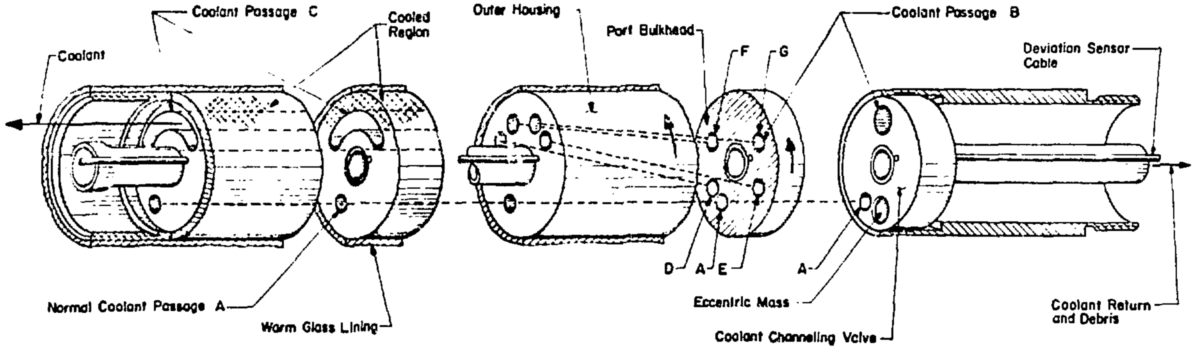
One method of applying a realigning turning force to a heated penetrator while melting a hole is to selectively cool one side of the outer housing of a section of the hole-forming assembly (HFA). This can be accomplished by diverting the inlet-coolant flow as shown in Fig. 22. A gravity-activated coolant-channeling valve, rotationally aligned with the stem, makes it possible to select the azimuthal location of the cooled side on the advancing housing and thus to apply directive force to the HFA from the control console. Construction and operation of such a device are outlined in Fig. 22. The gravity-activated coolant-channeling valve is an eccentrically weighted disk that is free to rotate on frictionless ball bearings within the outer tube of the alignment-control section. Thus, if the stem is rotated at the stem advancer end, the coolant-channeling valve retains its relevant position with respect to the melted hole. In addition to a passage for the inner coolant- (and debris-) return tube, the coolant-channeling valve has two ports: one, labeled A in Fig. 22, is for total coolant bypass when no corrective force is required. The second passage, B, is used to selectively channel the coolant flow into Coolant Passage C to provide an azimuthally chilled portion of the outer tube. This cooler region will tend to cause a deflection of the tube,which, in turn, will generate a moment to act on the penetrator (see Appendix).



HFA Deviation, mm								
Reading					Total			
No.	Up	D	L	R	Up	D	L	N
1	10		20		10		20	
2		30		30		20		30
3		50		40		80		70

Fig. 21. HFA deviation plot board.

Immediately downstream of the coolant-channeling valve is a bulkhead with five ports. Port A is for normal flow bypass and is spaced between Ports E and D, two of the



. Fig. 22. Alignment control section.

four ports (D, E, F, and G) spaced 90 deg apart for selective flow control. These four ports are led through the outer housing so that all four connect with Coolant Passage C. Coolant Passage C extends along one side of the outer housing for a distance sufficient to produce the required turning force when coolant is ducted through.

For normal flow bypass, the stem is rotated until Port A in the coolant-channeling valve is in line with Port A in the bulkhead with Coolant Passage C facing up. This position is marked at the stem-advancer end with a fiducial protractor clamp placed on the advancing stem. When deviation of the heated penetrator from the center line of the hole is detected and shown on the surface display (Fig. 20), the operator can make the necessary correction. For example, if the display shows left deviation, the operator rotates the stem 90 deg to the right, so that the coolant passage, C, is moved to the right-hand side of the hole and Port B is aligned with Port G in the bulkhead; Port A is blanked off. Differential cooling of the outer housing will turn the HFA back toward the hole center line, at which time the coolant is returned to normal bypass flow by returning the stem-position indicator at the advancer to the Passage-C up position.

Other systems of alignment control can be visualized, such as having three or four equally spaced coolant passages and adjusting the coolant flow in the HFA with remotely controlled valves. The smallness of a 76-mm-diam hole and the restricted volume available for HFA control suggested the concept of a gravity-activated coolant-channeling valve for alignment control.

VI. OPERATIONS

The components listed and described in Sections III and IV will be selected or designed to be modular and interchangeable.

The HFA can be assembled in any of the following configurations:

- Consolidating penetrator with stem centralizers.
- Consolidating penetrator with deviation indicator and stem centralizers.
- Consolidating penetrator with deviation indicator, stem centralizers, and alignment-control section (ACS).
- Extruding penetrator with any of the above options.

The correct HFA will be selected to fit the individual job requirements, including the desired accuracy in the location of the melted hole. When maximum accuracy is desired, the center line of the hole can be established by conventional methods, e.g., by usual land-surveying as indicated in Fig. 23.

The stem advancer and support equipment are then moved to the starting point of the hole. The HFA (and a section of stem) are clamped in the stem-gripping clamps. A transit and stadia rods are used to check alignment of the bearing and the inclination angle determined by the survey. Adjustments are made by blocking and wedging the stem-advancer base. The support equipment is located as the terrain permits, with the control console close to the stem advancer. All equipment is started, operated, and serviced according to the manufacturer's instructions. Service lines are attached, and melting of the hole is started.

Stem-gripping clamps on the pairs of advancing hydraulic cylinders are used alternately: While one clamp is advancing, the other is retracting in preparation for a continuous advancing stroke. All functions related to advancing and retracting the stem and the HFA are controlled from the console, with the exception of adding (or removing) additional stem sections.

When additional stem is required, the operator:

- Reduces power and coolant flow to zero.

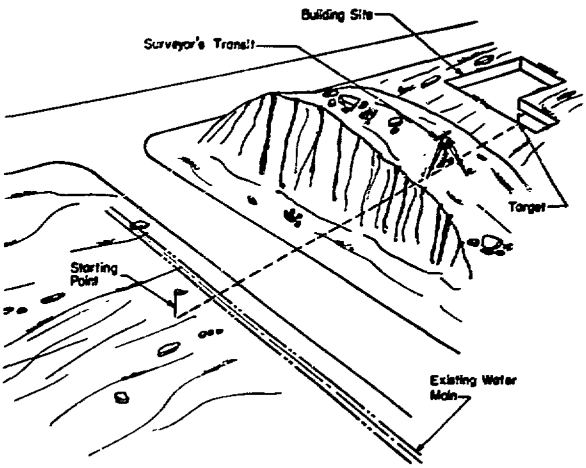


Fig. 23. Establishing the hole center line.

- Stops advancing pressure and releases the rear stem-advancing clamp, returning this clamp to the full-out position.
- Releases bladder pressure in quick-disconnect service head (QDSH).
- Slips off QDSH and unplugs signal leads.
- Adds stem section and tightens connection after plugging-in signal leads.
- Slips on QDSH, replugs signal leads to console and repressures bladder.
- Raises power and coolant flow to previous values.
- Regrips stem and applies previous load.

The stem is retracted (when the hole is finished or for any other reason) with the following steps; the operator:

- Reduces stem load to zero.
- Reduces power to zero.
- Reverses thrust load to retract mode.
- Maintains coolant flow until the stem pulls freely (stem drag only).
- Shuts off retraction force.
- Reduces coolant flow to zero and removes QDSH.
- Pulls out stem until the next stem connection is accessible. Loosens and unscrews connection.
- Unplugs signal leads and racks stem section.
- Continues the two previous steps until HFA is out of hole.
- Secures all equipment.

If required, the hole can then be surveyed by visual observation or instrumentation to evaluate straightness, glass-casing thickness, etc.

VII. CONCLUSIONS AND DISCUSSION

The development of small-diameter Subterrene rock-melting penetrators has reached the stage where the design of a 75-mm (3-in.)-diam system for forming horizontal, glass-lined holes is possible. Contacts with utility companies and requests for information from industrial firms have indicated the need for such a device.

A comprehensive development program would have to address two major areas:

- The development of an alignment-control subsystem.
- The conduct of an economic study and a market survey.

A most attractive feature of horizontal hole-melting Subterrene systems is the capability of varying the accuracy of hole straightness to match job requirements. This is achieved by including or omitting the appropriate sections in the hole-forming assembly.

The information and experience gained from the development and commercialization of the horizontal hole-melting system will be of value to other Subterrene system developments. The benefit derived can be anticipated to be:

- Field data on service life and reliability of components, particularly penetrators.
- Extension of the technology to the melting of holes with curved paths.
- Experience that will lead to horizontal hole-melting systems with increased diameter and range.
- Adaptation of the perfected alignment-control scheme to vertical hole-melting systems.

The successful development of the horizontal, small-diameter melting system can contribute significantly to further developments in subsequent Subterrene programs. This influence is shown schematically in Fig. 24. In addition to valuable experience and direct data on service life and reliability obtained in commercial applications, the effort will help in forming a scientific and engineering basis for design and optimization of subsequent devices. The very small-diameter melting penetrators (see Fig. 25 for an early prototype) can find uses such as punching holes in concrete or masonry walls, but difficult miniaturization problems will need to be solved if long holes are to be made. In addition, the experience with 75-mm-diam units will contribute to the development of a Geoprospector,[14] illustrated in Fig. 26, and will offer early inputs to the solutions of position sensors and guidance problems.

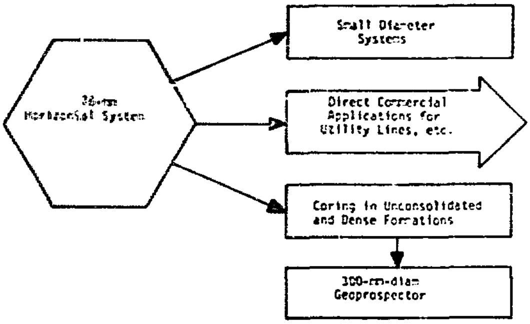


Fig. 24. Effect of 75-mm-diam horizontal Subterrene system on subsequent research and development.

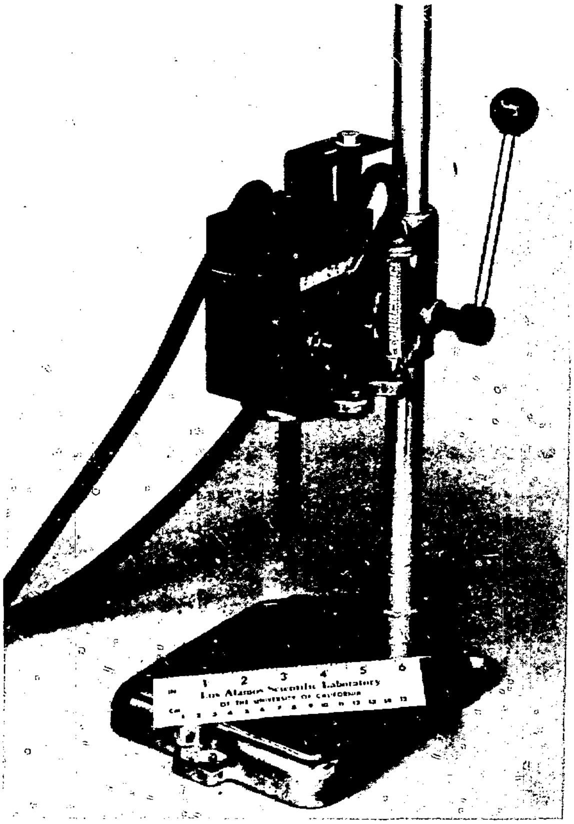


Fig. 25. Early prototype of 10-mm-diam rock-melting subterrene.

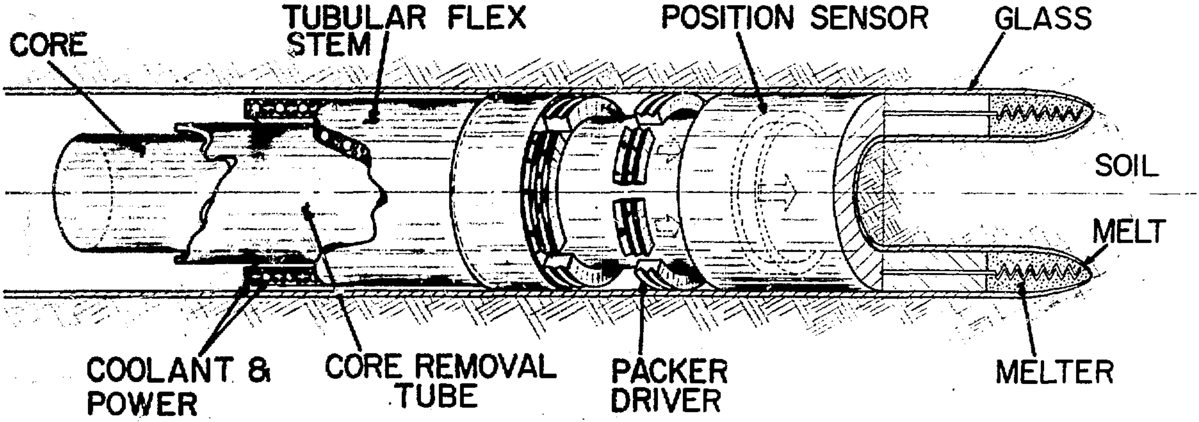


Fig. 26. Coring Geoprospector with position sensor and directional guidance systems capability.

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APPENDIX

ANALYSIS OF PROPOSED ALIGNMENT CONTROL SCHEME

The parameters affecting the design and performance of the alignment control section (ACS) proposed in the main body of the report can be derived by reference to Fig. A-1. The temperature difference established across the diameter of the ASC by the diverted coolant will induce a curvature in the housing given by

$$\frac{1}{\rho} = \frac{\bar{\alpha}\,\Delta T}{D}, \qquad \text{(A-1)}$$

if the unit is free to deflect [Fig. A-1(a)], where ΔT = effective temperature difference;

ρ = radius of curvature

$\bar{\alpha}$ = mean coefficient of thermal expansion

D = diameter of the housing.

Typical values for the projected design and materials are:

$\bar{\alpha} \simeq 6.0 \times 10^{-6}$, K^{-1}

D = 75 mm ≡ 0.075 m

ΔT = 100 K.

The curvature and radius of the deflected path are

$$\frac{1}{\rho} = \frac{6.0 \times 10^{-6} \times 10^{8}}{0.075} = 0.008\ m^{-1}$$

$$\rho = 125\ m.$$

Therefore, if the length, L, of the ACS unit is 1.0 m, the derivation at the end of the unit will be given by

$$\Delta = \frac{\bar{\alpha}\,\Delta T}{2D} = 0.0033\ m \equiv 3.3\ mm.$$

If the ASC is initially rigidly fixed by a centralizer section at one end and the penetrator at the other end, Fig. A-1(b), it will exert a moment given by

$$M = \frac{E\,I}{\rho}, \qquad \text{(A-2)}$$

where

E = elastic modulus of the material from which the ACS is constructed

I = area moment of the ACS cross section.

Taking E = 207.0 GPa (30 x 10^6 $lb_f/in.^2$), the data above, and combining Eqs. (A-1) and (A-2), the moment (M) and induced stress (σ) are:

M = 2.6 x 10^3 N·m (2.27 x 10^4 in. lb_f)

σ = 62 MPa (9.000 $lb_f/in.^2$).

This moment is of sufficient magnitude to induce the required path deviation while generating only low stresses in the hole-forming assembly.

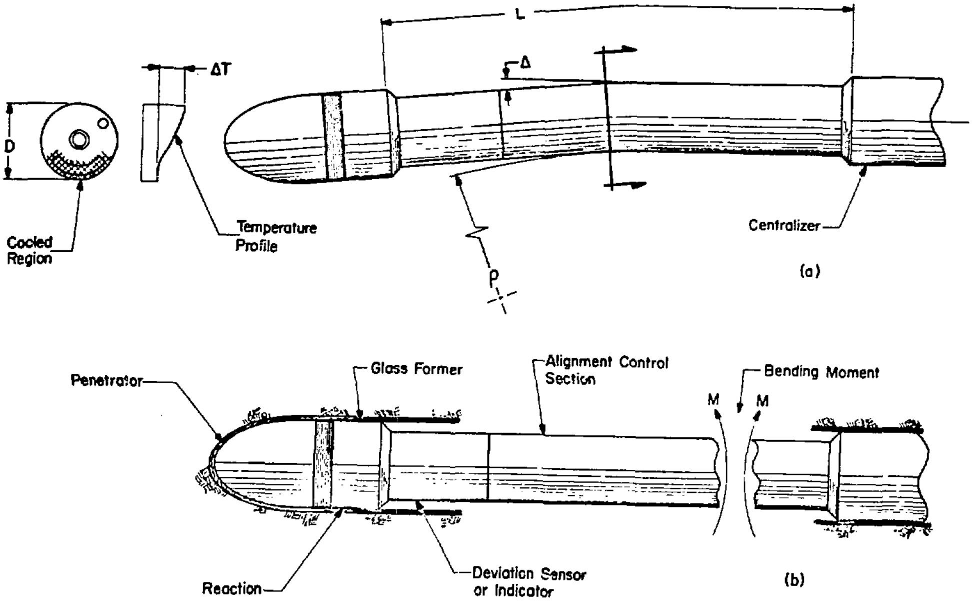

Fig. A-1. Proposed alignment control scheme.