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THE SUBTERRENE ROCK-MELTING EXCAVATION PROGRAM

by

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ABSTRACT

The objective of the Subterrene program is to develop new, innovative systems for drilling and tunneling based on the rock-melting concept. Rocks are mixtures of minerals and therefore, melting points are relatively low. The common igneous rocks, which are especially difficult to penetrate mechanically, in general become fluid at temperatures in the vicinity of 1470 K. Refractory metals, such as molybdenum and tungsten, have melting points much higher than this and are available for the development of the required rock-melting penetrator structures.

This proposed excavation method, which is relatively insensitive to variations in rock formation, produces a liquid melt whose behavior can be predicted by the laws of fluid dynamics. The basic rock heat transfer and melting processes are well defined and amenable to theoretical analyses and the rate of advance is dependent on the power supplied to the hot penetrator. The rock melt can be chilled to a glass and formed into a dense, strong, firmly attached hole lining. Thus by the use of a melting penetrator, permanently self-supporting holes can be produced even in unconsolidated sediments.

INTRODUCTION

Rock-melting offers new solutions in the three major areas of the excavation process; making the hole or excavation, providing structural support for the bore hole, and removing the debris or cuttings. Rock melting offers these potential technological advances because of its unique feature of liquifying the rock and its subsequent ability to chill the melt into useful structural forms such as a hole lining or casing. The liquid melt can also be frozen into a variety of unique debris forms.

The principal development activity in establishing the basic rock-melting technology is the design and development of a sequence of small-diameter prototype penetrators[1]. Two basic mechanisms exist for the redistribution of rock melt to permit the passage of the penetrator. These mechanisms are deposition of the melt by a solid penetrator into the immediately adjacent rock and removal of the rock and rock melt by extrusion through a hole, or holes, in the penetrator with subsequent ejection through the hollow stem. Melt deposition occurs either by consolidation (density compaction) of a porous rock to produce a higher density glass lining, or by forcing the melt into cracks that either existed in the rock or were formed by thermal and/or mechanical stresses imposed by the hot penetrator. Penetrators incorporating melt extrusion are more universal in their applicability and can be used in both porous ground and hard dense rock.

The known melting temperatures of refractory metals for structural components, graphites for electrical heaters and thermal insulators, and a variety of nitrides and oxides for electrical insulators show that materials with sufficient temperature margin relative to rock and soil melting temperature ranges are available for construction of rock-melting penetrator systems. The penetration rate is predicted and experimentally found to be essentially directly proportional to the heater power. The maximum penetration rate is limited by the heat flux that can be transferred from the heater, through the internal structure of the penetrator, through the melt layer and into the solid rock. This limit is practically determined by the maximum temperature levels at which the internal components of the penetrator can operate, which in turn are related to the operating lifetime of the device.

POWER SOURCE DESIGN AND DEVELOPMENT

A wide variety of electrical heaters for small-diameter Subterrene penetrators have been designed, constructed, and tested [2]. The basic materials problem is the incompatibility of refractory materials at the required operating temperatures of ≈ 2000 to 2400 K, while the basic design problem stems from the requirement for large heat fluxes from the heater surfaces. These high fluxes are necessary to maintain the outer surfaces of the penetrator at operating temperatures high enough to melt rock at useful rates. Thermal resistances of materials required for electrical insulation must be kept low to reduce internal temperature gradients.

The successful use of pyrolytic graphite as a radiant heating element and the low thermal resistance of a polycrystalline (POCO) graphite radiation receptor were combined to produce a very stable heater assembly. The heater consists of a stack of oriented pyrolytic-graphite disks held in a graphite-lined cavity by a spring-loaded graphite electrode. A cross-sectional view of a typical assembly is shown in Fig. 1.

The direct-current path is down the center stem to the graphite electrode, down the electrode to the pyrolytic-graphite heater stack, through this stack to the molybdenum penetrator body, back up the body to the withdrawal structure, and through this structure to the afterbody and outer stem. The center conductor is made positive with respect to the outer stem to suppress thermal electron emission from the stack, thereby reducing the tendency for arcing between the heater stack and the receptor. The heater cavity is filled with helium to enhance the radial heat transfer. Heat fluxes of up to 2 MW/m^2 have been obtained from pyrolytic-graphite radiant-heater elements. The features of this design which contribute to efficiency and durability can be summarized as follows:

- A heater cavity containing only graphite in the high-temperature region.
- The use of a specialty graphite (POCO) for the receptor whose thermal expansion characteristics match those of molybdenum and whose absorptivity for radiation energy is near unity.
- A nonisotropic pyrolytic-graphite heater stack oriented so that the high electrical resistivity ("c" direction) is parallel to the penetrator axis, and the high thermal conductivity ("a-b" direction) is normal to the penetrator axis and in the direction of principal heat transfer.
- A hollow heater cavity to allow control of the relative heat generation along the penetrator length.
- Utilization of the exceptional combination of high compressive strength and low thermal conductivity of pyrolytic graphite ("c" direction) for the insulator between the heated penetrator body and the cooled afterbody.

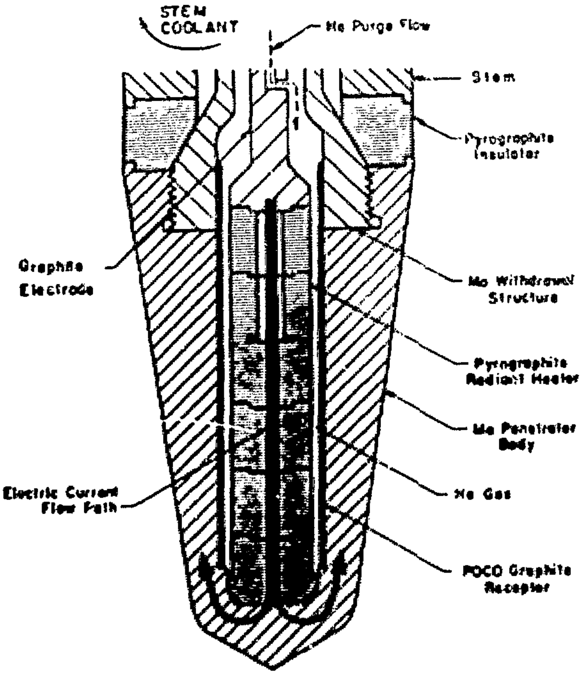


Fig. 1. Cross section of a consolidating penetrator with stacked pyrographite radiant heater and a POCO graphite radiation receptor.

PROTOTYPE PENETRATOR DEVELOPMENT AND TEST

Consolidation Penetrator Experiments

Penetration by melting and subsequent density consolidation relies upon the porosity of the parent rock or soil. This process is illustrated in Fig. 2 which shows how the rock melt is formed into a glass lining and how the larger hole diameter is melted to accommodate the lining [3].

This method of penetration eliminates the debris-removal process. The ratio of outer to inner radius of the glass lining is therefore related to the properties of the rock and lining by the conservation of mass. The resulting radius ratio is:

$$\frac{r_m}{r_p} = \sqrt{\frac{1}{1 - \frac{\rho_R}{\rho_L}}}$$

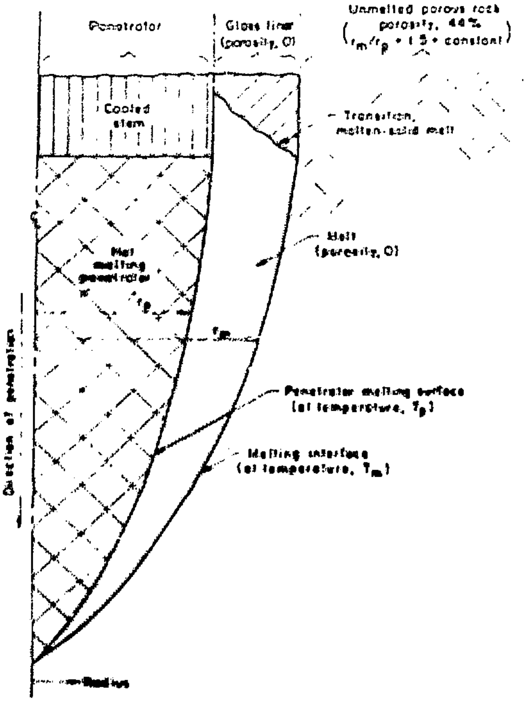


Fig. 2. Schematic of density consolidation in porous rock.

where r_m is the outer radius of the glass lining, r_p is the radius of the penetrator or inner glass lining, ρ_R is the density of unmelted rock, and ρ_L is the density of the glass lining. Penetrators utilizing density consolidation for melt disposal are referred to as melting-consolidating penetrators (MCPs).

Consolidation penetrator designs have been developed to the point where compressed-air cooled, oxidation-resistant, easily replaceable penetrators are in satisfactory use for both laboratory experiments and field demonstrations. Test results indicate that the glass hole linings are of the predicted thickness and higher thrust loads are beneficial in obtaining higher advance rates and smooth, high-strength glass linings of lower porosity. A test was performed in which the tuff specimen was tilted deliberately while being penetrated by a 75-mm-diam consolidating penetrator, thus simulating a guided penetrator in which steering is accomplished by stem-warping. The test demonstrated that a path deviation of 1.5 degrees per 80 mm of advance is feasible (radius of curvature ≈ 4 m).

Extrusion Experiments in Hard, Dense Rock

Extrusion penetrators are required in dense materials and are designed to continuously remove the debris from the bore hole [4]. As indicated in Fig. 3 the melt flow, confined by the unmelted rock and the hot melting face of the penetrator, is continuously extruded through a hole (or holes) in the melting face. This material is chilled and freezes shortly after the circulating cooling fluid impinges upon the extrudate exiting from the extrusion region. If freezing is accomplished quickly, the material will be in the form of frozen glass rods, pellets, or rock wool. The flowing coolant can then transport these small fragments up the stem to the exhaust section. Typical pellets and rock wool that were formed from frozen extrudate and removed by the cooling fluid during a basalt test are shown in Fig. 4.

Extruding penetrators have been used successfully to produce glass-lined bores in samples of tuff, alluvium, basalt, and granite. In view of their demonstrated versatility in varying rock and ground types, they are referred to as "Universal Extruding Penetrators" (UEPs).

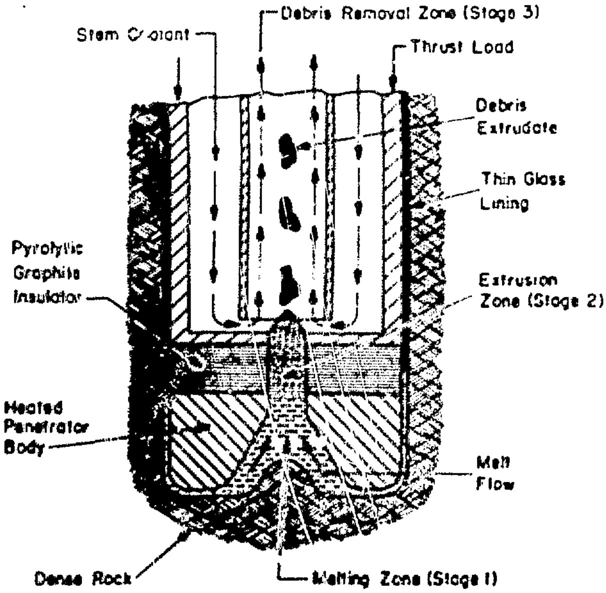


Fig. 3. Extruding penetrator concept.

Fig. 4. Debris from basalt hole made by extruding penetrator showing rock wool and glass-pellet constituents.

Experiments in Diversified Rock Types

The ability of MCPs to produce smooth, strong, firmly attached glass linings in a variety of consolidated or unconsolidated low-density rocks and soils has been continually demonstrated since the inception of the program. Typical examples are the thick glass lining associated with a hole melted in tuff illustrated in Fig. 5 and a self-supporting glass-lined hole melted in unconsolidated alluvium illustrated in Fig. 6. A more novel application involves a series of tests using 50- and 75-mm-diam MCPs melting into frozen (200 K) alluvial specimens containing ≈ 16-20% water by weight (simulated arctic permafrost). The penetrators readily produce glass-lined holes in the frozen specimens.

In hard, dense rock, UEPs incorporating coaxial-jet debris-removal systems have successfully penetrated and glass-lined bores in basalt and granite, with the granite hole illustrated in Fig. 7 representing a typical sample. Experiments have also been carried out with the UEPs melting in porous materials such as tuff. The tuff extrudate consisted of glass

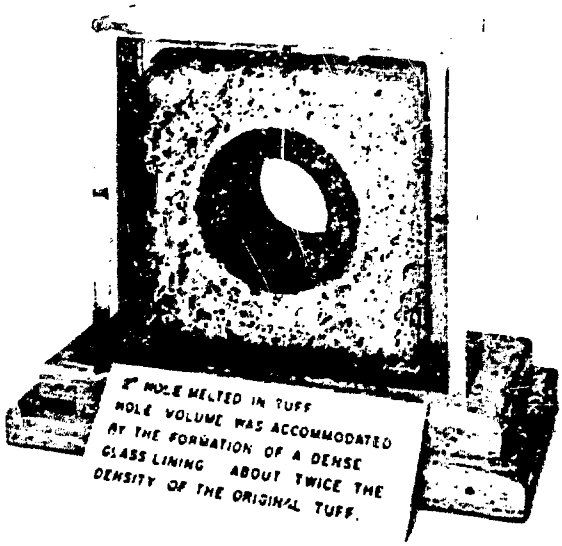
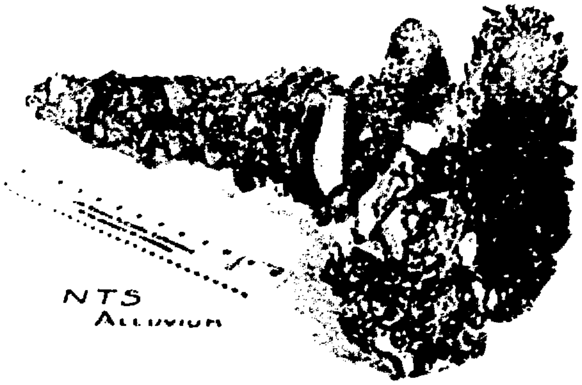


Fig. 5. Cross section of hole melted in tuff.

Fig. 6. Exterior view of self-supporting glass-lined hole melted in unconsolidated alluvium.



rods that broke off only when the rod extended the length of the experimental stem. The differences between the basalt and tuff extrudate are ascribed to the large difference in viscosity between the two glass melts and to the significant volume fraction of unmelted quartz crystals in the tuff melt. The UEP produced a thin glass lining on the hole, in contrast to the thicker linings formed in tuff by MCPs.

A design has been completed and fabrication started of an 82-mm-diam extrusion penetrator having a large surface heat-transfer area, multiple melt-flow passages, and multiple heater stacks. Based on the enhanced surface area, reduced operating melt layer thickness, and high thrust capability, analyses predict that this unit will melt rock at a significantly faster rate than previous UEP designs.

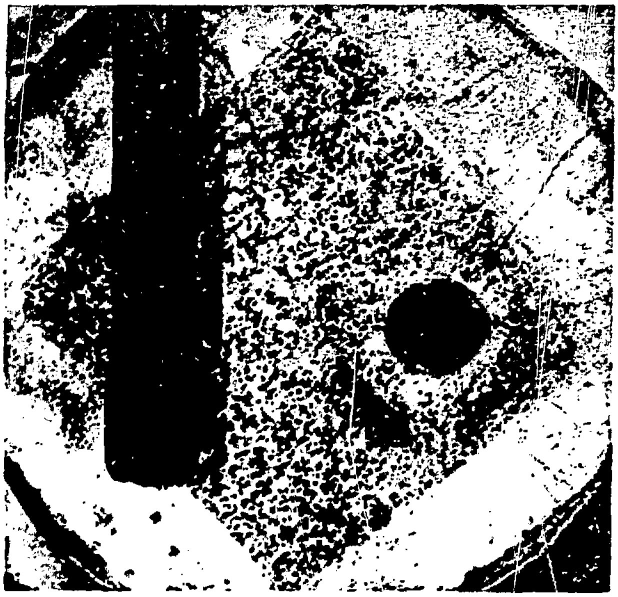
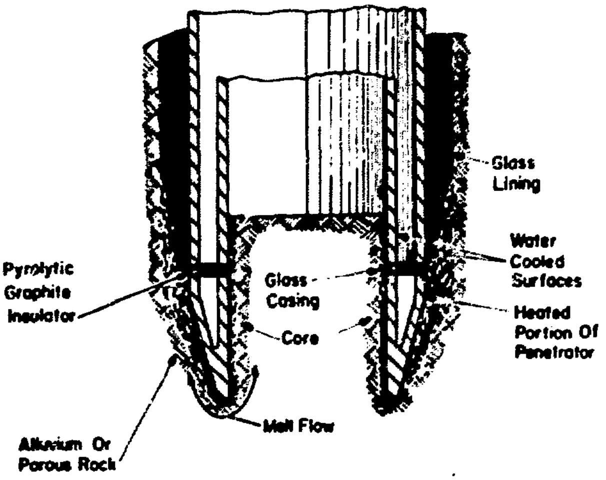


Fig. 7. Hole in coarse-grained biotite granite sample melted by UEP.

Coring Penetrator Development

The Subterrene concept of rock penetration by progressive melting has been expanded to include a technique for obtaining continuously retrievable geologically interesting core samples from the material being penetrated. The coring concept utilizes an annular melting penetrator which leaves an unmelted core in the interior that can be removed by conventional core-retrieval techniques. Although the concept is applicable to either the extrusion or consolidation mode of melt-handling, initial emphasis has been placed on a consolidating-coring penetrator as illustrated schematically in Fig. 8.

Fig. 8. Schematic of consolidating-coring penetrator.



A 114-mm-diam consolidating corer intended for use in porous alluvial soils has been designed, constructed, and calibration-tested in the laboratory. The core diameter is 64 mm and the melting body, which is vacuum-arc-cast molybdenum, is fabricated as a single-structural component as illustrated in Fig. 9. The water cooling system incorporated represents a departure from the conventional gas systems and has been successfully checked in the laboratory. Minor adaptations of commercially available core extraction tools are in progress for use with the alluvium corer.

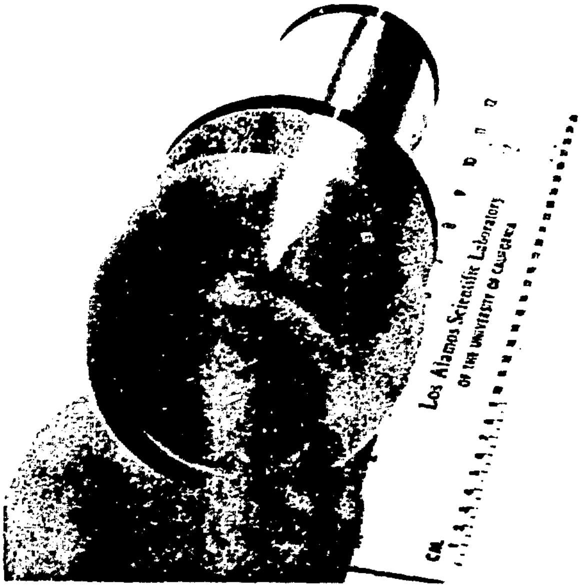


Fig. 9. Photograph of 114-mm-diameter consolidating-coring penetrator.

Glass Forming Tool Development

Consolidation penetrators have been tested with high thrust loads into tuff specimens, and the glass walls of the resulting holes have been of much better visual quality than noted previously. It is postulated that the higher thrust loads and associated higher pressures in the rock melt minimize gas-bubble evolution which can cause voids in the glass walls. Theoretical calculations of thermal histories for glass linings have been initiated [5]. These thermal histories follow the radial temperature profiles through the glass thickness and indicate the time spent by the freezing melt in the softening regime, working range, and annealing range of temperatures. Studies of the relative influence of cooling by the surrounding rock and the cooled stem will be used to assess the history of radial gradients in the glass wall and will therefore indicate residual stress/strain states. These time-history studies have yielded results which indicate the design directions for optimization of the thermal design of the glass-forming afterbodies of penetrator systems.

Materials Science and Technology

The high temperatures reached in Subterrene penetrator systems require a set of materials maintaining not only structural and physical integrity, but also a high degree of chemical inertness over extended periods of time [6]. Realization of this ideal situation becomes difficult at the suggested operating temperatures of the system, 1600 to 2300 K, and possibly higher in the case of certain radiant heater designs. The material temperature range is wide because a high power density must be transmitted from a central core of the heater so that ample heat flux can be conducted to the surface in contact with the rock. Because most materials will react with one another to some degree in this temperature range, intrinsic thermodynamic and kinetic lifetime limitations must be investigated.

Both a pretest and a post-test molybdenum penetrator have been examined by x-ray radiography. The pretest "shadowgraph" will be used as a basis for nondestructive examination after long-term operations. Radiographs of the used unit showed that corrosion can be observed by this technique and that the state of the graphite heater pills inside may also be seen. Static compatibility testing has been initiated with studies of the corrosion or dissolution reactions of molybdenum with standardized basalt rock. Figure 10 shows a typical penetrator coated with basalt glass after completion of a laboratory rock-melting test.

Fig. 10. Penetrator coated with basalt glass after withdrawal from hole.

Power Source Materials

The basic chemical reactions involved in Subterrene power-source materials are those of the refractory metal-carbon system, with some possible contributions from impurities within the metal, carbon, and helium gas that surrounds the heater. The motivating reason for studying these chemical reactions is the possibility of predicting and enhancing penetrator lifetime, a most important economic factor. The lifetime of a penetrator unit must be ultimately dependent upon the internal refractory metal-graphite interactions for the prototype radiant-heater penetrators currently being used. Internal chemical reactivity in prototype Subterrene radiant-heater penetrators has been investigated by means of sectioning and examining metallurgical samples. Dimolybdenum carbide, Mo_2C, is the major reaction product formed between the base metal and the graphite receptor interface. In those regions where carbiding has occurred, temperatures have been computed by means of measurement of the carbide layer thickness and the use of reaction-rate data for the Mo-C system. These temperatures have been compared to those calculated from thermal-analysis considerations [7]. As illustrated in Fig. 11, agreement is very good, with the calculated values being ≈ 50 K higher.

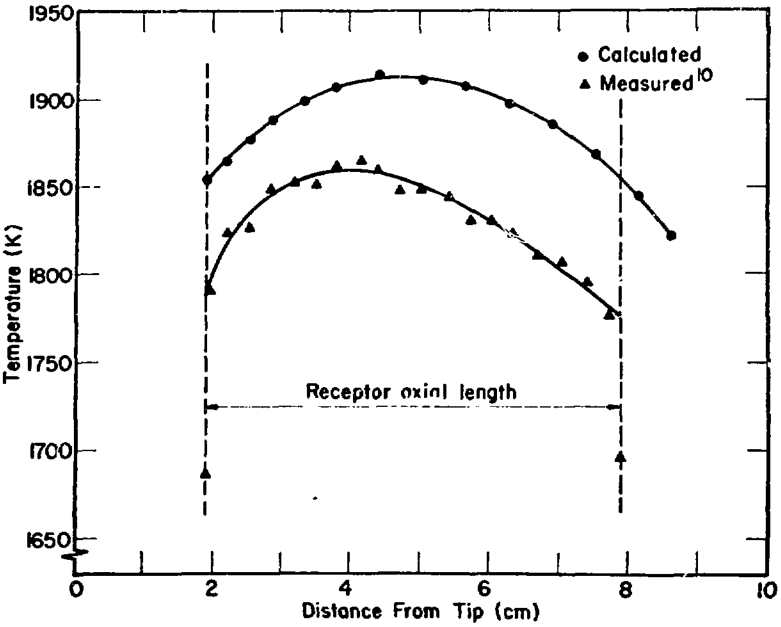


Fig. 11. Comparison of calculated and experimentally indicated penetrator temperatures at the graphite receptor - molybdenum body interface.

Refractory Alloy Fabrication

The majority of penetrators thus far have been fabricated from molybdenum. The several tungsten penetrators that have been fabricated and tested have clearly demonstrated that tungsten has the capability of operating at higher temperatures and hence yielding greater penetration rates. An extensive effort has been initiated to ensure acquisition of tungsten stock in the proper sizes and shapes for forthcoming Subterrene penetrator fabrication. Refractory-metal machining techniques have advanced to the stage where large, fluted, profiled bodies are being fabricated and deep holes are being drilled in molybdenum parts. In addition, techniques have been developed for high-temperature (2000-2300 K) vacuum furnace-brazing of penetrator components.

FIELD DEMONSTRATION UNITS

The principal objectives of field-testing complete penetrator systems are the performance evaluation of the system under actual field conditions and the acquisition of realistic data on system reliability and expected service life. Data and experience from field tests form an important input in the penetrator system-design optimization process. Field tests also demonstrate prototype system performance at a level of development approaching that required for commercial applications.

The field-test program was established with the design, construction, and utilization of the first portable, modularized field-demonstration unit (FDU) [8]. This initial FDU provided a self-contained unit for demonstrating small-diameter rock-melting penetration system capabilities at locations away from the immediate Los Alamos area. The unit was designed to produce glass-lined bores in low-density rocks or soils and to achieve the following specific objectives:

(1). Provide field demonstrations of basic rock-melting principles and capabilities.
(2). Produce glass-lined drainage holes in archaeological ruins.
(3). Melt prototype utility holes under roadways.
(4). Test improved glass-forming designs.
(5). Provide extended-lifetime test data for the refractory metal penetrators.
(6). Serve as a prototype and yield data and experience for the design of larger units for future field tests of Subterrene systems.

The FDU is easily transportable and capable of remote, self-contained operation utilizing an air-cooled stem. A schematic sketch of the completed FDU is shown in Fig. 12. The various modularized components are designed to be stored and transported in one trailer.

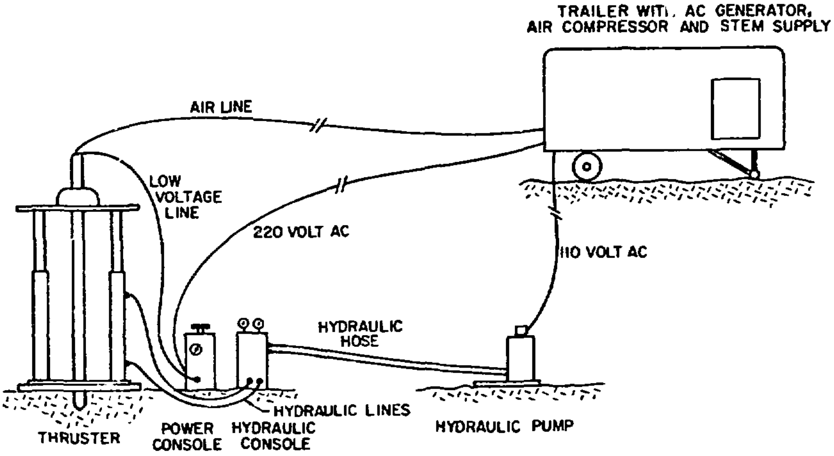


Fig. 12. Schematic of initial field-demonstration unit.

The major components of the FDU and their basic functions are described below:

Thruster - Two double-acting hydraulic cylinders and a mechanical chuck are used for gripping the stem and thrusting the heated penetrator into the rock formation and also for extracting the penetrator.

Hydraulic Power Supply and Control Console - An electric-motor-driven hydraulic pump supplies pressurized oil to the console for use in operating the thruster. The control console provides control of the thruster (i.e., of its direction and amount of thrust applied) by means of regulating valves.

Electric Power Supply and Control Console - Electrical power is supplied by a gasoline-engine-driven generator which provides ≈ 10 kW of 220-V single-phase 60-Hz power. The control console modulates the power to the penetrator and contains a rectifier to change the 60-Hz to direct current, a step-down transformer to provide lower-voltage/higher-amperage power, a Variac for voltage control, and associated instrumentation.

Air Compressor - A gasoline-engine-powered air compressor is used to supply cooling air to the penetrator stem and for chilling the rock-glass lining.

Stem Sections - Modified sections of standard drill pipe commonly used in oil-field drilling are used. They are fitted with an internal copper tube which serves as a conduit for the cooling air and as a conductor for the electrical power to the penetrator heater.

Preliminary technical achievements with the field demonstration unit include:

- The use of a FDU to make a 13-m and a 15-m horizontal penetration into Bandelier tuff [9]. The field-demonstration unit is shown in place in Fig. 13.
- Two very straight glass-lined holes, one vertical and one horizontal, have been produced in Bandelier tuff with a field-demonstration unit. These holes are each ≈ 13 m long and deviate from straightness by less than 10 mm along their entire length.
- Numerous penetrations into various loose and unconsolidated soil samples, including layered samples formed from different loose materials, have been conducted to examine the resulting glass liners. The glass liners have been of good quality and the smooth transition across the layered samples was particularly encouraging.
- Eight water drainage holes were melted with a FDU at the Rainbow House and Tyuonyi archaeological ruins at Bandelier National Monument, New Mexico, in cooperation with the National Park Service [10]. By utilizing a consolidation penetrator, the required glass-lined drainage holes were made without creating debris or endangering the ruins from mechanical vibrations. Figure 14 shows the rock-melting demonstration unit in place at Rainbow House. Specifically, this operation has shown that Subterrenes can be operated successfully under field conditions in areas remote from the laboratory and a consolidating penetrator can melt its way through alluvial formations containing some

moderately sized basaltic rocks by thermally cracking the rocks and forcing the melt into the surrounding soil through the cracks.

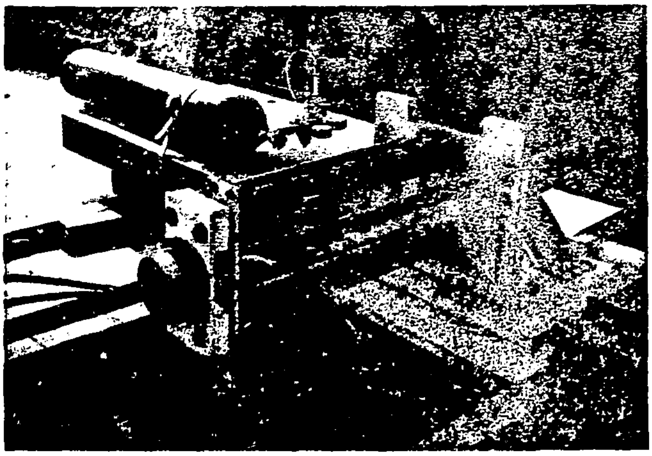
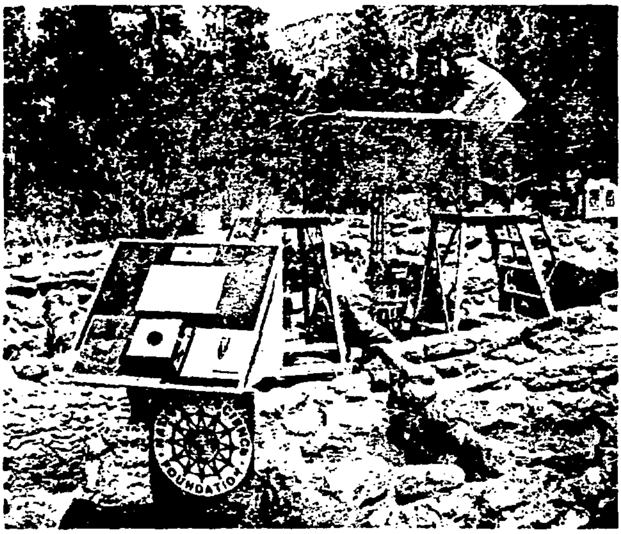


Fig. 13. Field-demonstration unit in position for horizontal penetration.

Fig. 14. Rock-melting demonstration unit at Rainbow House ruins.



THEORETICAL ANALYSIS

Theoretical analysis efforts have been directed toward the development of new analytical and numerical techniques for analyzing the combined fluid dynamic and heat-transfer performance of melting penetrators and the application of these techniques to specific penetrator designs and concepts. Numerous thermal analyses involving two-dimensional heat-conduction solutions have been performed in support of the prototype design and development effort to predict temperature profiles in critical regions of penetrator systems. The analytical problem of a heated penetrator advancing into solid rock requires a study of the nonlinear fluid dynamics of creeping viscous flow with high thermal flux-energy interactions. Although some aspects of the analysis are similar to classical areas of investigation in slow viscous flow theory, the complete problem formulation represents a discipline of its own. Solutions will be characterized by the following features:

(1). The characteristic fluid velocities involved are very low even for the most optimistic penetration rates. As a consequence, the fluid dynamics problem is inherently incompressible and the very low Reynold's numbers allow the inertia terms to be neglected in the Navier Stokes equations.

(2). The viscosity of the melted rock materials is very high and strongly temperature-dependent.

(3). Initially, only steady-state axisymmetric solutions need be considered.

(4). In addition to the sensible-heat transfer, an effective latent heat of melting must be included in the thermal energy balance.

(5). The energy contribution from viscous heating is negligible and hence the dissipation function can be neglected in the energy equation.

The motion of a heated penetrator through a melting medium can be formulated in terms of the partial differential equations governing the physics of the process. In axisymmetric cylindrical coordinates (r, z) with radial velocity ν_r and axial velocity ν_z, these equations are:

$$\frac{1}{r}\frac{\partial}{\partial r}(r\,\nu_r) + \frac{\partial \nu_z}{\partial z} = 0\ ,$$

the continuity equation;

$$\frac{\partial P}{\partial r} = \frac{2}{r}\frac{\partial}{\partial r}\left(\mu r\,\frac{\partial \nu_r}{\partial r}\right) - \frac{2\mu\nu_r}{r^2} + \frac{\partial}{\partial z}\left[\mu\left(\frac{\partial \nu_z}{\partial r} + \frac{\partial \nu_r}{\partial z}\right)\right],$$

the r-direction Navier Stokes equation;

$$\frac{\partial P}{\partial z} = \frac{1}{r}\frac{\partial}{\partial r}\left[\mu r\left(\frac{\partial \nu_z}{\partial r} + \frac{\partial \nu_r}{\partial z}\right)\right] + 2\,\frac{\partial}{\partial z}\left(\mu\,\frac{\partial \nu_z}{\partial z}\right),$$

the z-direction Navier Stokes equation; and

$$\rho c\left(\nu_r\,\frac{\partial T}{\partial r} + \nu_z\,\frac{\partial T}{\partial z}\right) = \frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda\,\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(\lambda\,\frac{\partial T}{\partial z}\right),$$

the energy equation;

where P is the pressure and μ, ρ, c, λ, and T are the rock-melt dynamic viscosity, density, specific heat, thermal conductivity, and temperature respectively.

In consideration of the typical penetrator geometries, it is convenient to cast these equations in a general curvilinear orthogonal coordinate system that corresponds to the melting penetrator shape. This generalized coordinate system is illustrated in Fig. 15 where the new transverse coordinate is η, the meridional or streamwise coordinate is S, ℓ is the local melt-layer thickness, and β_0 is the angle between the penetrator surface and the axis of revolution.

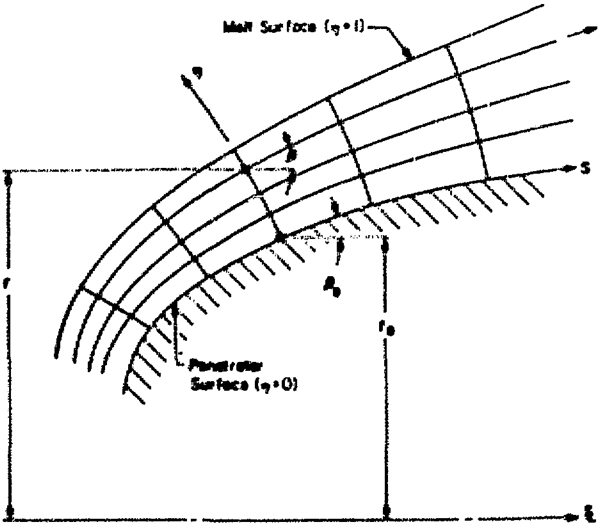


Fig. 15. General curvi-linear orthogonal coordinate system.

Rewriting the basic equations in the new coordinate system and neglecting lower-order terms, the simplified equations are:

$$\frac{\partial}{\partial \eta}(\sigma r v) + \frac{\partial}{\partial S}(\ell r u) = 0 \quad ,$$

the continuity equation;

$$\frac{\partial}{\partial \eta}\left[\sigma^3 \, r\mu \, \frac{\partial}{\partial \eta}\left(\frac{u}{\sigma}\right)\right] = \sigma \, \ell^2 r \, \frac{dP}{dS} \quad ,$$

the S-direction Navier Stokes equation; and

$$\frac{\partial}{\partial \eta}\left(\sigma \, r \, \lambda \, \frac{\partial T}{\partial \eta}\right) = \sigma \, \ell \, r \, \rho \, c \, v \, \frac{\partial T}{\partial \eta} + \ell^2 r \, \rho \, c \, u \, \frac{\partial T}{\partial S} \quad ,$$

the energy equation;

where v is the transverse velocity component, u is the meridional velocity component, and $\sigma = (dS^*/dS)_\eta$ where S* is the meridional distance along any constant η line. As in typical boundary layer theory, the η direction Navier Stokes equation contains only lower-order terms and is replaced in this case with an integral form of the continuity equation.

These equations, together with appropriate boundary conditions, have been solved numerically by using a finite-difference technique [11].

The results have been incorporated into a computer program for performing detailed lithothermodynamic analyses of melting penetrators.

Utilizing the newly developed lithothermodynamic computer program, calculations have been performed for the 114-mm-diam alluvium-coring penetrator. These calculations indicate that the penetration rate will be ≈ 0.2 mm/s for a uniform surface temperature of 2000 K and typical conductivities of solid and melted rock. For a uniform penetrator surface temperature of 1800 K, the penetration rate decreases approximately linearly with the decreasing temperature difference available for melting. Calculated results for the melt-to-solid interface location for various penetration rates in tuff are shown in Fig. 16.

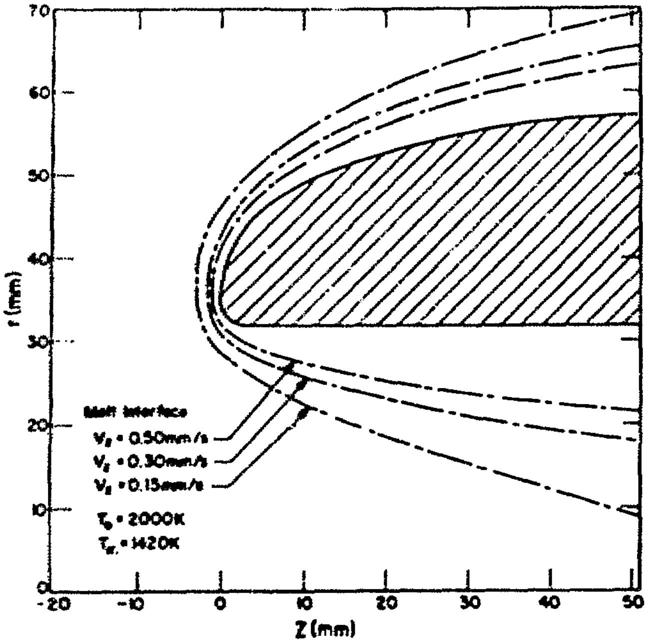


Fig. 16. Melt interface location as a function of penetration rate for an alluvium-coring penetrator.

Parametric analyses have also been conducted on consolidating penetrators with different geometrical shapes. Calculational results for a hemisphere-cylinder geometry based on typical local tuff properties are shown in Fig. 17. The theoretical penetration rate in the consolidation mode is shown to be proportional to the heated length of the penetrator as represented by the length-to-diameter ratio for a 75-mm-diam penetrator. As indicated by the cross-plot lines of constant melt-layer thickness at the penetrator tip, the maximum penetration rate could be limited by unmelted hard particles such as quartz crystals. Note that the calculational results presented in Fig. 17 do not satisfy the consolidation relation locally, but only require that the melt layer at the end of the heated penetrator afterbody be sufficiently thick for complete density consolidation of the melt. Penetrators exhibiting this type of melt-layer control are referred to as Melt Transfer Consolidation (MTC) penetrators to denote the fact that molten rock is transferred according to a calculated axial velocity profile from the leading-edge surfaces of the penetrator to its afterbody where the final density consolidation melt-layer thickness relation is satisfied.

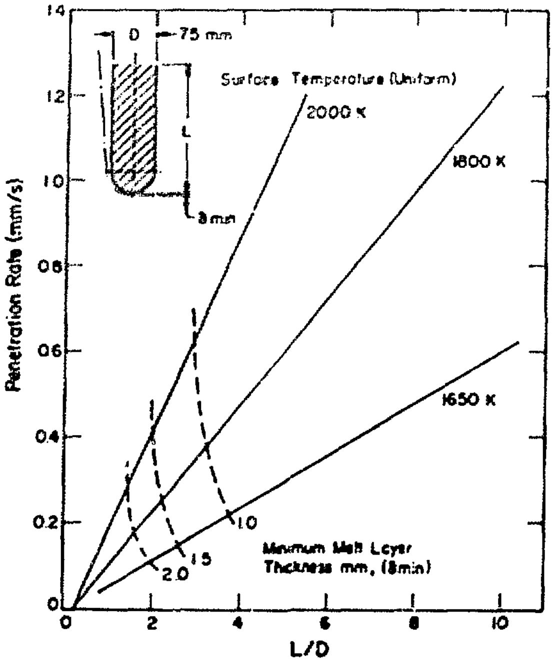


Fig. 17. *Calculated litho-thermodynamic performance of a hemisphere-cylinder consolidating penetrator in tuff.*

The calculated penetration rate, surface temperature, and minimum thrust requirement as a function of heating power (not including stem-conduction losses) for a different 75-mm-diam consolidating penetrator are shown in Fig. 18. These calculations show that the theoretical penetration rate of this double-cone shape is considerably lower than that of the hemisphere-cylinder geometry shown in Fig. 17 for the same surface temperature and the same length-to-diameter (L/D) ratio. This conclusion was also verified for a parabolic penetrator, indicating the importance of penetrator geometry on advance rate. The rapidly

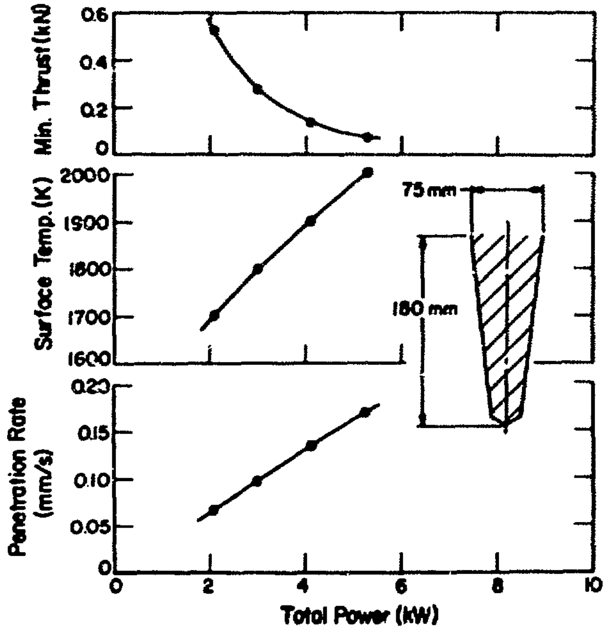


Fig. 18. *Calculated litho-thermodynamic performance of a double-cone consolidating penetrator in tuff.*

decreasing minimum thrust depicted in Fig. 18 is a result of the strongly decreasing viscosity associated with the higher penetrator surface temperatures.

CONCEPTUAL DESIGN OF A GEOPROSPECTOR

A Subterrene system with immediate applications would be a relatively small-diameter (300 mm), electrically powered minitunneler that would be remotely guided and self-propelled to form a hole along a proposed tunnel route while continuously extracting core samples. Such a system would enable detailed analyses to be made of the geology along a proposed tunnel route. This system, termed a Geoprospector, is intended to perform this survey task [12].

The conceptual design of a Geoprospector is well advanced and the general design features of the system are illustrated by the isometric sketch in Fig. 19. The device is electrically powered, requires ≈ 100 kW of power to melt an accurate 300-mm (1-ft)-diam glass-lined hole while removing a 200-mm (8-in.) glass-cased core at a rate of 0.4 mm/s (5 ft/h). The accurate diameter and stable hole lining allow the use of a packer-thruster unit located in the hole-forming assembly. Provision is made for an orientation-sensor package and a guidance unit, also located within the hole-forming assembly. A hollow, flexible stem which trails behind the assembly contains the electric power, coolant, and instrumentation lines; and provides a debris passage for removal of the chilled melt. Core sections are removed through the flexible stem intermittently with conventional wire-line core retrieval hardware.

The melting face is envisaged to have multiple axial channels through which rock melt flows to the chill-jet nozzles. The penetrator body is designed to operate at a surface temperature of 1870 K and will be fabricated from molybdenum-tungsten alloy either forged in a continuous-ring rolled shape or assembled from separate modular units. Auxiliary melt-flow channels will be provided adjacent to the melting surface to enhance the effectiveness of the melt-removal process by

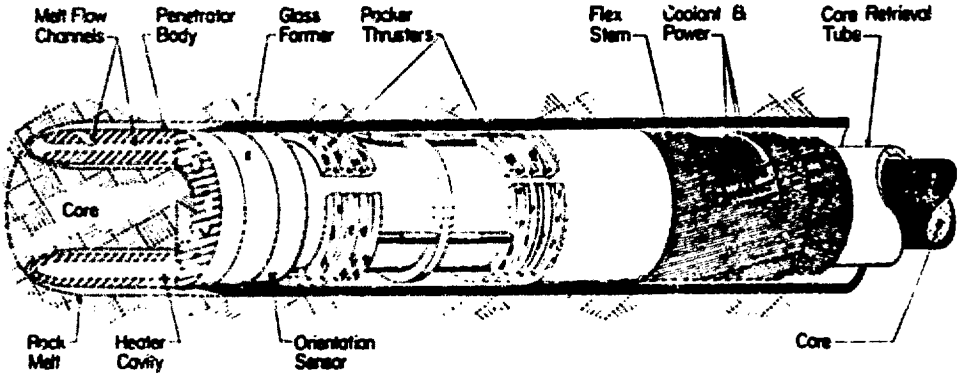


Fig. 19. Geoprospector conceptual design.

directing melted rock into the channels leading to the chill-jet nozzles. Except for the factors governed by the relatively large assembled size of the penetrator, the technology necessary to build and operate the penetrator body and melting surface is being tested as part of the current Subterrene rock-melting technical activities.

The major functions of the rock-glass forming and debris-removal system are (1) to form a dense structural glass lining on the wall of the hole and (2) to duct the melted rock from the annular melting face through an array of melt-chilling jets where the scoria will mix with a coolant fluid, be frozen into particles and then be removed by fluid transport via the flex stem.

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*These reports can be obtained from the U.S. National Technical Information Service, Dept. of Commerce, 5285 Port Royal Road, Springfield, VA 22151.