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STATUS REPORT

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# Rapid Excavation by Rock Melting
# -- LASL Subterrene Program --

**December 31, 1972, to September 1, 1973**

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

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Compiled by

R. J. Hanold

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CONTENTS

## PROJECT ABSTRACT

Research is continuing on establishing the technical and economic feasibility of excavation systems based upon the rock-melting (Subterrene) concept. A series of electrically powered, small-diameter prototype melting penetrators have been developed and tested. Research activities include optimizing penetrator configurations, designing high-performance heater systems, and improving refractory-metals technology. The properties of the glass linings that are automatically formed on the melted holes are being investigated for a wide variety of rocks and soils. Thermal and fluid-mechanics analyses of the melt flows are being conducted with the objective of optimizing penetrator designs. Initial economic models of the rock-melting concept extended to large tunnelers are being developed. Field tests and demonstrations of the prototype devices continue to be performed in a wide range of rock and soil types. The conceptual design of the electrically powered, self-propelled, remotely guided, horizontal tunnel-alignment prospecting system (Geoprospector) has been initiated. Such a device will also find applications in energy transmission, i.e., utility and pipeline installations.

The long-term goal of the research is to develop the technology and prototype hardware that will ultimately lead to large tunneling devices, with improved advance rates and reduced tunnel project costs. The rock-melting concept includes elements that will result in innovative solutions to the three major functional areas of tunneling: rock disintegration, materials handling, and hole-support linings. The proposed excavation method, which is relatively insensitive to variations in rock formation, produces a liquid melt that can be chilled to a glass and formed into a dense, strong, firmly attached hole lining.

Unique applications to large automated tunneling systems, ultradeep coring for geoscience research, and hot-rock penetration for geothermal energy development are being investigated.

## I. INTRODUCTION AND SUMMARY

### A. Objectives

The technical efforts and resources of the LASL rock-melting (Subterrene) program have been distributed to yield a balance of prototype hardware of increasing complexity and size, laboratory experiments, practical field-test experience, design and economic analyses, electric heater development, materials development and applications, and theoretical studies. The results of these technical activities are planned to yield:

- The demonstration of the basic feasibility of rock-melting as a new excavation tool for applications up to 150 mm (6 in.) in diameter.
- Operational and field-test data from prototype devices of a range of sizes and configurations, and the verification of preliminary theoretical modeling needed to scale to larger diameters, predict performance, make cost estimates, and optimize advance rate and reliability.
- Refractory materials technology sufficiently established to permit predictions of component life and to generate materials selection criteria for prototype development needs and projections of service life for systems in practical applications.
- Field-test experience and operational demonstrations sufficient to project commercial use in the important practical application of coring in loose or unconsolidated materials, and to demonstrate the potential utility of the smaller-diameter prototype devices.
- Theoretical models and analytical techniques needed to describe the heat transfer and fluid mechanics of the rock-melting and penetration processes for the purposes of optimizing configurations, predicting performance, and scaling of system dimensions.

### B. Technical Approach

The technical effort is organized into five technical activity areas whose functions are:

- Prototype Design and Test.
- Directed Research and Development.
- Power Source Design and Development
- Field Test and Demonstrations
- Systems Analysis and Applications.

The significant results and achievements in the research and development program are summarized for each of these five technical activities in five major sections of this report for the period December 31, 1972 to September 1, 1973.

### C. Summary

The beginning of this year has seen a considerable expansion of the LASL research and development efforts in applying rock- and soil-melting techniques to excavation technology. Extended laboratory and field activities have been initiated. The technical staff assigned to the program and the laboratory facilities have been increased significantly. The Program staffing and technical tasks are planned to form the nucleus for an effort that would be directed toward the application of rock-melting to large-diameter tunneling systems.

The design and development of the initial configuration of an extruding penetrator was finished. Laboratory experiments with this 66-mm-diam, single-melt-flow-channel, extruding penetrator were successfully completed and holes were melted in basalts, granite, and a variety of low-density and loose soils. These universal extruding penetrators (UEPs) showed the basic features of rock-melt flow handling. Debris in the form of glass pellets, glass rods, or rock wool was formed by chilling the melt and carrying the debris out of the stem with the coolant flow. A larger-diameter (82 mm) high-advance-rate UEP was designed and fabricated. The 114-mm-diam coring-consolidating penetrator system that produces a 63-mm-diam, glass-cased core was designed, fabricated, and initially tested. The conceptual design study for a 300-mm-diam coring Geoprospector was finished. This electrically powered minitunneler is intended to be the major design study of the current program and is based upon the experience, data, analysis, and concepts developed by the prototype-penetrator design and development effort.

At the relatively high temperatures, 1600 to 2300 K, of rock-melting penetrator system operation, most materials react with one another to some extent and thermodynamic and kinetic lifetime limitations are therefore under investigation. Component and field data have confirmed a service life of ~ 200 h. Materials research in the interaction of refractory metals with liquid rock melts thus far indicates that a life goal of 1000 h is possible. Techniques for rock-glass property evaluation and optimization are under development. The aim of the work is to perfect rock-melt glass as an in situ structural element to serve as hole support in the excavation. Refractory materials fabrication techniques necessary for development purposes have been established. Thermal- and physical-property data sufficient for input to analyses have been acquired.

The design, materials selection, and testing of a wide variety of electrical heaters for small-diameter penetrators have been accomplished. Resistively heated, pyrolytic-graphite heater elements, which radiate energy to the refractory metal penetrator body, have proven to be most satisfactory for the development efforts. Increased advance-rate goals (~ 0.5 to 1.0 mm/s) require high-heat-flux heaters. Investigation of new designs and materials, heat pipes, and alternative approaches to resistance-heating have been initiated to enhance heater heat-flux capabilities. Life tests of heater assemblies have been initiated.

Field-test units for a small-diameter penetrator system were designed, fabricated, and operated. Evaluations of consolidating and extruding penetrator systems have provided valuable data and experience on reliability and service life. A practical application of melting glass-lined drainage holes in Indian ruins was demonstrated to visitors of the Bandelier National Monument, NM. Mobilization of field units for a public demonstration in Washington, DC, or at other locations has been completed. The design, specifications, and purchase of a mobile rig for large-diameter penetrators with 300-m stem-length capacity have been completed

Conceptual designs of large-diameter tunnel-boring machines were established for the extremes of the difficult tunneling conditions of unconsolidated ground and very hard abrasive rocks. A benefit-to-cost study was completed and indicated that savings on projected transportation demands through 1990 were sufficient to give a benefit/cost ratio of 8.5 for a development cost of $\$100 \times 10^6$. Theoretical analyses of the heat transfer, of the melting processes, and of the fluid mechanics of melt-flow are well advanced. Numerical solutions of the coupled melt-flow and energy relations, accounting for the strong temperature dependence of rock-melt viscosity, and studies of a variety of penetrator geometries have been accomplished. These theoretical studies give direction toward penetrator designs which will maximize the advance rate and minimize thrust requirements. Optimizations of configurations for both consolidating and extruding penetrators have been performed. Significant operating maps for past and current penetrator designs have been developed. Confirmation by laboratory operating data for some penetrators have established the validity of those analyses. Therefore, a detailed predictive method for the melting concepts has been perfected, and design and scaling to large-diameter tunnelers can now be accomplished reliably. Computer programs for thermal conduction and structural analyses have been developed.

The study of applications of Subterrene systems to a wide variety of excavation tasks continued. Particular interest in a small-diameter system for forming glass-lined horizontal holes for utility emplacement and drainage applications motivated a preliminary design of such a system. The Geoprospector concept, especially the self-propulsion and remote-guidance features, continues to elicit interested responses from the excavation industry. Pipeline installation and the placing of transmission lines underground are major application areas. The melting of holes in permafrost for support pilings of arctic oil and gas pipelines have been discussed extensively with interested industrial firms.

The work conducted during this reporting period has clearly delineated the design directions and solution approaches needed to solve the major outstanding technical problems: increased penetration rate and extended service life.

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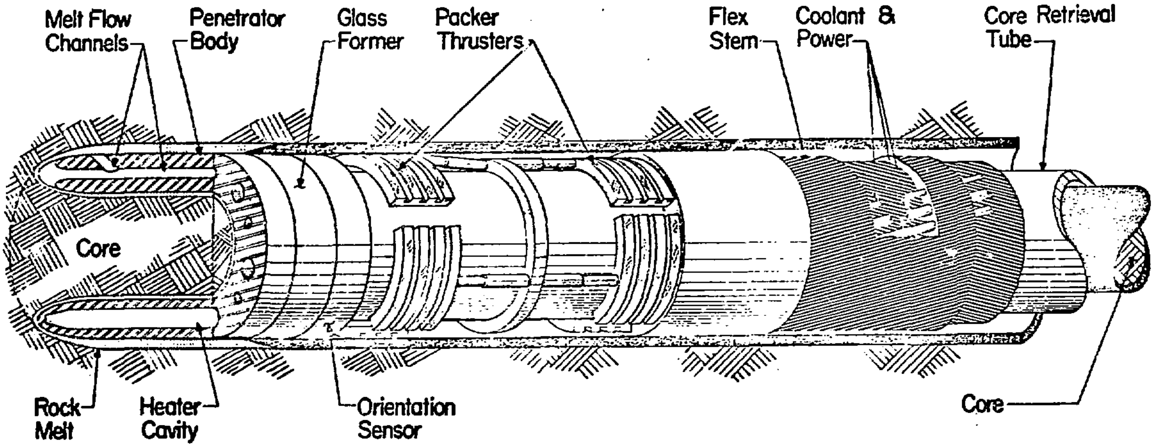


Fig. 1. Geoprospector conceptual design.

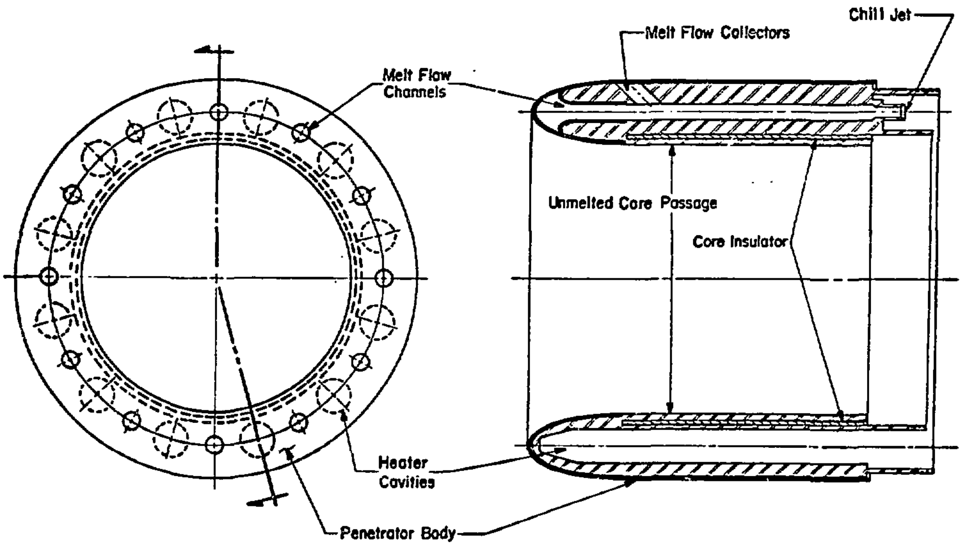


Fig. 2. Penetrator body and melting-surface configuration.

## II. PROTOTYPE DESIGN AND TEST

### A. Preliminary Design of Geoprospector

#### 1. Introduction

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 and additionally to serve as a small-scale prototype in anticipation of some problems that will arise in the future development of larger-diameter nuclear-powered Subterrene tunnelers.

#### 2. Conceptual Design

The conceptual design of the Geoprospector is well advanced and the general design features of the system are illustrated by the isometric sketch in Fig. 1. 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.

#### 3. Penetrator Body, Glass Forming, and Debris Removal

The configuration of the penetrator body and melting surface is shown in Fig. 2. The melting face is envisaged to have 12 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 12 separate modular units. Auxilliary melt-flow channels will be provided adjacent to the melting surface to enhance the effectiveness of the melt-removal process by 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.

Two distinct heater design options are available for the Geoprospector concept. In the first, the heaters would be located in the penetrator body in a circumferential pattern, and radiation heat transfer would be utilized to deposit the required melting energy into the refractory metal melting surfaces. The second design would locate the heater farther away from the melting surface and would couple the thermal energy to this surface through a series of high-temperature, liquid-metal heat pipes. The relative advantages of the two heater-system options are being critically examined.

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. These functions are illustrated in Fig. 3.

### B. Penetrator Development

#### 1. Consolidation Penetrator Experiments

Penetration by melting and subsequent density consolidation relies upon the porosity of the parent

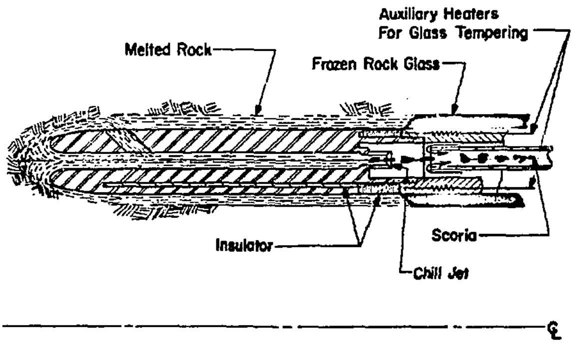


Fig. 3. Rock-glass-forming and debris-removal system.

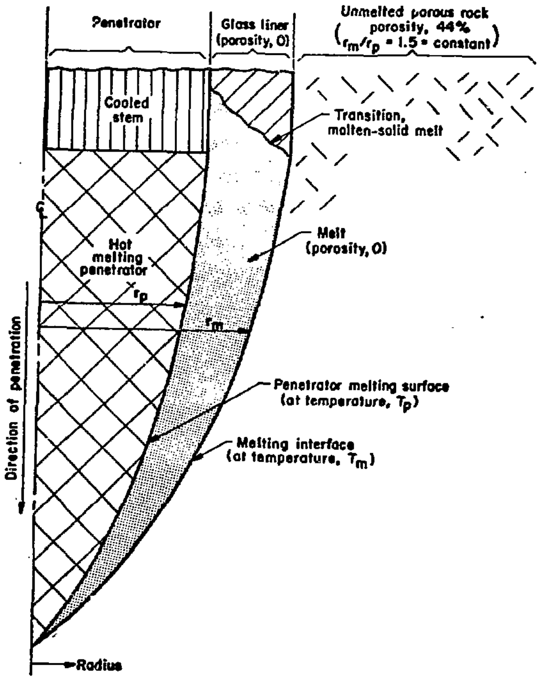


Fig. 4. Schematic of density consolidation in porous rock.

rock or soil. This process is illustrated in Fig. 4, which shows how the rock melt is formed into a glass lining and how the larger hole diameter is melted to accommodate the lining

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:

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

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

Significant technical achievements in this area include:

- 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.
- A 75-mm (3.0-in.)-diam MCP has been designed, constructed, and laboratory tested. At heater powers of ≈ 6.1 kW and thrust loads of 2.5 to 7.5 kN, advance rates up to 0.15 mm/s were obtained. The glass linings of the holes were of the predicted thickness and the higher thrust loads resulted in smooth, high-strength glass linings of lower porosity.
- A small, 12-mm-diam desk-top penetrator was designed and tested successfully. Several units were produced and used in demonstrations of the melting process.
- The design of a revised 75-mm-diam penetrator system has been completed to initiate investigations of steering and guidance methods by a series of experiments in making horizontal holes.
- A series of tests were carried out with the 75-mm-diam MCP melting into specimens of tuff and alluvium to obtain performance data on the variation of penetration rate with thrust load. These tests generated significant data, indicating that higher thrust loads (in alluvium particularly) are beneficial in obtaining higher advance rates.
- A test was performed in which the tuff specimen was tilted deliberately while being penetrated by the 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).
- The design of a 50-mm-diam penetrator with a fluted body was completed, which should have some structural and melt-flow advantages over a conventional configuration.

2. 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. As indicated in Fig. 5 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.

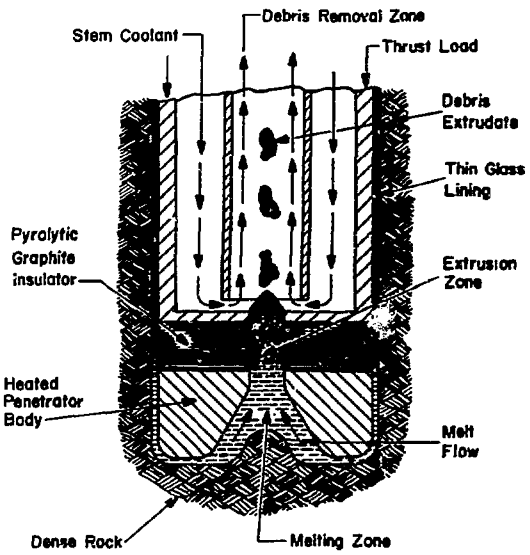


Fig. 5. Extruding penetrator concept.

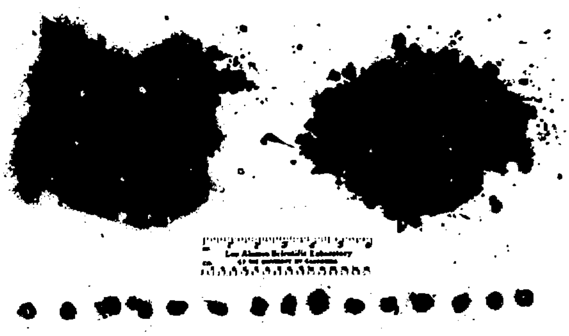

Fig. 6. Debris from basalt hole made by extruding penetrator showing rock wool and glass-pellet constituents.

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. 6.

Significant technical achievements in this area include:

- 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 will be referred to as "Universal Extruding Penetrators" (UEPs).
- A 66-mm-diam UEP was assembled and tests were initiated. A series of laboratory melting and endurance tests were conducted in preparation for field tests in a basalt ledge.
- A 65-mm-diam extrusion penetrator melted a hole in a concrete specimen.
- The design of a UEP with a higher advance rate was completed and fabrication has commenced. The design required a diameter of 82 mm to accommodate the requisite melt-flow channels and three sets of pyrolytic-graphite heater stacks. This design introduces the concepts of extended melting surfaces and multiple melt-removal or -transfer channels to promote thinner melt layers. A sketch of this penetrator is shown in Fig. 7, and the predicted performance map for this penetrator melting in basalt is included as Fig. 8.

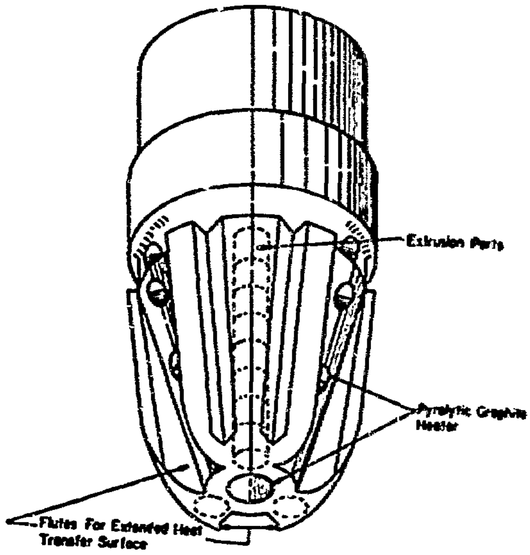


Fig. 7. Extended-surface 82-mm-diam UEP.

3. 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

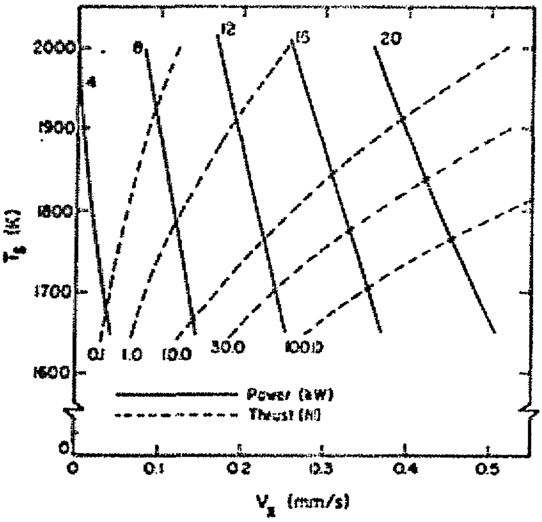


Fig. 8. Projected lithothermodynamic performance for 82-mm-diam high-advance-rate UEP in basalt. Penetration rate, $V_x$, vs penetrator surface temperature, $T_s$, showing curves of constant power and thrust.

Fig. 10. Exterior view of self-supporting glass-lined hole melted in unconsolidated alluvium.

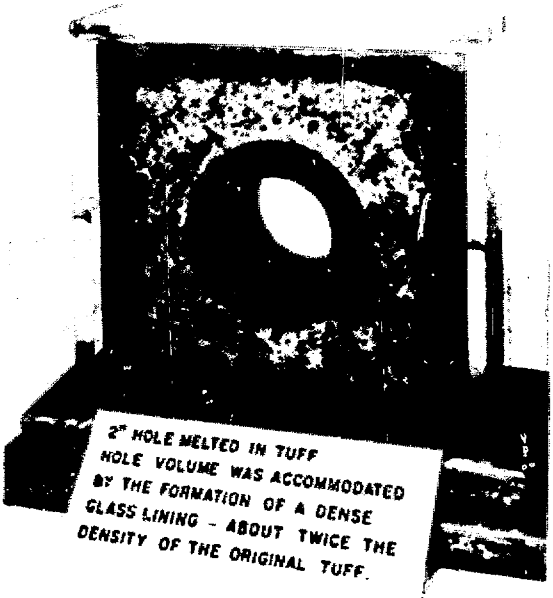


Fig. 9. Cross section of hole melted in tuff.

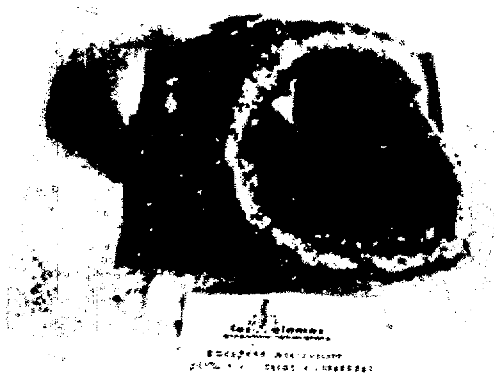

Fig. 11. Sample of glass-lined bore melted in simulated artic permafrost.

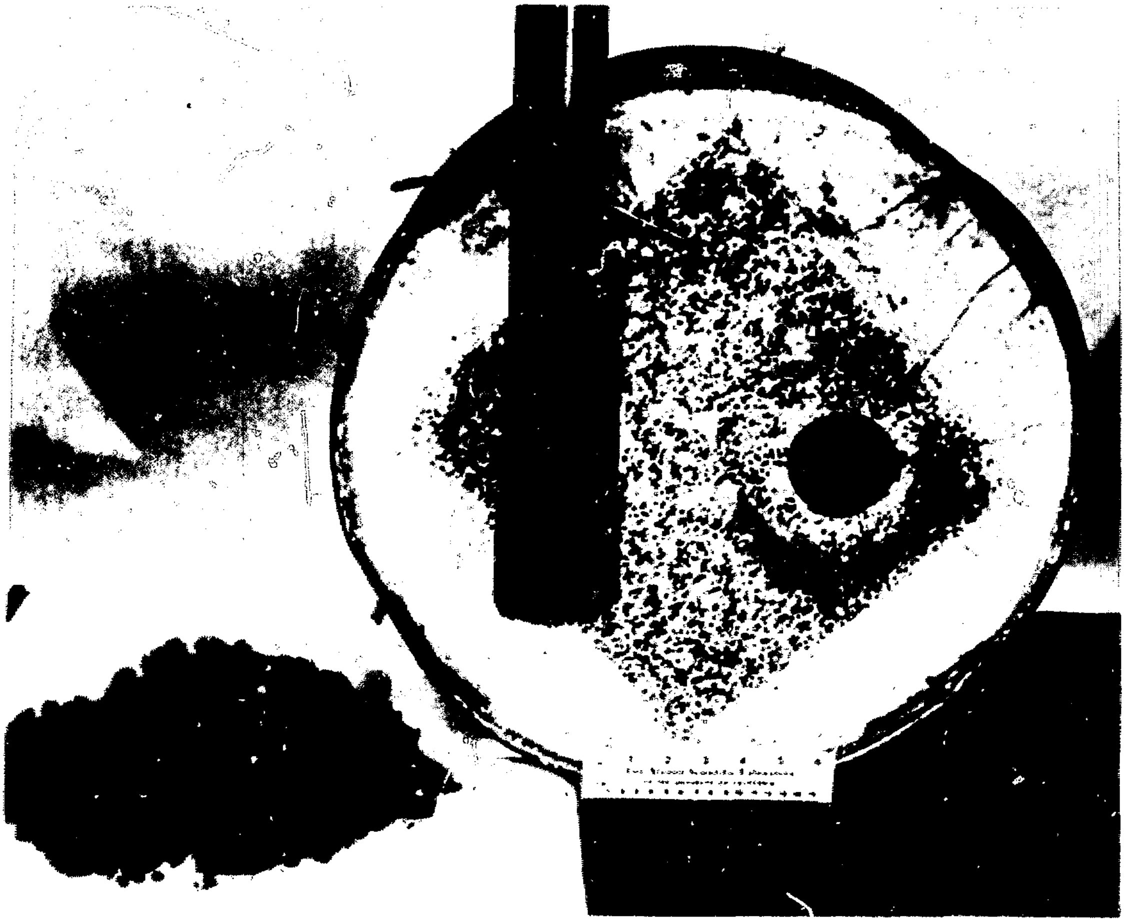

Fig. 12. Hole in granite sample melted by UEP. Note extruded debris and thin glass lining.

inception of the program. Typical examples are the thick glass lining associated with a hole melted in tuff illustrated in Fig. 9 and a self-supporting glass-lined hole melted in unconsolidated alluvium illustrated in Fig. 10. 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 produced glass-lined holes in the frozen specimens as depicted in Fig. 11.

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 and debris illustrated in Fig. 12 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 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. The thin glass lining and extruded glass rods are illustrated in Fig. 13.

To provide further standardization in rock-melting penetration tests, a set of eight standard rock types commonly used in rock mechanics research has been ordered. This set includes basalt, granite (3 types), limestone (2 types), quartzite, and sandstone.

Fig. 13. Hole in tuff melted by UEP. Note rods of extrudate and thin glass hole lining.

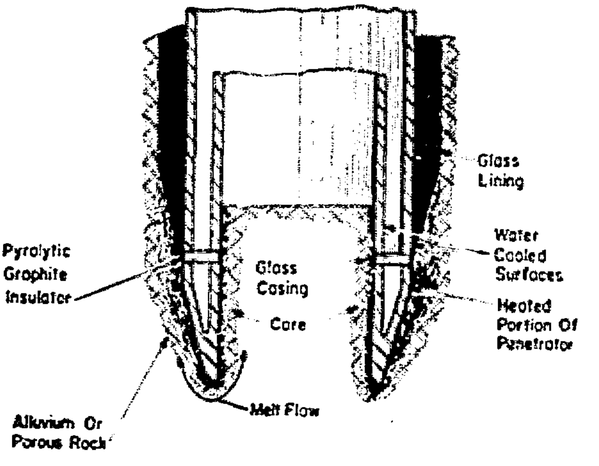


Fig. 14. Schematic of consolidating-coring penetrator.

4. High Advance Rate Experiments

As indicated in Section II-B, 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 (~ 3x) rate than previous UEP designs. A design study has also been initiated on a high-advance-rate consolidating penetrator that will incorporate the favorable aspects of the melt-transfer consolidation (MTC) concept detected by analytical studies. The theoretical analysis of this concept is covered in detail in Section VI-B. Advance-rate goals of from 0.4 to 0.8 mm/s (~ 5 to 10 ft/h) have been chosen.

## C. Alluvium 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. 14.

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. 15. 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. Design power level is 13 kW, and initial testing was accomplished at 9 kW in alluvium with low thrust loads and penetration rates in

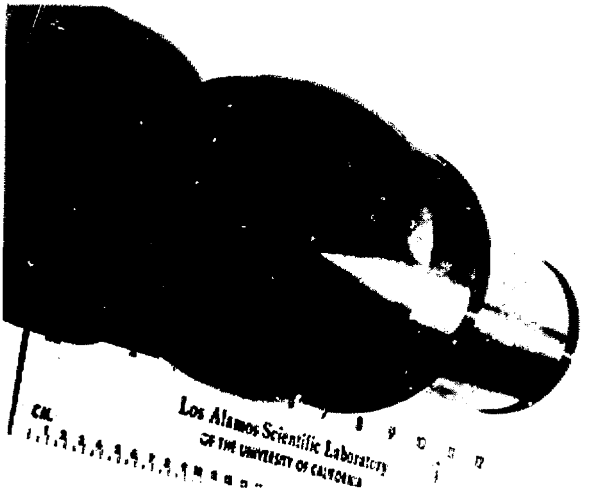

Fig. 15. Photograph of 114-mm-diameter consolidating-coring penetrator.

the range from 0.05 to 0.15 mm/s. Initial testing supported by two-dimensional heat-conduction calculations verified that rock-melt temperatures were undesirably high behind the insulating pyrolytic-graphite washer, resulting in high stem temperatures. This portion of the coring penetrator is being redesigned to alter the thermal fluxes, and further testing will commence after these design changes are implemented. A detailed litho-thermodynamic analysis of the performance of this design has been developed and directions for significant improvements in advance rate have been indicated.

D. 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. 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.

## A. Materials Science and Technology

### 1. Introduction

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. 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.

### 2. Refractory Alloy-Rock Melt Interactions

A literature survey was conducted on the types of apparatus suitable for determining interaction rates between penetrator refractory alloys and rock melts. Although dynamic testing systems will eventually prove desirable, intentions are to initially use static compatability tests between molybdenum and tungsten and various rock melts. Static compatibility testing has been initiated with studies of the corrosion or dissolution reactions of molybdenum with standardized basalt rock. Figure 16 shows a typical penetrator coated with basalt glass after completion of a laboratory test. In these experiments the rock "standard" is melted in a molybdenum crucible and held at temperature for known periods of time. After cooling, the amount of metal dissolved in the rock glass is measured and the sectioned crucible is examined metallurgically for evidences of corrosion and chemical reactions. Prior to the actual test, the standardized rock is powered and a sample submitted for chemical analyses. The crucibles are likewise characterized with regard to chemical purity and pretest microstructure.

The first experiments, run at temperatures of 1528, 1913, and 1898 K are being analyzed. These experiments will investigate quantitatively the effects of time and temperature on the reactions between molybdenum and rock glass melts. Information on reaction rates will be obtained, as well as on activation energies, equilibrium solubilities, and reaction mechanisms.

Compatibility experiments have been run between titanium and vanadium on the one hand, and basalt and tuff on the other. The objective was to determine a suitable brazing material for use at the aft end of penetrator bodies. At 1675 K the titanium was severely attacked, whereas reactions with the vanadium were much less severe suggesting its use as a brazing material.

Postmortem metallurgical examinations of several molybdenum penetrators (including a unit field-tested under especially harsh conditions for 295 ks = 82 h) are in progress. 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

Fig. 16. Penetrator coated with basalt glass after withdrawal from hole.

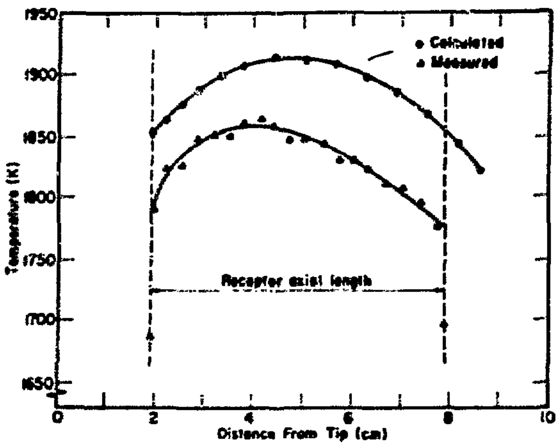


Fig. 17. Comparison of calculated and experimentally indicated penetrator temperatures at the graphite receptor - molybdenum body interface.

that the state of the graphite heater pills inside may also be seen.

3. 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.

Significant technical achievements in this area include:

- 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. As illustrated in Fig. 17, agreement is very good, with the calculated values being ~ 50 K higher. The comparison is limited to those regions where the carbide layer has not delaminated internally.
- The present radiant-heater design is considered superior to that using the molybdenum/boron-nitride/carbon set of materials in view of a marked reduction in complexity and number of potential chemical reactions. Higher operating temperatures are also possible.
- Similar experimental techniques should be applicable to penetrators fabricated from other refractory metal-carbon systems for which appropriate reaction-rate data are available.
- Using available molybdenum-graphite reaction-rate data, the graphite receptor thickness required for a 1000-h lifetime at a given temperature has been calculated. The results for a thin-walled cylindrical receptor and a plane receptor are shown in Fig. 18. Note that these data are strongly temperature-dependent. By using the activitation energies it can be shown that a temperature increase in the receptor of 200-300 K will increase the carbiding rate constant by a factor of ten and hence reduce the life by a corresponding factor. These calculations are being extended to the case of tungsten penetrator bodies and TaC-coated receptors.
- Preliminary experiments have been initiated to evaluate thin vapor-deposited TaC coatings on graphite receptors to serve as a barrier in preventing excessive internal carbiding within the molybdenum penetrator body. Graphite receptors and electrical contact rods have been coated with a layer of TaC having an average thickness of 0.33 mm. Initial results indicate that the diffusion barrier will be useful in extending receptor life, particularly for molybdenum penetrators.
- Additional internal oxidation protection for molybdenum extraction portions of penetrators has been provided through the use of either platinum or $MoSi_2$ coatings.

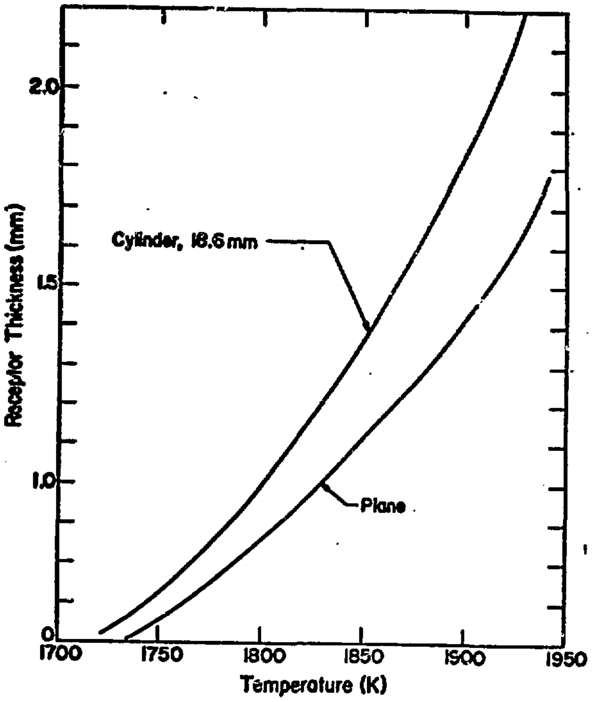


Fig. 18. Calculated graphite receptor thickness required for 1000 h life vs temperature for thin-walled cylinder and plane geometries.

- Penetrator service life goals of 1000 h have been established, and efforts are in progress to define life-limiting mechanisms and to indicate directions for solutions.

4. Rock Glass Technology

The Corning Glass Works, Corning, New York, were visited to acquire technical information about glass technology that can be applied to rock glasses and thereby form the basis for a rock-glass optimization development program. In addition, the groundwork was established for technical collaboration with Corning in the Subterrene program relative to such tasks as rock-melt viscosity determinations. As a result of this visit, a rock-glass development and strength-optimization program has been outlined and initiated.

B. 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. General Electric Co., Cleveland, OH, can produce tungsten blanks as large as 200 mm in diameter, and Wah Chang Corp., Albany, OR, is optimistic about working in large forged and ring-rolled shapes of tungsten and moly-tungsten alloys. The fabrication technology required to pierce and ring-roll large tungsten shapes is not expected to introduce any particularly new problems.

A new alloy, Mo-30 wt% W, has been obtained and is undergoing metallurgical examination. Consolidating 50-mm-diam penetrators have been fabricated from this alloy, and manufacturing ease was found to be equivalent to that of molybdenum even though the alloy has a melting temperature 100 K higher.

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.

C. Geosciences

Significant technical achievements in this area include:

- A literature search was conducted to locate the general rheological and thermal properties of basalt melts. A report compiling these properties for basalt has been prepared.
- Preliminary planning for petrological examination of parent rock and derived rock-glass samples is in progress. The potential correlation of petrographic information with physical properties and ultimately its extension to Subterrene design and performance are the desired goals.
- Melting tests have been conducted on several samples of concrete, in particular those used in the 66-mm-diam UEP test. Results indicate that this grade of concrete melts in the vicinity of 1525-1575 K and should be capable of extrusion. Not all components melt, however, but this problem also exists in tuff which has been extruded successfully.
- The melting behavior of granitic gneiss samples has been determined. These samples

were obtained from a quarry on the grounds of Ft. Belvoir, VA, the site chosen for the Washington, DC, display and demonstration.

- Compatibility experiments between molybdenum, tungsten, and basement granites obtained from a borehole made in conjunction with the Geothermal Energy program have been completed.
- A diamond coring setup to obtain small samples of rocks and glasses has been completed. Cores may range up to 25 mm in length and from ~ 3 to 25 mm in diameter. This setup coupled with the Isomet saw and a diamond wire cutter will provide precision-sampling capability.
- Melting-range experiments have been completed on Nevada Test Site alluvial soil, NV; Tuzigoot National Monument, AZ; and Pecos National Monument, NM, rock samples.
- A precision air pycnometer has been added to the laboratory rock-diagnostic equipment. Coupled with adequate sample preparation and weight measurement, it will be possible to accurately determine the density, bulk density, and degree of porosity of the various rocks and minerals.
- Analysis of the total free silica in Bandelier tuff to a depth of 38 m has been completed. The average free $SiO_2$ content is 30.8 ± 1.8%, including cristobalite, with a gradual but distinct trend towards higher $SiO_2$ content with increasing depth. These data supplement the chemical, mineralogical, and water-content information already obtained.

## A. Electric Power Sources

### 1. Introduction

A wide variety of electrical heaters for small-diameter Subterrene penetrators have been designed, constructed, and tested. 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 penetrators 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, because large gradients would require increased heater temperatures which, in turn, would accelerate the chemical reaction rates between the heater surfaces and adjacent materials.

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. 19.

The direct-current path is down the center stem conductor, through the spring-loaded electrode connector 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:

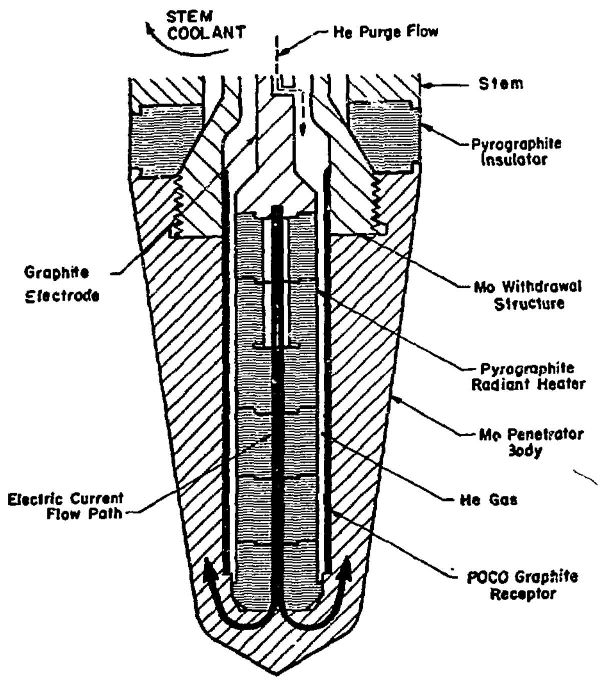


Fig. 19. Cross section of a consolidating penetrator with stacked pyrographite radiant heater and a POCO graphite radiation receptor.

- 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 absorbtivity 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.

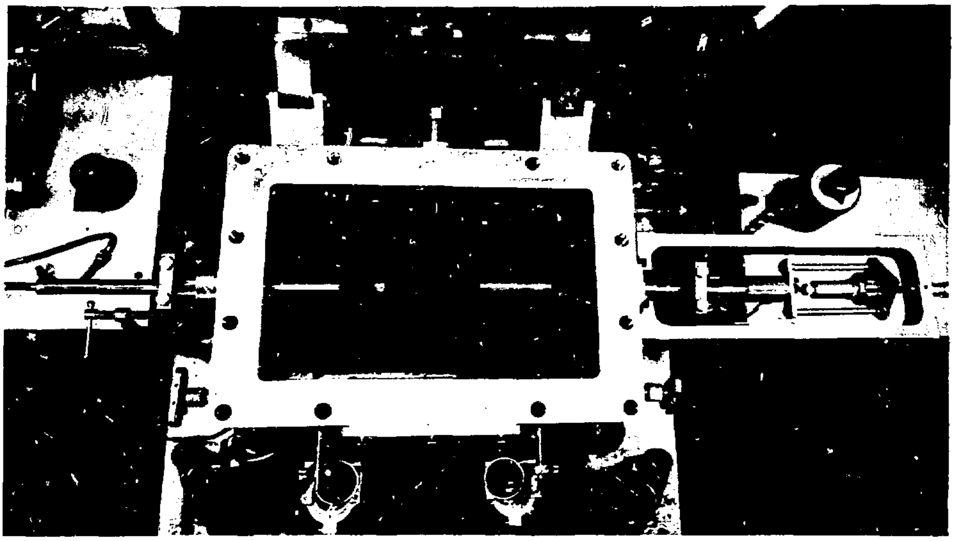

Fig. 20. Photograph of heater characterization apparatus.

2. Heater Development and Characteristics for Penetrator Research

Significant technical achievements in this area include:

- The design, fabrication, and field-testing of an improved electric heater for consolidation-mode penetrators (in which the penetrator body, withdrawal structure, heater elements, and graphite electrode are a hermetically sealed unit) was completed. Included in this development program was the fabrication of a special heater-processing apparatus for filling the penetrator with helium and testing the hermetic seal at operating temperatures. This apparatus is installed in the heater-development laboratory and is also used for temperature-cycling the completed penetrator system by using the internal heater.
- The design, fabrication, and utilization of a heater-characterization apparatus has been completed. Characterizations of pryolytic-graphite heater assemblies to be used in 50-mm MCPs, 66-mm UEPs, and 114-mm ACPs with respect to overall electrical resistance, specific resistivity, and heating uniformity at temperatures up to 2600 K were accomplished. A photograph of the heater-characterization apparatus is shown in Fig. 20, and typical resistance-vs-temperature plots for stacked pryolytic-graphite heaters obtained from this apparatus are shown in Fig. 21. Each heater element that will be used in a field or laboratory test penetrator is routinely characterized in this appatus to verify heater uniformity and quality control.
- The design, fabrication, and utilization of the first heater test apparatus has been completed. The heater test apparatus evaluates heater performance under realistic conditions, but in a carefully instrumented situation and without the presence of molten rock. Various heater designs can be tested for performance in terms of operating temperature, input power, and heat-flux distributions as well as for electrical and chemical stability. A photograph of the apparatus taken during the initial assembly is shown in Fig. 22. The apparatus basically consists of: (1) a 50-mm-diam molybdenum cylinder which is analagous to a penetrator body, (2) a heater element identical to that used in the 50-mm MCP; (3) a closely fitted water-cooled copper jacket that acts as a heat sink for the energy rejected by the molybdenum cylinder, and (4) the associated instrumentation for monitoring the test.

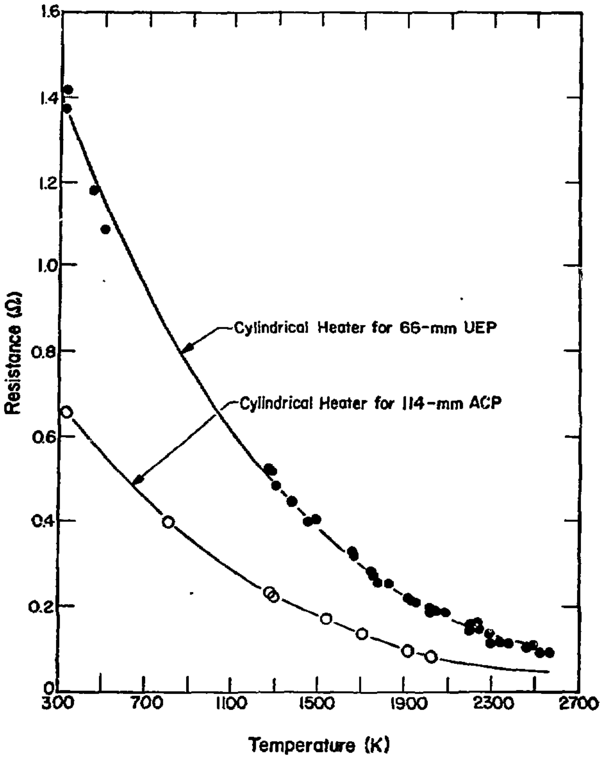


Fig. 21. Typical resistance-vs-temperature plots for pyrolytic-graphite heaters.

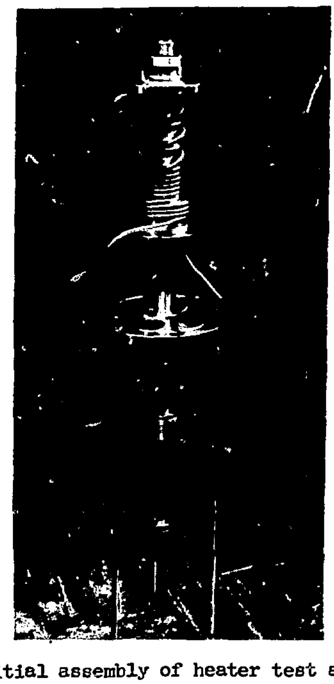

Fig. 22. Initial assembly of heater test apparatus.

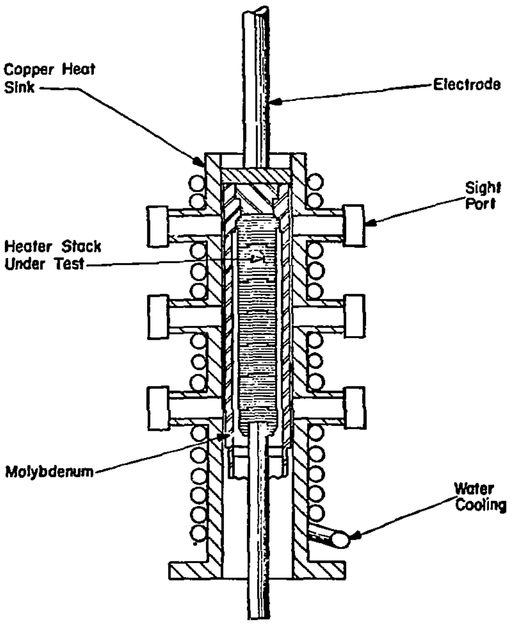


Fig. 23. Cross section of heater test apparatus.

The heater cavity and the gap between the cylinder and the cooling jacket are filled with a helium-argon gas mixture, the exact composition of which is adjusted to produce a wide range of power demands for a given cylinder surface temperature. A cross-section of the heater test apparatus is illustrated in Fig. 23. Typical test data relate heater temperature to input power and molybdenum-cylinder surface temperature.

- The first heater-lifetime test stand to perform extended laboratory heater lifetime tests has been built. One unit has been completed and five more stations are being constructed. The heater lifetime test stands are similar in design and operation to the heater test apparatus. The first lifetime test was terminated after 720 ks (200 h) although the heater was still performing satisfactorily. Data from these tests will be used for reliable estimates of prototype heater lifetimes.
- Design concepts have been formulated for high-advance-rate penetrator heaters aimed toward supplying more thermal energy directly to the leading edge of the penetrator.

- The low-temperature resistivity of a supply of pyrolytic graphite was measured so that future heater fabrication can utilize these resistivity differences to meet design needs.
- The use of a TaC-coated receptor to reduce the carburization of the molybdenum penetrator body has been verified in the laboratory. Test operating conditions were: body surface temperature, 1800 K; heater temperature 2450 K; power input, 4.6 kW; and a heater surface heat flux of $\sim 1.4$ MW/m$^2$.
- Annular or ring-shaped pyrolytic-graphite heaters have been designed and characterized for use in UEP and ACP designs. Heaters of this design have been operated in laboratory tests of the ACP and performance was essentially as predicted.

3. Alternatives to Direct Resistance Heating

One possible approach to increasing the heat flux at the leading edge of penetrators and also alleviating the need for very high currents in higher-power-demand systems is to employ electron-beam heating of the penetrator body. The energy in the beam can be controlled over a wide range of voltages and currents, and stem design can be focused on insulating for the higher voltages with conductors of relatively small cross sectional area. One design employs a diode gun structure with the cathode in the form of a concentric double tube. Initially, heat is supplied to raise the cathode to its operating temperature of $\sim 2500$ K by direct resistance-heating. As the penetrator body reaches its operating temperature of $\sim 1800$ K, only a small amount of power would be required to maintain cathode temperature. Electron emission from the cathode is a strong function of temperature, and the desired voltage-current relationship is therefore maintained by controlling the heating current applied to the cathode.

The second design uses an electron gun with a suitable beam-shaping anode plate. The relatively small cathode area can be heated initially by a lower current than the diode design, and this current would be reduced further as the penetrator body approaches its operating temperature.

In addition, the use of high-temperature liquid-metal heat pipes for enhancing the energy flow to critical penetrator areas is being studied. High thermal heat fluxes, low operating temperature gradients, and the ability to locate the heat source remotely are a few of the potential advantages of heat-pipe systems.

B. Power Source Controls

The design, construction, and calibration of a digital readout system for monitoring penetrator power, voltage, current, and heater resistance for both laboratory and field-test operation has been completed. The design and fabrication of an automatic power-system control unit to be used initially as a part of the lifetime test stands has commenced. This unit will be incorporated into a more sophisticated advance rate-power control system including feedback control loops.

## V. FIELD TEST AND DEMONSTRATIONS

### A. Field Demonstration Units

#### 1. Introduction

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). 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:

- Provide field demonstrations of basic rock-melting principles and capabilities.
- Produce glass-lined drainage holes in archaeological ruins.
- Melt prototype utility holes under roadways.
- Test improved glass-forming designs.
- Provide extended-lifetime test data for the refractory metal penetrators.
- 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 in place of the laboratory water or inert-gas cooling systems. A schematic sketch of the completed FDU is shown in Fig. 24. The various modularized components are designed to be stored and transported in one trailer.

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

- <u>Thruster</u> - 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.

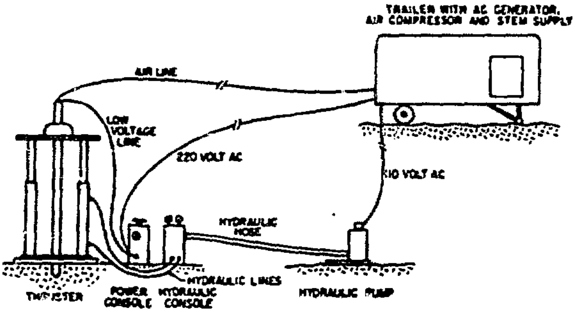


Fig. 24. Schematic of initial field-demonstration unit.

- <u>Hydraulic Power Supply and Control Console</u> - An electric-motor-driven hydraulic pump supplies pressurized oil to the control 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. An accumulator in this console provides a reservoir of available hydraulic power for rapid movement of the thruster or for emergency use in retracting the penetrator in the event of an electrical failure.
- <u>Electric Power Supply and Control Console</u> - Electrical power is supplied by a gasoline-engine-driven generator which provides ~ 10 kW of 240-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.
- <u>Air Compressor</u> - A gasoline-engine-powered air compressor is used to supply cooling air to the penetrator stem and for chilling the rock-glass lining.
- <u>Melting-Consolidating Penetrator</u> - This part is a sealed penetrator unit designed to operate with the air-cooled stem for penetrating porous rocks and soils.
- <u>Stem Sections</u> - Modified sections of standard drill rod commonly used in oil-field drilling are used. They are fitted with an internal

Fig. 25. Consolidating penetrator at exit of ~ 15-m-long horizontal hole in tuff.

copper tube which serves as a conduit for the cooling air and as a conductor for the electrical power to the penetrator heater.

2. Technical Achievements

Significant technical achievements in this area include:

- The design, fabrication, and successful utilization of two field-demonstration units for use with 50-mm-diam air-cooled, sealed, consolidating penetrators.
- The use of a FDU to make a 13-m and a 15-m horizontal penetration into Bandelier tuff. The exiting penetrator is shown in Fig. 25 for the 15-m-long hole, and the field-demonstration unit is shown in place in Fig. 26.
- 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.

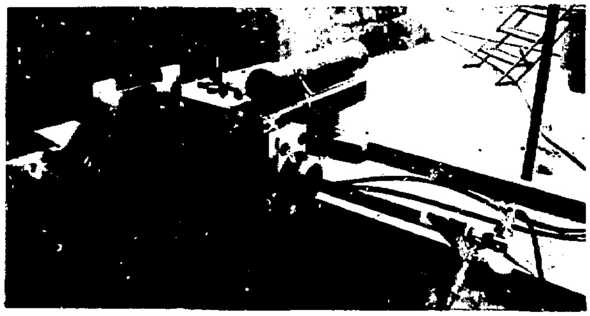

Fig. 26. Field-demonstration unit in position for horizontal penetration.

- Eight water drainage holes were melted with a FDU at the Rainbow House and Tyuonyi archaeological ruins at Bandelier National Monument, NM, in cooperation with the National Park Service. By utilizing a consolidation penetrator, the required glass-lined drainage holes were made without creating debris or endangering the ruins from mechanical vibrations. Fig. 27 shows the rock-melting demonstration unit in place at Rainbow House and Fig. 28 shows the unit at the plaza in the Tyuonyi ruins. Specifically, this operation has shown the following:

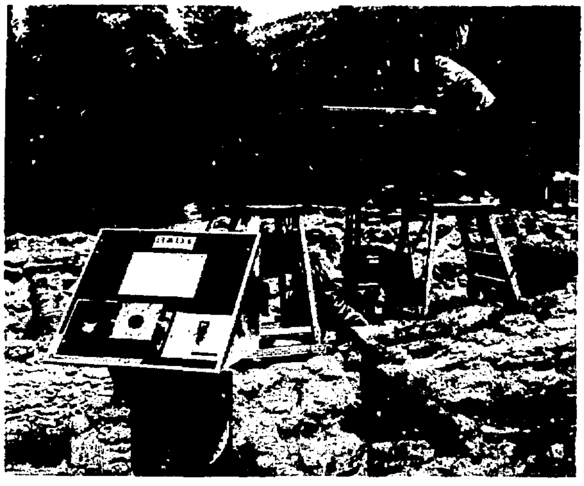

Fig. 27. Rock-melting demonstration unit at Rainbow House ruins.

Fig. 28. Rock-melting demonstration unit at Tyuonyi ruins.

(1) Subterrenes can be operated successfully under field conditions and in areas remote from the laboratory.

(2) The consolidating penetrator can make 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.

(3) The Subterrene has demonstrated its first useful and unique application and has been established as more than a laboratory device.

- The Subterrene rock-melting unit was turned over to the National Park Service (NPS) after completion of the first five holes at Bandelier and after suitable training of NPS personnel. The NPS subsequently melted three more holes with minimal LASL supervision.
- A field-demonstration unit which will operate with a 66-mm-diam universal extrusion penetrator for hard-rock penetrations has been designed, fabricated, and successfully tested in basalt.

3. Public Demonstrations

The initial melting of drainage holes in Indian ruins at Bandelier National Monument has been completed. Considerable interest in the Subterrene operation was shown by the tourists and visitors to the Monument. An invitation has been received to conduct a Subterrene demonstration in Washington, DC, in early October. Plans for this event are in progress, a site has been selected, and the penetrator equipment and mobilization trailers are available.

B. Large Diameter, Mobile Test Rig

The design of a mobile test rig has been completed and the unit is being fabricated. This rig will be used with penetrators from 50 to 127 mm in diameter, with initial testing accomplished with the 114-mm-diam alluvium-coring penetrator. The primary components of the rig are:

- Trailer-mounted thruster and stem tower.
- 125-kW electric power supply.
- 125-kW rectifier and power conditioner.
- Control consoles, instrumentation displays, and recording equipment.

The thruster will be able to support pipe stems 300 m long and will produce a downward force of 80,000 kN. Through the use of a double set of gripping mechanisms and dual thruster systems, the unit will provide continuous movement of the stem during field melting operations.

C. Tower Rig

Melting Consolidating Penetrator systems of 50 mm diameter were used to melt several vertical holes in local Bandelier tuff to depths of 16 and 25 m. These experiments were significant because the holes were made continuously under field conditions into undisturbed in situ volcanic rock. However, the electric-power, stem-cooling, and instrumentation systems were derived from laboratory facilities.

The test stand consisted of an 18-m-tall rigging tower which supported (1) the stem-and-penetrator assembly during hole melting; and (2) the pulldown assembly that guided the MCP into the ground. Figure 29 shows the tower rig and Table I lists the operating performance parameters for the 16- and 25-m-deep holes.

Two 8-m-deep holes ~ 300 mm in diameter have been drilled in the tuff formation under this rig and filled with alluvium from the Nevada Test Site so that the 114-mm-diam alluvium coring penetrator can be tested without moving the tower rig from its present location. A modified thruster has been installed and the tower rig is ready for testing the coring penetrator.

TABLE I

TYPICAL OPERATING PERFORMANCE PARAMETERS FOR 16- AND 25-m-DEEP HOLES MADE IN TUFF

| Materials | Input | Results |
|---|---|---|
| Rock, local volcanic tuff | Voltage, 32 V | Hole diameter, 50 mm |
| Penetrator body and tip, molybdenum | Current, 110 A | Total penetration, 15.5 and 25.0 m |
| Heater, pyrolytic graphite | Total electric power, 3.5 kW | Penetration rate, $\sim$ 0.2 mm/s |
| Stem, steel tubing | Penetrator temperature, $\sim$ 1870 K | |
| Stem coolant, nitrogen gas | Heater temperature, $\sim$ 2500 K | |
| | Downward thrust, 4.5 to 13.3 kN | |
| | Downward stroke increment, 0.9 m | |
| | Withdrawal force required, 6.7 kN | |

## D. Penetrator Life Test Facility

A facility is being designed to test the long-term abrasion and corrosion wear rate of melting penetrators. The facility will consist of two units, each of which will control the operation of two penetrators. The penetrators will travel in 5-m-long troughs filled with alluvium or other types of compacted soils or rocks. After each test run the glass linings will be removed and new material will be added to the troughs for the next test. The facility will be housed in a sheltered area to control the moisture content of the materials and to permit extended, uninterrupted operation.

## E. Test Site Location and Preparation

A basalt formation in Ancho Canyon near Los Alamos has been selected as the Subterrene Basalt Test Site (designated as LASL Technical Area 56) for field demonstration of extruding penetrators. Overburden has been removed to expose the surface of the basalt layer for convenience in conducting the field tests. Easy access has been provided to this area, and the 66-mm-diam FDU has been assembled and is operating at this location.

Fig. 29. Tower rig for melting holes with preassembled stem length of $\sim$ 15 m. Rigged for melting holes in tuff with a MCP.

## A. Large Tunneler Design and System Definition Study

### 1. Introduction and Conceptual Design

The most challenging and potentially significant application of the rock-melting concept is its adaptation to a large, continuous tunneling machine. The extension of the technology to a large-diameter concept is a natural outgrowth of the program in progress at LASL to develop small prototype penetrators. The list of existing and potential applications for rapidly produced, relatively inexpensive large holes, tunnels, and underground excavations is very long and offers solutions to many of man's most urgent ecological and technological problems. The implementation of these applications while protecting the environment and preserving the natural landscape is the goal of advancements in excavation technology.

In their 1968 publication on the subject of rapid excavation, the Committee on Rapid Excavation of the National Research Council (NRC) defined ten specific individual research projects that should be pursued on the basis of their potential contribution to the field of underground excavation. Of these ten recommended research projects, no less than seven are directly relevant to the research activities on rock-melting technology and its application to the large-tunneler concept and to an automated geological coring device termed Geoprospector.

Unlike the small-diameter applications of the rock-melting concept where a single technique for material removal may be utilized, the volume requirements of a large tunneler system lead quite naturally to a combination of such techniques. Although numerous combinations of penetration-mode techniques appear feasible, two combinations are noteworthy because they attack the two extremes of undesirable ground conditions. A conceptual design of the penetrating face of a tunnel-boring machine for soft or unconsolidated ground utilizing the rock-melting kerfing technique is illustrated in Fig. 30. The tunnel bore is formed by a series of segmented peripheral kerf-melting elements. The unsymmetrical profile of these kerfing elements directs the melted rock radially outward to form a thick molten layer utilizing density consolidation for melt disposal. A glass-forming section, located directly behind the melting elements, conditions the molten rock into a smooth, continuous, glass tunnel lining. The individual segments forming the peripheral kerf melter could be serviced or replaced as separate units. An array of conventional soft-ground mechanical cutters is located on a rotating face contained within the peripheral kerf melter. Gage cutters are not required as a result of the melted and glass-lined tunnel bore and a continuous conveyor or hydraulic slurry pipeline could be used for conventional muck removal.

A conceptual design of the penetrating face of a tunnel-boring machine for hard, dense, and abrasive rock incorporating the rock-melting kerfing technique and thermal-stress fracturing is illustrated in Fig. 31. The tunnel bore is again formed by a series of segmented peripheral kerf-melting elements. These elements employ the universal melt-extruding concept and direct the melted debris to a continuous removal system leaving only a thin molten layer along the tunnel bore. A glass-forming section conditions this molten rock into a smooth, continuous glass lining. An array of small-diameter universal melt-extruding penetrators is located on the machine face contained within the peripheral kerf melter. These penetrators advance behind the melting kerf in a pattern sufficiently dense to cause thermal-stress fracturing of the heat-affected rock. The melted debris from these small-diameter penetrators is directed to the continuous melt-removal system. The concept envisions the use of many closely spaced small-diameter penetrators to keep the total melted volume low while still initiating high thermal stresses in the rock regions between adjacent penetrators. The muck resulting from thermal-stress fracturing could be either removed by a separate conventional system or mixed with the melt debris and introduced into a fluidized pipeline transport system.

### 2. Nuclear Subterrene Tunneling Machine (NSTM)

Based on preliminary calculations, a power-source requirement of ~ 15 MW (thermal) would be required for a kerf-melting tunneler for desirable penetration rates in the 6-m-diam range. Although electric heaters will be studied for a variety of geometries and power levels, it is anticipated that

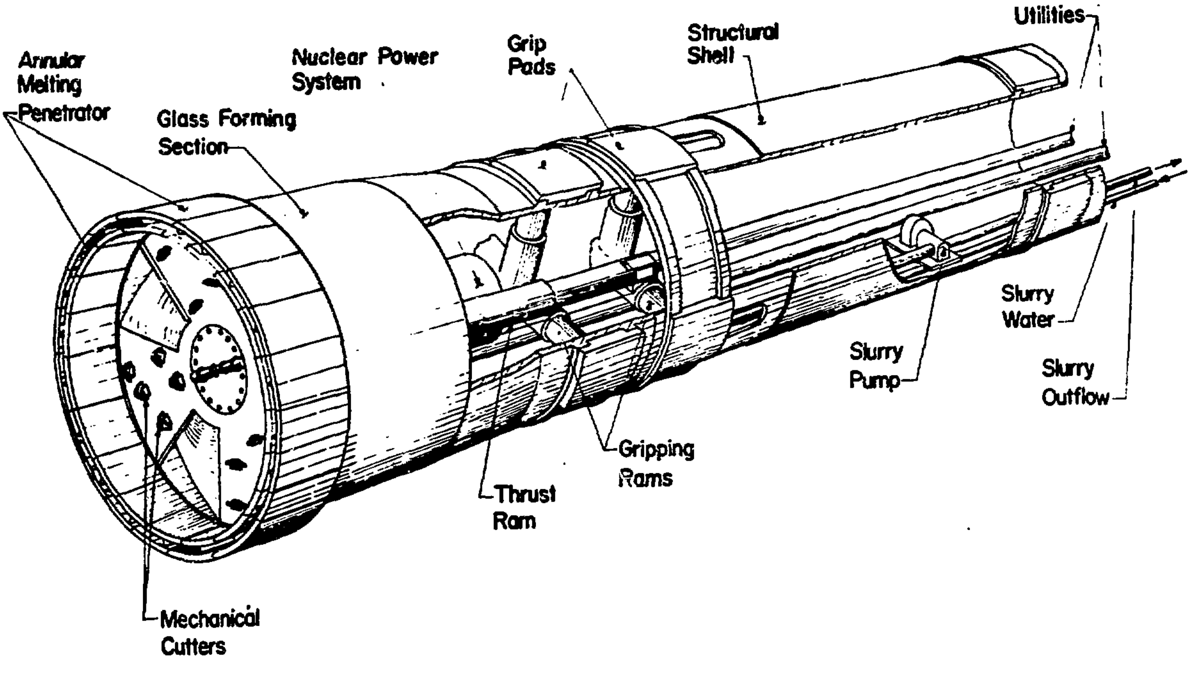


Fig. 30. Design concept of the penetrating face of a soft-ground rock-melting tunneler utilizing the kerfing technique.

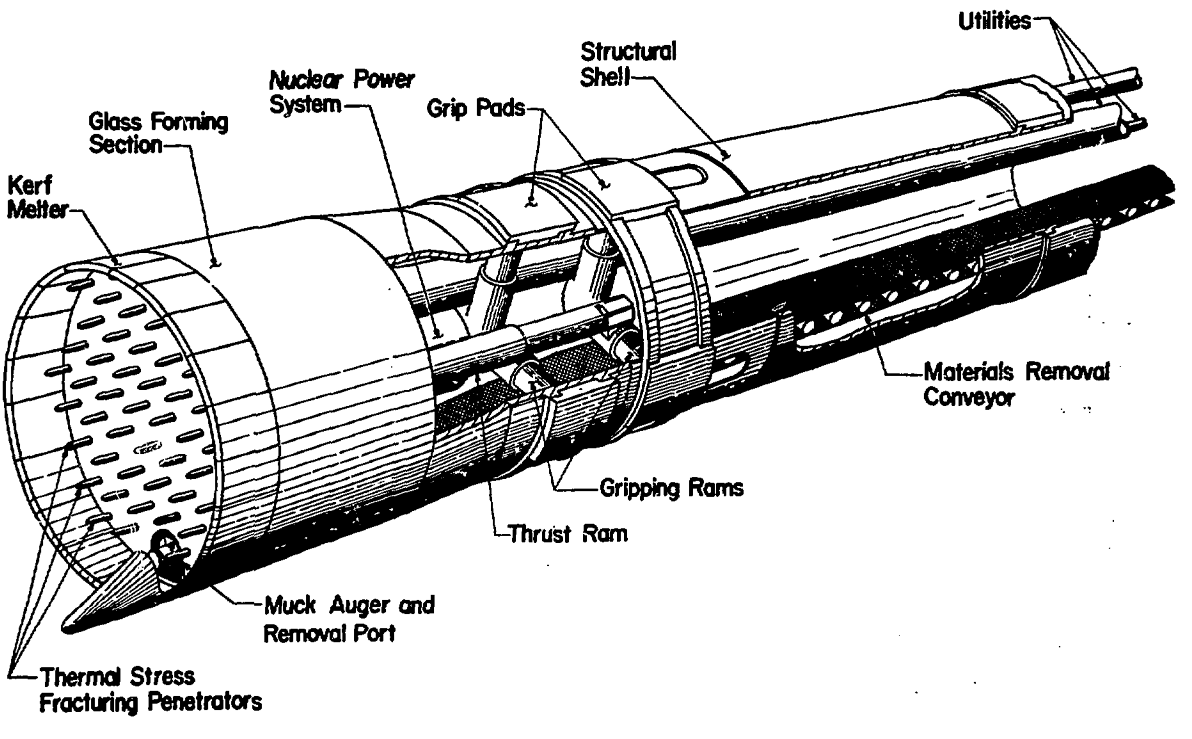


Fig. 31. Design concept of the penetrating face of a hard-rock melting tunneler utilizing the kerfing technique and thermal stress fracturing.

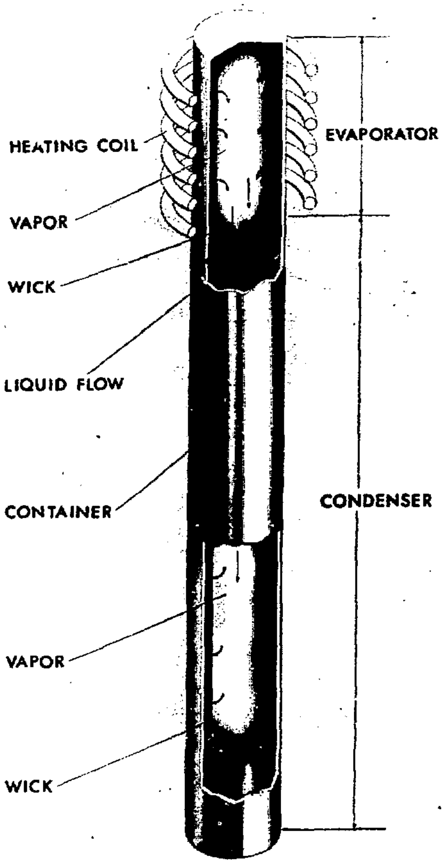


Fig. 32. Basic components of a liquid-metal heat pipe.

economic and technological tradeoffs will favor a compact nuclear power source at a total power requirement less than 10 MW. A compact nuclear reactor could supply the energy for even a very large penetrator advancing at a high rate and would permit the conceptual design of a self-contained unit controlled by telemetry from the surface. The size of such a source, even including elaborate shielding, would allow its use in diameters appreciably smaller than the 6-m size used as an example.

Development work on systems that would optimize the energy transfer from the power source to an array of melting penetrators has led to the utilization of the LASL-developed heat-pipe technique for both nuclear and larger electrical sources. For Subterrene applications, the evaporator end of the heat pipe is embedded within the electrical or nuclear heat source, and the condenser section would be adjacent to the rock-melting surface. The basic components of a liquid-metal heat pipe are illustrated in Fig. 32.

The general field of heat-pipe-cooled nuclear reactors has been investigated at LASL, and experimental work has been performed to establish the feasibility of such designs. The use of heat pipes for cooling and transferring energy from a reactor is attractive because it permits the design of highly redundant systems. The conceptual design of a compact nuclear reactor which could be adapted for Subterrene application is shown in Fig. 33. Numerous heat pipes transport the reactor energy to the melting face of the penetrator. Two-dimensional heat-transfer calculations have indicated that a sufficient number of heat pipes of overdesigned capacity can be included in such a design to permit sustained operation of the reactor with allowable fuel-element temperatures in the event of isolated heat-pipe failures. Reactor power is controlled through the use of multiple control rods which are withdrawn through the aft radiation shield.

### 3. Potential Sources of Economic and Technological Gains

Stressing the total system concept, the objective is to provide a well-matched tunneling concept that attacks the three major aspects of tunneling: excavation, materials handling, and supports and linings. Although novel rock-disintegration techniques have been categorically criticized on the basis of their higher specific-energy consumption, the fact that power costs represent a very small percentage of the tunnel cost has been documented. The following potential advantages of NSTMs are noted:

- The elimination of temporary tunnel supports by substituting a formed-in-place glass lining, especially in weak and broken rock.
- The elimination of permanent tunnel linings in those applications for which the formed glass lining is independently adequate.
- Cost reductions resulting from the use of completely prefabricated permanent tunnel linings made possible by the dimensionally stable and precise geometry of the glass linings.
- Penetration-rate advances in hard rock by the use of a continuous process as opposed to the intermittent drill-and-blast technique.

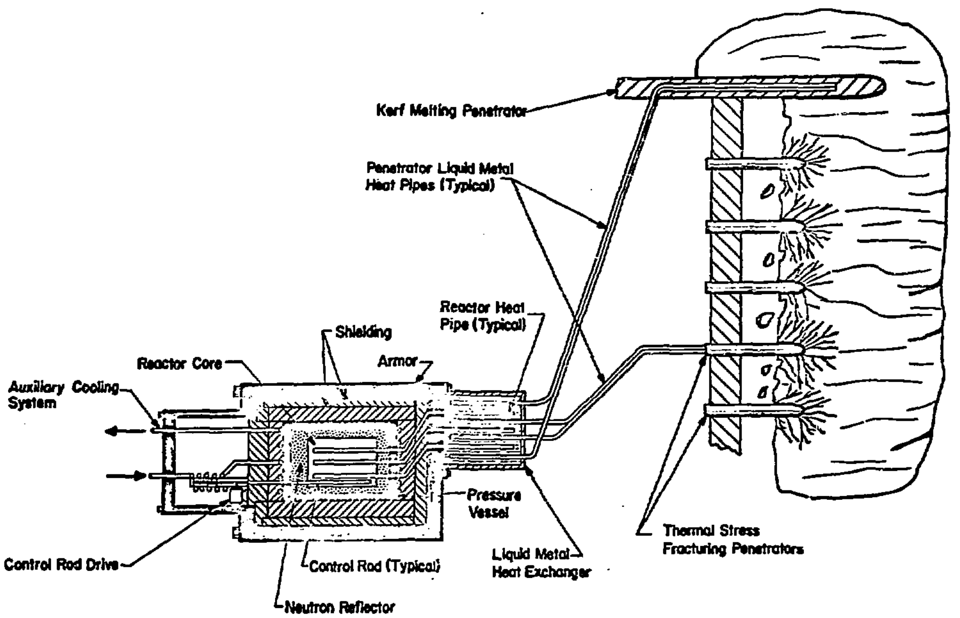


Fig. 33. Schematic of a shielded, heat-pipe-cooled nuclear reactor for Subterrene applications.

- Penetration-rate advances in loose or unconsolidated ground through the elimination of the serious risk of roof failure.
- Additional tunnel stability through the use of a hard-rock disintegration technique that preserves rather than reduces the inherent strength of the unexcavated rock mass.
- Reductions in tunneling-machine downtime through the elimination of gage cutters and reductions in the number of mechanically wearing components.
- Reductions in excavation cost resulting from the ability to produce bores of any desired cross-sectional shape.
- Improved environmental control through the elimination of hazards resulting from excessive dust, noise, ground shock, fumes, and ground collapse.

## B. Theoretical Analysis

### 1. Introduction

Theoretical analysis research has progressed in both the analytical formulation and the numerical analysis directions. Efforts have been directed toward the development of new analytical and numerical techniques for analyzing the combined fluid dynamic and heat-transfer (lithothermodynamic) 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.

### 2. Computer Code Development

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 respresents a discipline of its own. Solutions will be characterized by the following features:

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

- Initially, only steady-state axisymmetric solutions need be considered.
- In addition to the sensible-heat transfer, an effective latent heat of melting must be included in the thermal energy balance.
- 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 $v_r$ and axial velocity $v_z$, these equations are:

$$\frac{1}{r}\frac{\partial}{\partial r}(r\, v_r) + \frac{\partial v_z}{\partial z} = 0, \text{ the continuity equation;}$$

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

the r-direction Navier Stokes equation;

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

the z-direction Navier Stokes equation; and

$$\rho c\left(v_r \frac{\partial T}{\partial r} + v_z \frac{\partial T}{\partial z}\right) = \frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda \frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right)$$

the energy equation;

where P is the pressure and $\mu$, $\rho$, c, $\lambda$, 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. 34 where the new transverse coordinate is $\eta$, the meridional or streamwise coordinate is S, $\ell$ is the local melt-layer thickness, and $\beta_0$ is the angle between the penetrator surface and the axis of revolution.

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

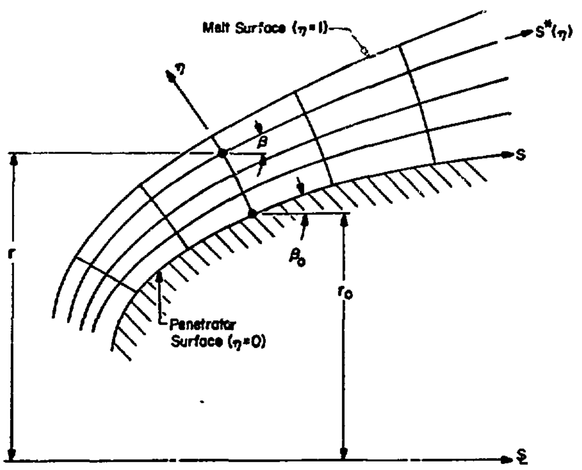


Fig. 34. General curvilinear orthogonal coordinate system.

$$\frac{\partial}{\partial \eta}(\sigma r v) + \frac{\partial}{\partial S}(\ell r u) = 0, \text{ the continuity equation;}$$

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

the S-direction Navier Stokes equation; and

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

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 $\eta$ line. As in typical boundary layer theory, the $\eta$ 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. The results have been incorporated into a computer program for performing detailed lithothermodynamic analyses of melting penetrators.

For future stress-analysis calculations on penetrator bodies, extraction, and stem components, a new computer program named PLACID has been developed. PLACID is a finite-element stress-analysis program capable of generating plane stress, plane strain, and axisymmetric solutions. A unique feature of this code is that all input is programmed by the

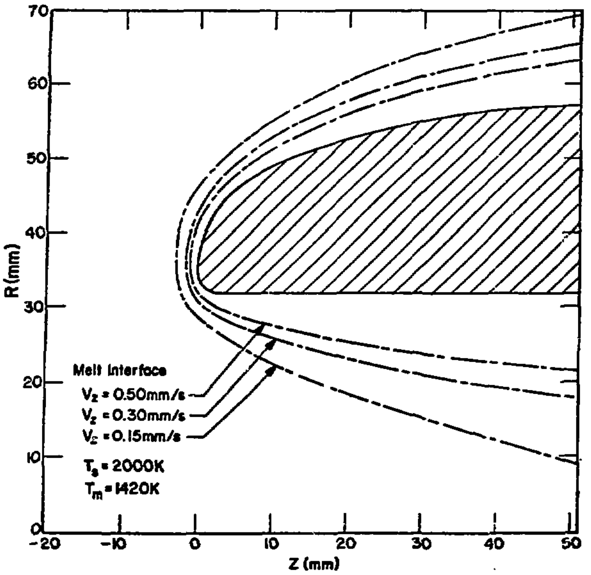


Fig. 35. Melt interface location as a function of penetration rate for an alluvium-coring penetrator.

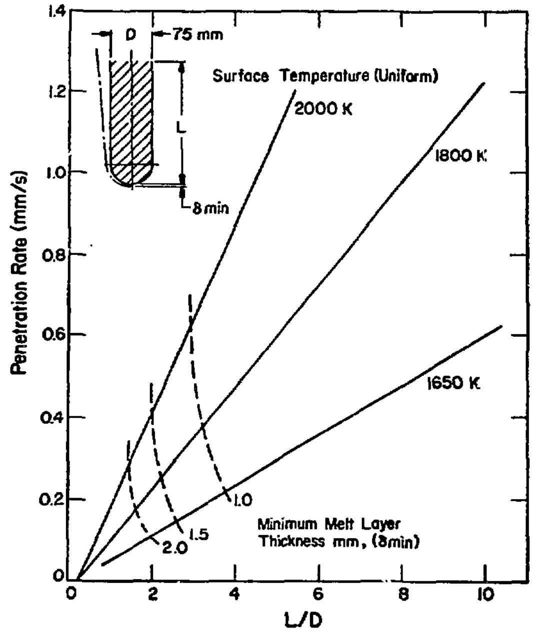


Fig. 36. Calculated lithothermodynamic performance of a hemisphere-cylinder consolidating penetrator in tuff.

user via subroutines. As a result, material properties can be nonlinear, time- and/or temperature-dependent, and can also possess three-dimensional anisotropy.

3. Significant Analytical Results

Noteworthy technical achievements in this area include:

- 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. 35.
- Calculations were performed to predict the significant lithothermodynamic characteristics of the high-advance-rate 82-mm-diam UEP. The predicted performance map for this penetrator design melting in basalt was presented in Section II-B of this report.
- Parametric lithothermodynamic analyses have 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. 36. 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. 36 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 will be referred to as Melt Transfer Consolidation (MTC) penetrators

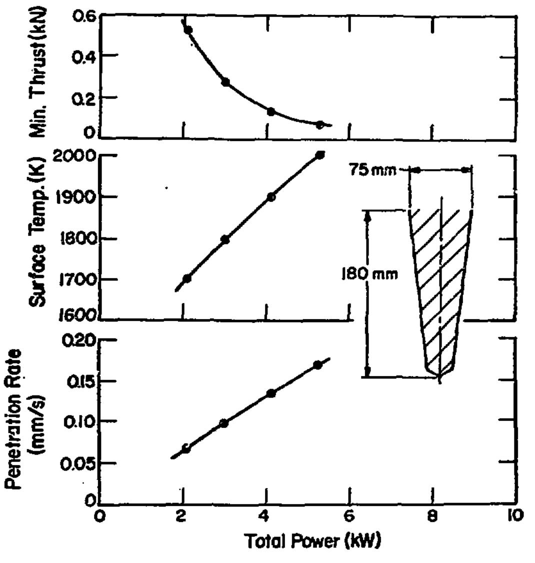


Fig. 37. Calculated lithothermodynamic performance of a double-cone consolidating penetrator in tuff.

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.

- The calculated penetration rate, surface temperature, and minimum thrust requirement as a function of heating power (not including stem-conduction losses) for the 75-mm-diam consolidating penetrator are shown in Fig. 37. 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. 36 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 decreasing minimum thrust depicted in Fig. 37 is a result of the strongly decreasing viscosity associated with the higher penetrator surface temperatures.

- A theoretical investigation on the effectiveness of extended melting surfaces was performed. For UEPs, extended melting surfaces can be used advantageously particularly when combined with multiple melt-removal ports which direct the external melt to the interior of the penetrator. By preserving a thin external melt layer, the effectiveness of the extended surfaces is greatly enhanced. In the consolidation mode, however, the melt layer can only be kept thin over the leading edge of the penetrator and the potential advantages of extended melting surfaces rapidly diminish along the remainder of the penetrator body.

## C. Systems Integration and Model Studies

The first major systems integration and model study, incorporating both technical and economic model developments, has been performed for the large tunneler concept. Three specific objectives were established for this study: First, to develop technically sound conceptual designs of nuclear Subterrene tunneling machines (NSTMs). Second, to make a cost comparison between the conceptual NSTMs and tunneling with Tunnel Boring Machines (TBMs) or conventional excavation methods. And third, to determine the benefit-to-cost ratio for a projected major Subterrene development program costing $\sim$ \$100 x $10^6$ over an eight-year period. The basic characteristics and assumptions involved in the systems model development are outlined below:

- Two conceptual designs for NSTMs, similar to those described in Section VI-A, were utilized in the model study.
- Tunnel sizes studied ranged from 4 to 12 m finished diameter and the average operational sustained advance rate was 1.5 m/h.
- Thermal energy for rock-melting was obtained from a compact nuclear reactor with liquid-metal heat pipes being used to distribute the energy to the rock-melting face.
- The NSTM-generated glass tunnel liners eliminated any other form of temporary support. The glass liner thicknesses assumed for costing purposes were 4% of the finished tunnel diameter for unfavorable conditions and 2% of the finished tunnel diameter for sound, hard rock.

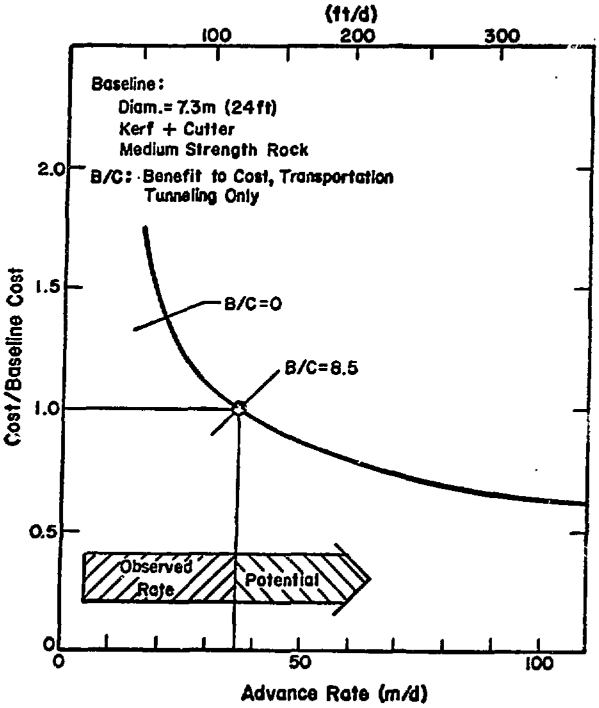


Fig. 38. Effect of advance rate on baseline tunnel cost.

- The permanent tunnel liners consisted of the rock glass plus a conventional concrete liner, with overall liner thickness equaling 8% of the tunnel diameter.
- The excavation face was sealed by the NSTM; muck removal was by the hydraulic-slurry method; and the glass liner, reactor components, and tunnel air were water-cooled.

The study results indicated that for very hard rock or unfavorable soft ground (e.g., wet, running, bouldery), average cost savings of NSTMs over TBMs or conventional methods were estimated to be of the order of 30 and 50%, respectively. Excellent cost benefits for the development of NSTM systems were indicated, considering only U.S. transportation demands up to CY 1990. The predicted effect of advance rate on tunnel cost for a baseline case is shown in Fig. 38. Many other potential benefits in addition to transportation applications also exist. The nuclear thermal-power requirements were calculated to be 7 and 63 MW for 4- and 12-m-diam tunnels, respectively, as illustrated in Fig. 39. The

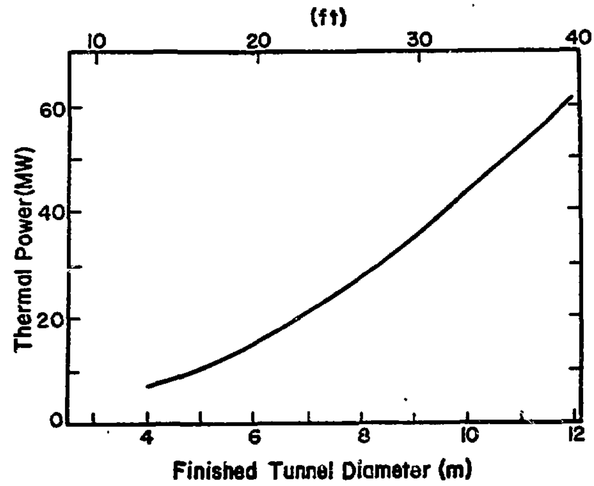


Fig. 39. Reactor thermal power vs finished tunnel diameter.

cost of the thermal power required to melt the rock was ~ 4 to 7% of the total excavation project cost.

## D. Applications and Technology Utilization

The number of novel and conventional applications of Subterrene technology that have been investigated continue to increase and range from deep hot-rock penetrations for geothermal-energy exploration to emplacements in arctic permafrost.

Particular interest in small-diameter, horizontal, glass-lined holes motivated a separate study, which has been completed. These small horizontal borings can be used as underground utility conduits for the installation of telephone, gas, water, and television lines; as glass-lined holes for high-explosive shot emplacement; and as drainage holes to stabilize roadcuts and embankments. The study indicates that hole straightness requirements can be met by adding deviation sensors and alignment-control units to the hole-forming assembly.

The technical reports on all phases of Subterrene activities continue to be in demand and are forwarded to all interested parties. Lists of completed and in-progress Subterrene technical reports, including those intended for publication in scientific journals, appear in Section VII. The Subterrene was featured on the front covers of the June 1973 issue of "Mining Engineering" and the July 1973 issue of "Water Well Journal." Both issues contained accompanying articles. An article entitled

"Subterrene Rock Melting Devices-Showing the Way to New Tunneling Techniques" has been prepared at the request of the editor of "Tunnels and Tunnelling" magazine. This publication is the news outlet for the British Tunnelling Society. In conjunction with the large-tunneler study, all major U.S. tunnel-boring machine manufacturers were visited and briefed on the Subterrene concept. Technical comments and suggestions from their engineering staffs were utilized as guidelines in the conceptual NSTM study.

Technical briefings presented to interested individuals and groups by the Subterrene staff continue at the rate of about ten per month. Interested individuals and groups include United States Senators, representatives of major industrial concerns, representatives of the armed forces, utility and power distribution specialists, drilling and oil-field specialists, University professors, technically oriented professional engineers, and college students.

As a result of discussions with Westinghouse Corp., an Industrial Staff Member has been assigned to the LASL Subterrene project and is currently working in the area of penetrator thermal analysis.

A contact was made with Mr. Walter W. Long of the University of New Mexico, NASA Technology Applications Center (TAC). Discussions of the possible interest by TAC in doing a real-time study of the Subterrene technology transfer efforts, methodology, and successes indicated that the TAC would be interested in such a collaborative effort.

The structure of the proposed Subterrene Technology Advisory Panel has been established with the following initial membership:

- Chairman - A person with broad engineering experience.
- One member from a Federal Agency with interest and responsibilities in tunneling and excavation.
- A University professor from a civil, mining, or geological engineering department with well-recognized expertise in excavation technology.
- An economist with expertise in excavation technology (desirable).
- Three representatives from related industries.

Initial impact in the area of public demonstrations has been achieved through the use of a mobile Subterrene field-demonstration unit in Bandelier National Monument, NM. In addition, a short documentary color film on the Subterrene concept has been produced, and narration via a cassette tape will be available shortly.

## VII. TECHNICAL REPORTS

Copies of the reports listed below can be obtained from:

National Technical Information Service (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151;

the completed reports are identified by their LA-MS numbers by NTIS.

Discussions of the technical reports can be directed to individual authors at:

University of California
Los Alamos Scientific Laboratory
P.O. Box 1663
Group Q-23
Los Alamos, New Mexico 87544
Telephone: (505) 667-6677

### A. COMPLETED TECHNICAL REPORTS

| LASL Report No. | Title | Author(s) |
|---|---|---|
| LA-4959-MS | Thermodynamic Stability Considerations in the Mo-BN-C System. Application to Prototype Subterrene Penetrators. | M. C. Krupka |
| LA-5094-MS | Internal Reaction Phenomena in Prototype Subterrene Radiant Heater Penetrators. | M. C. Krupka |
| LA-5135-MS | Internal Temperature Distribution of a Subterrene Rock-Melting Penetrator. | R. G. Gido |
| LA-5204-MS | Subterrene Penetration Rate-Melting Power Relationship. | R. G. Gido |
| LA-5205-MS | Design and Development of Prototype Universal-Extruding Subterrene Penetrators. | J. W. Neudecker<br>A. J. Giger<br>P. E. Armstrong |
| LA-5206-MS | Identification of Potential Applications for Rock Melting Subterrenes. | D. L. Sims |
| LA-5207-MS | Heat Loss Calculations for Small Diameter Subterrene Penetrators. | D. J. Murphy<br>R. G. Gido |
| LA-5208-MS | Phenomena Associated with the Process of Rock-Melting. Application to the Subterrene System. | M. C. Krupka |
| LA-5209-MS | Development and Construction of a Modularized Mobile Rock-Melting Subterrene Demonstration Unit. | R. E. Williams |
| LA-5210-MS | Large Subterrene Rock-Melting Tunnel-Excavation Systems. A Preliminary Study. | R. J. Hanold |
| LA-5212-MS | Design Description of Melting-Consolidating Prototype Subterrene Penetrators. | J. W. Neudecker |
| LA-5213-MS | Description of Field Tests for Rock Melting Penetration. | R. G. Gido |
| LA-5354-MS | Systems and Cost Analysis for a Nuclear Subterrene Tunneling Machine - A Preliminary Study. | J. H. Altseimer |
| LA-5370-MS | Use of the Rock-Melting Subterrene for Formation of Drainage Holes in Archaeological Sites. | R. E. Williams<br>J. E. Griggs |

## B. TECHNICAL REPORTS IN PROGRESS

| Title | Author(s) |
|---|---|
| Rock Heat-Loss Shape Factors for Subterrene Penetrators. | G. E. Cort |
| Thermal Design Analysis of a Subterrene Universal Extruding Penetrator. | R. G. Gido<br>G. E. Cort |
| Description of the AYER Heat Conduction Computer Program. | R. G. Lawton |
| A Versatile Rock-Melting System for the Formation of Small Diameter Horizontal Glass Lined Holes. | D. L. Sims |
| Conceptual Design of a Coring Subterrene Geoprospector. | J. W. Neudecker |
| Numerical Solution of Melt Flow and Thermal Energy Transfer for a Rock-Melting Penetrator - Lithothermodynamics. | R. D. McFarland |
| PLACID - A General Finite Element Computer Program for Stress Analysis of Plane and Axisymmetric Solids. | R. G. Lawton |
| Field and Laboratory Results for Consolidating Penetrators from 25 to 75 mm in Diameter. | C. A. Bankston |
| Unique Refractory Fabrication Techniques for Subterrene Penetrators. | W. C. Turner |
| Selected Physico-Chemical Properties of Basalt Rock, Liquids, and Glasses. | M. C. Krupka |
| Carbon Receptor Reaction in Subterrene Penetrators. | W. A. Stark<br>M. C. Krupka |
| Design, Analysis, and Tests of a Consolidating, Coring Penetrator. | H. D. Murphy, et al |

## C. PRESENTATIONS AND JOURNAL ARTICLES

### University of California Regents (Invited Lecture)

| | | |
|---|---|---|
| J. C. Rowley | LASL Subterrene Program | Los Alamos, NM April 12-13, 1973. |

### Committee on Advanced Developments (Invited Presentation)

| | | |
|---|---|---|
| J. C. Rowley | Subterrene Concepts for Mini-Tunneler for Undergrounding of Power Transmission Lines. | Edison Electric Institute, Los Alamos, NM, May 1, 1973. |

### Rocky Mountain Science Council (Invited Presentation)

| | | |
|---|---|---|
| J. C. Rowley | Rock-Melting Excavation and Tunneling. | Los Alamos, NM, May 11-12, 1973. |

### Aerospace Instrumentation Symposium

| | | |
|---|---|---|
| J. W. Neudecker | Subterrene Instrumentation Requirements; Instrumentation in the Aerospace Industry, Vol. 19, W. Washburn Ed., pp. 7-10, 1973. | Instrument Society of America, Las Vegas, NV, May 21-23, 1973. |

### Technical Seminar on Rapid Tunneling & Excavation Technology (Invited Presentation)

| | | |
|---|---|---|
| J. C. Rowley<br>R. J. Hanold<br>D. L. Sims | The Subterrene Rock-Melting Concept In Future Excavation Technology. | U.S. Air Force, Weapons Laboratory Civil Engr. Res. Div. Albuquerque, NM, May 31, 1973. |

| | | |
|---|---|---|
| | Arkansas River Basin Group (Invited Lecture) | |
| J. C. Rowley | The LASL Subterrene Program. | Los Alamos, NM, July 17, 1973. |
| | 21st Meeting of National Refractory Composites Working Group (Invited Presentation) | |
| P. E. Armstrong | Subterrene Penetration Materials. | Los Alamos, NM, July 18-19, 1973. |
| | Engineering & Planning Committee Meeting (Invited Talk) | |
| R. J. Hanold<br>J. W. Neudecker | The LASL Subterrene Program. | WEST Associates, Los Alamos, NM, August 13-14, 1973. |
| | Tunnels & Tunneling (Invited Article) | |
| J. H. Altseimer | Subterrene Rock Melting Devices -- Showing the Way to New Tunneling Techniques. | British Tunneling Society, September 7, 1973 (Intended for next issue.) |
| | 15th Symposium on Rock Mechanics (Presentation) | |
| R. J. Hanold | The Subterrene Concept and Its Role in Future Excavation Technology. | U.S. National Comm. on Rock Mechanics & Dept. of Mining Engr., Sept. 17-19, 1973. |
| | 26th Regional Meeting (Presentation, Abstract Accepted) | |
| M. C. Krupka<br>W. J. Stark | Refractory Material and Glass Technology Problems Associated with the Development of the Subterrene -- A Rock Melting Drill. | American Ceramic Society, Oct. 31-Nov. 2, 1973. |
| | 1974 Offshore Technology Conference (Paper Abstract) | |
| D. L. Sims | Melting Glass Lined Holes in Rock and Soil with the Los Alamos Scientific Laboratory Subterrene. | SPE of AIME Dallas, TX, May 5-8, 1974. |
| | 24th Heat Transfer & Fluid Mechanics Institute (Abstract) | |
| R. D. McFarland<br>R. J. Hanold | Viscous Melt Flow and Thermal Energy Transfer for a Rock-Melting Penetrator -- Lithothermodynamics. | Oregon State Univ. Mech. Engr. Dept. Corvallis, OR, June 12-14, 1974. |
| | 3rd International Congress (Abstract Submitted) | |
| J. C. Rowley | Rock Melting Applied to Excavation & Tunneling. | International Society for Rock Mechanics Denver, CO, September 2-7, 1974. |

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