IN-SITU ROCK MELTING APPLIED TO LUNAR BASE CONSTRUCTION AND FOR EXPLORATION DRILLING AND CORING ON THE MOON

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An excavation technology based upon melting of rock and soil has been extensively developed at the prototype hardware and conceptual design levels for terrestrial conditions. Laboratory and field tests of rock melting penetration have conclusively indicated that this excavation method is insensitive to rock soil types, and conditions. Especially significant is the ability to form in-place glass linings or casings on the walls of boreholes, tunnels, and shafts. These factors indicate the unique potential for *in situ* construction of primary lunar base facilities. Drilling and coring equipment for resource exploration on the Moon can also be devised that is largely automated and remotely operated. It is also very likely that lunar melt glasses will have changed mechanical properties when formed in anhydrous and hard vacuum conditions. Rock melting experiments and prototype hardware designs for lunar rock melting excavation applications are suggested.

INTRODUCTION

The Los Alamos National Laboratory conducted a research and development project in excavation technology from 1960 to 1976 (Armstrong *et al.*, 1962; Hanold, 1973b, 1977; Smith, 1971). The project subsequently developed the potential advantages of a rock and soil melting excavation process for lunar applications (Rowley and Neudecker, 1980). Field and laboratory demonstrations of prototype rock and soil melting penetrator systems under terrestrial conditions have illustrated the unique features of this technology that may have application to lunar base facilities construction and exploration drilling and coring on the Moon. These basic features are detailed here. (1) The melting method is relatively insensitive to rock or soil types or conditions; (2) the technique can be automated for remote and untended operation; (3) the melting penetrators create a formed-in-place rock-glass structural lining (casing) for boreholes, tunnels, or shafts; (4) selective formation of debris (or "cuttings") as glass wool or glass pellets is possible; and (5) electrical energy is used for resistive heaters for the melting penetrators, although direct heating by nuclear power is possible for larger equipment. These results were obtained with soil and rock samples at terrestrial ambient conditions of moisture and partial pressures of oxygen.

It is anticipated that vacuum conditions and essentially zero moisture content of the lunar soils and rocks should have significantly reduced thermal diffusivity relative to terrestrial counterparts. Therefore, reduced heat losses could be expected for lunar applications. The absence of moisture and oxygen should reduce the corrosion rate of the refractory metal penetrators. The most important parameter in the rock and soil penetration process of excavation is the viscosity of the soils and rocks. This property for lunar soils and basalts, as reported in the literature (MacKenzie and Claridge, 1980), appears to be within the same range as terrestrial materials of roughly the same composition. In any event, tests and experiments at vacuum condition could be performed in order to extend and optimize the penetrator designs perfected in the previous Los Alamos work to lunar soils and rocks.

This paper summarizes the results of the previous Los Alamos research and development project with emphasis on those concepts: laboratory test hardware, field tests, and equipment designs as related to lunar uses. After recording what is known, the discussion turns to concepts and hardware that might be used for lunar base facility excavation and construction, especially primary structures. In addition, the potential for borehole and shaft "drilling" applications and for exploration core holes on the Moon is reviewed.

The final section deals with suggested research and development activities that could extend and optimize the rock and soil melting technology and hardware to lunar conditions. As indicated, these efforts would focus on a few basic experiments to determine lunar rock and soil melt properties at hard vacuum and anhydrous conditions; an effort to develop preliminary equipment design for projected needed lunar construction and drilling tasks; and most importantly, a study performed to evaluate the structural properties of lunar glasses (LG). In this latter area, we would like to strongly support the ideas of Blacic (1985) that suggest the LG may have very desirable structural properties. This prospect should be especially pursued because the advantages of formed-in-place linings or casings could be enhanced considerably.

The original work at Los Alamos termed the terrestrial excavation devices for soil and rock melting "the Subterrene." Perhaps for lunar applications a more appropriate term would be "Subselene."

PREVIOUS RESULTS

In the course of the previous Los Alamos subterrene research and development project, many different terrestrial soil and rock samples were melted under laboratory conditions to assess the performance of rock melting penetrator designs. Tables 1–3 illustrate the range of samples investigated, melting behavior, crush strengths, and two basalt compositions. The compositions of the two basalts recorded in Table 3 are especially relevant because of the close similarity to those cited by Blacic (1985) as the "average" for the lunar regolith. Boreholes were melted in an extremely wide variety of samples, both wet and dry: soils, sands, clays, shales, gravels, tuffs, basalts, and granites (Table 1). In all these experiments the melting penetrators formed competent glass walls on the borehole wall (Fig. 1a) or a separable, free-standing glass structure (Fig. 1b).

In the course of the research project several detailed evaluations were made of formed-in-place glass linings. One example is the Bandelier tuff rock-melt glass (Roedder, 1980)

Table 1. Typical Rock Melting Behavior

Material	Melting Temperatures, K Start	Melting Temperatures, K Complete	Remarks
Bandelier Tuff	—	1750	Melt viscosity increased as quartz crystals were consumed.
Jemez basalt-1*	—	1570	Melts uniformly with some gas evolution.
Jemez basalt-2†	—	1510	
Dresser basalt	—	1570	
Charcoal granite**	—	1670	Dark phase melted first and then proceeded to consume the matrix.
Westerly granite	—	1760	
Sioux quartzite	—	1760	
Tennessee pink marble	—	—	Heated to 2270 K without melting; some decomposition.
Shale, Santa Fe County, New Mexico	1470	1560	Discrete phase melting accompanied by gas evolution. Viscosity increased as more material melted.
Caliche, Santa Fe County, New Mexico	1570	1850	
Green River Shale, Cuba, New Mexico	1550	1600	
Concrete	1620	1700	Localized melting. Less gas evolution than from shales or caliche.

†Started with rock fragments—1 to 3 mm
*Started with powder <1 mm
**Also called St. Cloud gray granodiorite

Table 2. Typical Crush Strength of Rocks and Rock Glasses

Item	Material	Average Crush Strength, MPa	Number of Specimens
1	Jemez basalt	44	10
2	Jemez basalt-glass*	108	4
3	Bandelier tuff	2.8	3
4	Bandelier tuff-glass from 51-mm-diam-hole wall		
	Axial	55	5
	Tangential	36	2
5	Bandelier tuff-glass from 114-mm-diam-hole wall		
	Axial (2.3 Mg/m^3)	126	4
	Axial (2.2 Mg/m^3)	110	3
	Radial (2.3 Mg/m^3)	115	3
	Tangential (2.3 Mg/m^3)	132	3

*Uniform glass prepared by Corning Glass Works

Table 3. Typical Chemical Compositions of Rocks and Rock Glasses

Constituents	Composition, wt %			
	Dresser Basalt	Dresser Basalt-Glass	Jemez Basalt	Jemez Basalt-Glass
SiO_2	48.2	49.52	50.01	50.09
Al_2O_3	16.13	15.54	16.82	16.81
Fe_2O_3	7.65	8.19	2.83	4.38
FeO	5.41	4.68	7.60	6.53
MgO	6.25	6.50	6.70	6.69
CaO	8.69	10.05	9.62	9.68
Na_2O	2.54	2.47	3.94	3.40
K_2O	0.96	0.97	0.97	0.94
H_2O	0.38	0.004	0.14	0.003
TiO_2	1.45	1.66	1.38	1.46
P_2O_5	0.16	—	—	—
CO_2	0.048	0.003	0.02	0.003
B_2O_3	—	—	—	—
MnO	—	0.18	0.15	0.15

(a)

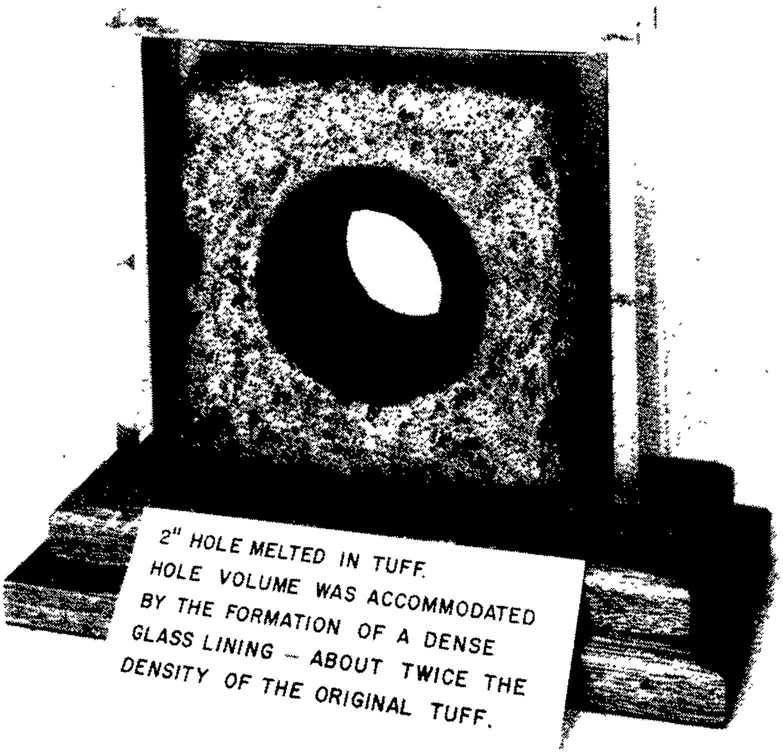
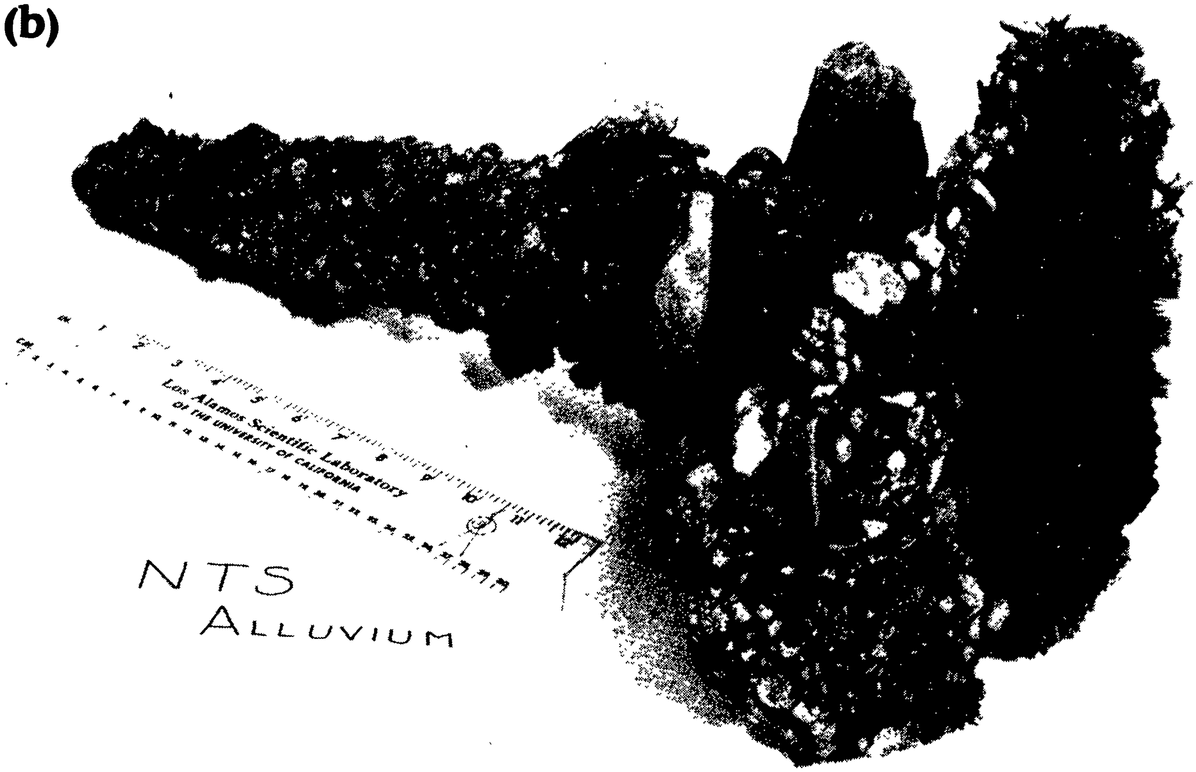


Figure 1. Typical glass-lined holes: (a) Cross section of glass-lined hole (51-mm-diameter) melted in tuff rock; (b) Exterior view of glass-lined hole melted in loose soil and rock.

(b)



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where the properties of the glass-lining material were glass as summarized in Table 4. The study concludes that "the glass-lined hole formed by the penetrator is much more competent than an unlined hole and presents the possibility of engineering applications." The tuff-derived glass structures are somewhat less homogeneous than the glassy, basaltic melt glasses. Several reports on rock-melts, glass linings, and subterrene structures and the formation process were prepared by Nelson *et al.* (1975) and Krupka (1973, 1974).

The most basic conclusions reached from the laboratory research efforts were these. (1) Formed-in-place glass linings could be practically formed through proper handling, forming, and thermal processing (chilling) of the soil and rock melts (Lundberg, 1975; Stanton, 1974), and because these methods applied to all soils and rocks tested, a single penetrator design could be effectively used for virtually all natural terrestrial materials. (2) The melting process is quite insensitive to rapid variations in rock or soil types, void space, water content, or competence of the rocks or soils, and it is especially effective in consolidating "mixed ground" (*i.e.*, gravels or soils with rocks and cobbles). (3) A very uniform and precisely dimensioned borehole could be produced. (4) A high-temperature electric heater technology was perfected that used efficient low-voltage direct current resistance heaters (Armstrong, 1974; Krupka, 1972; Stark and Krupka, 1973). (5) Heat losses to the surrounding rocks or soils were low and predictable (Murphy and Gido, 1973; Cort, 1973; McFarland, 1974). (6) Low mass loss from the refractory metal penetrator

Table 4. Properties of Tuff and Tuff-Glass

Property	Tuff*	Tuff Glass†
Density (Mg/m^3)	1.40	2.23
Grain Density (Mg/m^3)	2.54	2.40
Permeability (md)		
(a) No Confining Pressure	>100	2 to 5
(b) 50 MPa Confining pressure	—	0.1 to 0.3
Compressive Strength (MPa)	~4	~50
Moduli Average		
(a) No Confining Pressure		
E (GPa)	—	7
υ	—	0.3
G (GPa)	—	2.6
(b) 50 MPa Confining Pressure		
E (GPa)	—	55
υ	—	0.2
G (GPa)	—	7.0
Tensile Strength (MPa)	~1	~1

*A soft, friable, highly porous (41–45%) material.
†Grain size ~2 mm.

would lead to long equipment life (Stark and Krupka, 1975). Lastly, (7) materials, design methods, fabrication techniques, and analytical procedures were available to systematically construct and predict penetrator performance that scaled with size.

The subterrene project included a wide range of penetrator configurations (Fig. 2). The depicted shapes include nearly all concepts of hole making by melting. Figure 2a illustrates a "consolidating" penetrator (Neudecker, 1973) used in higher porosity materials; all the rock melted during formation of the hole will be densified, forming the glass lining. No debris removal is required. An alternate configuration for a melting penetrator, shown in Fig. 2b, is termed an "extruder" (Neudecker *et al.*, 1973). Pass-through port(s) allow the melt to flow back through the penetrator head into a device that chills the melt and forms "debris" (or "cuttings" or "muck," depending upon whether drilling or tunneling are considered). These solids can easily be formed as glass pellets, rods, or a glass wool-like material (Fig. 3). The core-consolidating mode of operation is shown in Fig. 2c, and cores with a glass encasement are possible (Murphy *et al.*, 1976). The final configuraton in Fig. 2d was not fabricated, but the knowledge and methods are all in hand to design and construct a kerf melting, coring extruding penetrator. This configuration might be the conceptual design for a large size tunneler. The cross section of the hole (tunnel) could be any (non-circular) geometry.

The project also developed and prepared the analytical tools (Lawton, 1974a,b) needed to perform design analyses and trade studies of the several excavation processes, *i.e.*, drilling and tunneling. These computer methods can be directly used to design soil and rock melting penetrators for lunar base application and exploring the Moon's subsurface structure and resources.

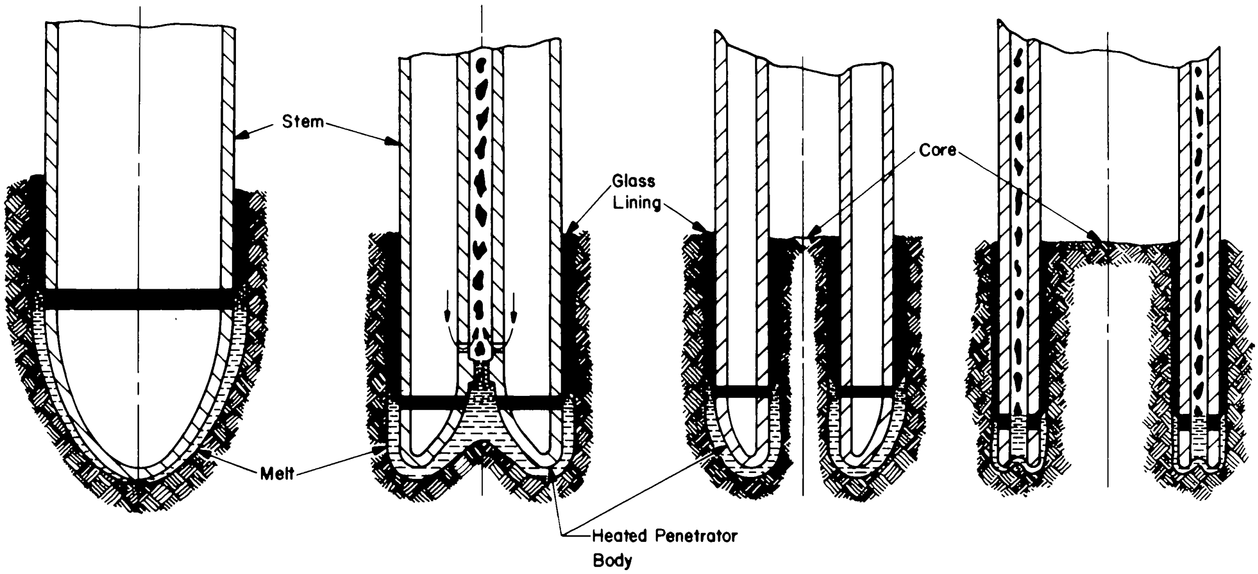

Figure 2. Schematic cross sections of different rock melting penetrators. (a) Consolidation of porous rock and soils, no debris produced. (b) Extruding of glass fiber or pellets to remove material in more dense materials. (c) A coring-consolidating configuration with glass-lined hole and core. (d) An extruding-coring combination mode of hole formation.

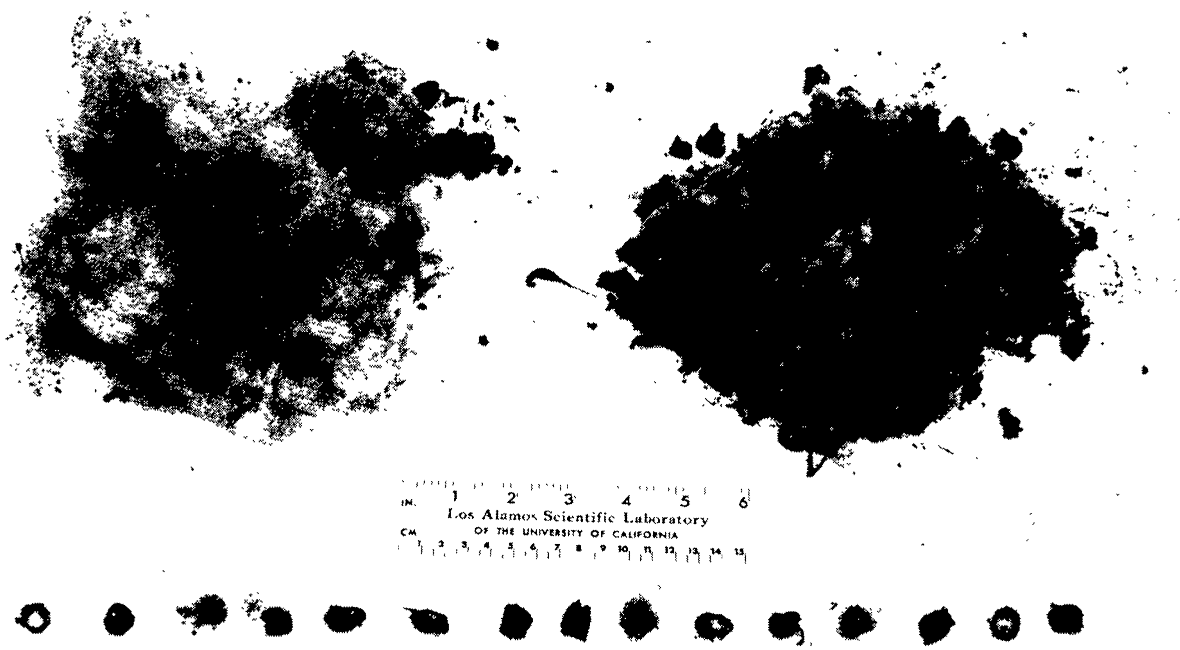

Figure 3. Typical debris or cuttings formed by extruder-type rock melting penetrators, glass pellets, and wool.

POTENTIAL APPLICATIONS ON THE MOON

It would be a straightforward process to develop design concepts and system designs for rock and soil melting in the lunar environment. Sensitivity, trade-off, and cost analyses can be performed as they were for geothermal well drilling (Altseimer, 1976) and tunneling equipment and operations, based on melting as the hole-making technology. The principal thrust would be to design glass-lined or stabilized openings, *i.e.*, to make structures or boreholes with in-place LG structural linings or casings. This would reduce the dependence on materials transported to or refined and fabricated on the Moon. To illustrate these concepts, two areas of excavation technology are outlined here: construction of subsurface primary structures, *i.e.*, tunnels or rooms, and drilling and coring.

The requirements for fairly deep burial as solar flare protection indicate that a tunneling procedure, in contrast to trenching and back-covering, may be more efficient. If the primary structural member of the tunnel walls can be formed-in-place LG, then a significant further advantage is achieved. If the LG surface can be sealed by continuous, direct vapor sputtering with a coating of metal (perhaps iron), then an airtight (or low leak rate) barrier may also be formed.

Figure 4 is a tunneler design (Hanold, 1973a; Altseimer, 1973) for loose soils or unconsolidated ground, and this design could be used on the Moon to produce such glass-lined tunnels in the regolith. The power source could be electric cables or a self-contained nuclear reactor. Such equipment will have only a few moving parts, chiefly

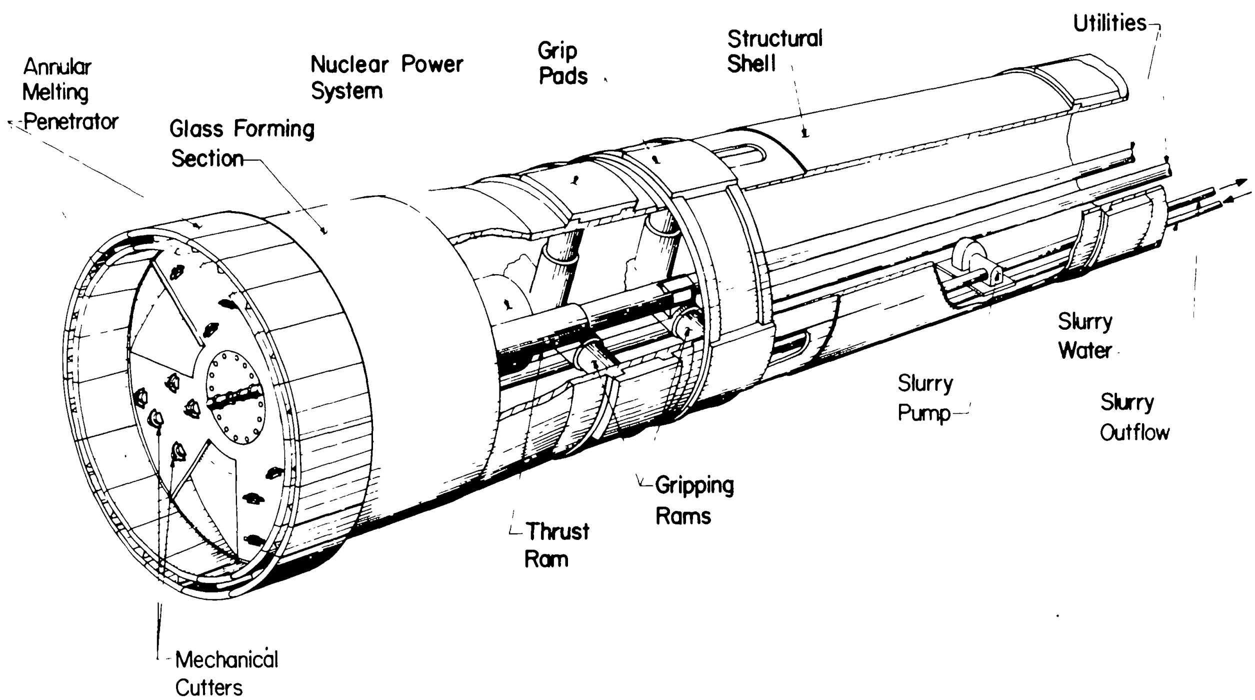

Figure 4. Large tunneler conceptual design for lunar base subsurface facilities construction. Glass lining is formed in place in the lunar regolith.

in the muck-handling system. Bulkheads of LG and LG fiber composites would provide extensive spaces for habitation, fabrication facilities, storage, and laboratories. A second concept for surface construction is illustrated in Fig. 5. A mound of regolith is prepared, and then a supporting LG "roof" is formed with a portable subselene system (shown schematically). The interior would then be excavated to form a room for use as a warehouse, vehicle storage, or large equipment housing, *etc.* The roof shape would be designed to support the overburden loads as well as side and edge reactions. A prototype of such

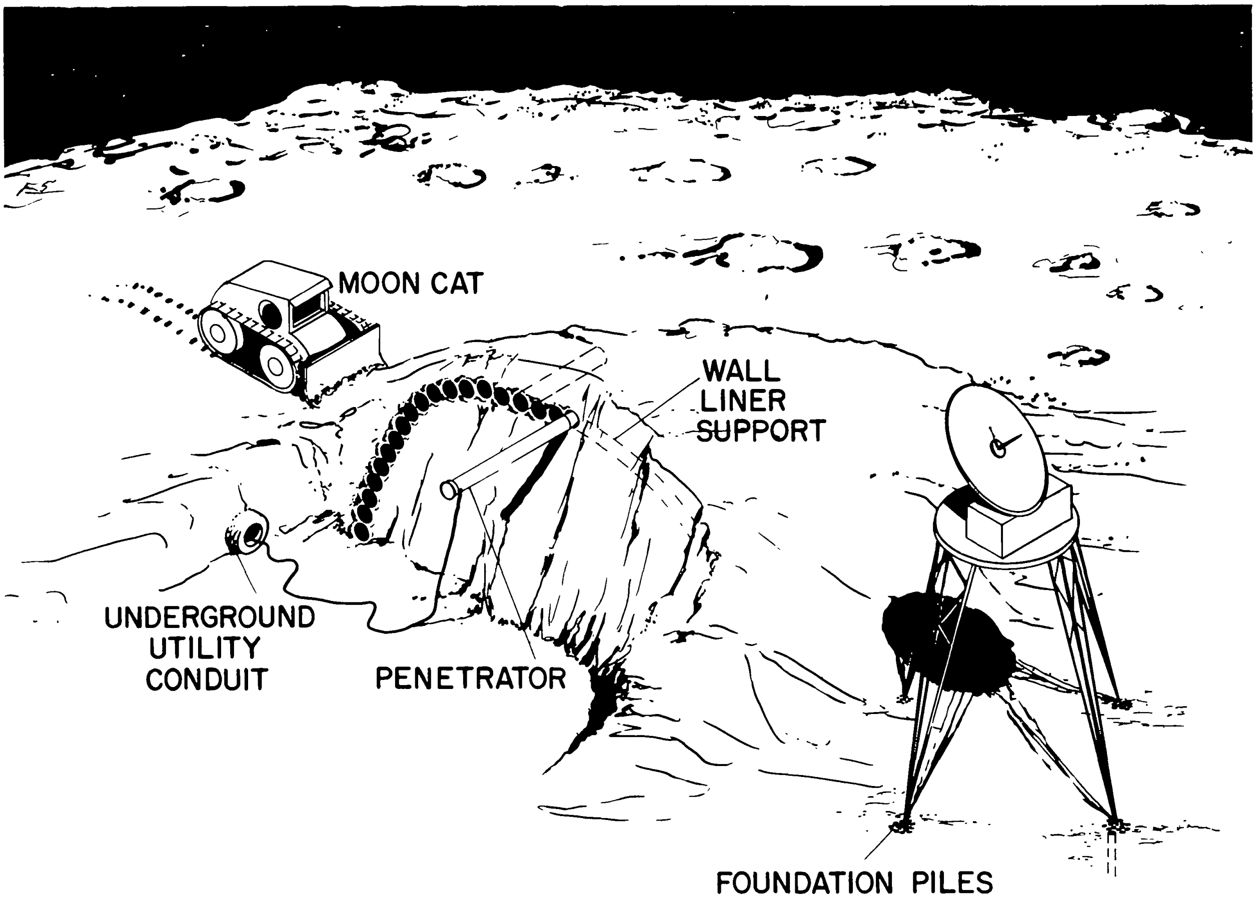

Figure 5. Conceptual sketches of possible applications of rock and soil melting for lunar base facility construction using melted-in-place glass lining.

a structure was built in the fashion described (Fig. 6), and though crude in appearance, it is quite adequate to support the overburden loading. Other applications are sketched in Fig. 5, such as horizontal holes (Sims, 1973) for utility installation.

A second area of application of lunar rock and soil melting is drilling equipment that could be adapted for lunar conditions, such as borehole or shaft drilling and coring applied to exploration (Fig. 7). It appears that vertical-hole-melting systems could be readily designed for use on the Moon, and the potential exists for essentially self-contained, remotely operated drill rig equipment (Altseimer, 1973). These possibilities result from

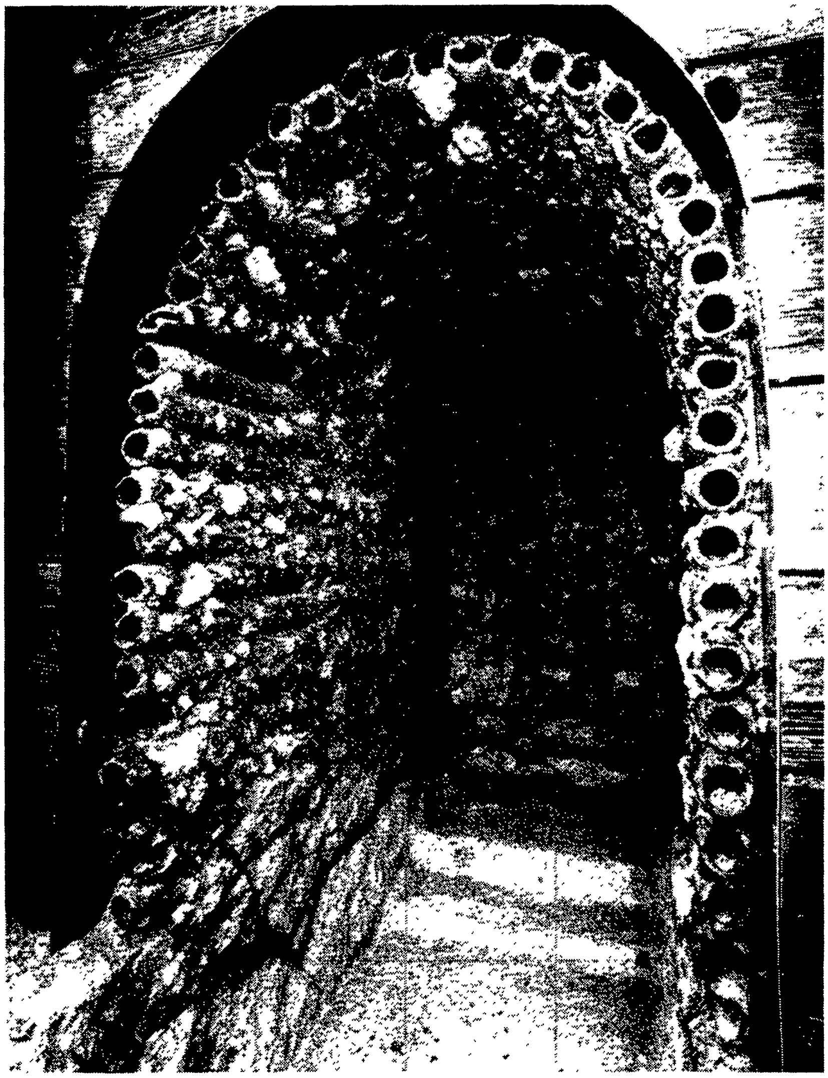

Figure 6. Photograph of prototype melted-in-place structure. Dimensions are 2 by 1 m at the opening, and 2 m deep. Interior rock and soil excavated after melting construction of arch and walls.

the automation potential of the melting methods and insensibility to subsurface conditions. An additional, inherent problem will be closed debris handling and separation systems.

A horizontal coring tool (Neudecker, 1974), termed a "geoprospector," has been devised for use on Earth. It is a mini-tunneler that is self-propelled, is remotely guided, and produces a continuous core. Such a device might be useful to explore along a proposed tunnel route.

RESEARCH ISSUES

Most of the basic concepts and methods to design subselene systems are available. However, a few areas of investigation are recommended if such equipment is to be developed. The tasks are primarily activities needed to extend or optimize the results available for terrestrial conditions to lunar environments. The recommended activities are as follows:

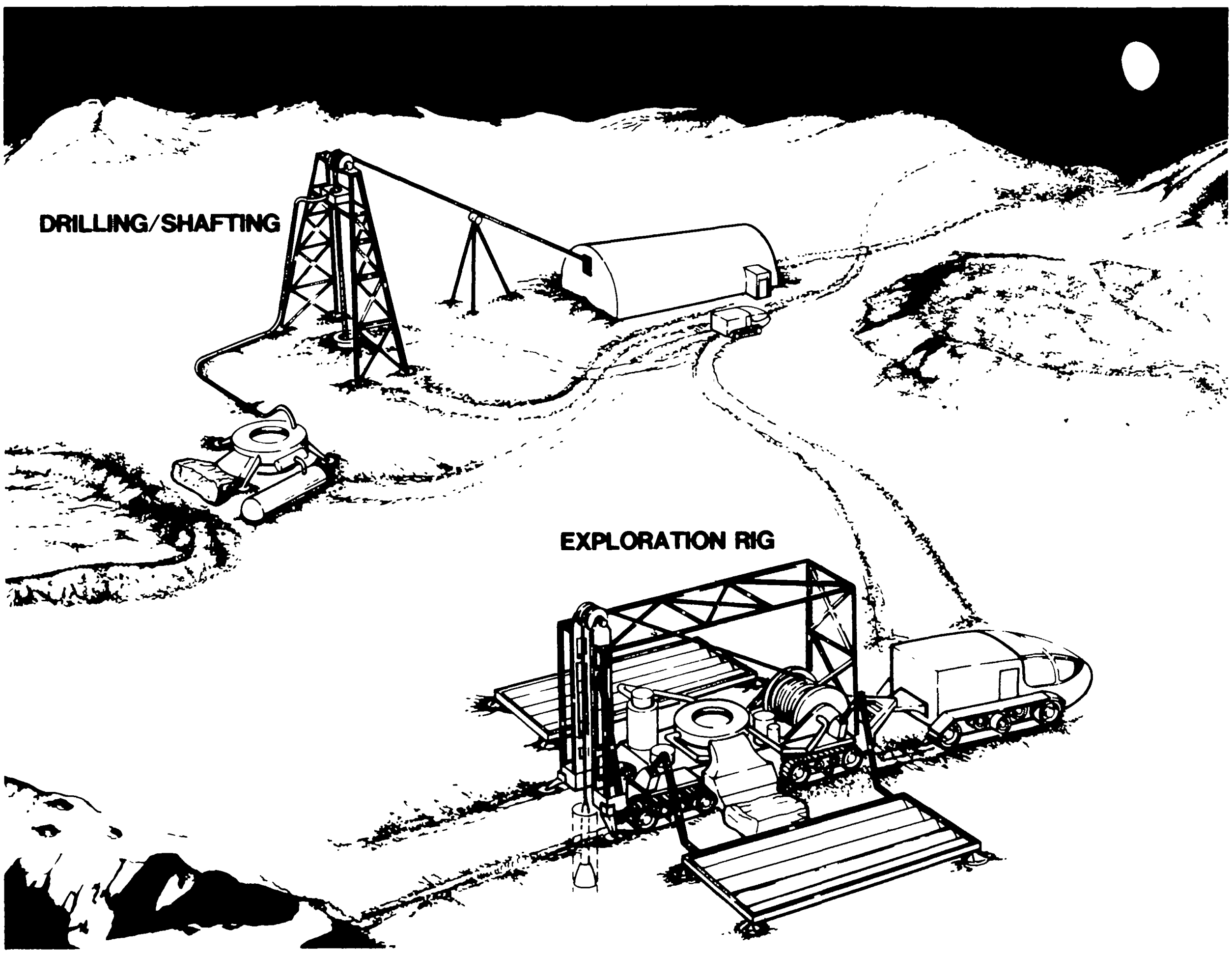

Figure 7. Conceptual sketch of automatic, remotely operated drilling/coring and shafting equipment for exploration of the Moon.

(a) Measure lunar rock and soil melt properties such as viscosity, conductivity, and melting data for hard vacuum and anhydrous conditions simulating lunar conditions.

(b) Determine corrosion rates of penetrator material in lunar conditions by testing refractory metals in lunar rock melts under hard vacuum and very low moisture contents.

(c) Conduct conceptual prototype design, sensitivity, operation, and cost studies of lunar subselene hardware and equipment for both construction and drilling/coring functions.

(d) Produce subcomponents for the most promising reference designs and conduct laboratory and field tests. Automation and remote operation schemes should be explored.

(e) Create designs for debris-handling systems for drilling and coring applications; the approach should provide for a closed circulation of debris-handling fluids and a loss-free debris/fluid separator.

Power source designs and requirements would be an important element in such studies.

In addition, the very important aspect (outlined by Blacic, 1985) of determining the potential for very high strength LG should be investigated. The potential exists for obtaining even more efficient structures from melted-in-place lunar base structures and casings for boreholes or core holes.

SUMMARY

A major advancement in excavation technology that already exists appears to be ideally suited to lunar base facility construction chores for primary structures. Rock and soil melting technology is simple, and the basic hole-making process has no subsurface moving parts. A lunar glass structural lining or support can be formed in the melt chilling process. Tunneling machines based upon soil melting technology have been designed and could be extended and adapted to lunar use with modest effort. Another promising area of application is drilling, coring, and shafting. Here the benefits of remote and automated operations are potentially available. These uses will require some further development of debris-handling techniques and closed fluid and cooling systems.

The potential for direct use of glass derived from lunar materials for primary structures, linings, casings, and the like would reduce Earth-lift mass requirements, should reduce import costs from Earth significantly, and should require much less commitment and use of lunar-based structural materials refinement and fabrication facilities.

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