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INITIAL PLANETARY BASE CONSTRUCTION TECHNIQUES AND MACHINE IMPLEMENTATION

William W. Crockford
Research Associate
Texas Transportation Institute
Texas A&M University
College Station, Texas 77843

Conceptual designs of (a) initial planetary base structures, and (b) an unmanned machine to perform the construction of these structures using materials local to the planet are presented. Rock melting is suggested as a possible technique to be used by the machine in fabricating roads, platforms, and interlocking bricks.

Identification of problem areas in machine design and materials processing is accomplished. The feasibility of the designs is contingent upon favorable results of an analysis of the engineering behavior of the product materials. The analysis requires knowledge of several parameters for solution of the constitutive equations of the theory of elasticity. An initial collection of these parameters is presented which helps to define research needed to perform a realistic feasibility study.

A qualitative approach to estimating power and mass lift requirements for the proposed machine is used which employs specifications of currently available equipment from various manufacturers.

An initial, unmanned mission scenario is discussed with emphasis on (a) identifying uncompleted tasks which necessitate manned follow-up missions, and (b) suggesting design considerations for vehicles and primitive structures which will use the products of the machine processing.

The period of research was 16 June - 8 August 1986. The use of names of manufacturers does not constitute official endorsement of such products or manufacturers by NASA or any U.S. government agency.

NASA Colleague: Ann L. Bufkin ED2 X2536

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INTRODUCTION AND PROBLEM DEFINITION

Planetary base construction will involve multiple missions due to mass and volume lift requirements from earth. This paper describes a concept for an early unmanned mission which will accomplish the initial tasks of base construction. The mission concept includes, as a key element, the conceptual design of a planetary materials processing machine which will accomplish the initial construction tasks. The machine is intended to produce bricks, roads, and platforms using materials local to the planet. The machine subsystems should be modular in the sense that new technologies which appear before launch can be implemented with a minimum of additional design effort.

Monetary costs of the machine are not directly addressed in this paper. However, the costs in terms of mass lift, operating power, and planetary resource utilization are discussed briefly.

The words "soil" and "regolith" are used interchangeably in this report. The primary emphasis is on lunar base applications because more data is available, it will act as a stepping stone to the other planets, and it is potentially more harsh an environment in which to test ideas and technology than, for example, Mars.

BACKGROUND CONSIDERATIONS

Chemical Processing. The conservation of planetary natural resources is an issue which must be addressed very early in the planetary infrastructure development program. For example, because water is so vital to human presence on the planets, it seems imprudent to make structures of concrete even on Mars (and even using water reducing agents as suggested by Young in [46]) where water, atmosphere, and non-zero relative humidity exist. The carbonation curing mentioned by Young [46] may hold some promise, but is not discussed in this paper. Although it is true that recent advances in cements, water soluble polymers, and metal and polymer fibers have resulted in excellent concrete products (compressive strengths 30-40ksi (200-300MPa), see Young in [46]), the use of earth-based portland cement concrete technology should be postponed at least until after the establishment of planetary factories which can produce the necessary components of the mix.

Although inorganic polymer chemistry seems to be a promising approach to the problem of concrete type material processing, the progress in this field is apparently confined to linear chains (see Lee in [10]). Lee also briefly reviews a promising technique for the production of high toughness metal glasses which are not discussed herein. In fact, glass may be considered to be an inorganic polymer [67] and is considered as an option, in this paper, for structural material.

Urethane foamed plastic stabilization of lunar soil simulants has resulted in unconfined compressive strengths on the order of 4-5ksi (27.58-34.48MPa) [48]. However, the technique was primarily studied using soil grouting techniques. Extension of the testing to vacuum environments led to problems with the stabilization procedure [49]. Phenolic resins were also tested with unsatisfactory results [49]. Problems with conventional stabilization techniques using stabilizers such as portland cement, foamed plastics, resins, and asphalt products should not come as a surprise if one considers vapor pressure in the analysis. These techniques may be successful on Mars but should not be expected to perform flawlessly on the moon.

Based on qualitative considerations and experimental results, chemical processing of materials for structural purposes was eliminated from consideration.

<u>Passive and Semi-active Mechanical Processing.</u> Two concepts are of interest here: (1) semi-active techniques such as controlled rock fracturing for shaping building stones or soil moving and placing, and (2) passive techniques such as simple building rock recovery and replacement or adaptation of existing planetary crust formations (e.g. craters, lava tubes). Of these techniques, only soil moving and placing and

adaptation of existing formations are techniques for which the machine is designed. Controlled rock fracturing and building stone recovery and placement are tasks which are too time intensive and which require too much articulation on the part of the machine.

Unperfected Methods of Processing. The use of lasers and microwaves for rock fragmentation by differential heating of minerals within the rock has been under study by the Bureau of Mines. The use of explosives in a vacuum for rock fracturing has also been studied (see Podnieks and Roepke in [46]). These techniques are not discussed in this paper.

For the production of construction materials such as "bricks", microwave processing is a very promising technology (see Meek et al. in [46]). The total energy requirements are much lower than those of conventional heating techniques. Meek et al. have used 2.45GHz ultra high frequency (UHF) microwaves to induce diffusion bonded ceramic-glass-ceramic junctions. Waves of this particular frequency couple well with ilmenite inducing the necessary initial temperature rise. While this technology may very well become the solution to the power requirement problem on the processing machine, several unanswered questions have, unfortunately, precluded much more than a cursory discussion of the technology in this paper. Very little information on this technique has been published [PC-13] with the most current and informative article being that authored by Meek et al. in [46]. Some questions of interest follow.

(1) Do microwave processed materials have better engineering properties (e.g. strength, toughness) than those processed with conventional methods? A qualitative assessment based on inferences by Meek et al. [46] would indicate an answer to this question in the affirmative. However, quantitative information is needed to confirm this supposition.

(2) Are coupling agents at this frequency too valuable or scarce to be relied upon for extended usage? The abundance of lunar ilmenite is generally less than 2% and may be a valuable source of Fe, Ti, and O [69]. Mars materials contain valuable water [53] which will couple.

(3) Is the variability of coupling agent presence over the surface too great to allow product uniformity? Is it a simple matter to identify variations in coupling agents and to adjust the wavelength to couple with a different agent?

(4) Meek et al. [46] state that the ilmenite in an ilmenite-rich basalt couples first causing a temperature rise which, in addition, is sufficient to cause the basalt to couple. Can this "domino coupling" effect be expected to create strong, diffusion bonding in any regolith (i.e. not only in ilmenite-rich basalt)?

In Situ Melt Processing. The Los Alamos Scientific Laboratory (LASL) perfected a drilling technique in 1976 which utilizes simple ohmic heating in a penetrator which creates a dense glass lining around the hole as it drills (see [4], [35], or Rowley in [46]). Because of the relatively complete nature of the research, development, and documentation of this process, this technique was chosen as the process of primary interest. The glass product of this process has higher density, and higher compressive strength than the parent materials (see Rowley in [46]). The process is apparently equally effective regardless of soil or rock composition. There are disadvantages with both the process and the product which are discussed later in this paper.

MATERIALS CONSIDERATIONS

Lunar Materials. Table 1 contains some of the parameters for lunar materials and glass products which are necessary for solution of the constitutive equations of the theory of elasticity and for the solution of other equations used for terrain-vehicle system calculations. Mitchell et al. [51] recorded moduli of subgrade reaction which indicate that insensitive structures may be successfully placed on foundations made of the in situ lunar material. However, the sensitivity of the modulus of subgrade reaction is in question even in the best of circumstances (Horonjeff in [68]). For sensitive structures (e.g. observatories [38]), Mitchell et al. [51] suggest that burying footings deeper where the lunar soil is more dense (which could be done with a

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rock-melting penetrator) or compacting the construction site may be desired to reduce settlements to tolerable levels. Mitchell et al. also found the soil at approximately 4-8in (10-20cm) depth to be, in general, at a very high density. The density distribution with depth is approximated by [51]:

$$\rho = \rho_o + k \ln(z+1) \tag{4.1}$$

where ρ_o is approximately 1.27g/cc, b=0.121, z is in cm, and ρ is in g/cc. The density varies considerably at the surface on the scale of approximately 3-6ft (1-2m) laterally.

Table 1. Approximate Lunar Properties.

Parameter	Value(s)	Source
g_o	0.167g	[15]
k	N/A	
α	2.5E-5/degC	[69]
ρ	0.87-1.93g/cc	[51]
Tm	1400degC	[69]
SG	2.9-3.24	[16]
e	0.67-2.37	[51]
c	0.1-1.0kN/m**2	[50, 51, 16, 17]
ϕ	28-50deg	[50, 51, 16, 17]
ksg	800-1600kN/m**2/m	[51]
β	N/A	

As will be illustrated later in this report, the machine concept addresses the problems of compaction, removal of soil to higher density depths, and a method of making the density of the surface layer more homogeneous from point to point. Modification of the gradation curve is not a primary purpose of the machine. The lunar grading curve and soil classification indicate a well-graded silty sand to sandy silt (SW-SM to ML in the Unified system [51]) and further modification to the gradation is not deemed necessary or desireable by this author. However, the machine does perform a crushing function as part of the preprocessing of soil intended for brick production. This crushing is simply a method of insuring a maximum desired particle size for the brick, given any soil input.

The lack of a lunar atmosphere, and, in particular, the lack of water vapor pressure results in much lower crack speeds (at the same stress intensity factors) than those reached at higher water vapor pressures. Alternatively, one could consider the stress intensity factor required to attain a given crack velocity to be significantly greater in the lower pressure environment [61] as shown in Table 2.

Table 2. Fracture of Lunar Analogue Glasses.

Crack Velocity	Water Vapor	KI
1E-5m/s	10 Torr	21.2N/(mm**1.5)
1E-5m/s	0.001 Torr	25.3N/(mm**1.5)

<u>Lunar Products and Terrestrial Analogues.</u> In situ melt processing of lunar materials will produce a glass which may have questionable strength properties. Specifically, cracking may be a problem. The cracking may be a manifestation of residual stress problems or thermal stress induced fatigue. However, cracking may not be as serious as it first appears, especially in the absence of corrosive agents such as water vapor. If angular "aggregates" result from cracking of the glass, roads and platforms may still perform acceptably due to aggregate "interlock". In the case of bricks and melt-tracks, however, performance may be seriously impaired by cracking.

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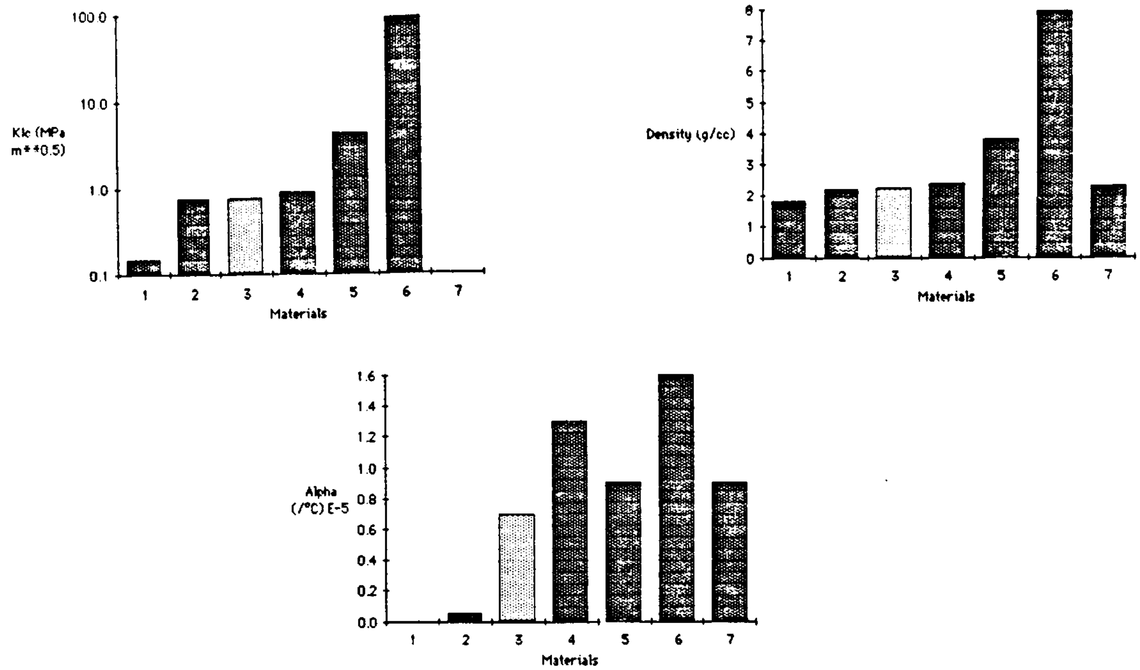
Table 3. Approximate engineering properties.

Item	Tuff Glass	Dry Bldg Brick	PCC	Silica Glass	10%SC	Al2O3	18Ni Steel
E(GPa)	7	N/A	14	70	2.5	350	207
ν	0.3	N/A	0.18	N/A	0.15		0.29
k(W/mm/degC)	7E-4	6E-4	10E-4	12E-4	N/A	290E-4	150E-4
α (/degC)	0.69E-5	0.9E-5	1.3E-5	0.05E-5	N/A	0.9E-5	1.6E-5
ρ (g/cc)	2.23	2.3	2.4	2.2	1.8	3.8	7.93
σ_c (MPa)	50***	55	34	137	N/A	2000	N/A
σ_y (MPa)	1	N/A	3	10	1.1**	172	1930
KIc (MPa m**0.5)	0.77*	N/A	0.87	0.75	0.15	4.2	94
JIc (N/mm)	N/A	N/A	0.035	N/A	0.0085	N/A	N/A

* Estimated from [61] lunar glass analogue
** Indirect tension [24]
*** Hollow cylinder test [55]
N/A Not Available in sources referenced

The glass lining of the rock-melt drilling process has been characterized as transversely isotropic (cylindrical coordinates) by Nielsen et al. [55]. The axial and tangential material properties were found to be equal (E=8GPa, 20GPa, ν=0.34, 0.24 at 0 and 50MPa confining pressure, respectively). The radial properties were found to be slightly different (E=6GPa, 14GPa, ν=0.26, 0.16, at 0 and 50MPa confining pressure). In Table 3 and Figure 1, a comparison of important engineering parameters extracted from various sources [12, 24, 31, 36, 43, 47, 55, Rowley in 46, 61, 70] is presented.



1=SOIL CEMENT, 2=SILICA GLASS, 3=TUFF GLASS, 4=PCC
5=AL203, 6=18NI STEEL, 7=DRY BUILDING BRICK

Figure 1. Graphic presentation of selected parameters from Table 3.

It is difficult to compare many of the values in Table 3 and Figure 1 because of the different test methods involved. However, it is useful to note that lunar glasses, fused silica, and a rather ordinary plain portland cement concrete (PCC) have fracture toughnesses of the same order of magnitude. An order of magnitude study also indicates that glass from rock melting has a compressive strength comparable to both plain PCC and ordinary dry building brick.

Martian Materials. Little information is available concerning engineering properties of the martian regolith. However, some properties have been approximated by studying footpad penetrations, descent engine induced surface behavior, and surface sampler data [53, 54]. In Table 4, some of the available parameters of interest are presented.

Table 4. Approximate Martian Properties.

Parameter	Value(s)	Source
g_m	0.38g	[53]
k	N/A	
α	N/A	
ρ	0.6-1.69g/cc	[53]
Tm	N/A	
SG	N/A	
e	N/A	
c	0.01-14kN/m**2	[53, 54]
ϕ	18-45deg	[53, 54]
ksg	207-1600kN/m**2/m	estimated [51, 53]
β	39deg	[53]

The problem of working with martian soils may, at first, seem much simpler than working with lunar soils because of the presence of water as a processing aid. However, several factors make the martian base at least as challenging as the lunar base.

(1) Minimization of the nonrecoverable use of water is mandatory.

(2) The presence of water and high relative humidities [25] delete the advantages for glass utilization present on the moon. That is, nonzero water vapor pressure tends to act as a mechanism for enhancement of stress corrosion cracking. Carbon dioxide atmospheric effects are not studied in this paper.

(3) The occurrence of freeze-thaw cycles [53] is virtually assured.

(4) The presence of montmorillonitic clays [53] may be detrimental to structural materials during wet-dry and freeze-thaw cycles. On Earth, these type clays often exhibit dimensional instabilities in the presence of wet-dry cycling.

Air entraining agents are often used to help alleviate the problems associated with freezing and thawing. The agents insure a discontinuous pore system made up of very small bubbles by acting as surface-active agents. The process used for making structural materials out of martian regolith may require (a) removing all water from the system, except perhaps for tightly bound water interior to the double diffuse layer, and/or (b) waterproofing the component. It may be possible to accomplish freeze-thaw protection using a combination of sintering and rock melting techniques, but the protection may come at some unknown cost in terms of an increased susceptibility to stress corrosion cracking.

INTERIM SOLUTION

The materials processing requirements are temporarily met by a conceptual design which allows removal of soil from the surface down to a depth which gives a relative density [51] of 90% (i.e. approximately 20cm). Manufacturing of bricks may be done as the soil is piled in windrows during the removal operation. The density at 20cm depth is on the order of that of stabilized base materials. Compaction to 95% relative density is then accomplished by rollers. Pressure applied by pad feet is arbitrarily set at 23kg/cm**2 (e.g. Caterpillar model CP323), single lift of 10cm which requires approximately 27.6kg/cm**2 to give proper compaction. If the pad foot could be made large enough (i.e. if the vehicle were heavy enough), the operation could be completed in one pass. Realistically, however, multiple passes would be required. Excavation and melting of shallow trenches would be the next operation for the making of a glass track or "rail" system for follow-on vehicles. The vehicles could be maneuvered in the trench-rails by mobile controls (e.g. [PC-10]). The "road" would be made straight and level by using a laser system (e.g. [PC-3]) or some other navigational aid.

Utilization of rock melting or even hot press sintering techniques will probably require on the order of 4.5kW power. Using 5.14W/kg [8] for a conservative radioisotope thermoelectric generator (RTG) power to weight ratio results in an 875.5kg power unit. In Figure 2, power versus weight is illustrated for various equipment (88 construction machines of 4 manufacturers).

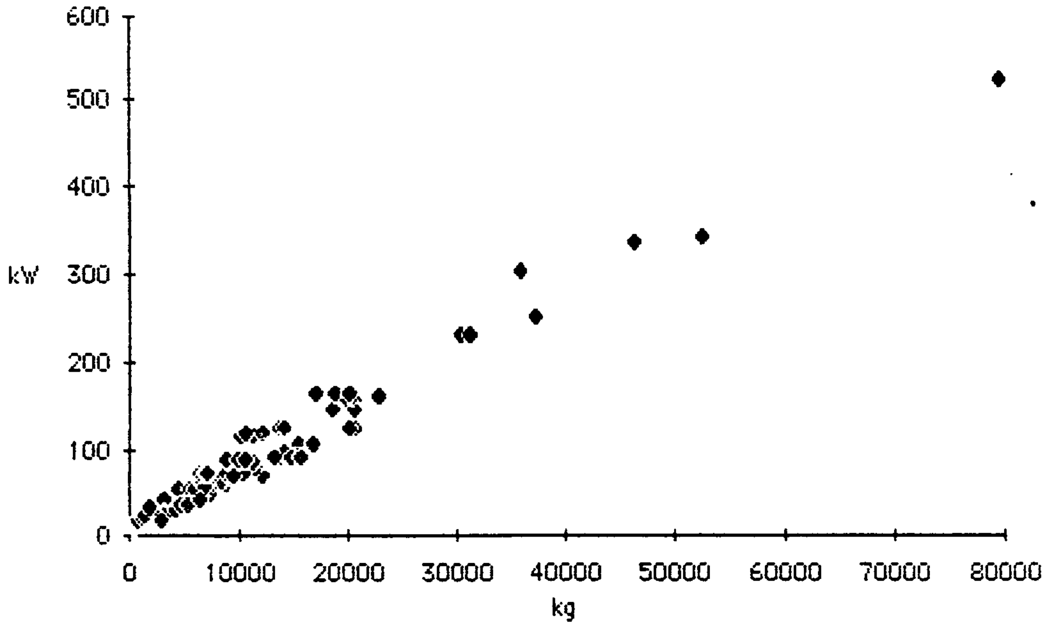


Figure 2. Power versus weight for various construction machinery. Y=0.11(X**0.72), R-Square=0.93, N=88.

As an illustration of general power versus weight requirements, assume the planetary soil has an earth unit weight of approximately 1600kg/m**3 in the loose state and we desire to push 0.75m**3 of the soil (e.g. John Deere 650). Using a conservative coefficient of traction factor of 0.5 for loose earth, dry sand and clay loam [18], the minimum total vehicle weight should be on the order of

1600*0.75=1200kg
or 456kg on Mars

456/0.5=912kg total machine weight on Mars

Using the regression model of Figure 2, a power requirement of 14.8kW is suggested. Therefore, the machine would be underpowered by approximately 10kW for soil working purposes in terms of existing manufacturer's equipment.

Using the Caterpillar models 815 and 825 compactors for the sake of example, it is seen that the weight of engine and fuel is approximately 65% of the weight of the vehicle. This would imply that an RTG weighing 1560kg on earth and producing on the order of 25W/kg will allow successful design of the aforementioned underpowered vehicle. The SP-100 program (see French in [46]) gives a glimmer of hope that this power capability is attainable. This analysis leads us to an estimate of the size requirement for the macnine on the order of a John Deere model 675 (approximately 9 cubic meter volume, 3.2m long, 1.6m wide, and 1.8m high). This vehicle size is also on the order of magnitude of the Boeing LRV [22].

Comparisons using the regression relationship of Figure 2 may be somewhat qualitative when one considers that (a) the regression is for gasoline and diesel engines manufactured in discrete power ranges, not for electric power supplies and motors, (b) it is suspected that design procedures for common earthworking equipment has not really attempted to maximize production while minimizing both weight and power requirements, (c) there is a very small difference between the weight of the power unit and the weight of the complete machine in the case of the 5.14W/kg RTG example, and (d) the RTG and SP100 units contain their own fuel system while the fuel weight for the engines of earth construction equipment is impounded in the vehicle operating weight.

Bricks will be made from the top 20cm of soil which was removed in the original clearing operation. The windrows of soil would be removed from the surface and transported by a belt system to a crusher and sieve before entering the mold for hot pressing, sintering, and/or melting. Gravity flow of the material through bins is not necessarily straightforward, but has been studied [56]. The question of the desireability of a hot pressed, sintered brick versus melting to a glass coated or solid glass brick will not be resolved without experimental study. However, if the glass layer is annealed properly, and good bonding with and compaction of the interior of the brick is attained, the glass brick may have two advantages over the standard brick:

(1) Higher density surfaces may allow decreased thicknesses of protective radiation shielding.

(2) The relatively high stiffness glass layer may (depending on the silica content and the effectiveness of the annealing process in combating cracking) result in higher strengths than the sintered material not only because of the inherent material properties but also for the same reason that a testing machine using a steel platen will yield higher concrete strengths than a "brush" platen [47].

Glass coated "bricks" are not an idea new to the natural lunar environment. Several glass coated rock specimens have been studied. Some of the samples have excellent strengths and impact resistance while others are very fragile [PC-2]. The difference in impact resistance of the glass layers of different samples is thought to be caused by thermal treatment over geologic time [PC-2]. An effort should be made to understand the cause of the difference in glass layer impact resistance and hypothesize how the process can be accelerated for use as a construction material processing technique. Elastic wave velocities are available for some samples such as lunar sample 60015 [58], but other strength and material properties are needed for this and similar samples.

<u>In Situ Rock Melting.</u> Both lunar and martian soils contain volatile elements [15, 69] which can be driven off by heating. It has been noted [35] that the evolution of gas during melting may cause voids in the glass. This problem was solved in the LASL research program by increasing the melt pressure at the glass-forming section. Apparently, attainment of high pressure ahead of the penetrator stagnation point is mandatory (see LASL Mini-review 75-2 in [57]). Outgassing of lunar soil was also observed in compression and shear testing by Carrier et al. [17]. The penetration rate is limited by the heat flux that

can be provided at the leading edge or stagnation point [35].

In the brick manufacturing process proposed for the planetary materials processing machine discussed herein, maintenance of pressure in the mold using the limiting case of the flat plate melter will not be a significant problem. However, in the case of the track-melt process discussed later in this paper, confining pressure may become slightly problematic. It is suspected that the problem is not catastrophic.

The thickness of the melt layer in a given soil or rock can be controlled by causing electric heating current to flow directly through the rock melt layer, by using a long conduction heating section, or by introducing pellets of material to be melted [2]. Since the glass layer is typically of the order of 4-15mm thick in the LASL studies [2], control of the glass thickness may be required. Specifically, thicker layers may often be required. A new concept specifically formulated for the planetary materials processing machine is introduced to identify a procedure for thickening a glass layer. It is speculated that annealing of a horizontal glass plate (or hole lining) may be accomplished simultaneously with increasing the thickness of the plate as follows:

(1) Form the initial glass lining.

(2) Add loose raw material on top of the plate. The amount of added material may govern the depth of annealing.

(3) Melt the new material so as to anneal the lower portion of the initial glass lining.

In this manner, heat treatment of the glass lining may proceed from the outer lining material toward the melter body. The last layer would have to be annealed in a separate operation.

The glass layer produced by this technology will, undoubtedly, have cracks similar to the radial cracks observed by Nielsen et al. [55]. It is not known at this time whether annealing, high pre-melt in situ porosity, or mineral composition of the materials will allow production of an uncracked lining. One should expect to use fracture mechanics as the method of failure analysis because preexisting sharp flaws are virtually inevitable. Theoretically, a very thin glass layer is less likely to break due to thermal stresses [64] and may decrease the tensile stress (even resulting in compression) in the top layer of a three layered semi-infinite half-space [71]. The layered elastic result is, of course, dependent on modular and thickness ratios of the two top layers (top/middle) [71]. Given the existence of cracks in the glass layer and that the tensile stresses in a stiff top layer may also be reduced by increasing the thickness of the top layer in relation to the middle layer, maximization of the top layer thickness is considered prudent. The desire for increasing thickness should decrease as the modular ratio decreases. Shear and deflection are also affected by changes in these parameters and must be considered in the analysis.

Theoretical analyses using features of the AYER finite element code [see 35] and experimental verification are needed to transform the speculative concept of simultaneous annealing and thickening into a viable process.

The penetrators used in the LASL study usually employed ohmic heating [4]. At least on the moon, electron-beam heating [4] may be an interesting alternative because of the availability of a vacuum environment.

Power requirements of the LASL penetrators in the 2-6kW range are plotted in [34] as the abscissa in plots describing the calculated performance of a double-cone consolidating penetrator (approximately 75mm diameter, 180mm long). In general, penetration rate (approximately 0.05-0.17mm/s) and surface temperature (approximately 1700-2000K) both increase with total power, while the minimum required thrusting force decreased at a decreasing rate (approximately 0.6-0.1kN). The power requirements of the LASL penetrators are capable of being satisfied by RTGs [8] or SP100s (see French in [46]).

<u>Planetary Materials Processing Machine</u>. The machine concept was formulated by defining its mission and searching for existing technology which could be adapted to the mission. Three primary machine tasks

were identified: (1) clearing and grading (i.e. bulldozing), (2) compacting, and (3) brick and wearing surface fabrication. The capabilities to fracture, rip, mill, adjust compaction drum weights, provide vibratory compaction, and/or vertical articulation of the drums (e.g. Ingersoll-Rand model LF-450) were considered, but eliminated from the design for two reasons: (a) cost in terms of machine complexity and expected reliability, and (b) clever choice of the initial landing sites can be used to eliminate the necessity for these additional capabilities. Steel track beadless tires [18] and track systems, including new low ground pressure tracks [PC-7] were considered, but eliminated from the design because of the desire for compaction. Tracks could be placed over the drums after the compaction operation but this operation would probably require a manned presence. In addition to the required processing capabilities, the machine is intended for an unmanned mission and must have good mechanical reliability (which is much more important than production rate for this mission), excellent navigational capabilities, and remote control/data analysis functions. The resulting machine concept is basically a static compaction machine with a bulldozer blade and a brick making unit. The machine is vaguely reminiscent of equipment such as the Ingersoll-Rand models SPF-56B, DA-28, or the Caterpillar models CP-323, 815B, 816B, CB-214, combined with the Boeing LRV. A diagram of the chassis and drum wheel system is presented in Figure 3.

The size of the machine has been scaled down in this paper in order to lower the power requirement. The overall size of the machine and especially the drum size should be increased to the maximum size possible at launch time. A lander vehicle will house a data/remote control link with Earth and a Laserplane [PC-3] type transmitter. The laser receiver is placed on the rear left corner of the machine chassis. The melter of Figure 6 is mounted at the bottom of the chassis between the wheels, is capable of vertical articulation, and is positioned with the longitudinal axis parallel to the y-axis of Figure 3 with the "bullet" nose pointing in the negative-y direction. Redundant systems should be available for all primary systems except the power generator (e.g. the machine should be able to carry out its mission even if part of the four wheel drive capability is lost).

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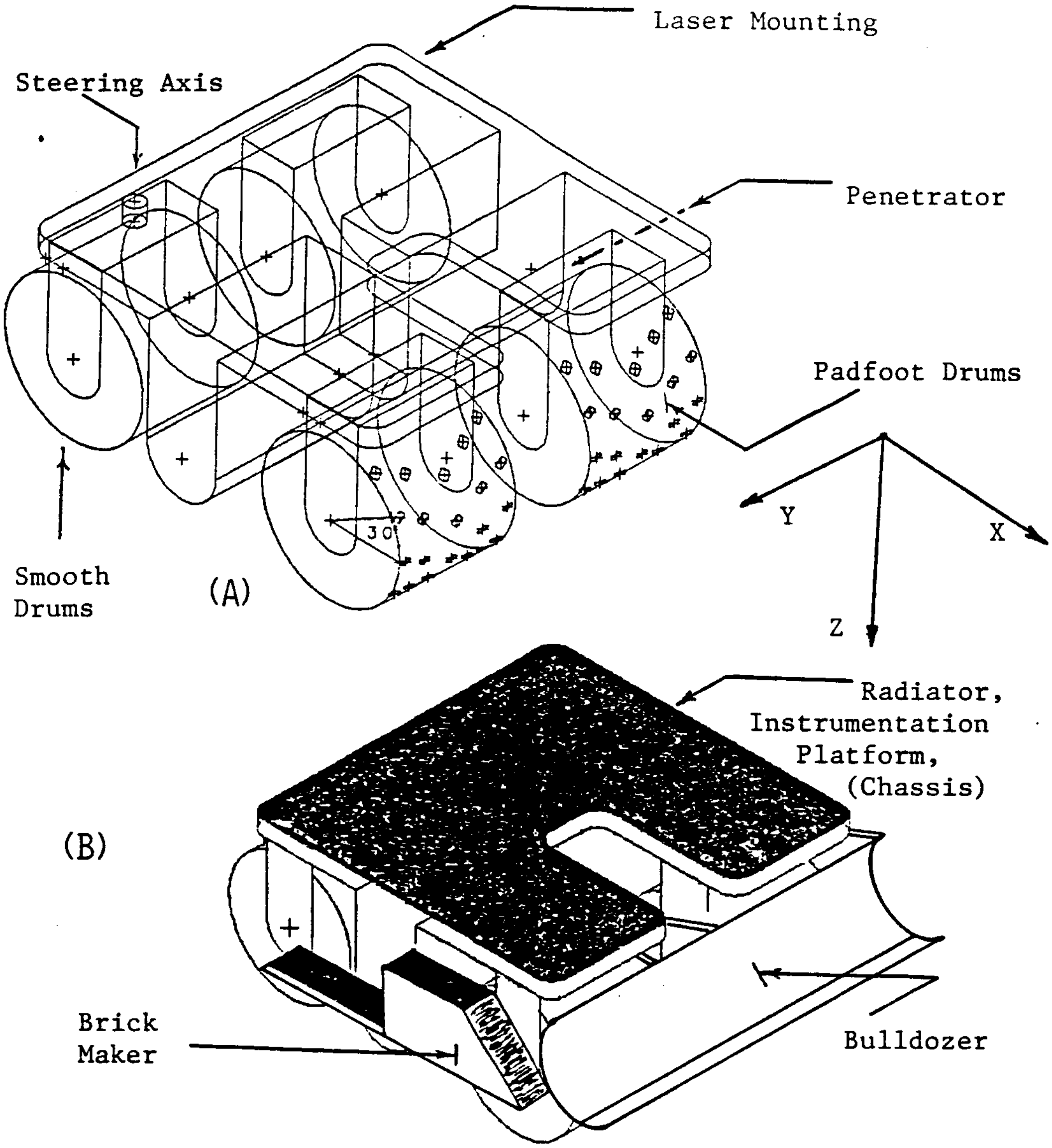
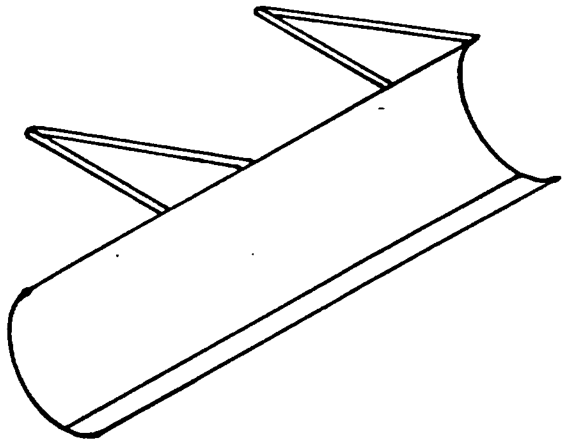
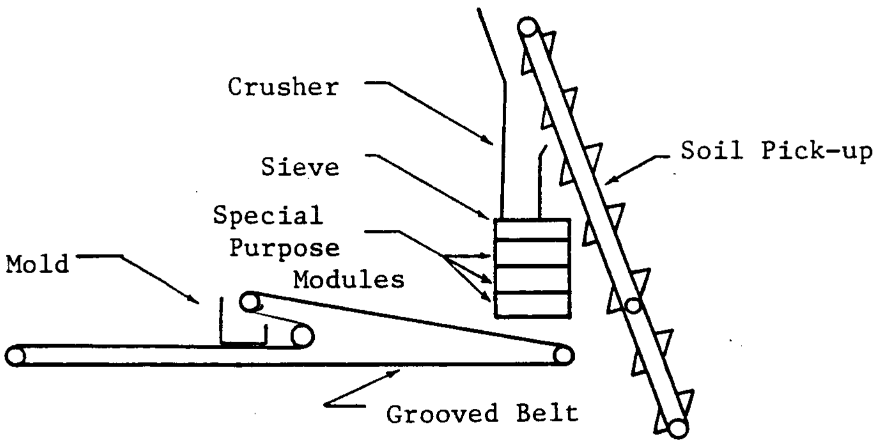


Figure 3. General concept of the machine:
(a) transparent, (b) solid model with attachments.

The concept of the bulldozer blade and the brick making system is illustrated in Figure 4.

(A)





(B)

Figure 4. Concepts for (a) blade, and (b) brick maker.

In general, systems which are normally driven by hydraulic actuators on earth machinery will be driven by electric servomotors and jackscrews. The machine subsystems are categorized as follows:

Chassis:
- Thermoelectric power generation and transmission
- Heat disposal
- Navigation (primarily LASER)
- Track melter

Drum wheels:
- Steering

Propulsion

Blade:

Servomechanisms

Materials processing unit:

- Belt system
- Crusher
- Sieve
- Raw material preheater
- Brick producing mold
- Brick cooling system

The drum wheels rotate 90 degrees either direction about an axis parallel to the z-axis in Figure 3. This rotation is necessary for three operations: (1) generation of windrows is accomplished by angling the wheels (which also allows immediate pickup of raw soil for brick production if properly designed), not by angling the dozer blade as is typically done on earth based machines, (2) final smoothing of a surface layer can be done by turning the drums to the 90 degree position so that only the smooth drums contact the surface while the padfoot drums are off the smooth surface, and (3) generation of the melt tracks discussed later in the report require the full 90 degree rotation. Discarded designs which also utilized the 90 degree rotation capability included the use of a flat, heated dozer blade for the construction of vertical walls and a microwave concept for binding individual bricks to each other (somewhat like slipforming the mortar in a brick wall). Since the machine basically has no suspension system (i.e. no vertical articulation of the drums), machine stability considerations dictate that the dozer blade is required not only for making smooth and level platforms, but also for leveling ahead of the machine. The center portion of the chassis is designed to house the major, heavy components of the power unit allowing the center of gravity to be lowered.

The machine is envisaged as being able to make only one brick at a time. An "interlocking" brick design for use without mortar is illustrated in Figure 5. A heated mold for the brick is used. The "sides" of the mold are stationary, while the top plate applies pressure (directly opposed by the heated bottom plate) during heating. The bottom plate is hinged so that the top plate can be used to extrude the finished brick. The process of making the brick is estimated to take approximately 1-3 hours (estimated from [3]).

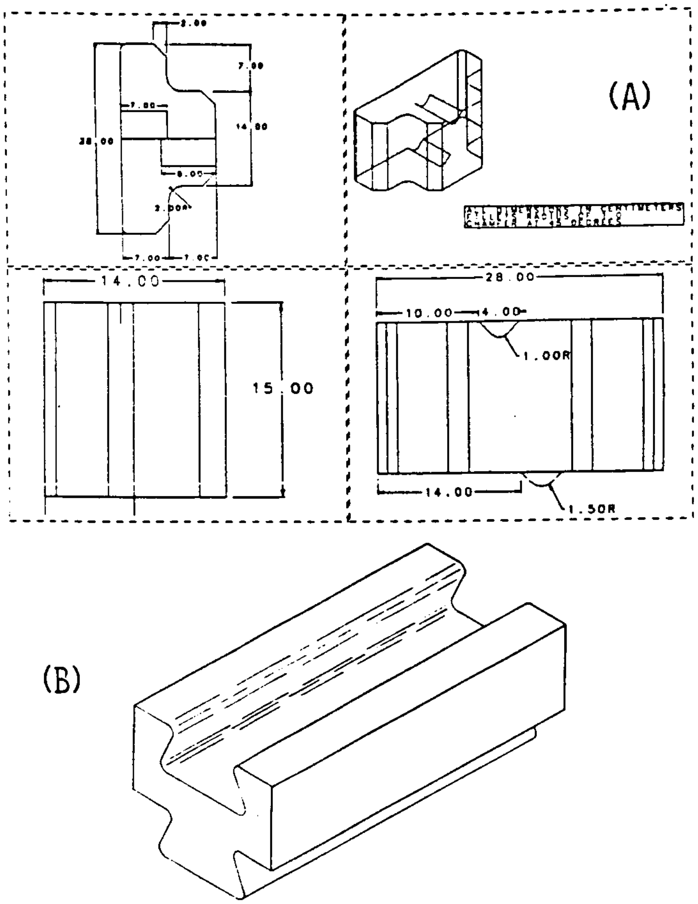


Figure 5. Mortarless brick design: (a) T shaped, (b) Dove tail.

No detailed overall machine design has been accomplished. Problems which must be addressed before detailed design can be done include, but are not limited to:

(1) Brickmaker: Is the problem of gas evolution serious, or very simply handled by the pressure induced by the top plate of the mold? How critical is the fit between the top plate and the sides of the mold? How will cooling be controlled? Is complete melting to glass desired, or is a standard hot press technique actually better?

(2) Drums: Padfoot design (e.g. height, cross sectional area, and geometric design) must be optimized for the expected soil conditions and machine weight. Typical static pad foot pressures of 20-50kg/(cm**2) are attained with earth machinery. Lighter machines and smaller cross sections of the pads will result in the requirement for more passes to attain desired compaction. The smooth steel drums were originally intended to be heated for rock melting of large platforms, but the idea was discarded due to power requirements and due to anticipated problems with the thermodynamics of the melt layer. The smooth drums are retained in the design in order to provide some static compaction in sandy soil and to act as finishing rollers. If desired, the smooth drums may be wrapped with a treaded belt to gain some of the advantages of rubber-tired rollers. Drum diameter will be determined by the soil conditions, vehicle weight, and desired dozing capability.

(3) Blade: The blade has not been designed in this report. Some considerations on the design can be found in [5, 7].

(4) Penetrator: A design of the glass forming section of the penetrator is needed which will address the question of confining pressure. A proposed design is illustrated schematically in Figure 6.

In the pursuit of the solution to the detailed design problem, modules to be added to existing computer programs are proposed. Specifically, bulldozer and melt processing modules should be incorporated into the MSFC LRV analysis program [22]. The modified LRV program should then be incorporated in the IDEAS**2 package [PC-1]. Extension of the AYER [35] finite element program to three dimensional analyses (i.e. beyond the axisymmetric case) should be attempted at this stage of research. Solution of several of the equations in the terrain-vehicle interaction modules requires knowledge of the Bekker soil value parameters [7] which are given for lunar type soils in Table 5.

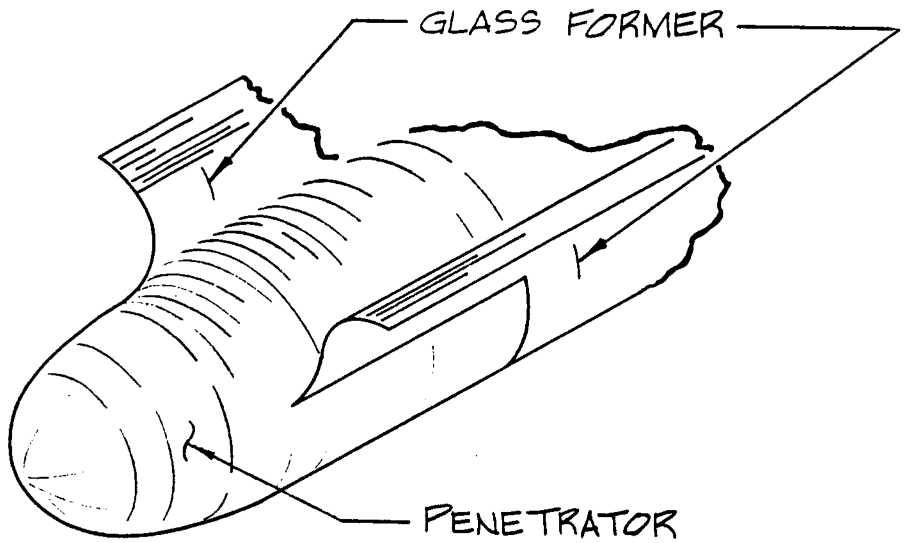


Figure 6. Schematic of track melting penetrator.

Table 5. Bekker soil values [22].

n	k_ϕ (lb/(in**(n+2)))	k_c (lb/(in**(n+1)))
0.92*	6.26	1.13
1.0**	3.0	0-0.4

* sand, basalt
** estimate for lunar soil

The resulting computer output should allow computation of the ratio of (power available/power required) versus total machine mass. It is anticipated that the correct solution is attained in an iterative fashion when the ratio is greater than or equal to 1.0 and the total mass of the machine is large enough to accomodate the mass and volume of the power supply. The suitability of Bekker's approach to the locomotion problem has been challenged in one case [48]. Since Bekker's method is not completely analytical (i.e. several empirical constants are required), careful review of the equations involved and of the statics and dynamics of the problem are required prior to implementing any computer codes.

On the other hand, three problems not directly associated with the machine design can be formulated and solved in the short term (upon acquisition of the material properties of the brick] using the finite element method.

(1) Thermally induced stresses or displacements in the brick due to surface temperature fluctuations on the order of 290 degrees C may be calculated in preparation for failure analysis of the brick.

(2) Stresses or displacements resulting from opposing distributed loads on the top and bottom of the brick are needed. The impact of meteorites and moon quakes (on the order of Richter 4 [69]) on assembled walls should also be assessed.

(3) Stresses or displacements in the soil volume ahead of a bulldozer blade are needed.

Incorporation of probability distributions into the finite element code as a statistical approach to handling the problem of inhomogeneous, possibly nonisotropic material should be a long term goal of the computer code research.

STRESS ANALYSIS REQUIREMENTS

Bricks and Walls. The use of bricks for walls may be necessary for purposes such as radiation protection even in the cases where reactors are placed in craters (e.g. French in [46]). Stress analysis of the bricks will probably take place in a finite element context because the geometric boundary conditions will make a purely analytical derivation difficult at best. The walls must be analyzed for performance under the following loads: (a) meteorite impact, (b) thermal cycling, (c) quakes on the order of Richter 4, (d) degradation by the solar wind; and, for Mars, (e) wind loads [60], and (f) stress corrosion induced by the atmosphere.

An early concept for an igloo shaped structure (shell of revolution) with a very large base diameter to height ratio was originally considered for use as a storage and habitat facility. The concept was to pile material in a mound, roll over the mound with the melting drums, and then excavate the loose material from beneath the glass melt shell (similar to concepts discussed by Khalili in [46]). Although the shell of revolution often allows relatively thin structures to be built, this method was considered to be impractical for several reasons not enumerated herein. In addition, excluding the drum melters during the redesign of the machine has precluded this option. Shell structures will therefore have to be launched from Earth or made using a curved brick design which has not been done in this paper.

Melt Tracks. Geotextiles were considered for use as road surfaces but were eliminated from the design. A concept of a melt track rail system which is of interest is illustrated in the initial base shown in Figure 7.

The melt track system may be useful as a test bed for the following concepts:

(1) Mining car transportation of materials may proceed by means of linear induction motors placed in the soil between the melt tracks and with guidance of the car assisted by laser or other mobile control systems [PC-10]. Propulsion of rather large payloads at 17fps is attained routinely, with much higher speeds attainable for optimized linear induction designs [PC-9]. Pressure applied to the tracks by the cars will be an important factor in the feasibility of this operation.

(2) If the speed of vehicles using the tracks can be increased to a reasonable rate, the system can be used for rapid transit of astronauts from frequently visited work areas remote from protective habitats back to the habitats in the event of harmful solar activity.

C-2

(3) If the glass melt technique can be perfected, it may even be possible to use a modified form of this concept in mass driver design. The system could be designed for very low friction, thus minimizing the time and distance needed for acceleration.

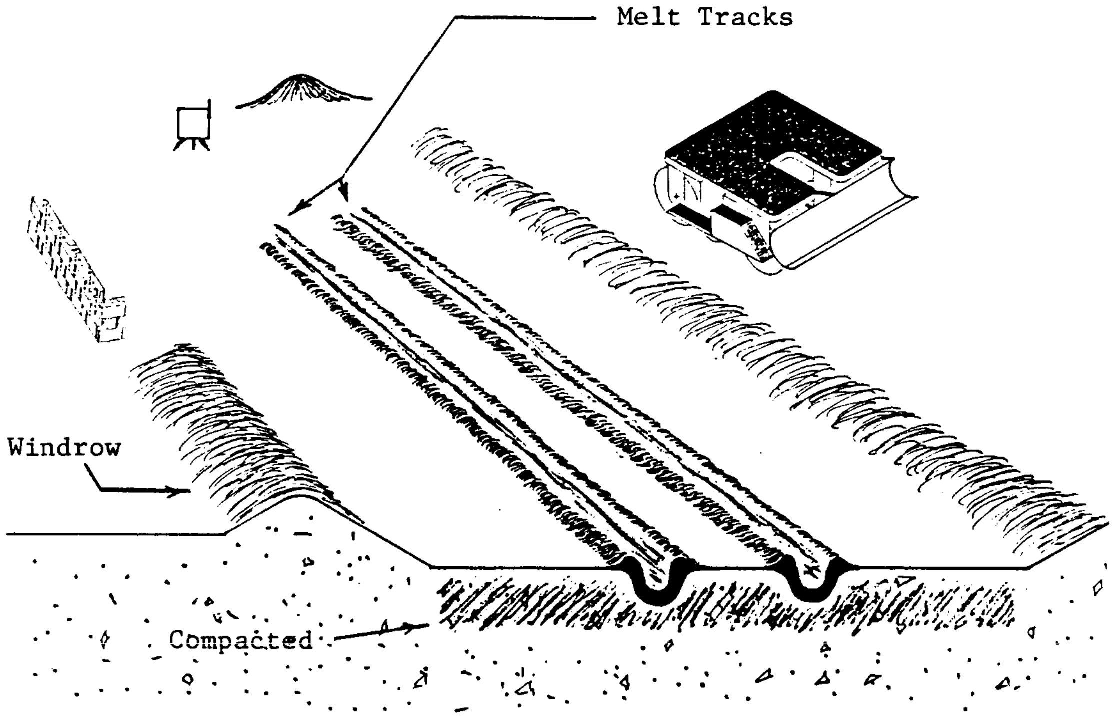


Figure 7. A portion of the initial base.

The three operations mentioned above are nothing more than wishful speculation without a stress analysis of the track system. In Figure 8, the problem is defined.

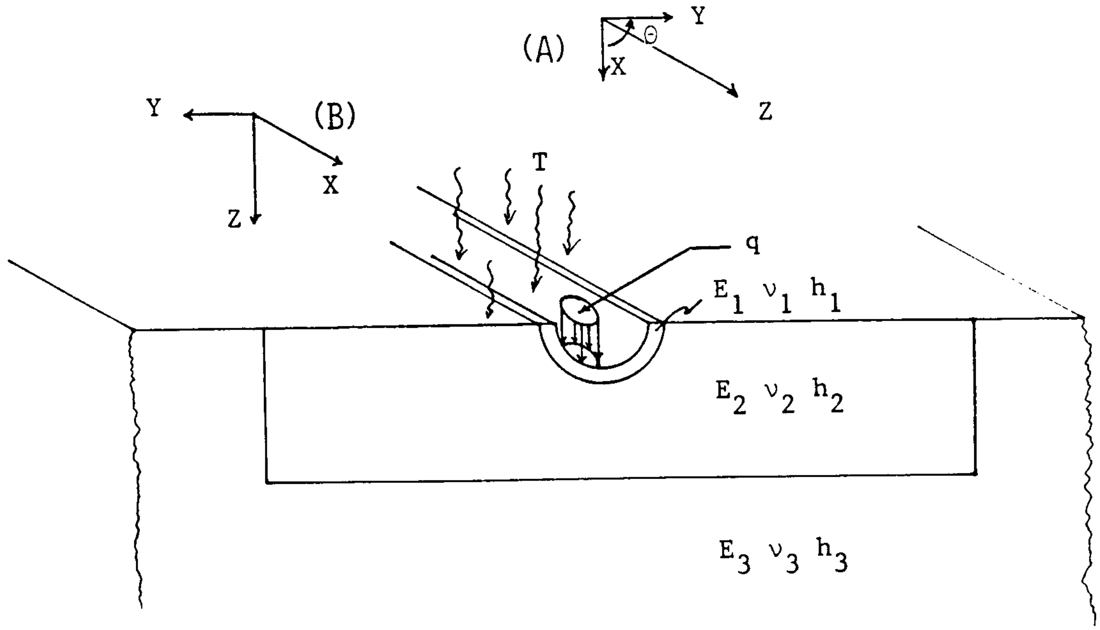


Figure 8. Problem definition: melt track.

An attempt to solve the problem using an analytical approach to the solution of the stress field in the glass track may precede a finite element analysis. The necessity for the liberal use of the principle of superposition in the derivation must be tempered by a critical assessment of whether or not superpostion applies (e.g. the displacements and displacement gradients should be small so that the Lagrangian and Eulerian infinitesimal strain tensors are approximately equal). As is often the case when some lack of understanding is present and approximate solutions are acceptable, linear elastic behavior and superposition validity are assumed. Returning to Figure 8, it is noted that the wheel loads can be placed in the interior of the glass track where St. Venant's principle tells us that the end effects become less important, or the load can be placed on an end of the glass track simulating an expansion, construction, or terminal joint. The general problem is reduced to three problems, the solutions of which may be superposed.

(1) an axisymmetric thermal effects problem,

(2) a distributed load over a portion of the boundary of a multiple layered plate with a semi-infinite bottom layer, and

(3) the penny-shaped crack normal to a boundary, or the crack in a cylindrical shell.

An example of the general approach to the solution of the problem follows.

Using axis system (A) of Figure 8, the approach to problem (1) generally follows the guidelines given in Timoshenko et al. [64] with the result that (a=interior radius of the melt layer, b=exterior radius)

$$\sigma_r = \frac{\alpha E}{1-\nu}\frac{1}{r^2}\left(\frac{r^2-a^2}{b^2-a^2}\int_a^b Tr\,dr - \int_a^r Tr\,dr\right) \quad (4.2)$$

$$\sigma_\theta = \frac{\alpha E}{1-\nu}\frac{1}{r^2}\left(\frac{r^2+a^2}{b^2-a^2}\int_a^b Tr\,dr + \int_a^r Tr\,dr - Tr^2\right) \quad (4.3)$$

$$\sigma_z = \frac{\alpha E}{1-\nu}\left(\frac{2}{b^2-a^2}\int_a^b Tr\,dr - T\right) \quad (4.4)$$

The maximum tangential stress at a free end is modeled as a beam on an elastic foundation by taking a longitudinal strip from the shell [64].

$$(\sigma_\theta)_{max} = \frac{\alpha ET}{2(1-\nu)}\left(\frac{\sqrt{1-\nu^2}}{\sqrt{3}} - \nu + 1\right) \quad (4.5)$$

The approach to problem (2) begins with the Boussinesq solution (see [64]) for a load distributed over part of the boundary of a semi-infinite solid as modified by Burmister [13, 14] for three layered systems. Computer implementations of layered elastic analyses have already been accomplished and can be used for thickness design of the melt layer, given basic material properties of the various layers. These programs sometimes give only the stresses, strains, and displacements at the layer boundaries. Therefore, an attempt must be made to correct the stress distribution [64]

$$\sigma_r = \sigma_\theta = \frac{q}{2}\int_0^a [-2(1+\nu)z(r^2+z^2)^{-3/2} + 3z^3(r^2+z^2)^{-5/2}]r\,dr \qquad (4.6)$$

for multiple layers so that an analytical, continuous form is available within layers to be projected onto the crack plane in problem (3). In equation (4.6), axis system (B) of Figure 8 is used with 'a' being the radius of a circularly distributed load on a flat boundary. It is expected that the load will actually be elliptical and distributed on a curved boundary as depicted in Figure 8.

In the solution to problem (3), it is expected that the Schwarz-Neumann alternating method [see 41] will be used. Basically, the thermal and wheel load stress solutions will be superposed to give the stress distribution at the location of the crack and the stress distribution remote from the crack (i.e. at the surface). This process will establish the initial traction or displacement boundary conditions. The alternating method is then used to generate the cracked body solution for the strain energy density factor.

After all this theoretical work is done, it will be necessary, once again, to apply some sort of statistical method to results. This adjustment is required because of the difference between the real material and an ideal continuum. It is also necessary because no consideration has been given to the interaction of crack tips, nor has consideration been given to possible dynamic effects in this scenario. Alternatively, the influence of multiple cracks may be approached by using a technique based on anisotropy of elastic response resulting from the assumption of or knowledge of a crack density tensor [40].

MATERIAL TEST PROCEDURES

Some of the ASTM test procedures which would be useful in determining the needed parameters for evaluation of alternative products of the machine are identified in Appendix D. Many of the tests mentioned should be used as guidelines for the development of new methods rather than rigid procedures because of the nature of the materials and geometries involved. The most important tests to accomplish in the short term are those which yield the parameters needed for stress and displacement field analyses and those which define failure mechanisms.

It is expected that a maximum principle strain criterion will be appropriate for many of the product materials and that the Mohr-Coulomb [see 62] failure envelope will be quite useful. Failure by fracture of these materials is expected, but will probably involve mixed modes and multiple crack interactions. One approach to the problem of microcracking around a macrocrack as applied to concrete can be found in [6].

The parameters needed for the penetrator and brick mold plates are already available through LASL. The pad feet and drums for the compactor are usually made of work hardened manganese steel [PC-8] for which data are available, thus allowing only a small laboratory testing program with anticipated materials in the appropriate planetary environment simulation. The scraper edges for the dozer blade are often made of rolled DH-2 steel [PC-11] for which data are also available.

MISSION SCENARIOS

Unmanned. From Earth, launch the machine depicted in Figure 3 attached to a lunar lander. Construct the base as shown in Figure 7. Perform automated shutdown.

From consideration of the conceptual design of the machine, three events which will result in complete mission failure immediately come to mind:

(1) Primary power system failure,

(2) Excess sinkage (i.e. getting stuck due to high ground pressure wheels, and

(3) Rollover/hangup.

Manned. Prepare vehicle for launch to Mars for initial base construction there (e.g. replace worn parts, insert Mars specific modules). Inspect, test, and evaluate melt tracks, bricks, and compacted materials. Place bricks. Test melt-tracks with a rover type vehicle.

CONCLUSION

The use of rock melting and hot pressing techniques for making building materials seems the most appropriate approach at this time. The use of typical adhesives such as portland cement and mortar is considered to be impractical unless the heat intensive methods outlined in this paper fail to produce useable materials. Experimental data documented in the literature on materials similar to materials proposed as construction products indicate that useable materials can be successfully produced.

With the present and near term future developments in thermoelectric power generation and electric motors, it is apparently feasible to manufacture a device which can make planetary surface transportation systems and protective structures. Considerable research into the engineering properties of product materials is needed before detailed design of the machine can be accomplished. However, if the basic missions of the machine outlined herein are considered appropriate, a modular, conceptual design of the machine may be performed which will minimize the effect of changing technologies.

ACKNOWLEDGEMENT

Concepts for the bricks illustrated in Figure 5 were provided by Marc Piehl and Mike Fox. Marc Piehl drafted Figures 3(a) and 5(a) using computer software. Mike Fox drafted Figures 5(b) and 6. Joe Goldberg assisted with the production of Figures 1, 2 and Appendix C.

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PC-14. Pope D., Spectra-Physics, (800) 538-7800, (not contacted).

PC-15. Rowley J.C., LASL, Earth and Space Sciences Division, (505) 667-1378.

APPENDIX 4-B: LIST OF SYMBOLS

a	radius
b	constant
c	cohesion
E	elastic stiffness (Young's modulus if isotropic)
g	earth gravitational acceleration
g_m	Mars gravity
g_o	Lunar gravity
JIc	Fracture toughness, Energetic
k	thermal conductivity
k_c	constant in Bekker model
KIc	Fracture toughness, Stress intensity factor
ksg	modulus of subgrade reaction
k_ϕ	constant in Bekker model
N	sample size
n	exponent in Bekker model
q	distributed load
r	radius
SG	specific gravity
T	Temperature
z	depth
α	linear coefficient of thermal expansion
β	angle of repose
Θ	angle
ν	Poisson's ratio
ρ	density (used interchangeably as unit weight)
σ_c	compressive strength
σ_y	yield strength (or indirect tension or ultimate tensile strength)
ϕ	angle of internal friction

AYER	LASL system software
DDM	NASA/JSC system software
IDEAS**2	NASA/JSC system software
JSC	Johnson Space Center
LASL	Los Alamos Scientific Laboratory
LRV	Lunar Roving Vehicle
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration

APPENDIX 4-C: DATA FROM MANUFACTURER'S LITERATURE

Manufacturer	Model	HP (kW)	Operating Weight (kg)	Approximate Machine Volume (m^3)	Dozer/Loadr Available, Capacity (m^3)
Caterpillar	CB214	24.0	2300	5.4	N
Caterpillar	CB224	24.0	2450	6.4	N
Caterpillar	CB314	41.0	3357	6.7	N
Caterpillar	D3B	48.0	6915	11.2	1.21
Caterpillar	IT12	48.0	7554		Y
Caterpillar	CP323	52.0	4560	20.8	Y
Caterpillar	CB414	52.0	5780	14.8	N
Caterpillar	CS431	52.0	6110	20.5	N
Caterpillar	D3BC75	56.0	7371	11.2	1.21
Caterpillar	D4E	60.0	9090	13.2	1.7
Caterpillar	CP433	60.0	6750	23.6	Y
Caterpillar	CS433	60.0	6720	27.2	N
Caterpillar	IT18	63.0	8660		Y
Caterpillar	D4H	67.0	12252	25.0	1.89
Caterpillar	PR105	67.0	7711	26.3	N
Caterpillar	CB514	68.0	9730	22.5	N
Caterpillar	D5B	78.0	11619	21.2	2.57
Caterpillar	IT28	78.0	9633		Y
Caterpillar	D5H	90.0	13890	32.4	2.66
Caterpillar	518	96.0	14243	60.3	Y
Caterpillar	D6D	104.0	15695	23.6	3.06
Caterpillar	CB614	115.0	11340	34.4	N
Caterpillar	CS551	115.0	10400	41.3	N
Caterpillar	CP553	116.0	12200	50.4	Y
Caterpillar	CS553	116.0	10780	43.0	N
Caterpillar	D6H	123.0	20612	40.0	4.08
Caterpillar	D7G	149.0	20666	30.6	6.42
Caterpillar	814B	157.0	20580	54.8	2.91
Caterpillar	815B	157.0	20037	87.5	Y
Caterpillar	816B	157.0	20628	86.0	Y
Caterpillar	D7H	160.0	22796	46.1	6.42
Caterpillar	824C	231.0	30380	72.9	4.67
Caterpillar	826C	231.0	31310	115.5	Y
Caterpillar	D8L	250.0	37417	66.6	13.6
Caterpillar	834B	336.0	46355	98.1	7.27
Caterpillar	D9L	343.0	52478	71.6	18.5
Caterpillar	D10	522.0	79619	95.1	29.07
Dresser	VOST2-42,	25.7	3257	12.1	N
Ingersoll-Rand	DA30	24.0	3200	7.2	N
Ingersoll-Rand	DA28	24.6	2275	4.7	N
Ingersoll-Rand	DA40	57.0	6990	13.5	N
Ingersoll-Rand	SPA50	70.0	7410	24.4	N
Ingersoll-Rand	SPA56	70.0	9160	31.3	N
Ingersoll-Rand	SP48	70.0	6600	20.1	N
Ingersoll-Rand	SP48DD	70.0	6920	23.0	N

Ingersoll-Rand	SPF48	70.0	7240	24.2	N
Ingersoll-Rand	SP56	70.0	8913	29.5	N
Ingersoll-Rand	SD100	71.6	10500	29.5	N
Ingersoll-Rand	SD100F	82.8	11500	29.5	N
Ingersoll-Rand	SP56DD	84.0	9389	33.0	N
Ingersoll-Rand	SPF56	84.0	10206	33.5	Y
Ingersoll-Rand	DA48	86.0	9099	21.1	N
Ingersoll-Rand	DA50	86.0	10020	28.2	N
Ingersoll-Rand	SP84	123.0	13900	36.2	N
Ingersoll-Rand	SPF84	123.0	14210	36.2	N
Ingersoll-Rand	DS84	146.0	20684	34.7	N
Ingersoll-Rand	DF84	146.0	18733	43.3	N
Ingersoll-Rand	LF450	160.0	20455	100.2	Y
Ingersoll-Rand	SP60DD	164.0	17101	45.2	N
Ingersoll-Rand	SPF60	164.0	18870	46.4	N
Ingersoll-Rand	SPF60C	164.0	20140	49.6	N
Ingersoll-Rand	LF750	302.0	35835	148.5	Y
John Deere	655	11.9	732	5.3	Y
John Deere	316	11.9	354	2.1	Y
John Deere	650	12.0	744	5.5	Y
John Deere	330	12.0	408	2.1	Y
John Deere	318	13.4	354	2.1	Y
John Deere	755	14.9	764	5.9	Y
John Deere	430	14.9	533	3.9	Y
John Deere	750	15.0	907	5.1	Y
John Deere	855	17.9	827	4.2	Y
John Deere	30	18.0	3000		N
John Deere	850	19.0	1222	7.0	Y
John Deere	570	23.0	1515	6.9	Y
John Deere	50	29.0	4355		N
John Deere	675	32.8	1991	9.2	Y
John Deere	355D	36.0	5625	14.2	0.75
John Deere	350D/630	36.0	4810	18.7	Y
John Deere	350D	36.0	5465	20.9	Y
John Deere	70	41.0	6620		N
John Deere	444D	67.0	9595	38.7	1.15
John Deere	544D	86.0	10820	47.9	1.34
John Deere	655B	90.0	15240		2
John Deere	750B/650	90.0	14900	53.0	Y
John Deere	750B	90.0	13489	39.0	Y
John Deere	750BLGP	90.0	15806	55.0	Y
John Deere	755B	104.0	17000		2.25
John Deere	850B	123.0	20124	66.9	Y
Boeing	LRV		707	7.3	N

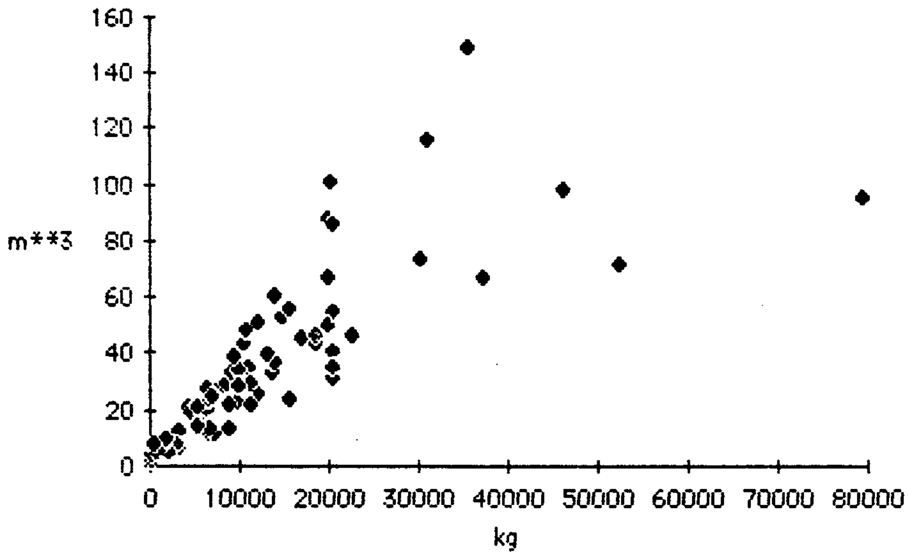

Figure C-1. Volume versus weight for various construction machinery.

APPENDIX 4-D: SELECTED ASTM TESTS *

C7	Paving brick
or	
C131	Resistance to abrasion of small size aggregate by use of the Los Angeles machine
or	
C418	Abrasion resistance of concrete by sandblasting
or	
C779	Abrasion resistance of horizontal concrete surfaces
C67	Sampling and testing brick and structural clay tile
C158	Flexure testing of glass
C589	Apparent impact strength of preformed block-type insulating materials
or	
E23	Notched bar impact testing of metallic materials
C598	Annealing point and strain point of glass by beam bending
C623	Young's modulus, shear modulus, and Poisson's ratio for glass and glass-ceramics by resonance
C637	Aggregates for radiation-shielding concretes
C638	Constituents of aggregates for radiation-shielding concrete
D1195	Repetitive static plate load tests of soils and flexible pavement components, for use in evaluation and design of airport and highway pavements
D1883	Bearing ratio of laboratory-compacted soils
D3397	Triaxial classification of base materials, soils, and soil mixtures
D4535	Measurement of thermal expansion of rock using a dilatometer
E18	Rockwell hardness and Rockwell superficial

hardness of metallic materials

E399 Plane-strain fracture toughness of metallic materials

E510 Determining pavement surface frictional and polishing characteristics using a small torque device

E647 (on fatigue crack propagation)

E813 JIc, a measure of fracture toughness

* Compiled primarily from the 1979 annual books of ASTM standards. Applicable new standards and modifications to the above standards may exist.