tures. The LIBS pulses may impart sufficient energy into the ground to also serve as seismic sources. The following table summarizes the estimated instrument gross specifications.

TABLE 1. Instrument summary.

	LIBS	XRF/XRD	MS	Geophys	Total
Mass (kg)	30	10	20	20	80
Average regulated power (W)	7	10	35	20	72
Data rate (bits/s)	1 M	10 k	40 k	50 k	1.1 M

The TOPLEX operates in a mobile, exploration-and-sample acquisition mode during the lunar day and in a stationary, sample-analysis mode during the lunar night. The rover vehicle that carries the instruments is estimated to mass 100 kg and require 25 W of average power. Vehicle requirements/specifications include the following: Range – 200 km; maximum speed – 500 m/hr; communications – high-gain antenna and data rate consistent with teleoperation; endurance – 4 to 6 months; and must be self-deploying from the lunar lander. In addition, the rover will have stereoscopic vision with zoom and selectable band filtering, and a robotic arm for sample acquisition, preparation (i.e., powdering), and conveyance to appropriate instruments.

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DRILLING AND DIGGING TECHNIQUES FOR THE EARLY LUNAR OUTPOST. Walter W. Boles, Department of Civil Engineering, Texas A&M University, College Station TX 77843-3136, USA.

Introduction: The theme of this workshop is lunar resource assessment. Topics include identification, quantification, and location of useful elements on and below the lunar surface. The objective of this paper is to look at another side of the issue—how to remove soil from the stiff lunar-soil matrix once useful deposits are located.

The author has been involved with the study of digging and excavating on the Moon for several years. During that time he has overheard some disturbing comments such as the following:

"We know what works best here [on the Earth]. Just make the systems such as power and thermal control work in the lunar environment and the machine will work well on the Moon."

"Just send something up there that looks like a front-end loader with a back hoe. It will work. Don't worry about it."

Comments such as these are disquieting, to say the least, because even if a machine's subsystems are designed to operate well in the lunar environment, it may still perform its tasks poorly. Also, one cannot assume that the operational characteristics of terrestrial machines, based upon terrestrial heuristics, will be similar to machines operating on the Moon. Finally, due to the suspect accuracy of terrestrial soil-tool interaction theories, one cannot justifiably argue that these theories can be used along with terrestrial heuristics to make accurate predictions of the performance of various excavating methods on the Moon. The need is great, therefore, for quantitative and verifiable evidence of the performance of various digging methods. This evidence is necessary for the confident selection of appropriate methods for further research and development.

The goal of this paper is to challenge comments such as those mentioned above and to cause those who think that digging or excavating on the Moon is a trivial problem to rethink the reasons for their opinions. Another goal is to encourage them to view total reliance upon terrestrial heuristics with suspicion. This paper will focus primarily upon digging since another paper will focus primarily upon drilling.

Lunar Soil: Much is known about the lunar soil. The characteristics of interest here, however, are those that tend to make the soil difficult to excavate. The soil is composed of very angular, abrasive, fine-grained particles that have re-entrant corners. As a result, they tend to cling to each other. The soil matrix is very loose (low density) at the surface and is very hard (high density) at relatively shallow depth. It is believed that the soil approaches 90% to 100% relative density at a depth of approximately 0.7 m. Additionally, it is reasonable to assume that rocks and boulders will be encountered in any digging activities. The regolith has been described as a dense, interlocking soil matrix [1].

The lunar soil, therefore, will be very difficult to penetrate below about 0.5 m. Penetration of blades, scoops, and cutters will require crushing and shearing of many soil particles since the soil nears 100% relative density at shallow depth. This crushing and shearing action requires high forces. Encounters with rocks and boulders will serve to make a difficult situation worse. Expected performance of traditional terrestrial methods, therefore, is low.

Lunar Experience: During the Apollo missions, hollow stems were augered into the lunar soil. The first attempts were only able to drill to about 1.5 m. This was due to discontinuous auger flights at splice locations on the stem. It is assumed that the soil particles seized the stem at the joint and caused the stem to fail. On later missions the stem was redesigned with continuous auger flights and depths of approximately 3 m were reached. The rate of penetration, however, had to be kept low since the stem would tend to screw itself into the soil and was difficult to remove [1].

There are two major problems regarding drilling. The first one is the removal of cuttings. The second one is cooling of the drill bit. Both these problems are usually solved on the Earth with fluids. The use of fluid to remove cuttings and cool the bit is obviously a problem on the Moon.

Shoveling on the Moon was relatively easy in the top 10 to 15 cm. Below this depth the shoveling became very difficult. Also, hammer tubes were driven to a depth of approximately 0.7 m before the resistance became too great [1]. It is interesting that this depth corresponds well with the depth at which the regolith is assumed to approach 90% to 100% relative density. In summary, these limited data tend to verify data in the previous section. It also tends to confirm that digging in the lunar regolith will be very difficult.

Excavation Methods: Typical terrestrial excavation methods include bulldozers, hoes, shovels, scrapers, draglines, bucket-wheel excavators, and continuous miners with rotating cutting heads. All these methods depend heavily upon gravity to generate downward and horizontal forces. These forces are necessary for the machines to perform well. With the gravity of the Moon approximately one-sixth that of the Earth's, one can expect a corresponding decrease of the machines' performance. For example, the maximum productivity of a 15,000-lb bulldozer on Earth, over a 100-ft haul distance, is approximately 100 yd^3/h. On the Moon,

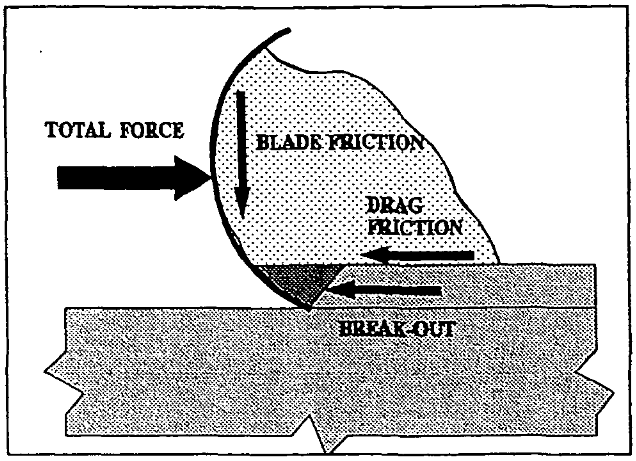

Fig. 1. Balovnev's model.

however, with appropriate efficiency factors [2] and an assumed one-sixth reduction due to the reduced gravity, the output may plummet to only 2 or 3 yd^3/h. This seems ridiculously low for a 15,000-lb machine. Compounding this problem of low productivity is a size and power constraint. Machines that will actually be in use on the Moon will probably have about as much capability and mass as the average riding lawn mower.

Every suggested method the author has seen in print is based upon terrestrial methods. It is the author's opinion that these methods will prove to be very limited in performance and capability. This implies that total reliance upon terrestrial methods is unwise, and innovative methods must be found that will perform well on the Moon.

Soil-Tool Interaction Theories: Most soil-tool interaction theories were developed for soil-tillage applications and focus upon draft or drawbar-pull forces. They do not consider penetration or vertical forces. Verification testing was typically conducted in soft soils. The models were developed assuming the soil to be uniform with fluid properties. The models were also developed for small tools such as tines [3-6].

One often-quoted reference of a bulldozer model is by Balovnev [7]. This model looks only at drawbar forces and attributes the total drawbar force required to four factors—dragging of the soil prism in front of the blade, friction between the blade and soil, bending of the soil layer, and break-out of the soil at the cutting edge. Bending of the soil layer is assumed to be negligible. These forces are as indicated in Fig. 1. There is no gravity factor in the model. Soil weight is a factor, however. If one reduces the soil weight appropriately and uses reasonable estimates of other factors such as an angle of internal friction of 45°, one sees that approximately 90% of the total force required is due to break-out forces while other frictional forces represent only about 10% of the total force required. This result is quite revealing because it again tends to verify that penetration of blades or cutting devices into the lunar soil will require high forces.

Current Research: The author is aware of research conducted at several universities. Studies at the University of Maryland found that the compacted lunar soil simulant was very difficult to penetrate [8]. The difficulty was so great with the testing equipment available that explosive methods were investigated in order to loosen the soil so that excavation could be performed. Research is currently underway at the University of Colorado. The author has not seen published results of this research. He believes, however, that this research involves the use of vibration to reduce penetration forces.

Research at Texas A&M University is focusing on small-scale experiments to enable more accurate predictions of excavating forces and productivities to be encountered on the Moon for various digging methods. The objective of the testing is to compare traditional as well as innovative methods in terms of certain measures of merit such as low forces, high productivities, and low power. The testing device, as depicted in Fig. 2, will be small so that verification testing can be conducted on board NASA's KC-135 airplane to simulate the Moon's gravitational field. Once testing is complete, a better understanding of the expected performance of different digging methods will promote the selection of promising methods for further development.

One particularly interesting method that is being investigated involves the use of a rotary wire (or wirelike) brush for excavation. The concept was first proposed by the Army Corps of Engineers [9]. It was intended to sweep up loose regolith that was assumed to lie on top of a smooth rock surface. The importance of this concept, however, lies in its ability to excavate the dense lunar soil matrix and it may prove to have advantages over methods that require penetration of an implement into the stiff lunar soil matrix.

High penetration forces, for example, will not be required since the bristles will remove soil particles from the surface. As soil particles are removed, other particles are exposed and removed by subsequent bristles. This may be a major advantage since, as indicated previously, break-out forces may represent 90% of the forces required. The method may also prove to be relatively rock tolerant since the bristles will deflect over rocks and not become immobile when rocks are encountered. This may make the device relatively easy to automate. The device may also be designed to collect soil particles up to a certain size depending upon stiffness of the bristles. This has obvious advantages for subsequent processes that would otherwise require sifting or crushing to achieve a small grain-size distribution. Preliminary indications are that the wire-brush method will also be much more productive than traditional methods. Disadvantages of the method may include high rates of wear, high power consumption, and difficulties in collecting the ejected soil particles. The generation of dust may also be a problem to overcome.

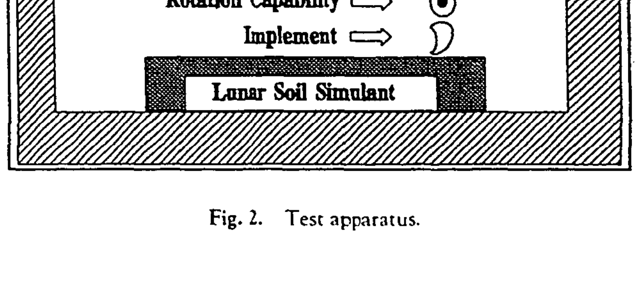

Fig. 2. Test apparatus.

Conclusions: It is the author's opinion that there has been too much dependence upon terrestrial heuristics in suggesting digging methods for the Moon and not enough attention to basic forces, required mass, required power, and expected production rates. Progress toward more basic research is being made, however. Results of work at the University of Colorado and Texas A&M University will prove important for the selection of efficient methods. Short-term results at Texas A&M University are expected to reveal quantitative and verifiable evidence as to which methods are more promising. Long-term results are expected to include candidate methods for prototype development and testing.

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SHOCK-TREATED LUNAR SOIL SIMULANT: PRELIMINARY ASSESSMENT AS A CONSTRUCTION MATERIAL. Mark B. Boslough[1], Leonhard E. Bernold[2], and Yasuyuki Horie[2], [1]Sandia National Laboratories, Albuquerque NM 87185, USA, [2]North Carolina State University, Raleigh NC 27695, USA.

In an effort to examine the feasibility of applying dynamic compaction techniques to fabricate construction materials from lunar regolith, we have carried out preliminary explosive shock-loading experiments on lunar soil simulants. Analysis of our shock-treated samples suggests that binding additives, such as metallic aluminum powder, may provide the necessary characteristics to fabricate a strong and durable building material ("lunar adobe") that takes advantage of a cheap base material available in abundance: lunar regolith.

Introduction: Because of transport cost considerations, it is clear that the vast majority of construction material for lunar structures must be indigenous. The most readily attainable material on the Moon is regolith, so an obvious question is: What is the easiest method of converting lunar regolith to a construction material?

One technology that has been used to modify materials involves the use of shock treatment [1,2]. The principal concept relies on exerting an extremely high dynamic force on a certain base material that is mixed with an agent and thus changes its properties. If such a process could be emulated on the Moon, new soil-based "lunar adobe" construction materials could be created. Although this technology has been proven on Earth, research is needed to study the feasibility of such an approach under lunar conditions and to evaluate the consequences on the design, engineering, and construction of lunar bases.

Experimental: We have performed two shock recovery experiments on samples of a lunar soil simulant. These experiments made use of the Sandia "Momma Bear" explosive loading fixtures to achieve well-characterized shock states. These recovery fixtures allow samples to be shocked in a controlled, reproducible manner. A planar shock wave is generated by detonating a high-explosive lens next to an explosive pad. The shock wave passes through an iron pulse-forming plate and into the copper fixture, which contains the 5 cm^3 powder sample. The entire assembly has cylindrical symmetry. Because of the large impedance difference between the sample and copper, and the finite lateral extent of the sample, the shock loading is not a simple, one-step uniaxial process. On the contrary, the initial loading is due to a radially converging shock wave, and the final shock state at a given position is reached by a series of shocks.

Shock pressure and temperature histories were determined numerically by two-dimensional computer simulations [3,4]. These calculations are based on the geometry of the sample holder, the type of explosive, and the initial packing density of the powder (in general, the lower the packing density, the higher the shock temperature as long as nothing else is changed). The two experiments for the present study made use of the explosive Baratol, and the peak shock pressure range was 510 GPa, with the peak pressure a function of position within the sample.

For the first experiment (13B917) the sample was "Minnesota Simulant" Lot 2, with particle size between 50 and 100 mesh, and a mean initial powder density of 1.896 g/cm^3. The second experiment (14B917) made use of the same simulant, with an admixture of aluminum metal; CERAC A-1189, 99.99% pure with a particle size less than 325 mesh. The mean initial powder density of the mixture was 2.051 g/cm^3. The material used in these experiments was intended to simulate the crystalline fraction of basaltic lunar regolith. The simulant was taken from the fine-grained basalt of the Duluth Complex, Minnesota, and was provided by P. W. Weiblen [5].

Results: Macrocracking was only observed in the sample with aluminum binder. It is possible that the cracking was created during the postshock handling of the compacts. The samples appear to have been compacted to densities in the range from 70 to 85%, but they had very little mechanical strength. However, strong metallurgical bonding of nonmetallic powders by weak shock in the peak pressure range of 5–10 GPa cannot be expected. A rough estimate of the threshold pressure required for shock consolidation is twice the Vickers microhardness of the solid materials. Thus, without the use of binding additives, several tens of GPa are required to consolidate lunar simulants.

TABLE 1. Impression tests of lunar material.

Sample	$E_c \left(= \frac{d\sigma_c}{d\epsilon_c}\right)$ [MPa]	σ_c^y [MPa] 0.2%	0.5%	UYP	LYP	σ_c^{max} [MPa]	ϵ_c^{max}	K^* [MPa]	n^*
Lunar #2-1	1057	37.5	36.5	38	36.7	54.9	0.077	494	0.945
Lunar #2-2	1078	58.2	60.3	58.2	58.2	73.8	0.093	396	0.904
Lunar #2-3	1329	54.3	52.5	56.4	52.4	67.2	0.064	388	0.810
#2/Al Binder	8957	175	207	—	—	210.6	0.032	5021	0.971