Practical Aspects of Terrestrial Mining for Use in Extraterrestrial ISRU Concepts. M. Meinshausen[1], [1]632 Arden Ave. Glendale, CA 91202, martin_meinshausen@yahoo.com.

Introduction: This paper gives the conference an overview of currently used terrestrial mining equipment and methods, explores their implementation in space, as well as discusses the possibility of scaling up current space exploration equipment by addressing areas of improvement and concern. Its purpose is to start a conversation about these topics to further the viability of ISRU utilizing four categories - *Heavy Equipment*, *Material Transportation Methods, Use of Explosives*, and *Underground Mining.*

Heavy Equipment: We must evaluate commonly used equipment essential for material movement, like Dozer, Skid Steer, and Scraper, and the how to optimize them for use on highly abrasive materials comparable to lunar regolith. For example, on CAT dozers the high drive is already elevated to lessen exposure to dirt and thus minimizes wear and tear on the drive.


Fig. 1: CAT D8 and D9 dozer with ripper
Fig. 2: John Deere: Skid Steer on rubber tracks and on tires.

On the Skid Steer, it still needs to be discussed if rubber tracks, with or without high drive, are an effective solution for lunar applications. One advantage of rubber tracks over tires is their better performance on rough uneven terrain e.g., providing better stability on slopes and less prone to get stuck or flip over. However, this advantage may be outweighed by their reduced reliability due to higher maintenance requirements. Employing high maintenance equipment in space can easily lead to a total loss of equipment. Ultimately, the decision of which system will be used depends on if/ how effective autonomous maintenance can be provided in space (swarm robotics, self-healing, etc.).

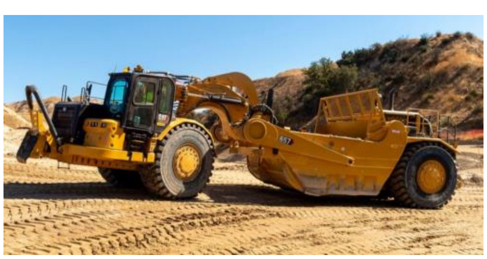


Fig. 3: Caterpillar CAT Scraper 657

A scraper is a good example for a multi-use machine to load, haul small distances, and dump in designated areas by spreading the material on the ground.
pro: fewer machines needed.
con: no backup machine if this one break down.

Material Transportation Methods: Primarily the decision of trucking vs. conveying of bulk materials depends on the hauling distance from excavation to processing facility. The economics of each system dictate the cut-off distance where conveying is more economical than trucking. In general, the longer the distance the more efficient the use of conveyer belts.

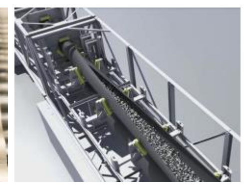



Fig. 4 & 5: BeumerGroup conveyor bulk material

Using haul trucks on the lunar surface requires significant haul road design, dust emission suppression methods and a sufficient predictive maintenance program. Conveyor belts on the other hand are a more effective and low-cost method of transportation [2]. A special pipe conveyor also (Fig. 5) encloses the bulk material and thus keeps dust emission to a minimum.

Use of Explosives: A common explosive used in mining is ANFO which contains 94% ammonium nitrate as oxidizer and 6% diesel as fuel. Without oxygen a fire cannot exist, but an explosion can happen if there is an oxidizer available.
pro: delivers best rock fragmentation.
con: creates flyrock

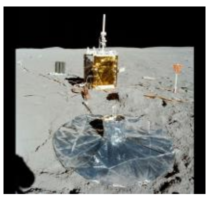
In open pit mining the flyrock created by surface mine blasting is of paramount concern; this will be even more so in low gravity environments where flyrock distance is exaggerated. If not sufficiently contained it can cause severe damage to anything in its path e.g., astronauts, housing, space crafts, scientific instruments and other nations stations.

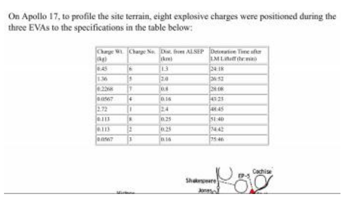
Flyrock has an initial velocity of around 2000m/s. (For comparison a golf balls initial velocity is about 70m/s.) On earth flyrock slows down within a few hundred feet and then falls back to the ground. On the moon it will fly for a long distance since there is no atmosphere to slow it down.

Parameters to predict flyrock distance can be calculated based on “hole diameter, power factor, burden, explosive charges per meter and stemming length”. [1] These parameters can be altered to minimize flyrock distance, however flyrock cannot be eliminated. Blast mats covering the blast area are a common method to contain flyrock even further (on earth up to 90%).

For extraterrestrial use these parameters and the use of mats needs to be optimized to contain flyrock even more than 90%, ideally 100%.

The possibility of 3d printed carbon fiber mats for extraterrestrial use should be explored.





On Apollo 17, to profile the site terrain, eight explosive charges were positioned during the three EVAs to the specifications in the table below:

Charge Wt. (kg)	Charge No.	Dist. from ALSEP (km)	Detonation Time after LM Liftoff (hr:min)
0.45	6	1.3	24:18
1.36	5	2.0	26:52
0.2268	7	0.8	28:08
0.0567	4	0.16	43:23
2.72	1	2.4	48:45
0.113	8	0.25	51:40
0.113	2	0.25	74:42
0.0567	3	0.16	75:46

Fig. 6 & 7: NASA ALSEP Apollo 16, LSPE Apollo 17

A plastic bonded explosive composed of HNS and TEFLON were used on the moon during the Apollo 17 mission LSPE.

Fig. 8: Drilling Rig

Fig. 9: Loading Blast-Hole

Fig. 10: Rock Muck Pile

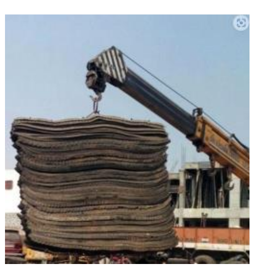


Fig.11: Blast Mats

Underground Mining: By establishing an underground operation, the blast area can be contained to ensure no flyrock will be exposed to the surface. Starting with a horizontal mine entrance from a moon crater bottom seems feasible. Preferred equipment would be an autonomous underground drill rig (Fig.12) with several booms, which needs to be scaled down from current size for lunar operation. Alternatively, a tunnel bore machine could be utilized.
pro: contained blasting, contained volatiles, less exposure to radiation and extreme temperature variations. **con:** possible need for roof support.

Fig. 12: Boomer Drill Jumbo underground

Summary: Some terrestrial Heavy Equipment, Material Transportation Methods, Use of Explosives, and Underground Mining were described and their possible use for extraterrestrial ISRU concepts discussed. The collaborating efforts are promising and exciting at the same time. Humanity looks forward to see concrete developments on the moon materializing.

Further Development:

A: Develop viable lunar drilling and blasting concepts and lunar underground mining concepts.

B: Find a company/facility to conduct testing/establish testing procedures and parameters.

C: Cooperate with moon missions for physical test.

References:

[1] Murlidhar B. R. et al. (2021) *JRMGE, Volume 13, Issue 6*, 1413–1427.
[2] Cassandra (2017) *LOCKER,*

Glossary:

ALSEP: Apollo Lunar Surface Experiments Package
ANFO: Ammonium Nitrate Fuel Oil
LSPE: Lunar Seismic Profiling Experiment
HNS: HexaNitroStilbene