

Introduction: Living and performing scientific tasks on the lunar surface will require machines to shape and move regolith and bedrock. The materials may be used for resource processing, construction, insulation, crew protection or scientific sampling. Lunar excavation is unique given the harsh environment and dry abrasive material. Terrestrial solutions to similar materials offer an opportunity to learn but will not apply directly to lunar tasks. Terrestrial design solutions are problematic given upmas constraints, power required, lubrication, lack of convection, maintenance limitations, limited retooling options and out gassing of fluids. Lunar design solutions may follow mining models, construction models, agricultural models or hybrids. Teams that understand the issue of space design and operations reside in a different industry than the teams that design and operate terrestrial machines. These separate communities of knowledge must be fused to create innovative design solutions to perform necessary lunar excavation. Given the harsh penalty for failure and finality of an expendable Launch Vehicle launch it is essential to address these design issues thoroughly and early in the mission planning phase. The potential questions and solutions will shape the requirements and could enable new science.

Regolith: Lunar regolith is difficult to sample and excavate as experienced by the Apollo crew. Several improvements were made to the tools between missions. The regolith is composed of jagged particles that tend to cling together and to porous objects. Regolith is very abrasive similar to blast grit used to abrade paints and corrosion on metals. Regolith is packed tightly just under the surface. This is a stark contrast to soil that contains liquid water and organic matter that tends to stay loose and easy to excavate. This contrast is the difference between cultivating a farm field and a packed road base. The machines required are very different in terms of mass and force required.

Environment: The lunar environment with its hard vacuum and large thermal swings limits design options for machines. For example if we chose a multipurpose agricultural compact tractor to work on the lunar surface. The tractor selected has a 30 hp motor and a front mounted bucket. The rear has a quick release system and various implements. These imple-

ments could grade, microwave seal the surface, drill, lift and tow various objects. Beyond the obvious conversion to electric power the radiative surfaces are inadequate to dissipate heat from the transmission and hydraulic fluid. The transmission and hydraulic fluids would gel at the lower temperature extremes. Slip fits become pressed fits and mechanisms bind. Any leaks would outgas rapidly and coat cooler objects contaminating the area. The seals will dry out creating more leaks and out gassing. Conventional wisdom would be to convert to electromechanical devices and eliminate hydraulic systems. This conversion would be at the expense of ease of control, force per weight and functionality.

Model Selection: Various earth bound models exist for lunar applications. For example the agricultural model example where the machines are adaptive with numerous attachments for various tasks over the seasons. The construction model is one where machines are more optimized for specific tasks with no or few attachments. In mining this is carried to the extreme, tasks are very specific and repetitive. A hybrid solution may be optimal where regolith processing is accomplished with a mining approach with very specific optimized equipment while a general purpose machine is available for less frequent tasks (road building, drilling and module moving).

Rover Derivatives: Another approach is to grow our current space rovers to perform excavation tasks. Given the compact tractor discussed above weighs as much as a mid sized car the power, strength and mass of the rovers is minute in comparison the machine required is very unique. We have built nothing for earth or space applications that can do the lunar tasks.

Dust Considerations: The Apollo crews had hardships caused by the lunar dust. The dust bound joints in the space suits and covered essential radiators on the rover. When regolith is excavated or transported dust will require management. The dust can bind bearings and render radiators ineffective. Electromechanical devices will require dust mitigation approaches. It may be as simple as moving slowly during certain operations or hermetically sealing devices.

Requirements: The definition and requirements of the specific tasks will drive design decisions. Un-

Understanding the technology limits and design knees will assist with the refinement of requirements. For example if a small amount of regolith will be processed a batch operation may work. The material could be stockpiled periodically for processing. If large amounts of regolith must be processed a continuous collection and conveying approach would be more appropriate.

Several intermediate choices are available to collect and move regolith. It can be scraped and transported in the same machine. Another approach is to dig and load it into the beds of transporters. Do these transporters have wheels or tracks? If wheels how many? If tracks what material?

Resources Available: The power available to charge batteries or directly power equipment will set the speed at which it can perform tasks, possibly the duration and specific task starting time.

The launch mass allocated to the equipment will drive the speed of operation and ability to dig or grind packed regolith. Some compensation for light equipment mass could be accomplished by pilling regolith on the machine. This is similar to filling tractor tires with fluid to add stability and ballast to offset loads or attachments.

Operator time for crew-operated items will certainly be a design driver. Repetitive tasks may be accomplished autonomously while the crew could accomplish one-time assembly tasks.

Distance to suitable resources will be a driver for design and operational strategy.

Maintenance time, materials and parts availability will be a factor in equipment design. Are actuators interchangeable? How much lubrication is required? What is the mean time between servicing? What is the service life of the machine? How maintainable of a machine is required?

Design Trades: Some design considerations are very subtle when working with materials. Each contour and shape on an implement is there for a reason. It is important to understand how terrestrial equipment functions to avoid poor design implementation.

Why do some buckets have teeth and other are smooth. The teeth tips are used when you need to dig or pry hard materials. The machine can produce a specific amount of force at the tooth tips or bucket lip (edge). Teeth have less contact area for the same amount of force producing high contact stress for digging. A smooth lip is used where the material is soft or a smooth finish is important.

What sets the size of a bucket? The lift capability of the machine and density of material moved. 100

tons of iron ore fills only the bottom of a hopper railroad car while 100 tons of coal is heaped above the sill of the hopper.

Why does excavator and backhoe buckets have the curved geometry? When very hard material is encountered the bucket is used like a lever to break it loose. The bucket is pressed into the bottom of the hole and rolled at the same time to develop maximum digging power. If very hard material is encountered and the operator simply pulls on the material the machine will tilt towards and possibly topple into the hole?

Summary: Terrestrial excavation is complex and difficult in hard material similar to regolith. Resources are limited in a harsh environment. Knowledge of terrestrial excavation and space flight exist in different industries. These bodies of knowledge must be merged to successfully build the space equipment for lunar science and exploration.

References: The Lunar Source Book