LUNAR SURFACE MINING EQUIPMENT STUDY

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ABSTRACT

In response to the Space Exploration Initiative (SEI), a large number of lunar base scenarios have been proposed by various members of the research community. The National Aeronautics and Space Administration (NASA) authored a 90-Day Study that discusses lunar base architectures. These architectures include only lunar surface mining methods and equipment, which support the lunar base by utilizing surface resources. In this paper, the U.S. Department of Interior, Bureau of Mines (Bureau), presents the results of a NASA-sponsored assessment of the various proposed lunar surface mining equipment concepts submitted to NASA. The proposed equipment was reviewed and evaluated considering equipment design criteria, basic mining principles, and the lunar environment. Based on this assessment, two pieces of mining equipment were conceptualized by the Bureau for surface mining operations: the-Ripper-Excavator-Loader (REL), also capable of operating as a load-haul-dump vehicle, and the Haulage-Vehicle (HV) capable of transporting feedstock from the pit, liquid oxygen containers from the processing plant, and materials during construction. The general findings indicate that reliable and durable lunar mining equipment is best developed by the evolution of proven terrestrial technology adapted to the lunar environment.

INTRODUCTION

In the last decade, different lunar base scenarios have been proposed that involve mining and processing of lunar deposits in order to utilize the in situ resources. The pioneering work in this area dates back to 1962 when

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the Bureau participated in the Working Group on Extraterrestrial Resources (WGER) to develop an extraterrestrial mining and processing technology (Atchison and Schultz, 1968) using analogue lunar rocks (Fogelson, 1968). Currently the Bureau has been working closely with NASA in the Space Resource Utilization Program. Research needs for lunar mining technology to support a lunar base have been outlined by Podnieks and Roepke (1985).

The Bureau, in cooperation with the U.S. Army Corps of Engineers, organized a Workshop on Extraterrestrial Mining and Construction in May 1989 to establish future guidelines in developing lunar mining technology (Register, 1990). The workshop members represented a cross section of disciplines involved in lunar mining and construction and were drawn from Government agencies, mining and construction industries, and research and academic institutions. The evaluation process used in this study is based heavily on the workshop findings.

The Space Exploration Initiative (SEI) has identified the need to develop lunar resources in order to sustain a lunar base and support further space exploration. A lunar base is expected to become a vital link in interplanetary travel. A considerable amount of planning and general studies have been conducted to provide concentrated directions and fulfill the goals of the SEI. NASA's 90-Day Study presented lunar base architectures with a variety of construction and mining equipment used for base construction and lunar surface mining (NASA, 1989). The Syntheses Group, formed by the National Space Council, has evaluated the contribution of the Outreach Program and provided a comprehensive report on future SEI planing and research needs (Synthesis Group, 1991).

In the planned SEI missions, a variety of construction and mining equipment will perform vital functions that must be conducted reliably and with long service life. Malfunctioning and unsafe conditions cannot be tolerated. In designing extraterrestrial mining equipment, the operational environment plays the most significant role (Podnieks, 1988). Other considerations include the type of deposit, material characteristics, mining method, topography of the surface, geology of the underground strata, and production requirements. Other factors include power source, reliability, ease of maintenance, transportation and assembly, parts compatibility, simplicity, and service life. The lunar landings during the Apollo program and subsequent research substantiate the significance of environmental effects on equipment operating on the lunar surface (Siekmeier and Podnieks, 1990).

The vacuum, temperature variations, radiation, and micrometeorite impacts will create considerable equipment design problems. During mining operations, especially surface mining, other factors must also be considered. The brightness and orientation of the sun obscure vision, dust settles on optical sensors and communication equipment, and low gravity causes decreased vertical stability against lateral loads and lower traction for equipment.

These environmental and operational effects must be taken into account during the design of lunar mining equipment and, therefore, they must be incorporated into the lunar mining equipment conceptual design criteria. To verify the design effectiveness and performance of prototype equipment in lunar mining situations, tests must be conducted in a simulated lunar environment that models both the operational environment and material to be mined.

The Bureau, in cooperation with the NASA Planet Surface System's Office, has conducted this lunar surface mining equipment study to assess the proposed equipment and evaluate its effectiveness based on basic mining equipment design criteria and the lunar environment. Others suggested lunar mining equipment design criteria based on terrestrial technology (Gertsch and Gertsch, 1990a, Gertsch and Gertsch, 1990b, Sharp, et al., 1990). In addition, other approaches have been developed that quantitatively measure the effectiveness of various construction scenarios by considering terrestrial construction experience and uncertainty (Boles, 1990). The Bureau study is intended to serve as a broad guideline for the design of lunar mining equipment.

MINING EQUIPMENT DESIGN CRITERIA

Design criteria were established before the previously proposed mining equipment were evaluated. These design criteria are intended to provide a guide for designers of new lunar mining equipment. The design criteria define many of the engineering parameters that should be considered during the conceptual design process allowing designers to focus their efforts on realistic designs.

The design criteria were established based on the mining tasks required and the environment in which the tasks would be performed. The mining tasks include: fragmentation, excavation, loading, hauling, and dumping. The environmental factors include: deposit, topography, and atmosphere. The number of pieces of equipment and specific capabilities of each piece of equipment were not prescribed. Thus, a single piece of equipment could be designed to accomplish multiple tasks or several pieces of equipment could work together to provide the same capability. Flexibility and commonality must be considered before overly specialized equipment is developed.

The equipment should be flexible and able to accomplish generic tasks such as excavation, lifting, and hauling. This would allow the mining equipment to be used during base construction and during daily operations. Specialized mining equipment, such as continuous miners, bucket-wheel excavators, draglines, slushers, and conveyors would be highly productive, but inflexible and not be well suited for the scale of mining operations currently proposed by NASA for the initial lunar base. Therefore, high production mining systems are not needed at the present time.

The design criteria include a large number of engineering parameters that were grouped into the following major categories.

General operational parameters describe the scale of the proposed mining operation and include the radius and period of operations. The radius of operations defines the size of the mine and would be governed by the production requirements and the quality of the deposit. The period of operations would be governed by the production requirements, deposit quality, equipment production, and the electric power available for mining activities.

Equipment size would be defined in terms of stowed and assembled sizes. The stowed size would be governed by the Earth/Moon transportation system, which mandates low mass and volume. The assembled size would be governed by the size of the task assigned to each component of the system. The number of mining machines and size of each affect the fundamental concept envisioned for the mining operation. For example, two smaller pieces of equipment could be transported fully assembled to the Moon work together on a specific task or one large piece of equipment could be assembled at the lunar mine and accomplish the same task.

Power requirements for excavation and transport should not exceed 70 kW based on the power allocated for the equipment proposed by NASA (NASA, 1990). On-board power supplies could be used, or power could be transmitted from a common source. The power should be supplied in such a way that the mobility and performance of the equipment is not impaired.

The control system should include telerobotics and provide clear visibility of the work area through the use of cameras and other sensors. The system should monitor the actuators, wheels, and load, and provide feedback that would allow improved performance. The effort required by the operator should be minimized and automation should be used to the greatest extent possible. The ability to manually override the remote control systems should be possible during Extraterrestrial Vehicular Activity (EVA) to allow disabled equipment to be returned to the base.

Long-term operation with minimal maintenance will be required for lunar mining equipment. Available technology should be used to the greatest extent possible to minimize breakdowns caused by unproven technology. The design life would be specified by NASA and equipment tested in a simulated lunar environment to show compatibility and durability. The equipment should have the ability to monitor performance, test for maintenance needs, and diagnose problems. The presence of the pervasive lunar dust should be considered. Fire suppression should be provided in areas where combustion would be possible. When evaluating the durability of materials, the effects of radiation, temperature, vacuum, and micrometeorites should be considered. The design should incorporate simple, rugged, and reliable components and provide redundancy to the greatest extent possible. The design should allow maintenance to be performed in the field by incorporating standardized interchangeable components that would be easily accessible. The components should be designed to allow repairs to be made in a shop at the lunar base using a minimal mass of imported material. Temperature control design must consider the lack of convection in the lunar atmosphere and must optimize the radiation of waste heat. The effect of the ultra-high vacuum on tribology and lubrication must be considered.

Mobile equipment should maximize maneuverability and stability. The acceleration, average speed, and braking should not be less than those specified by NASA. The equipment should be capable of climbing a 30° slope and the ground clearance should be greater than 0.25 m. Grading and shaping ability should be incorporated into mining equipment to allow the work area and haul roads to be maintained. The wheel design should consider the variation in the compaction of the regolith and the lower lunar gravity. Cleats should be used to increase traction and the likelihood of increased wear should be considered due to the abrasiveness at the lunar surface. Tracked equipment is not recommended due to the high wear of the many moving parts and the associated maintenance that would be required at all the linkages. Tracks have been discarded by the Jet Propulsion Lab in their lunar vehicle studies due to lack of reliability and limited mobility (Pivirotto, 1991).

Operational requirements will be determined by task specific parameters. Excavation equipment shall possess the breakout force capable of breaking up highly compacted regolith and removing small boulders (Bernold, 1991). Increased wear of the cutting surfaces due to the abrasiveness of the regolith should be considered. The width of the cut should not be less than the width of the equipment and the equipment should be able to excavate a minimum of 0.25 m below grade. Loading equipment design should consider material density, digging depth, horizontal reach, loading height, cycle time, and should avoid compacting the material. Haulage equipment design should consider travel speed, payload mass, and volume.

Conceptual design guidelines are qualitative criteria that would be critical to the successful operation of lunar mining equipment. The equipment should be versatile, flexible, and adaptable to allow its use in a wide variety of applications not only for mining, but also for base construction and daily operation. All equipment designs should emphasize simplicity and commonality.

ASSESSMENT OF LUNAR MINING EQUIPMENT PROTOTYPES

Over the last decade, a variety of lunar mining and exploration equipment has been proposed and prototypes designed, constructed, and demonstrated. NASA and the Bureau jointly determined that these configurations should be evaluated with respect to the basic mining equipment design criteria and the lunar environment. The proposed equipment can be grouped into three categories; exploration, excavation, and haulage:

Exploration vehicles must travel over uncharted areas and overcome sizeable obstacles. Wheeled vehicles, with multi-axle tandem suspensions, and legged vehicles, which are complex to operate, have been proposed. Wheeled vehicles would be more versatile and provide faster movements on relatively smooth terrains (Pivirotto, 1991). Also, telerobotics and automation would be easier to incorporate into wheeled vehicles due to the reduced complexity of the movements. There are several proposed lunar vehicles, primarily designed for exploration, that have been equipped with mining attachments. These attachments could be used for sampling surface materials, but would not be capable of production-scale mining.

Excavation techniques include linear cutting or ripping, rotary cutting by auger or drum, and rotary brushing.

- A tool such as bucket or ripper would cut the surface layer provided the equipment could produce a sufficient tractive force to enable the tool to penetrate the regolith. Some of the proposed equipment did not show ballast or counterweights, which would be required to increase traction and breakout force.

- An auger or drum with rigid cutting bits could remove the surface layer, loosen denser layers, and assist loading. A proposed continuous miner did not show sufficient ballast, would not be capable of dealing with boulders, and would not be able to excavate to the full width of the machine, which would make the machine ineffective for multiple cuts.

- A rotary brush would sweep the surface layer. This system would require high-rotational speeds for the brush in order to accelerate the soil particles through a duct to the storage bin. The required strength, stiffness, and number of bristles would be controlled by the density of the mined deposit. The design of the brush, duct, and bin should avoid generation of dust, adhesion of particles to the walls of the duct, and packing of the particles inside the bin making discharge difficult. Cobbles and boulders could not be handled by a rotary brush.

The excavation equipment could be propelled by wheels or tracks. Tracked equipment would have good traction, but as stated previously, would encounter operational problems due to the many moving parts connected with rotating bearing surfaces. These surfaces would tend to wear excessively in the lunar environment due to increased friction resulting from the ultra high vacuum and the adhesion of dust particles.

Some of the proposed excavation equipment was shown to be powered by solar collectors. These collectors would not be capable of supplying enough energy since the solar flux on the lunar surface is only about twice that available at the Earth's surface and, thus, the collectors required would be too large to be carried on mobile equipment. Greater power densities could be transmitted to the mobile equipment by beaming electromagnetic energy from a stationary nuclear reactor or

large solar array. Hydrogen/oxygen fuel cells are recommended for mobile equipment due to their simplicity, and their past success in terrestrial and space applications.

Haulage includes loading, transporting, and unloading of the mined deposit and would be greatly affected by cohesion of the load and adhesion of the load to the equipment. The use of certain components, such as conveyor belts for loading and transporting, would be hampered by adhesion of material to the belt and require effective scraping devices. Terrestrial belts have this problem which is a source of maintenance problems and accidents. In order to allow the mining equipment to be used for other lunar base operations, wheeled haulage vehicles would be the best choice since they could transport mined material, tailings, tools, and construction materials. This capability has been highly recommended in many technical planning sessions.

PROPOSED SCENARIO

Based on the design criteria and the assessment of previously proposed lunar mining equipment, the Bureau conceptualized two pieces of lunar mining equipment: the Ripper-Excavator-Loader (REL) (Fig. 1) and the Haulage-Vehicle (HV) (Fig. 2). Though both the REL and the HV are described here as mining equipment, both would, also, be utilized extensively during lunar base construction. Excavations would be made and construction materials transported using this equipment. This conceptual combination was selected as best suited to the initial mining operations by the 1989 Workshop on Extraterrestrial Mining and Construction (Register, 1990).

The Ripper/Excavator/Loader (REL) is an example of production class mining equipment designed to support a lunar mine that produces 1,500 - 18,000 mt/yr of ilmenite rich feedstock for a 5 - 60 mt/yr oxygen production facility. The vehicle would be equipped with a ripper capable of loosening compacted regolith. The 0.25 m^3 bucket would excavate, self-load, load other vehicles, and transport regolith. The versatility of the vehicle would allow both loose and compacted regolith to be excavated and small boulders to be cleared. Eight cleated conical wheels, each driven by a separate electric motor, would provide an efficient interface with the lunar surface. The REL would primarily operate in a telerobotic mode, but would be designed to allow manual override in emergencies by using a hand-held control unit that would be plugged into the vehicle during an EVA. The REL would be powered by hydrogen/oxygen fuel cells. The onboard hydrogen and oxygen tanks would be refilled

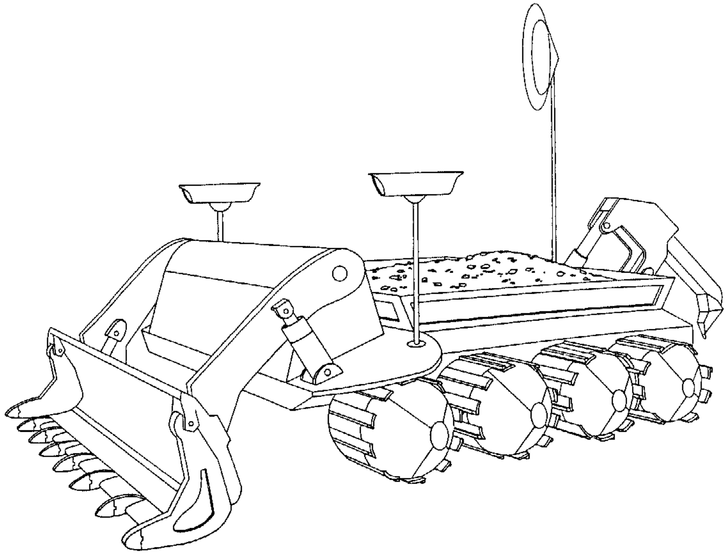

Figure 1.--Ripper-Excavator-Loader (REL)

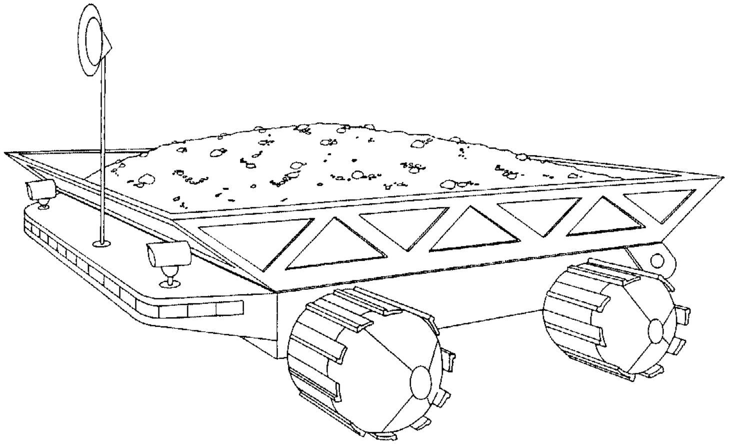

Figure 2.--Haulage-Vehicle (HV)

at a stationary electrolysis unit that would separate the water produced by the fuel cells into hydrogen and oxygen. The electrolysis unit would receive electric power from a nuclear power plant.

The Haulage Vehicle (HV) is an example of a production class vehicle designed to support a lunar mine producing 1,500 - 18,000 mt/yr of ilmenite-rich feedstock for a 5 - 60 mt/yr oxygen production facility. The vehicle would be equipped with a 2 m^3 rear-dump bed and four cleated conical wheels. Each wheel would be driven by a separate electric motor. The vehicle would be designed to optimize the transport of feedstock from the mine to the processing facility and tailings from the production facility to the dump. In addition, the bed would be used to transport a variety of tools and supplies during lunar base construction and operation. The vehicle could also be utilized to transport tanks of liquid oxygen from the production facility to the launch pads. This teleoperated vehicle would be equipped with EVA manual override and be powered by hydrogen/oxygen fuel cells.

During the initial stages of mine development and base construction only the REL would be needed. The REL would excavate, self-load, haul, and dump a load of regolith or construction materials. When production requirements increased beyond the REL's capacity, the HV would be added. The HV would be designed to optimize hauling and would be capable of higher ground speeds. After the introduction of the HV, the REL would optimize its capacity to excavate and load by filling its haulage bed with regolith to provide ballast for increased traction, thus allowing compacted regolith to be ripped and loaded.

CONCLUSIONS

The assessment of the lunar mining equipment proposed to NASA by various sources indicates that few would perform as anticipated in an actual lunar mine. There has been a tendency to develop novel mining equipment without regard to basic mining principles. Many times novel concepts have been selected over those that would provide simpler and more practical operation. In general, little consideration has been given to the complex effect of the environment on mining equipment design. Frequently, the need to integrate the proposed mining equipment into the overall lunar mining operation has been overlooked and there has been no clear indication of the intended application of the equipment (i.e. exploration, small-scale production, or large-scale production). The prototypes built to date have not been tested in a simulated lunar environment under actual operating conditions. The determination of reliability and endurance must be made from test bed results. Computer models that simulate environmental effects are not sufficient.

RECOMMENDATIONS

In order to design workable lunar mining equipment, terrestrial mining equipment design and mine operation must be fully understood. Proposed mining equipment must meet basic terrestrial mining operational requirements as a prerequisite. Only then can the special effects of lunar environment be incorporated. Novel ideas require evaluation with regard to the basic principles of mining equipment design and should be evaluated by the mining industry, universities, and government organizations with decades of experience in mining equipment design and operation. A novel mining approach should be proven effective terrestrially before being considered for lunar mining. Equipment test beds must be established using simulated lunar environment and ground conditions. Implementation of these conclusions and recommendations would help to assure a successful lunar mining operation capable of supporting the President's goals for the future of the nation's space program.

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