TERRESTRIAL MINING TECHNOLOGY APPLIED TO LUNAR MINING

E. R. Podnieks* and J. A. Siekmeier**
Bureau of Mines
U.S. Department of the Interior
Minneapolis, MN

Abstract

Space exploration and extraterrestrial resource utilization research programs are being encouraged to develop equipment systems faster, cheaper, and better. In support of this philosophy, the U. S. Bureau of Mines is applying terrestrial mining experience and technology to the conceptual design of lunar mining equipment. Previously proposed lunar surface mining equipment designs were reviewed for compliance with the lunar environment and for adherence to mining principles. Current Bureau mining research programs were evaluated for potential lunar application. Several projects that have operational terrestrial prototypes, which could be adapted to the lunar environment, were identified and are presented in this paper.

Introduction

When humanity expands its horizons to the Moon and other planets in the solar system during the next century, the utilization of in situ space resources will become imperative due to the high cost of resupplying from Earth. The U.S. Bureau of Mines has been active in extraterrestrial resource utilization research for over 30 years as part of its mission to ensure the Nation with an adequate supply of minerals far into the future. Bureau involvement began with the Working Group on Extraterrestrial Resources (WGER) during the Apollo Program and continues today in cooperation with NASA's space program and with the International Academy of Astronautics' lunar development program.

During Apollo, the Bureau's emphasis in mining and processing was mainly on basic research in areas of resource identification, rock fragmentation, materials handling, and ground control. The importance of creating a simulated lunar environment for research and testing purposes was found to be significant. Experiments and observations were conducted to evaluate lunar environmental effects.[1-7]

In the post-Apollo era, lunar mining has been addressed by a wide variety of organizations with different non-mining backgrounds. Many mining methods have been suggested using novel and unique prototype equipment. However, these novel and innovative approaches are appropriate only if they are based on sound principles that have been proven in terrestrial mining operations and tested in a simulated lunar environment. A Bureau review of lunar mining equipment was initiated because many proposed conceptual designs were either an over-simplified adaptation of terrestrial mining technology or based on completely novel designs that did not comply with basic mining principles and operational requirements. A lunar mining method must evolve from established workable terrestrial methods with proper modification for the unique lunar environment and ground conditions.

Today, more than ever, there is a need to design space mining equipment that is less expensive, simpler, and based on existing terrestrial counterparts. Knowledge of the lunar environment can be gained from the Apollo missions. Besides a wealth of scientific information, the Apollo mission reports provide very valuable operational experiences that will help in mine design, equipment design, and mine operation.[8-13] The merits of designs based on terrestrial technology and Apollo experience are significant and far reaching. Space projects based on this evolutionary principle have been very successful, whereas many

* Senior Staff Scientist.
**Civil Engineer, Twin Cities Research Center.

ultra-novel designs have failed because they did not meet space environment requirements, did not receive adequate testing, or were not used in operations for which they were well suited. Lunar mining equipment that is developed based on terrestrial mining technology and Apollo experience should avoid many of these problems.

Recently, a tendency has developed in space programs to both rush development and cut costs by not properly testing the systems or components in simulated environments using analogue test materials. In most cases, the time and costs saved are minute in comparison with the possible losses due to later malfunctions. Proof-of-concept testing using analogue materials in a simulated environment must be incorporated into the develop-ment cycle of lunar mining equipment to assure success at a reasonable cost and schedule.

Currently, there is a movement to start using higher risk cutting edge technology in the space program. However, to ensure reliable performance, novel technology must be developed far enough to prevent failures. For this reason NASA Office of Advanced Concepts and Technology (OACT) is spending 10 million dollars to create test beds for developing technology for specific missions.[14] Only thoroughly tested novel concepts can become significant additions to extraterrestrial technology and encourage commercialization.

Overview

Developing lunar mining and processing technology is very similar to advancing terrestrial mining and processing technology. However, there are two major modifying factors: (1) space logistics and associated economics and (2) the lunar environment. Logistics and economics impose limits on the size, weight, and power available for lunar mining equipment in addition to requiring increased simplicity and reliability. The lunar environment will greatly influence all aspects of mining on the Moon and require mine planners to carefully consider environmental effects while developing mining methods.[15]

Currently proposed lunar and planetary surface mining equipment cover a wide spectrum of equipment types from exploration to fragmentation, excavation, and haulage. This paper will focus on fragmentation, excavation, and haulage equipment and its compliance to the lunar environment and mining operations. The equipment will be sized for the support of an initial lunar base designed to supply oxygen for Mars missions. This production level would encourage small, mobile, and versatile equipment that could be used for both mining and construction, rather than large stationary dedicated mining machines.

The Apollo landings and subsequent research substantiate the significance of environmental effects on equipment operating on the lunar surface.[16] The vacuum, temperature variations, radiation, and micrometeorite impacts will create considerable equipment design problems. Other considerations include: the brightness and orientation of the sun obscuring vision; dust settling on optical sensors, communication equipment, and radiators; and low gravity causing decreased stability against lateral loads and lower traction. 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 design criteria for lunar mining equipment.

Design Criteria

Design criteria were established to form a foundation for the review of previously proposed mining equipment and were based on the mining tasks and the lunar environment. These criteria define many of the engineering parameters that should be considered during the conceptual design of realistic lunar mining equipment.[17]

Flexibility and commonality of mining equipment should be considered in the early stages of lunar base development before specialized equipment is introduced. The equipment should be able to accomplish generic tasks such as excavation, lifting, and hauling to allow the mining equipment to be used during base construction and daily operations. Specialized mining equipment, such as continuous miners, bucket-wheel excavators, draglines, slushers, and conveyors would be highly productive for larger mining operations as the base expands. However, since they would be inflexible or stationary they would not be well suited for the scale of mining currently proposed by NASA for the initial lunar base.

Equipment size is 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 on the Moon would be governed by the mining task assigned and the required operational efficiency.

Power requirements would be met by on-board power sources or transmitted from a central power station. 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 that provide clear visibility of the work area through the use of cameras and other sensors. The system should also have the ability to test for maintenance needs, diagnose problems, and promote improved performance with artificial intelligence methods. Operator effort should be minimized and automation should be used to the greatest extent possible for cyclic tasks. The ability to manually override automated systems should be available during extraterrestrial vehicular activity (EVA) to allow disabled equipment to be recovered and returned to the base for repairs.

Long-term operation with minimal maintenance will be required for lunar mining equipment. The effects of radiation, temperature, vacuum, micrometeorites, and dust should be considered based on the results of the Apollo and the Long-Duration Exposure Facility programs. The effect of the ultra-high vacuum on tribology and lubrication must also be considered, especially for long-term operations. The design should incorporate simple, rugged, and reliable components and provide redundancy to the greatest extent possible. Modular design should be used to allow maintenance to be performed in the shop or in the field with standardized interchangeable components that are easily accessible.

Maneuverability and stability should be maximized on mobile equipment. Wheel design should consider variation in the regolith compaction and the lower lunar gravity. Cleats should be used to increase traction and increased wear should be expected due to the abrasiveness of the regolith. Tracked equipment is not recommended due to the high wear of the many moving parts and the extensive maintenance that would be required. Tracks have been discarded by the Jet Propulsion Laboratory in their lunar vehicle studies due to lack of reliability and limited mobility. Wheeled vehicles have been found to be more versatile and provide faster movements on relatively smooth terrains.[18] The extensive development of the Russian lunar rover has led to the same conclusions. Legged vehicles have certain advantages on rocky ground, but are complex to operate and would make the use of telerobotics and automation much more difficult due to the complex-ity of movements.

Proof of Concept Testing is required in order to be confident that the designed equipment will perform as anticipated. It is a well established engineering practice that conceptual ideas be tested in a simulated working environment.[19] Failure to test the concept first will almost certainly result in malfunction of the system and an expensive, time-consuming redesign. Proof-of-concept testing requires that extreme care be exercised when establishing a simulated lunar environment for realistic testing. Since supplies of actual lunar and planetary rock soil samples are very limited, an analogous sample suite is vital to provide a consistent and reliable engineering experimental base.[20] For this reason, the Bureau, with other members of WGER, developed a 14 rock suite analogous to the range of anticipated lunar rocks.[21, 22] This need was again recognized by NASA in April 1989, when NASA conducted a U.S. Government Requirements and Policy Meeting for the Planetary Surface Analogue Facility where both environment simulation and analogue planetary materials were discussed. The pre-Apollo analogue rocks need to be replaced with a new suite of analogue rocks with properties that better match those of the actual rocks returned for the Moon in the same way that soil simulants have been developed based on the Apollo samples.[23]

<ins>Application of Terrestrial Mining Technology</ins>

The equipment used on the Moon during the Apollo missions was based on terrestrial technology adapted to the lunar environment of vacuum, sharp temperature changes, and excessive dust. Terrestrial mining has been developed systematically over hundreds of years to operate in a wide variety of climatic and geological conditions, and will provide a solid base for further adaptation to lunar operational conditions. By following an evolutionary path, lunar mining equipment will be developed faster, more reliably, and less expensively since readily available and proven workable components and methods would be used.

As part of the research to improve terrestrial mining methods and provide a safer work environment in the Nation's mines, the Bureau of Mines has developed mining methods and equipment that could be adapted to both surface and underground lunar mining. The most applicable research projects are machine automation and control using remote sensing and guidance methods. These systems have been developed and tested in surface and underground mines and are fully operational units.

<ins>Teleoperations</ins> research at the Bureau was initiated ten years ago with a study on continuous miners in deep, thin coal seams.[24] This feasibility study resulted in the development, design, and fabrication of a computer-based control system (fig. 1). The system was successfully tested with a new thin-seam continuous highwall mining system in which a single teleoperator controls all the coal mining and haulage equipment. The Bureau is currently evaluating laser sensor systems to track and control the movement of mining machinery, and also the Modular Azimuth Position System (MAPS) to determine the equipment heading and x-y position. The MAPS system is based on all-electronic ring laser gyroscope making it a completely independent, stand-alone system.[25]

A teleoperated compact load-haul-dump or minimucker was developed through a Bureau contract with Foster-Miller Inc. to replace slusher muckers in narrow-vein underground mines (fig. 2).[26]

Fig. 1 Controls for teleoperated highwall coal mining system

Fig. 2 Teleoperated loadhaul-dump miner

The minimucker is a six-wheel drive, skid-steered, machine that loads muck at the front with novel slide-bucket system and ejects the material out the without turning around. A computer-based, radio-controlled teleoperation method was used first and was supplemented with an automatic guidance system using ultrasonic ranging sensors and a wall-following algorithm.

The teleoperation principle has found other applications in mining operations. The Bureau has developed a teleoperated fire-fighting vehicle for extinguishing underground mine fires (fig. 3).[27] It is equipped with a video camera, a through-smoke infrared viewing system, and various proximity, temperature, and gas sensors that enable the operator to effectively navigate the vehicle through the mine workings to the fire.

tion rate of an automated mobile splitting machine consisting of three independent boom-mounted drill-split units has been estimated at 25 mt/hr.[29] The splitter would do far less damage than blasting to the rock left in place, which must remain of high quality in order to reduce or eliminate support elements such as rock bolts, wire mesh, and shotcrete.

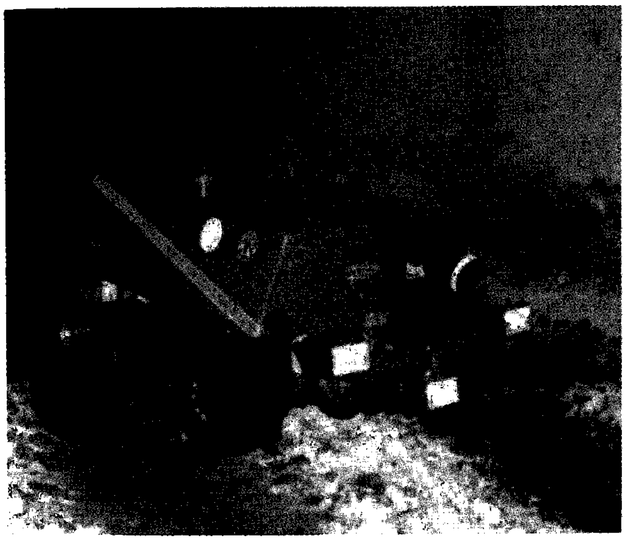

Fig. 3 Teleoperated mine fire fighting vehicle

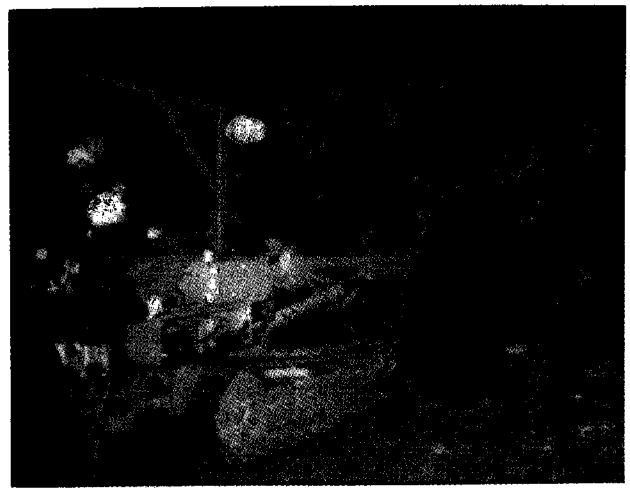

Fig. 4 Radial-axial rock splitter

The teleoperation of mining equipment represents a present-day application of advanced electronic technology to protect the miner from a hazardous working environment. Similar technology has potential for lunar application. Over the next decade the present teleoperational systems should lead to highly automated systems guided by artificial intelligence.

<u>The Radial-Axial Rock Splitter</u> is a rock fragmentation method that has been used in surface and underground mining operations (fig. 4). The radial-axial splitter would be well-suited for the lower lunar gravity since it does not require large external reaction forces.[28] The splitter generates rock breaking stresses internally by a wedge and feather system, which anchors the splitter within a borehole allowing a hydraulic ram to react against the bottom of the borehole and remove a cone of rock. The terrestrial produc-

<u>Electromagnetic Sealing</u> of rock surfaces would be used in an underground lunar mine to create an internal pressure and maintain a terrestrial working environment and habitat within parts of the underground excavation. A portal would be constructed and compartmental seals established as the mine expands.[16] The Bureau has conducted experiments on basaltic rocks using electromagnetic power sources to melt the rock surfaces and seal the cracks.[30] The results indicate that this method may be feasible to seal an excavation in a basaltic rock strata.

<u>The Ripper/Excavator/Loader</u> (REL) is an example of mining equipment designed to support a lunar mine that produces 1,500 - 1,800 mt/yr of ilmenite-rich feedstock for 5-60 mt/yr oxygen production facility (fig. 5).[17] 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

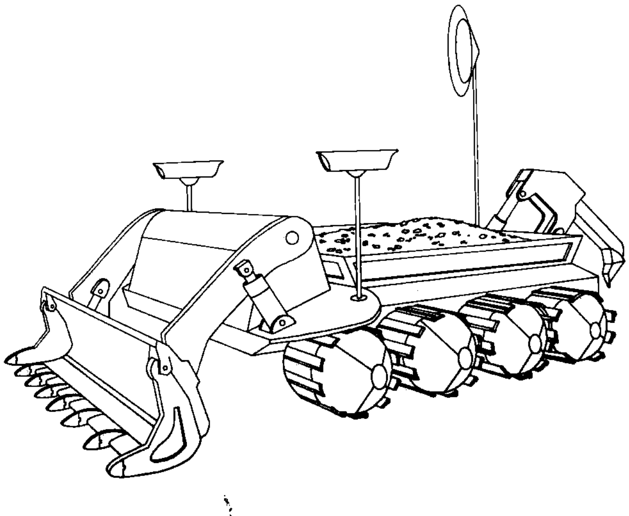

Fig. 5 Teleoperated ripper-excavator-loader

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 tele-robotic 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 EVA. The REL would be powered by hydrogen/oxygen fuel cells. The onboard hydrogen and oxygen tanks would be refilled 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 stationary nuclear power plant.

<u>The Haulage Vehicle</u> (HV) is another example of a mining vehicle designed to support a lunar mine and oxygen producing facility (fig. 6).[17] The vehicle would be equipped with a 2 m^3 rear-dump bed and four cleated conical wheels, each wheel 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

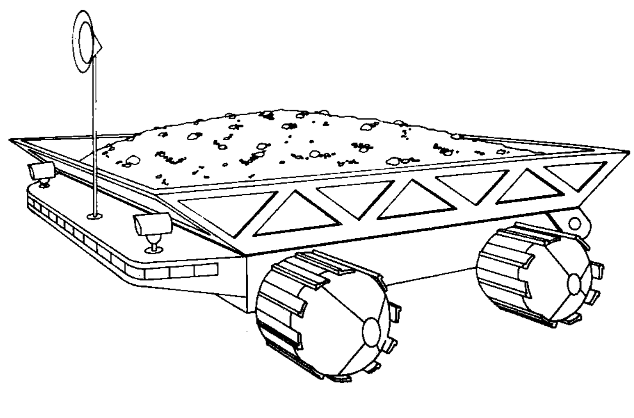

Fig. 6 Teleoperated haulage vehicle

construction and operation, and to transport tanks of liquid oxygen from the production facility to the launch pads. This teleoperated vehicle would also be equipped with EVA manual override and be powered by hydrogen/oxygen fuel cells.

Conclusions

Applying terrestrial technology to lunar mining will speed up development and reduce costs if the equipment and systems are fully evaluated and tested for space applications. The key to successfully applying terrestrial technology will be to fully understand the of harsh lunar environment. The Apollo missions provide valuable insight into the environmental effects on operations at the lunar surface. Despite the fact that this information was obtained 20 years ago, it represents the only actual data gathered by humans on the lunar surface, rather than expectations and speculations of conditions that may exist on the Moon.

Transfer of terrestrial mining technology for use in developing lunar mining will also have an impact on advancing terrestrial mining technology. This two-way transfer process has taken place in the past where military technology, developed from existing commercial technology, has resulted in novel, more economical, and more reliable commercial products. Terrestrial mining technology will also benefit as the results from lunar operation are made available and utilized by the mining industry.

A variety of examples of current terrestrial mining research projects which have potential application in space have been presented. Research in teleoperations, remote computer controls, and new rock excavation methods have direct application to resource recovery in space. To succeed, lunar mining technology must build on our long terrestrial mining experience supplemented by first-hand experience gained during the Apollo program. The novel technology needed for utilizing lunar resources can then be confidently developed and deployed.

References

1. Podnieks, E. R., P. G. Chamberlain, and R. E. Thill, (1972). Environmental Effects on Rock Properties. Proc., 10th Symp. on Rock Mechanics: Basic and Applied Rock Mechanics, SME of AIME, Denver, CO, pp. 215-241.

2. Roepke, W. W., (1969). Friction Tests in Simulated Lunar Vacuum. Proc., 7th Annual Mtg., Working Group on Extraterrestrial Resources, NASA SP-229, pp. 107-111

3. Podnieks, E. R., and P. G. Chamberlain, (1970). Method for Rock Property Determination in Ultrahigh Vacuum. Proc., 5th Space Simulation Conf., NBS Special Publ. 336, pp. 209-223.

4. Johnson, B. V., W. W. Roepke, and K. C. Strebig, (1973). Shear Testing of Simulated Lunar Soil in Ultrahigh Vacuum. BuMines RI 7814, 18 pp.

5. Lindroth, D. P., (1974). Thermal Diffusivity of Six Igneous Rocks at Elevated Temperatures and Reduced Pressures. BuMines RI 7954, 33 pp.

6. Atkins, J. O., and S. S. Peng, (1974). Compression Testing of Rock in Simulated Lunar Environment. BuMines RI 7983, 21 pp.

7. Roepke. W. W., (1975). Experimental System for Drilling Simulated Lunar Rock in Ultrahigh Vacuum. NASA Contract Report CR-149419, Accession No. N17617401, 13 pp.

8. Apollo 11 Preliminary Science Report, (1969). NASA SP-214, 209 pp.

9. Apollo 12 Preliminary Science Report, (1970). NASA SP-235, 234 pp.

10. Apollo 14 Preliminary Science Report, (1971). NASA SP-272, 313 pp.

11. Apollo 15 Preliminary Science Report, (1972). NASA SP-289, 502 pp.

12. Apollo 16 Preliminary Science Report, (1972). NASA SP-315, 636 pp.

13. Apollo 17 Preliminary Science Report, (1973). NASA SP-330, 710 pp.

14. NASA to Adopt Higher Risk Science Philosophy, (1993). Space News, V. 4, No. 11, p. 9.

15. Podnieks, E. R., (1990). Lunar Mining Outlook. Proc., AIAA Space Programs and Technologies Conf., AIAA 90-3251, AIAA, Washington, D.C., 11 pp.

16. Siekmeier, J. A., and E. R. Podnieks, (1990). Mining Technology for Lunar Resource Utilization. BOM-NASA Project Report, OFR-37-91, 62 pp.

17. Podnieks, E. R., and J. A. Siekmeier, (1992). Lunar Surface Equipment Study. Proc., Space '92 - Engineering, Construction and Operations in Space, ed. by W. Z. Sadeh, S. Sture, and R. J. Miller, ASCE, New York, NY, pp. 1104-1115.

18. Pivirotto, D., (1991). Rovers: Using Mobile Robots as Planetary Explorers. The Planetary Report, V. 11, No. 4, pp. 8-13.

19. Ferguson, E. S., (1993). How Engineers Lose Touch. Invention and Technology, V. 8, No. 3, pp. 16-24.

20. Allton, J. H., C. Galindo Jr., and L. A. Watts, (1985). Guide to Using Lunar Soil and Simulants for Experimentation. Lunar Bases and Space Activities of the 21st Century, ed. by W. W. Mendell, LPI, Houston, TX, pp. 497-506.

21. Fogelson, D. E., (1968). Simulated Lunar Rocks. Proc., 6th Ann. Mtg., Working Group on Extraterrestrial Resources, NASA SP-177, pp. 75-95.

22. Fogelson, D. E., (1969). Simulated Lunar Surface Materials. Presented at Symp. Chemistry and Physics of Lunar Surface Materials, Met. Soc. Spring Mtg., Pittsburgh, PA.

23. Weiblen, P. W., and K. L. Gordon, (1988). Characteristics of a Simulant for Lunar Surface Materials. Symposium on Lunar Bases and Space Activities of the 21st Century, (Abstract only), LPI, Houston, TX, p. 254.

24. Murphy, J. N., G. H. Schnakenberg, and A. J. Kwitowski, (1990). Computer-Assisted Mining. The Mining Engineer, V. 149, No. 348, pp. 99-106.

25. U.S. Bureau of Mines, (1992). New Technology Promotes Safer, Faster Mining. Coal, V. 97, No. 3, pp. 31-33.

26. Ruff, T. M., (1991). Ultrasonic Guidance and Remote Control of a Compact Loader/Trammer. Proc., International Symposium on Mine Mechanization and Automation, V. 1, ed. by L. Ozdemir, R. King, and K. Hanna, Colorado School of Mines, Golden, CO, pp. 6-45 - 6-54.

27. Pomroy, W. H. and M. A. Ackerson, (1991). Remotely Controlled Mine Fire Fighting Concepts. Proc., International Symposium of Mine Mechanization and Automation, V. 2, ed. by L. Ozdemir, R. King, and K. Hanna, Colorado School of Mines, Golden, CO, pp. 15-11 - 15-20.

28. Podnieks, E. R., and R. L. Schmidt, (1990). Lunar Mining: Surface or Underground? Proc., Space '90 - 2nd Conf. on Engineering Construction, and Operations in Space, ed. by W. Z. Sadeh, S. Sture, and R. J. Miller, ASCE, New York, NY, pp. 315-324.

29. Anderson, S. J., D. A. Larson, and R. L. Schmidt, (1990). U. S. Bureau of Mines Introduces Two New Mechanical Hardrock Fragmentation Systems. Proc., 7th Australian Tunneling Conf., Sept. 11-13, 1990, Sydney, Australia, pp. 69-75.

30. Lindroth, D. P., and E. R. Podnieks, (1988). Electromagnetic Energy Applications in Lunar Mining and Construction. Proc., 18th Lunar and Planetary Sci. Conf., March 16-22, 1987, Houston, TX, Cambridge University Press/LPI, Houston, TX, pp. 365-373.