LUNAR RESOURCE RECOVERY: A DEFINITION OF REQUIREMENTS

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The capability to locate, mine, and process the natural resources of the Moon will be an essential requirement for lunar base development and operation. The list of materials that will be necessary is extensive and ranges from oxygen and hydrogen for fuel and life support to process tailings for emplacement over habitats. Despite the resource need, little is known about methodologies that might be suitable for utilizing lunar resources. This paper examines some of the requirements and constraints for resource recovery and identifies key areas of research needed to locate, mine, and process extraterrestrial natural resources.

INTRODUCTION

Exploration and settlement of the solar system is an integral part of the civilian space agenda (*National Commission on Space,* 1986; *Ride,* 1987). Included in this agenda is the establishment of intermediate bases to satisfy immediate goals, as well as to facilitate other long-term targets (*Duke et al.,* 1985). Implementation and attainment of these goals is heavily dependent on the ability to exploit extraterrestrial natural resources.

The energy required to transport resources from Earth to high-Earth orbit is almost 20 times greater than that required to transport the same mass from the lunar surface. The associated transportation costs alone effectively preclude transporting the necessary resources from Earth. Given the resource-rich bodies of the Moon and those beyond, a viable alternative can be envisioned. A technology base must be developed to facilitate exploitation of existing extraterrestrial resources. Although the experience and even some of the components of terrestrial mining and processing systems may be adapted and used extraterrestrially, the aggressive lunar environment will likely force consideration of unique solutions to unique problems. The highly evacuated, low gravitational, cosmically bombarded lunar environment, subject to massive temperature swings, presents untold challenges and hardships in terms of mere daily survival. Superimposing on this regimen the hardships and risks associated with mining, reputedly one of the most hazardous endeavors in the terrestrial environment, is indeed a challenge.

CONSIDERATIONS FOR RESOURCE RECOVERY

The successful utilization of extraterrestrial resources requires access to reserves of suitable concentration and quantity to facilitate timely and economic recovery. One result of the Apollo legacy is a baseline knowledge of the abundant lunar resources. Oxygen-rich minerals in the regolith could be mined and processed to satisfy six-sevenths of the need for rocket fuel. It may even be possible to extract sufficient hydrogen to supply the remaining one-seventh of the fuel (*Carter,* 1985; *Friedlander,* 1985). Other fundamental uses of the materials would be to manufacture water and a habitable atmosphere. Even the unprocessed regolith would be useful as propellant for mass-driver engines, as a shielding material to cover habitats (*Kaplicky and Nixon,* 1985), and for soilless media for agriculture. Water may be available within the regolith located close to polar regions where it may remain locked as ice (*Arnold,* 1979). Alternatively, manufactured forms are available from alkalai-hydroxide-based schemes (*Cutler,* 1984) or from hydrogen reduction of ilmenite (*Agosto,* 1985). To catalyze the processes, initial supplies of hydrogen may have to be transported directly to a lunar base as liquefied hydrogen, methane, or ammonia; alternatively, it could be produced by microwave bombardment (*Tucker et al.,* 1985) or microbial processing of the regolith (*White and Hirsch,* 1985).

The integrated systems approach to the problem of extraterrestrial resource recovery is illustrated in Fig. 1. The research effort must be driven by resource needs, such as ilmenite or habitable space. Lunar resource recovery is an essential but supporting operation to NASA's mission objectives; as such, resource recovery strategies must be commensurate with these objectives. Given the mission objectives and available information on lunar geology and ore, it is first necessary to develop integrated systems concepts for resource recovery.

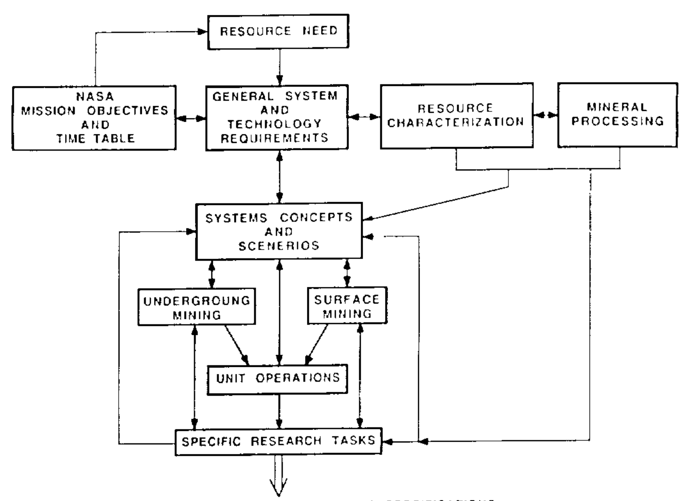

Fig. 1. Systems approach to lunar resource recovery.

RESOURCE REQUIREMENTS

Resource requirements consist of materials required to construct, operate, and sustain a permanent base and to satisfy deep space exploration and space-based manufacturing. The list of required raw materials is long. Of these, oxygen and hydrogen are of paramount importance, not only because of their use in recyclable forms necessary for the life-support systems but also in expendable rocket fuels. Other carbon-based gases must be sought if any lunar-based agriculture is contemplated together with iron, silicon, titanium, manganese, and other metals to support product manufacture.

While ilmenite is the most obvious and important mineral to locate and extract in quantities sufficient to supply oxygen needs on the Moon, other minerals may be exploited as well, if found in sufficient quantities. These include the following: anorthite ($CaAl_2Si_2O_8$), from which aluminum and oxygen could be extracted; pyroxene ($MgFeSi_2O_6$), from which magnesium, iron, and oxygen could be extracted; and minerals associated with layered mafic complexes that would yield copper, platinum, nickel, cobalt, and sulfides. Anorthite is known to be abundant in the lunar highlands, pyroxene in the mare regions, and layered mafic complexes possibly exist in the large, impact-generated mare regions. In addition, the various sites where transient lunar phenomena (TLMs) have been observed should be investigated as potential sources of water, carbon dioxide, carbon monoxide, and methane; they tend to be associated with the boundaries of the larger mare.

It has been established that oxygen can be obtained through a reduction process of ilmenite (*Simon,* 1985; *Gibson and Knudsen,* 1985), an apparently abundant lunar resource. The recovery of "solar wind trapped hydrogen" in lunar soils is more speculative (*Carter,* 1985), but should be considered as part of the extraction process for other ores. Any beneficiation operation of lunar regolith for ilmenite should also address the feasibility of recovering hydrogen, as well as suitable treatment of the tailings for use in local construction or agricultural purposes.

Habitable space must also be available to support lunar activities. Prefabricated and regolith-shielded structures (*Land,* 1985) may be the method of choice, although novel techniques utilizing traditional cements (*Lin,* 1985) or hybrid ceramic derivatives (*Young,* 1985; *Khalili,* 1985) have potential. Regolith burial offers protection from high external radiation levels but leaves structures susceptible to micrometeorite impact (*Gehring,* 1970). Deeper basing in lava tubes (*Hörz,* 1985) or remnant-mined cavities offers protection from hypervelocity impacts and the possibility of providing, to a certain degree, controlled habitable environments with reduced diurnal temperature swings.

The severity of the economic constraints applied to lunar basing and attendant mining operations depend primarily on the perceived utility of the effort. If the establishment of a base and the development of an associated mineral extraction and processing capability is perceived primarily as an issue of geopolitical prestige and strategic importance, economic concerns may not be paramount. However, many different engineering and scientific studies must compete for finite resources, in which case relative allocations among disciplines must be determined by current priorities. To provide a clear justification for propellant manufacture on the lunar surface, it is conceivable that lunar production will at some stage be subject to comparisons with delivered costs from the Earth's surface. In the case that lunar production is unable to compete directly with that from Earth, the shortfall may be justified on the grounds that lunar prototypes may be used directly to develop propellant manufacture on more distant planets. Production of high payback ratio products such as He^3 from the lunar surface may, however, completely defray the production costs required in the production of propellant from ilmenite.

EXPLORATION CONSTRAINTS

Three crucial areas may be identified representing *exploration, mining,* and *mineral processing* activities. Initially it will be necessary to utilize the lunar soils for resources as a lunar base is becoming established. Over time, however, it will be desirable to locate other and more concentrated deposits. The need for resources not found in the lunar soils will also impose a requirement to locate currently unknown deposits. Thus it will be necessary to develop suitable prospecting techniques to satisfy these needs and to characterize the materials *in situ* prior to mining and mineral processing.

During the initial phase, remote sensing and other synoptic exploration methods would be used to identify the most suitable candidate sites for a base. Ilmenite concentration, regolith morphology, and size distribution of ilmenite-bearing rocks, together with geographic location, would be the criteria used in site selection. As the base progressively develops, it can be anticipated that the simplistic surface mining of regolith will become increasingly undesirable due to the large investment of time and energy required to extract relatively little ilmenite. Given the prospects for finding much higher concentrations, efforts will be required to locate these deposits. Once located, the ore bodies must be characterized prior to mining. It is likely that the higher grade deposits in bedrock will probably consist of differentiated lava flows or sills and will require underground mining. While an underground operation will be decidedly more complex than a surface one, there will be inherent benefits to offset the increased complexity. A byproduct of the underground operation will be environmentally controlled space, which might be used for habitation, storage, or emplacement of nuclear reactors. An underground operation will probably offer other economies as a centralized mining and processing center, developed with years of potential reserves. It may even be desirable to "mine" solely for the purpose of creating habitable space in certain locations. Although the creation of a habitable structure through mining would represent a radical departure from the "turn-key" approach, it would eliminate many difficult problems associated with Earth-based delivery and erection of habitats.

MINERAL EXTRACTION CONSTRAINTS

The development of innovative mining methods and equipment offers the strongest possibilities of technological gain in autonomous resource exploitation. The development of innovative mining systems and equipment that will meet the mission objectives will require an integrated examination of the overall system, including the pre- and postmining activities of exploration and mineral processing.

Ore extraction requires knowledge of various rock and rock mass properties, including those of the ore. This information is necessary to extract the material and is needed to make ancillary decisions such as those related to stability and artificial support. Currently, these parameters are determined through manual measurements. Thus, developments in the areas of intelligent signal processing of computer vision signals, ground-penetrating radars, and microseismic techniques, among others, will be needed to support resource extraction.

Excavation and extraction within the hostile and dangerous underground mining environment are prime contenders for the development of autonomous and teleoperated equipment. Autonomous mining machines must have an inherent capability to detect incipient failure; a self-repair capability is also desirable. Monitoring and signal-processing methods designed to identify fundamental deterioration mechanisms in the electrical, mechanical, and hydraulic systems are desirable adjuncts to autonomous vehicle operation and will be necessary to allow early detection of incipient failures. Improved methods of horizon and interface sensing and guidance control are also mandated if practical application of autonomous equipment is envisioned. Pattern recognition and expert system approaches are both under investigation and development.

The development of efficient methods of rock fragmentation is crucial to the success of lunar mining operations. The behaviors associated with rock fragmentation (*Trent,* 1977) and strength (*Johnson et al.,* 1973; *Carrier et al.,* 1973) will be different due to environmental factors such as the hard vacuum and anhydrous conditions (*Williams and Jadwick,* 1980). Most terrestrial mining systems use either mechanical cutting or blasting. Mechanical cutting as a principal winning mechanism can be deemed undesirable on the Moon, based on the anticipated lubrication and tribology problems. Because of these problems, the life of a continuous mining machine or tunnel borer might be unacceptably low.

A modified boring machine, using thermal rather than mechanical penetration, has been proposed (*Rowley and Neudecker,* 1985); however, preliminary calculations suggest that its energy requirements would be prohibitively large. Mechanical drill penetration is known to be problematic in lunar regolith due to clogging and vacuum adhesion problems (*Podnieks and Roepke,* 1985; *Blacic,* 1985), and alternatives are sought. Jet piercing would not be practical in a location where oxygen is not plentiful; however, other thermal penetration methods might be viable (*Thirumalai and Demou,* 1970; *Lindroth,* 1974). The *in situ* melting concept might be better adapted to produce small diameter blast holes rather than large diameter tunnels. If a satisfactory means of creating the holes can be developed, the innate advantages of blasting could be available. This alternative may prove fertile since it is also known that explosives will work in a hard vacuum.

Of particular interest are the strength and abrasion resistance properties of fractured granular media and rock in the lunar vacuum. Laboratory and micromechanical models used to describe behavior will be key to the development of rock excavation, penetration, handling, and breakage, together with the feasibility of *in situ* processing. Fundamental understanding of the *in situ* strength is necessary in the dimensioning of excavations formed during mineral extraction and utilized as pressurized habitable space.

Electrical energy production with appropriate failsafe and backup capabilities is necessary to ensure an uninterrupted supply for life support. Requirements of several kilowatts for the maintenance of a habitable environment will be greatly exceeded by the demands placed by a significant mineral extraction and processing operation. Although life support requirements may be met by solar energy (photovoltaic), yields of the order obtainable only from nuclear plants will be required for mining and manufacturing operations. Continuous outputs from regolith-shielded nuclear units suggest the utility of round-the-clock mining operations in the absence of easily utilized energy storage mechanisms. Excess thermal energy from these units could be used in the habitable environment or in material processing.

MINERAL PROCESSING CONSTRAINTS

Processing of ores in the low gravity and evacuated lunar environment requires the adoption of special approaches to mineral comminution and separation problems. Breakage and size reduction issues may be addressed in studies of ball mill centripetal comminution processes. Generic mineral and ilmenite reduction processes may also be approached using electrostatic, nonaqueous, liquid-liquid, and pyroprocessing methods. Individual components of these studies may best be addressed in separate multidisciplinary research efforts.

SUMMARY

The successful recovery of the necessary materials from lunar resources will require the capability to locate, mine, and process the available natural resources. Much of the technology to achieve this is as yet undeveloped. The tightly interrelated nature of exploration, mining, and processing dictates that necessary research and development work be undertaken with this in mind. An integrated systems approach is necessary. Similarly, equipment development must be completed to satisfy the exploration, mining, and processing needs, rather than constraining candidate methodologies for exploration, mining, and processing to the capabilities of developed equipment.

While it will be necessary to develop innovative and new solutions to the lunar resource recovery problem, the knowledge base of terrestrial mining provides a wealth of information that is directly applicable to lunar exploration and mining. Current research in terrestrial resource recovery, such as *in situ* resource characterization and autonomous mining, will have application in the lunar setting. In a complementary manner, specific advancements required to facilitate lunar mining should provide a significant benefit in terrestrial resource recovery.

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