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SPIRAL MINING FOR LUNAR VOLATILES

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Spiral Mining for Lunar Volatiles

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Abstract

Lunar spiral mining, extending outward from a periodically mobile central power and processing station represents an alternative for comparison with more traditional mining schemes. In this concept, a mining machine would separate regolith fines and extract the contained volatiles. Volatiles then would be pumped along the miner's support arm to the central station for refining and for export or storage.

The basic architecture of the central processing station would be cylindrical. A central core area could house the power subsystem of hydrogen-oxygen engines or fuel cells. Habitat sections and other crew occupied areas could be arranged around the power generation core. The outer cylinder could include all volatile refining subsystems. Solar thermal power collectors and reflectors would be positioned on top of the central station.

Long term exploitation of a volatile resource region would begin with establishment of a support base at the center of a long boundary of the region. The mining tract for each spiral mining system would extend orthogonal to this boundary. New spiral mining systems would be activated along parallel tracts as demand for lunar He-3 and other solar wind volatiles increased.

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Introduction

Identification of the potential of lunar helium-3 as a fuel for 21st Century commercial fusion power (Wittenberg et al., 1986) has sparked increasing interest in the extraction of solar wind volatiles from the lunar regolith (Kearney, 1989, Augustine, 1990, and Stafford, 1991).

Extraction of one metric tonne of helium-3, that necessary to provide about 1/25 of the annual U.S. electricity consumption or 10 GWe-yr (Kulcinski and Schmitt, 1987), will require the mining of about 11 km^2 of the lunar surface to a depth of three meters, assuming a recoverable grade (see Cameron, 1988) of 20 ppb and regolith density of 1.5 g/cm^3. The regolith mining, beneficiation, and processing concept ultimately chosen to accomplish this task will clearly influence the final economics of volatile extraction and the architecture of lunar bases and settlements.

Rectilinear mining concepts, with mining, beneficiation, and volatile extraction systems integrated into a single, self contained mobile unit, have received important attention (Sviatoslavsky and Jacobs, 1988, Li and Wittenberg, 1988, and Cameron, 1990). Such concepts envision interim storage of extracted volatiles in pressurized tanks which would then be picked up and transported to a central processing location at a permanent lunar base. Long duration, full service, and permanently emplaced support facilities appear to be required to support such concepts. Once mining operations reach the practical limits of transportation support, an entirely new base and transportation network must be established at another location in the resource region.

Spiral Mining Concept

Spiral mining, extending outward from a periodically mobile central station (figure 1), represents an alternative concept for comparison with more traditional mining schemes. With spiral mining, the mobile mining machine would be attached to the central station by a telescoping support arm. The miner would extract regolith fines in an outward spiral away from the central station. Using solar thermal energy collected at and beamed from the central station, the miner's internal systems would then beneficiate the fines, extract solar wind volatiles, and recover waste heat. Cooled, spent fines would be deposited at the rear of the miner. In these particulars, the spiral mobile miner and the

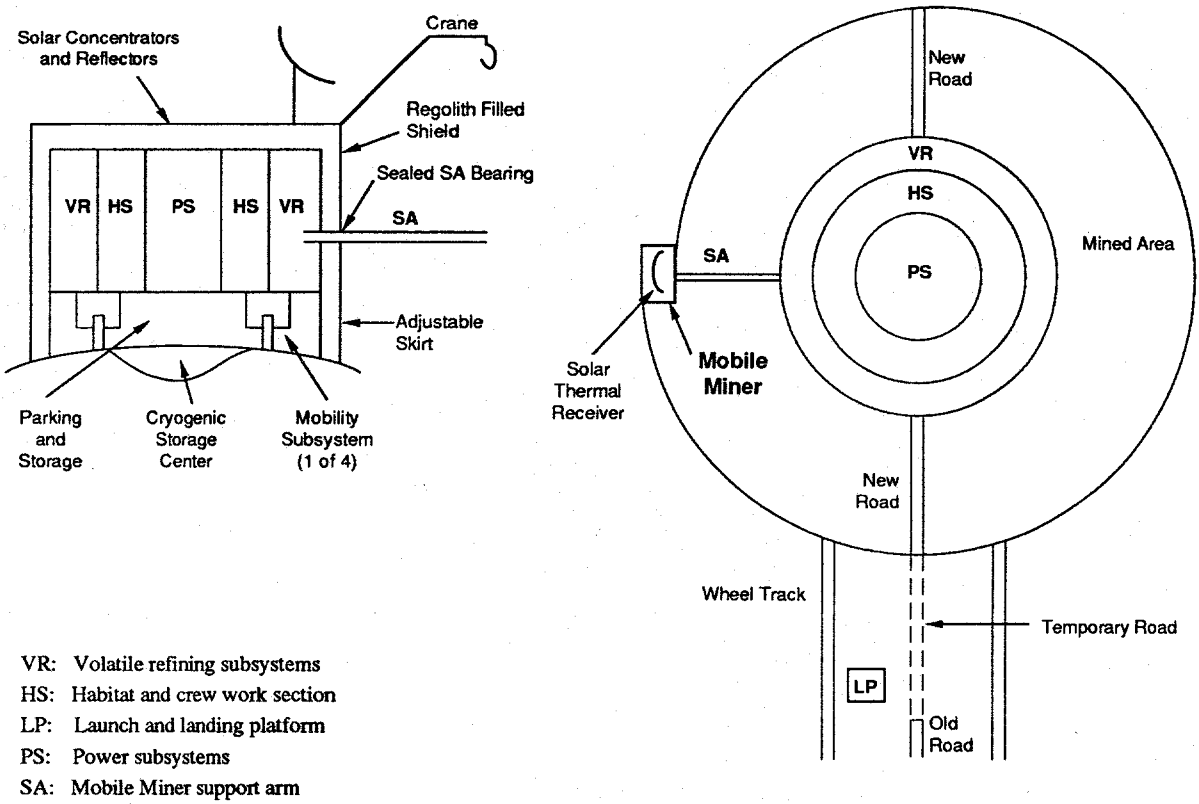

Figure 1. Conceptual representation of a lunar spiral mining system.

rectilinear miner are comparable.

Five major characteristics distinguish spiral mining from rectilinear concepts. First, the spiral mobile miner would receive electrical power from the central station to operate its mobility, excavation, and mechanical processing subsystems. Second, telerobotic operation of the miner could be along optical fiber, directly from the central station. Third, extracted volatiles would be pumped continuously from the miner to the central station for refining. Fourth, refined volatiles would be shipped to terrestrial or space users directly from each central station or stored in recoverable caches beneath the station. Fifth, routine maintenance and repair of the mobile miner would be performed at the station.

Preliminary evaluation of the alternatives of fluidized or conveyer transport of regolith fines from the miner to the central station indicates that power requirements would impose an excessive additional cost

(2-17w/m/t/hr and 0.5w/m/t/hr, respectively, as indicated by Cheremisinoff, 1984). The possibility, however, of conveyer transport through the support arm should not be ignored in the event other factors force reconsideration of the extraction of volatiles within the mobile miner.

Mobile Miner

During normal operations, the mobile miner of a spiral mining system would mine its way through the upper three meters or so of the lunar regolith, supplementing its mass with the regolith moving within its systems and possibly with extra regolith as ballast. A look-ahead radar system should make it possible to either avoid or excavate boulders too large to deal with normally. Blocky craters as well as major boulder concentrations would be avoided by extending and contracting the telescoping support arm.

Continuous processing of the mined regolith would take place within the miner (see Sviatoslavsky and Jacobs, 1988), including separation of fines and rejection of coarse material, beneficiation of fines, heating of fines to extract volatiles, and recovery of waste heat prior to disposal of spent fines. Thermal energy for the continuous extraction of volatiles from regolith fines initially could be collected by appropriately placed solar collectors on the top of the central station. This thermal energy, or thermal energy from any other potential source, would be transmitted by reflectors or the support arm to the miner and directed into the extraction heat exchangers.

The mobile miner may be fully automated or operated telerobotically from the central station. Design should provide, however, both for human inspection and maintenance and for temporary human operation in the event that automated or telerobotic systems require extensive down time for repair.

Central Station

The central station of a spiral mining system, in addition to providing support facilities for its inhabitants, would supply electrical and solar thermal power to the mobile miner. The station also would perform command and control functions for teleoperation of routine mining. Extracted raw volatiles, pumped from the miner, would be processed and tanked for export or storage. Refined and liquefied helium-3 and other volatiles would be launched to Earth or space from a launch and landing platform (LP), placed along the support road from the main lunar base so as to serve two of more central station sites. Other liquefied volatiles, in excess of those needed to operate the station or for export to space based users, would be stored in radiatively cooled cavities within the insulating regolith and beneath the central station.

Some considerations suggest that the standard operating duty cycle for each station would be daytime mining, beneficiation, and volatile extraction and nighttime volatile refining. Such a cycle would take maximum advantage of sunlight for mining and volatile extraction and of the deep space cold sink during volatile refining. Electrical power could be generated by hydrogen-oxygen engines and/or fuel cells with a very small net utilization of the extracted volatiles. This duty cycle also would provide convenient work cycles for the station's crews in multiples of two weeks, such as six weeks on and two weeks off.

The basic architecture of a spiral mining central station might have a cylindrical plan as also shown in figure 1. A central core area could house the power subsystem (PS). Habitat sections (HS) and other crew occupied areas could be arranged around the power subsystem core. Finally, the outer cylinder could include volatile refining subsystems (GP), feeding directly into the mobile miner support arm. This configuration, along with appropriately located regolith fill in the station's outer walls, also would provide radiation shielding for the crew.

Wheel assemblies, motors, gear boxes, and other components of the station's mobility subsystem could be located in four internally accessible compartments beneath either the habitat or the volatile refining cylinders. Preplanning of the station's actual mining track should make it possible to center each mining spiral over an appropriately sized crater that can then be configured to contain the cryogenic storage subsystems for excess volatiles. The insulating cover placed over storage vessels could then be used as a prepared area for storage, vehicle parking, and routine vehicle maintenance and repair.

Mine Planning

Under the spiral mining concept, long term exploitation of a volatile resource region would begin with establishment of a permanent support base at the center of a long boundary of the region. Alternatively for very elongated resource regions, the initial support base could be situated at a point lying at the maximum economical transportation distance from the future mining tract that would parallel a roughly orthogonal edge of the region. For some particularly large resource regions, economics may dictate that support bases be laid out along a center line of such a region. Appropriately located permanent support bases would provide administrative, agricultural, medical, recreational, manufacturing, and shop support beyond that possible at the spiral mining central stations.

The mining tract for each spiral mining system would proceed orthogonal to a long boundary of the volatile resource region (figure 2). New mining systems would be activated along parallel tracts as demand for helium-3 increased. Closest packing of the spirals between unminable blocky craters in adjacent tracts would result in processing about 90 percent of the recoverable regolith (see discussion in Cameron, 1990).

The first tract to be mined probably would extend directly away from the permanent support base, connected to that base by a road that would be extended as mining progressed. Rock aggregate for this and other roads can be derived from normal mining operations. The road along the center line of a mining tract also would link volatile storage sites and remotely located launch and landing platforms. As terrestrial demand requires new helium-3 production capacity, later mining tracts would be developed on alternate sides of the initial tract in order to maintain minimum transportation costs.

The practical limit which spiral mining can reach away from the central processing station has not been determined and will be subject to many weight and operational tradeoffs. (A one kilometer radius of mining to a depth of three meters would produce about 280 kg of helium-3 in a typical volatile rich mare area where recoverable helium-3 concentrations of 20 ppb would be encountered in regolith of about 1.5 gm/cm^3 density. Using the mining rate estimates for the mobile miner of Sviatoslavsky and Jacobs (1988) of 1 km^2 per year to a depth of 3 m, this 280 kg would require about 3 years to produce.) Once such a practical limit has been reached, the central station would be moved twice this distance on self contained tracks or wheels along the planned line of mining. Caches of stored excess volatiles could be recovered as markets develop.

Conceptually, a lunar base supporting spiral

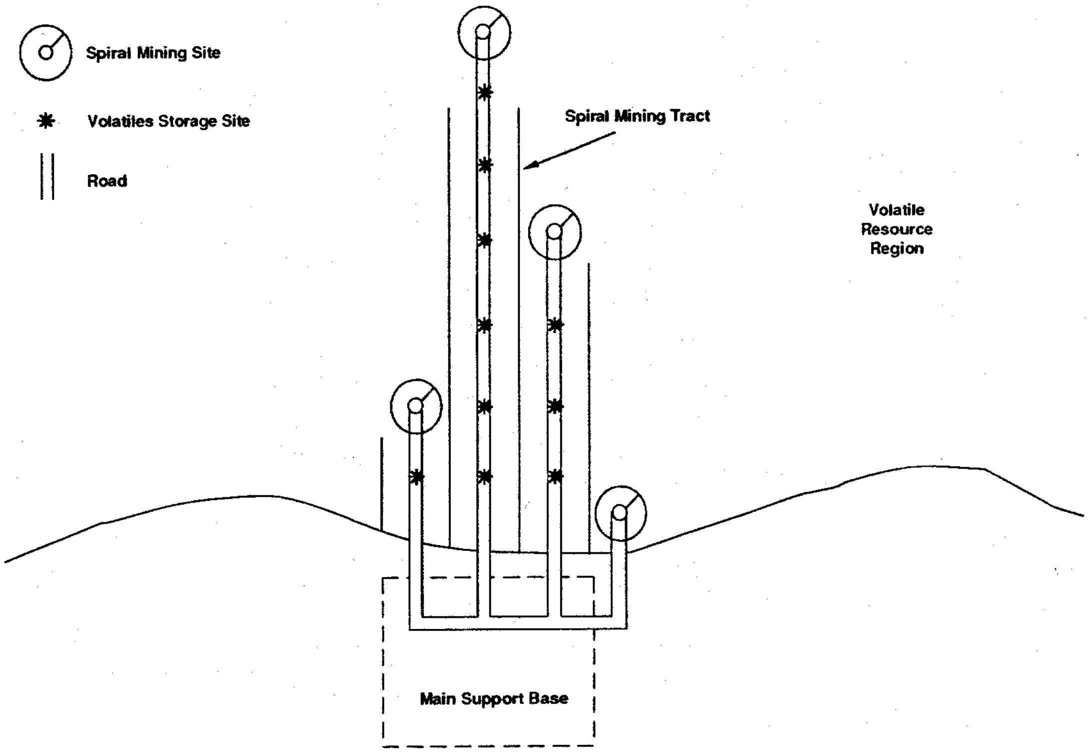

Figure 2. Generalized representation of a regional mine plan, employing lunar spiral mining systems.

mining tracts would relate to the central processing stations as Fairbanks and Anchorage, Alaska, relate to the oil production facilities on the North Slope. A permanent and expanding network of roads connecting the bases with mobile central stations and caches of excess volatiles obviously would develop over time. Distance and excess hydrogen and oxygen, however, may eventually encourage development of suborbital transportation systems in place of an ever expanding road network or a continued proliferation of permanent support bases. Each permanent lunar base also would support fixed site scientific facilities as well as lunar wide geoscientific exploration.

Conclusions

Major features of a spiral mining system to extract volatiles from the lunar regolith include a periodically mobile central power and processing station, a mobile miner operating at the end of a telescoping support arm extending radially from the central station, and a fixed support base central to the resource region. Conceptual evaluation of these features suggests several qualitative advantages over other possible mining systems.

The absence of electrical power generating subsystems on the mobile miner both reduces the complexity and size of the miner and permits integration of power requirements for mining with power needs of other support activities. This should allow for the design of relatively large and efficient power subsystems within the central station. A direct connection between the miner and central station also provides several options for thermal power transmission from solar collectors (or other sources) on the central station to heat exchangers on the miner.

In addition to power transmission, the telescoping support arm permits direct transport of extracted volatiles from the miner to refining subsystems in the central station and simplifies telerobotic operation of the miner itself. Concentration of all operating control and routine support functions in the mobile central station lets the more distant, permanent fixed support base focus on longer term maintenance, crew support, and research issues.

These and other detailed considerations suggest that spiral mining systems would be worth detailed evaluation in comparison with the technical and economic aspects of other mining concepts.

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