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## Asteroid Mining

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The earliest studies of asteroid mining (e.g., Johnson and Holbrow 1977) proposed retrieving a main belt asteroid. Because of the very long travel times to the main asteroid belt, attention has shifted (Billingham, Gilbreath, and O'Leary 1979, O'Leary 1983) to the asteroids whose orbits bring them fairly close to the Earth. In these schemes, the asteroid would be bagged and then processed during the return trip, with the asteroid itself providing the reaction mass to propel the mission homeward. A mission to one of these near-Earth asteroids would be shorter, involve less weight, and require a somewhat lower change in velocity ( $\Delta V$ ). Since these asteroids apparently contain a wide range of potentially useful materials, our study group considered only them.

### Asteroid Materials and Properties

The forces driving the consideration of asteroid mining are their varied materials and favorable retrieval  $\Delta V$  (see John S. Lewis's paper in this volume). Combining information from spectral studies of asteroids and laboratory analyses of meteorites, investigators have

postulated near-Earth bodies rich in volatiles (water, halogens, and organics) and metals (structural, precious, and strategic). While no asteroid prospect has yet been identified, the possibility of obtaining such materials for cislunar operations from a source requiring low  $\Delta V$  is exciting and should be pursued.

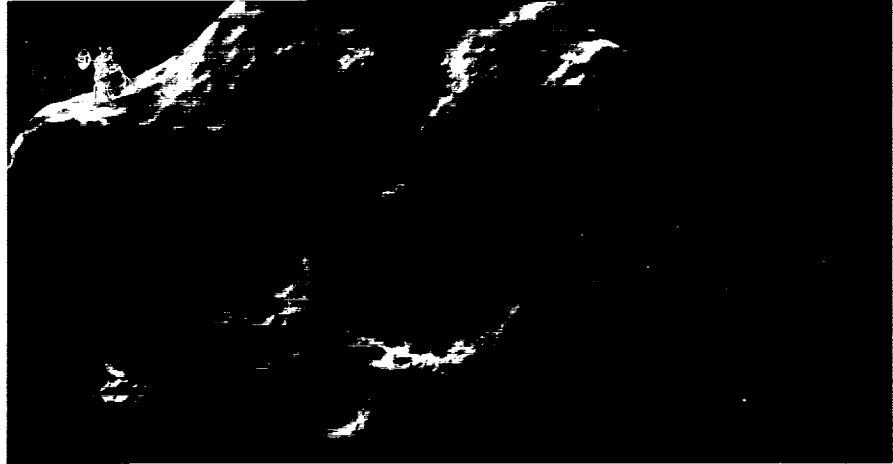
Furthermore, samples in the form of carbonaceous chondrites and similar classes of meteorites indicate that their parent asteroids may have favorable mechanical properties. Some of these materials break up easily at pressures as low as a few bars ( $10^5 \text{ N/m}^2$ ) (see table 17 in John Lewis's paper). This breakup pressure is much less than that for most terrestrial materials. For example, some material can be crushed by hand. Although other asteroids may be fundamentally tougher, impacts may have broken up their surfaces into regolith (soil). Thus our study group came to believe that material from a near-Earth asteroid should be easily excavated and rather easily crushed by mechanical comminution equipment already developed for terrestrial applications.

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### **Asteroid Mining**

*Asteroids have resource potential, notably the potential for providing water, which can be decomposed into hydrogen and oxygen for propellant use. Asteroids may have rough cratered surfaces, as illustrated in this painting. If they are water-rich, they are likely to be similar to carbonaceous chondritic meteorites, which are very black, with extremely low albedos. Such asteroids may be rather soft and friable and thus easily mined.*

*Artist: Dennis Davidson*



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## **Asteroid Mission Selection**

While the latest studies of retrieval and processing methods indicate that the project is feasible, the selection and the execution of an asteroid return mission are still fraught with problems. These problems stem from two basic causes: no candidate asteroid has been identified and the long trip time imposes severe limits on the mission. The results seem attainable but only with much more work.

### **Identifying an Asteroid Prospect**

From the perspective of the terrestrial mining industry, lack of a specific asteroid candidate or prospect means that no project exists. Mining projects are so sensitive to actual site characteristics that an asteroid mining mission cannot be justified on circumstantial evidence. This is particularly true of an unmanned mission, where everything must work properly the first time and without human intervention.

Confidence that a feasible asteroid prospect exists in the near-Earth environment is based on statistical analysis. Given the known distribution of near-Earth asteroids and studies of their compositions, it seems probable that a candidate

can be located, if enough resources are applied to the search effort (see Michael J. Gaffey's paper in this volume). Physical properties of prospective candidates—mineral grades, mineral variability, specific mechanical characteristics of the asteroidal material, and orbital characteristics—must be determined before significant development of an asteroid mission proceeds.

Nevertheless, a basic understanding of what an asteroid mission might entail is readily at hand. Using the possible orbits, mineral compositions, and mechanical properties of the near-Earth asteroids, one can construct a range of potential missions. The feasibility of such a mission can be established and comparison can be made to a lunar mission, such as the LOX-to-LEO project. Sensitivity analysis of asteroid mission profiles and comparisons to lunar projects can begin almost immediately. Criteria can be developed that will guide selection of candidate asteroid bodies. The expected range of flight characteristics, combinations of ore grades, ore types, mechanical properties, flight durations, and transportation costs can be determined and the range compared to that of a lunar project.

### **Long Mission Duration**

Long travel times to near-Earth asteroids pose significant economic and operational problems. Physical sampling of the candidate body would take as long as the mining mission, so the flow of risk-reducing information is slow. The sampling mission would take a year or more, there may be a long wait for the next mission window, and then the mining mission would take another year or more. Thus, the lead time could be very long. When the mining mission finally flies, an expensive mining plant would have been in orbit a year or more before use. This unproductive time significantly raises the mission's cost. The round-trip time of 2 years or more lowers the rate of return on investment in plant and equipment.

Mission feasibility depends on the right choice of three basic types of missions: a long-duration manned mission, an automatic or teleoperated mission, or a mission in which the manned portion accepts high  $\Delta V$  and the equipment arrives by slow Hohmann transfer orbit. Determining the proper choice will require extensive research and development, which, of course, increases mission cost. Each type has its advantages and disadvantages, both during the mission and in later technology transfer. The basic tradeoff question—manned or

automatic/teleoperated—has yet to be answered.

## **Manned Versus Automated Missions**

### **Manned Missions**

While the problems and expense of a manned mission are obvious—long-term exposure to zero gravity, exposure to dangerous solar radiation, designing controlled ecological life support systems, and man-rating a deep space vehicle (just for starters)—our study group, with its terrestrial mining perspective, suspects that an asteroid mining mission will require human miners. The reason is our skepticism about the ability to economically automate such a mission. Not only has progress in terrestrial mine automation been slow, but also the prospect of applying such technology to an environment with so many unknowns is daunting.

### **Automated Missions**

The benefits of automation are derived from economic considerations and not simply from eliminating people from the production loop. If automation decreases production costs, it should be used. This principle is important even in highly automated industries such as automobile manufacturing. Tasks that are

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repetitive and boring yet require precision are the best candidates for automation. In this realm, the experience of General Motors illuminates the point. GM's new, largely automated assembly plant has yet to reach production goals and has a myriad of problems. Increasing the production rate and maintaining the required quality while lowering or maintaining production costs justifies the increased capital cost of automation.

Some mines, particularly longwall coal mines, have successfully achieved partial automation of a relatively repetitive mining system. It was accomplished in small steps: One easily defined machine operation or task was automated while the rest of the operations remained manual. After debugging and redesign, the automated operation achieved the required degree of reliability. Then, another candidate for automation was selected and the process was repeated. Over several years, a reliable and integrated but not fully automated system may thus be painstakingly built. In general, terrestrial mine automation has been confined to remote sensing of mine parameters, such as ventilation and equipment status, and production monitoring.

Complete mine automation has been shown to have too great a capital cost to be effectively amortized over the production life of a mine. Furthermore, mining operations have a much greater number of degrees of freedom than does automobile manufacturing. Besides increasing capital (and R&D) costs, operations that are not exactly repetitive have more automation problems than do repetitive operations. Thus, mining costs are not lowered by automation as much as product manufacturing costs are. The fact that the harsh mining environment is much harder on equipment than is a closed plant environment only aggravates the problem.

This experience does not close the door on automatic/teleoperated asteroid missions. It does indicate caution when contemplating these missions. The automatic/teleoperated asteroid mining equipment must work perfectly. Even small equipment failures cause the mission to fail. An expensive R&D effort is needed to ensure such perfection. As with the lunar case, the lessons learned in flying an automatic/teleoperated asteroid mission may find extensive terrestrial application, helping to amortize the large R&D costs.

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### **A Manned Alternative**

One possible compromise in the manned/automated tradeoff is to send the equipment on a low  $\Delta V$  flight and launch the human operators separately on a much shorter, high  $\Delta V$  flight. The astronauts would mine the body, start the materials on a slow trip back to cislunar space, and themselves make a fast trip back. It should be noted that any manned mission would have the possibility of refining some or all of the fuel required for the return trip.

### **Teleoperated Missions**

Teleoperation resolves some of the difficulties of automated operation. A greater range of the unforeseen problems the system will encounter become solvable. However, actions are carried out by the same actuation devices in both automation and teleoperation. This fact imposes limitations in mining operation control. The Viking lander case is illuminating. The Viking mission, which cost about \$1 billion (in 1970 dollars, about \$3 billion now), included an extendable scoop experiment that was teleoperated. Although the scoop was relatively simple in design and operation, with few degrees of freedom, first attempts to actuate it failed. A good deal of evaluation and effort ensued before the scoop was successfully operated.

Teleoperation from Earth would be somewhat hampered by a control delay due to the long distances and the speed of signal propagation. However, it seems likely that the effect could be overcome.

### **Mining in Zero Gravity**

Although it might seem easier to move materials in zero gravity than on Earth, inertia, not overcoming gravity, is the major effect to consider. Little experience has been gained in weightlessness. One sample problem is that of holding fracturing and excavation tools to the face of an asteroid. On Earth, equipment hold-down is accomplished solely by gravity. Another sample problem is containing the excavated material, either large or small fragments. Rock fracturing places an initial velocity on the broken material. On Earth, gravity quickly collects the broken rock. In weightlessness, the broken rock will behave like out-of-control billiard balls, a potentially destructive game. Furthermore, the fines that are always generated by rock fracturing may obscure vision and clog equipment. Our study group did not have time to consider the full significance of working complex equipment in zero  $g$ , but we note that this problem needs in-depth study.

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## A Conceptual Asteroid Mining Method

The study group did not have the time or the resources to fully design a baseline asteroid mining method. This incomplete concept of an asteroid mining method is intended to illustrate how some of the problems could be overcome. As with the lunar proposal, the concept should be used to promote discussion of asteroid mining problems, but not to promote the method itself. Assuming that the  $\Delta V$  for the available asteroid is small and that only a modest amount of material is needed, I propose the following method to accomplish a first mission.

After arriving at the asteroid, the operators place one or more cables around the body. The asteroid proposed to the group for study was no more than a few hundred meters in diameter. Placing a cable around the body appeared to us much easier than anchoring the end of a shorter cable. Anchoring in rock can be a difficult process. If augering is used in weightlessness, a method must be devised to hold the augering tool down while it is working. The most desirable asteroids have very low strengths, good for mining but poor for anchoring. Quite long cables are possible, on the order of

1000 meters. The cable is easily placed and provides easy movement of the mining tool.

One disadvantage of a long cable is the mass; for example, a cable 1 inch in diameter weighs 1.6 pounds per foot on Earth (has a mass of 2.4 kg/m).

The cable holds a cutter head or other rock-fracturing tool in place and provides sufficient working force for it. The cutter head is designed to excavate in addition to fracturing the soft rock. A conical Kevlar collection bag is placed over the area to be mined and is held in place by the same cable (fig. 24). The flexible bag holds its shape because of the rotation of the asteroid. The spin also aids in collecting the fragmented asteroid material.

The cutter head travels back and forth along its restraining cable, cutting material until the collection bag is filled (fig. 25). The cutter is similar to the coal shear currently used in longwall operations but is designed to overcome the asteroid's low gravity and fling material past synchronous orbit so that centripetal force effects collection. Dust production around the cutter head remains a problem. Dusty environments obscure vision and thus increase problems in controlling teleoperated systems or in monitoring automated systems.

However, direct vision may not be so important on a body that proves to be homogeneous in structure and composition.

After the required amount of material is collected in the bag, it is "lowered" away from the body, allowing the bag and material to steal angular momentum from the asteroid. For low  $\Delta V$  return flights,

there may be sufficient energy available to slingshot the load back to Earth. Deceleration at Earth could be accomplished by aerobraking. The collection bag might be designed to act as an aerobrake shield in addition to being reusable. The bag could also serve as a retort for carbonyl or other types of processing during return.

Figure 24

#### **Concept for an Asteroid Miner**

The shear breaks material and throws it away from the asteroid into the collection bag. The bag is moved when the shear moves to a new mining area. The collection bag can be used to transport the material to the Earth. The bag could also be used as an aerobrake shield or a processing container.

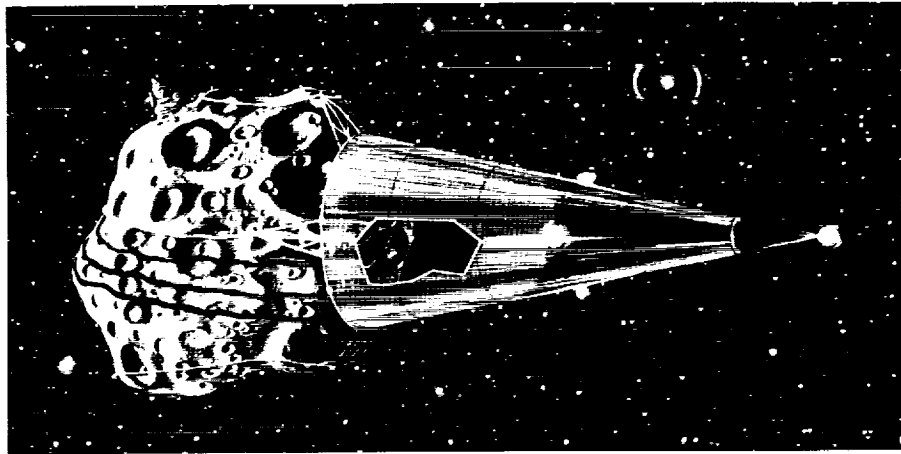
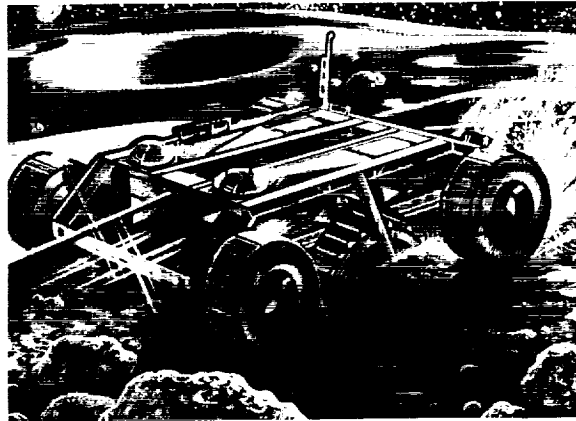


Figure 25

#### **Detail of the Shear**

The shear is derived from coal-cutting technology. It performs a dual role: it cuts the asteroid material and throws the material into the collection bag. In this illustration, the wheels are too small; larger, high-flotation wheels will help negotiate rough terrain. There should also be chutes to direct material past synchronous orbit and into the bag. And the shears conflict with the wheel path; they should be either inside or outside the wheels.





An alternative, but basically similar, method still uses the bag and cable. However, a large block of asteroid material is collected, not by mechanical excavation but by blasting material into the bag. Instead of a shear, which could have trouble negotiating the asteroid surface, an explosive is used. The cable holds in place a drilling machine, which drills a series of blast holes. The drill holes and charges are carefully designed to excavate a large section of the asteroid. The explosive charges break out the desired amount of material, and the force of the explosion moves the material into the collection bag. Pattern drilling designed to create shaped explosions has achieved some success on the Earth and is finding more applications. The explosive method appears simpler in equipment and operation than the shear, but the blasting must have a very high degree of control. Uncontrolled fragmentation of the cabled body would be a disaster. I have not considered a suitable blasting agent. The reader can visualize this alternative method by imagining a drill rig instead of the shear in figures 24 and 25.

While the sizing of the return loads requires further study, the same basic mining scheme should be able to handle a range of sizes. It is not completely clear whether one large load or several smaller loads would be better, although several

smaller loads might be more manageable, while allowing more flexible return flight plans.

## Conclusions

Because it appears to be easier and cheaper to accomplish, the lunar mine is probably a better first project to exploit nonterrestrial materials than is the asteroid mine.

While not causing any increased transportation costs, the long, slow travel to and from the near-Earth asteroids would decrease the rate of return on capital investment.

As in the lunar LOX-to-LEO project, the asteroid mining system must be kept as simple as possible. Simplicity eases problems and lowers the costs of development, equipment, and operations.

A manned mission would make the mining operation much simpler, but it would greatly increase the complexity and cost of the deep space transport vehicle.

Teleoperation seems a good compromise between automation and manned missions, but the choice requires much more study.

Even if specific space program goals or higher costs eventually preclude an asteroid mission, the rich and varied asteroid materials require that the option of mining

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an asteroid be studied. Given a goal of providing a range of materials for use in cislunar space, lunar projects must be demonstrated to be superior before asteroid missions are abandoned.

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