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Retrieval of Asteroidal Materials

BRIAN O'LEARY, MICHAEL J. GAFFEY, DAVID J. ROSS, and ROBERT SALKELD

Earlier scenarios for mass-driver retrieval of asteroidal materials have been tested and refined after new data were considered on mass-driver performance, favorable delta-V opportunities to Earth-approaching asteroids with gravity assists, designs for mining equipment, opportunities for processing volatiles and free metals at the asteroid, mission scenarios, and parametric studies of the most significant variables. We conclude that the asteroid-retrieval option is competitive with the retrieval of lunar materials for space manufacturing, while a carbonaceous object would provide a distinctive advantage over the Earth as a source of consumables and raw materials for biomass in space settlements during the 1990's. We recommend immediate studies on asteroid-retrieval mission opportunities, an increased search and followup program, precursor missions, trade-offs with the Moon and Earth as sources of materials, and supporting technology.

INTRODUCTION

O'Neill proposed that lunar and asteroidal materials may be economically mined and processed in space for the construction of high orbital habitats (ref. 1) and satellite solar power stations (ref. 2). The 1976 NASAAmes Summer Study on Space Settlements (ref. 3). corroborated early estimates that these concepts could be carried out on a large scale in the 1990's with an initial investment comparable to that of the Apollo program using present technologies. In the scenario considered, an electromagnetic mass driver on the Moon would propel lunar material into free space for subsequent transfer to a space manufacturing facility (SMF) for chemical processing and fabrication into large structures. The mass driver would also serve as an orbital transfer vehicle, possibly reducing the cost of transport from low Earth orbit, where the external tanks for the Space Shuttle would be pelletized into reaction mass (ref. 4).

O'Leary (ref. 5) explored the possibility of using mass-driver tugs to move Earth-approaching asteroids at opportunities of low-velocity increment to the vicinity of the Earth. Carbon, hydrogen, nitrogen, and free metals, apparently scarce on the Moon, may be abundant on some asteroids; possibly, the retrieval of asteroidal materials may be cost-competitive with that of lunar materials in an early program of space manufacturing. A scenario was developed (ref. 6) where a 100-MW mass driver, assembled in space with about 50 Space Shuttle flights, would retrieve about 22 percent of a 200-m-diameter ($1X10^7$ -metric ton) asteroid through a velocity increment ΔV of 3 km/sec in 5 years. Many such objects are believed to be within reach of Earth-based telescopes in ongoing search programs.

The current study tests the assumptions made in earlier work and refines the existing scenario. Two companion papers describe, in detail, (1) delta-V requirements for favorable round-trip missions to currently known candidates and probable future ones (ref. 7) and (2) asteroidal resources and recommendations for expanding the search program, followup for orbital determination and chemical classification, and identification of precursor missions (ref. 8).

This paper describes scenarios for asteroid retrieval (1) for a real object (asteroid 1977 HB with gravity assists from Earth, Venus, and the Moon) and (2) for a likely hypothetical case, given an increase in the asteroid discovery rate and improved mission-analysis techniques. Several topics are discussed: values for delta V, energy requirements, role of man, design of outbound massdriver system, assembly and attachment to asteroid, mining operations, timing and logistics of the retrieval operation, the selection of volatiles and free metals, and options for using hydrogen and oxygen processed at the asteroid for fuel. The second section places this scenario in a parametric context, which will identify the most significant variables in comparing the economics of transport, into a stable high orbit, of asteroidal, lunar, and terrestrial materials. This paper concludes with recommendations for a research and development program designed to provide technology readiness for asteroid retrieval by the mid-1980's. An appendix, by Robert Salkeld, presents a cost comparison of asteroidal vs lunar derived materials.

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GROUND RULES AND ASSUMPTIONS

First, we assume that it is desirable to minimize the mass of the equipment required to retrieve the asteroid: rendezvous engine and propellants, mining apparatus, equipment for preparing reaction mass at the asteroid and for successfully returning the asteroid (or portions thereof). The mass of the retriever must be kept low because of the large Earth-to-orbit launch costs (at about \$700/kg and \$240/kg for an upgraded Space Shuttle) and equipment costs (assumed to be \$400/kg or three times that of modern aircraft).

The selection of an optimal exhaust velocity V_e for the asteroid-retriever mass driver depends on various parameters, which were recently revised by the Mass-Driver Study Group of this summer study. The earlier asteroid-retrieval study (ref. 6) considered $V_e \sim$ 2km/sec, which was optimized for maximum returned mass per unit power imparted to the reaction mass through a total one-way delta V of 3 km/sec, a value that appears reasonable for the most favorable known cases (ref. 6). This value suggested commonality in design with the lunar mass driver and mass drivers designed for orbital transfer between high orbits (e.g., long-term SMF orbits, lunar orbit) and geosynchronous orbit. A higher-thrust mass driver would act as a booster to spiral the asteroid retriever from low-Earth orbit to high-Earth orbit, as in the lunar scenario (ref. 4).

However, further consideration of the relationship between exhaust velocity and mass-driver mass for constant thrust and an analysis of the requirements for the outbound leg of the retrieval mission led us to conclude that a single-stage, high-thrust mass driver alone may perform the retrieval. For a nominal delta V from Earth escape of 3 km/sec, in addition to the 6.4 km/sec required to achieve escape from low-Earth orbit by low thrust, $V_e \sim$ 8 km/sec appears to be a reasonable value for the mass-driver retriever. Commonality in design is again possible when the former booster becomes the retriever itself.

The use of the same mass-driver design for diverse tasks suggests minimal development costs which would be uniquely attributable to the asteroid retriever. We have assumed that a mass driver would be used for the first asteroid retrieval because of the common design property and because the mass driver has some attractive features not offered by most alternative propulsion systems: high throughput-to-mass ratio, relative ease of preparation and use of asteroidal material as reaction mass (the fuel is "free" at the asteroid), high efficiency of operations, and near-term technology required for timely development.

We have further assumed that the size of the asteroid fragment to be retrieved is about 100 m in diameter ($1X10^6$ metric tons). Such a fragment is at the lower end of the size range of objects accessible to telescopic search programs. It would provide about $0.5X\ 10^6$ metric tons of material in high-Earth orbit, which is comparable to a few years throughput of lunar material in the lunar resource retrieval scenario (ref. 3). This size would be appropriate for first mission(s) where "one-time" development costs would be in reasonable proportion to total mission costs while their sum would be within the scope of current NASA planning and would require moderate, temporary use of an upgraded (class II) Space Shuttle. A more quantitative investigation of this assumption is presented later. If the best initial candidate is more massive than 10^6 metric tons, it would be necessary to break off a piece for the first recovery.

We assume that the first asteroid retrieval mission will be manned. In our opinion, the assembly and mining operations are sufficiently complex, with real-time decisions governing equipment several light-minutes from Earth, that an automated mission would be a formidable task. It follows that the total mission time should be kept as low as realistically possible, with crew changes only about once a year. Such crew changes could be conveniently carried out at times of Earth gravity assist (described later). A minimum round-trip time for an asteroid mission would be about 1 year, corresponding to a one-way Hohmann transfer time of about 6 months from Earth to the asteroid on an Earth-like orbit. But most optimal transfer times are considerably longer, particularly when gravity assists are used (ref. 7). For the optimal retrieval of a 10^6 metric-ton asteroid, a throughput of about 4 kg/sec of reaction mass would be required for a 3-year return time.

VOLATILE AND FREE METAL RETRIEVAL FROM ASTEROIDS

Most ordinary and low-grade carbonaceous chondrite meteorites - and, by inference, asteroids - contain $\gtrsim$ 10-percent free metals, water, and carbon. Water and carbon dominate this phase in carbonaceous objects of types I and 11; metals dominate in ordinary chondrites. One class of carbonaceous objects has appreciable percentages of all three, comprising about 20 percent of the body by weight. At a modest additional cost in the mining operations of the asteroid, the free metals can be sifted out and magnetically separated and H_2O, and CO_2 can be extracted by heating the asteroidal fragments in a solar furnace to about 600^{o} C. After the H_2O and CO_2 are extracted, the remaining material would serve as reaction mass. This operation would be continuous at the asteroid, corresponding to the nominal throughput of 4 kg/sec for a 3-year mission to return about $0.5X10^6$ tons of material.

The SMF site would receive about 100,000 metric tons of free metals (mostly Fe/Ni), 50,000 metric tons of water, 20,000 metric tons of carbon compounds with the remainder for reaction mass, shielding, and processing into oxygen, ceramics, glasses, and metals.

The 1977 Summer Study projected that 3100 persons could be in high orbit by 1991 to process, in space, nonterrestrial materials into satellite power stations. If it is assumed that 3 kg/person/day is required for consumables (half of which is water in "wet" food with some additional nitrogen and oxygen to replace airlock leakage) and about 0.5 ton/person of carbon, hydrogen, and oxygen imported for biomass to establish farming operations in space, it follows that about 30,000 tons of water, carbon compounds, and nitrogen will be required for the first decade of large-scale production of satellite power stations from nonterrestrial materials. Unless trapped volatiles are found in permanently shadowed areas on the Moon, these materials must come from Earth or asteroids. Processing a 10^6-ton carbonaceous asteroid for volatiles will provide more than enough material for consumables and for establishing space farms.

A plant will be required to process the appropriate alloys and to fabricate them into useful structures, but the power requirements for this are more than an order of magnitude less than those for extracting aluminum from lunar soil.

The relative energy requirements to produce structural elements from lunar ore (aluminum oxide) and from asteroidal ores (iron-nickel metal grains) can be estimated from basic chemical data. The energy necessary to reduce iron oxide to metallic iron in a blast furnace is about 17X 10^6 J/kg (metal) and the theoretical lower limit (heat of formation) is about 7.5X 10^6 J/kg (metal). The energy needed to melt metallic iron (heat of fusion, about 10 cal/g; heat capacity, about 0.15 cal/g, 300-1600 K) is about 9X10^5 J/kg (metal). The ratio between the energy required to reduce an oxide and to melt the metal per unit of metal is about 8 (independent of efficiency). The heat of formation ratios to produce metal from an oxide for aluminum versus iron is between 2 ($Fe_2 O_3$) and 3 (FeO). Thus the energy required to produce metallic aluminum from lunar oxide ore is 15 to 25 times higher than that needed to melt a metallic aestroidal ore per unit mass of metal.

The actual relative energy requirements will depend on system designs (e.g., melting by means of solar furnace vs electrolysis and associated electricity -producing efficiency), the number of melt-freeze episodes necessary to refine the iron-nickel to construction grade alloy, and the ratio of metal mass necessary to provide the same structural strength (about 2 to 3 times more favorable for aluminum). The economics should also consider trace element recovery from NiFe (Ni, Co, Ge, Pt, etc.) during the refinement process of iron.

If the asteroidal NiFe metal is used, the mass and complexity of the SMF chemical processing plant may be reduced considerably, reducing the cost of an early program of nonterrestrial material processing. It also appears that virtually all the materials required for SMF operations - consumables plastics, graphite for radiators, solar reflectors, and possibly germanium for solar cells - would be available. If a lunar program is more feasible at first, the economics of volatile and metal extraction from asteroids may be immediately competitive- . If serious problems were to develop with the structural dynamics of mass drivers, water could possibly be used at the asteroid as fuel (liquid oxygen and hydrogen produced from electrolysis) or as a working fluid to return appreciable quantities of asteroidal materials. Details of these concepts are explored later.

A representative scenario was developed for capturing a 10^6-to asteroid (see fig 1.). A single mass-driver is used to accelerate the crew and the equipment for mining and retrieval to rendezvous with the asteroid. That mass driver is then used to return a large fragment of the asteroid to Earth orbit. The scenario chosen uses a low-thrust delta V of 6.4 km/sec to achieve Earth-escape speed, a lunar gravity assist maneuver, and a further delta V of 3 km/sec to intersect and rendezvous with the asteroid. Also, in the outbound trip, one or more gravity-assisted maneuvers are used with Earth and perhaps Venus (ref. 7). Return delta V is taken to be 5 km/sec, including insertion into a 2:1 resonant SMF orbit (ref. 7)(see fig 2.) A mission to capture a portion of the asteroid 1977 HB was used as a basic mission (ref. 2).The results of this investigation are shown in table 1. In this case, which was not optimized but was arrived at by trial and error, the outbound delta V was intolerably large, even with gravity assist. But the return delta V was between 2 and 3 km/sec (the lower value obtainable with an extra Earth gravity assist). We concluded that, upon further analysis, opportunities will be found for missions to currently known asteroids in which either the inbound or outbound delta V is on the order of 3 km/sec, with the other leg larger. The strategy will be to find opportunities where some combination of both delta V values is minimized The 5-km/sec return delta V was chosen because lowering the delta V of the initial leg will most likely increase the final-leg velocities. As shown in a later section (Parametric Consideration of Asteroid Capture), these values are not critical to mission economics. Since the primary effort of the mission is to expend moving mass out of the Earth's gravity well, the cost per kilogram of returned asteroidal material will increase only slightly if the delta V values are increased by 2 or 3 km/sec. Nevertheless, the best opportunities should be identified.

Two considerations strengthen the belief that considerably better missions than that shown in table 1 are possible.

TABLE 1 .- RETRIEVAL MISSION TO 1977 HB
(TOTAL MISSION TIME, 1974 DAYS)

Location	Operation	Date	Delta V required km/s
Earth	Depart high orbit	April 28, 1984	6.32
1977HB	Arrive	Nov. 28, 1984	2.53
1977HB	Depart	July 1, 1985	2.04
Earth	Flyby	April 15, 1987	-
Venus	Flyby	March 10, 1988	-
Earth	Flyby	Aug 29, 1988	1.04
Earth	High orbit arrival	Sept. 23, 1989	1.5 lunar gravity assist

Missions are found by trial and error and, therefore, finding a good mission depends directly on how many cases are considered. Time severely limited the number of cases we analyzed; with more time, the study of known objects can be extended considerably. An increased discovery rate for this type of object would increase the number of good cases and should therefore be pursued.

Given these caveats and uncertainties, we now describe the scenario. The retrieval of asteroidal material includes the following steps: achieve a low-Earth orbit, transfer to high-Earth orbit, lunar gravity assist and departure, intermediate gravity-assisted maneuvers, rendezvous operations, including despinning, mining, and processing operations; and mass-driver coupling and deployment; and return. (Each step is described in detail in-the following sections.)

Low-Earth Orbit (LEO)

Components of the asteroid-retriever mass driver, fuel for the outbound leg, and mining and processing equipment would be Shuttle -launched from Earth and the component systems should be assembled and tested in low-Earth orbit. If it is assumed that Shuttle payloads are arranged to be mass-limited rather than volume-limited, and if the Shuttle hydrogen tanks (30 metric tons) are used as massdriver reaction mass, about 55 metric tons may be lifted to 250-km-altitude orbit per launch. When the assembly and testing phases are completed, the crew is Shuttle-lifted to the waiting vehicle. This 21-man team would live in one or more Shuttle hydrogen tanks similar in design to that envisioned for an early space habitat. Escape from near Earth space is achieved in two stages: first, with a delta V of about 6.4 km/sec, the asteroid-retrieval package is raised to high-Earth orbit by a slow spiral orbit. This stage requires 2 weeks to complete, using a mass driver (or its equivalent) with an exhaust velocity of 8 km/sec. The mass driver is optimized to place the asteroid retrieval package in suitable orbit for the minimum number of Shuttle flights, and ideally would be identical to that designed for low-to-high Earth orbit transport (ref. 4). Recent data provided by the MassDriver Group of this study, from conservative assumptions made about the component masses and length, indicate a total mass of 2500 tons at an acceleration of 800 gravities. The propellant throughput is 4 kg/sec. The crew and their life-support system have a mass of 291 tons; the mining facility has a mass of 560 tons. A total outbound delta V of 9.4 km/sec requires the launch of 10,000 tons to low-Earth orbit. With an assumed return delta V of 5 km/sec and an asteroid fragment of 10^6 -ton mass, this enables 532,000 tons to be brought to Earth orbit. The second departure phase involves a lunar gravity assist which gives a 1.5-km/sec escape velocity.

Gravity-Assisted Maneuvers

Besides the lunar-gravity-assisted maneuver, other possible maneuvers permit a considerable saving in deltaV requirements and hence in mass lifted to lowEarth orbit. These are described in reference 7 and are summarized as follows. Of the planets, only Earth and Venus are suitable for missions to Earth approaching asteroids because the other planets are either too small or too far away. The low-thrust EGA technique uses the Earth alone and is therefore always available. After launch from Earth, the mass driver imparts a small delta V to the system and causes it to re-intersect the Earth with a higher relative velocity than that with which it departed. These times of close encounter with the Earth offer excellent opportunities for crew rotation, about every 400 days, except during the trips to and from the asteroid. This relative velocity is changed in direction by the close Earth encounter, and the final Sun-centered velocity may be altered greatly.

The second type of gravity-assisted it maneuver, called VEGA, uses both Earth and Venus. The mission leaves Earth to intercept Venus. A close Venus encounter rotates the relative velocity vector and directs the retrieval package back to Earth. A second flyby of the Earth bends the relative velocity vector and the final Sun-centered velocity may be greatly increased. The mass driver may improve conditions further by thrusting during the EarthVenus or the Venus-Earth passage. In all these ways, a considerable saving in delta V and thus in launch mass may accrue. The mission leg from the last planetary encounter will probably require additional thrust to intercept Earth and will certainly require thrust to match orbital velocities. The return trip may use similar gravity assisted maneuvers to further reduce thrust requirements.

Asteroid Rendezvous Operation

Rendezvous with the asteroid includes the following events (fig. 3): orbital matchings, fragmenting, despinning and bagging the asteroid, establishing the mining and processing operation, and packaging material for reaction mass and for return. Orbital matching is achieved in about 1 day, with a total velocity change of about 1 to 2 km/sec.

After rendezvous, a small jeep will land on the pole and its crew will find a suitable fragment of the asteroid for return to Earth. This fragment, which will have a mass of approximately 10^6 metric tons, will be near the equator and will be separated from the asteroid by a small chemical explosion. The jeep will then land on the detached mass and proceed to despin it. Asteroids rotate at different rates, but 4 revolutions/day may be considered representative of asteroids in the 100-m-diameter size range. A jeep will land at the pole of the fragment and establish a line of small Y-shaped pylons around its equator (fig. 4). These pylons will be either driven into the asteroid (if it is firm enough) or held in place by some kind of anchor. The jeep crew will then wind the asteroid in the direction of its rotation with 5 km of very lightweight cable, using the pilons to hold the cable. One end of this cable will be firmly anchored to the asteroid and the other end to the tug. Launching the jeep with a very minimal velocity to just escape the weak field of the asteroid would result in the cable being unwound as the asteroid rotates. A very tiny thrust from the jeep would be required to keep a light tension on the cable (a few Newtons), which would have a minimal effect on the despin operation. After 2 days, the cable will be unwound and will start to rewind in the other direction. The jeep will thrust against this with 34 N for 4 days (fig. 4). For an exhaust velocity of 4 km/sec, 29 tons of propellant will be used to despin the asteroid completely. Cable and pilons will be stored for return.

After despinning, the asteroid fragment will be bagged along with the entire processing plant. The bag is a slightly pressurized covering constructed of 1-mm composite material resembling fiberglass plastic-coated to make it gas-tight. This bag, with a volume of 10^6 m^3, contains debris and gas produced by mining and processing operations and keeps the surrounding region clean. The asteroid fragment itself is surrounded by a net of 1 km^2 area composed of 0.5-cm aluminum cable spaced 1 m apart. This net will be preassembled and can be rolled out quickly by the crew. The net distributes the thrust loads over the asteroid surface and must be able to withstand the 32 tons of thrust developed by the mass driver. The total mass of the bag and net is 160 tons. The mass driver is now brought alongside the asteroid and coupled to the net. Considerable adjusting will be required to ensure that the mass driver thrusts through the center of mass of the system. Care must be taken in processing the asteroid during return so as not to misalign the thrust by shifting the center of mass.

After the asteroid has been cradled, tied down, and bagged, the mining and processing operations must be established (fig. 5). The design requirements for the mining and processing equipment will depend on the character of the asteroidal material being used (ref. 8). Three possible types of material containing abundant volatile and/or free metal phases are listed in table 2.

TABLE 2 .- MINERALOGICAL, CHEMICAL AND PHYSICAL PROPERTIES OF THREE POSSIBLE ASTEROIDAL MATERIALS

Type	Metal-rich carbonaceous (~C2)[a]	Matrix-rich carbonaceous (~C1-C2)[b]	Type 3-4, L-H chondrite
Fe[c]	10.7	~0.1	6-19
Ni (metal)	1.4	-	1-2
Co (metal)	.11	-	~0.1
C	1.4	1.9-3.0	~.3
H_2O	5.7	~12	~1.5
S	1.3	~2	~1.5
FeO	15.4	22	~10
SiO_2	33.8	28	38
MgO	23.8	20	24
Al_2O_3	2.4	2.1	2.1
Na_2O	.55	~.3	.9
K_2O	.04	.04	.1
P_2O_5	.28	.23	.28
Minerals	Clay mineral matrix Mg Olivine	Clay mineral matrix Olivine	OLivine Pyroxene Metal

	with FeO inclusions		
ρ (g/m^3) Metal grain size strength	3.3 ~.2mm moderately friable	2.0-2.8 -- Weak-moderately friable	3.5-3.8 ~0.2mm moderately friable

[a] Data from metal-rich C2 meteorite *Renazzo*.

[b] Data from C2 meteorite *Murchison* and average C1-C2 types.

[c] Chemical analysis is weight percent.

In this scenario, a metal-rich carbonaceous material is considered to be the most desirable material to recover. We also assume that the metals (NiFe) and volatiles are sufficiently valuable to justify the extra steps necessary to extract or concentrate these materials. There are six major processing steps to follow between the raw asteroidal material and its use as reaction mass in a mass driver: mining, crushing, and sizing; metal extraction and storage; volatile extraction and storage; gas-dust separation ; and dust fabrication for mass-driver use. Figure 6 is a schematic diagram of the asteroid processor. The physical situation at the asteroid requires special types of processing and handling. For an object in the mass range of interest, the surface gravity is about a few microgravities, which corresponds to a surface acceleration of some thousandths of a centimeter per second per second or a few tens of micrometers per second per second. Initial acceleration proposed for the mass-driver system is about 50 μm/sec^2 and increases as the body mass decreases. A body of this size in the solar system is almost certainly a collisional fragment (or a portion of one) and will be strength-limited by internal fractures. A relatively simple netting arrangement should suffice to hold it together against the relatively small accelerations contemplated. (This netting was described previously.)

Mining- The major problem in any mining scenario is to hold the cutting equipment against a surface with sufficient force to cut into the fragment, In tunneling operations, pressure can be exerted on the walls to provide stabilization, but for fractured, relatively low strength rock, tunnels must be spaced to provide relatively thick walls (e.g., about 1 tunnel diameter), which limits the usefulness of this technique, particularly if much of the material is to be used for reaction mass.

An alternate surface technique involves a covered flail excavator that cuts a 5-m-wide, 1-m-deep trench. This excavator is held against the surface by anchor rods driven into the ground around it; the excavator pulls itself forward with these anchors. The forward progress needed to supply 4 kg/sec is about 0.03 cm/sec or about 1.3 m/hr. This device delivers appropriately sized fragments (e.g., $\lesssim$20 cm) through a pipe or conveyor system to the main processing facility.

Crushing and sizing- Because the materials being considered are relatively soft, crushing them should be fairly easy. The crushing device used has a rocking jaw arrangement for coarse crushing ($\lesssim$1 cm) and a series of rollers for fine crushing (fig. 7). The crushing elements are arranged radially in a rotating cylindrical housing to provide a radial acceleration from the hub (input) to the final powder (~0.1 g at 10 rpm of a 3-m-radius device). Mean particle sizes of about 0.2 mm. or slightly less are desirable for metal extraction.

Metal extraction and storage- After crushing, it is probably desirable to use gasdynamic transport to move the materials. Gas pressure can be quite low (~1 millibar) and still be effective for transport in this low-gravity environment. A low gas pressure simplifies system construction since leak rates and material strength requirements are minimized. The carrier gas could be either CO_2 or H_2O, both of which are available. Leakage into a moderately contained environment (e.g., the surrounding processing facility) can be minimized by cold-trap pumping in a passive mode.

To extract most of the metallic phase, the gas stream and its entrained dust are passed through a magnetic field (fig. 8). An enriched fraction ($\gtrsim$80 percent NiFe)

will contain most of the coarse-grained metal particles (~70 percent by weight). This enriched fraction (metal sand) will be diverted to a storage facility (large, relatively weak tank or bag). It is doubtful that any subsequent processing of this metal-rich phase would be economically feasible enroute.

Volatile extraction and storage- To recover the volatile phases (H_2O, CO_2, hydrocarbons), the material must be heated (fig. 9). The temperatures required depend on the desired recovery rate. Water chemically bound into the clay minerals of Cl-C2 matrix material begins to come off near 100° C and continues to come off until about 400' C. Carbon dioxide is produced by the disassociation of hydrocarbon compounds and by reaction of elemental carbon with oxide phases (e.g., $C + 2Fe_2O_3\ CO_2 + 4FeO$). Hydrocarbons volatilize or break down in the range 100°-700° C, releasing a variety of compounds, including methane and petroleum-like vapors.

The energy requirements depend on the recovery rate, which is dominated by the heat of vaporization of water. Considering the various heat capacities of the phases, about 200 cal/g are required to raise raw C_2 carbonaceous matrix material to about 700° C and to vaporize the volatile components. A 4-kg/sec throughput would require a solar collector about 60 m on a side focused on a collector area about 60 m across. Dust entrained in a carrier gas (~2-10 kg/m^3) is introduced into a heat-exchange system at the mirror focus for a period of 30-60 sec. The dust is separated from the gas by a cyclonic separation (dust settles rapidly to the outer wall of a curved conduit). Counterflow of gas and dust is used to heat incoming stream and cool outgoing stream. The gas stream is directed to a shaded heat exchanger and into a storage tank that also serves as a heat exchanger. To condense all products to ~200 K, a radiator area must be about 100 m on a side. The heat released by condensing water may limit the total volatile recovery program. A double condenser system may solve some of this difficulty; the first tank operates near 250 K and precipitates much of the H_2O (depending on vapor pressure) and hydrocarbons. A second tank operating near 150 K and at slightly elevated pressure condenses the remaining H_2O and CO_2 vapors (see fig. 10). The metallic sand is stored in both tanks to increase the thermal conductivity of the ices.

Dust fabrication for the mass driver- The dust fraction of the cooled product is delivered to a storage tank, then to either the mass-driver loading point or to a central fabricating facility. The dust is separated from the entraining gas and is stamped or poured into appropriate molds. The character of these mold requirements is presently unspecified. However, laboratory experience has shown that relatively low pressures are required to form a reasonably solid pellet.

Mass Requirements for Mining, Processing, and Storage

The cost of feasibility of mining and processing an asteroid for reaction mass, volatiles, and metals will depend greatly on the mass and associated costs of transporting equipment to the asteroid to accomplish these tasks. The necessary equipment includes that for mining and processing (crushers, metal and volatile extractors), storage containers, radiators, and support equipment (piping, blowers, "nets," and "bags"). An initial estimate of the mass of the necessary equipment can be made by fixing a preliminary design for each component and by then making a reasonable estimate as to the mass of that component. Certain elements of the proposed system are sized to a particular mass-flow rate. Each component is discussed briefly below and its associated mass is estimated.

Reaction-mass storage and "pumping" facilities include the system needed to store and feed reaction mass for the outbound leg (analogous to a fuel tank). For a throughput of 4 kg/sec, this tank must have a storage capacity of about 20,000 m^3 and is envisioned as a gas-tight (~1 mbar pressure) bag, 20 m in diameter and 65 m long, opening slightly "downward" with a gas-agitated grating at the bottom. The bag material is assumed to be a composite (canvas and plastic or appropriate substitute of mass 3.75 kg/m^2, e.g., 5-mm-thick composite or 2.5-mm-thick aluminum) with a mass of 25 tons. Gasdynamic transport using blowers (five blowers at 2 tons each with motor), composite pipes (about 1 km, 7 kg/m^2 , and with a 2-m diameter weighing about 22 tons), and a gas-dust separator and bucket loader (about 4 tons and 10 tons, respectively). Such a structure would have a mass of about 71 tons, and if we apply a safety factor, the estimate is 120 tons.

"Big bag" is a slightly pressured gas-tight covering for an entire work area (1 mm of composite), which encloses a volume of 10^6 m^3 and has a mass of about 60 tons. The asteroid is enclosed and suspended in a net (1 km^2 of 0.5cm aluminum at 1-m spacing weighing about 100 tons).

The mass of the processing equipment corresponds with the throughput of material. The 50-kg/sec mass flow, considered the maximum case, is discussed here. (For other mass-flow rates, estimates are provided below.) The equipment includes: miners (three at 50 tons), crushers (two at 75 tons), a magnetic separator (10 tons), blowers (five at 2 tons), volatile extraction baker and mirror (200 tons), and volatile storage and radiators (two at 350 tons). The total mass requirements depend on throughput as given below: 0 kg/sec, 300 tons; 4 kg/sec, 560 tons; 10 kg/sec, 650 tons; and 50 kg/sec, 1500 tons.

Alternatives to the Mass Driver

Of any presently known system, the mass-driver concept allows an asteroid mission to return to Earth orbit with the largest amount of material. But other devices are available that could also return large quantities of material. For any asteroid recovery mission, it may be preferable to process the material where it is obtained and to bring only the most valuable portion back to Earth. The disadvantage of a longer waiting time at the asteroid may be more than compensated for if processing the asteroid in situ allows either a faster manned return or the use of a propulsion system that can be fully automated. We have indicated that establishing machinery to process volatiles and free metals at the asteroid does not impose severe economic penalties.

Two schemes suggest themselves for the return flight: a rocket that uses either water or volatized rock as a working fluid and the solar sail. Solar power could convert water from a carbonaceous asteroid into liquid hydrogen and liquid oxygen by electrolysis. LH_2 and LOX would then be used as fuel and oxidizer in a low-thrust rocket engine that has an extended operating time. Although this is a roundabout way to extract propulsion energy from sunlight, the very high efficiency of the electrolysis makes it feasible. The conversion process would be continuous throughout the return flight, a factor that might enable the return mission to be entirely automated. To avoid the use of large cryogenic storage tanks, the rocket motor would, ideally, also operate continuously on the return flight. This introduces the complication of a long-thrusting rocket motor that uses LH_2 and LOX, but the mass of the rocket motor is negligible compared to either conversion system or payload so that several could be used sequentially.

An in-house General Dynamics study (E. Bock, Convair Division, personal communication, 1977) provided the basic figures for the electrolysis and refrigeration plant. It was assumed that, excluding this plant, the mass of the supporting structures and the rocket motor and its subsidiary systems would not together exceed 300 tons. This latter figure appears reasonable since, if the payload is stored in the shadow of the solar collector, it will be solid condensate and should not require an elaborate bracing system to transfer the modest thrust to it. The exhaust velocity, taking into account various losses, is assumed to be 4400 m/sec and all missions have a 1 -year return time. The exhaust velocity is compatible with low delta-V mission requirements. This type of rocket is well configured for a water-retrieval mission. Changing the mission time directly alters the thrust and collector area requirements, but has only a secondary effect on the mass of the system itself. Processing rates are assumed constant for both outbound and return legs and therefore the thrust, but the rocket operates only during a portion of the outbound leg. Since a conventional rocket may be started or stopped easily, this requirement for noncontinuous thrust on the outbound leg presents no serious complication.

Collector area is based on an assumed 10-percent solar collector efficiency and a 95-percent electrolysis efficiency. Both are reasonable, and the possibility of using germanium solar cells with a sunlight concentrator instead of silicon may make the first figure conservative. Collector areas and power requirements are moderate and thrust requirements may be fulfilled with very small engines. For equivalent delta-V values up to 8 km/sec, the mission returns more mass from the asteroid than it used to reach the asteroid. This is necessary if the returned material is primarily water but is desirable in any case. All scenarios assume a return payload of 10^4 tons of water. For low equivalent delta V values, the mass of water in high Earth orbit may be multiplied many times by this device. The same scenario as presented alone is used here - an outbound delta V of 3 km/sec from high-Earth orbit and a return delta V of 5 km/sec from the asteroid. Power supply and electrolysis plant scales inversely with mission return time. For a 2-year return flight, the solar rocket fully fueled in high-Earth orbit has a mass of 2084 tons. The rocket has a mass of 1054 tons, 463 tons of which are the power supply and electrolysis plant and 291 tons are the crew and their life-support system. The remaining mass is a processing plant for extracting water and other derived mass from the asteroid. For continuous operation, the power requirement is a modest 19 MW. For the return trip in this nonmass-driver scenario, an initial mass of 33,000 tons results in 10,000 tons brought to high Earth orbit, a tenfold increase in the mass of fuel used for the outbound journey.

A second alternative to the mass driver, one that further reduces the mass brought to Earth by a factor of 10 but which could more easily be automated, is the solar sail. This device consists of a very large mirror of thin metal foil or a microlayer of metal or plastic; it relies on solar radiation pressure - caused by momentum transfer at reflection - for propulsion. Although the maximum force available at Earth orbit is only 9.3 N/km^2 , the need for propellant has been eliminated.

The recent development of new sail material with lightness ratios (ratio of solar radiation pressure to solar gravitational force) of 5 or more has returned the solar sail to consideration for low to moderate delta-V low-thrust missions. The lightness ratio is constant regardless of distance from the Sun.

It is assumed that the structural mass excluding the sail is 10 percent of the returned payload. If a 1000-metric-ton (10^6 kg) payload must be returned and if it is assumed that 38 percent of perpendicular thrust can be used, lightness ratios of 5 and 1 both yield satisfactory results. For most missions, the sail area depends very little on sail lightness ratio and therefore the sail area can be varied inversely with mission time.

For the specific scenario used previously, a 2-year return time requires a 22.7-km 2 sail area and a sail mass of 7.2 tons for a sail lightness ratio of 5, and a 23.4-km 2 sail area and a sail mass of 37 tons for a sail lightness ratio of 1. In both cases, 1000 tons of material may be brought to Earth orbit. If these devices are automated, a fleet of these may be launched from a suitable asteroid and later retrieved near Earth. While the mass driver promises to be very useful in returning large quantities of asteroid material to Earth orbit, it is not crucial to such a mission. Either alternative presented here appears feasible and there are surely other possibilities. The solar rocket hybrid is within reach of current technology, while the solar sail is not far beyond it.

PARAMETRIC CONSIDERATIONS OF ASTEROID CAPTURE

The estimated masses of an asteroid mining vehicle sized to capture a 10^6 -ton asteroid are shown in figure 11 as a function of mass-driver exhaust velocity. As exhaust velocity increases, the mass-driver mass increases sharply because of increasing power requirements, while the mass of the mining system including personnel accommodations decreases more slowly because the reaction mass throughput decreases.

It is postulated that the asteroid can be captured by a single-stage mining vehicle starting from LEO, which attaches to the asteroid and returns with it to far Earth orbit. The required start mass in LEO is shown in figure 12 as a function of exhaust velocity for a typical mission requiring ideal velocity gain on the outbound trip of 9.4 km/sec (6.4 km/sec for escape and 3.0 km/sec for transit and rendezvous maneuvers) and 3.0 km/sec on the return trip. Since, in the range of feasible exhaust velocities, LEO start mass always decreases with increasing exhaust velocity, a value of 8.0 km/sec was selected and is used henceforth. For this value, the captured mass is $0.535X\ 10^6$ tons.

The sensitivity of LEO start mass and capture - the start mass ratio - to variations in outbound and return velocity requirements is shown in figure 13. Note that the post-escape outbound velocity requirement doubles, but there is no more than about a 45-percent increase in LEO start mass and a corresponding decrease in capture mass. Also, a 67 percent increase in return velocity requirement produces only a 21-percent reduction of capture to start mass ratio. Therefore, it can be concluded that a comfortable range of potential asteroid orbits can be accommodated without severe losses.

Figure 14(a) is a schematic of the asteroid capture mission; it also includes a parametric cost equation expressing total program costs per kilogram of asteroid captured. Also shown for comparison is a similar expression for the corresponding costs of terrestrial material. In the terrestrial case, it is postulated that the material is procured on Earth, transported to LEO, and then carried to geosynchronous orbit by the same mass driver as used in the asteroid case, which subsequently returns itself to LEO to pick up another cargo. In the terrestrial case, costs are amortized over a cumulative delivered mass equal to the asteroid capture mass, processed to the same degree. (Notation for the equations in fig. 14(a) and numerical values assumed are summarized in fig. 14(b).)

The cost expressions in figure fig. 14(a) are plotted in fig.15 using the values assumed in fig. 14(b) . Several observations were made:

1. For capture of a 10^6 -ton asteroid, estimated total program costs are from \$12-14 billion or about \$24/kg of captured mass. If RDT & E are excluded, the captured mass cost reduces to about \$4/kg. These values assume up-rated Shuttle as the Earth-to-LEO transporter, with transportation costs of \$240/kg.
2. These results are only moderately sensitive to Earth-to-LEO transportation cost and reaction mass cost because of the relatively high RDT & E and hardware procurement costs.

3. Delivery to geosynchronous orbit (GSO) of a total mass of terrestrial materials equal to the asteroid capture mass would involve, on the same basis of comparison, a total program cost of about $663 billion and a delivered cost/kilogram of about $355/kg, including RDT & E costs ($343/kg, excluding RDT & E costs).
4. If the asteroid mass were increased, RDT & E and procurement costs would increase somewhat, but capture mass would increase proportionately with asteroid mass, resulting in significant reductions in cost/kg captured. Thus for a 10^6 -ton asteroid, cost/kg captured might be reduced to about $.50/kg.
5. While support operations costs are not considered here, it seems likely that their magnitudes relative to the costs considered would be similar for both cases, and not dominant.
6. This preliminary parametric assessment confirms suggestions that asteroids may be promising sources of materials for support of space activities on a growing scale in the future, and that this possibility should receive increased attention.

CONCLUSIONS AND RECOMMENDATIONS

The present study has determined that, through the techniques of multiple gravity assists by the Earth, Moon, and Venus, the total one-way delta V from Earth escape (or capture) to rendezvous (depart from) existing asteroids, in favorable cases, is from 2 to 4 km/sec. The mission analysis described here indicates that a single-stage, lowEarth orbit to asteroid mass driver with an exhaust velocity of about 8 km/sec may be the most cost-effective alternative. Minimizing delta V in the outbound leg of the mission was found to be more important than minimizing inbound delta V, in terms of the amount of Earth-launched mass required to perform the retrieval mission. A large delta V for the inbound leg (e.g., 5-8 km/sec) increases the mass of the mining operation to prepare reaction mass, thereby reducing the amount of asteroidal material retrievable, but has no significant bearing on the total mass required to start the mission in low-Earth orbit, which appears to be the major cost driver. But a modest increase in the delta V of the outbound leg to values up to 6 km/sec from escape would not impose severe penalties. Therefore, there are mission opportunities to existing targets that can be immediately investigated. Further refinements of mission-analysis techniques for known objects will permit a more precise determination of known opportunities. In addition, opportunities will arise as the number of known objects increases appreciably over the coming years.

The total asteroid-retrieving mass consists of the mass driver, mining equipment, and reaction mass for the boost. In the range of delta V values likely to be encountered, the total mass required for launch to low-Earth orbit to retrieve about half of a 10^6 -ton asteroid is near 10,000 tons, similar to the lunar case. During the mid-to-late 1980's, a cost of about $2 billion, this magnitude of mass could be launched by an upgraded (class 11) Shuttle with the external tanks used as reaction mass. Development costs (about $10 billion) would dominate and would be absorbed in subsequent, larger-scale asteroidal retrievals. Alternatively, reaction mass could become available in lowEarth orbit in the form of lunar materials obtained in an early, modest program of lunar mining (ref. 4).

Perhaps the most unique aspect of retrieving asteroidal materials is the availability of large quantities of volatiles (water and carbon compounds) and free metals. These materials may not be available in large quantities on the Moon. Since about 30,000 tons of consumables are required for space settlements that support the construction of satellite power stations, most of these consumables preferably could come from the asteroids rather than from Earth. Moreover, free metals separated at the asteroid and alloyed at the space -manufacturing facility (SMF) into useful structures may eliminate many of the complex chemical processing steps required in the lunar case.

Much of the 500,000 tons of asteroidal material that would arrive at the SMF could be water and carbon if a type I or II carbonaceous object at a low to moderate delta V could be discovered. It is possible that the Earth-approaching asteroid Betulia is carbonaceous, and statistical considerations suggest that such a discovery, in an expanded search and followup program, is probable at some time over the next few years (ref. 8). Such an object would obviously be a prime target for a precursor mission.

The retrieval of asteroidal materials for space manufacturing appears to be cost-competitive and contemporary with the retrieval of lunar materials, and considerably less expensive than transporting consumables from the Earth if a type I or II carbonaceous object with reasonably favorable delta-V characteristics could be found. Therefore, the asteroid option for space manufacturing should be kept open. We recommend that the following studies and programs be carried out immediately to better assess the details of this option:

1. Continued studies of retrieval mission opportunities: Late in this study, we recognized that gravity assists in a low-thrust mission significantly reduce the mass requirements and that the delta V in the outbound leg should be minimized; also the economics of asteroid retrieval are not severely affected for moderate delta V values (one way, about 6 km/sec). From an analysis of the asteroid 1977 HB, the inbound delta V was found in one case to be from 2-3 km/sec. Many more cases and a scheme for selecting the best ones - must be studied. Several known candidate asteroids can be studied over the next few years, and new ones as they are discovered.
2. Increased asteroid search and followup program: The Current inventory of 39 Earth-approaching asteroids whose orbits are known can be increased appreciably with a modest investment in dedicated Earth-based telescopes and perhaps orbital telescopes. The followup work of orbital determination and chemical analysis is also important. Such an inventory would identify carbonaceous objects with low-to-moderate delta-V opportunities.
3. Precursor missions Because of the potential importance of obtaining volatiles - and possibly free metals - from asteroids, clearly, a precursor mission to the prime carbonaceous candidate(s) is paramount. Such a mission is also important to assess mineralogical structure for designing the mining and processing apparatus. We recommend a new start in the NASA budget aimed toward single- or multiple-asteroid rendezvous and landing missions that would answer these questions for one or more objects between 1982 and 1985.
4. Continuing studies of the potentials of asteroidal retrieval: These studies would continue to assess the trade-offs between the retrieval of asteroidal, lunar, and Earth materials for space manufacturing in the light of new information as it comes in.
5. Technology support: Design concepts of asteroid-retriever mass drivers and mining and processing equipment must be further developed; technology development milestones must be established in parallel with the lunar option.

Appendix Preliminary Comparison of Estimated Costs for Asteroidal and Lunar Materials

IV-3

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