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Asteroid Retrieval by Rotary Rocket

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ASTEROID RETRIEVAL BY ROTARY ROCKET*

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Abstract

A new technique is proposed for recovering asteroid resources. The target asteroid would be equipped with a "rotary rocket" propulsion system consisting of a rapidly spinning, tapered tube of high strength material driven electrically by solar or nuclear power. Pellets of asteroid material would be released from the tube ends with velocities of a few km/s, achieving specific impulses comparable with the best chemical rockets. The ejected pellets could be launched on trajectories to near-earth space for capture, or they could be expended as reaction mass to bring the remainder of the asteroid to high earth orbit for the construction of solar power satellites or space habitats.

I. Introduction

In the development of large-scale structures for solar power generation, space communication, or space habitats, large quantities of mass are required for structure, shielding, atmosphere, and propellant. Advanced launch vehicles have been proposed to lift large payloads from the earth, but environmental concerns may limit the rate at which earth resources can be orbited. The use of lunar resources has also been suggested, either by the use of a linear motor mass driver[1] or by anchored lunar satellite launch.[2] The use of lunar resources would enjoy the advantages of the shallower gravitational well of the moon; however, the moon lacks appreciable quantities of carbon and hydrogen, both of which are vital to space habitation.

The newest potential source for space resources is the class of asteroids known as carbonaceous chondrites, which are relatively rich in hydrocarbons. Asteroidal resources have been considered in the past, and renewed interest has been elicited by the recent discovery of new members of the class of earth-orbit-approaching bodies belonging to the Apollo and Amor groups. Some of these asteroids are in orbits that require less energy to reach than the lunar surface. Considering the lack of lunar hydrocarbons and the pollution inherent in orbiting earth resources, the Apollo asteroids represent an attractive potential resource. Their value may be gauged from the fact that the Apollo asteroid that hit the earth 1.8 billion years ago near present-day Sudbury, Ontario, provides half the world's nickel and has produced billions of dollars of value in copper, nickel, silver, platinum, and gold.

Various techniques have been suggested for the recovery of asteroid resources. Niehoff[3] examined the round-trip requiren nts to return samples of 1976 AA and 1973 EC using conventional rockets and the space shuttle. To retrieve entire asteroids, Cole and Cox proposed the use of nuclear explosives[4], and O'Leary et al, have analyzed the use of the mass driver.[5] This paper proposes a new technique, the use of the rotary rocket, for asteroid recovery.

II. The Rotary Rocket Concept

The rotary rocket is a derivative of the orbital tower, an extremely elongated synchronous satellite which extends from the surface of a planet to some distance beyond the synchronous altitude balance point. This structure is theoretically capable of extracting energy from the rotation of the planet and transferring it to the linear motion of payloads released from the upper end, providing them with escape velocity.[6] A rapidly rotating asteroid could be fitted with a synchronous orbital tower, but an enormous length would be required to achieve a reasonable tip velocity. An asteroid with a typical period of 4 hours would require a tower 6900 km long to attain a tip speed of 3 km/s. At this slow rotational rate, payloads could be launched only twice each 4 hours.

A better approach may be to use a rapidly spinning tower with its axis attached to the asteroid. The concept is shown in Figure 1 as pairs of relatively short, high-velocity, dual- ended launch tubes attached to an asteroid and contra-rotated to prevent a net angular momentum. The launch tubes are maintained in rapid rotation by an electric motor whose power may be solar or nuclear. Small masses to be expelled are fed into the hollow interior of the launch tubes and are then released from the ends. The exhaust velocity of this rotary rocket is a function of the tip velocity attainable.

For a material with a density and a working stress o, the maximum tip velocity attainable for a uniform rod may be found by equating the load-carrying capacity, σA, to the centrifugal force due to the rotating mass:

$$\sigma A = \int_0^R \frac{v(r)^2}{r} dm \tag{1}$$

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* This research is not part of the author's official duties.

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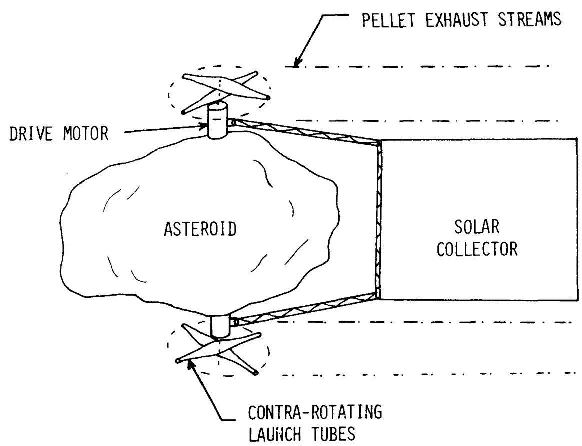

Fig. 1 Rotary rocket concept.

Since dm = ρAdr and v(r) = $v_R r/R$, where v_R is the tip velocity, we have:

$$\sigma A = \rho A v_R^2 \int_0^R \frac{r}{R^2} dr = \frac{\rho A v_R^2}{2} \tag{2}$$

The maximum tip velocity can be called the "critical velocity" of the material:

$$v_C^2 = v_R^2 = 2\sigma/\rho \tag{3}$$

This is a surprisingly simple relationship between the strength-to-density ratio of the material and its maximum tip velocity for a uniform rod, The critical velocity of a material is a useful measure of its performance in a rotating launcher. The parameters of a few materials of interest are shown in Table 1. In general, conventional metals show v_c of about 0.5 km/s. composites show v_c of about 1.25 to 2 km/s, and whisker materials show the potential of achieving v_c = 3 to 4 km/s. Table 1 also shows the strength/density parameter in terms of the characteristic height, $\sigma/\rho g_0$, which was used as a design parameter for orbital towers[6] and lunar anchored satellites.[2]

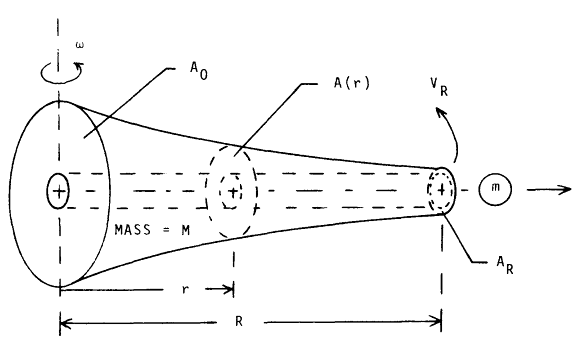

Fig. 2 Launch tube characteristics.

Table 1 Construction material parameters

MATERIAL	DENSITY kg/m^3	WORKING STRESS GPa	CHARACTERISTIC HEIGHT km	CRITICAL VELOCITY km/s
METALS:				
ALUMINUM	2700	0.3	11.3	0.47
STEEL	7900	4.2	54.2	1.03
COMPOSITES:				
GRAPHITE/EPOXY	1550	1.24	81.6	1.26
E-GLASS	2550	3.5	140	1.66
KEVLAR 49	1400	2.7	197	1.96
WHISKERS:				
SIC	3200	20	638	3.54
GRAPHITE	2200	19	881	4.16

These values indicate that the electrically driven rotary rocket has the potential capability of providing a high level of performance. A tip velocity of 4 km/s corresponds roughly to the specific impulse of a liquid-hydrogen/liquid-oxygen chemical rocket.

III. Rotating Launcher Design

A uniform rod is limited in tip velocity to its critical velocity, as we have seen. Higher tip velocities can be achieved for the same material, however, by tapering the rod. The design of the tapered launch tube is optimized by using a cross-sectional area that varies along the length so as to produce a constant stress. The details are shown in Figure 2, where the tube of radius R has a cross-sectional area A(r) at distance r from the axis. The tube has a cylindrical hole in which the propellant masses move outward. The tip area of the tube is sized to be able to hold the mass m against the tip velocity ωR. From Figure 2, the radial force at any point r, with positive toward the axis, is:

$$dF = \sigma dA = -\rho A(r)\omega^2 r dr \tag{4}$$

$$\frac{dA}{A} = -\frac{\rho\omega^2 r}{\sigma} dr \tag{5}$$

Integrating and substituting A_0 = A(r = 0) gives:

$$A(r) = A_0 exp[-\frac{\rho\omega^2}{2\sigma} r^2] \tag{6}$$

Using v_c^2 = $2\sigma/\rho$, v_R^2 = $\omega^2 R^2$ gives:

$$A(r) = A_0 exp[-\frac{v_R^2}{v_c^2}\frac{r^2}{R^2}] \tag{7}$$

The area taper ratio is defined as the ratio of the cross-sectional area of the tube material on the axis to that at the tip:

$$TR = A_0/A_R = exp(v_R^2/v_c^2) \quad (8)$$

This tapered tube can support a force at the end of σA_R. If a small mass m is attached at the end, it experiences a force of $m\omega^2 R$ or mv_R^2. The cross-sectional area of the tube at any point r can be expressed in terms of this mass m as:

$$A(r) = \frac{mv_R^2}{\sigma R} exp[\frac{v^2}{v_c^2}(1 - \frac{r^2}{R^2})] \quad (9)$$

The total mass of the launch tube, from r = o to r = R, is then:

$$M = \int_0^R A(r)dr = \frac{mv_R}{v_c}\sqrt{\pi} exp(\frac{v_R^2}{v_c^2}) erf(\frac{v_R}{v_c}) \quad (10)$$

where erf is the error function. This result was obtained by symbolic integration using the MACSYMA computer program.[7] The error function is related to the area under the normal curve with mean μ and standard deviation s by the equation:

$$\frac{1}{s\sqrt{2\pi}} \int_{-\infty}^{X} exp[\frac{-(t-\mu)^2}{2s^2}]dt \quad (11)$$

$$= \frac{1}{2}[1 + erf(\frac{x-\mu}{s\sqrt{2}})] \quad (12)$$

This is to be expected, because A(r) is an e^{-r^2} function, a normal probability curve in the square of the ratio of tip velocity to the critical velocity. The total mass is therefore a function of the area under this gaussian probability curve from x = 0 to x = R.

The results of equations 8 and 10 are shown in Figure 3, where the area taper ratio A_0/A_R and the mass ratio M/m are shown in terms of the ratio of the tip velocity to the critical velocity. Both the mass ratio and the area ratio are strong exponential functions of the velocity ratio. This means that for a reasonable mass of the launcher the exhaust velocity of the rotary rocket is limited to a few times the critical velocity of the launch tube material.

The exhaust velocities, c, and specific impulses, I_{sp}, achievable by the rotary rocket are shown in Figure 4 as functions of the taper ratio. In general, metal launch tubes can achieve I_{sp} in the range of 100-200 sec, composites can provide 200-500 sec, and whisker materials, when available, promise I_{sp} of 400-1000 seconds. These surprising results show that the rotary rocket has the theoretical capability of exceeding the performance of present liquid-fuel rockets by using any inert material as a fuel. The rotary rocket has no inherent limit on its thrust duration, can be stopped and restarted an arbitrary number of times, and can be throttled down to zero exhaust velocity.

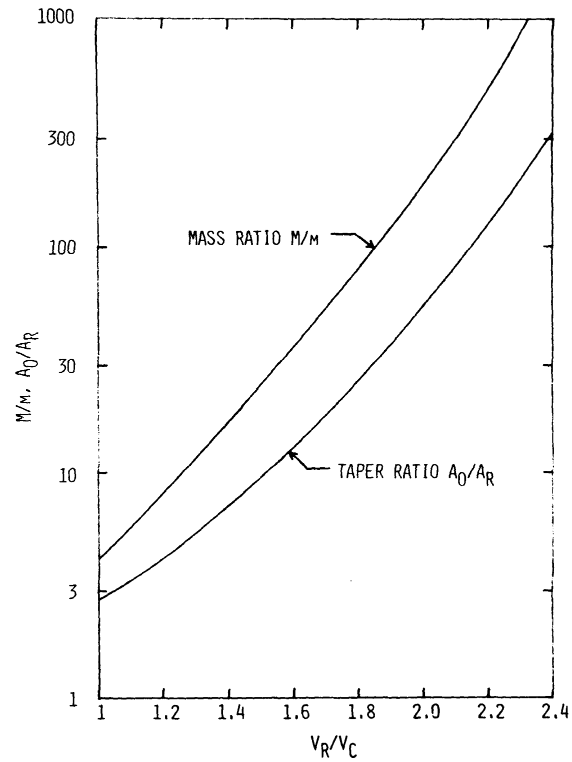

Fig. 3 Mass ratios and taper ratios for single-ended launch tubes.

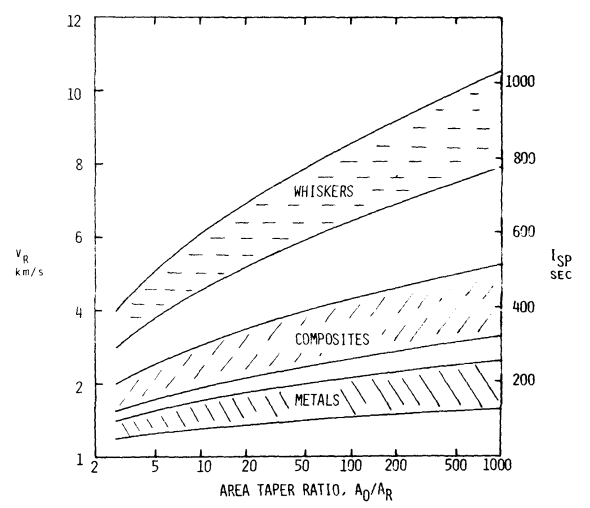

Fig. 4 Tip velocities and specific impulses available using various materials.

One difficulty in the rotary rocket design is to release the stream of pellets into a collimated jet. This requires that a pellet be released once each revolution, just as the launch tube reaches the desired pointing direction. This may be done by allowing one pellet at a time past a release cam controlled by the tube rotational angle, as shown in Figure 5. The cam is at the tip of the tube, allowing the bore to be filled with pellets, assumed to be roughly spherical. The cam can be rotated electrically at the same angular velocity as the launch tube, allowing one pellet to escape at the same angular position each revolution. A variation of up to $\pm\ 8^o$, however, will maintain 99% thrust.

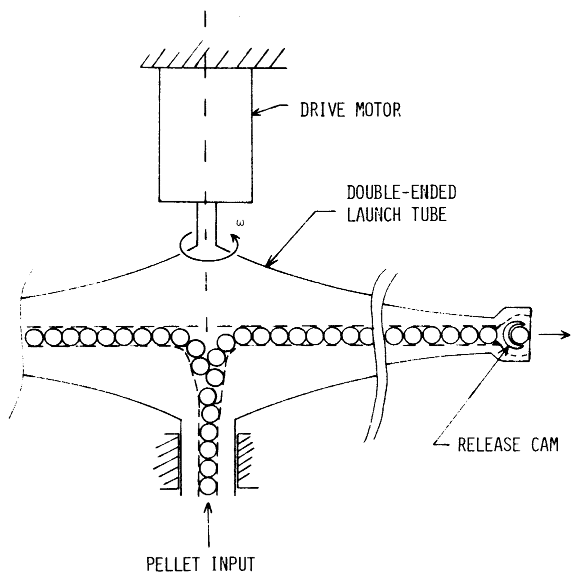

Fig. 5 Pellet feed and release mechanism.

IV. Asteroid Retrieval Missions

Now we are ready to examine the application of the rotary rocket to an asteroid recovery. The easiest mission is to retrieve a small member of the Apollo or Armor families of earth-orbit-crossing asteroids. These objects include many carbonaceous types rich in hydrocarbons, ranging in size from a few kilometers across to, presumably, a few meters across.[8] Their orbits are not energetically very distant from that of the earth. A minimum A of about 3 km/s for return to earth is a reasonable value from a low inclination orbit and a return via Venus and moon gravity assists.[9]

Using this velocity change as a design input, we need to create a rotary rocket and power system to bring back a small asteroid in a reasonable amount of time. If we assume a manned expedition, an upper limit of five years for the round trip may be a reasonable choice.

The exhaust velocity of the rotary rocket can be chosen to maximize the returned mass. The fraction of the asteroid mass that can be retrieved is given by the rocket equation:

$$\frac{m_i}{m_f} = e^{\Delta/c} \tag{13}$$

where m_i and m_f are the initial and final masses. The energy required is given by:

$$E = 1/2(m_i - m_f)c^2 \tag{14}$$

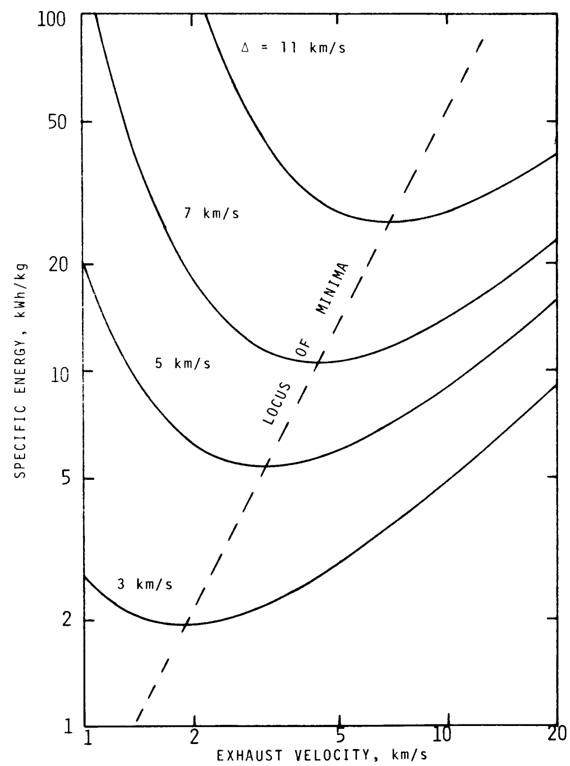

Fig. 6 Specific energy vs exhaust velocity.

The energy invested per unit retrieved mass is then:

$$\frac{E}{m_f} = \frac{m_i - m_f}{2m_f}c^2 \tag{15}$$

After some substitution, this reduces to:

$$\frac{E}{m_f} = \frac{\Delta^2(e^{\Delta/c} - 1)}{2(\Delta/c)^2} \tag{16}$$

To minimize the energy invested per unit mass, we define a non-dimensional energy efficiency, ϵ:

$$\epsilon = \frac{E}{1/2m_f\Delta^2} = \frac{e^{\Delta/c-1}}{(\Delta/c)^2} \tag{17}$$

The minimum value of ϵ can be found easily as a function of Δ/c. The result is seen in Figure 6, which shows the specific energy, in kWh/kg, needed to retrieve a mass through various velocity changes. Each curve is seen to have a minimum at Δ/c = 1.594. The minima are not sharp, however, and other factors such as the available power may require a higher value of Δ/c.

Choosing the minimum specific energy for a Δ of 3 km/s gives an optimum exhaust velocity, c, of 1.88 km/s. With this exhaust velocity, a metal tube with taper ratio of about 100 or a composite tube with a taper ratio of about 10 will give strength to spare, as seen from Figure 4.

If the asteroid is retrieved in time T, the power required is:

$$P = \frac{E}{T} = \frac{m_f \Delta^2}{2T} \cdot \frac{e^{\Delta/c} - 1}{(\Delta/c)^2} \tag{18}$$

Using Δ = 3 km/s and Δ/c = 1.6, the required power is shown as a function of the asteroid mass for various retrieval times in Figure 7. The required collector area is shown on the right scale, assuming that the electrical power is generated by solar cells with an overall output of 100 W/m^2. The initial asteroid mass, 4.95 times the final mass, is shown on the top scale.

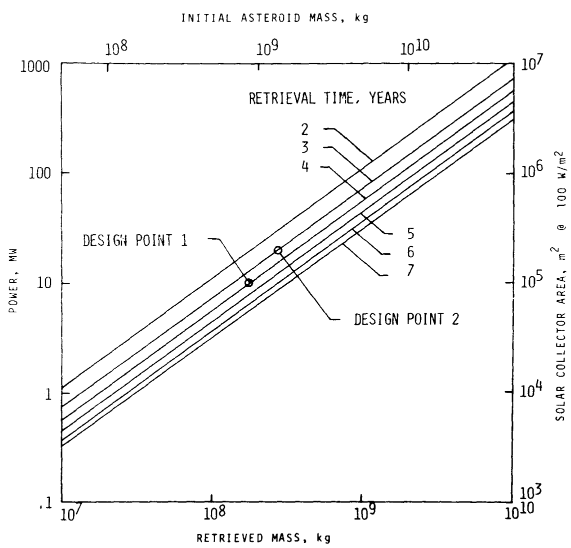

Fig. 7 Electric power and solar collector area required vs asteroid mass.

Choosing a first design point of 10 MW as shown, 1.78 x 10^8 kg could be retrieved in four years. Given the typical composition of carbonaceous chondrites, there would be 110 million kg of water, 16 million kg of carbon compounds, and 16 million kg of free metals retrieved; 36 million kg of silicates would be left after the rest was used as propellant.

The power of 10 MW and an exhaust velocity of 1.88 km/s requires a mass flow of $\dot{m}$ = 2P/c^2, or 5.66 kg/s. Choosing a composite material with v_c = 1.63 km/s and ρ = 1500 kg/m^3 for the launch tubes, we find that a taper ratio of 30 is required for an exhaust velocity of 3000 m/s. This velocity would be used for the outbound trip to minimize fuel usage and still consume the entire 10 MW of power.

A set of four dual-ended launch tubes rotating at 3600 RPM would be 8 m in radius. Each dual-ended launch tube must have a mass of 195 kg in order to support the mass of the pellet cam and the 400 pellets (0.012 kg each) that fill the hollow interior of the launch tube.

The cross-sectional areas required are A_0 = .044 m^2, and A_R = .00146 m^2. With a feed tube 1.96 cm in diameter, the launcher is 4.74 cm in diameter at the tip and 23.7 cm in diameter the base. The characteristics of the rotary rocket system are shown in Table 2. The specific mass of the solar array is from Glaser,[10] and of the mining system is from O'Leary et al.[11]

Table 2 Asteroid retrieval mission desiqns

		MISSION 1	MISSION 2
ELECTRICAL POWER	P	10 MW	50 MW
VELOCITY CHANGE	A	3 km/s	5 km/s
MISSION TIME	T	5 yrs (1 yr out)	4 yrs (1 yr out)
ASTEROID MASS	m_i	8.91 x 10^8 kg	1.30 x 10^9 kg
MASS RETRIEVED	m_f	1.78 x 10^8 kg	2.45 x 10^8 kg
MASS FRACTION	m_f/m_i	.203	.189
EXHAUST VELOCITY	c	1.88 km/s (3 km/s out)	3 km/s
MASS FLOW RATE	$\dot{m}$	5.66 kg/s (2.22 kg/s out)	11.11 kg/s
PELLET MASS	m	.0118 kg	.0232 kg
LAUNCHER RADIUS	R	7.96 m	7.96 m
LAUNCHER ROTATION		2255 RPM (3600 RPM out)	3600 RPM
TOTAL LAUNCHER MASS	8M	980 kg	2860 kg
SPECIFIC MASSES:			
SOLAR ARRAY[10]		2.5 kg/kW	2.5 kg/kW
ELECTRICAL MOTORS		2.2 kg/kW	2.2 kg/kW
LAUNCH TUBES		0.3 kg/KW	0.2 kg/kW
TOTALS		5.0 kg/kW	4.9 kg/kW
TOTAL MASSES:			
PROPULSION SYSTEM		5 x 10^4 kg	2.45 x 10^5 kg
CREW SYSTEM[11]		3 x 10^5 kg	2.95 x 10^5 kg
MINING SYSTEM[11]		8 x 10^5 kg	7 x 10^5 kg
TOTAL INITIAL MASS		1.15 x 10^6 kg	1.24 x 10^6 kg

The initial mass in space near the earth is 1.15 x 10^6 kg, dominated by the mining system. To carry this mass through a Δ of 3 km/s to rendezvous with a well-situated asteroid will require 1.98 x 10^6 kg of propellant, to be supplied from lunar soil. The total initial mass is then 3.13 x 10^6 kg, or 1.8% of the mass to be retrieved. A large part of the structure could be obtained from the lunar resources, lifted by anchored satellite or mass driver.

It is obvious from Table 2 that the mass of the 10 MW system is dominated by the mining and crew systems. To observe the effect of increased power and shorter mission times, a second design point of 50 MW and a 3-year return trip was examined and is also shown in Table 2. The total system mass is only 8% higher than design 1, but it returns 38% more final mass. The mining system would consist of an excavator, a solar furnace, a pelletizer, and holding tanks for water, oxygen, hydrocarbons, and silicates. The latter would be discarded or pelletized for fuel, or they could be retrieved for use in solar power satellite construction.

The results of Table 2, when compared with those of O'Leary et al,[11] show that the rotary rocket has a smaller specific mass than the linear mass driver and seems to be better suited for missions with exhaust velocities less than 3-4 km/s. Higher exhaust velocities would require much greater specific masses for the rotary rocket;

here the linear mass driver has the advantage.

Each particular asteroid retrieval mission would have its own required A, implying a distinct value of c for energy optimization. In general, the trip out to the asteroid would be made at the highest possible exhaust velocity, in order to minimize the propellant required. In this mode the rotary rocket is exhaust-velocity limited. On the return trip, the exhaust velocity would be reduced, if necessary, to Δ/c = 1.6; in this mode, the system is power limited. The power available then determines the amount of time required to retrieve a given asteroid mass.

The relative difficulty of retrieving asteroid resources is small compared with the difficulty of launching earth resources into high earth orbit. The Apollo asteroids require a Δ of 3 to 9 km/s, depending strongly on their orbital inclinations. Launching earth resources into high orbit requires about 11.5 km/s, and the main- belt asteroids require more than 13 km/s. Only the lunar resources, which lack hydrocarbons, can be obtained for a lower velocity increment.

V. Alternate Techniques

Rather than expending 80% of the asteroid mass to bring back the remaining 20%, it may be more advantageous to launch larger masses with the proper velocity to return directly to the earth-moon system. In this case we might launch only 20% of the mass of the asteroid, but it would all be retrieved for use. This technique would have the advantage of producing the first payload in a matter of a year instead of 4 to 5 years.

The incoming stream of material would be aimed to pass near the unstable Lagrangian point L2, behind the moon, where it would be retrieved by a "mass catcher."[12] By stationing the mass catcher some distance beyond L2 on a lunar anchored satellite, the relative velocity of the incoming payloads would be minimized. The catcher would need to stop payloads moving at only 200-250 in/s from asteroid 1947 XC, for example, which has a perihelion distance of 0.83 AU.[9] The launch errors involved in this technique might require a very large catcher or limit its use to larger masses that could be economically fitted with small guidance rockets. A slowly rotating launcher capable of launching greater masses would be used, minimizing the precision required during release. For asteroid 1947 XC, a launch velocity of 1.44 km/s and a midcourse correction of only 1 m/s might be required. This mode of operation would also eliminate the countless chunks of debris that may be a problem with the mass driver.[13] The details of this technique have not been analyzed.

There is an alternate method for pellet release that operates near the axis of rotation. In this case the pellets are allowed to accelerate radially outward along the tube and are released from the open end. This technique has been proposed for stationkeeping of a mass catcher stationed at L2.[14] The total radial velocity achieved is found to be just equal to the tip velocity of the tube. The effective exhaust velocity is then $\sqrt{2}v_R$, or 1.414 times that of the design with the cam at the tube end. However, this "gun barrel" design results in wear on the inner surface of the tube because of the high velocities involved. The stress in the tube material is also increased by the Coriolis force on the moving masses, requiring higher mass ratios. In this design, a replaceable tube liner would be required. In the previous design, a replaceable end cam may be required.

VI. Conclusions

The rotary rocket is a potential candidate for asteroid recovery that could produce effective exhaust velocities as high as the best chemical rockets, with an efficiency comparable with the linear mass driver. The rotary rocket has the potential advantages of continuously variable exhaust velocity, variable exhaust pellet size, and long-term operation. Analysis shows that, although both the rotary rocket and the mass driver asteroid retrieval missions are dominated by the mass of the mining and crew systems, the rotary rocket is less massive than the mass driver for moderate exhaust velocities. Because of the high potential and the simplicity of the rotary rocket, further study seems warranted.

Acknowledgment

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