the STS-8 and STS-5 atomic oxygen effects flight experiments[7] where the VUV dose was low as a result of maintaining the materials samples in ram orientation during exposure on orbit. The FEP Teflon reaction efficiency estimated from the Solar Max satellite repair mission samples[8] is comparable to the Los Alamos result. The Solar Max satellite exposed silver-backed Teflon components to relatively high doses of VUV radiation and heat in addition to atomic oxygen. No measurements can be made at Los Alamos without VUV in the atom beam at this time.

VUV radiation also produced an enhanced atomic oxygen reactivity in Kel-F. Results are summarized in Tables 1 and 2. In the afterglow, no difference between the control and VUV specimen could be detected at the lower VUV flux (0.5 VUV suns) with both samples showing a mass loss rate not significantly different from zero. At the higher VUV flux (4 VUV suns) the mass loss rate was about one-third the rate of the Kapton reference specimen. At Los Alamos, Kel-F showed a reaction efficiency nearly equal to that of Kapton (and much higher than that of FEP Teflon) in the argon-oxygen beam, however, a reaction efficiency lower than that of either Kapton or FEP Teflon was obtained in the neon-oxygen beam. The neon-oxygen beam contained 3 eV oxygen atoms and 1 VUV sun of VUV radiation whereas the argon-oxygen beam contained 1.5 eV oxygen atoms and 5 VUV suns of VUV radiation. The reactivity of Kel-F with atomic oxygen increases more rapidly with VUV dose rate than that of FEP Teflon. It is significant that FEP Teflon became cloudy on exposure to VUV radiation and atomic oxygen in the afterglow whereas Kel-F did not.

The silverbacked Teflon material also displayed an increased reactivity with oxygen atoms when exposed simultaneously to VUV radiation in the flowing afterglow apparatus. Results are summarized in Table 1. With 0.5 VUV suns, the silver-backed Teflon showed a mass loss rate about the same as that of the Kapton reference sample. The silver-backed Teflon mass loss rate was about the same as that of the Kapton reference sample with 4 VUV suns. The silver Teflon also became cloudy.

VUV radiation also had an effect on the reactivity of Kapton in the flowing afterglow system. Four VUV suns increased the mass loss rate of Kapton by about 30%. The mass loss rate of the VUV sample returned to normal when the lamp was turned off. With higher atom energies, however, the reactivity of Kapton is independent of VUV dose. Nearly the same reaction efficiencies are obtained at Los Alamos in both the argon and neon-oxygen beams and in LEO during the STS-8 and STS-5 flight expriments.[7,8]

Conclusons

Low levels of VUV radiation can significantly alter the reactivity of some materials with atomic oxygen over a wide range of conditions. FEP Teflon, Kel-F, and silver-backed Teflon all show little or no reactivity with atomic oxygen in the absence of VUV radiation. With simultaneous exposure to VUV fluxes comparable to those experienced in LEO, the reactivity of FEP Teflon, silver-backed Teflon, and Kel-F increase to become comparable to that of Kapton. VUV radiation has also been shown to increase the reactivity of Kapton with thermal-energy oxygen atoms. Though the experiments reported here do not perfectly reproduce the LEO environment, it has been demonstrated that VUV radiation can significantly enhance the atomic oxygen reactivity of flurocarbon and chloroflurocarbon polymers under a wide range of conditions. The synergistic effects of atomic oxygen and VUV radiation should be given serious consideration during materials selection and design of spacecraft intended to operate in the LEO environment.

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Tumble Orbit Transfer of Spent Satellites

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Nomenclature

l	= arm length
m_1	= service vehicle mass
m_2	= target satellite mass
R	= orbital radius
V	= orbital speed
ΔV	= velocity increment of combined system
ΔV_1	= velocity increment given to service vehicle
γ_i	$= m_i/(m_1+m_2)$ = mass fraction of mass m_i to total mass
ϕ	= rotational velocity
μ	= product of the gravity constant and Earth's mass

Subscripts

1	= service vehicle
2	= target satellite
a	= apogee
p	= perigee
C	= original circular orbit

I. Introduction

ORBIT transfer of Earth-orbiting objects via a service vehicle will constitute an important part of space infrastructures in the very near future. Some missions will require

Received May 30, 1989; revision received Oct. 11, 1989.

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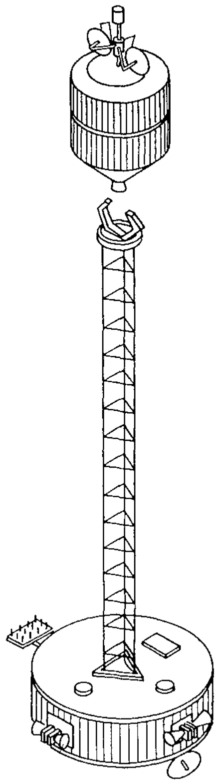

Fig. 1 Spent satellite capture by service vehicle.

less orbital precision but more operational economy. A typical mission among these will be spent-satellite deorbiting from geosynchronous to a higher orbit and from a low-Earth orbit into Earth's atmosphere. For these missions, the service vehicle returns from the new orbit to the original, for continued service or refuel. System economy is greatly dependent on the fuel consumption for the round trip of the vehicle[1] and the ease of capturing noncooperative versatile objects. Tumble orbit transfer is a method particularly suited to these missions. The target satellite is simply connected to the service vehicle by an arm, preferably extendable (Fig. 1). The vehicle then activates its thrusters, which simultaneously causes velocity change and tumbling of the combined system. This method effectively utilizes a periodic momentum exchange between the two masses of a tumbling dumbbell system. This method provides an efficient means of applying the propellant energy consumed by the service vehicle to alter the captured satellite orbit. In an ideal case, none of the energy is wasted on the service vehicle. It is like having a zero-mass engine on the captured satellite. Besides the energy efficiency, the capturing mechanism can be made very simple. This method does not require a rotational stiffness in the mechanism to maintain relative attitude fixed during engine maneuvers. Therefore, versatile objects in orbit can be captured and transferred using a simple grapple mechanism.

II. Orbit Transfer Maneuvers

The service vehicle, whose mass is m_1, is connected to the dumb target satellite, whose mass is m_2, by a rod length l. Initially, this dumbbell system is assumed to be in a circular orbit of radius R_c, where the orbital velocity is V_c. The dumbbell system is first oriented along the local vertical. Mass 1 activates its thrusters in a direction parallel to the orbital velocity vector, which is perpendicular to the axis connecting both masses. Let the resultant velocity increment of mass 1 only be termed ΔV_1. The ΔV_1 causes the orbital velocity increment of ΔV and rotation of ϕ around the center of mass. The ΔV and ϕ are

$$\Delta V = \gamma_1 \Delta V_1, \qquad \phi = \Delta V_1 / l \tag{1}$$

where γ_1 is a mass fraction of the vehicle equal to $m_1/(m_1+m_2)$. The system is now injected into a new orbit, whose apogee radius is R_a and perigee is $R_p = R_c$. The R_a and R_p are related through the well-known energy equations:

$$-\mu/(R_a+R_p) = V_p^2/2 - \mu/R_p = V_a^2/2 - \mu/R_a \tag{2}$$

where μ is the product of the gravity constant and the mass of the Earth; V_p and V_a are velocities at perigee and apogee, respectively. When $V_p = V_c + \Delta V$, and assuming $|\Delta V| << |V_c|$

$$R_a = \mathrm{R_c}(1 + 4\Delta V/V_c), \qquad V_a = V_c - 3\Delta V \tag{3}$$

Instantaneous velocities for each mass are different from each other, depending on the system orbital velocity, the rotational velocity, and phase. So, if the masses are separated, each mass will have a corresponding orbit. For simplicity and usefulness, separation occurs when the dumbbell axis is Earth oriented, either at the apogee or at the perigee of the new orbit and where the orbital velocity is perpendicular to the vertical. As shown in the latter sections, the apogee manevuer puts the dumb satellite into a circular orbit, and the perigee puts it into an elliptical orbit. Larger ΔV will put it even in a hyperbolic orbit in a similar manner, but Eq. (3) is no more valid. The tumble orbit transfer procedures are illustrated in Fig. 2.

A. Circular Orbit Injection

At a proper rotational phase, around the apogee as shown in Fig. 2, the horizontal velocities are

$$V_1 = V_c - 3\Delta V - \gamma_2 l\phi - V_c - (3\gamma_1 + \gamma_2)\Delta V_1 \tag{4}$$

for mass 1 and

$$V_2 = V_c - 3\Delta V + \gamma_1 l\phi = V_c = 2\gamma_1 \Delta V_1 \tag{5}$$

for mass 2, where $\gamma_2 = m_2/(m_1+m_2)$. The velocity of mass 2 is exactly equal to the circular velocity at the radius R_a. The velocity of mass 1 is less than system apogee velocity. Therefore, if both masses are separated, mass 1 will have a path that crosses the original orbit, and the second mass will be injected into a circular orbit of radius R_a.

B. Elliptical Orbit Injection

At the perigee, where the orbital is $V_c + \Delta V$, the instantaneous velocities for each mass are

$$V_1 = V_c + \Delta V - \gamma_2 l\phi = V_c + (\gamma_1 - \gamma_2)\Delta v_1 \tag{6}$$

$$V_2 = V_c + \Delta V + \gamma_1 l\phi = V_c + 2\gamma_1 \Delta v_1 \tag{7}$$

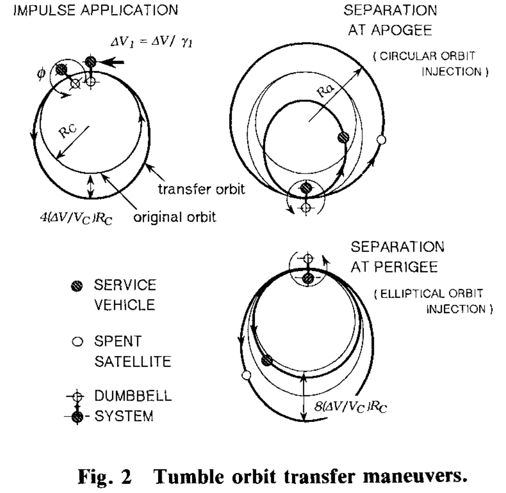

Fig. 2 Tumble orbit transfer maneuvers.

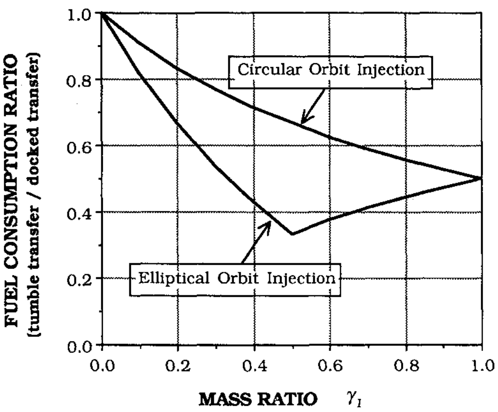

Fig. 3 Fuel consumption reduction ratio of tumble orbit transfer compared to docked orbit transfer.

where the rotational phase has advanced by 180 deg from the instant of the impulse application. Note that the velocity increment for mass 2 is twice as large as that of the system. If the masses are separated at this instance, the apogee increment is twice as high. Mass 1, or the service vehicle, will stay in an orbit slightly different from the original circular orbit. If both masses are identical, $\gamma_1 = \gamma_2 = 0.5$, then mass 1 remains in the original orbit.

III. Fuel Consumption

It was shown in the previous section that the fuel consumption in putting the dumb satellite into a new orbit is exactly half of what is required in a normal orbit transfer. Assuming further that the service vehicle returns to the original circular orbit after separation, total fuel consumption in terms of the velocity increment of the service vehicle is obtained. In the case of circular orbit injection, mass 1 must be accelerated again to the Hohmann orbit, whose perigee path is tangential to the original circular orbit. Therefore, mass 1 requires two impulses in the return journey. Velocity increments are $\gamma_2 \Delta V_1$ and $\gamma_1 \Delta V_1$, respectively. Including the first maneuver, the total velocity increment of the service vehicle is $2\Delta V_1$.

Elliptical orbit injection requires a simpler maneuver. The required impulse is $|\gamma_1 - \gamma_2| \Delta V_1$ at the perigee to adjust to the circular velocity. The total velocity increments are

$$[1 + (\gamma_1 - \gamma_2)]\Delta V_1 = 2\gamma_1 \Delta V_1 \qquad (\gamma_1 > \gamma_2) \tag{8}$$

$$[1 + (\gamma_1 - \gamma_2)]\Delta V_1 = 2\gamma_1 \Delta V_1 \qquad (\gamma_1 < \gamma_2) \tag{9}$$

To show the advantages of tumble orbit transfer, velocity increments required for an ordinary docked mode are also calculated. The docked system requires two impulses of ΔV_1 each to reach the circular orbit of radius R_a. The return journey will also require two impulses, each requiring $\gamma_1 \Delta V_1$. The total velocity increment is $2(1 + \gamma_1)\Delta V_1$. To inject the dumb object into an elliptical orbit, identical to 2.2, the service vehicle in docked system mode imparts a velocity equivalent to $2\Delta V_1$. Immediately after the acceleration, the vehicle separates and decelerates by $2\gamma_1 \Delta V_1$ to recover its original speed. The total is $2(1 + \gamma_1)\Delta V_1$.

The fuel requirement ratios in tumble orbit transfer compared with those of the ordinary docked transfer are shown in Fig. 3.

IV. Discussions and Conclusions

The feasibility and usefulness of tumble orbit transfer are shown under simplified assumptions. Fuel requirements can be substantially reduced compared with conventional orbit transfers in docked configuration. In the circular orbit injection, this method is particularly attractive when the payload mass is small compared with the service vehicle mass. In an extreme case, tumble transfer saves half of the fuel otherwise required. In the case of elliptical orbit injection, this method is most useful where the payload mass is similar to the service vehicle mass, saving two-thirds of the fuel.

The length l of the rod that connects the vehicle and the payload is arbitrary in theory. A very short rod or even a direct connection might look feasible. However, the rotational velocity ϕ increases inversely proportionally to l. So, in actual application, the maximum ϕ will be determined by considerations of allowable centrifugal load and timing capability at thrustering and separation. As an example, for the velocity increment $\Delta V_1 = 10$ m/s, the rod length $l = 10$ m produces a load equivalent to 1 g and a rotation period of 6 s. The rod can be replaced by a long flexible tether, since only the force acting between the two masses is an axial force, and bending rigidity is not required in the connecting structure. When the rod or the tether length becomes too long, the system no longer tumbles around the center of mass. Instead, it oscillates around the local vertical by the gravity gradient moment. Under this condition, the momentum is similarly transferred from the service vehicle to the payload.

Removal of spent satellites and debris will be vital for safety and continuation of future space activities. Tumble orbit transfer will be able to provide an effective means for this purpose. The principle also will be applicable to wider classes of orbit transfer once its capability in terms of insertion precision is demonstrated by those spent satellite removal missions.

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Conversion of Omnidirectional Proton Fluxes into a Pitch Angle Distribution

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Introduction

WITH the anticipated long-duration radiation exposures of astronauts in an oriented space station, accurate prediction of expected doses requires consideration of both the mass distribution of the spacecraft and the direction of the incident high-energy proton flux. The two components of the directionality of the high-energy proton radiation are the highly peaked local pitch-angle distribution and the east-west effect. Since the omnidirectional flux at some point along a field line is an integral over the pitch angle distribution, in principle, an inversion of this integral should yield the desired

Received Aug. 25, 1989; revision received Nov. 9, 1989.

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