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EXCERPTS FROM SOLAR SAIL CONCEPTS AND APPLICATIONS

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ABSTRACT

This paper excerpts material applicable to Mars missions from an earlier study covering a broader range of applications of solar sails. The basic principles of solar sail operation are provided, and the implications on trajectories and missions ate discussed briefly. Concepts of solar sails and interplantary vehicles are described and discussed. Some of the important solar sail material considerations are presented and some selections criteria are provided.

INTRODUCTION

Most of the mission analysis work on solar sails has been done since 1975, yet it has never been collected for publication. This memorandum is a revision and update of a 1976 draft report.

Most of the work presented herein was done at the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the National Aeronautics and Space Administration.

In order to minimize the size of this section, all information not directly related to solar sail technology and Mars missions has been excised. The mission analysis is clearly out of date and not applicable to mission opportunities at which a manned Mars mission might be flown. However, the data will suffice to give insight as to the general capabilities of a solar sail vehicle to support Mars missions. The purpose for including this information is to provide some data on possible alternative approaches to a manned mission.

The solar sail is a means of using solar radiation directly as a method of propulsion. The sail is a large, flat, lightweight, highly reflective first-surface mirror. Mission applications for the solar sail range from probes to the Sun to trips to all of the planets and escape from the solar system. The solar sail concepts currently considered the most promising are based upon supporting the sail by means of spars and, alternatively, by centrifugal force. Astronaut assistance in the testing, development, and operation of solar sails may become very desirable.

PRINCIPLES

Reflection

Photons carry momentum, therefore when they are reflected they experience a change in momentum and a force is exerted against the reflecting surface. This resulting force is proportional to the incident solar radiation power. It is inversely proportional to the square of the solar distance and is proportional to the cosine squared of the angle between the sail and the direction of the Sun. This force is also proportional to the reflectivity of the mirror surface and, therefore, performance of the solar sail is also proportional to the surface reflectivity. This case of the ideal sail is illustrated in Figure 1.

Solar Wind

The solar wind is composed of electrons, protons, and heavier charged particles. The solar wind particles which impact a sail will exert a very light force which is several orders of magnitude less than the pressure from solar radiation. The solar wind may have a degradation effect upon the reflectivity of the solar sail because of erosion of the reflecting surface by the particles.

Performance

For a given reflectivity, the inherent performance of a solar sail is a function of the total unit loading on the sail, that is , the total mass of the sail plus supporting structure and mass of the spacecraft divided by the total sail area. Most solar sail missions can be flown with a wide range of total unit loads on the sail. A heavier payload necessarily means a heavier unit load on a particular sail and a longer trip time. Missions to Mercury, for example, may have sail loadings as much as $50 g/m^2$ or greater while the requirement for a rendezvous with Halley's comet may be as low as $6.1 g/m^2$. The mission to Halley's comet has the most demanding requirement in terms of the sail unit load of any of the missions so far identified for the 1980's. If a sail were constructed of currently available materials, the resulting total unit load might range from about 7 to 10 g/m^2. Thus the mission to Halley's comet may require some improvement in the current technology of materials processing; whereas for other missions which are less demanding, currently available materials may be quite satisfactory.

Trajectories

The sunlight acting upon the sail results in a component of force continuously acting in the radially outward direction from the Sun, unless the sail were turned edge-on to the Sun. The sail may be tilted so as to have a force component perpendicular to the solar radius line. This component may be directed along the velocity vector to increase the energy and angular momentum of the vehicle, moving the vehicle outward, or it may be directed against the velocity vector, reducing energy and angular momentum and allowing it to spiral in toward the Sun. This lateral force component may also be directed out of the plane of the vehicle's velocity vector, thereby changing the inclination of its orbit. In spite of the continuous existence of the radially outward force component, the solar sail is very versatile and can probably be directed to any destination in the solar system envisioned as a target in this century.

MISSIONS

Inner Planets and Solar

An interesting comcept for a solar sail vehicle is that of the role of an inner planet shuttle. This vehicle is envisioned as being a reuseable solar sail which would have the role of delivering spacecraft to various inner planets or solar orbit. The sail may carry multiple payloads on a single mission, and after completing all of its deliveries would return to an Earth parking orbit for its next mission. While the sail is in this orbit, it may undergo any necessary repairs or refurbishment prior to its next mission. If a solar sail is developed for use with the Halley's comet mission, it may be feasible to design the sail module in such a manner that it can readily be adapted to a reuseable configuration.

The sail would enable the return of a sample from Mercury, and if used at Mars, could probably provide for the return of a sample significantly greater than what could be achieved by purely ballistic means. A Mars lander of 5 to 6 tons might be delivered by a sail of the design used for a Halley rendezvous.

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FIGURE 1. SOLAR PRESSURE ON SAIL

PRESSURE = $0.90 \times 10^{-5} \times \frac{\cos^2 \theta}{R^2}$ N/m^2

TOTAL SAIL LOADING

σ_T = TOTAL MASS/SAIL AREA, g/m^2

CHARACTERISTIC ACCELERATION

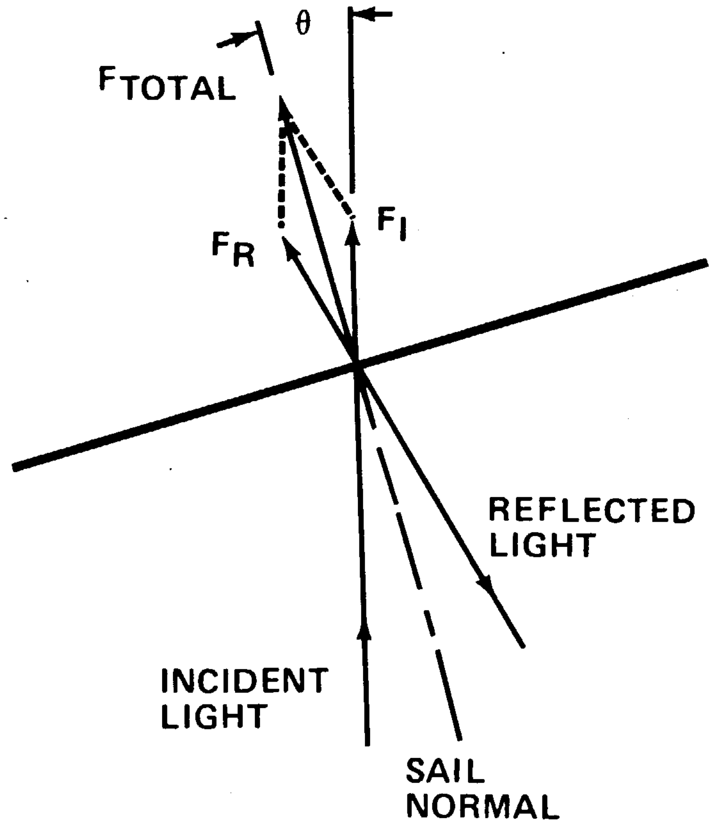
$a_c = 9 \times \eta/\sigma_T$, mm/sec^2

(η = SAIL EFFICIENCY $\approx$ 85%)

TYPICAL VALUES

$0.2 \leqslant a_c \leqslant 1.3$

$40 \geqslant \sigma_T \geqslant 6$



CONCEPTS

Many concepts for solar sail configurations have been considered since the sail first appeared in the literature. These concepts have included a parachute type, the heliogyro, and others. All of these concepts are still being considered; however, the following concepts are those which appear to be the most promising at the present time.

Square Sail

The square sail and the heliogyro were studied extensively for the Halley Rendezvous mission (Friedman, 1978). Although they are very different design concepts, they were found to have essentially the same performance capability for that mission. Both designs were found to be workable, but the heliogyro was selected for that mission.

The square sail is supported by spars extending to the corners of the sail. For a large sail it is necessary to stabilize the spars with tension lines to avoid massive spars. This would mean using a mast and numerous mast-spar and spar-spar lines. Although the design may be intricate, it has a low structure-mass-to-sail-area ratio. Automated deployment is possible but entails high risk. This is responsible for the decision against the square sail for the Halley's comet mission.

The spacecraft is 3-axis stabilized, with attitude control provided by solar pressure venes (small solar sails themselves), or by a center-of-mass shift mechanism, or both. Once the sail is deployed, the structure can remain essentially dynamically inert. The spacecraft is easy to control and can be balanced in the desired attitude. Attitude changes typically require less than one hour, and up to a few hours for large changes.

Sail area can be up to about 10^6 m^2 with automatic deployment, and several times that if erected in space.

Heliogyro

The heliogyro has a shape and dynamic function like a helicopter rotor. It can have 3 or more blades; the Halley's comet design had 12, in 2 banks of 6. The blades form the reflective surface with the sail material supported by edge tendons.

The blades are stored on rollers for launch. After the spacecraft receives an initial spin-up, the blades are partly unrolled. The blades are given a collective pitch to add more angular momentum as deployment continues - a process requiring about 2 weeks. The deployment process is relatively simple and reliable compared to the square sail.

The thrust vector can be changed and directed to some extent by collective and cyclic pitch changes, as with a helicopter. Cyclic pitch changes can be made in less than one hour, but a major reorientation of the spacecraft can require more than one day. Cruise operation of the spacecraft is more complex than with the square sail.

Sail area can be up to about 10^6 m^2. The Halley's comet design had blades about 8 m wide by more than 6 km in length.

MATERIALS

Sail Sheets

There are four principle materials which appear suitable for use as a solar sail sheet. These are known by trade names Kapton, Paralene, B-100, and Mylar. These materials differ principly in the maximum temperatures at which they may be used. Kapton appears to be serviceable at temperatures up to 700^o F or above, while paralene is useable up to slightly lower temperatures, B-100 is also good at high temperatures. Mylar is serviceable only up to 300 to 350^o F. Considerable testing must be done to determine the capabilities of these materials to withstand the intense ultraviolet radiation to which they would be subjected in space. In addition, tests must be run to determine the rate at which rips would propagate in the material once the material was punctured. Tests must also be conducted on suitable methods of fastening seams, whether by chemical bonding or heat welding. Paralene and Mylar are commercially available in thicknesses very near the minimum requirement for solar sail sheets. Kapton is presently available in material about three times the thickness needed for solar sails.

Reflective Coatings

There are presently two known coatings which appear to best meet the needs of solar sail applications; these are silver and aluminum. Silver has a higher overall reflectivity than aluminum but it has an abrupt transparent window in the ultraviolet region. this would allow ultraviolet radiation to penetrate the silver coating with the danger of degradation occurring in the material below the silver. An additional concern with silver is its tendency to oxidize into a dark coating in the prescence of atmospheric oxygen. While aluminum has only a slightly lower reflectivity than silver, it has a full spectrum response to solar radiation and appears to be the best overall choice. Other possible materials would include gold and other metals or possibly a combination of aluminum and silver.

ENVIRONMENTAL EFFECTS

Pressure Load

A solar sail would approach close to the Sun in its trajectory. The total pressure load upon the sail would increase by the inverse square of the distance from the Sun. The increase in pressure would cause a greater deflection in the sail and in any supporting spars, which would lower the overall efficiency of the sail. This results from the fact that the local angle of incidence with respect to the Sun would increase at some points on the sail. Since the pressure force is a function of the cosine^2 of the local angle, this would cause a lower total force upon the sail; thus, the sail will have a somewhat lower efficiency as it gets nearer the Sun. However, this is more than offset by the increase in pressure which results from the decrease in solar distance.

Temperature

The front surface of the sail is highly reflective, turning away approximately 90% of the incident solar radiation. The backside of the sail will have a reasonably high emissivity value, which will result in the backside of the sail acting as a huge radiator surface. As a result, the sail will achieve equilibrium temperatures which are rather moderate considering some of the approach distances to the Sun. At a distance of 0.3 a.u., sail equilibrium temperatures may range from 250 to 400° F while at 0.2 a.u. the equilibrium temperatures may range from 500 to 700° F. These resulting temperatures are within acceptable ranges for at least some of the potential sail materials. However, this will remain true only as long as the sail front surface maintains a high value for its reflectivity.

Aging

The aging effects on the solar sail are a definite matter of concern, but the magnitudes of the effects are not yet known. There are at present known processes which could contribute to aging effects of the sail material. The first of these is erosion, which is caused by dust and solar wind particles. Since this is basically an impact phenomenon, the effect will probably be localized around the area of the impact. The effect will principally be physical damage resulting from a puncture or cratering of the coating or sail material. Breaks in the reflective coating could lead to localized degradation of the substrate material behind the coating. Another factor is outgassing from the plastic, causing local eruptions, with results similar to particle impacts. Another aging factor is that of ultraviolet radiation passing through the reflective coating. The prime effect of the radiation is to change the molecular structure of the sail material substrate, which can lead to embrittlement of the material. The degree to which this embrittlement occurs and the resulting problems have not yet been quantified. It appears likely that the effect of the radiation can be controlled to some degree by the proper selection of the reflective coating and the thickness to which it is applied.

Photoelectric Effect

A significant photoelectric effect is expected to occur with the solar sail. The front surface of the sail is exposed to the incident photons from the solar radiation. These photons will strike the surface of the sail. As this positive charge builds up, it will influence the components of the solar wind striking the sail. That is, protons in the solar wind will tend to be deflected and electrons attracted, with the result that charge would probably build up on to some equilibrium value. It will be possible to control the degree of this charge by the use of electron or proton emitters.

Tear Resistance

The sail materials which have been identified to date are all relatively tough materials with good stress properties. However, when these materials are subjected to high tension and then punctured in such a manner as to leave a sharp cut in the material, tears will readily propagate through the material. For this reason, it is thought that rip-stoppers will be necessary on the sail sheet. Seams in the sail sheet may serve as rip-stoppers in one direction and the addition of special rip-stoppers would thus be required in only the remaining direction. The network of rip-stoppers is not expected to add greatly to the overall weight of the sail but the effect will nonetheless probably be significant. Sail configurations which have lower stress values in the sail sheet may have a much reduced requirement for the presence of rip-stoppers.

INTERPLANETARY SHUTTLE

Concept

The Interplanetary Shuttle is a recoverable solar sail vehicle capable of returning samples from planets and small bodies. The vehicle itself may be reusable for subsequent missions. It would use either a Shuttle/Capture launch or a spiral escape from Earth and a spiral capture upon return. The sail vehicle may interface with Earth-based vehicles at an orbital space dock facility. This facility may be located at an altitude of about 1000 km or at a higher altitude above Earth's radiation belts. The vehicle would be based upon designs developed for the first solar sail mission applications, in particular, the Halley's comet rendezvous and the Mars Surface Sample Return.

The vehicle is envisioned as being one which is relatively autonomous. The economics of returning a vehicle require low mission operations costs. The vehicle would determine its own trajectory in a simplified manner, computing and maintaining the proper sail angle to reach its destination. The computer program constants would be updated and special commands sent periodically. In this manner, the vehicle would be making simplified computations allowing it to follow trajectories close to the optimum. Earth-based mission control will assume command near the vehicle's destination, removing residual errors (although a fully automated terminal sequence may be possible by the time the solar sail vehicles are operational). The vehicles would be self-monitoring and report any detected problems or anomalies.

Capabilities

The capabilities of the Interplanetary Shuttle summarized in Table 1 are based upon the use of the square sail configuration.

Performance and Cost

The different solar sail concepts under consideration are expected to have some what differing values of sail loading (total mass/sail area). These differences are most prominent when lightweight payloads are being carried; when heavier payloads are carried the percentage differences in sail loading becomes much smaller. These differences can always be expressed as differences in flight times to the destination for the given payload. This allows differences in sail loading to be expressed as cost differences for specific missions because of the difference in total mission operations cost due to differences in flight times. The differences in total mission costs are a function of the sail vehicle costs, costs resulting from differences in the mission operation cost rates, and differences resulting from the times of flight.

Operating Range

The region of space in which a sail vehicle operates can have a strong influence on its design. This will generally show up in terms of the sail loading and the thermal characteristics of the sail. It is expected that the design of the first sail vehicle will be such as to allow subsequent vehicles of the same design to operate anywhere in the solar system beyond a minimum solar distance of about 0.3 a.u.. If a specific vehicle is built to operate only in a restricted region, such as that between Earth and Mars, then that vehicle may follow the general design of a Halley's Comet Rendezvous vehicle, but some aspects of the design may be altered to take advantage of the more benign environment in which it would operate. Based upon present knowledge, it seems reasonable to impose the requirement upon the sail vehicle design that it be capable of operating anywhere in the solar system outside of 0.3 a.u..

Commonality

Once a solar sail vehicle becomes operational, subsequent mission applications may follow fairly quickly. Time and founding constraints will probably not allow the development of new solar sail designs for each mission application. Careful attention should then be given to making the first sail design be capable of carrying a wide range of payloads to destinations located as described in the preceding paragraph.

TABLE 1

INTERPLANETARY SHUTTLE SIZE AND PERFORMANCE FOR MARS

Square Sail Size (meters)	Outbound Trip Time (days)	Payload (metric tons)
700	400	1.8
	500	3.9
	700	6.0
1000	350	1.6
	400	3.7
	500	8.0
	700	12.0
2000	350	6.4
	400	15.0
	450	25.0
	500	32.0
1000[#]	350	3.4
	400	5.5
	500	9.8
	700	14.0
2000[#]	350	14.0
	400	22.0
	450	32.0
	500	39.0

Notes: Based upon total mass excluding payload

- Sail efficiency 85%
- Baseline 1982 sail (sail loading = 4.8 g/m^2)
- Advanced sail (sail loading = 3.0 g/m^2)
- Based upon total mass excluding payload

\# Advanced sail

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