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AN OPEN CYCLE LIFE SUPPORT SYSTEM FOR MANNED INTERPLANETARY SPACEFLIGHT

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Technical Paper prepared for presentation at Stepping Stones to Mars Meeting of the American Institute of Aeronautics and Astronautics and the American Astronautical Society
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ABSTRACT

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This paper proposes a solution to the problem of supporting human life during manned interplanetary space missions, in which the life support system is integrated with the propulsion system. It is proposed that the propellant of the propulsion system be stored in the form of food, and utilized by the thrustor in the form of metabolic wastes from the crew. It is shown that this life support system is compatible with anticipated manned interplanetary missions and payloads, if suitable electric propulsion systems are used.

Author

INTRODUCTION

One can acquire a feeling for the dimensions of the life-support problem by examining table I, which compares estimates of the basic human metabolic waste production given by Ingram, et al.,[1] Ingram,[2] Mason and Burriss,[3] and Popma.[4] The basic metabolic waste production lies in the range of from 3.5 to 6.0 kilograms per man-day. A reasonable estimate for preliminary mission analysis is 4 kilograms per man-day. Table II contains an estimate by Ingram, et al.[1] of the water requirement for purposes other than metabolism. Recent findings from the 62-day confinement of a four man crew in a space simulator indicate that at least 4.5 kilograms per man-day of water is desirable for sanitary and hygienic purposes[5,6]. Throughout the rest of this paper, a generous estimate of

15 kilograms per man-day will be assumed for the total metabolic and sanitation waste output. On a 500-day round trip to Mars, for example, as much as 7500 kilograms of food, water, and oxygen must be provided per crew member, 2000 kilograms of which is for metabolic needs alone. Clearly, the jettisoning of this much mass incurs a severe mass penalty, and should be avoided if at all possible.

A life-support system that has received recent attention is a partially closed ecological cycle, in which the water and/or oxygen are recycled in closed loops, but the solid residues are jettisoned as they are produced.[3,4,7,8] A schematic diagram of this system is shown in Figure 1. Typically, the water used for metabolic and sanitation purposes is purified and reused, while oxygen is extracted from the metabolic CO_2. As one may see from table I, the solid residues are a small fraction of the total daily requirement, and can be jettisoned without a severe mass penalty. The problems associated with this life support system have been overcome,[5] at least for periods up to 62 days. Although this system is available for use if required, it would be desirable to have as large as possible an amount of water available for daily use, and to eliminate the relatively elaborate and heavy processing equipment which this life support system requires.

A PROPOSED LIFE-SUPPORT SYSTEM

What characteristics should an ideal life-support system have? Obviously the situation aboard the spacecraft should duplicate terrestrial conditions as closely as possible. The life-support system should provide the spacecraft crew with enough fresh air, fresh water, and good food to satisfy their physiological and psychological needs, and at the same time dispose of wastes in a way that is not repulsive to an average individual. Such a system can be most easily realized by an open cycle rather than a closed cycle.

The ideal life-support system can be closely approximated by an open cycle in which the metabolic and/or sanitation wastes are used as the propellant of the thrustor. This concept was first published in qualitative form by Meyerand.[9] A schematic diagram of such an open cycle system is shown in Figure 2. In the simplest form of this concept, the propellant, in the form of food, water, and oxygen, passes through the crew where it is converted into CO_2, H_2O, and solid wastes. The CO_2 and water could then be used as propellant by the thrustor, which might be an electron-bombardment ion engine, an oscillating-electron ion engine, an MHD accelerator, an arc jet, or some other suitable device. The solid residues, which amount to 0.14 to 0.27 kilograms per man-day, are small enough to be jettisoned. If the mission restricted the flow rate of propellant, some or all of the water used for sanitary purposes might be recycled. Since the metabolic and sanitary waste production is constant in time, and since the mass flow rate of an optimum interplanetary mission is not constant, it may be necessary to have some means of waste storage in order to supply the thrustor with the mass flow required by the mission.

MISSION ANALYSIS OF THE OPEN CYCLE LIFE-SUPPORT SYSTEM

To demonstrate the feasibility of the concept described above, one must show that the average propellant mass flow rate required by manned interplanetary missions is at least as large as the daily human metabolic waste production. In reference 10 it is shown that the ratio of propellant mass M_p to payload mass M_x for an orbit-to-orbit space vehicle moving in a central gravitational field, with constant thrustor efficiency η and a constant specific mass of α kilograms per kilowatt is given by

$$\frac{M_p}{M_x} = \frac{\gamma^2(\kappa + 1)^2}{\kappa - \gamma^2(\kappa + 1)} \qquad (1)$$

where γ is the mission difficulty parameter defined by

$$\gamma = \sqrt{\frac{\alpha \int_0^{T_b} a^2 \, dt}{2\eta}} \qquad (2)$$

The integrand is the square of the local acceleration of the vehicle and is integrated over the mission time, T_b. Values of this integral are given by Moeckel[11] and Melbourne[10] for many interplanetary missions of interest. The quantity κ is defined by

$$\kappa = \frac{M_v}{M_x} \qquad (3)$$

that is, the ratio of the vehicle mass to the payload mass. If this ratio is optimized in such a way as to minimize the total mass placed into orbit, one finds from Melbourne[10] that

$$\kappa^{opt} = \frac{\gamma}{1 - \gamma} \qquad (4)$$

If equation (4) is substituted into equation (1), then

$$\frac{M_x}{M_p} = \frac{(1 - \gamma)^2}{\gamma} \qquad (5)$$

If there are n crew members, M_x/n kilograms of payload per crew member, and a mission duration of T_b days, then the resulting average flow rate of propellant per crew member k is

$$k = \frac{M_p}{nT_b} = \frac{1}{T_b}\left(\frac{M_x}{n}\right)\left(\frac{M_p}{M_x}\right) \text{ kilograms per man-day} \qquad (6)$$

The average propellant flow rate k should at least be equal to the metabolic daily requirement in order that the propellant be usable for life-support purposes.

APPLICATION TO A MARS MISSION

For the sake of a specific example, consider the applicability of this concept to the heliocentric phase of a round-trip Mars mission, in which the mission time T_b includes 50 days for descent into Martian orbit, waiting, and reascent to the heliocentric phase. The heliocentric phase has been chosen for analysis partly as a matter of convenience, because the acceleration integrals are readily available, and partly because the heliocentric phase of the trip involves the lowest propellant mass flows. If this life-support system can be shown to work for the heliocentric phase of interplanetary manned missions, then it will certainly work in the planetocentric phase in which the mass flows are larger. It is assumed throughout that the thrustor efficiency is constant at $\eta = 0.90$, and the mission is examined for two values of the specific mass, $\alpha = 5$ and 10 kilograms per kilowatt. These values were substituted into equation (2) along with the values of the mission integral given in Moeckel.[11] A graph of the mission difficulty parameter γ against the mission time T_b in days is shown in Figure 3 for the two specific masses under consideration. The ratio of M_p/M_x in equation (5) is plotted as a function of γ in Figure 4. For most interplanetary missions of interest, $0.2 < \gamma < 0.6$. Below $\gamma \approx 0.2$, the mission times are too long; above $\gamma \approx 0.6$, the ratio of the total vehicle mass to the payload mass is too large to allow low thrust systems to compete with chemical or nuclear systems.

Equation (6) is plotted in Figure 5 for specific masses of 5 and 10 kilograms per kilowatt and payloads of 5 and 10 metric tons per crew member. One can estimate the payload mass per crewmember by considering that each crewmember, his spacesuit, and his personal effects will weigh about 300 kilograms, and that the supplies necessary to support him during the 50 days at the target planet assumed in the mission will weigh about 750 kilograms at 15 kilograms per man-day. If it takes about 5 kilograms of vehicle and fuel to take 1 kilogram from orbit to the Martian surface and back, the minimum payload per crewmember for the interplanetary phase is at least 5 metric tons per crewmember. The payload per crewmember for other planetary missions will be even larger, since the deeper gravitational wells of other planets will require more propellant mass for the round trip to and from their surface.

Figure 5(a) shows that for $\alpha = 5$ kilograms per kilowatt, the average propellant flow rate will be above the total daily life-support requirement for round-trip missions of less than 600 days. For missions with $\alpha = 10$ kilograms per kilowatt, Figure 5(b) shows that the required propellant flow rate is greater than the total daily life-support requirement for round-trip missions of less than 750 days. All serious studies of manned expeditions to Mars have shown that it is very unlikely that the values of mission duration and payloads per crewmember will be such as to decrease the average flow rate below the total daily metabolic requirement.

The above analysis is conservative in that it not only provides a generous estimate of the mass required for life support, but also ignores the propellant required in the planetocentric portions of the mission. This propellant mass will, in general, be far greater than the life-support requirements, and any excess waste mass produced during the heliocentric portion of the trip could simply be stored until the planetocentric portions of the mission.

DEVELOPMENT OF SUITABLE THRUSTORS

From the point of view of mission analysis and of human factors, it seems that the open ecological cycle described previously has many advantages, and no important disadvantages. The only major obstacle to this system of life support is the development of a thrustor that will operate on such metabolic wastes as CO_2 and H_2O. The prospects of making an efficient ion thrustor operating on human wastes may be evaluated by considering an expression for thrustor efficiency as a function of specific impulse

$$\eta = \frac{\eta_u I_s^2}{A + I_s^2} \qquad (7)$$

The efficiency η is the ratio of the energy of a particle moving at the average velocity of the exhaust beam to the total energy expended by the powerplant per particle; η_u is the utilization efficiency of the thrustor, and A is proportional to the fixed losses due to dissociation and ionization of the propellant. Equation (7) gives a moderately good fit to efficiency data reported by Kaufman[12] for an electron bombardment ion engine using mercury as propellant. Equation (7) should be approximately true for all thrustors that depend upon ionization of the propellant.

Unless polyatomic propellants such as H_2O and CO_2 have a value of A far in excess of monatomic propellants, A will be negligible compared to the square of the specific impulses characteristic of interplanetary missions. There is some evidence that the value of A for electron bombardment ion engines is large for polyatomic propellants, and for propellants of low atomic weight.[13] Such thrustors may not be suitable for use in the open cycle concept, at least in their present form.

Ion thrustors have received much engineering attention and have been developed to the point where their efficiency is nearly 90 percent for a specific impulse characteristic of interplanetary missions.[14,15] Not enough experimental data are available at present to write down an expression equivalent to equation (7) for plasma thrustors and arc jets. In spite of a much less intensive developmental program, low pressure arc jets have recently operated on polyatomic propellants at an efficiency of 47 percent and at high specific impulses that are suitable for interplanetary missions.[16] High pressure, low specific impulse arc jets have operated on polyatomic propellants at efficiencies up to 55 percent.[17]

It might prove impossible to develop plasma thrustors or low pressure arc jets which are more efficient than existing ion engines. If the less efficient thrustors are capable of operating on metabolic wastes, their lower efficiency is tolerable, provided that the additional powerplant mass required is not greater than the life support mass saved. For a typical 500-day Mars mission, the vehicle would develop about 8000 kilowatts of electrical power. Use of the open cycle concept instead of one of the closed cycle systems would result in a saving of about four metric tons of reserves and processing equipment, which could be used to generate about 500 kilowatts of power if this mass were applied to the powerplant. An efficiency reduction of 6 percent below that of ion engines would therefore be tolerable in a thrustor using metabolic wastes. If metabolic wastes of 4 kilograms/man-day were jettisoned by an eight-man crew for 500 days, a total of 16 metric tons would be jettisoned, which could be applied to the powerplant. Under these conditions, a decrease in thrustor efficiency of 25 percent below that of ion engines would be tolerable.

The brief mission analyses above are intended to be illustrative only. Exact comparisons between the two life support systems for a real mission would require a much more extensive study of the many factors involved. At present, it is sufficient to point out the advantages of the open cycle system, subject to the assumption that a propulsion system will become available which can efficiently accelerate H_2O and CO_2.

Existing arc jets and plasma thrustors are probably not efficient enough to permit the open cycle concept to demonstrate a mass saving over the closed ecological cycle, used in conjunction with existing ion engines. However, arc jets and plasma thrustors have been subject to a much less intensive developmental program than the more efficient ion thrustors. A systematic attempt to develop efficient thrustors that use metabolic wastes may make possible an open-cycle solution to the life support problem.

CONCLUSIONS

The life-support system described in this report can provide a spacecraft with food, water, and oxygen of a quantity and quality no different than that to which one is accustomed in daily affairs. The crew could enjoy wines, steaks, frozen vegetables, pastries, and desserts rather than the less desirable diets associated with the closed cycle concept. Not only could the crew be fed in a normal manner, but they could have an adequate supply of water for sanitary and hygienic purposes. The open cycle life-support system described above, instead of contributing to the problem of manned space flight, should be a positive aid to maintaining crew morale.

The life-support system described herein can reduce or eliminate the mass required by other life-support systems, since the propellant must be taken along whether or not there is a crew aboard. If electric propulsion is used, this system is feasible for all forseeable interplanetary missions, provided only that suitable thrustors can be developed which will efficiently use human metabolic wastes, primarily CO_2 and H_2O, as propellants. This engineering problem would replace the physiological and psychological problems associated with closed cycle systems.

The proposed open cycle concept also has the advantages of increased mission flexibility and enhanced crew safety, since any reserve of propellant could be used for navigational corrections, for extra radiation shielding, for extra food, or for all of these.

In the planning of future space missions, if other factors leave no clear choice between propulsion systems, the considerations given above tend to favor electrical propulsion systems, on grounds where chemical and nuclear propulsion systems cannot readily compete.

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TABLE I. - DAILY HUMAN METABOLIC WASTE PRODUCTION

	Reference					
	1 and 2				3	4
	Liquid wastes, kg/man-day		Solid wastes, kg/man-day		Average metabolic wastes, kg/man-day	
	Minimum	Maximum	Minimum	Maximum		
CO_2	1.0	1.0	-----	-----	1.03	1.03
Perspiration and respiration	.80	3.48	-----	-----	1.0 to 3.5	1.00
Urine	1.2	1.5	0.060	0.075	1.52	1.39
Feces	.053	.08	.017	.020	.182	.114
Total	3.13 to 6.155				3.732 to 6.232	3.534

TABLE II. - DAILY WATER REQUIREMENT FOR SANITATION PURPOSES (REF. 1)

	Liquid wastes, kg/man-day		Solid wastes, kg/man-day	
	Minimum	Maximum	Minimum	Maximum
Food preparation	1.0	4.0	0.010	0.040
Personal hygiene	1.5	4.5	.015	.045
Clothes washing	3.0	4.0	.030	.040
Cabin cleansing	1.0	5.0	.010	.050
Subtotal	6.5	17.5	.065	.175
Total	6.565 to 17.675			

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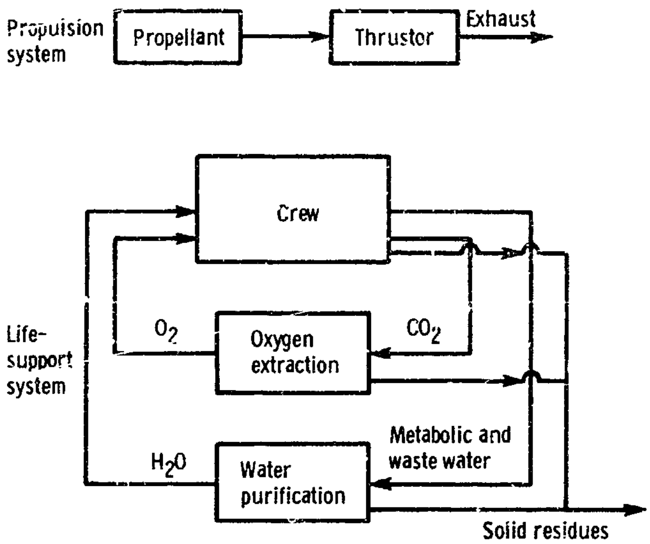


Figure 1. - Schematic diagram of closed ecological cycle, showing complete separation of propulsion system and life-support systems.

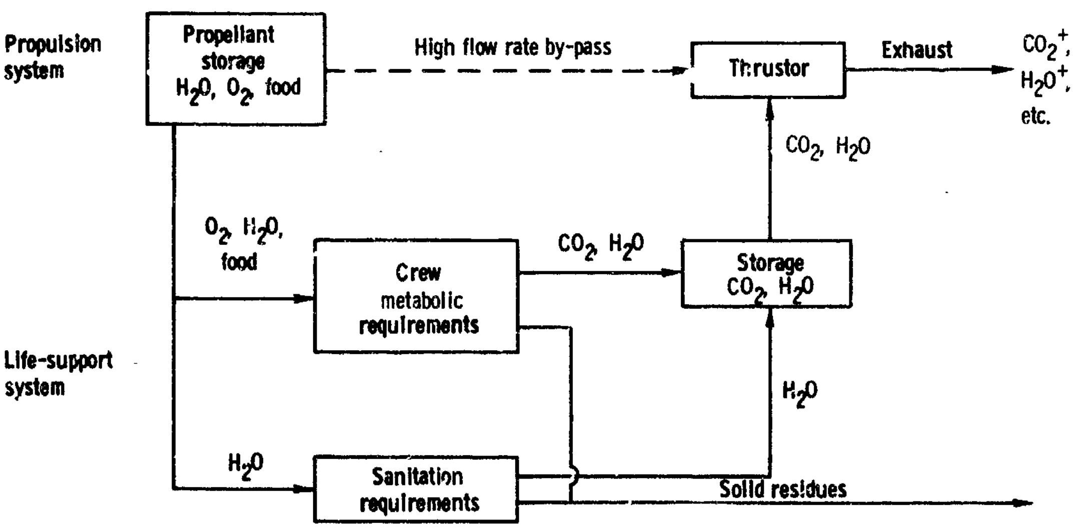


Figure 2. - Schematic diagram of open cycle system, in which propellant is used for metabolic and sanitation requirements of crew before flowing to thrustor. If mass flow is greater than life-support requirements, propellant can flow directly to thrustor.

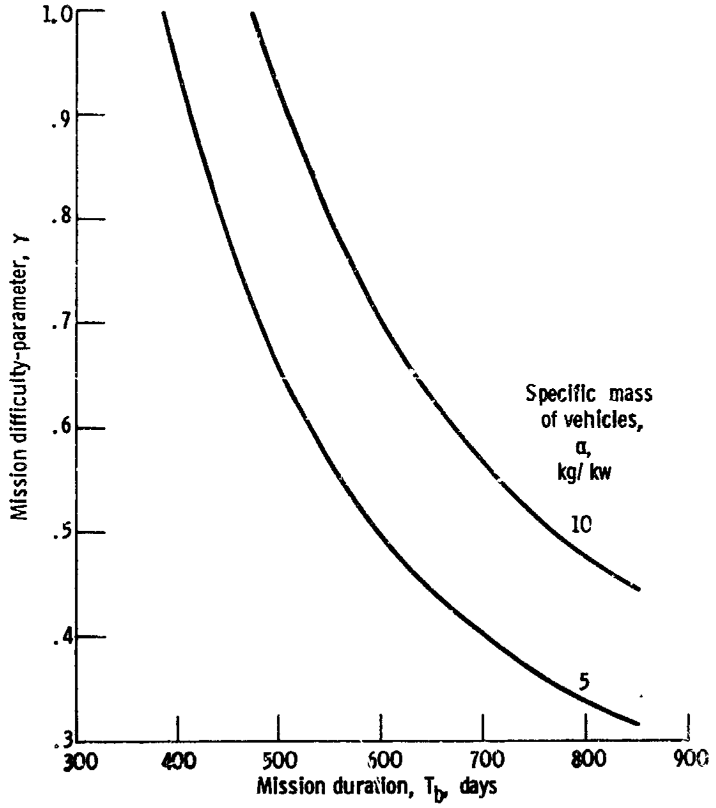


Figure 3. - Graph of mission difficulty parameter γ as a function of mission duration. Heliocentric portion of round trip to Mars; specific mass of vehicle, 5 and 10 kilograms per kilowatt; efficiency, 0.90; values of acceleration integral $\int_0^{T_b} a^2\,dt$ taken from reference 11.

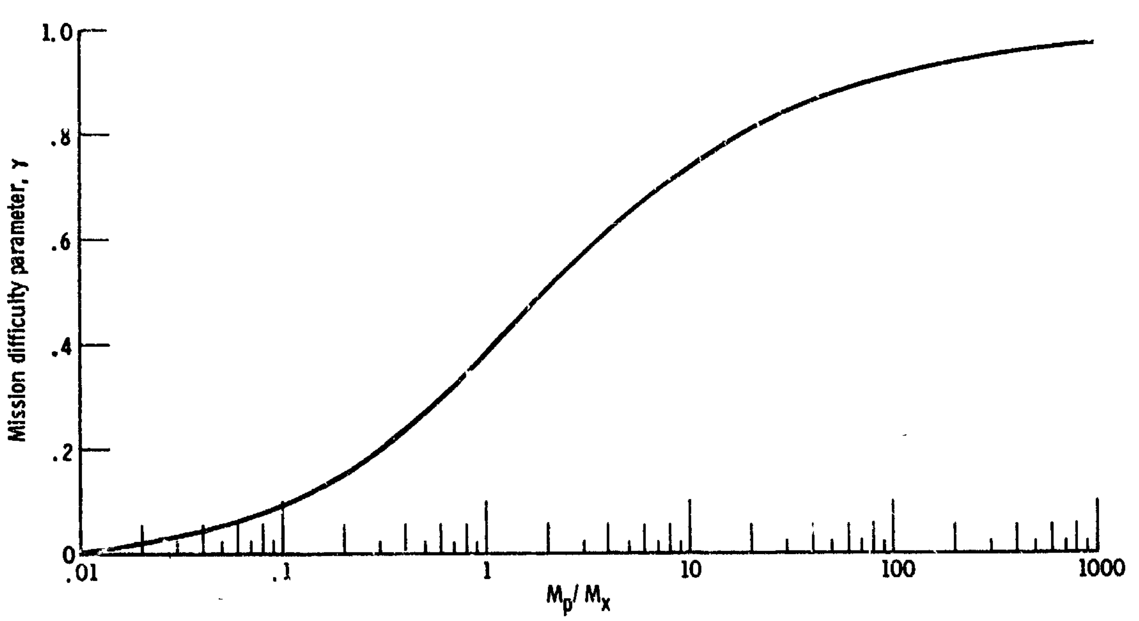
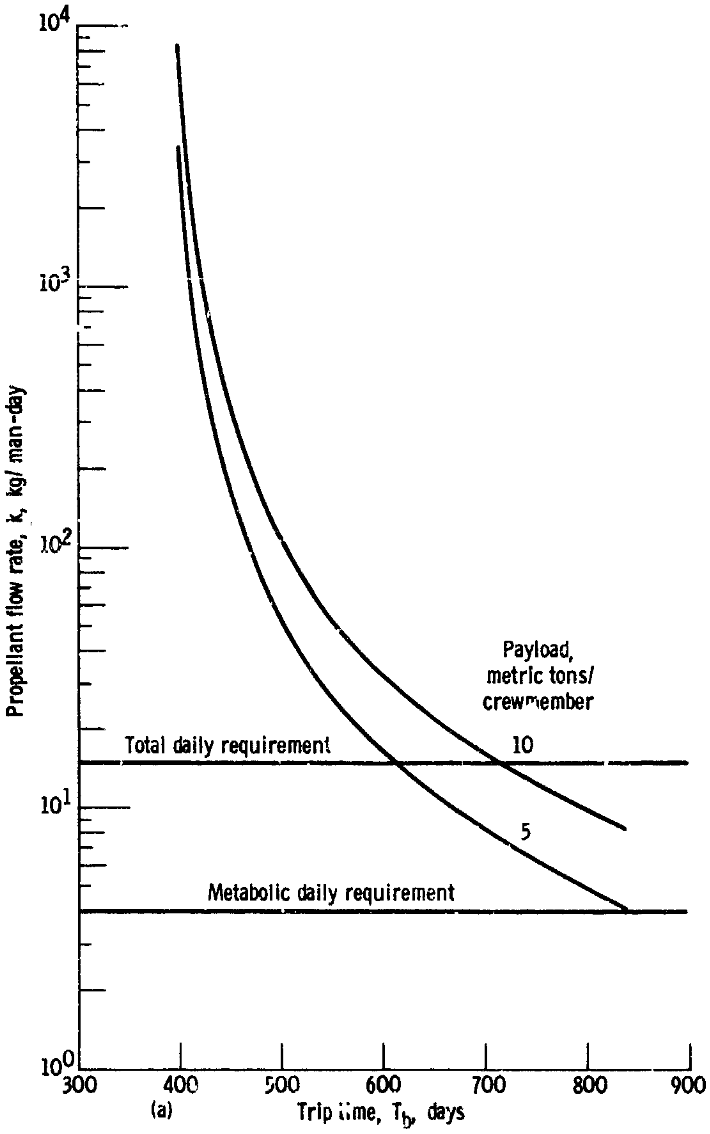
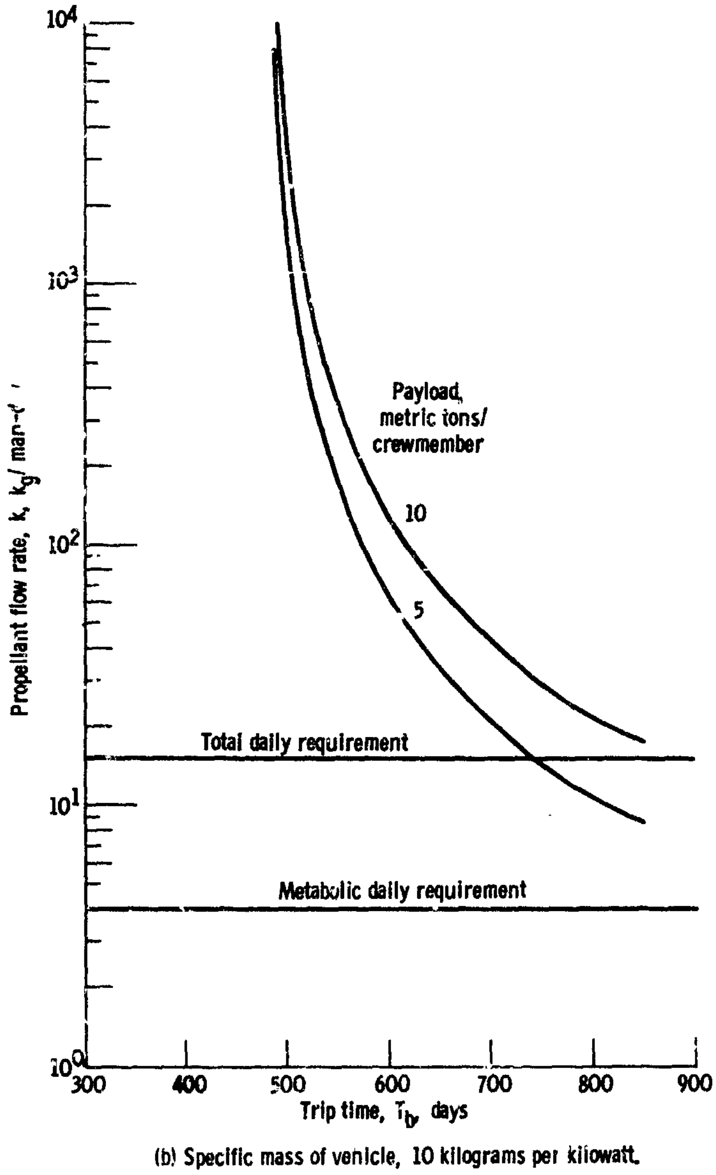


Figure 4. - Ratio of propellant to payload mass as a function of mission difficulty parameter.



(a) Specific mass of vehicle, 5 kilograms per kilowatt.

Figure 5. - Propellant flow rate as a function of trip time for payloads of 5 and 10 metric tons per crewmember.



(b) Specific mass of vehicle, 10 kilograms per kilowatt.

Figure 5. - Concluded. Propellant flow rate as a function of trip time for payloads of 5 and 10 metric tons per crewmember.