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A POSSIBLE APPROACH TO SCIENTIFIC  
EXPLORATION OF THE PLANET MARS

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A POSSIBLE APPROACH TO SCIENTIFIC  
EXPLORATION OF THE PLANET MARS

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I. INTRODUCTION

The commitment to manned lunar exploration by both the United States and the Soviet Union during the current decade prepares the foundation for the scientific exploration of the terrestrial planets, long a desire of that part of the scientific community interested in the planetary sciences and cosmology. Next to the Moon in importance for providing us with physical data and environmental details is the planet Mars. It is therefore no wonder that Mars is considered by many to be the next target after the Moon for manned scientific exploration. Also, it is a well-known fact that minimum-energy transfer orbits to Mars (including landing) require only a little more propulsive energy than lunar-landing missions if aerodynamic entry is used.

This paper ~~will~~ deal with some possible objectives of a Mars expedition, operational approaches that promise early feasibility, and their technological foundation. It <sup>Does not deal</sup> ~~will deal not~~ with specific solutions optimized for minimum objectives, but with ways to obtain a foothold for a scientific team, and to support it continuously, the aim being to achieve increasing

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*From 111*  
self-sufficiency in the later phases of the establishment of a Mars base. ←

The published details of the considered approaches to manned lunar exploration can set the pattern for the exploration of Mars, and much of the equipment, technique, and experience resulting from lunar exploration will be directly applicable to Mars. Of the many proposed technological steps to be taken and solutions to be considered, some will have the advantage of early availability and proximity to the existing state of technology, reducing the technological risks involved and insuring a reasonable chance of success. Mission size will determine the level of support required and may become a major contributor to the eventual success of this historic undertaking.

## II. OBJECTIVES OF PLANETARY SYSTEM EXPLORATION AND ITS POSSIBLE REWARDS

A successful manned expedition to the Moon and back would require a pooling of technological resources, knowledge, and human ingenuity never before achieved for one single and peaceful objective. The human effort and national resources required would be exceeded only by those applied in the major wars of the last half-century. The fact that this effort will widen the human horizon, reveal more about the evolution of life on Earth and the history of the solar and the galactic systems, and tap the natural resources of the nearby planets is a truly worthy cause and may affect the future of the human race much more than any other single event in the past.

Many will ask the question: Is this plan worth the effort and are the needed resources not better applied to relieve the human misery around the world? This question is not typical among American only; Russian planners of space missions face the same question, find themselves confronted with literally the same newspaper editorials as their American colleagues, and have to ask themselves whether to apply their efforts and national resources widening knowledge in this particular discipline or to relieving human misery as much as possible. One Russian newspaper published a letter under the heading, "Is it not too early to flirt with the Moon?", referring to the many unresolved social problems within the Soviet Union. One justification there, as here, is that answers to scientific questions, and knowledge not directly obtainable on Earth, may provide solutions (unobtainable otherwise) to problems on Earth. Here, as there, one of the answers is that money spent to achieve these national objectives is not spent on the Moon or Mars but right here on Earth, providing jobs, knowledge directly applicable to our society, and improved living conditions. The greater the scientific challenge to the

human mind, the more of our best thinkers and engineers will devote their lives to the solution of the associated problems, which in turn will yield benefits unimaginable without this apparent detour. History is full of examples to prove the case.

Potential rewards are better understanding of physical laws; the merits and penalties of life under very adverse conditions; development of closed ecological systems to overcome detrimental effects of environment (on Earth we have many areas which are presently excluded from settlement because of their unsuitability for supporting life, but population pressures could force man to live there and produce food in the not too distant future); utilization of natural resources of the nearby planets and possibly access to elements not available in quantity on Earth; solutions to problems of human relations in closed ecological systems; and many others of equal importance. The objective of peaceful exploration and utilization of the Moon and nearby planets will not be achieved, however, unless an equal participation of all nations in this scientific endeavor is assured.

III. THE STATE AND AVENUES OF TECHNOLOGY  
TO ACCOMPLISH AN EARLY MARS EXPLORATION

Since the plans for manned lunar missions will be based on approaches close to existing technology, early exploratory Mars missions will greatly benefit from the experience gained in developing the manned lunar landing and return capability and experiences gathered during this process. Present indications are that to achieve the first U.S. manned landing, technologies will be used that are based on chemical propulsion rather than electrical or nuclear primary propulsion, which appear to have performance advantages but are less advanced as to successful and demonstrated operational availability and reliability. It also can be proven that just to build a larger chemically propelled space system with the associated increase in payload efficiency can provide a solution almost as good but involves fewer risks as far as departure from existing technology is concerned. This should not be interpreted to mean that more advanced technologies should be neglected. However, one should not lose sight of the fact that that solution is the best which secures earliest success and based on accumulated working knowledge promises to be the most reliable approach to achieve this goal. The parallel developments of the "direct ascent" and of the "space rendezvous" appear at this time to be not only separately as mutual back-ups to this goal, based on moderate departure from existing technology, but jointly to provide the necessary capability of the manned Mars expedition.

Many disciplines of scientific endeavor beyond the mere process of space transportation have to contribute to make this enterprise an early success and not a few of these lack the proving grounds to test and demonstrate the capability and performance of their contributions. These proving grounds are space environment and the natural satellites and planets themselves.

Delay of development of these associated areas will delay achievement of the primary goals if the required technological advancement becomes the controlling factor. From these aspects the development of both the large-capacity chemical boosters and the rendezvous techniques in parallel is a sound national goal. Simultaneously, other early technical solutions emerge which will identify the pattern of early space exploration. This is the area I should like to give special attention, since it will also pattern the most promising modes of early interplanetary operations.

While nuclear primary power may or may not figure in the first lunar flights, auxiliary or secondary nuclear powerplants will certainly be the sources of electric power for lunar bases. A supplement will be the hydrogen-oxygen fuel cell, to be used as a flight-vehicle power source, a mobile surface-vehicle power source, an interim power source before completion of nuclear reactor installation, and as a standby power source in case of reactor maintenance. A close competitor will be hydrogen-oxygen expansion turbines or perhaps a combination of fuel cells and hydrogen expansion turbines.

During low-duty cycles, nuclear-reactor powerplants will regenerate the fuel-cell fuels so that these can be used over and over again. One of the objectives of the first lunar base will be to find means to achieve as high a degree of self-sufficiency as possible under local circumstances at an early date. The selection of cryogenic oxygen and hydrogen as fuel goes far towards this goal, as we shall see later in this paper. Finding "local" fuel sources will be a big step toward self-supporting operation. High cost of transportation is not the only reason, particularly since there is evidence that new developments in chemical-fuel utilization may eventually bring considerable reductions in operating cost, particularly when re-use of so

far non-recoverable elements of space boost systems is achieved.

One local fuel source may be the water of crystallization in crystalline rocks (found in many such rocks on Earth, and to be expected with a high degree of probability on the Moon and the terrestrial planets). This is very important, since, as we know, both the Moon and Mars are devoid of bodies of water. However, there is the possibility of underground ice deposits (like those found in arid areas of New Mexico) which could be utilized if they could be located. To find these will require surface mobility and the possibility of quick geological exploration of formations, strata, and basic geological composition. Development of this capability and its use will free valuable payload space, which otherwise would have to be used for carrying return fuels. Techniques to develop these fuel resources will be valuable for the establishment of bases not only on Mars but on one of the two natural satellites of Mars (Phobos and Deimos), which are, like the Moon, devoid of any atmosphere and will permit the use of landing gear developed for the Moon. In fact, equipment developed for use on the Moon might be useful on Phobos.

Since water and oxygen are vital elements of ecological systems to support human life, one can see that resolving the problem of "local fuel production" by freeing water from rocks will also help the realization of self-containing life-support systems. Another consideration is recovery of oxygen from exhaled  $\text{CO}_2$ . Photosynthesis yields oxygen, as do hydroponic gardens, which are not only efficient food producers but also one of the lowest-weight oxygen regenerators, considering over-all efficiency under long-term operation.

Hydroponic gardens can be maintained with nutrient solutions consisting of 99.65 to 99.8 per cent water and approximately 11 to 15 different dissolved

elements, of which six are major constituents, the balance being trace-elements needed to maintain proper plant growth rates, health, and resistance against plant diseases. For maximum growth rate, the close pH control of the nutrient solution is mandatory. The established percentages of the minerals have to be maintained within close tolerances, differing somewhat for the various edible plants to be grown, since the mineral needs change from one plant species to another. Since the total mineral content of the nutrient solution is in the neighborhood of 0.2 to 0.35 per cent of the weight of the solution, only the major elements (besides water) are needed in larger quantities and should be produced locally as soon as possible. Theoretically, all could be reclaimed from plant waste and waste products of the human metabolic cycle. The minor elements, required in amounts of a few parts per million in the solution, could be part of the regularly scheduled payloads supplying the Mars base. There is every expectation, that the major elements of the nutrient solutions can all be found on Mars and the Moon in relative abundance and as constituents of chemical compounds permitting easy extraction, possibly using ion exchange methods. Table 2 shows a representative composition of a hydroponic nutrient solution which was used successfully on Aruba Island to supply vegetables to U.S. troops during World War II and thus reduced the food supply volume requirement to be shipped under wartime conditions. Today nutrient solutions are used to grow vegetables, commercially, to grow mushrooms, and cattle feed, as well as to support plant research.

Water, then is the first basic compound to be found in starting a cycle of self-sufficiency for a lunar or planetary outpost and in reducing the continuous-support requirement. It provides over 99.65 per cent of the

Table 1

## PHYSICAL DATA ON MARS AND ITS SATELLITES

Information	Mars	Phobos	Deimos
Mean distance from sun	141.5 x 10 <sup>6</sup> mi 227.7 x 10 <sup>6</sup> km	Same as Mars	Same as Mars
Mean orbital velocity	15.0 mi sec <sup>-1</sup> 24.1 km sec <sup>-1</sup>	1.3375 2.14	.8398 1.3512
Mean angular velocity	.524°/day	47°/hr	11.87°/hr
Sidereal period	687.979 days	.319 day	1.264 days
Rotational period	1.027 days		
Eccentricity of orbit	.0933	.02	.003
Inclination of equator to orbit	25.20°	Unknown	Unknown
Inclination of orbit to ecliptic	1.85°	26°30'	26°58'
Mass, lb	1.41 x 10 <sup>24</sup>	2.268 x 10 <sup>16</sup>	1.512 x 10 <sup>15</sup>
Density (water = 1.00)	4.12 - 4.02 ± .1	3.5 ?	3.5 ?
Force constant $\mu = GM$ [miles <sup>3</sup> sec <sup>-2</sup> ]	1.026 x 10 <sup>4</sup>		
Solar radiation intensity [Earth = 1]	.4315 (mean)	.4315	.4315
Mean diameter	4140 mi 6739 km	~ 10 16	~ 5 8
Oblateness ( $\frac{a-b}{a}$ ) dynamical	.00521; ( $\frac{1}{192}$ )	Spherical?	Spherical?

Table 1 -- continued

Gravity at surface [ft sec <sup>-2</sup> ]	12.7	Mars gravity on surface 1.672	.2658
Fraction of Earth gravity	0.39 ± 0.01	6 to 10 x 10 <sup>-4</sup> g	2 x 10 <sup>-4</sup> g
Escape velocity at surface [miles sec <sup>-1</sup> ]	3.15	7.7 x 10 <sup>-3</sup> (n.a.)	.96 x 10 <sup>-3</sup> (n.a.)
Satellite velocity at surface [miles sec <sup>-1</sup> ]	2.23	5.47 x 10 <sup>-3</sup> (n.n.)	.68 x 10 <sup>-3</sup> (n.a.)
Sun's gravity at planet's orbit [ft sec <sup>-2</sup> ]	.0084 = 2 x 10 <sup>-3</sup> g	.0084 or 2.10 <sup>-3</sup> g	.0084 or 2 x 10 <sup>-3</sup> g
Rotational velocity on Mars surface [equator, fps]	795	Unknown	Unknown
Albedo	.15	.15 or less	.15 or less
Length of day [Earth days]	24 <sup>h</sup> 37 <sup>m</sup> 22.6 <sup>sec</sup>	7 <sup>h</sup> 39' 26.65"	30 <sup>h</sup> 21' 15.68"
Surface pressure [mb]	85 ± 4 or 230 g cm <sup>-2</sup>	0	0
Temperature lapse rate	3.7° C km <sup>-1</sup>		
Altitude above Mars [mi]	n.a.	3700	12500
Apsidal motion [deg per Julian year]		158.5	6.54
Orbit inclination to Martian equator [deg]		1° 8' (variable)	1° 46' (variable)
Change of orbital period due to oblateness of Mars [sec per orbit]		+11	+7
Pressure decrease in feet per order of magnitude depending on selected atmosphere model	120,000 200,000	n.a.	n.a.

Table 1 -- continued

Surface temperature [ $^{\circ}$ F]	80 $^{\circ}$ F max - 150 $^{\circ}$ F min	Not determined	Not determined
Boiling point of water [ $^{\circ}$ C]	25	n.a.	n.a.
Distance from Earth at opposition [mi] at superior conjunction [mi]	49 x 10 <sup>6</sup> 235 x 10 <sup>6</sup>	Same as Mars	Same as Mars

The indicated mass and gravity data of Phobos and Deimos are derived, using 10 mi diameter for Phobos and 5 mi diameter for Deimos and a relative density of 3.5. Estimates of the density of these satellites range between 2.7 and 3.5. The diameters have been estimated assuming the same albedo as that of the parent body (.15). In reality, the albedo should be somewhat less than .15, which would lead to somewhat larger diameter. In this event, the estimated mass would relate to a lower specific density.

Table 2

HYDROPONIC GARDEN DATA

Daily food requirement per man (lb)	2.300
Daily oxygen requirement per man (lb)	2.200
Total daily food and oxygen requirement for 18-man crew (lb)	81.300
Approximate yield of food and oxygen per day per ft <sup>2</sup>	.023
Required production area (ft <sup>2</sup> )	3,600.000
Total water required (lb)	30,000.000
Weight of supporting system (lb) (exclusive of rockfill, found locally, and discarded rocket fuel tanks and frame material)	10,000.000
Power requirements for artificial light and pumps (hp)	20.000

The mineral content of the solution is between .2 and .35% in solution weight. The illumination requirement is 400 to 1000 foot candles (Earth receives 1700 foot candles). Mars receives an average of 900 foot candles (43% of the Earth-rate); however, due to the lower albedo of Mars, about 60% of the Earth-rate are actually received. On Phobos, only 43% direct light would be received, but diffuse reflection from the Mars atmosphere would supply some illumination while Phobos is not exposed to direct sunlight.

Nutrient solution elements:

Major elements		Trace elements	
Potassium	29.5%	Iron	.173%
Nitrogen	26.5%	Chlorine	.091%
Calcium	25.2%	Manganese	.065%
Sulfur	8.2%	Boron	.057%
Magnesium	6.0%	Molybdenum	.007%
Phosphorus	4.2%	Zinc	.005%
<u>Subtotal</u>	<u>99.6%</u>	<u>Copper</u>	<u>.002%</u>
		Subtotal	.400%

The above sample solution is a typical solution. Research has shown that the actual solutions change from plant to plant and from phase to phase during plant life. Plants need more nitrogen while growing and more potassium and calcium while growing seeds, etc.

weight of the nutrient solution of hydroponic gardens, reducing  $\text{CO}_2$  to  $\text{O}_2$  and hydrocarbons and supplying vegetables as byproducts; approximately 0.35 per cent of the weight of the nutrient solution would have to be shipped in if it could not be found locally and processed (possibly 100 per cent of the weight would have to be shipped in if no self-sufficiency is achieved). Water, provided that nuclear-electric powerplants supply electricity and heat, can be extracted from crystalline rocks and decomposed into  $\text{H}_2$  and  $\text{O}_2$  for operating hydrox fuel cells and hydrogen blow-down or expansion turbines, reconstituting air to the proper oxygen and moisture content for breathing, and providing cryogenic  $\text{H}_2$  and  $\text{O}_2$  for the operation of space ships during their return flights to Earth (in case of chemical and later nuclear or electric propulsion systems). This is one of the most important reasons for using cryogenic  $\text{H}_2$  and  $\text{O}_2$  as propellants in the early stages of space operations rather than fluorine compounds, since one single water-extraction plant together with a nuclear-electric powerplant of the SNAP IV type can start the most important part of a self-contained planetary or lunar base operation well on its way. We see from this example that the degree of self-containment of planetary bases really determines the volume of support needed from Earth; progressive increase in self-containment of planetary expeditions or bases is therefore a requirement of the first order.

Much of the research toward and development of equipment needed to support achievement of self-contained base operation and local return-fuel production can, of course, be done here on Earth and should go on concurrently with the development of our lunar-mission capability.

Another area of importance is the development of lunar and interplanetary payloads. In order to explore the Moon and Mars, the members of the expedition have to be protected against local hazards, have to live in pressurized

shelters, and have to be able to move about on the surface to perform their assigned tasks and exploration objectives. Since exposure to the surface environment should be as brief as possible, the amount of physical work done outside closed shelters should be a minimum and should be necessary only when manual dexterity is definitely superior to automatic and/or remote-controlled operations. The conclusion to be drawn from this is that human efforts needed to establish the first lunar or planetary base should be at an absolute minimum consistent with those actions which cannot be performed in advance and sufficiently well on Earth or done automatically in space. This requires that the base units be brought over as complete, self-contained modules, ready to work in the new environment or requiring a minimum of operations to be joined together. Present-day guidance capability would permit the landing of living-shelter modules close to their final permanent locations (excavation methods might well be avoided, and the base modules ought to be emplaced with a minimum of soil movement). If protection against solar flares, cosmic radiation, etc. is necessary in addition to protection against climatological variations, covering the base-modules with sandlike aggregate is simple and would require less specialized equipment than excavating or tunneling. In other words, if the base can be delivered pre-assembled and pre-packaged to its destination, the specialized labor required to assemble the base is at a minimum. The skilled man power needed for assembly of base-modules on Mars may cost \$15,000 to \$25,000 per hour, transportation and subsistence included, while here on Earth the same man power may cost \$10.00 to 15.00 per hour, overhead and fringe benefits included. Little is known about the surface environment and the atmospheric composition of Mars. About the only atmospheric constituent definitely

established is  $\text{CO}_2$  (Kuiper, 1952), which is about 16 times more abundant than on Earth. However, the most probable atmosphere models postulate that the Mars surface density corresponds to a 50,000-foot altitude Earth-density, somewhere between 85,000 and 105,000 feet both are equal (10 mb), and that above these altitudes the Mars atmosphere is denser than the Earth's. An Earth orbit of 300 statute miles corresponds to a Mars orbit of about 1000 statute miles as far as mean free path of atoms and molecules is concerned. Very little free oxygen is expected in the Mars atmosphere, since free atomic oxygen can escape from Mars (Urey, 1959). However, it has been speculated that oxygen in the form of ozone exists near the Mars surface and is possibly responsible for the reddish-brown color of Martian desert areas, which could be explained by an abundance of oxidized iron compounds (e.g., fersite or limonite). Except for the existence of winter ice caps, which is generally accepted, water appears to be present only as water vapor or ice crystals, suspended in air, with an estimated partial pressure of only  $0.043 \text{ g/cm}^2$ . The abundance of molecular nitrogen is estimated to be 95 per cent with argon at 3 per cent being the next abundant element in the Martian atmosphere. The absence of oxygen as well as the abundance of  $\text{CO}_2$  requires that oxygen will have to be supplied for breathing, and an artificial atmosphere will have to be maintained for living and working shelters and for the pressure suits that will have to be worn by expedition members when outside closed, pressurized shelters.

To perform surface exploration as well as geological research, the members of the expedition have to have mobility. For short distances, surface transportation suitable for roadless surfaces, Martian gravitation ( $12.6 \text{ ft/sec}^2$ ), and the Martian atmosphere have to be designed. As indicated

before, vehicles designed for lunar locomotion, propelled by fuel-cell-operated electro-motors or hydrogen expansion turbines appear to be a logical choice, particularly since problems of heat rejection will be less severe than on the Moon. This type of equipment should be particularly valuable in the early periods of exploration and occupancy of Mars.

There should be fewer surface feature problems than on the Moon, since it is generally accepted that Mars lacks the rugged surface structure of the Moon. As soon as direct knowledge of the composition of the Martian atmosphere is known, the availability and use of atmospheric compounds as fuel for locomotion should be investigated. The low density of the atmosphere leads to high landing speeds for airplanes of even very low wing loading, so that only very smooth surfaces would permit landing by aerodynamic vehicles. However, hydrogen oxygen-fueled glider-type aircraft of very low wing loading ( $\leq 10$  psf) could provide fast transportation (150-200 knots) over longer distances up to 3000 nautical miles (see Fig. 1), particularly if jatos are used for takeoff and after runways have been provided. For shorter distances, helicopters appear to be superior to surface vehicles in carrying capacity and speed for Mars altitudes up to 9000-10,000 ft. The lower surface gravity does not fully offset the effect of the low surface density so that the touchdown velocities for the same landing  $c_L$  and wing loading would be approximately 2.08 times higher than on Earth. This fact places a considerable problem for aerodynamic entry vehicles of the Earth re-entry variety on Mars, unless the design considers these particular properties. The use of horizontal landing Earth re-entry vehicles would be permissible only if landing wing loadings of less than 20 psf are used and runways provided,

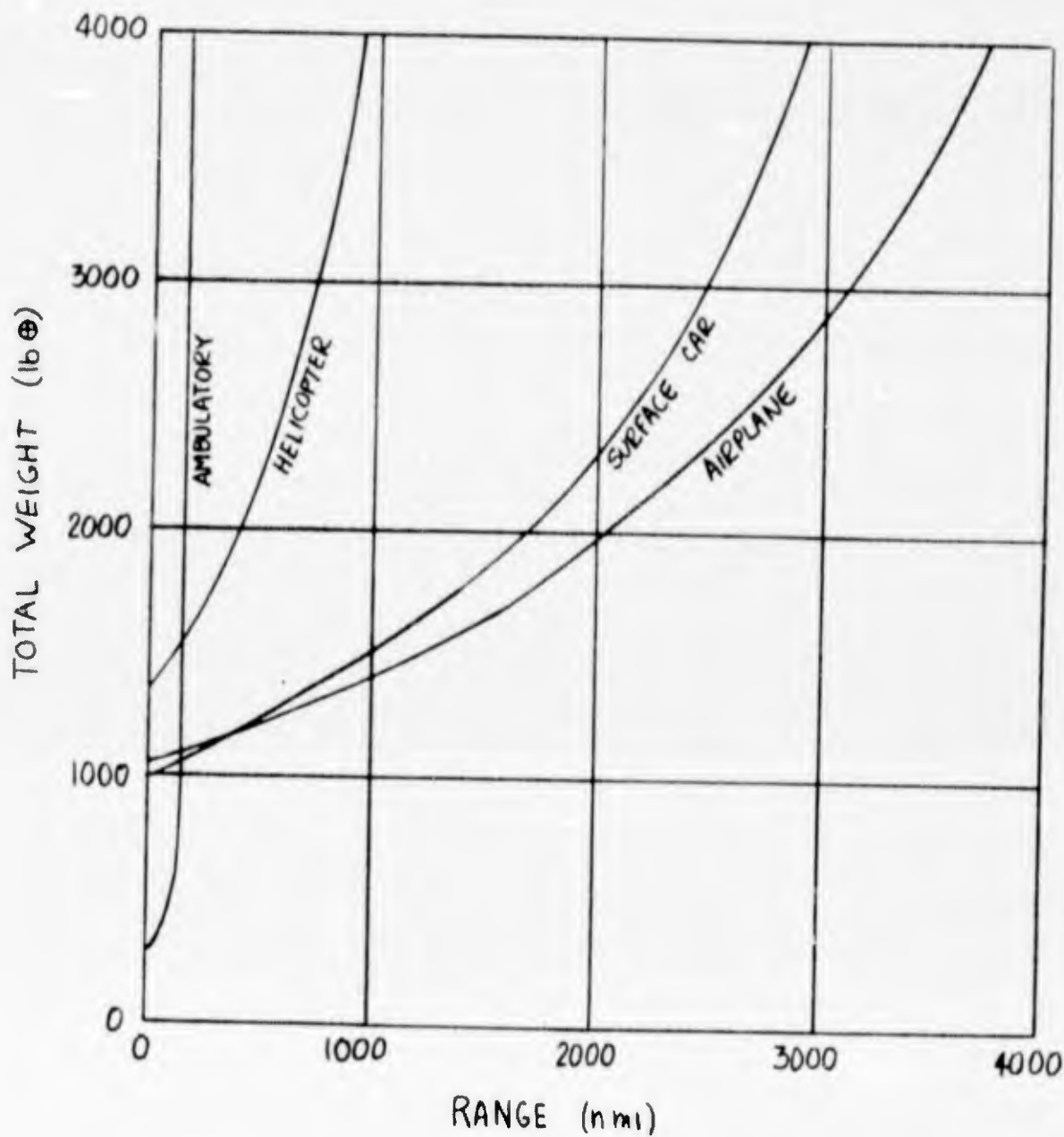


FIG. 1 RELATION BETWEEN VEHICLE WEIGHT AND ONE-WAY RANGE FOR VARIOUS MARS TRANSPORTATION MEANS (REF. RAND RM-2539)

permitting skids or retro-thrust application.

While the use of the Moon as an interim space launch base does not appear to offer advantages, the use of Martian natural satellites, Phobos particularly, may be advantageous and should be further investigated. Clyde Tombaugh, one of the foremost experts on Mars, expects that Phobos consists of basically the same materials as Mars itself. If this should be correct, the material of Phobos could be used to supply water and return fuels. Instead of using an artificial orbiting Mars base, a natural Mars base could be used to establish the initial Martian beachhead. A nuclear reactor of sufficient capacity could be installed together with a plant for reclaiming water from crystalline rocks. Excess power then could be used to dissociate water to  $H_2$  and  $O_2$  and provide power for their liquefaction. The cryogenic fuels can be stored in insulated empty fuel tanks until needed for return flights. An artificial orbiting base would not offer this possibility. Also chemicals needed to provide the nutrient solutions for hydroponic gardens could be expected to be found either partly or completely on Phobos, and as the capabilities of the base increase, one after the other could be included into the extraction process, making the base more and more self-contained. For landing on Phobos, the same techniques as for landing on the Moon could be used except for the fact that the gravitational pull of Mars and the Sun exceed that of Phobos even on Phobos' surface. ( $g_{\text{phobos}} = 6 \cdot 10 \times 10^{-4} g_{\text{Earth}}$ ) Therefore, little penalty will be paid to overcome the effects of Phobos' gravitational field either at take-off or landing, in contrast to the Moon as an intermediate planetary departure base, where approximately 9,000 fps velocity change is required after arrival from Earth to soft-land on the Moon; the same amount

is needed to escape from the lunar gravitational field again to continue the journey to the target planet. The orbital velocity of Phobos around Mars is  $\sim 2.13$  km/sec or  $\sim 6990$  fps, and its orbital plane is inclined  $26.50^\circ$  from the plane of the ecliptic, and  $1^\circ.8''$  from Mars' equatorial plane.

Since space ships from Earth would probably reach Mars very nearly in the plane of the ecliptic, non-aerodynamic entries would land between  $\pm 25^\circ$  latitude, depending upon the position of Mars in its heliocentric orbit, whereas aerodynamic entry vehicles could cover areas outside this latitude belt, depending on L/D, wing loading, and g-loads. Aerodynamic heating would be considerably less than that during Earth re-entry, such that the maximum temperatures encountered on leading edges or other heat-exposed surfaces would be reduced to at least half those at Earth re-entry. If the rendezvous with Mars and Phobos were properly timed, the condition could be selected, at which the motion of Phobos is retrograde with respect to the direction of the motion of Mars in its heliocentric orbit, with a velocity component parallel to the Mars orbit in the plane of the ecliptic. At this instant the relative velocity between Phobos velocity component in the plane of the ecliptic and the spaceship velocity would be a minimum, however, with Phobos having a lateral velocity component  $v_{\text{Phobos}} \sin 26.50^\circ = 3140$  fps, while the velocity component in the plane of the ecliptic is  $6990 \cos 26.50^\circ = 6230$  fps. The space ship has to increase its velocity by  $\sim 7600$  fps to cancel Phobos' lateral motion and match its velocity, since both Mars and Phobos are overtaking the space ship from the rear. Little maneuver fuel will be needed to hover over the desired landing surface due to the low gravitational pull near the Phobos surface, which is less than one-tenth the local Mars gravity value (see Tables 1 and 3).

In order to soft-land from Phobos on Mars, a total velocity increment of 15,500 fps is needed, disregarding drag losses during descent. Of this total increment, approximately 1900 fps are needed to initiate a transfer ellipse from Phobos to Mars towards the Mars surface. A second velocity increment of 13,600 fps with respect to the rotating planet is needed to cancel the velocity of the vehicle near the surface. Since the density of the Martian atmosphere above  $\sim 85,000$  feet is higher than the density of the Earth's atmosphere at equal altitudes (Mars density changes one order of magnitude about every 120,000-200,000 feet of altitude change), use of non-lifting entry bodies augmented by retro-thrust or parachutes as well as those using aerodynamic lift entries makes sense and could save not only part of the 1900 fps velocity increment required to separate from Phobos but also all of the 13,600 fps required to cancel the remaining energy with respect to Mars' surface. The merits of this approach will be further dealt with below.

Another question to be resolved is the size of the expedition required to support a successful mission. In the published literature, various mission sizes have been considered, ranging from crews of 6 to 15 members to as large as 100 to 150 crew members. A reasonable approach for determining mission size is to require that all skills needed to make the mission a success should be represented. Furthermore, each crew member should have training to perform at least two required mission skills so he can substitute in case of sickness or unavailability of the crew member whose primary responsibility it is to perform the task. In case of malfunctions in one vehicle, companion vehicles have to be able to take over crews and/or missions by transferring personnel, payloads, and fuels while on the several legs of

Table 3

VELOCITY REQUIREMENTS FROM 300 N MI EARTH ORBIT TO  
HELIOCENTRIC ORBITS NEAR MARS, MARS CAPTURE AND  
ENTRY, LANDING ON PHOBOS VELOCITY, AND RETURN FLIGHTS

	<u>Velocity (fps)</u>
Earth surface to circular 300 n mi Earth orbit	27,500
Earth orbit to transfer to Mars, including 500 fps midcourse maneuver	11,900
Mars capture	6,125
Mars landing (direct)	12,475
Earth orbit to Mars orbit	18,025
Earth orbit to Phobos landing	19,000
Phobos to Mars surface	15,500
Earth orbit to Mars surface, no aerodynamic braking	30,000
Earth orbit to Mars surface, aerodynamic braking	20,000
Mars surface to Earth capture, including midcourse correction	30,000
Mars surface to Earth surface, including aerodynamic braking	20,000
Phobos surface to Earth capture, including midcourse correction	20,500
Phobos surface to Earth surface, aerodynamic braking and midcourse correction	8,100
Total round trip Earth orbit to Mars surface and back, no braking on Mars	60,000
Total round trip Earth orbit to Mars surface and back, aerodynamic braking on Mars and aerodynamic landing on Earth	40,000
Earth orbit to Phobos and back to Earth orbit	39,500
Earth orbit to Phobos and back to Earth surface, aerodynamic braking	29,100
Phobos surface to Deimos surface, soft landing	3,450
Gain due to Mars rotation, eastbound launch at Mars equator	795

the mission. Abort capability for each individual ship of the mission should exist by such transfer to other companion ships. In other words, the over-all mission should have built-in operational redundancy to permit return of the full crew, regardless of which ship malfunctions or fails. Since in early phases of Mars exploration, mission durations of 200 days or more may be the rule for outbound or inbound trips, the distance and time requirements to rescue missions from Earth or from Mars are too large in urgent cases to permit rescue operation from either terminal, in contrast to aborts on lunar missions, in which rescue can be initiated immediately. This deficiency has to be overcome by having a group of vehicles in an individual mission which fly relatively close formations, so that each ship can obtain assistance within a short time whenever required. This philosophy of operation requires a larger crew than a minimum type mission not having this built-in redundancy and rescue capability. The simultaneous departure of a group of space ships, crew ships, and cargo ships intermixed may be still difficult from Earth launching sites even within the next decade. However, using in-orbit refueling and launch operations, this approach will be less difficult and promises a high success rate, since only one stage will have to work successfully to reach escape velocity. Malfunctions during this phase will keep this vehicle in Earth orbit and therefore accessible to rescue missions from Earth. Malfunctions during Mars capture will place the vehicle into Mars orbit and therefore again make it accessible to rescue action by the companion vehicles. An operating scheme could be worked out which provides a maximum flexibility in mission modifications to overcome effects of vehicle malfunction and aborts, maximizing crew safety and the probability of safe return.

Before going into more operational details of the Mars mission and including Phobos and possibly Phobos and Deimos into such schemes, it is well to know somewhat more about them beyond the physical data presented in Table 1. As we learn from these, Phobos revolves faster around Mars, than points on Mars' surface. This makes Phobos appear to be rising in the west and setting in the east. Its low altitude of  $\sim 3750$  miles above Mars prevents its visibility at latitudes greater than  $69^\circ$ . Its synodic period is  $11^h .106$  (interval between successive meridian crossings). It will be visible from horizon to horizon at Mars' equator for  $4^h .257$  and for shorter periods at higher latitudes. Deimos, 12,550 miles above Mars, can be seen at latitudes below  $82^\circ$ . While it can be seen from the same points at the Martian equator for 60 hours, with shorter periods at higher latitudes, its synodic period is  $135^h .45$ . It is not known whether Phobos or Deimos rotate around their own poles at the same rate as Mars and like the Moon show the same area of their surface permanently to Mars (like many other natural satellites of the Solar Planetary System and possibly even Venus), or whether they have independent periods of revolution. Another interesting fact is that during spring and fall seasons, Phobos and Deimos undergo frequent eclipses and will be obscured during large portions of their orbits, while during high summer and winter no eclipses will occur.

Escape velocity on the surface of Phobos is approximately 40 fps and the surface circular orbit velocity is  $\sim 29$  fps. This information permits to determine window, time, and velocity tolerances to accomplish spaceship "capture" on Phobos. Performance of the midcourse and terminal guidance equipment can be based on this information. Escape velocity on Deimos is  $\sim 5$  fps, while its surface orbital velocity is  $\sim 3.6$  fps.

With the duration of complete Mars missions under minimum-energy transfer conditions of about 970 days, and waiting periods of 450 days on Mars or Phobos before return to Earth again, a considerable part of the payload will be devoted to life support, scientific instrumentation, base modules, base erection equipment, communication equipment, and power supplies. Existence of ionospheric layers similar to those in the Earth's atmosphere will restrict frequency use and may make particular power demands to maintain communications up to maximum Earth-Mars separation. Penalties in ideal velocity requirements for fast missions of transfer times of less than 200 days and shorter waiting times may be at least partly offset by savings in supporting payloads. With a maximum degree of initial self-sufficiency of the Mars satellite base (Phobos), and only exploratory flights to Mars itself of relatively short duration, a total crew of 18, distributed to three manned vehicles and the use of six cargo-vehicles, carrying scientific equipment, nuclear-electric powerplants, ready-to-operate base modules, operating fuels, return and mission fuels, and possibly a water extraction, a water dissociation and liquefaction plant for production of cryogenic  $H_2$  and  $O_2$  from local resources, receiving power from one of the nuclear-electric powerplants, appears to be a reasonable example for studying operational and support requirements of such a mission. Since capabilities of chemical boost systems, use of space rendezvous, introduction of nuclear upper stages, and progress in partial self-support of Phobos or Mars bases will increase as time goes on, the originally slow Mars missions will be replaced by faster transfer-time missions and more frequent missions. This may lead to the desire to retain occupancy of a once-established base and to consider tours of duties of crews, skipping a return flight before returning

to Earth again, using a fast type return, and abbreviated second-turn waiting times.

Since booster size will be the limiting factor at all times, one can expect that at the time of operational availability (e.g., of Nova) the demands on payload capability per flight again will exceed the existing capability of the most advanced vehicle. As is planned for lunar missions now--to use Saturn vehicles in combination with orbital operations (space rendezvous) to increase the payload capability per flight at escape velocity, Nova's could be refueled in orbit to keep technological pace with the increasing payload-size demands. In due time, recoverable space boost systems will handle space refueling missions and so could make full payload capability available for planetary missions. The next step to improve space travel efficiency is to refuel at the destination planet or on the natural or artificial satellites provided for this objective.

In order to give a picture of the savings to be made, using Phobos as a Mars space flight terminal and commuting from Phobos to Mars and back with vehicles having aerodynamic lift-entry capability, we can look at departure payload weights to perform the various mission modes, having an Earth escape velocity weight of 150,000 lbs from a 300 n mi Earth orbit (36,500 fps). A specific impulse of 430 sec is assumed, using  $H_2$  and  $O_2$  as fuels and oxidizers for all phases, following Earth departure.

#### IV. OPERATIONAL ASPECTS OF A MARS EXPEDITION

##### A. DETERMINATION OF THE VELOCITY REQUIREMENTS OF THE VARIOUS MARS MISSION MODELS

###### 1. Mission Modes and Operational Objectives

All missions to Mars require a minimum escape velocity of 36,500 fps if Hohmann transfer datums to Mars heliocentric orbits are assumed with transfer angles of  $180^\circ$ . The  $\Delta v$  requirements detailed in Table 3 are applicable to the involved mission sections, using 256 days transfer flight time to Mars, 485 days waiting time on Mars, and 256 days return flight to Earth orbit. Heliocentric orbits of Mars and Earth and coplanarity of both orbits are also assumed except in the case of landing on Phobos. The inclination of the Phobos orbit to the plane of the ecliptic was assumed to be  $26.50^\circ$  and the required lateral velocity component to match Phobos' orbit included into Phobos landings from Earth orbits. The timing of landing on Phobos was selected such that the relative velocity between Phobos and space vehicle is at a minimum at the time of orbit matching, which is an additional constraint as to arrival time at the Mars capture orbit. Midcourse correction fuel in form of an extra  $\Delta v = 1500$  fps is included.

Faster orbits or shorter waiting times can lead to total round trip  $\Delta v$ 's up to four and more times the minimum round trip  $\Delta v$ 's. Since these extreme cases cannot be handled by planned chemical propelled vehicles, and it is not expected that nuclear propelled or ion-propulsion power plants will be available during early manned Mars missions, they are not considered in direct Mars or Phobos missions.

The following mission modes will be compared:

1. Direct landing on Mars using impulsive entry, and direct return to Earth using aerodynamic re-entry.
2. Direct landing on Mars using aerodynamic entry, and direct return to Earth Orbit.
3. Direct landing on Mars using aerodynamic entry, and direct return to Earth surface using aerodynamic re-entry.
4. Direct landing on Phobos, return to Earth orbit.
5. Direct landing on Phobos, return to Earth surface by use of aerodynamic re-entry.
6. Direct landing on Mars using impulsive entry, return to Phobos.
7. Direct landing on Mars using aerodynamic entry, return to Phobos.

The following mission objectives are considered:

- A. Establish Mars base within  $\pm 25^\circ$  latitude on Mars. Set up Mars base and keep Mars base occupied after first landing. Make Mars base self-contained to as high a degree as commensurate with 1970 technology at as early a date as possible. Produce fuel locally.
- B. Establish a Phobos terminal and keep it occupied. Make Phobos base self-contained at as early a date as possible and produce fuel on Phobos. Make exploratory flights to Mars only, and maintain temporary occupied base.
- C. Establish Phobos terminal and make base self-contained and fuel-producing at earliest possible date. Occupation permanent.  
Establish Mars base by flights from Phobos and make it self-contained as soon as Phobos base is fully established and produce fuel on Mars for Mars-to-Phobos flights. Occupy Mars base permanently.

- D. Establish Phobos terminal, make it self-contained and fuel-producing. Establish Mars base in parallel with supplies from Phobos and build it up as main base, later using Phobos for fuel production and intermediate stops to and from Mars. Keep Phobos manning at minimum after maximum degree of self-sufficiency of Mars base is achieved.

These objectives cover a relatively wide range of mission and operational approaches. The permanent manning strength is established at 18 men, arriving at their destinations in groups of either 3 or 6, depending upon objective of individual tasks. To arrive at greater manning strength, support requirements increase these requirements in the ratio  $\frac{\text{Desired strength}}{18}$ .

## 2. Approaches to Operation of Mars and Phobos Bases Under Various Operational Objectives

Direct landings on Mars require either impulsive braking (as will be used in lunar soft landings) or aerodynamic braking. For the latter, again two modes are possible: firstly, a Mercury type of non-lifting landing with parachute deceleration before touch-down and possibly use of retro-rocket thrust just before touch-down, or airbags to reduce impact shock under low Martian surface density; secondly, use of aerodynamic lift deceleration and horizontal landing. Since due to the low surface density on Mars, landing velocities at the same  $c_L$  and wing loading will be more than twice as fast as those on Earth despite the lower surface gravity on Mars, and will require wing loading below 10 psf on smooth but unprepared surfaces, and below 20 psf on prepared, graded, smooth surfaces to prevent or reduce landing damage. Horizontal manned landing will be preferable, particularly for flights from Phobos and return to Phobos. One of the

assets of this mode of operation is the large footprint of the landing vehicle as compared to no-lift entry, which permits relaxation of timing conditions and avoiding of detrimental local weather conditions, using alternate bases as soon as such can be set up. A miss with a nonlifting landing mode may require rescue operations, comparable to rescue operations in extremely uninhabited Earth areas and unavailability of efficient surface or air transportation means. Therefore, lifting type landing modes should be adopted as soon as feasible and also alternate Mars bases set up as soon as the early Mars occupation and base establishment has made sufficient progress.

### 3. Mission Objective A

The mission objective A requires the highest  $\Delta v$  (18,000 fps) for arrival on Mars, using only impulsive braking. Empty weight  $W_e$  of arriving vehicle, if single stage operation during Earth departure and Mars injection is used, is derived from  $\Delta v = \ln \frac{W_o}{W_e} I_{\text{spec.}} \times g$

with  $I_{\text{spec.}} = 430 \text{ sec}$ , and

$$g = 32.16 \text{ ft/sec}^2$$

$W_o = 143,000 \text{ lb}$  at Mars injection or  $150,000 \text{ lb}$  at Earth escape.

$$\ln \frac{W_o}{W_e} = \frac{18,400}{13,829} = 1.38$$

$$\frac{W_o}{W_e} = 3.78 \qquad W_e = \frac{W_o}{3.78} = 32,800 \text{ lb}$$

Since the inert weight of this vehicle would be approximately 17,500 lb (derived from an initial weight of 343,800 lb before departing from 300 n. mile circular Earth orbit), 15,300 lb payload would arrive on Mars.

No return capability into Mars orbit or landing on Phobos would be possible without using additional vehicles, bringing fuel and supplies.

If the vehicle would be two-stage, the mass-ratio would be halved and higher payload efficiency achieved ( $\Delta v = 9,200$  fps)

$$\ln \left( \frac{W_{o1}}{W_{e1}} \right) = \frac{9,200}{13,829} = 0.665$$

$$W_{e1} = \frac{W_{o1}}{1.945} = 73,500 \text{ lb}$$

$$W_{o2} = W_{e1} - W_{str} = 73,500 - 15,000 = 58,000 \text{ lb}$$

(Note reduced  $W_{str}$  due to deletion of soft landing).

$$W_{e2} = 30,000 \text{ lb}; \quad W_{str2} = 2,500 \text{ lb}; \quad W_{pe} = 27,500 \text{ lb}.$$

This arrangement could bring 27,500 lb of cargo in one vehicle, unmanned, and a crew of three in a second manned vehicle, including two weeks life support supply, shelter, power supply, and, among the cargo, two complete planetary surface vehicles, capable of grading reasonably soft soil or sand type surface to prepare runway for horizontal entry and landing vehicles. No return capability without additional vehicles landing to additional fuel and supplies.

Use of aerodynamic entry vehicles would require a

$$\Delta v = 6500 \text{ fps or } \ln \left( \frac{W_o}{W_e} \right) = 0.47 ;$$

$$W_e = \frac{143,000}{1.6} = 89,500 \text{ lb};$$

$$W_p = 89,500 - 22,500 = 67,000 \text{ lb}$$

The higher inert weight of the stage of 22,500 lb is due to parachute, recovery gear, etc. The weight could again consist of a crew of three men, two surface vehicles, shelters, scientific equipment and life support for months. After two weeks to two months, the vehicle, leaving all disposable equipment on Mars, could fly up to Phobos and join the main part of the expedition, after runway and emergency facilities have been established on a preselected Mars site. During the Earth-Mars transition, the Mars capture fuel is used for crew shielding purposes, the return fuel to Phobos as temporary shielding before embedding the temporary base crew shelters in about a 1-foot layer of loose Mars surface aggregate. With the weight of the stripped vehicle reduced to 15,000 lb, 40,000 lb of fuel are needed to fly up to Phobos, using rocket power. Since the 15,000-lb stripped down vehicle is part of the original 22,500 lb inert weight, approximately 27,000 lb are available for consumable supplies, instrumentation, personnel shelter, surface vehicles, fuel and evaporation losses, etc. For direct return to Earth re-entry, additional supply vehicles have to arrive at Mars. The shielding of 1 foot of aggregate should provide sufficient protection for the short duration of stay on the Martian surface against solar flares of up to  $3^+$  intensity.

Two-stage arrangement can increase payload capability for direct flights to Mars still further.

$$\Delta v = 3250 \text{ fps}; \quad \ln \left( \frac{W_{o1}}{W_{e1}} \right) = \frac{3250}{13,829} = 0.235$$

$$W_{e1} = \frac{143,000}{1.265} = 113,000 \text{ lb}$$

$$W_{str1} = 13,000 \text{ lb}, \quad W_{p1} = 113,000 - 13,000 \text{ lb}$$

$$W_{o2} = 100,000 \text{ lb}$$

$$W_{e2} = \frac{100,000}{1.265} = 79,000 \text{ lb}$$

$$W_{str.2} = 5,000 \text{ lb including recovery equipment}$$

$$W_{p2} = 74,000 \text{ lb}$$

We see that this mode of operation increases payload by about 10 per cent, but also increases complexity of operation. The actual payload gain is higher, since of the structural and crew weight of the return stage of 10,000 lb, 4,000 lb come out of the 5,000 lb of the landing stage, and only 26,600 lb of fuel are needed to return to Phobos. The actual net payload gain than is 4900 lb plus 6500 lb saved on fuel, or 11,400 lb. However, it still has to be decided whether this is the most desirable mode of operation. For direct return, again several vehicles are needed to bring additional supplies, fuel and Earth return vehicle.

#### 4. Mission Objective B--Landing on Phobos

$$\Delta v = 7,600 \text{ fps}; \quad \ln \left( \frac{W_o}{W_e} \right) = \frac{7,600}{13,829} = 0.55$$

$$W_e = \frac{W_o}{1.735} = \frac{143,000}{1.735} = 82,500 \text{ lb}$$

$$W_{\text{str.}} = 17,500 \text{ lb (Not to be discarded)}$$

$$W_p = 65,000 \text{ lb}$$

This payload is approximately 3 per cent less than the payload landed directly on Mars, but it permits direct return flights to Earth with no additional refueling if this fuel is included in the payload and the manned Earth re-entry vehicle is part of this payload. Power supply fuel, life support, water supply, etc. are used for preliminary shielding on Phobos. A 3 foot loose aggregate cover on the crew shelters is provided against cosmic rays and 3<sup>+</sup> solar flares for the first three days on Phobos and later is augmented to a cover 10 feet thick to reduce radiation levels to approximately long-term average Earth surface dose level. In each manned vehicle, 300,000 lb of life support supplies, stored in shelter units, arrive, sufficient for a 450-day stay on Mars and a 260-day return trip to Earth. The balance consists of nuclear electric power supplies, scientific instrumentation, communication gear, and fuels. It should be noted, that with 50,000 lb of fuel, the inert weight of the landing stage can be returned to 300-n. mile circular Earth orbit, there refurbished and refueled to be used again (255,940 lb of fuel and 67,000 lb of payload exclusive of attitude control fuel and 10,000 lb of life support supplies for manned return, and 77,000 lb of payload for unmanned return). Refueled with 255,940 lb on Phobos, it could bring the same cargo load to Earth orbit. This fact shows that local refueling capability is a significant achievement, which could considerably reduce over-all operating cost and should be achieved as

early as technically feasible. Due to the low gravity on Phobos the vehicle would need only a low-thrust chemical-fuel power plant, 50,000 lb of thrust being sufficient in either way operation.

In order to provide radio communications, life support, shelters, repair facilities, scientific instrumentation, recreation facilities, and mobile surface vehicles, approximately 400,000 lb of payload are required to be landed on Phobos or on Mars, not including the fuels for the manned return flights. To establish an increasing degree of self-sufficiency, at least another 200,000 lb of payload are needed. Besides tanker vehicles, nine vehicles including three manned vehicles are needed to staff the base, while building up self-sufficiency will require another three cargo vehicles. For the return of the crews from Phobos, two tanker vehicles have to arrive on Phobos. For each manned excursion from Phobos to Mars, approximately 26,600 lb of fuel excluding losses have to be provided for returns to Phobos. Based on this figure, one tanker can supply three excursions to Mars from Phobos, either for airdrop of supplies or for manned landing and return.

Exploratory flights to Mars should use aerodynamic entry. The critical phase of the flight is the touch-down phase on Mars, which in case of a horizontal landing should be performed with a wing loading of less than 10 psf on an unprepared landing site, and of less than 20 psf on a prepared site. The vehicles in the event of lifting aerodynamic entry can fly to their respective landing sites with wing loadings of 50 to 75 psf, if they can discard (airdrop) their excess cargo before landing. They can carry canisters of fuel with them, which are dropped with parachutes at low speed and altitude, using air bags to reduce impact shock. Also payloads and

equipment can be brought down this way and the vehicle itself lands after having reduced its touch-down weight to the prescribed limits. If the unfueled return weight of the vehicle is 10,000 lb, 26,600 lb of fuel are needed to return to Phobos again. With 1000 sq ft effective lift area, 40,000 to 65,000 lb of payload can be brought down to Mars' surface, which after deduction of 26,600 lb of fuel would provide 13,400 to 38,400 lb net payload.

It is not necessary that the landing vehicle land after the first deposit of payload; it can return to Phobos. All necessary base equipment can be deposited, first checked out by telemeter, emplaced by remote control, using air dropped planetary surface vehicles to accomplish this, and even operated remotely to grade the runway before the first landing. Also, personnel can be dropped before the first landing to check out and operate delivered equipment. This possibility points out the superiority of the operation of landing on Phobos first and using landing techniques already tested in the lunar soft-landing program.

Simultaneously, the achievement of self-sufficiency should be promoted as quickly and energetically as possible. The first nuclear reactors of the type SNAP IV or possibly more advanced types should be landed with one or two cargo vehicles on Phobos, emplaced, and covered with Phobean loose aggregate to provide reactor shielding. After completion of the emplacement, the power cable is unreeled from the reactor and connected to the base power center. Prior to this time, power is supplied by one of the  $H_2-O_2$  fuel cells or hydrogen expansion turbines. Before switchover, the reactor is activated, heat-rejecting radiators properly positioned and the nuclear-electric power plant checked for proper operation. Then the second unit is set up in identical fashion, checked out, and connected when needed.

Two chemists and geologists, being part of the expedition on Phobos, could investigate the availability of crystal-water-containing rocks. If enough of the required rock compounds are found, one of the modular water-extraction plants, using approximately 5 to 10 per cent of the available power of one of the reactors, could be set up and operated, with the collected water being stored in the highly insulated, pressurized, empty fuel tanks of the cargo vehicles. After this process is checked out and properly working, chemists and geologists could search for rock suitable for use as gravel aggregate for the prepackaged hydroponic garden. During the journey from Earth, oxygen could have been regenerated from  $\text{CO}_2$ , using the Sabatier process and gaseous hydrogen, byproduct of  $\text{CH}_4$  (Methane), which is stored for possible later use. The oxygen regeneration, using the Sabatier Process (see Table 4), is superior to oxygen reconversion by algae and more suitable for flight vehicles. As soon as 40,000 lb of water has been extracted and suitable gravel found and processed, the hydroponic garden could be placed into operation, and with 3600 sq ft of surface area, could supply all the food and oxygen needed for an 18-man crew if properly controlled and operated, the required additional light being supplied again from the nuclear-electric power plants. The Sabatier plants should be kept in stand-by position and operated during periods in which the output of the hydroponic garden does not balance or meet the crew requirement for oxygen.

The next step in achieving self-sufficiency then should be to set up a water-dissociation plant to provide oxygen make-up for the life-support equipment and to supply hydrogen for the Sabatier process. Run at full capacity, the water-dissociation plant will consume 330 kw of power and can

Table 4

COMPARATIVE SYSTEM WEIGHTS AND ENERGY REQUIREMENTS  
FOR SABATIER O<sub>2</sub> - RECOVERY PROCESS

(Reference: RAND Research Memorandum RM-2542)

Item	Stored (Non-regen- erative) System	Water Recovery Only	Chemical Oxygen Recovery	Photosyn- thetic Oxygen Recovery
Resupply Rates (lb/man-day)				
Food (dry basis)	1.250	1.250	1.250	0.625
Contained water	0.125	0.125	0.125	0.062
Packaging	0.138	0.138	0.138	0.069
Water	6.875	0.000	0.521	0.000
Tankage	0.688	0.000	0.052	0.000
Oxygen	2.000	2.000	0.000	0.000
Tankage	1.000	1.000	0.000	0.000
Water-purification materials	0.000	0.500	0.500	0.500
(C) Total	12.076	5.013	2.586	1.256

Power and Radiator Requirements (per man)

Electrical power, watts	172.8	269.0	552.9	7597.0
Radiator surface, ft <sup>2</sup>	4.8	9.1	13.3	243.3

Added Weights of Fixed Equipment (lb/man)

Equipment	18.8	52.2	120.0	1266.0
Prorated power supply	187.7	195.1	215.9	508.0
Radiator (at 1.0 lb/ft <sup>2</sup> )	4.8	9.1	13.3	243.3
Total	211.3	256.4	349.2	2017.3
$\Delta W_F$	0	45.1	137.9	1806.0
$t_c$ , days <sup>a</sup>	---	6.4	38.2	1253.0 <sup>b</sup>

<sup>a</sup>Time in which system becomes lighter than the system in the column to the left of it.

<sup>b</sup>3.44 years--applicable only if used in closed spaceships, permitting no outside supply of water, etc., during operation period.

dissociate enough water in 100 days to supply all the hydrogen and oxygen for a full payload return flight from Phobos into a 300-n. mile circular Earth orbit. However, to accomplish this, a hydrogen-oxygen liquefaction plant using all the advantages of operation on Phobos should be provided, including the required nuclear-electric power plant for its operation, again using the same type as provided for base operation. Having accomplished this, a further step towards increasing self-sufficiency is to provide sources for the major elements needed for the make-up of the nutrient solutions of the hydroponic garden, while the minor or trace elements are represented in such small concentrations (few ppm to fractions of ppm) that their local production would not provide any advantages but rather would be a nuisance.

Since the water-extraction plants are of modular type, several are needed to supply all needs, plus at least one or two stand-bys for maintenance and repair. This available redundancy would lead to the next objective.

##### 5. Mission Objective C and D

During the time the Phobos base is brought to full operation, exploratory flights and later landings could take place on Mars, leading among others to the selection of the best primary and alternate base sites, considering among other items availability of water collection or extraction capabilities. As soon as these are secured, one of the standby extraction plants could be landed on Mars and placed into operation together with the required nuclear-electric power plant, and a dissociation and liquefaction plant should follow as soon as reliable water supply is obtained. Return flights from Mars to Phobos will require from  $1/3$  to  $1/10$  of the fuel capacity needed for the direct return flights to Earth, depending upon the

objective, either to return crews with landing on the Earth's surface, empty boosters, or boosters with full payload to the original exit orbit at Earth. Within a period of 450 days waiting time before return to Earth, the Mars base can be built up with a minimum of risk and with the same degree of self-sufficiency as the Phobos base (Mission objective D). From then on, the major base operation could be transferred to Mars, and Phobos could be used only as a refueling and maintenance base, since the low gravitational acceleration on Phobos would permit crew members to walk around literally carrying weight of 20,000 to 100,000 lb with no strain. It is easy to understand the advantage of assembling even big boosters manually with a few people and a minimum requirement on maintenance structures (Phobos gravity is between 6 to  $10 \times 10^{-4}$  of that of Earth gravity).

With the refueling capability given on Phobos, return vehicles can take off from Mars with a  $\Delta v = 15,500$  fps. The mass ratio required for flights to Phobos is 2.66. With a  $W_0$  of 400,000 lb or approximately 16.5 per cent higher than at its departure from earth orbit, the  $W_e$  will be  $400,000 \text{ lb} / 2.66$  or 160,000 lb. The available payload will be  $W_e - W_{\text{str}} = 160,000 - 17,500 = 132,500$  lb, or approximately twice the payload which can be carried from Phobos to Earth orbit. The excess payload therefore would be either supplies for Phobos or would require the return of two cargo ships to Earth orbit to accommodate the weight. Another way to utilize the payload capability of the cargo vehicles is to load part of the payload with fuel and perform fast returns, requiring a higher  $\Delta v$  for the transfer. After establishment of self-sufficiency of the Mars and Phobos bases, supply requirements will decline more and more and the savings in supplies and logistics will permit a larger fraction of the ships available

load capacity to go into fuel and so will permit reduction of waiting time on Mars and also faster transfer flight, reducing round-trip times to half or less. After achieving refueling capability on Mars, the outbound trips could land directly on Mars using nonlifting or lifting aerodynamic entry.

## B. THE MARS ENTRY VEHICLE

The Mars entry vehicle should be Phobos-based and built to permit landing velocities corresponding to the highest achievable  $c_L$ , an average L/D of three or better at supersonic speeds, and have minimum wing loading of 10 psf (empty except for crews of one or two, including life support for duration of the mission plus 24 hrs). It could be constructed of beryllium, its alloys, or lithium-magnesium alloys to achieve the lowest possible structural weight commensurate with the aerodynamic heating conditions encountered, which will be lower by a factor of at least two due to the lower entry velocity from Phobos as compared to the direct entry from Earth. The leading-edge temperatures will be less than 1500°F, and the surface temperatures of the skin near the leading edges will be in the neighborhood of 1000 to 1200°F. It should have skids for horizontal landing, or skids and a nose wheel for better control after touch-down. It should have vertical take-off capability under rocket power and land under reaction jet control on Phobos. The empty weight including crews and life support should be in the order of 10,000 lb or less, and the take-off weight on Mars to Phobos would be approximately 36,600 to 37,000 lb.

## C. CREW SHELTER UNITS

The crew shelter units should be completely self-contained cylindrical units with emergency power supply, sealed, with airlocks to provide minimum leakage and air losses. They should be designed so that a minimum fire hazard exists. A recommended diameter range is 10 to 12 feet, with unit length of 25 to 30 feet, providing office space, recreation space, laboratories, and sleeping quarters. They should have flat floors and ceilings, with about 6-1/2 to 7 feet ceiling height, with all space below

floors and above ceilings utilized to contain water storage, power supplies, life support equipment, heating and cooling units, electrical wiring, plumbing, and emergency equipment. All vital items should be easily accessible, exchangeable, and maintainable, creating no fire hazard. The units should be covered immediately with about 3 feet of loose aggregate, and later 10 feet of loose aggregate on Phobos, and about 3 feet of loose aggregate on Mars to reduce radiation levels due to cosmic radiation and solar flares to the average long-term level of the Earth surface exposure rates. Placement and installation of these units should require minimum physical labor. On Phobos the low level of gravity of the order of 6 to  $10 \times 10^{-4} g$  should pose no emplacement problem since a single man could move or carry a whole shelter around with no physical effort. Inter-connection of several units also could be handled by a minimum of personnel involved. Dis-assembly or re-assembly of space ships would involve a minimum of scaffolding involving extremely light weight structure.

On Mars, with the surface gravity of approximately .4 Earth surface gravity ( $12.6 \text{ ft} \times \text{sec}^2$ ) emplacement of housing units will require use of planetary surface vehicles designed to operate under Mars surface environmental conditions. These units will have to be equipped with auxiliary tools like graders, rock drills, hydraulic lifts, loaders, etc., to assist to a maximum extent in base establishment. They should permit remote control and remote operation, using TV monitoring, so that the expedition personnel can operate this equipment without leaving their shelter or command post.

D. WATER EXTRACTION AND DISSOCIATION

Many chemical compounds of crystalline rocks contain water of crystallization in varying percentages, with some hydrates containing up to 45 per cent water. Hydrates can be changed to anhydrides by heating to temperatures of 800 to 1000°F. At these temperatures the crystal structure decomposes and releases its water of crystallization. It appears, that feldspar and/or limonite are observable as constituents of the Mars surface, and also magnesium silicate can be expected as surface material if the abundance ratios of elements in cosmic space are applicable to the Martian crust.

<u>Composition</u>	<u>Water content (%)</u>
Magnesium Silicate $3 \text{ Mg O } 3 \text{ Si O}_2 \text{ } 2\text{H}_2\text{O}$	10.7
Limonite $2 \text{ Fe}_2\text{O}_3 \text{ } 3 \text{ H}_2\text{O}$	14.5

Assuming 50 per cent efficiency of the extraction, then approximately 5 per cent actual water yield can be expected if magnesium silicate is used as material. The energy required to separate crystalline water from rocks is approximately 2000 to 7000 Btu per lb H<sub>2</sub>O and temperature of 800 to 1000°F are required to separate respectively liberate water. Details of extraction processes have been described in the literature. To decompose water, approximately 220 kwh are needed to dissociate 33.5 kg of water into 30 kg of O<sub>2</sub> and 3.5 kg of H<sub>2</sub>. During 100 days, and with 220 kw power consumption, 8400 kg of H<sub>2</sub> and 72,000 kg of O<sub>2</sub> can be dissociated, producing 175,000 lb of rocket fuel during this time, provided the gases can be liquefied and stored. Using 330 kw, the fuels for one return vehicle, carrying a full payload back into Earth orbit from Phobos, could be provided. The weight of a plant of a daily capacity of 1 ton of cryogenic H<sub>2</sub> and O<sub>2</sub> is estimated to

be 30,000 lb. One megawatt of power would be needed to extract, dissociate, and liquefy one ton of water to cryogenic oxygen and hydrogen. With a yield of 5 per cent water, 1600 tons of rock would have to be processed, or 16 tons a day. It is of interest to know that on Phobos these 16 tons weigh approximately 35 Earth lb and could easily be lifted by one man and hand-carried to the rock crusher.

The required process rate goes down if either a higher extraction rate can be obtained or a rock compound of higher water content can be found. This example shows that search for higher-yield compounds should have priority. Another source of water is subterranean ice deposits which could possibly be found near volcanically active formations on Mars or in crevices at higher latitudes, since the low vapor pressure of ice prevents sublimation at low temperatures (as exemplified by the ice caves in the New Mexico desert). The probability of finding such deposits during early Mars occupation phases is considered very remote. Volcanic activity is not expected on Phobos.

#### E. HYDROPONIC GARDEN OPERATION

Hydroponic gardens are soilless garden cultures, in which plants are grown in inert sand or gravel. A nutrient solution is drained once or twice daily through the sand or gravel beds, wetting the plant roots and the sand or gravel. If the nutrient solution has the optimum mineral composition needed by any one plant, and the environmental temperature is close to the mean temperature that the specific plant needs to attain its maximum growth rate, growth occurs as fast or faster than under natural environment. Many plants need a diurnal temperature cycle to grow best, and in these cases the hydroponic culture also needs this cycling to be most successful. Draining the nutrient solution through the sand or gravel beds provides an

aeration of the roots not obtainable in nature. Since the solution is in contact with the gravel or sand beds only a few minutes every day, the same solution can support many gravel beds, as long as its composition is closely controlled and its basic pH value maintained. Besides providing vegetable food or organic foods, hydroponic gardens are efficient converters of  $\text{CO}_2$  into  $\text{O}_2$ , using photosynthesis. Algae are more efficient converters of nutrients but only 1 to 2 per cent of algae weight can be supported by the nutrient solution, whereas up to 30 per cent of the water in circulation can be contained in the plants of hydroponic gardens if a good utilization of the water is achieved. For planetary ecological systems, hydroponic gardens are quite important as oxygen recovery systems as well as sources for fresh vegetables and vitamins; they appear to provide more palatable food than algae and, what is most important, a variety and combination of foods that man is used to. It has been claimed that it would take up to eight years before the effort to set up a hydroponic garden would break even with the direct supply of life supports from Earth. However, this is only the case if the water utilization in the hydroponic garden is poor, no construction materials for the garden are taken from discarded space ships, and no local inert gravel or sand supplies are used. If water can be found or extracted locally, discarded fuel-tank sections can be used to provide the shells of the hydroponic gardens, and these can pay off in less than half a Mars mission cycle, contributing much to the achievement of base self-sufficiency. Table 2 presents vital design data for a hydroponic garden to provide all the vegetable foods for a crew of 18.

V. SUMMARY

The preceding analysis shows that the natural satellite Phobos might well be used as a terminal for a scientific Mars expedition, before manned landing on Mars is attempted. With the surface gravity of Phobos being only one thousandth of the gravity of Earth, the only penalty paid for the use of the satellite is the velocity increment required to match the Phobos orbit with an orbital plane inclination of approximately  $26.5^{\circ}$  to the arrival plane of Earth space ships, if Hohmann transfers are used. This velocity increment is approximately 7600 fps, which is somewhat more than the velocity increment needed to achieve Mars orbit capture and somewhat less than that needed to soft-land on the Moon. From this, the conclusion can be drawn that at the time a manned-lunar-landing capability has been achieved, the capability to land on Phobos will have been obtained. After setting up a manned base on Phobos, optical observation and mapping of the Mars surface can be done before exploratory flights near the Mars surface are performed to choose a promising base site. Even delivery of cargo, supplies, and base modules, setting up the base by use of remotely operated and TV-monitored planetary surface vehicles, and runway grading can be performed before the first manned vehicle lands. It is also shown that achievement of a self-contained-base capability as early as possible and the ability to extract water from rocks could lead within present technology to production of cryogenic hydrogen and oxygen on Phobos and Mars, thus relieving the need to transport fuels for return flights to the Earth or its satellite. With the reduction in logistics requirements, return cargos can be brought to Earth. It appears that the study of these approaches may lead to earlier planetary

exploration and utilization of Mars than could be expected by waiting for the availability of nuclear or ion propulsion systems. On this basis, the original transfer stages used for transit from circular Earth orbit to landing on Phobos and back would continue to be used after self-sufficiency of the planetary stages has been achieved due to the reduced cargo-requirement. In this case, a larger share of fuel and therefore a higher mass ratio will be achieved, leading to a higher  $\Delta v$ , now permitting faster transfer and/or reduction in waiting times. The then possible re-use of the vehicles will lead to a better utilization of the original investment. After completion of the Mars base and achievement of a fuel-production capability, flights can be made directly between Earth and Mars, using Phobos as a return, refuel, and maintenance base. Possible approaches towards achievement of self sufficiency are discussed. Tables 5A and 5B summarize the results, which show that case B<sub>a</sub> has the lowest vehicle requirement (12) for establishment of a temporary base on Mars and full capabilities of the transfer booster for return to Earth orbit. Case D<sub>a</sub>, not treated in detail in Section IV, is almost numerically identical to Mission Objective C, having a requirement for 13 vehicles, but represents a full permanent-Mars-base capability and maintenance-and-refueling capability on Phobos. This appears to be the far superior solution.

Table 5A

A, B, C, D, = Mission types

Subscript 1 = impulsive landing on Mars

a = aerodynamic landing on Mars

1 = single-stage transfer vehicle between Earth orbit and Mars orbit

2 = two-stage transfer vehicle between Earth orbit and Mars orbit

18-man-mission strength, 3 manned vehicles to return to earth.

400,000-lb cargo at destination if self-contained; 600,000 lb if fuel-producing for return flights; 400,000 lb on Mars and 400,000 lb on Phobos produce all fuels for return flights to Earth, flights on Mars, and Mars-to-Phobos flights.

Mission Type	Amount of Cargo Landed on Mars per Vehicle (lb)	Amount of Cargo Landed on Phobos per Vehicle (lb)	Fuel for Return of Manned Vehicle to Earth Surface (lb)	Fuel per Cargo Vehicle for Return to Earth Orbit (lb)
A <sub>11</sub>	17,500	none	~90,000	350,420
A <sub>12</sub>	27,500	none	~90,000	?
A <sub>a1</sub>	67,000	none	~90,000	350,420
A <sub>a2</sub>	87,400	none	~90,000	?
B <sub>a</sub>	28,000 to 38,000	65,000 <sup>a</sup> 70,000 <sup>b</sup>	~20,000	303,000
C <sub>a</sub>	65,000	65-70,000	~20,000	303,000
D <sub>a</sub>	65,000	65-70,000	~20,000	303,000

a. Manned vehicle

b. Cargo vehicle

In the case of single-stage operation, the Earth-escape vehicle can be used both ways and therefore is fully recoverable if fuel is produced at the destination; two-stage transfer vehicle would lose the lower stage in transfer and would have lower return payload capability, which has not been computed but is expected to be on the order of 1/3 that of the single-stage vehicle. For Phobos landing, only single-stage vehicle have been considered.

Table 5E

A, B, C, D = Mission types  
 Subscript 1 = impulsive landing on Mars  
 a = aerodynamic landing on Mars  
 1 = single-stage  
 2 = two-stage

400,000-lb payload on destination required to complete base.  
 600,000-lb payload, including return fuel, required to achieve self-sufficiency.

Manned vehicles are returned to Earth with aerodynamic re-entry, in each case. Cargo vehicles are returned to 300 n mi circular orbit, if return fuel is produced at departure station. In the case of a permanent base on Phobos, 3 vehicles deliver cargo on Mars and return to Phobos, of which at least one lands on Mars and returns crew.

Mission Type	Payload on Mars (lb)	Payload on Phobos (lb)	Number of Vehicles Required to Complete Mission	Return Cargo per Vehicle (lb)
A <sub>11</sub>	400,000	none	44	0
A <sub>12</sub>	400,000	"	28	0
A <sub>11</sub>	600,000	"	40	27,800
A <sub>12</sub>	600,000	"	26	27,800
A <sub>a1</sub>	400,000	"	12	0
A <sub>a2</sub>	400,000	"	9	0
A <sub>a1</sub>	600,000	"	11	27,800
A <sub>a2</sub>	600,000	"	9	27,800
B <sub>a</sub>	107,200	400,000	10	0
B <sub>a</sub>	107,200	600,000	12	79,500
C <sub>a</sub>	400,000	600,000	16	79,500
D <sub>a</sub>	400,000	400,000	13	79,500

Note: Difference between B<sub>a</sub> and D<sub>a</sub> is that in B<sub>a</sub> only a temporary base exists on Mars with no direct return capability to Earth, while D<sub>a</sub> permits return either way and can make use of fast return trips. In D<sub>a</sub>, Phobos has limited crew facilities but is a maintenance and refuel base.

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