INTERIM REPORT

MARS LANDER/ROVER VEHICLE DEVELOPMENT

An Advanced Space Design Project

for

USRA and NASA/OAST

FALL 1986

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UTAH STATE UNIVERSITY
Logan, Utah

INTERIM REPORT (32 Pages)

THE MARS LANDER/ROVER (MLR)

An Advanced Space Design Project
for
USRA and NASA/OAST

by
UTAH STATE UNIVERSITY

Growing interest in a future manned mission to Mars illuminates a critical need for more information on the Martian environment, surface conditions, weather patterns, topography, etc. While the Viking landers provided valuable information of this type, they did it only from fixed locations. There is a real need for Viking type information from a number of locations on the Martian surface in order to adequately survey the planet for future landing and exploration sites. Current site survey mission discussions range from Mars orbiters to sample return missions. The limited data return from the former and the extreme expense of the latter suggest consideration of a "middle ground" mission which provides needed survey information for an acceptable investment.

Utah State University (USU) proposes to design a MARS LANDER/ROVER (MLR) for use in gathering needed environmental and surface information from Mars. Philosophically, the MLR will resemble a mobile Viking; that is, it will move from location to location on the Martian surface, measuring environmental conditions, analyzing soil samples, charting topographical features, etc. Measured data will then be telemetered to Earth for further analysis.

Conceptually, it is envisioned that the MLR survey locations will be rather widely separated. In that sense, the MLR will not be a terrestrial vehicle limited to local movement about a fixed location. Rather, it will have the capability for movement over long distances to reach widely separated locations.

The design focus, then, will be upon a MARS LANDER/ROVER that will leave an orbit around Mars, reenter and soft land on the Martian surface, and move sequentially to widely scattered locations to sample, measure, and analyze Martian environmental and surface conditions.

The design course will be offered for 1 credit hour during Fall Quarter. Primary goals will be payload mass and size definition, characterization of the Martian atmosphere, selection of sampling locations, identification of alternative design concepts, selection of a preferred design, team organization, and preparation for the detailed design phase. The tempo (and credit) of the course will increase substantially during Winter and Spring Quarters as the detailed design phase is entered and completed.

The MARS LANDER/ROVER (MLR) design project at Utah State University (USU) commenced Fall Quarter 1986 with the goal of determining preliminary information pertaining to design constraints, feasibility, and system mass. In order to accomplish these objectives, the class was divided into four groups: Payload Sizing, Soft Landing, Trajectory and Environment, and Rover Systems. Each team investigated their area and presented weekly progress summaries in class meetings. These meetings provided an opportunity for exchange of information between the groups and discussions with an emphasis placed on the interdependency of systems in this type of design task.

A good portion of the quarter was spent becoming familiar with current information concerning Mars and the various probes which gathered that data. Two major sources of information were the NASA Advisory Council document: Planetary Exploration Through Year 2000: An Augmented Program and the Viking Mission to Mars book from which some of the following pages have been reproduced for reference.

MORE FACTS ON MARS

VIKING: Viking 2 transmitted data until 1980, and Viking 1 sent data until 1982.

TOPOGRAPHY: Mars' northern and southern hemispheres are radically different. If one were to draw a line on a 35° tilt from the equator, it would bisect the planet where the two different topographies meet. The northern hemisphere seems to have older geographic features than the southern hemisphere. It is smoother than the southern hemisphere, yet the large volcanoes, such as Olympus Mons which could fill the heart of Texas, are found in this hemisphere. The surface seems to have been heavily eroded and resurfaced by lava flows from the numerous volcanoes in this region. There are very few craters in this region. The southern hemisphere, on the other hand, is heavily cratered; it is cratered to saturation. There is a giant crater up to 4 km deep called Hellas Planitia that could swallow up Alaska with room to spare. The cratering appears to be similar to that on the bright lunar highlands which happened more than 4 billion years ago. It is believed that both the lunar and martian craters were formed at approximately the same time. This means that the geologic features on Mars are very old because most of them were formed previous to the meteor bombardment. The landforms on Mars have remained unchanged for billions of years.

POLAR CAPS: During the winter, the polar ice caps expand to about the 40° latitude line. In the summer, they shrink to about the 80° latitude line. In the summer, the northern ice cap seems to be mostly water, and the southern cap appears to be mostly carbon dioxide.

DUST STORMS: Mars has fierce dust storms that can go as high as 50 km.

CLOUDS: Mars also has water-ice clouds as high as 10 to 25 km.

ORBIT: Mars has an off-center nearly circular orbit that loops at one end 42.4 Mkm further from the sun than at the other end. If Venus swung out that far, it would intersect the Earth's orbit. Mars is at its closest to Earth every 15 to 17 years.

SAMPLE RETURN/ROVER MISSION TO MARS

The basic scientific objectives for Mars exploration are:

(1) the need to characterize the internal structure, dynamics, and physical state of the planet;

(2) the need to characterize the chemical composition, mineral composition, and physical character of surface materials over the planet;

(3) the need to determine the chemical composition, mineral composition, and absolute ages of rocks and soil for the principle geologic provinces;

(4) the need to determine the chemical composition, distribution, and transport of volatile compounds in order to understand the formation and chemical evolution of the atmosphere and the interaction of the atmosphere with the surface material;

(5) the need to determine the quantity of polar ice, and estimate the quantity of permafrost present on Mars;

(6) the need to determine the processes that have produced the landforms on the planet;

(7) the need to characterize the dynamics of the martian atmosphere on a global scale;

(8) the need to characterize the planetary magnetic field and its interactions with the upper atmosphere, incoming solar radiation, and the solar wind;

(9) the need to determine what organic, chemical, and biological evolution has occurred on Mars and explain how the history of the planet constrains these evolutionary processes.

NASA has several missions planned for the 1990's which will try to accomplish these objectives. One of these missions is the MARS OBSERVER which will try to determine the global elemental and mineralogical character of the surface material; define globally the topography and gravitational field; establish the nature of the magnetic field; determine the time and space distribution, abundance, sources, and sinks of volatile material and dust over a seasonal cycle; and explore the structure and circulation aspects of the atmosphere.

Then, there is the MARS AERONOMY OBSERVER which will try to determine the diurnal and seasonal structure variations of the upper atmosphere and ionosphere; determine the solar wind interaction with the atmophere; and measure the escape rates of atmospheric constituents and infer what these rates indicate for the history and evolution of the martian atmosphere.

Also, there is the MARS NETWORK OBSERVER which will try to determine the seismicity and internal structure of Mars; measure the local atmospheric temperature and pressure continually for a Mars year at several locations to provide understanding of the general circulation of the martian atmosphere; and determine the chemical composition of martian near-surface material.

And finally, there is the SAMPLE RETURN/ROVER mission. NASA's objectives with a sample return mission are the following:

(1) the sample return mission should not include activities that are objectives of the other missions in NASA's core program;

(2) as many experiments as possible should be done on Earth to reduce bulk as well as to allow re-experimentation using the same samples;

(3) each of the following key geologic units should be sampled: young volcanic units; intermediate age volcanic units; ancient cratered units; layered units; and polar units;

(4) key material to be sampled on Mars for return to Earth are: fresh igneaous rocks; weathered igneaous rocks; breccias; sedimentary rocks;

regolith; wind-blown sand and dust; and possibly atmosphere;

(5) the prime sampling objective of a first mission is to collect both fresh and weathered samples of the most abundant types of materials in the neat vicinity of the lander;

(6) special sampling tools and containers are required in order to sample a wide range of martian materials that include hard rock, regolith, non-cohesive materials, and possibly atmosphere;

(7) significant sampling mobility, significant sampling time, and a reasonable returned sample mass, are required to properly sample the materials available at a single VIKING-like landing site;

(8) to be assured of being able to reach outcrops of fresh igneous rocks from the landing site, it will be necessary to have even more sampling mobility, ranging from one to two kilometers from the landing site in young volcanic regions to ten to twenty kilometers from the landing site in ancient cratered regions;

(9) the environment imposed on the samples during return to Earth should maintain, as closely as possible, the conditions which the samples experienced on Mars;

(10) the currently available VIKING imaging data are sufficient to identify suitable candidate landing sites for sample return missions;

(11) the capability to provide a small landing error ellipse, combined with fairly extensive sampler mobility would permit sampling of several key geologic units from a single landing site;

(12) the capabilities developed for a mobile sampler could also make it possible to carry out some prime scientific objectives of a surface rover mission.

The rover as a part of this mission should be designed to carry out the functions that a field geologist would perform. It should do nothing unrelated to sample collection. The rover should be able to lift samples, to examine their details closely, and to estimate their weight and density, thereby evaluating the amount of weathering. It should carry out simple chemical tests like those made with a geologist's traditional Geiger counter or acid bottle. And, it should be able to provide this information to Earth so that a decision can be made, either to collect a given sample or to discard it and move on to another.

The main reason for bringing the samples back to Earth for testing is because it enables scientists to perform extra tests on a sample based on unexpected results. The VIKING experiments produced many unexpected results that scientists were unable to follow up on because the probes were not prepared to perform other experiments. Scientists on Earth can also perform the experiments with state-of-the-art technology. Bringing the samples back also allows effective separation and concentration of mineral phases, based on the specific properties of the sample. Scientists can even defer certain experiments to a later date when better analytical technology or understanding is available.

The samples should not be sterilized. They should be contained in an atmosphere as close to the martian one as possible. The space station could play an important role by making it possible to perform preliminary analyses on the samples without risking contamination of the Earth biosphere.

The space station could also be used as a possible fueling station or relay station for the Martian Sampler. NASA would like the sampler to return on many missions to get as many samples as possible.

The site selected for the landing should be as close to the different kinds of topography as possible. There are four major kinds of sites on Mars:

ancient units (heavily cratered terrain), volcanic units, polar units, modified units (hummock terrain with chaotic, fretted, and knobby features, interspersed with channel deposits, plains and grooved terrains.) The data needed for site selection can be obtained from previous missions to Mars.

A study by JPL indicates that the working premises of a martian sampler mission should include the following:

(1) five kilograms of samples are collected by a 400-kilogram Rover and are returned to Earth in a 50-kilogram Earth return capsule;

(2) a precursor imaging mission is not necessary due to the amount of pertinent data from previous missions;

(3) the 1996 launch opportunity for Mars is used as a baseline;

(4) and several different mission possibilities should be considered:

(a) direct entry to Mars vs. out-ot-orbit entry

(b) direct return to Earth from the surface of Mars vs. return to Earth from Mars orbit following a Mars-orbitalk rendezvous

(c) insertion into Mars orbit with a propulsive stage, followed by aeroballistic entry into Mars vs. insertion into Mars orbit by aerocapture, followed by aeromaneuver entry.

A mission should also consider the possibility of manufacturing some of the fuel needed from the martian atmosphere itself. A brief study indicates that enough oxygen is in the atmosphere to be the oxidizing agent in a propulsion system consisting of methane and oxygen. Only the methane needs to be carried by the sampler. The launch mass requirements would be reduced by about 30% for missions involving Mars-orbital rendezvous and about 50% for missions involving direct return to Earth. The technology is still in an early stage of production, but could feasibly be used in future missions.

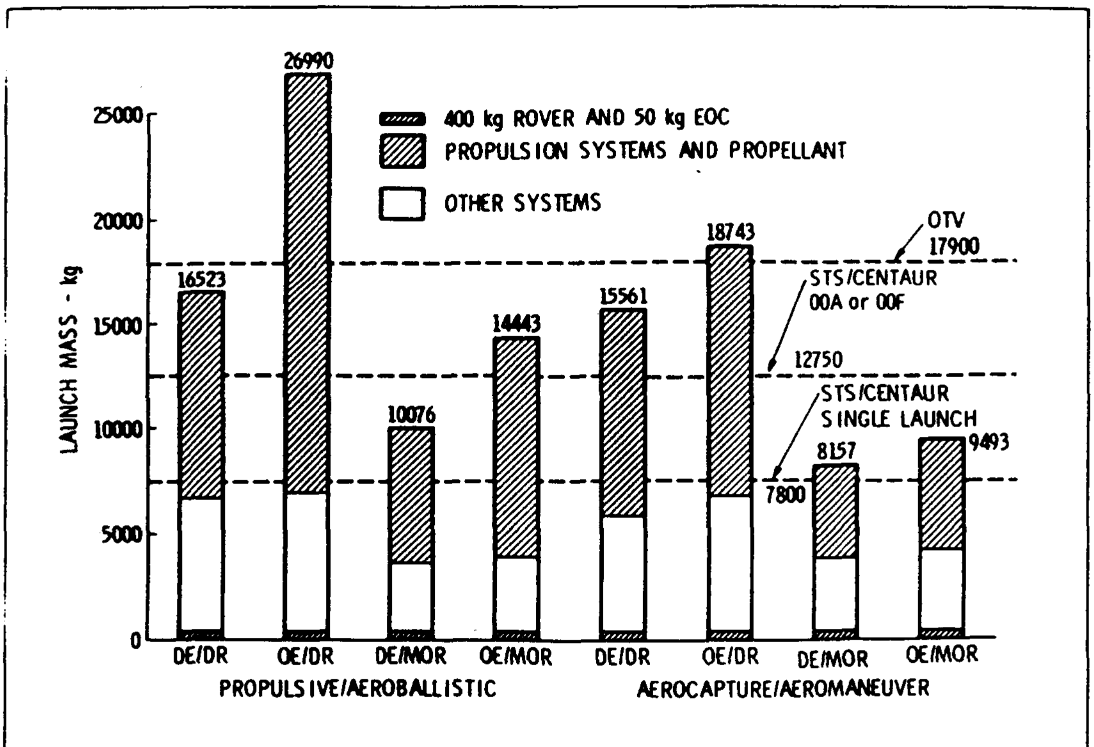


Figure 3. *MSR* Mission Options–Launch Mass Requirements (1996). Abbreviations: DE = direct entry into Mars atmosphere from Earth, followed by landing; OE = out-of-orbit entry into Mars atmosphere, followed by landing; MOR = Mars orbital rendezvous after ascent from Mars surface; DR = direct return to Earth from Mars surface.

Mars Sample Return Mission: Candidate Landing Sites*

Site	Approximate Coordinates	One-Way Linear Roving Distance Required (km), Given Landing in Ellipse (km x km)		Sampling Objectives
North Pole A	86.5°N, 120°W	0	(50 × 80)	Perennial north polar ice
North Pole B	84.5°N, 105°W	30	(50 × 80)	Perennial north polar ice; soil from perennially ice-free trough
Arsia Mons West	8°S, 132.5°W	4.5	(50 × 80)	Young volcanic rocks
Apollinaris Patera Northwest	5°N, 190°W	6	(50 × 80)	Young volcanic rocks; eolian sediments
Chryse Planitia (VL-1 Site)	22.5°N, 47.9°W	2.5	(50 × 80)	Impact-crater ejecta; fluvial (outflow channel) sediments
Schiaparelli Basin Southwest	8°S, 336°W	18	(50 × 80)	Oldest martian crustal rocks from ancient, heavily cratered terrain
Tyrrhena Terra	7°S, 243°W	5	(5 × ?)	Oldest martian crustal rocks from ancient, heavily cratered terrain;
		5	(30 × ?)	Old volcanic rocks that mantle ancient crust
Iapygia	11°S, 278°W	5	(same as for Tyrrhena Terra)	
Candor Chasma	6.3°S, 73.8°W	5	(5 × ?)	Layered rocks from a canyon
Hebes Chasma	7°S, 77°W	5	(5 × ?)	Layered rocks from a canyon

DE/DR OPTION	(kg)	OE/MOR OPTION	(kg)
		Orbiter	800
		Propellant	460
		Earth Return Vehicle	210
		Propellant (2.2 km/s)	410
		Earth Orbit Capsule	100
		Total Orbiting Systems	1980
Earth Orbit Capsule	50	Sample Canister	20
Earth Return Vehicle	270		
Propellant: (2.3 km/s)	520		
Ascent Systems	550	Ascent Systems	680
Ascent Propellant (4.2 km/s)	5980	Ascent Propellant (4.5 km/s)	1940
Rover	400	Rover	400
Lander	1300	Lander	1080
Total Landed Systems	9070	Total Landed Systems	4120
Entry Systems	4310		2400
Cruise Support	330		---
Midcourse Propellant	1110		580
Adapter and Bioshield	780		420
Total Launch Mass	15600		9500

Centaur G-prime capability (full tanks) 12750 kg

Figure 4. Preliminary Mass Breakdown of DE/DR Option vs. OE/MOR Option.
For definitions, see Figure 3 and text.

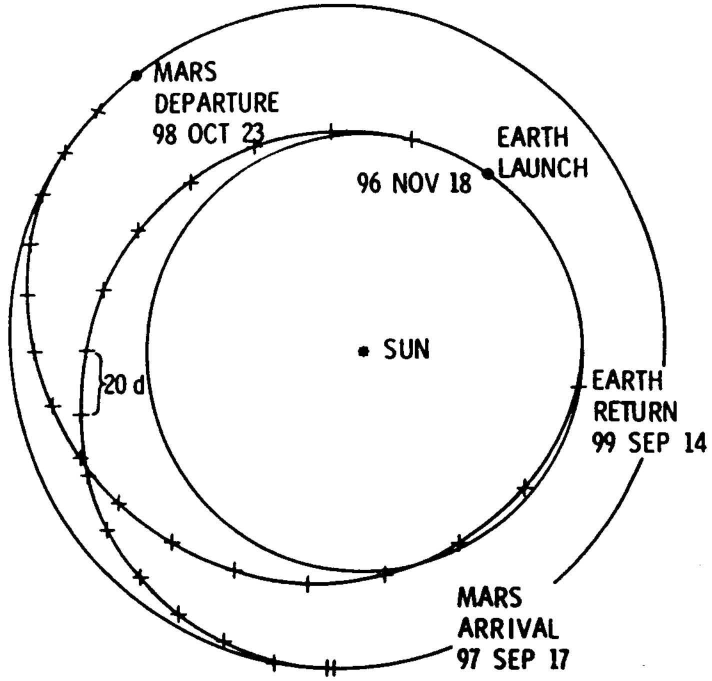


Figure 6. Heliocentric View of Interplanetary Trajectory

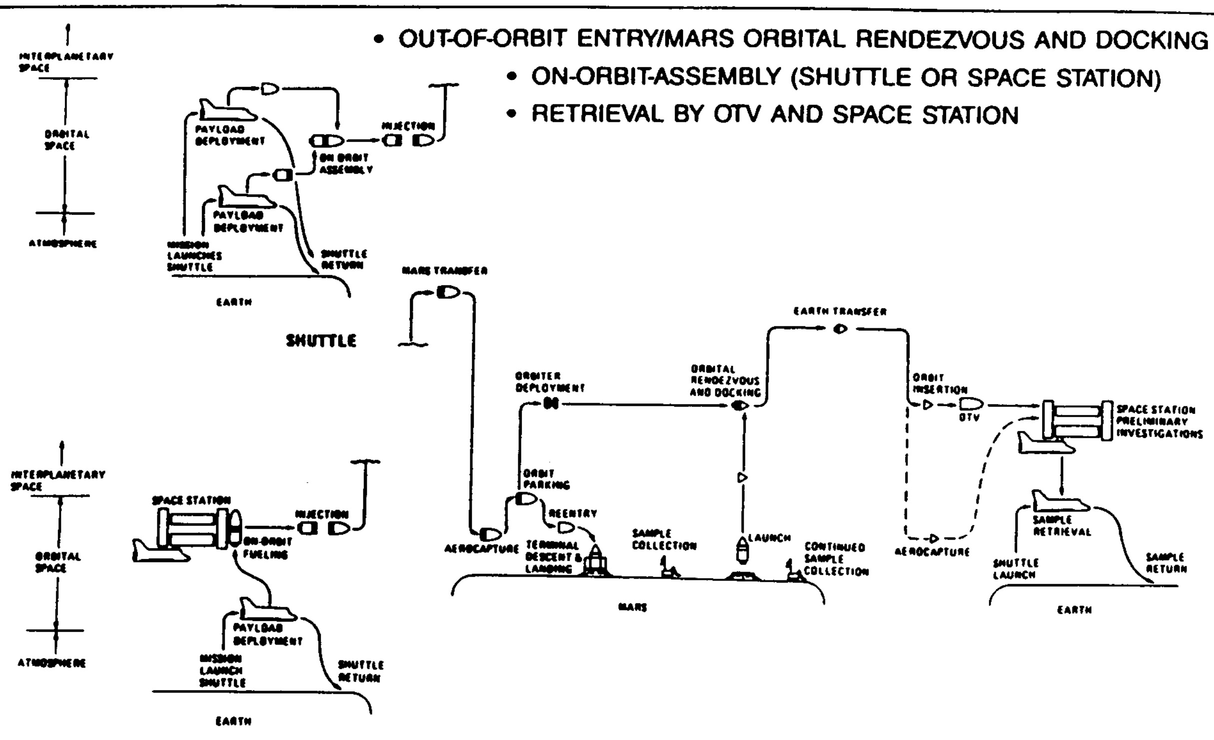
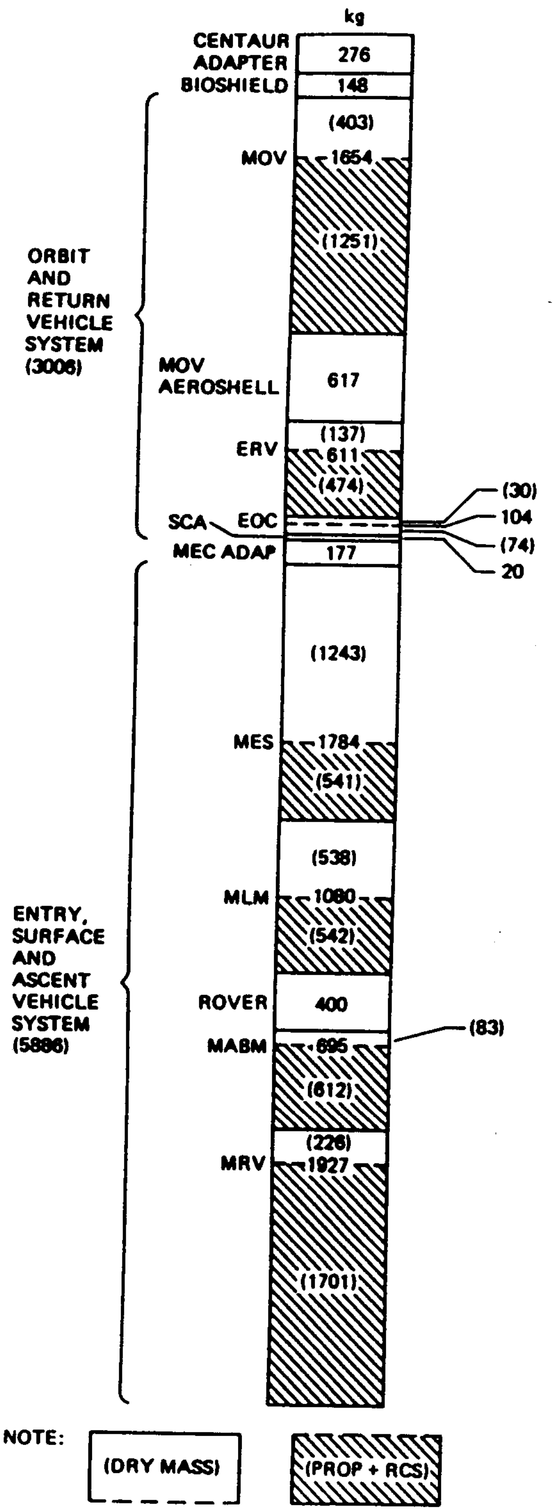
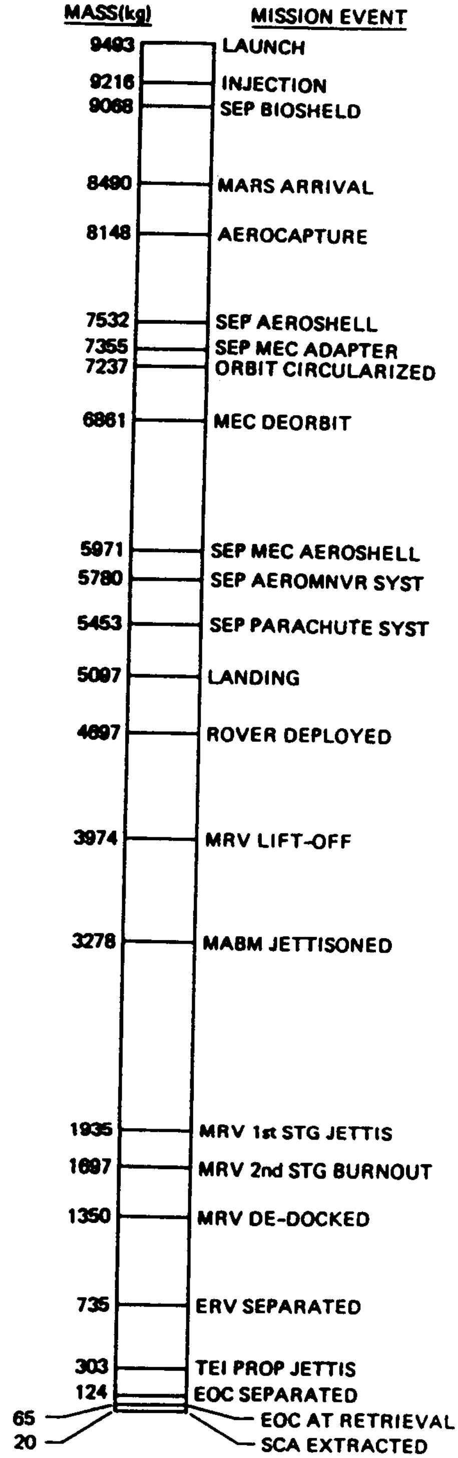


Figure 7. ***MSR*** **Schematic Mission Sequence**



a. BY VEHICLE/MODULE



b. BY MISSION SEQUENCE

Given this and other data, estimates of system requirements, sizing, and other parameters were made. Through interactive discussion in class, outside of class meetings and research, interim reports were generated. These documents represent summaries of on-going studies, and, as such, should not be viewed as concrete. Rather, they should be viewed as baselines from which to proceed into the more definitive system design studies of Winter Quarter.

PAYLOAD SIZING

Early in the sizing process, certain initial assumptions were made in order to provide the first iteration estimations:

1. This system will employ a rover (or rovers) which will be deployed on the surface of Mars and will remain on Mars. These vehicles will perform various tests on soil and rock samples, employ television cameras and other sensors, and have the ability to store samples for a rendez-vous with a future sample return mission.
2. The mission will include an orbiter which will augment communications between the rover(s) and Earth, as well as providing remote sensing data. This precludes the possibility of direct entry into the Martian atmosphere.
3. An expendable lauch vehicle system, such as the Titan IV - Centaur, will be used for this mission.

The following calculations employed ratios based upon the Viking missions for sizing the mass delivered into Mars orbit:

Assumptions:

1. Present-day Titan IV-Centaur launch capabilities, in terms of mass delivered into a Viking-typical orbit (930 x 20,500 miles), is double that of the system which propelled Viking.

2. System masses vary linearly; that is, proportional scaling may be employed, based on Viking, in order to estimate the payload component masses for this first study.

3. The orbiter will have a mass 20% larger than that of the Viking orbiter.

In support of Assumption #1: The Titan IV-Centaur can deliver 10,000 lbm into GEO, as compared to 4,500 lbm for the system used for Viking.

Viking characteristics:

M	Mass delivered into Mars orbit	: 7,658 lbm	(3,481 kg)
M_{Lo}	Lander mass, prior to descent	: 2,633 lbm	(1,197 kg)
M_{L1}	Landed mass	: 1,320 lbm	(600 kg)
M_D	Descent system mass	: 1,313 lbm	(597 kg)
M_o	Orbiter mass (including fuel)	: 5,125 lbm	(2,330 kg)
M_{op}	Orbiter Propellent mass	: 3,137 lbm	(1,426 kg)

Orbiter Fuel Fraction: $O_f = M_{op}/M_o = 0.612$

Lander "Fuel" Fraction: $L_f = M_D/M_{Lo} = 0.4987$

Note: This "fuel: mass includes the mass of all descent system components; i.e., aeroshell, directional engines, parachute assembly, and terminal descent engines.

Mission Sizing:

In order to provide a mass margin, the delivered Mars orbiting mass is assumed to be 175% that of Viking (recall assumed launch/delivery capabilities as double):

$$M = 1.75(3{,}481 \text{ kg}) = \underline{6{,}092 \text{ kg}}$$

Orbiter mass, M_O, invoking Assumption #3, is 120% of the Viking orbiter mass:

$$M_O = 1.2(2{,}330 \text{ kg}) = \underline{2{,}796 \text{ kg}}$$

Therefore, the Lander mass prior to descent, M_{Lo}, is:

$$M_{Lo} = M - M_O = \underline{3{,}296 \text{ kg}}$$

The descent mass, M_D, is given by:

$$M_D = L_f M_{Lo} = \underline{1{,}644 \text{ kg}}$$

The remainder is the Landed mass:

$$M_{L1} = M_{Lo} - M_D = \underline{1{,}652 \text{ kg}}$$

Using the orbiter fuel faction, the Orbiter Characteristics are:

$$\text{Orbiter Fuel Mass} = O_f M_O$$
$$M_{Op} = \underline{1{,}711 \text{ kg}}$$

$$\text{Orbiter Dry Mass} = M_O(1-O_f) = \underline{1{,}085 \text{ kg}}$$

Summary and Discussion:

Total mass delivered into Mars orbit: 6,092 kg

Orbiter: Total Mass: 2,796 kg
Fuel Mass: 1,711 kg
Dry Mass: 1,085 kg
Fuel to Mass Ratio: 0.612

Lander: Total Mass on Orbit: 3,296 kg
Landed Mass: 1,652 kg
Descent System Mass: 1,644 kg
"Fuel" to Mass Ratio: 0.4988

Comments:

1. The total mass delivered to Mars orbit is felt to be reasonably conservative in light of the use of 88% of the assumed launch/delivery capabilities. Specific figures concerning present-day ELV capabilities will make these estimates more realistic.

2. The orbiter mass increase of 20% over that of the Viking orbiter, along with advances in miniaturization of electronics, should allow not only sufficient support services for the lander(s), but expanded remote sensing capabilities as well.

3. The landed mass of 1,652 kg represents an increase of 175% over that of the Viking missions. This figure provides for the mass which is likely to be required for global mobility and/or a multiple lander/rover system.

4. The above calculations depend largely upon the linearity of Assumption #2. It may evolve, especially in the descent system, that the masses do not vary in a linear fachion. This is a point to be investigated further during the remaining design procedures.

A more thorough analysis was performed next, again based upon mass figures from Viking. Assuming launch capabilities as described above, and employing 1.75 times the mass of Viking in Mars orbit or 6,158.2 kg, various systems and components were sized as described below. The assumed orbiter mass is 2,776 kg, leaving 3,382.25 kg for the lander/rover.

The vehicle dry mass (without fuel and/or descent system) was estimated using Viking-typical equipement with consideration for technological advances. The scientific payload includes experiments carried on Viking and provides for (at least) 50 kg additional scientific mass.

The dry mass of the vehicle is simply the allowable total mass minus the propellant. The payload mass is then the dry mass less the mass for all non-science components. Table #1 summarizes the estimated masses for the non-science equipment similar to that of Viking as a minimum scientific payload mass. The last two tables provide a break-down of estimated mass distribution for the lander/rover and orbiter, respectively. The contingency mass in Table #3 represents payload mass beyond the minimum scientific mass defined in Table #2. This could be used for greater payload capabilities, multiple rover systems, or a combination of these.

SUBSYSTEM AND ELEMENT	ESTIMATED MASS (Kg)	SUBSYSTEM MASS (Kg)
STRUCTURE (Lander+Rover)		250.0
Body (Lander+Rover=175+40)	215.0	
Legs	25.0	
Mechanisms	2.0	
Arm	3.0	
Harness (15 - 4,wire bundles)	5.0	
PROPULSION		60.0
Propellant Tank	10.0	
Landing Engines	50.0	
POWER		67.7
Batteries	40.0	
Radioisotope Thermoelectric Generators (2)	27.2	
Control Electronics (2 cards)	0.5	
THERMAL		16.2
Bioshield cap + base	5.0	
Aeroshell	5.0	
Heat Shield	5.0	
Heaters	0.2	
Insulation	0.5	
Control Electronics (2 cards)	0.5	
CONTROLS		2.5
Attitude Sensors	2.0	
Control Electronics (2 cards)	0.5	
TELEMETRY AND COMMAND		112.7
Parachute	70.0	
Data Aquisition & Processing	8.0	
Tape Recorder	5.0	
Inertial Reference Unit	14.5	
Radar Altimeter	5.2	
Terminal Descent & Landing Radar	3.0	
Computer	5.0	
Other Electronics	2.0	
TOTAL VEHICLE DRY MASS		509.1

TABLE : 1
ESTIMATED DRY MASSES FOR NON-SCIENCE PAYLOAD EQUIPMENT

SCIENCE PAYLOAD EQUIPMENT	ESTIMATED MASS (Kg)
UPPER ATMOSPHERIC MASS SPECTROMETER	6.12
LOWER ATMOSPHERE STRUCTURE EXPERIMENT (essential for guidance control)	1.25
CAMERAS (2)	14.52
METEOROLOGY INVESTIGATION (seismometer)	2.22
MOLECULAR ANALYSIS INVESTIGATION (fuel manufacturing experiment)	18.78
SAMPLE CAPSULE	5.00
OTHER EXPERIMENT ANTICIPATED	50.00
TOTAL =	102.77

TABLE : 2
ESTIMATED DRY MASS FOR SCIENCE PAYLOAD EQUIPMENT

MASS BREAKDOWN (Lander)	ESTIMATED MASS (Kg)
TOTAL LAUNCH MASS (i.e.,Lander+Rover)OE/MOR option	3382.25
PROPELLANT MASS (for Lander+Rover)	1758.77
ALLOWABLE DRY MASS	1623.48
Vehicle Dry Mass (i.e., structure+subsystems)	509.10
ALLOWABLE PAYLOAD MASS	1114.38
Science Payload Mass	102.77
CONTINGENCY MASS	+1011.61

TABLE : 3
MARS LANDER & ROVER MASS ALLOCATION

MASS BREAKDOWN (Orbiter)	ESTIMATED MASS (Kg)
ORBITER	1088.1
PROPELLANT	1701.9
TOTAL =	2790.0

TABLE : 4
MARS ORBITER MASS ALLOCATION

Launch Vehicle:

A Titan-Centaur combination was considered as a potential launch vehicle for this project. Also investigated was the use of the space shuttle, augmented by either the Centaur G-Prime or the Inertial Upper Stage (IUS). The Centaur G-Prime program was discontinued in June 1986, leaving the IUS as the only option, at present, for use with the shuttle. The IUS has been approved for use on the shuttle and is operational. It is capable of delivering 2,300 kg into GEO. The guidance system, a star scanner, has potential for use in this application. The mass limitation, however, may be too low for this mission.

Based upon this information, it was decided that the best candidate launch system is the Titan IV-Centaur. Due to the uncertainty of the shuttle launch schedule and present mass limitations with the IUS, this ELV system appears to be best suited to delivering the target mass into Mars orbit.

SOFT LANDING

The mission of the Soft Lander Team was to examine options for safely landing a rover vehicle on the Martian surface. Depending upon the type of rover, the landing system may have to be capable of multiple landings in varied terrain. Therefore, the development of a reusable system that did not require a large fraction of the total lander/rover mass or a lot of power was attempted. Other important considerations were the restrictions a particular landing system placed on the long-range roving system, such as the altitude required by a parachute in order to function effectively.

While designing for multiple landings, it was realized that the initial descent from orbit would be the most critical. Based upon actual flight experience with numerous landers, most notably the Viking and Mars vehicles, an aerobrake/parachute/rocket motor descent system is recommended for the initial landing. However, a parachute system is not practical for subsequent landings since storage of a separate parachute for each landing is mass-prohibitive. Further, a parachute, in the atmosphere of Mars, requires at least 8 kilometers of altitude to decelerate a 1,000 kg lander. This would require a very powerful surface launching mechanism.

To move the rover from place to place on Mars (on a global scale), three options were considered: a "hopper", an airplane/helicopter, and a balloon. (It should be noted that these systems were examined from a landing feasibility standpoint, leaving other considerations to the Rover Team.) The resulting evaluations are as follows:

A "hopper" vehicle would store potential energy upon landing by compressing a spring or gas, subsequently using that energy to "hop" from one point to the next. The range of a hopper would be limited and may not meet the range needs of the mission. It would also be extremely difficult to insure the integrity of a heavy lander/rover (over 1,000 kg) after numerous hops. A hopper was therefore deemed unsuitable for the rover, from a landing standpoint.

An airplane/helicopter "aerocruise" system could provide much greater range than a hopper, along with good control characteristics. It is feared, however, that an aerocruise system would be very complex, requiring large amounts of mass and power. Aerocruise systems are also quite sensitive to roughness of the terrain which could limit site selection to relatively smooth, potentially uninteresting terrain. This system was rejected for these reasons.

The balloon option offers good range and lift-off/landing capabilities at the expense of controllability. The mass and power needs are relatively small; one possible operating scheme uses solar energy to heat the balloon gas, requiring no power from the lander/rover. Stability in windstorms and some degree of controllability may be gained through the use of a zeppelin-type balloon shape.

In summary, the recommendations of the Soft Lander Team are:

1. Use of an aerobrake/parachute/rocket motor system for intitial entry from orbit. Based on the size of the Viking parachute, a suitable parachute for a 1,000 kg lander would be approximately 23 meters in diameter.

2. For subsequent lander/rover maneuvers use a balloon-type system, employing either CO2, helium, or a combination of the two.

Further analysis is needed on all aspects of the balloon system, including optimum configuration, airship feasibility, deployment schemes, and selection of balloon material and working fluid. Other areas of investigation include: parachute system sizing, parachute material selection, aerobrake performance, and terminal descent rocket performance analysis.

Note: The long-range mobility system described in #2 above assumes local mobility to be provided by a wheeled or similar vehicle.

ENVIRONMENT

Potential Landing Sites

In accordance with the recommendations set forth by the NASA Advisory Council in their report, Planetary Exploration Through Year 2000: An Augmented Program, the Environment/Trajectory Team endeavored to select potential landing sites which could provide a wide base of data for characterization of th Martian surface and lower atmosphere. The following suggestions are therefore made:

1. A probe placed at each of the Martian poles, allowing studies of the composition and seasonal variations of the polar ice caps and local soil conditions.

2. A lander to study the ancient lava flows and rock formations of Olympus Mons. Seismic data may be of interest at this and other sites. Being the largest volacanic mountain on the planet, it is felt that Olympus Mons provides the best potential of a benign landing site among the volcanic areas.

3. Landing a vehicle in Vallis Marineris, which is located near the equatorial plane, would allow examination of a cross-section of the Martian crust, as well as determination of the formative processes.

4. Investigating the Argyre Planitia would allow the collection of data about large cratered regions.

Regions similar to those where the Viking landers are were not considered in light of the data already collected, and the desire to develop a broad characterization of the planet.

ROVER DEVELOPMENT

Introduction

The Rover group of the MLR design class was composed of 8 members. After it was determined that there was no single time during the week at which all group members could meet, the group was divided into 3 sub-groups which were given special tasks from week to week. For example, one group was asked to evaluate the design matrix for a certain rover concept while another was asked to do the same for a different concept. Representatives of each sub-group would then meet together with the group leader each week to present the results. In this manner, the formulation of the most favorable design concepts for the rover was completed.

Objective

The purpose of the Rover group was threefold: (1) to generate a decision matrix by which concepts could be evaluated, (2) to develop preliminary concepts for the rover design, and (3) to narrow down the candidate concepts to a workable number in preparation for the efforts of the next quarter.

Method

The procedure centered around building and evaluating a decision matrix which was made up of system attributes and candidate concepts. The next sections describe how the matrix was constructed and evaluated.

Identification of System Attributes:

A search of some of the latest literature on the subject of a Mars rover revealed many of the basic desired attributes of a rover. The main source of information is listed as Reference 1. These attributes were modified somewhat by the scope of this MLR design course as defined in the original proposal, namely, (1) the MLR would represent a compromise between an orbiter and a sample return mission due to cost, meaning it would roam the Martian surface and collect and analyze samples, but not return them to Earth, and (2) the survey locations would be widely separated and not confined to the immediate landing area. With these things in mind, the system attributes were defined as follows:

1. Planetary mobility: ability to collect samples from widespread locations on Mars.

2. Local mobility: ability to collect samples within a large radius around a central point.

3. High payload mass fraction: a high percentage of the total rover mass which is available for sampling and analysis equipment.

4. Environmental hardness: ability to withstand temperature extremes, wind, dust, cosmic particles, radiation, etc.

5. Simplicity of guidance: ability to know and maintain position and course using simple instruments.

6. Terrain handling: ability to negotiate obstacles such as rocks, ditches, mountains, etc, without breakdown.

7. Reliability: probability of completing mission to collect and analyze samples.

8. Cost (self-explanatory)

9. Future mission interface: ability to transfer stored samples to a future vehicle which will return to a manned laboratory.

10. Mission life: ability to remain operational for the necessary length of time, i.e., until the planet has been sampled sufficiently and samples have been transferred to future return vehicle.

11. Autonomy: ability to act and make decisions without human intervention.

12. Communications: ability to send and receive telemetered data.

Several assumptions were made for baseline attributes where applicable to aid in comparing the concepts. These assumptions are as follows:

1. The baseline MLR will be able to visit 4 generic sites: a polar cap, a young volcanic region, an ancient cratered region, and a canyon [1]. A broad characterization of Mars could occur if surveys were performed and samples were analyzed from this minimum of 4 diverse sites.

2. The baseline MLR will have a mobility (total traverse length) of 10 km in the ancient cratered region and 1 km in the other regions mentioned above. It was pointed out in [1] that a characterization of an area could only occur if several samples were taken over an area, depending on the type of geology.

3. The baseline MLR will have a minimum mission life of one year, so that it can interface with future sample return missions.

Formulation of Concepts:

The various concepts which were brainstormed for the MLR were categorized into one of the following general areas:

1. Single surface rover: This is envisioned as being a tank-type or all-terrain vehicle type platform with tracks or wheels and thus restricted to surface motion only.

2. Multiple surface rovers: These would be a minimum of 4 scaled-down versions of a single surface rover, each of which would leave the initial orbit around Mars and land in one of the 4 desired sites, and, therefore, would not need the ability to traverse the planet to get from one scientific site to the next.

3. Balloon rover: This is envisioned as a hybrid between a surface rover for local mobility and a lifting body filled with helium or other lighter-than-Martian-air medium for long-range mobility. It was also assumed that the balloon could be either detached from the rover and/or deflated when necessary, as in the case of severe wind and dust storms.

4. Aerorover: This would also be a hybrid of a surface rover and a fixed or movable wing with sufficient propulsion to generate lift in the thin Martian atmosphere. It was also assumed that state-of-the-art technology would enable it to land and take off vertically if necessary to avoid the irregularities of the surface.

5. Missile rover: This concept combined a surface rover for local mobility with a propulsion system to provide long-range ballistic hops to the minimum of 4 survey sites.

It should be noted that each concept differs basically in the method of long-range travel between scientific sites, since it was assumed in the beginning that local mobility was needed to sample and characterize the area.

A few rough calculations in certain areas were made to prove or disprove the viability of each concept before actually rating each concept in the decision matrix. A balloon to lift the rover was rough-sized using data on the density of the Martian atmosphere, and a propulsion system for the missile rover was rough-sized. These calculations appear in the Appendix. The missile rover was quickly eliminated due to the massive propulsion requirements. The calculations for the balloon rover showed that it was indeed a viable concept.

Generation of Matrix:

The matrix was then constructed and weighting factors were given to each system attribute based on what the group felt was the relative importance of that attribute. The most important attributes were considered to be the local mobility, autonomy, and communication ability, as these were most likely to insure a successful mission to collect and analyze samples and thus characterize an area of Mars. The least important were considered to be the cost, the mission life, and the planetary mobility. The latter two were weighted lightly for the same reason: that a mission of some success could still be completed with a shorter mission life and limited long-range mobility. The cost was rated low so as not to jeopardize the entire mission by eliminating an essential technical concept.

Evaluation of Concepts:

At first, each group was assigned one or two of the concepts and asked to meet and rate those concepts using a raw score of 1 to 10 for each system attribute. It was then realized that a better way was to have each person rate each concept individually and then meet as an entire group to discuss the results. This was done, and, in the group meeting, each member reported their raw score for each system attribute of a concept. Major discrepancies were discussed and resolved, after which a final number for that entry in the matrix was agreed upon.

Results:

The final matrix is as shown on the next page. A by-product of the evaluation was an additional assumption found necessary so that all ratings were based on the same ground rules. This assumption was that each concept has a surface rover with the same basic capabilities for local maneuvering: guidance, terrain handling, autonomy, etc. Therefore, the system attributes in the matrix pertain only to a comparison of long-range roving capability, since that is how one concept differs from another.

Discussion of Results:

The single surface rover scored low in planetary mobility, simplicity of guidance, and terrain handling for the reason that it would have great difficulty in traversing long distances and avoiding obstacles such as ditches, large boulders, canyons, etc. However, it had the highest overall score.

The multiple surface rovers also scored low in several areas. Payload mass fraction was low because a minimum of 4 duplicate drivetrains would be needed, not to mention the 4 soft landing systems, which make the entire system very heavy. It scored low in cost for the same reason. The low score in future mission interface and communications were because of the widely scattered locations of the 4 individual rovers. It had the second highest score.

The balloon scored low in environmental hardness and reliability due to the susceptibility of the fragile balloon to damage by wind, dust, and cosmic particles. It received the 3rd highest score.

The aerorover had low scores in 5 areas. The payload mass fraction would be low due to the massive propulsion and lifting surface requirements for the thin Martian atmosphere. The other 4 areas, simplicity of guidance, reliability, cost, and autonomy, received low scores for the reason that the systems required to make such a craft of sufficient autonomy to make long traverses through the air and land safely would be very complex. It received a total score which was clearly out of the range of the other concepts, and it was decided to eliminate this concept.

General Comments and Recommendations:

It is interesting to note that the categories in which the surface rover scored low, the balloon rover scored well. This suggests that perhaps a more viable concept would be to combine the two, which in essence is the balloon rover concept, as it was initially assumed that it was a hybrid of a surface rover and a buoyant body. After the decision matrix had been filled out, literature was researched and found to be in favor of the balloon concept, both as a means of traversing the planet as well as a soft landing system component. This is supported by the fact that the Soviets are in the advanced planning stages of a balloon rover for Mars.

The weakness of the surface rover in negotiating over long distances is

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MARS ROVER 11/19/86

Candidate Concepts

A. Single Surface Rover
B. Multiple Small Surface Rover
C. Balloon Rover
D. Aerorover (Fixed or Movable Wing)
E. Missile Rover

(Note: Figures are the results of a final group discussion.)

Concept / Attributes and Weighting Factor	Single Surface Rover	Multiple Surface Rovers	Balloon Rover	Aero Rover	Missile Rover
Planetary Mobility (6)	5 / 30	9 / 54	6 / 36	7 / 42	
Local Mobility (9)	9 / 81	9 / 81	7 / 63	6 / 54	
Payload Mass Fraction (7)	8 / 56	4 / 28	7 / 49	5 / 35	
Environmental Hardness (8)	8 / 64	8 / 64	5 / 40	6 / 48	
Simplicity of Guidance (7)	5 / 35	8 / 56	7 / 49	3 / 21	
Terrain Handling (8)	4 / 32	10 / 80	7 / 56	8 / 64	
Reliability (8)	7 / 56	9 / 72	5 / 40	4 / 32	
Cost (5)	8 / 40	3 / 15	6 / 30	4 / 20	
Future Mission Interface (8)	8 / 64	2 / 16	7 / 56	7 / 56	
Mission Life (6)	8 / 48	8 / 48	7 / 42	6 / 36	
Autonomy (9)	8 / 72	9 / 81	6 / 54	3 / 27	
Communications (9)	8 / 72	5 / 45	8 / 72	8 / 72	
	650	640	587	507	

made worse by the fact that available Martian maps are of very low resolution, making it difficult to chart a safe path from one site to the next.

One very unsubstantiated rating number for the multiple rover concept is the payload mass fraction. This is due to the lack of certainty at this point about the allowable mass in Martian orbit, which is a function of the present-day U.S. launch capability. It was recently decided in class that the MLR program would not depend on an ability to perform on-orbit assembly or refueling operations as outlined in [1], but, rather, it would be designed for launch by an existing or near-future propulsion system. It would, therefore, be a reasonable assumption to say that the allowable orbit mass falls halfway between the figure mentioned in [1], which is 8,000 kg, and the orbiting mass of the Viking mission, which was roughly 3,800 kg, (2,500 kg of which was the orbiter). The orbiting mass of the MLR system would then be about 6,000 kg. Assuming an orbiter similar to Viking, 3,500 kg would be left for the rover and its soft landing system. Some rough calculations were performed to size a rover (see Appendix), resulting in a mass of 650 kg. The rover described in [1] was sized at 400 kg. The Viking lander was 650 kg, and its soft landing system was another 650 kg. The landed mass in [1] was 5,100 kg, and the soft landing system, 800 kg. A safe estimate for a soft landing system appears to be about 700 kg. This, added to the estimated rover mass of 650 kg, gives a minimum rover-soft lander mass of 1,350 kg. If a minimum of 4 rovers were needed for the multiple rover concept, then the total rover-lander mass would be 5,400 kg, which exceeds the 3,500 allowable. If a rover mass of 400 kg and a lander mass of 650 kg were assumed, and the orbiter was only 1,000 kg (similar to the one described in [1]), then the total orbiting mass for a 4-rover system would be 5,200 kg, which is within the total allowable orbit mass of 6,000 kg. The conclusion is that the multiple rover concept is on the borderline of being rejected due to payload considerations.

REFERENCES

1. Solar System Exploration Committe of the NASA Advisory Council, *Planetary Exploration Through Year 2000: An Augmented Program, Part 2 of a report*, Washington, D.C., 1986, pp. 58-101.

2. Author unknown, "Structure of Mars Atmosphere up to 100 km," *Science*, December 17, 1976, pp. 1277+.

APPENDIX

CALCULATION OF BUOYANT FORCE ON MARS

Mean molecular weight on Mars at surface is

$$\overline{M}_m = 43.34 \qquad \text{(Reference [2])}$$

Molecular weight of Helium is 4, so

$$\rho_m - \rho_{He} = \frac{P_m \overline{M}_m}{\overline{R}\, T_m} - \frac{P_m \overline{M}_{He}}{\overline{R}\, T_m}$$

$$= \frac{P_m}{\overline{R}\, T_m}\left(\overline{M}_m - \overline{M}_{He}\right)$$

$$= 39.34\, \frac{P_m}{\overline{R}\, T_m}$$

Average temperature on Martian surface is 220°K, and average pressure is 1034.2 N/m^2, so

$$\rho_m - \rho_{He} = 39.34 \,\tfrac{kg}{kgmole} \left(\frac{1034.2\ N/m^2}{\left(8314\ \frac{N\cdot m}{kgmole\ {}^\circ K}\right)(220^\circ K)} \right) = 0.022\ kg/m^3$$

Assume that rover mass is 650 kg (see Section 6 of report)

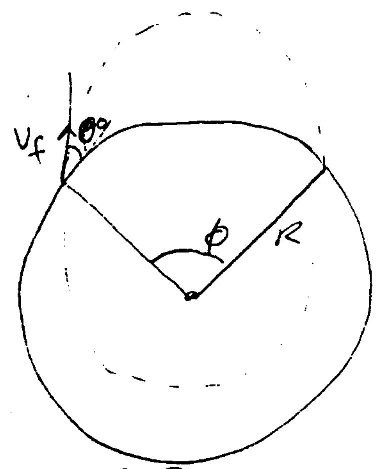
Then volume of He needed is

$$V = \frac{650\ kg}{.022\ kg/m^3} = 29{,}545\ m^3$$

and radius of a spherical balloon is

$$r = \left(\frac{3V}{4\pi}\right)^{\frac{1}{3}} = 19.2\ m$$, which is not too unreasonable

CALCULATION OF BALLISTIC MISSILE MASS RATIO $\mathcal{R}$



$$\tan\frac{\phi}{2} = \frac{-\left(\frac{R v_f^2}{\mu}\right)\sin\theta_0\cos\theta_0}{\left(\frac{R v_f^2}{\mu}\right)\cos^2\theta_0 - 1}$$

(4.12-2, Thomson, W.T., Intro. to Space Dynamics)

Let $\theta_0 = 45°$, $\sin\theta_0\cos\theta_0 = \cos^2\theta_0 = \frac{1}{2}$

$$\tan\frac{\phi}{2} = \frac{-\frac{R v_f^2}{\mu}}{\frac{R v_f^2}{\mu} - 2}$$

$$g = \frac{GM}{R^2} = \frac{\mu}{R^2}$$

$V_f = I_{sp}\frac{\mu}{R^2}\ln\mathcal{R}$, where $\mathcal{R} = \frac{\text{initial mass}}{\text{final mass}}$

$$\frac{R v_f^2}{\mu}\tan\frac{\phi}{2} - 2\tan\frac{\phi}{2} = -\frac{R v_f^2}{\mu}$$

$$\frac{R v_f^2}{\mu}\left(\tan\frac{\phi}{2} + 1\right) = 2\tan\frac{\phi}{2}$$

$$v_f = \sqrt{\frac{2\frac{\mu}{R}\tan\frac{\phi}{2}}{\tan\frac{\phi}{2} + 1}}$$

$x = R\phi \qquad \phi = \frac{x}{R}$

$$V_f = \sqrt{\frac{2\frac{\mu}{R}\tan\frac{x}{2R}}{\tan\frac{x}{2R} + 1}}$$

$$\ln\mathcal{R} = \frac{R^2}{I_{sp}\mu}\sqrt{\frac{2\frac{\mu}{R}\tan\frac{x}{2R}}{\tan\frac{x}{2R} + 1}}$$

$$\boxed{\mathcal{R} = e^{\sqrt{\frac{\frac{2R^3}{I_{sp}^2\mu}\tan\frac{x}{2R}}{\tan\frac{x}{2R} + 1}}}}$$

Mars:

$M = 6.342 \times 10^{23}\ kg$

$\mu = GM = 6.67 \times 10^{-11} \frac{m^3}{s^2 kg}(6.342 \times 10^{23} kg) = 4.23 \times 10^{13} \frac{m^3}{s^2}$

mean $R = 3430 \times 10^3 m$

Assume $x = 3000 \times 10^3 m$ is range (approximate mean distance between 4 desired sites)

For $I_{sp} = 250$ sec,

$$\mathcal{R} = \exp \sqrt{\frac{\frac{2(3430 \times 10^3)^3 m^3}{(250)^2 s^2 (4.23 \times 10^{13} m^3/s^2)} \tan \frac{3000 \times 10^3}{2(3430 \times 10^3)}}{\tan \frac{3000 \times 10^3}{2(3430 \times 10^3)} + 1}}$$

9.72

$= 22.6$

For 4 hops,

$\mathcal{R} = (22.6)^4 = 261,484$ Ridiculous

Say only wanted to go 1200 km ($\phi = 20°$)

From Fig. 4.17a, $R v_f^2 / \mu = .3$

$v_f = 1923$

$\mathcal{R} = \exp \frac{v_f}{I_{sp} g} = 7.2$

4 Hops

$\mathcal{R} = (7.2)^4 = 2673$ still ridiculous

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J. CANTRELL

GENERAL MLR MASS REQUIREMENTS MINIMUMS

* mission assumption

ENERGY

	watts
Rover (3hp motor)*	2.27×10^3
transmitter	5 *
Imaging	2 *
electronics	1 *
ground package	3 *

total energy requirement 2.3×10^3 watts

SOURCE	mass/energy	mass	S. AREA REQ'D (IDEAL CONDITIONS)
RTG (Radioisotope Thermal Generator)	1 kg / 5 W	460 kg	N/A
Photovoltaic arrays	4.5 kg/m^2	274 kg	61.33 m^2
Ni cad batterys / * (3 hour battery life)	1 kg / 30 whr	230 kg	N/A

basis of calculations

photovoltaic arrays

1.5 kg/m^2, 37.5 watts/meter^2, support mass = 3 kg/m^2

NiCad batteries 30 whr/kg

Photovoltaic arrays + batteries = 504 kg, heavier than RTG

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Mass of total system (MINIMUM)

ROVER

	kg	
DRIVETRAIN	120 *	
INSTRUMENTATION	20 *	
POWER GENERATION	460 *	(using RTG)
STRUCTURE	50 *	
TOTAL	650 kg	(NASA ASSUMED A 400 kg sampler in Ref. [1])

SOFT LANDING EQUIP

	900 kg	(Based on 5100 kg landed mass in Ref. [1])
total mass (min)	1550 kg	

Assume a 4-way mult. mission rovers

4 X 1550 kg = 6200 kg

* Total lander masses would exceed the 3000 kg orbital mass without even the consideration of a relay sattelite which I would deem as absolutely neccessary

balloon travel due to Martian surface winds

estimates of 300–500 km/day*

mission time = 1 year = 365 days
mean distance between 4 sites is 3000 km, so
total roundtrip dist ≈ 15×10^3 km

$$\frac{\text{day}}{300-500 \text{ km}} \times 15\times10^3 \text{ km} = 50 - 30 \text{ days travel time}$$

* based on article "Balloon Performance" by Erik Krumrey, based on wind patterns and no propulsion

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11/7/86

MARS ROVER TEAM ASSIGNMENTS

Evaluate the decision matrix for the candidate concepts assigned to you, as shown below:

Steve B., Neal, Kirt – Balloon Rover, Aero Rover
Colby, Rex, Mary – Single + multiple surface rovers
Steve W., Jim – Missile rover

1. Rate each concept using a raw score of 1 to 10
2. Perform rough calculations where possible
3. Assume the following:
   a. Total rover mass = 5000 kg
   b. Four sites: polar cap, young volcanic region, ancient cratered region, canyon
   c. Sample radius of 1 km in all regions except 10 km in ancient region
   d. Minimum mission life of 1 year
   e. Each rover must have local mobility capability

FALL QUARTER SUMMARY

The first quarter of this design course proved to be quite useful in orienting the participants to the task, as well as determining the viability of candidate solutions. Based upon the available and near-future launch capabilities, a mass of approximately 6,100 kg has been baselined for the package delivered into Mars orbit, translating into a landed mass of 1,650 kg and an orbiter mass of 2,800 kg. These figures may vary significantly as the descent system is defined.

The soft landing and roving systems need to be designed in a highly interactive fachion. It was recognized that efficiency requires that these systems be complimentary and dual-purpose, where reasonable. The planetary and local mobility capabilities will affect, to a large extent, the selection of the initial landing site(s) because of the degree of controllability in the various rover systems (balloon as compared to a wheeled vehicle).

Overall, the initial sizing and scoping exercises performed during this phase of design allowed the participants to focus upon the systems preferred for further study during Winter and Spring Quarters.

MODIFICATIONS

In light of information communicated to Dr. Frank Redd during the conference of December 1-3, 1986 the mass launch restrictions imposed during this design phase have been relaxed. Instead, the mass estimations employed in the NASA Advisory Council report will be used for subsequent investigations (landed mass approximately 5,000 kg).

WINTER QUARTER OBJECTIVES

During the next academic period, the candidate systems presented above, will be investigated more thoroughly and defined in terms of the baseline mission. These studies will include budgeting of power, options for locomotion (local and planet-wide), sizing of orbiter and orbiter subsystems, sizing and distribution of mass of lander/rover(s), and locating initial landing site(s). In light of recent balloon tests, the development of a lander volume/mass simulator is also being investigated. Such a device could be quite useful in the evaluation of potential balloon configurations.