Sustainable Mars Sample Return

ODU Mars Sample Return Team: Old Dominion University
Submission ID: kYlRn

Christie Alston
Sean Hancock
Joshua Laub
Christopher Perry

Faculty Advisor: Dr. Robert Ash

ABSTRACT

The proposed Mars sample return mission will be completed using natural Martian resources for the majority of its operations. The system uses the following technologies: In-Situ Propellant Production (ISPP), a methane-oxygen propelled Mars Ascent Vehicle (MAV), a carbon dioxide powered hopper, and a hydrogen fueled balloon system (large balloons and small weather balloons). The ISPP system will produce the hydrogen, methane, and oxygen using a Sabatier reactor, a water electrolysis cell, water extracted from the Martian surface, and carbon dioxide extracted from the Martian atmosphere. Indigenous hydrogen will fuel the balloon systems and locally-derived methane and oxygen will fuel the MAV for the return of a 50 kg sample to Earth. The ISPP system will have a production cycle of 800 days and the estimated overall mission length is 1355 days from Earth departure to return to low Earth orbit. Combining these advanced technologies will enable the proposed sample return mission to be executed with reduced initial launch mass and thus be more cost efficient. The successful completion of this mission will serve as the next step in the advancement of Mars exploration technology.

TABLE OF CONTENTS

INTRODUCTION

Technological advances have facilitated the progression of exploration from the earliest explorers of new land to the exploration of outer space and distant planets. Although virtually all contemporary scientific experiments are managed by humans, the scientists usually are separated from the actual physical experiment by an array of sensors, data transmission systems, software, interfaces and data displays. As the complexity of our scientific endeavors increases, technological advancements are in constant need. This increase in complexity also leads to increased mission costs to the point where sequential Earth-launched planetary missions are prohibitively expensive. However, the introduction of revolutionary technologies, rather than incremental improvements, will make these more complex planetary mission opportunities possible. Over the last 45 years, the exploration of Mars has provided a plethora of data and knowledge about Mars and its atmosphere. The first successful missions to Mars, starting in 1964, were *Mariners 4, 6, 7* and *9*, and beginning in 1999, the *Mars Global Surveyor, Mars Odyssey, Mars Express* and *Mars Reconnaissance Orbiter*, have produced orbital imagery and spectroscopic data of ever-increasing accuracy and detail [1]. The number of Mars surface sites worthy of detailed scientific investigation appears to be growing exponentially [1]. In order to carry out more advanced missions to explore such worthy sites, barriers and constraints currently limiting Mars rover technology must be overcome. Since Mars rovers must operate on the surface autonomously, the absence of obstruction-free, smooth terrain limits their speed to perhaps a kilometer per day. Furthermore, a variety of potentially important sites are inaccessible even using advanced autonomous entry, descent and landing technologies. This paper focuses on the application of new technologies and concepts that will support more ambitious future Mars exploration goals at a scale well beyond existing orbiter and surface rover limitations. In-Situ Resource Utilization (ISRU) can be exploited, enabling the retrieval of samples from dispersed locations and from distances not previously achievable with present-day technology.

A Mars sample return mission will return a 50 kg sample using indigenous ISRU hydrogen and methane and oxygen produced from Mars atmosphere and near-surface water ice. CO_2 from the atmosphere and extracted ice from the Martian regolith (within one meter of the surface) are the only feedstocks. The surface ice will be heated to sublimate, then water will be retrieved from the ice, and through the use of a Sabatier reactor and water electrolysis cells, hydrogen, methane, and oxygen will be produced. The ISRU-produced hydrogen will be used as the lifting gas to charge large balloon systems that can ride on wind currents, transporting rovers and other scientific equipment over great distances, while small hydrogen-filled weather balloon systems will provide *in situ* atmospheric and environmental monitoring data throughout the mission to provide scientific Mars environmental data and support future heavy cargo and crewed spacecraft landings. Methane and oxygen will provide the propellant to fuel the MAV for its return trip to low Earth orbit. Also, CO_2-powered hoppers will use CO_2 extracted from the Martian atmosphere to enable rovers and other scientific probes to ascend or descend steep terrain via "hops" of up to 1 km, permitting the investigation and possible retrieval of otherwise inaccessible samples from distant locations. The approach proposed here can greatly leverage and accelerate the development of space exploration technologies for Mars and for other planetary bodies with locally available resources.

PURPOSE

The purpose of this analysis is to design a Mars sample return mission that uses natural Martian resources for the majority of its operations, while allowing the exploration of Mars at a much larger scale that is possible with current technology and also demonstrating the successful use and benefit of new technologies in a relevant environment for use on a future fixed Mars base and/or future manned missions. Sending a smaller system all in one helps justify sending and constructing a large base on Mars and it allows the testing of all the technologies in one small mission before devoting billions of dollars and years of time and R&D on the development of a full scale fixed base. The system will consist of the following components: an In-Situ Propellant Production (ISPP) plant, a methane-oxygen propelled Mars Ascent Vehicle (MAV), a CO_2-powered hopper, and a balloon system (large balloons and small weather balloons). With these components, constant monitoring of the Martian weather and environment will be possible to ensure the most efficient acquiring of samples by the hopper and the most efficient conditions for launching the MAV. The ISPP plant will produce the needed hydrogen, oxygen, and methane using water extracted from Martian surface ice for the fueling of the balloon systems, rover technology, and the MAV. This self-sufficient autonomous system will successfully return a 50 kg sample from Mars back to Earth with a total mission time of approximately 1355 days. The high level mission requirements are summarized in Appendix A along with verification criteria.

CONCEPT OF OPERATIONS

The transportation concept of operations is represented in Figure 1. The mission originates as a single payload aboard a heavy-lift launch vehicle which will insert the payload into a low Earth

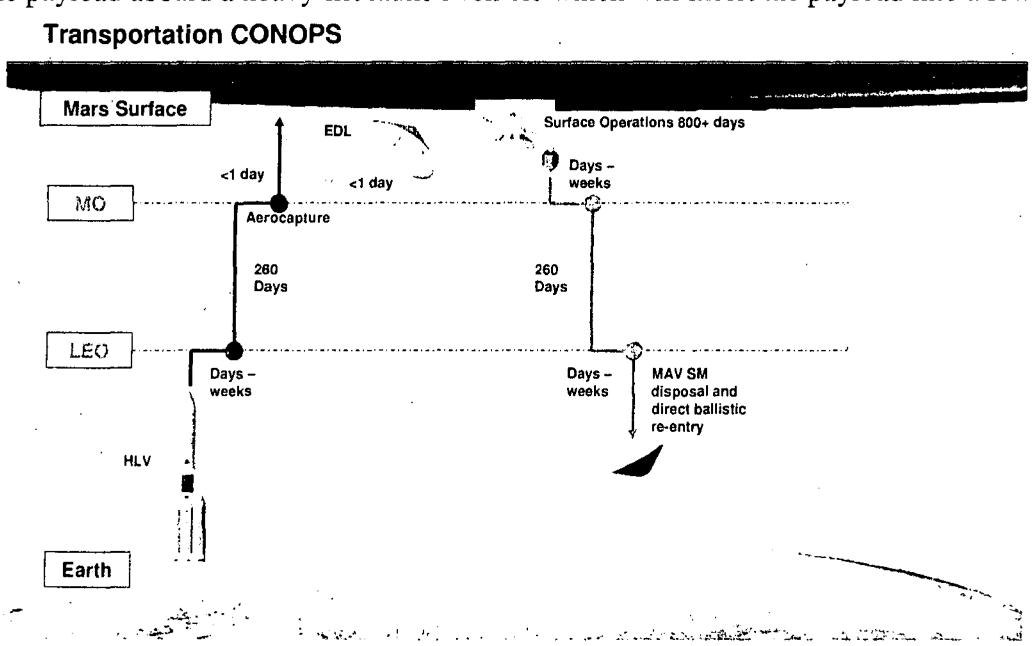


Figure 1: Transportation CONOPS

holding orbit. The overall flight element total, including a 15% mass margin is summarized in Table 1. The flight vehicle mass requires a launch vehicle of the class of the proposed EELV

Phase 2 or Phase 3 or an Ares V derivative. After check-out, the interplanetary cruise stage will execute a burn to provide the necessary hyperbolic transfer orbit to intercept Mars. The cruise stage will enter Mars orbit through an aerocapture operation and then commence EDL. The heavy landing mass currently exceeds the technology capability of Viking derived decelerators. EDL will require the use of an inflatable aerodynamic decelerator (IAD), currently being developed at NASA Langley Research Center, to deploy and initially slow the vehicle in the thin atmosphere. After the vehicle has reached subsonic speeds, a ring sail parachute deploys and the IAD will be discarded. In the final phase of EDL the lander will separate from the parachute and descend to the surface under rocket power [2]. Upon confirmation of a successful landing, the lander will begin systems checks and commence surface operations. The surface operations CONOPS are depicted in Figure 2.

S/C Bus* (kg)	2100
C&DH (kg)	114
Thermal (kg)	162
Balloon System (kg)	2014
ISPP (kg)	1500
CO2 Hopper (kg)	350
MAV (kg)	80
Margin (kg)	15%
*Includes 815 kg Entry System	
Flight Element Total (kg)	**7268**

Table 1: Flight Element Mass Summary

After sufficient samples are collected and propellant manufactured, the MAV will be launched, inserting itself into a Mars parking orbit before a ΔV burn for a hyperbolic trajectory back to Earth. Upon arrival at Earth the payload compartment of the return vehicle will be jettisoned in an impact resistant capsule for Earth recovery.

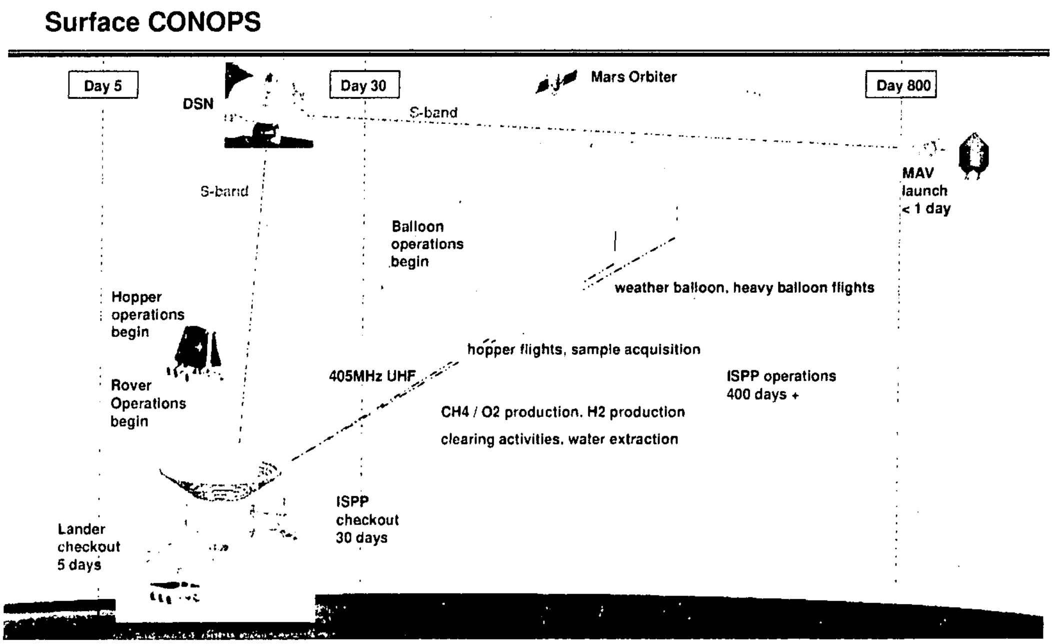


Figure 2: Surface CONOPS

Once checked out, the lander will deploy two ISPP rovers and the sample retrieval CO_2 gashopper. The rovers and gashopper will be mounted to ramps, on the side of the lander, that will fold downward to the surface to allow the rovers to drive off. The ISPP rovers will collect soil to be loaded into the ISPP to obtain water for separation and subsequent methane/LOX production. When sufficient hydrogen gas has been obtained for use by the Mars Autonomous Balloon Launcher (MABL), a large inflatable cone structure will be deployed atop the lander to aid in balloon launches. Hydrogen gas, which has been generated and stored in the ISPP from water electrolysis, will be used to inflate and deploy the weather and heavy lift science balloons. A total of 25 weather balloons and three heavy lift science balloons have been included in the landed payload. The CO_2 gas hopper will collect samples and return them to the lander. In addition, each of the three heavy lift science balloons will release a small methane-LOX hopper that will fly a 2kg sample on a parabolic trajectory towards the lander where it will be retrieved by the CO_2 gas hopper. When sufficient propellant has been manufactured and samples collected, the MAV will launch with the samples at the next available Earth-return opportunity. After samples have been returned and all balloons launched, the lander will continue science operations and function as a surface-based communications hub and a long duration weather monitoring station, and rovers deployed by the heavy lift science balloons can continue operating.

LANDING SITE SELECTION

Proximity to water is a driving force for a variety of desired scientific investigations on the Martian surface. Since local Martian wind patterns cannot be predicted reliably, future heavy-cargo Mars landings will be difficult unless landing areas have already been pre-designated and prepared. Since the presence of liquid water within one meter of Mars' surface is relatively certain, these areas can be optimized by using them as the primary landing and operational site for the proposed Mars sample return mission [3].

The Mars Exploration Program Analysis Group (MEPAG) has recently discussed the potential locations of such water rich areas in their Special Regions Report [3]. The definition of a "special region" is "a region within which terrestrial organisms are likely to propagate, or a region which is interpreted to have a high potential for the existence of extant Martian life forms. Given current understanding, this applies to regions where liquid water is present or may occur [3]." Figures 3 and 4, from the MEPAG report represent current knowledge of global accessibility of water ice in terms of the minimum regolith depth required for long-term ice survivability and the nominal minimum regolith depth for stable water ice deposits as a function of latitude. It is clear that there should be a great deal of water ice within one meter of the surface at latitudes between 30 and 90 degrees (north and south). Since the polar regions are difficult to reach from orbit and are shielded from the Earth part of each Martian year, regions between the 30 and 60 degree latitudes are more desirable landing site candidates.

The two classifications used when considering water on Mars are the parts at or close to thermodynamic equilibrium and the parts in long-term disequilibrium [3]. From various studies, it has been determined that areas on Mars at or close to long-term thermodynamic equilibrium do not possess the necessary attributes for the possible existence of water at or near the surface. However, there are areas of long-term disequilibrium that show significant probability of liquid water near the Martian surface. These potential special regions include gullies and "pasted-on" mantles.

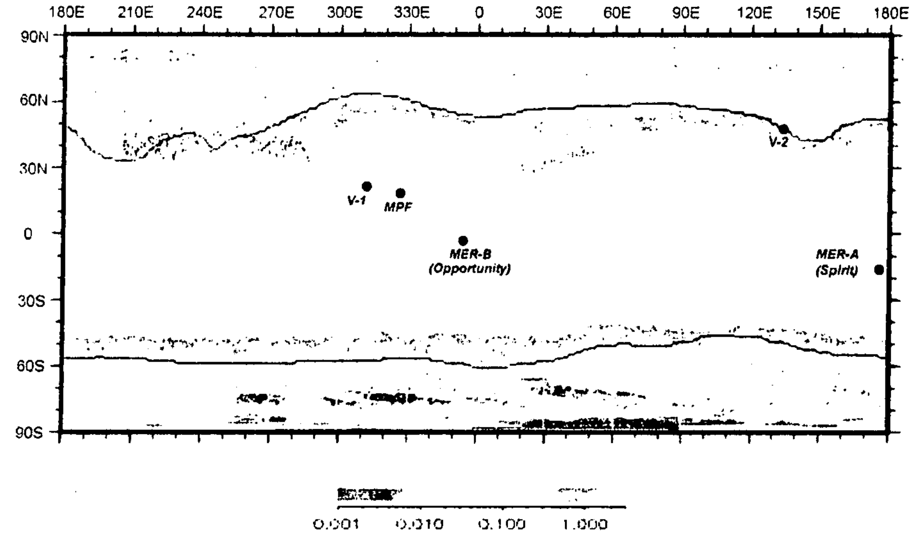


Figure 3: Map of latitude vs. depth to ice (depth in meters). [3]

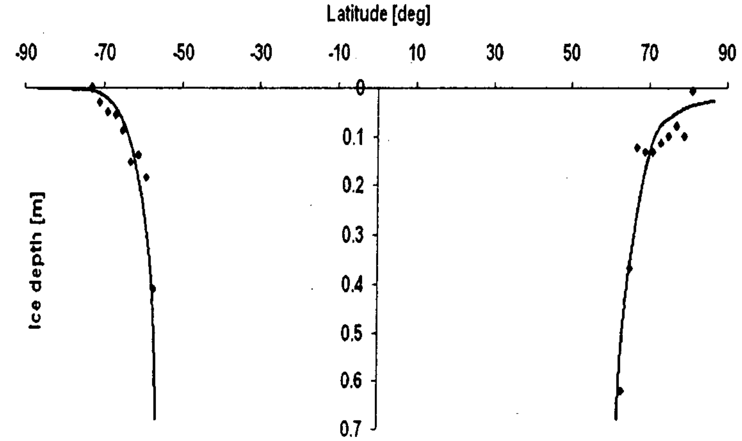


Figure 4: Two cross-sectional profiles showing latitude vs. the depth to ice (depth in meters). [3]

Although their age and origins are not fully understood, it is highly possible that the creation of Martian middle- and high-latitude gullies could have involved liquid water [3]. Almost all gullies are located poleward of 30° latitude in both hemispheres and on the north walls of Nirgal Vallis as seen in Figure 5. The primary locations of these gullies coincide with the near-surface water ice maps in Figures 3 and 4. Studies suggest that some of these gullies are sites where liquid water could have been present, at least for brief periods, on the contemporary Martian surface. Other studies also indicate that gullies are related to groundwater, melting of ground ice, and/or the melting of a surface-covering snowpack. Many also state that liquid water is involved in the formation of gullies. The determination of the age of the tens of thousands of gullies on Mars is a current concern that needs to be studied in greater depth in order to help determine which sites, if any, will produce liquid water in the near future or sometime within the next 100 years.

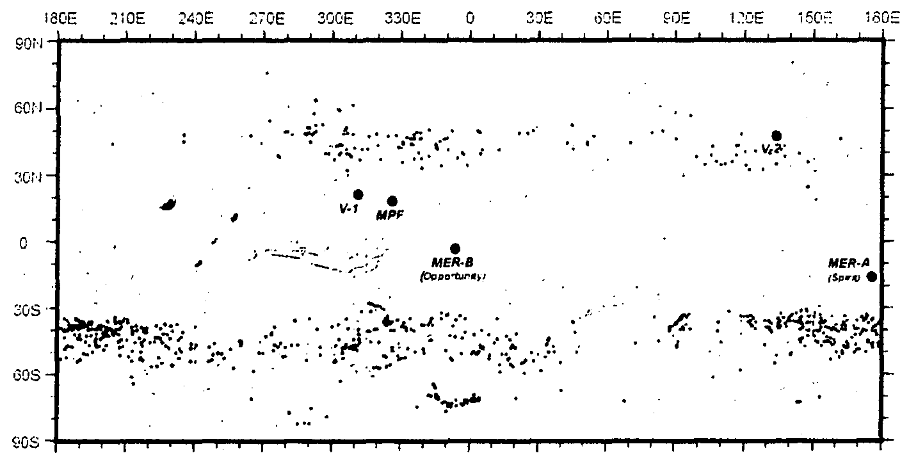


Figure 5: Map of Martian gullies. [3]

"Pasted-on" mantles are accumulations of materials found on poleward-facing slopes of mid-latitude topographic features, such as crater walls and massifs [3]. It is believed that these mantles may represent remnants of old snow accumulations and/or may be the source of water that creates mid-latitude gullies [3]. Figure 6 shows a map of Martian mantles, and it is clear that their locations are primarily within the same regions as those of the gullies in Figure 5. Due to their possible relationship with gullies, "pasted-on" mantles are also considered currently to have a high probability of liquid water near the Martian surface. With further research and the determination of the significance of gullies and their related mantles, pre-designated landing areas can be established.

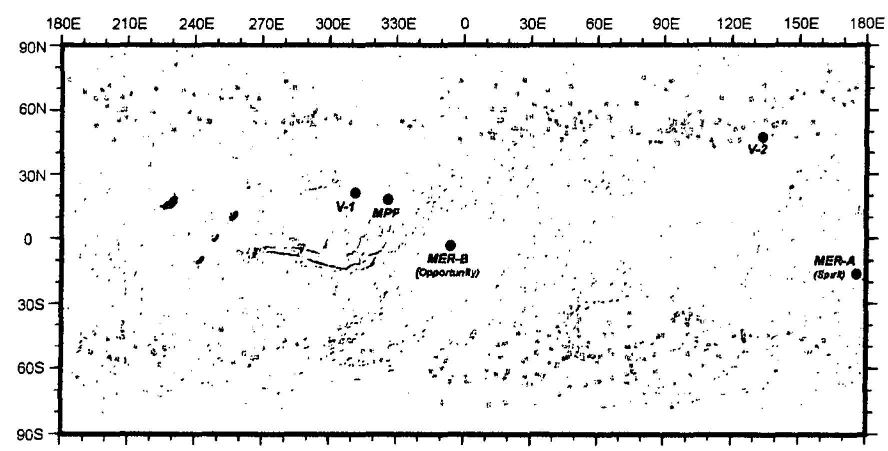


Figure 6: Map of Martian mantles. Colors indicate: localized removal (yellow), knobby/wavy texture (blue), and scalloped texture and total mantle cover (red). [3]

Boynton et al. [4] have discussed the distribution of hydrogen in the near surface of Mars, measured by the Mars Odyssey orbiter, which they believe is evidence for subsurface ice deposits. The fact that hydrogen is present is clear, but its chemical form is not so clear in all cases. In upper layers, hydrogen is likely present in the form of physically or chemically bound liquid water, which may not be distinguishable from the soil at mid-latitudes where ice is not stable [4]. However, in lower layers, ice may be the only reasonable phase that can be associated with such high levels of hydrogen due to hydrogen levels that exceed those that can be accommodated by the alteration of rock-forming minerals; the high concentrations being hard to sustain unless a volatility comparable to ice is responsible, and the fact that these regions are only found in colder regions similar to the conditions needed for ice [4]. Figure 7 shows a map of the epithermal neutron flux of Mars from the Neutron Spectrometer, an instrument on Mars Odyssey. The lower the epithermal flux, the higher the hydrogen concentration, and therefore, the probability of the presence of liquid water is higher. Regions marked in white are regions where water ice is predicted to be stable at 80 cm depth (not valid for regions poleward of 60 degrees latitude). It should be noted that these white regions seem to coincide with regions of low epithermal flux, with the exception of the small closed region of predicted ice stability. However, this small closed region does coincide with the purple (1 mm, depth) and blue (1 cm, depth) shaded regions shown in Figure 3 between the 30 and 50 degree latitudes north. Although this region does not have the lowest epithermal neutron flux, its flux is still low compared to other regions on the surface. It should also be noted that the areas with the lowest epithermal flux also seem to coincide with the areas and latitudes where the depth of ice is believed to be within one meter of the surface, as seen in Figures 3 and 4, and the general locations of gullies and mantles as shown in Figures 5 and 6.

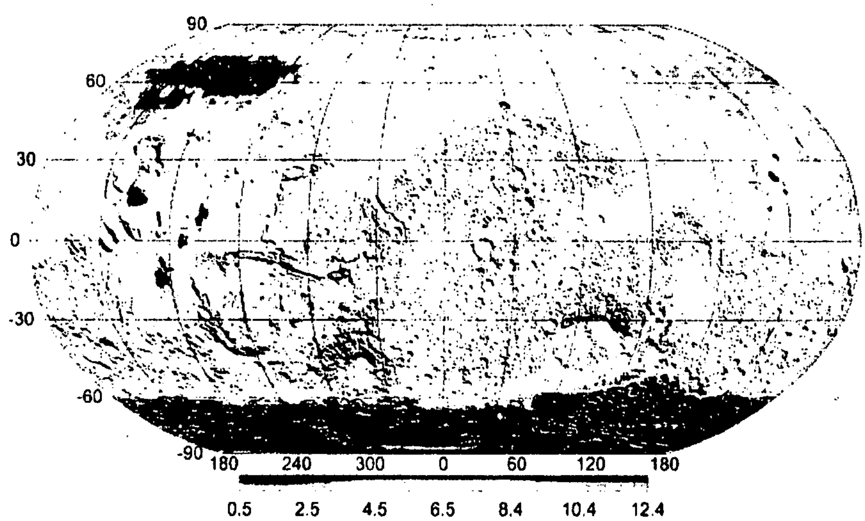


Figure 7: Map of epithermal neutron flux. [4]

The fact that numerous results and predictions as to the most probable locations of water on the Martian surface appear to overlay each other supports the selection of an optimal location for the operation of an ISPP system. The process of narrowing the possibilities for optimal sites using predictions of the presence of liquid water was used to determine an optimal site for this proposed sample return mission. The following criteria were used: sufficient access to water, located near 30 degrees north latitude for optimum year round solar collection (in the event that nuclear power is deemed unacceptable), low elevation to accommodate heavy landing systems, and relatively flat surface to aid possible solar panel deployment and for ease of traveling for sample collection and water extraction. From these criteria, five potential sites were selected. Their characteristics are shown in Table 2 and their locations are labeled on Figure 8, where it can be seen that they all lie in areas with reasonable lower-limit water mass fractions and within close vicinity of the 30 degree latitude, shown previously to be areas with high probabilities for the presence of water. In the end, the Northeast Amazonis (selection E) is being proposed for this mission for its low elevation and very flat plain.

	Name	Location	Elevation	Comments
A	Cerulli Crater	32°10'N 22°01'E	-3583 m	~60km diameter crater floor w/ central mound
B	"South Cerulli"	27°03'N 21°22'E	-2692 m	~50 km diameter flat crater floor
C	"North Maggini"	30°40'N 9°12'E	-2834 m	~120 km diameter flat filled crater
D	"East Maggini"	27°53'N 11°29'E	-4609 m	~30 km diameter flat crater floor
E	"Northeast Amazonis"	35°54'N 144°22'W	-3867 m	Large and very flat plain

Table 2: Potential Landing Sites

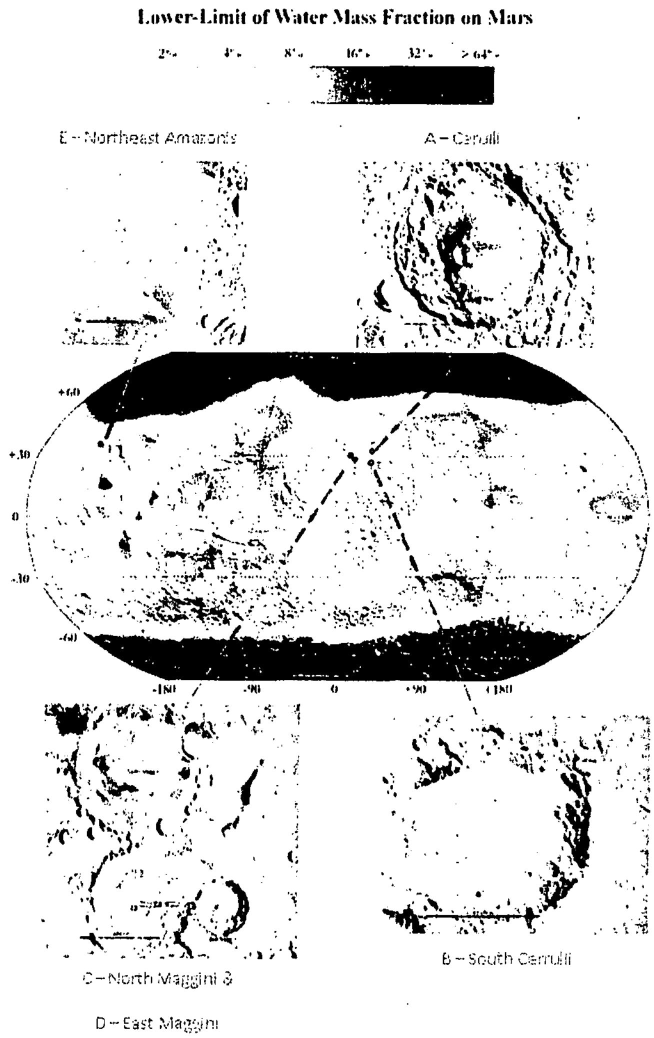


Figure 8: Map of Potential Landing Sites with Water Mass Fractions

OPERATING ENVIRONMENT

As shown in Table 3, CO_2 represents more than 95% of the Martian atmosphere.

Atmospheric Composition of Mars as measured by Viking Landers	
Carbon Dioxide	95.32%
Nitrogen	2.7%
Argon (40)	1.6%
Oxygen	0.13%
Carbon Monoxide	0.07%
Water Vapor	0.03%
Argon (36), Neon, Krypton, Xenon, Ozone, Methane	trace

Table 3: Atmospheric Composition of Mars as Measured by Viking Landers

Atmospheric pressure is known to vary locally by as much as 20% about the annual mean, primarily due to seasonal CO_2 condensation - sublimation cycles as shown in Figure 9. That figure also indicates sol to sol variations in pressure which can be significant. Shorter period ambient pressure cycles can be attributed to frontal weather activity, dust storms, and global oscillations. Frontal activity is indicated by large sol to sol variability. Pressure variations due to dust storms tend to have a longer period and typically show minimal sol to sol variation [5]. Global oscillations are seasonal and believed to be temperature dependant [6] with a nominal period of one sol.

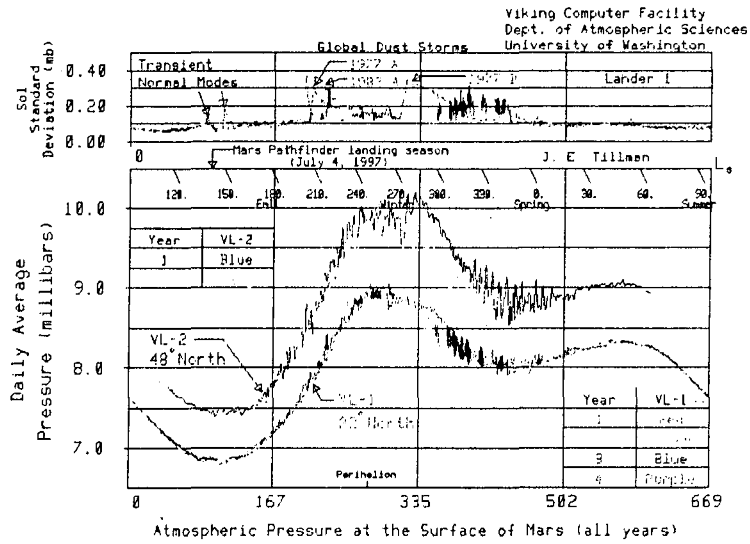


Figure 9: Surface Pressure at Mars as Measured by Viking Landers [6]

Ambient diurnal temperature cycles are influenced by sol to sol variations that may be caused by frontal activity or dust storms, and seasonal variations. Because the atmosphere is so thin, it has minimal thermal inertia, resulting in large temperature variations due to changes in heat input and mechanical forcing. Diurnal temperature variation is controlled primarily by solar heating and infrared cooling of the surface to the atmosphere and into space. Heat exchange between the atmosphere and the surface occurs in the planetary boundary layer whose local night time thickness varies from tens to hundreds of meters, and during the day time it is on the order of 5 km thick. Within this layer, the exchange of momentum, heat, and moisture between the surface and the atmosphere are due primarily to wind and turbulence, strongly affecting the thermal profile of the atmosphere.

While water vapor only makes up approximately 0.03% of Mars' atmosphere, during most seasons, the night time atmosphere is saturated over much of the northern half of the planet. During the day, the heated atmosphere becomes undersaturated. In the southern hemisphere during summer, the absolute humidity rises only until it reaches the water vapor concentrations characterizing the equatorial region (even though the atmosphere is capable of holding more water). While the north polar region has sufficient local water to saturate the atmosphere at night, water vapor in the southern polar region is transported through the atmosphere from the equatorial region [7]. High relative humidity can lead to ice-water clouds, forming fog around mountains, contributing to morning fog, and to the visible North Polar Hood.

Martian winds are created by the global sublimation-condensation cycle driving mass flow from the summer pole to the winter pole, and infrared heating and cooling causes warm air to rise, cold air to sink, and dense air at the surface to migrate towards areas where warm air is displaced upward. The Coriolis Effect results in average wind directions that are nearly parallel to the equator. Martian winds have generally been measured *in situ*, ranging from up to 10 m/s to near 30 m/s during fall and winter with stronger fronts. Winds can occasionally rise to gale force, especially near the poles. The winds lift small dust particles from the surface and those particles can impact larger regolith particles, ejecting them into the atmosphere (via saltation) and these wind-dust interactions sometimes produce dust storms that engulf the entire planet.

Dust devils are a common feature on Mars and have been observed at almost all elevations. Dust devils are thermally driven vortices that contribute significantly to overall dust and haze in the atmosphere. As a result, dust devils impact atmospheric temperature by affecting solar heating and infrared cooling. The low pressure core of the vortex has proven to be very effective at lifting even fine-grained particles; however the overall contribution of dust devils to atmospheric dust is still not fully understood. Terrestrial observations have found that dust devils occur in late morning and afternoon, with peak activity occurring between 1300 and 1400 h, then ending after 1700 h [8], and *Spirit/Pathfinder* data compare favorably with this [9]. Dust devils can be up to a few hundred meters in diameter and several kilometers in height and move with the general circulation. While it is predicted that the dust devil season should be summer for both hemispheres, observations from the Mars Express High Resolution Stereo Camera have detected a clear peak of activity in the southern hemisphere summer, but a majority of northern hemisphere dust devils have been observed in the spring [9].

Viking Lander wind observations indicated regular topographical slope winds which are attributable to the large diurnal surface temperature gradient, a result of the predominantly infrared nature of heat transfer with the surface. Daytime anabatic upslope winds form as the sun heats the slopes creating warmer, less dense atmosphere. At night, as the slopes cool, katabatic downslope winds result from descending cooler, less dense atmosphere. Katabatic downslope winds tend to be stronger than anabatic upslope winds. Conditions for slope winds are favorable on Mars in summer [10].

Because the atmospheric pressure on Mars is less than 1% of Earth ambient surface pressure, the wind forces (dynamic pressure) on Mars are lower than terrestrial wind forces by a factor of 10 than the force caused by a comparable terrestrial wind velocity. Currently, the lack of knowledge of Martian winds and their variability is the dominant error source in predicting entry trajectories.

The difficulty in accurately predicting the density of Mars' atmosphere was demonstrated by the aerobraking performance of the Mars Reconnaissance Orbiter (MRO). Atmospheric densities calculated from accelerometer measurements aboard the MRO differed by up to 200%

compared with the Mars Global Reference Atmospheric Model predictions [11]. The current version of the Mars-GRAM engineering level atmospheric model (Mars-GRAM 2010) is based on the NASA Ames Mars General Circulation Model (MGCM) for atmospheric variations with elevation, starting from the surface and extending up to 80 km, while the University of Arizona Mars Thermospheric General Circulation Model (MTGCM) has been employed for altitudes greater than 80 km [12]. MRO accelerometer-derived densities demonstrated that periapsis density varied significantly from orbit to orbit. Additionally, *in-situ* measurements showed strong latitudinal and seasonal variability in atmospheric density and the significant impact of dust storms, further complicate atmospheric density predictions.

SURFACE OPERATIONS SYSTEM OVERVIEW

S/C BUS

The primary requirements of the S/C Bus systems are to provide a controlled thermal environment in cruise and surface operations, target the entry vehicle to the required entry corridor, in order to decelerate and land the mission payload, and then to house and provide physical protection from the environment during mission operations. The S/C Bus also provides a foundation to mount the other sub-systems and to route power through. A mass of 2100 kg has been allocated to the S/C Bus; of this 815 kg is entry system mass.

BALLOON SYSTEM

The balloon system consists of a Weather Balloon Flight System (WBFS), a Heavy Balloon Flight System (HBLS), and a Mars Autonomous Balloon Launch (MABL) System. The functional breakdown of these systems is represented in Figure 10.

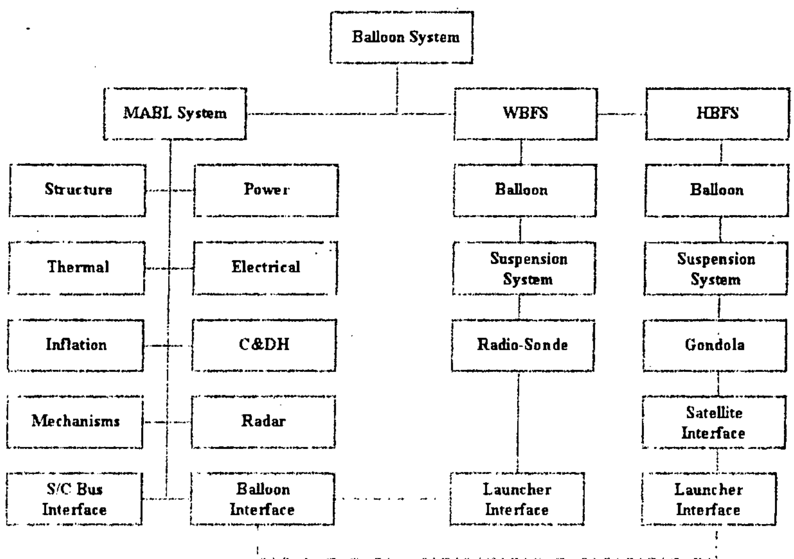


Figure 10: Balloon System Functional Diagram

The three most common types of balloons for scientific or meteorological research are extensible, zero-pressure, and super-pressure balloons. Recently, solar heated Montgolfier balloons have also been proposed as aerial platforms for Mars research.

Extensible balloons are employed terrestrially to deploy radio-sonde atmospheric probes. Those balloons are inflated with a lifting gas (hydrogen, helium, ammonia, or methane), sealed, and allowed to rise. As the balloon ascends, the balloon envelope – often latex – stretches, and the balloon volume increases until the balloon film ruptures.

Zero-pressure balloons are fabricated from non-extensible materials, and are used to carry scientific instruments to a predetermined density altitude. When partially filled with lifting gas at the surface and allowed to rise, the balloon ascends, and the lifting gas expands until the envelope is fully inflated – the altitude of first full inflation. At that point, the balloon system begins to vent excess gas causing free lift through an open duct. The balloon continues to rise until it reaches a constant-density equilibrium floating altitude where the buoyant force equals the weight and the pressure differential between the balloon lifting gas and the atmosphere is zero. The balloon will continue to float at that altitude, but its long-term behavior is controlled by its radiation environment. If the temperature increases due to radiant heating, more lifting gas is released; however the balloon stays fully inflated. When the balloon temperature decreases, the lifting gas density increases, causing the balloon volume to contract, thus causing the balloon to descend. The balloon will continue to descend toward the surface unless it reaches another equilibrium altitude or until ballast is released. Zero-pressure balloons cannot be used for long duration flights, because of the loss of buoyancy associated with night-time cooling.

Solar heated Montgolfier balloons are a special class of zero-pressure balloons that use the ambient atmosphere as the lifting gas and radiant heating of the lifting gas to provide the necessary buoyancy. Solar heated Montgolfier balloons have an opening at the bottom for filling. A controlled vent at the top of the balloon can release gas allowing the balloon to descend, or when closed allow the gas to be heated radiantly and expand, causing the balloon to rise. In this way, solar heated balloons can achieve somewhat controlled flight and even controlled soft-landings [13]. Solar heated balloons have been proposed for short-duration flights with the possibility of multiple landings for controlled roving/landing and also as an entry decelerator.

Super-pressure balloons are also fabricated from non-extensible material, but they are designed to float at a constant-density altitude with an internal pressure greater than the local ambient atmospheric pressure. Super-pressure balloons are partially inflated with a lifting gas, sealed, and allowed to rise. Like the zero-pressure balloon, as the balloon ascends, the lifting gas expands increasing the balloon volume until it reaches the altitude of first full inflation. From the altitude of first full inflation, the balloon continues to rise, converting excess free lift to internal pressures that are progressively greater than ambient atmospheric pressure, until the constant-density equilibrium floating altitude is reached. Unlike the zero-pressure balloon, the buoyancy of the super-pressure balloon is not affected by changes in the radiation environment. Changes in temperature cause changes in super-pressure but not in the balloon volume, so these balloons continue to float at a constant-density altitude. The tensile strength of the balloon envelope limits the maximum pressure differential between the lifting gas and the ambient atmosphere. As a result, a relief valve is included to prevent the balloon pressure from exceeding a predetermined value. Because a super-pressure balloon only looses lifting gas mass through valving caused by over-pressurization, leaking, or diffusion of the lifting gas through balloon envelope, super-pressure balloons are particularly well suited for long duration flights.

The design of Mars balloon systems is a heavily integrated process influenced by the flight environment, balloon type, balloon geometry, payload mass, suspension system, and material. As such, a systems engineering approach must be undertaken to insure proper consideration of the impact of all of these factors in the final design.

Balloons, by nature, are thermally-controlled. The mean temperature of a Mars balloon depends primarily on the thermal radiation environment in the vicinity of the balloon, and is subject to major variations diurnally, seasonally, geographically, with atmospheric dust load, and with altitude. Direct solar beam heating is small relative to the albedo and thermal inertia of the surface. The balloon temperature maximum and minimum control the differential pressure range required to maintain a superpressure balloon at constant volume. The pressure differential multiplied by the radius of curvature determines the stress level produced in the envelope material, and the ratio of this stress to material strength should be sufficiently small to maintain an appropriate Margin of Safety.

The low density of Mars atmosphere, combined with large thermal gradients results in the need for a large balloon made of light-weight, high-strength material. For a spherical superpressure balloon, the only way to increase the maximum allowable envelope differential pressure is to increase the film thickness which increases the empty balloon mass, necessitating even larger balloons, and thus increasing the envelope stresses for the same differential pressure. An elastica, natural shape, or "pumpkin" super-pressure balloon can withstand higher differential pressures by reducing the circumferential radius of curvature, but this shape requires an increase in the number of lobes. While the weight penalty is less than for a corresponding spherical balloon, the pumpkin balloon overall tends to be heavier than the corresponding spherical balloon.

In a spherical super-pressure balloon, the envelope carries most of the load which translates to meridional and circumferential stresses. This often makes the envelope material the limiting factor in balloon size and associated payload mass. Another challenge for spherical superpressure balloons is the attachment of the payload; a concentrated load normal to the balloon surface results in an "infinite stress" at the point of application, and a vertical force tangent to the sphere at the point of application results in a stress concentration [14]. Because of this, the payload is often supported by a harness of load lines which interface with the spherical balloon at a point where the discontinuity stresses are low enough to be compatible with the balloon envelope material—typically 30 degrees below the equator of the sphere. Another method of supporting the payload is by attaching it to a bottom fitting which is secured to a center load line, shorter than the balloon diameter, and attached to an apex fitting. This method transfers the payload load to the apex fitting. Both of these methods for payload attachment create operational problems when the balloon is deployed in windy conditions [15]. Despite these drawbacks, due to their simplicity and volumetric efficiency, lightly loaded spherical balloons have been flown successfully for a variety of terrestrial applications for many years. These balloons often use bilaminated polyester film [16] or Mylar film [15] for the envelope material.

The known limitations of spherical superpressure balloons prompted further investigation into how to increase balloon volume and associated payload without increasing the thickness of the film material. The result was the pumpkin balloon design, which is made up of a series of lobes created by excess circumferential material between high strength tendons at the edge of each gore. The tendons are longer than the envelope gore length, off-loading the meridional stress load from the film to the tendon. Circumferential stress in the skin is reduced by the reduced radius of curvature of the lobe surfaces. This allows the utilization of envelope material with required ultimate strengths that are significantly lower than the load tendons, while maintaining sufficient strength to tolerate high localized stresses. There is a limit to the lobing for a given number of gores before the balloon envelope buckles resulting in a cleft. This phenomenon is shown in Figure 11 for a fully inflated, full scale Ultra Long Duration Balloon (ULDB) flown from Australia in March, 2001.

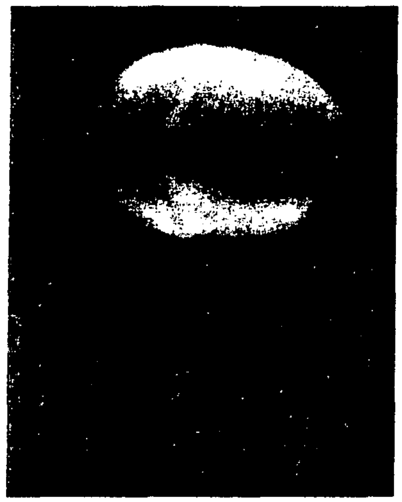


Figure 11: Full-Scale ULDB with Undeployed Material [17]

As the number of gores increases, the allowable amount of built-in lobing decreases. C. R. Calladine [18] developed a semi-empirical relationship:

$$n < 47 / \alpha^{2.5} \tag{1}$$

where α is the half-angle, in radians, of the lobed gore and n is the number of gores as shown in Figure 12. The manufactured gore width is defined by s and the distance between tendons is c.

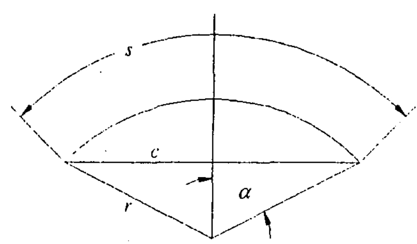


Figure 12: Lobed gore geometry

The Calladine relationship leads to a relationship for the maximum half-lobe gore angle and maximum width ratio [19]:

$$\alpha_{max} = (47 / n)^{0.4} \tag{2}$$
$$s / c_{max} = \alpha_{max} / \sin \alpha_{max} \tag{3}$$

The ULDB project tested this relationship by manufacturing a series of 48 gore model balloons of various gore designs. Balloons with constant lobe angles and varying lobe radius behaved according to the Calladine relationship. Those with constant lobe radius did deploy completely with an s/c greater than that expressed by the Calladine relationship. Pumpkin balloons have demonstrated the ability to withstand five times the pressure loads of an equivalent volume sphere [20].

While a pumpkin balloon design can result in lower stresses on the film for the same pressure as a spherical balloon, the envelope material must still possess sufficient ultimate strength to tolerate that stress.

In addition to ultimate strength, it is necessary to have an acceptable modulus of elasticity in the temperature range associated with the floating altitude. This may in fact be of critical importance, because if the modulus of elasticity is insufficient, superpressures will cause the envelope to stretch which in turn increases the volume and buoyancy of the balloon. If that is the case, the balloon will continue to ascend to even higher altitudes until it bursts. The higher the modulus of elasticity, the more stable the balloon float altitude.

Long duration flights require the balloon film to be resistant to pinholing along with a low permeability to the lifting gas. In addition to low permeability to the lifting gas, it is also desirable to have a low permeability to the constituents of the ambient atmosphere in order to insure that there is no appreciable diffusion of higher molecular weight atmospheric gas into the balloon volume at any point during the flight. Long duration flight systems must also resist degradation resulting from exposure to ultraviolet (UV) radiation. Since the intensity of solar radiation at Mars is about half of Earth, it is likely that any stratospheric balloon material used for high-altitude terrestrial applications will have sufficient UV resistance at Mars.

The mean temperature of the super-pressure balloon at float altitude is a primary concern, and the equilibrium gas temperature varies primarily as the result of the absorption and emission characteristics of the film material. Ideally, the effects of radiative heating can be minimized if the film material is transparent to the entire spectrum of solar and albedo radiation. In that way, the gas temperature varies primarily as a result of the more predictable night and day ambient temperature cycles.

For maximum volumetric efficiency with the least impact on overall spacecraft bus size, a high balloon system packing density is an important design consideration. Consequently, the balloon material must first withstand the packing and associated creasing stresses, along with possible plastic deformation and thermal processing that could occur during transit to Mars. The balloon material must tolerate abrasion caused by chafing during packing and storage, as well as during deployment. Creases in the film material can cause tears, and abrasion can cause pinholes.

Packing and storage concerns are magnified at higher temperatures. While on the surface of Mars, the material will be subject to ionizing radiation and cyclical temperature extremes. The balloon material will be required to maintain its integrity after being exposed to large temperature gradients. Additionally, it is necessary to know the capability of the balloon material to recover if exposed to transient peeks in temperature outside the range of design conditions. The response of the balloon fabric to temperature gradients may necessitate a thermal management system requirement. The effect of long term exposure (on the order of a year or greater) to ionizing radiation on the material needs to be understood so that it can be factored into the design.

Sterilization is required to prevent contamination of Mars with microorganisms from Earth. Methods of sterilization need to be tested to determine their effect on the balloon material and balloon reliability. Sterilization should not weaken or deform the material.

Lastly, the balloon material will require sufficient manufacturability that the finished balloon is reliable. The gores should be sealed gas tight with seal strengths equal to that of the parent film.

Zero-pressure balloons are not subject to the pressure differentials of superpressure balloons, and as such do not experience the same circumferential stresses. Additionally, the lack of superpressure reduces the design sensitivity to balloon film mechanical properties and transparency to solar and albedo radiation. Also, because the flight duration for zero-pressure balloons is typically short, they are less sensitive to permeability and resistance to pinholing requirements. Zero-pressure balloons must satisfy the other design requirements laid out for the other balloon systems.

The trades for the balloon system are listed in Table 4:

WBFS	HBFS
Balloon Type: Extensible, Zero-Pressure	Balloon Material: Mylar, Dartek, Composite
Balloon Geometry: Spherical, Elastica	Balloon Geometry: Spherical, Elastica
Envelope Storage: Folded, Wound, Rolled	Envelope Storage: Folded, Wound, Rolled

Table 4: Balloon System Trades

Weather Balloon Flight System (WBFS)

The WBFS consists of the balloon - envelope, seams, end fittings, and inflation tube; radiosonde; and suspension system. It is designed to carry a 150 g radiosonde payload to an altitude of 20 km while taking *in situ* atmospheric measurements. The system summary of the WBFS is given in Figure 13, including the overall mass budget.

Volume: 1161.8 m^3
Diameter: 13.04 m
Geometry: Spherical
Balloon Mass: 2.54 kg
Gas Mass: 167 g
Sonde Mass: 150 g
System Mass: 2.86 kg

Material: 3.4μm polyethylene
Material Strength: 410±40 kg/cm^2 MD
370±30 kg/cm^2 TD

Figure 13: Weather Balloon Flight System Design Summary

The minimum meteorological measurement requirements for a weather balloon are pressure, temperature, humidity, wind, altitude, and density. In order to reduce radiosonde mass (and therefore minimize the balloon size and mass), only pressure, temperature, and humidity are measured directly *in situ*. In order to reduce cost and risk, a key requirement is to exploit radiosonde sensors that are already space-qualified, and have a design heritage linked to previous Mars missions. From 1989 to 1994, the Finnish Meteorological Institute (FMI) performed space qualification testing on small, lightweight pressure, humidity, and temperature sensors based on the commercially available Barocap®, Humicap®, and Thermocap® sensors manufactured by Vaisala, Inc. During the testing, the sensors were exposed to temperatures ranging from -135°C to 60°C and impact shocks of up to 500g [21]. The specifications for the tested sensors are listed in Table 5. Some or all of those sensors have been used on the Mars-96 Small Stations and Penetrators, the Mars Polar Lander, Beagle 2, and Phoenix missions.

Characteristics of FMI Tested Sensors								
Sensor	Range		Resolution	Accuracy (3 sigma)	Temperature Dependence	Hysteresis	Mass (g)	Dimensions (mm)
	min	max						
Barocap® (hPa)	0	50†	<0.005	<0.02	40 hPa/K	<0.005	3	Ø15x8
Humicap® (%RH)	0	100	<0.1	<1	-	-	1	4x4x0.2
Thermocap® (K)	100	370	<0.02	<0.1	N.A.	-	1	Ø1.52x2.4

† Barocap® operating range is 0-1200 hPa

Table 5: Characteristics of the Finnish Meteorological Institute tested sensors [21]

The Barocap® is a capacitive aneroid sensor using a silicon diaphragm with an internal vacuum chamber. The Thermocap® is a capacitive wire sensor. The Humicap® consists of two sensors which are cyclically heated to prevent ice formation; the sensors are thin film capacitors which measure relative humidity directly.

Analog measurements are converted to digital outputs and transmitted to the ground station via a 405 MHz UHF transmitter, using a narrowband GFSK (Gaussian Frequency Shift Keying) modulated downlink signal which carries 2400-bit data frames at a data rate of 2400 bits/second and an output power of 200mW. The sonde is powered by a lithium-ion battery with a specific energy density of 150-250 W-hr/kg. Based on the component mass and the mass of a similar Vaisala RS92-D radiosonde, a mass budget of 150 g has been allocated to the radiosonde.

Wind speed and altitude can be obtained readily from ground station radar tracking of the balloon. Because the balloon material is transparent to radio waves, a reflective ribbon will be incorporated into the balloon tether. As a check, the altitude measurements will be compared to calculations made using the hypsometric equation with data from sonde measurements. Density will be calculated from the state equation.

Because of the small payload mass and the short flight duration, a zero-pressure spherical balloon was selected. Extensible latex balloons were considered, but the large volume required even at initial inflation translated to an unacceptable mass penalty. Zero-pressure balloons are deployed and flown regularly in the Earth's atmosphere. The spherical balloon shape was preferred due to its simplicity and the modest loads resulting from a very low mass payload.

The balloon group at the Institute of Space and Astronautical Science (ISAS), within the Japan Aerospace Exploration Agency (JAXA), has successfully flown ultra-thin polyethylene zero-pressure balloons with payloads up to 10 kg to altitudes greater than 50 km in Earth's atmosphere [22]. The ambient atmospheric conditions at those altitudes are comparable to Mars ambient conditions 20 km above the reference surface altitude. The mechanical properties for the films used in those balloons are summarized in Table 6.

	Thickness (μ m)	Ultimate Strength (kg/cm^2)		Ultimate Elongation (%)	
		MD	TD	MD	TD
25°C	3.4	410±40	370±30	520±50	960±60
	3.0	360±20	270±10	570±20	720±30
	2.8	340±20	250±20	610±20	790±20
-40°C	3.4	610±80	460±20	330±30	570±30
	3.0	420±20	310±20	360±20	310±40
	2.8	440±10	440±30	400±10	460±70
-80°C	3.4	690±50	640±70	220±20	380±30
	3.0	490±40	520±60	230±60	230±30
	2.8	660±40	460±20	230±20	210±30

Table 6: Mechanical properties of ultra-thin polyethylene film [22; 23]

A 3.4μm polyethylene of the type used in the JAXA ultra-thin film test flights was chosen as the envelope material. An iterative design tool was developed, utilizing a piecewise fit of Mars Global Surveyor temperature and pressure readings from April 1996, to size the balloon envelope based on the assumption of neutral buoyancy at 20 km given a payload mass of 150 g, assuming a lifting gas mass sufficient to provide 20% free lift at launch, and using the empirical balloon mass relationship $m_{ballon} = 0.23V_B^{2/3}$ [24]. The balloon is inflated through an inflation tube located on top of the balloon and each balloon is packed by folding.

When a launch command is executed, the MABL system radar and UHF receiver are activated, initiating appropriate system checks. In addition, the WBFS sonde pressure, temperature, and humidity sensor outputs are compared with ground station sensors to ensure proper operation of the sonde sensors, including reconditioning the humidity sensors, and proper operation of the transmitter. Lastly, in order to mitigate the risk of damage to the balloon by wind or dust, local go/no-go weather conditions are checked against launch criteria. Once a go condition is established, the balloon is inflated and released.

Heavy Balloon Flight System (HBFS)

The HBFS consists of the balloon (including envelope, seams, end fittings, and inflation tube), the payload gondola, and the suspension system. The system summary for the HBFS is given in Figure 14, including the overall mass budget.

In addition to small, short-lived radiosondes, planetary scientific needs require instruments that make measurements of magnetic properties, mineralogy, and imagery. Balloon borne payloads fill a resolution gap in measurements between orbiters and surface rovers. Analysis of magnetic properties with a balloon-borne magnetometer of sufficient resolution could provide understanding of the structure and source of Mars' remnant crustal magnetism [25]. Local concentrations of ice, hydrated minerals, or deposits on carbonates could be detected by neutronic devices, while electromagnetic sounding using radar altimeters may reveal sub-surface ice layers [26]. Detailed spectral surface measurements can be made using balloon-borne miniature grating and acoustic-optic spectrometers. 3-D image surface mapping can be created from balloon-borne laser altimeter topographic measurements. And, high resolution imaging can be performed from a balloon-borne aerial platform [25]. The HBFS is designed for a 50 kg gondola utilizing a generic payload. Whatever the instruments, the use of technologies developed for other micro vehicles can be leveraged. In addition, instruments will require sufficient robustness to remain calibrated for months to years, while providing capability for remote calibration. It is also apparent that scientific balloon payloads will require low power, which drives the need for lightweight and low-power communications systems with a relay infrastructure capable of handling the data-rate needs of the data generated [27] and operate via a communication protocol of existing Mars orbiters. Long duration payloads will likely require a means to generate power.

Volume: 22101 m^3
Diameter: 34.20 m
Geometry: Spherical
Balloon Mass: 74.83 kg
Gas Mass: 12.09 kg
Gondola Mass: 50 kg
Suspension System Mass: 500 g
System Mass: 137.42 kg
Float Altitude: 10 km

Material: 3.5μm Mylar/55 denier Kevlar scrim/ 3.5μm SF-372®PE
Areal Density: 19.66 g/m^2
Material Strength: >2500N/m

Figure 14: Heavy Balloon Flight System Summary

In addition to the science package, each gondola will include a miniature methane-LOX-powered gashopper transport. The mini-hoppers have an allocated mass of 10 kg with an additional 20 kg of propellant, for a total balloon launch mass of 30 kg out of the 50 kg gondola mass. Up to 50% of the propellant will be allowed to boil off during the course of the balloon mission. The mini-hoppers can be dropped by the balloon as it is passed over an area of interest. Once dropped, the mini-hoppers collect up to a 2 kg sample, allowing return samples to be collected on a planetary scale and from altitudes not accessible to rovers. After the sample is collected, the mini-hopper will fly an uncontrolled parabolic trajectory towards the lander, and land within a few kilometers of the lander where the sample can be retrieved by the CO_2 gashopper. A 22 kg hopper, including 10 kg of propellant, should be able to travel 800 km assuming a hard landing [28]. The reduction in payload mass will be offset by valving some of the lifting gas.

HBFS long duration flight requirements dictate the need for a superpressure balloon design. Mylar, Dartek, and a composite lay-up were compared for the envelope material. Mylar – polyethylene terephthalate (PET) – is a common superpressure balloon film manufactured by DuPont-Teijin Films. The thinnest standard gauge is 6μm. Dartek is a 6.6 nylon MDO film produced by DuPont with high strength in the machine direction and high elongation in the tear direction providing increased tear strength. Both of these materials are sufficiently ductile at low temperatures to be viable for use in the Martian environment. Mylar is prone to pinholes resulting from folding and storing. Improved manufacturing techniques have reduced the issue, but the potential still exists. Mylar also provides minimal resistance to crack propagation, particularly at low temperatures less than -80°C. Dartek is hydroscopic, which requires material handling considerations during manufacturing; however the trace moisture levels, even in humid Martian atmospheric conditions should not impact material performance [15]. Nylon balloons can fail at the seams, likely due to failure of the adhesive. The exhibited shortcomings of Mylar and Dartek warrant the use of a composite film for a Mars balloon envelope. The 2001 Mars Aerobot/Balloon System (MABS) proposed a five layer composite material – a 3.5 micron Mylar film for substrate stiffness, a layer of polyester based adhesive, a 55 denier Kevlar scrim in an orthogonal pattern with 160 yarns per meter to meet the strength requirements with minimal weight penalty, another layer of polyester adhesive, and a 6 micron layer of polyethylene film (Stratofilm 372) for pinholing resistance and crack initiation and propagation. The adhesive layers provide bonding between the primary layers while also providing additional pinholing resistance [29]. The layup for this composite structure is shown in Figure 15:

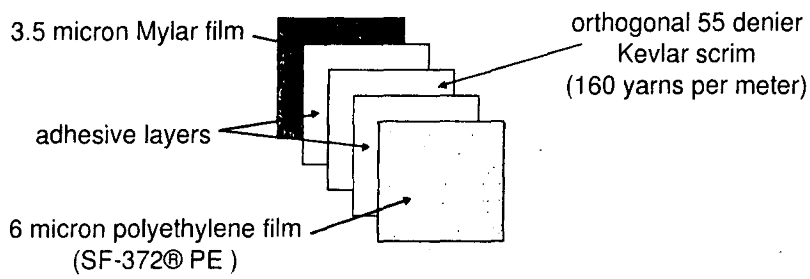


Figure 15: MABS Composite Structure Layup [30]

The mechanical properties for this composite for the expected mission environment are given in Table 7. The composite is sealed with a Mylar heat activated tape with seam strength of 88 percent of the parent material at 23°C and 98 percent at -140°C. In addition to improved fracture strength over standard Mylar and Nylon films, the composite showed no sign of degradation after 2 Mrads gamma ray exposure indicating suitability for sterilization [30].

Areal Density		(g/m²)	19.66
Strength (23°C to -140°C)		(N/m)	> 2500
Tear Toughness	23°C	(N)	12
	-140°C	(N)	43
Seam Strength (23°C to -140°C)		(N/m)	> 2500
Radiation Effect			No degredation in strength for radiation levels of 2 Mrads
Adhesive Performance			No observed component or adhesive delamination or embirttlement down to -198°C

Table 7: MABS Composite Mechanical Properties

A composite lay-up based on the MABS composite was selected because it not only satisfies the strength requirements, but also fulfills the ancillary requirements associated with a Mars mission. A spherical balloon was chosen, because the strength of the envelope material and the light payload did not justify heavier, more complicated pumpkin balloon geometries. Furthermore, the heritage of successful spherical superpressure balloon flights and the simplicity of design mitigated somewhat the risks associated with balloon failure. An iterative design tool similar to that for the WBFS was developed based on the assumption of neutral buoyancy at 10 km, which will allow a scientific balloon clear access to almost the entire planet with the exception of the highest peaks, and wind currents should route a balloon around those peaks [31]. A payload mass of 30 kg was assumed along with an associated suspension system mass of 500 g. The payload attaches to a fitting at the bottom of the balloon and is secured to a center load line attached to the apex fitting. The envelope mass was calculated using an areal density of 19.66 g/m^2 for the composite. A free lift of 10% was used to provide a slow ascent and to minimize the expected shock loads associated with an autonomous launch. The balloon will be filled through an inflation tube from the top, and will be packed by folding.

The expected responses of the HBFS to changes in local ambient atmospheric conditions are represented notionally in Figure 16.

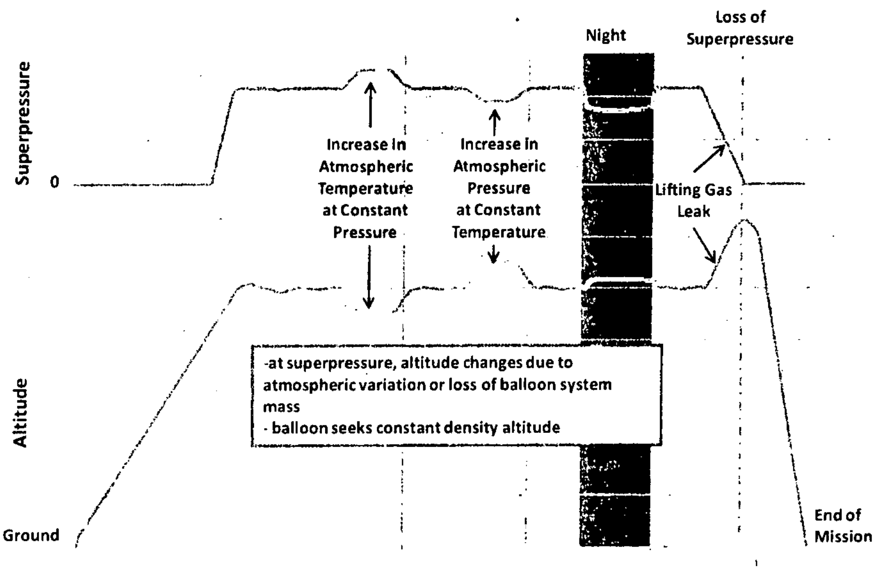


Figure 16: HBFS Response to Atmospheric Variations

After launch, the balloon will ascend until it achieves neutral buoyancy with the ambient atmosphere and continue to float subsequently at a constant density altitude. The balloon volume remains constant as long as the super-pressure is maintained and as long as the mass of lifting gas is maintained. A balloon can circumnavigate the planet during the course of a 100 sol mission [26]. The mass of lifting gas defines the life of the mission. Pinhole leaks and diffusion of the lifting gas through the envelope should be negligible; therefore tears will most likely be the primary cause of loss of lifting gas. As the lifting gas leaks, the balloon will rise until the balloon shape can no longer be sustained by super-pressure at which point it descends to the surface. Even with that type of failure, the balloon payload can descend and continue to operate as a surface-based scientific payload at a distant surface location. If the scientific payload is integrated into a micro-rover then it will be possible to greatly expand Mars surface coverage. Because the HBFS will be out of range of the lander for much of its mission, a communication link with a Mars orbiter will be necessary for data relay.

Mars Autonomous Balloon Launch System (MABL)

The thin Martian atmosphere translates to relatively large balloons for modest size payloads. The large size of these balloons translates to major autonomous launch challenges and most likely represents the riskiest part of these missions. The balloon launch system must be capable of launching 25 WBFS balloons and three HBFS balloons. It includes the structure, electronics, mechanisms, and inflation system, along with the tracking radar system. In addition, the MABL system includes a meteorology package with sensors of the type used in the WBFS radiosondes. An integral part of each launch will be the deployment and inflation of the *launch cone* atop the launcher. The launch cone is employed to stabilize the balloon during inflation and minimize the risk of damage or tearing of the balloon envelope. The MABL system sits atop the S/C Bus like a turret, and rotates until the payload is downwind of the lander. The balloon payload is then extended from the lander on a jib boom. The consumable hydrogen lifting gas is produced via electrolysis from Mars water resources via the *in situ* propellant production system (ISPP) described later in this document. After a "go" condition is established for a balloon flight, the inflation gas is injected into the balloon fill tube through a diffuser, slowly at first and then at a higher flow rate as the inflation bubble is established. The balloon is held in place in the launcher by a reefing collar with a tear strip and only the top portion of a balloon is inflated. Once the required lifting gas mass for the given balloon is injected into the balloon bubble, the reefing collar and clamps holding the payload are released and the balloon begins to rise with the envelope unfolding under it. The wind carries the balloon, which snatches the payload away from the lander. A mass of 1480 kg has been allocated for the overall MABL system.

IN-SITU PROPELLANT PRODUCTION (ISPP)

In-situ resource utilization (ISRU) technologies have the potential to reduce costs, risk, and mass, as well as increase capabilities on planets like Mars by allowing systems to be self-sufficient. The purpose of in-situ propellant production (ISPP) on Mars is to produce propellant for Mars vehicles using Martian atmosphere and water in order to eliminate the need to bring the required propellant from Earth. A major ISRU application is propellant for Mars ascent vehicles (MAV). MAVs transport Mars samples (as well as crew for manned missions) from the Martian surface into a low-Mars orbit for retrieval by earth return vehicles (ERV) [32]. If enough propellant is provided, the remainder of the return trip to Earth can also be completed using ISRU propellant, which could completely eliminate the need to bring significant quantities of propellant from Earth for the return trip, with the exception of small thrusters and other devices needing small amounts of hydrazine or other propellant. The ISPP plant is capable of successful operation for missions that span years or can simply continue to provide power and fuel for continued science operations well after the end of a mission given no system damages or failures. This clearly shows the potential benefits of this technology and why it should be implemented into future MAV and robotic designs.

The Mars atmosphere composition is shown in Table 3. A few propellant options using the Martian atmosphere include nuclear propellants, carbon monoxide and oxygen, and methane and oxygen. In the end, methane propellant proves to be the best candidate because it requires the use of well developed chemical processes while producing a high performance propellant [33]. Portions of the process are very well developed and are currently in use for space applications. The ISPP system for producing methane propellant consists of the following elements: acquiring and compressing carbon dioxide from the Martian atmosphere, conversion of pressurized carbon dioxide and hydrogen into methane and water using a Sabatier reactor, conversion of the water by-product into oxygen and hydrogen using water electrolysis, and the liquefaction and storage of the propellants (methane and oxygen). This process can be seen in the functional flow block diagram in Appendix C-1.

Assuming that there will be a minimum of 400 days of wait time after landing on Mars before an opportunity to return to Earth, analysis focused on producing 1 kg of methane-oxygen propellant per day. This results in the production of 400 kg of propellant in 400 days, which is enough propellant to fuel the MAV for the proposed Mars sample return mission. To achieve this rate of production, 1.4 kg of water and 0.825 kg of carbon dioxide must be supplied each day. However, with these inputs, the system will produce over twice the required mass of oxygen for an oxidizer/fuel ratio of 3.5. As a result, the tank size must accommodate for the storage of this excess oxygen. The hydrogen will be stored for the inflation of the balloon systems, while the remainder of the methane-oxygen propellant produced during the 800 day production cycle will be used to fuel the hoppers of the balloon payloads.

Atmospheric Carbon Dioxide (CO_2) Extraction

The fact that the Martian atmosphere is more than 95% carbon dioxide by volume makes CO_2 very attractive for use in ISRU processes. In order to concentrate the atmospheric CO_2, a NaX Zeolite system has been selected. Zeolite can selectively absorb CO_2 as Mars atmosphere flows through a canister at a low constant pressure. A blower can be used to remove any built up nitrogen and argon gases, but is not necessary because such small quantities of these gases will not affect the overall system and propellant production. Next, the canister is closed and heated using waste heat from the ISPP plant or from some other heat source. During heating, the CO2 is released and the pressure naturally rises. Once the desired pressure is achieved for entry into the Sabatier reactor, the canister valve is opened to release the pressurized CO_2 into the reactor. When the canister pressure finally begins to drop and the usable CO_2 has been released. the canister is closed and cooled for its next cycle. In order to minimize the canister size and NaX Zeolite mass, two units will be in operation and each unit will perform four cycles per day. This will result in a total of eight cycles performed per day with each cycle lasting approximately three hours. With the goal of producing 1 kg of methane-oxygen propellant per day and supplying 1.4 kg of water per day, 0.825 kg of atmospheric CO_2 must be extracted daily and fed into the Sabatier reactor. In order to account for design margins, it will be assumed that 1 kg of CO_2 will be extracted per day. This is equivalent to a demand of 0.125 kg of CO_2 per cycle. According to Sridhar et al. [34], the process has a CO_2 loading of about 14 wt% or about 14 grams of CO_2 per 100 grams of absorbent. When used in a comparable combined electrolysis/Sabatier ISPP plant for a sample return mission, the CO_2 separator and compression system have an estimated mass of 3.07 kg, a volume of about 4.42 L, and a power requirement of about 67.3 W [34]. Table 8 shows the nominal specifications for the system.

Number of Units	2
Number of Cycles	4 per unit per sol
Canister Material	Aluminum
Sorbent Material	NaX Zeolite
Specific Heat Capacity	0.9 kJ/(kg K)
Density	0.7 g/mL
Heat of Absorption	41 kJ/mol
Inlet Pressure	0.8 kPa
Outlet Pressure	101 kPa
Minimum Temperature	200 K (Mars ambient)
Maximum Temperature	348 K
Mass	3.07 kg
Volume	4.42 L
Power Required	67.3 W

Table 8: CO2 Separator and Compression Model Specifications. [34]

Surface Ice Processing Plant

The primary source of water is icy Martian regolith. It will be assumed that a well qualified, water rich landing site will be chosen based on previous scientific data. The ice can be extracted from ice-containing regolith within one meter of the surface utilizing an excavation robot equipped with ice core drills, bulldozers, dump beds, and water detection equipment. The rover technology will be discussed later in the report. A batch process will be employed for water extraction, whereby the raw material will be accumulated in the dump bed of the collector robot for transport to the ice processing plant. After arriving at the ice processing plant, the feedstock will be dumped down a chute leading to an initially unheated raw material processing chamber. The opening of the chute will have dimensions that are slightly larger than the width and maximum height of the elevated dump bed. Subsequently, the raw material batch will be confined in a closed volume and heated so that the ice is melted, allowing the water to be separated from the regolith. During heating, the entrance to the chute must be closed to maintain an elevated pressure in the chamber and to eliminate the possibility of any water vapor escaping through the chute. The floor of the chamber can be tilted to facilitate the removal of liquid water, enabling the liquid to flow from the raw material processing chamber into a distillation unit. The liquid water solution flowing from the processing chamber will be pumped through a filtration unit, prior to distillation in order to minimize particulate concentrations. Once the water has flowed from the chamber into the distillation unit and before the next feedstock batch arrives, the chamber is cooled and cleaned of residual regolith and rock. An auger system will be used to auger the feedstock into the processing unit and to auger the remaining material back outside the chamber after the extraction of the liquid water. After the distillation process, the processed water will be pumped to the water electrolysis cell for conversion into hydrogen and oxygen. In order to produce 1 kg of propellant per day, 1.4 kg of water must be electrolyzed per day. The amount of actual ice to be extracted per day will be determined by the density and water concentration of the surface ice in the particular area and depth of excavation. This will, in turn, determine the volume of the chamber required to hold a shipment of surface ice. Assuming that the regolith collected has a water mass fraction of 20% and that the processing plant will successfully extract 10% of the available water, 70 kg of regolith must be collected per day to provide the needed water for the proposed Mars sample return mission. It is estimated that the system (including the two excavation robots' mass of 200 kg each) will have a mass of approximately 500 kg and require a power of 800 W (including the excavation robots' power requirement of 300W each). It should be noted that these estimates will change pending future mission oriented data that will affect the sizing of the system.

Excavation Robotics

With reduced gravity, low ambient temperatures, low pressures, dust storms, and very hard water-ice/permafrost, it becomes a challenge to design a low mass, low power, excavation robot that can successfully extract ice from within a meter of the surface. However, deep ice core drilling technology proves to be a promising solution for Mars surface ice excavation. Deep ice core drilling uses a hollow drill to cut a cylindrical pathway around the core to be extracted. This technology is currently used in harsh conditions in Antarctica and similar conditions around the world for the drilling of hard ice and underlying bedrock up to several kilometers below the surface at temperatures as low as -90^{0} C, which is approximately the average ambient temperature on Mars. Two key aspects of this technology that must be achieved for successful use on Mars are autonomous operation and reliable core retrieval.

Both of these concerns were addressed in the design of the Mars Astrobiology Research and Technology Experiment (MARTE) as seen in Figure 17 [35]. Its purpose was to create an autonomous deep ice core drill for core collecting below the Martian surface. It utilizes dry rotary cutting techniques with carbide drag cutters and mono-crystal diamonds with a maximum electric power requirement of 150W during nominal drilling operations. While creating a 4.8 cm diameter bore hole, it is capable of drilling to depths of 10 m and produces 2.7 cm diameter, 25 cm long cores. The core hand-off system removes the core from the lead drill tube and places it in a core clamp for sample analysis preparation and delivery. There is a highly integrated sensor feedback control on all drilling axes, which allows for future integration of intelligent drilling algorithms and fully autonomous operation. The system is also equipped with a life detection system, a panoramic imager, and bore hole inspector. MARTE is based on a previous Honeybee Robotics design for the Mars Technology Program. Their system drilled a bore hole 8.3 meters deep with Mars "flight-like" power and thrust levels (less than 100W and less than 450N).

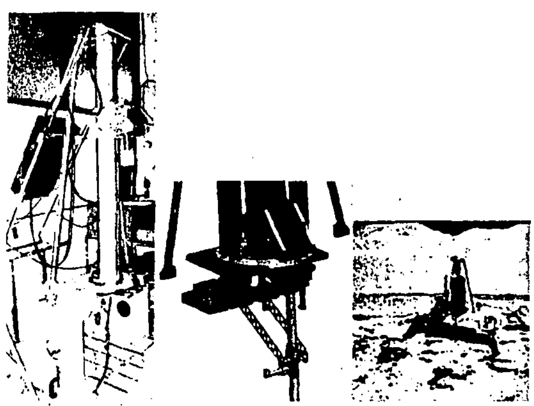


Figure 17: Mars Astrobiology Research and Technology Experiment (MARTE).

It is proposed that a similar technology be utilized by the excavation rover. The drilling process is identical, but the core hand-off system would transfer the collected cores to the robot dump bed for delivery to the ice processing plant after going through some or all of the scientific tests on board the rover. As mentioned before, the amount of surface ice to be collected per day will depend on the properties of the ice being collected at the excavation site. On the basis of the ISRU feedstock discussion, 70 kg of surface ice should be extracted per day. Based on the rate of operation of the drilling system, the power requirements, and the constraints on the size of core that can be brought to the surface, the amount of one shipment of surface ice can be determined. If it is calculated that the most current technology cannot produce the required amount of surface ice per day, then additional excavation rovers will be needed for the operation of the ISPP plant. For this concept design, it will be assumed that only two rovers will be needed and they will each have an approximate mass of 200kg (including the 50 kg drilling system) and a power requirement of about 300W (including 150 W for drill operation). The rovers will also be equipped with dump beds and bulldozer attachments on the opposite end of the drilling mechanism. These attachments can be used to clear and level research and/or water extraction sites when needed and to dig and collect surface regolith for water extraction or sample collection.

Water Electrolysis Cell

Water electrolysis technology for the production of hydrogen and oxygen is well developed. In the basic ISPP system, the hydrogen product will be fed into the Sabatier reactor and the electrolyzed oxygen will be cryogenically stored. For the proposed mission, the excess hydrogen that is not required for the Sabatier reactor will be stored in a tank for fueling the balloon systems. In all, approximately 46 kg of Hydrogen will be required to fuel the 3 large balloons and 25 weather balloons. At the proposed production rates, 0.135 kg of extra hydrogen will be produced each day. This excess hydrogen will be stored in a pressurized tank until distributed to the balloon systems once required amounts are achieved (about 7 kg of hydrogen for each large balloon and less than 1 kg of hydrogen for each weather balloon).

The water electrolysis cell operating currently on the International Space Station was built by Hamilton Sundstrand. It produces 2.3-9 kg of oxygen per day when operating continuously. Since the system is already being used in space applications, it does not need to be drastically redesigned, only modified to fit the requirements of the given mission. According to Ash et al. [33], for a system that is supplied 9 kg of water per day, running continuously at 67 bars, and with a mass of about 60 kg and volume of about 50 m^3, 1.875 kW of electric power is required. When these estimates are scaled down to the proposed sample return mission, only 292 W of power will be required for a 60 kg, 50 m^3 system running continuously at 67 bars.

Sabatier Reactor

Sabatier reactor design is a mature technology. Utilizing hydrogen and carbon dioxide feedstocks, the Sabatier reaction produces pure methane and water after a single pass through a nickel or ruthenium catalyst reactor bed [36]. The reaction is exothermic, so once started the process is self-sustaining and it operates optimally at about 400° C [36]. Hamilton Sundstrand has also produced a Sabatier Reactor System that produces about 2000 pounds of water per year on the International Space Station and is almost identical to the system that is needed for this study. Hence, the allocated reactor mass is 40 kg..

Cryogenic Propellant Storage

The difficulty with the methane-oxygen propellant is that the methane and oxygen need to be stored cryogenically on the surface of Mars. According to Ash [33], both oxygen and methane can be cooled to a temperature of 130K for liquefaction. There are a variety of refrigeration cycles, but it can be assumed that a system that cools at 30% of Carnot efficiency can be developed with a power requirement of about 550 W and an estimated system mass of about 95 kg [33]. For thermal control of long term cryogenic storage, multi-layer insulation (MLI) in a rigid vacuum jacket should be used to insulate the tank. The average vacuum jacket has a wall thickness of about 1-3mm and 100-125 layers (5.1-6.3 cm) of insulation should be sufficient [37].

The optimum tank shape is a sphere because it provides the most volume per surface area. Because the methane and oxygen can be cooled at the same temperature (130K), a spherical common bulkhead tank can be used. A common bulkhead tank consists of two independently pressurized compartments, one for fuel and one for oxidizer as seen in Figure 18 [38]. The cooling device can be placed in the oxygen portion of the tank, while the methane is cooled by heat transfer to the oxygen tank [37]. It is expected that 400 kg of propellant will be produced with this system in 400 days and it will also be the maximum amount of propellant stored in the tank at any time during the mission, so the storage tank will have a capacity of 1600 kg of propellant in order to account for excess oxygen produced. This results in a volume of 2 m^3 and a 1.56 m diameter. The tank dimensions can be altered based on defined MAV and other enhanced mission requirements. Its size could also be reduced if it does not have to accommodate the excess oxygen produced (i.e. the excess oxygen is vented instead of stored). This tank size is feasible given the previously proposed payload capacity of NASA's next generation heavy launcher, Ares V, whose payload inner diameter ranged from 4.52 m to 8.77 m. The empty tank mass is allocated to be 250 kg, for an expected total cryogenic propellant storage mass of about 345kg. There will also be a separate pressurized tank for Hydrogen storage. If, for whatever reason, the Hydrogen is not regularly dispensed to the balloon systems during the 800 day production cycle, the maximum amount that will be stored will be equivalent to the maximum amount produced in 400 days, which will be 54 kg. Accounting for design margins, the pressurized Hydrogen tank should be able to store up to 60 kg, which requires a diameter of 1.14 meters, an empty mass of 183 kg, and an estimated power requirement of 200W.

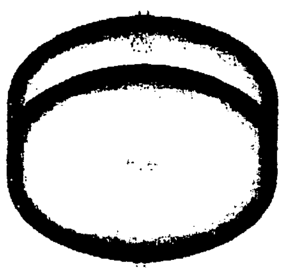


Figure 18: Common Bulkhead Tank

Total ISPP System Specifications

In summary, the entire ISPP plant will have an estimated mass of approximately 1500 kg with a 2.5 kW of power requirement. Table 9 shows the estimated mass and power required for each component of the ISPP plant.

COMPONENT	MASS (kg)	POWER (W)
ATMOSPHERIC CO2 EXTRACTION	3.07	67.3
SURFACE ICE PROCESSING PLANT	500	800
WATER ELECTROLYSIS CELL	60	292
SABATIER REACTOR	40	0
CRYOGENIC PROPELLANT STORAGE	345	550
HYDROGEN TANK STORAGE	183	200
RTG	300	0
MARGIN	68.93	590.7
TOTALS	1500	2500

Table 9: Total ISPP System Mass and Power Budget

Solar electric power and nuclear power were the only options considered to be viable for multi-kilowatts of electric power. The two systems were compared in terms of overall mass and footprint size, reliability, sensitivity to the Martian environment and environmental impact. However, for producing large amounts of power over an extended period of time, nuclear power has the advantages of providing continuous power, having a smaller size, having easier power transmission capabilities, having a longer duty cycle, and not being affected by the Martian atmosphere (i.e. wind and dust). A 2.5 kW electric power generator utilizing a radioisotope thermoelectric generator (RTG) integrated with the ISPP plant is feasible as well. The allocated mass of the RTG system is 300 kg. The system tier structure (product hierarchy) and system requirements are summarized in Appendices C-2, C-3, and C-4.

MARS CARBON-DIOXIDE HOPPER (MACHO)

A Mars sample return mission can be enhanced by utilizing sample acquisition systems that can gather samples from a wide area around the landing site. Surface rovers like *Spirit* and *Opportunity* (MER) rovers, operating currently on the surface of Mars can serve that purpose but they are very slow and cannot traverse difficult terrain. The MER rovers have traversed an averaged of approximately 10 m per sol [39]. The Mars Science Laboratory rover is to traverse on the order of 200 m per sol [40], but its ability to traverse difficult terrain is limited. A system that can exploit Mars' reduced gravity and fly over difficult terrain can provide the ability to achieve science objectives within the assumed 400-day sample return mission that are unachievable otherwise. A hopper vehicle that can propel itself on ballistic flight paths, over terrain, to reach its destination can greatly expand mission capabilities. Multiple hops can be achieved in order to reach specific locations. With CH_4 and O_2 in production for a Mars ascent vehicle, one hopper concept can be propelled using a Methane/LOX rocket. This type of rocket would be good for long distance hops, on the order of hundreds of kilometers, but would need to return to the base for refueling. Methane/LOX systems cannot be refueled at these distant locations, placing critical constraints on that type of sortie. A hopper system capable of producing its own propellant as it travels can overcome those constraints while providing enhanced capabilities for extricating itself from "potholes" or "quicksand" hazards. Utilizing CO_2 from the Mars atmosphere and compressing it onboard is the easiest option. Although CO_2 propulsion may not have the range of Methane/LOX, it can traverse large distances using multiple small hops. "Gashopper" is a term coined by Zubrin [41] for a CO_2 powered hopper. The operation of the propulsion system on such a CO_2 gashopper is as follows: Carbon dioxide is extracted from the atmosphere and stored under pressure in a tank. When enough CO_2 has been collected, the system is ready for use. Activation occurs when a valve is opened and the pressurized CO_2 flows into a heated pebble bed, initially at 1000 K, raising the gas temperature significantly. The heated CO_2 then flows through a supersonic nozzle and into atmosphere producing thrust. The delta-V required to reach a specific landing zone can be programmed, based on trajectory calculations, and the hopper can execute the maneuver. An onboard weather station allows the gashopper to input factors such as surface temperature, pressure, and wind speed and direction for pre flight trajectory calculations. The flight of the gashopper can be timed to occur with the pass of an orbiting spacecraft so the orbiter can track the gashopper and provide it with navigational commands. Approximately half of the propellant onboard is expelled during liftoff. The gashopper then begins to coast on its ballistic trajectory using CO_2-powered reaction control thrusters, utilizing the same tank as the main engine, to maintain proper attitude. Prior to landing, the hopper re-orients itself so that it can use the remaining propellant in the tank to slow down sufficiently for a 'soft' landing. The gashopper utilizes a ground sensing radar to detect the ground and properly time a braking fire of its engine. The radar also detects features of the landing zone that would make it unsafe such as the ground being too steeply inclined or a large boulder in the way. In this case the gashopper uses its fuel margin to maneuver away from these obstacles. When not in use, the reaction control thrusters must be covered to prevent them from clogging with dust during the time when the CO_2 tank is being recharged for the next launch. Once safely on the ground the hopper is able rove around its immediate surroundings to search for interesting targets for a sample return. While performing science duties and searching for samples the rover continues to charge its CO_2 tank. Once the hopper has completed its science objectives at a particular site, obtained a sample, and recharged the CO_2 tank, the process is repeated for a return to the base. Upon landing at the base, the gashopper will need to land some distance away from the base to avoid a collision that could damage critical equipment and threaten the health of the mission. The gashopper then drives to the base to drop off its samples, or hands them off to an ISPP rover.

For the gashopper to be an attractive option over current technology, it must represent a significant improvement in terms of mobility. The mobility of a gashopper is superior to that of a rover due to the fact that a gashopper can simply fly over hazardous terrain. A gashopper will thus provide access to very rough and mountainous terrain that would be otherwise inaccessible. Another important factor is the hopper range, or the distance it can travel in a certain period of time. The gashopper range is controlled by two main factors: the mass ratio, and the rate of propellant acquisition. A larger mass ratio will allow it to travel greater distances in a single hop, while increasing the rate of propellant acquisition will allow it to hop more often. Optimizing these factors can result in large increases in mobility. Williams, Ambrosi, and Bannister [28] baselined a gashopper with a mass ratio of 1.114. using 43 kg of propellant, and could achieve hops of 1 km. Zubrin et al [41] assumed that a CO_2 acquisition rate of about 0.5 kg of CO_2 per day was achievable. This would result in a range of 1 km every 86 sols, or about

11 m per sol. This falls far short of the 200 m per sol range of the Mars Science Laboratory. An increase in propellant mass can result in larger hops (a hop of over 17 km is needed to match the 200 m per day range). Freezing CO_2 out of the atmosphere is an attractive option and would produce dry ice at 60W/kg [28]. Ash [42] determined that it is possible to produce dry ice on Mars during the cold night, requiring approximately 7000 kJ/kg. With current battery density at about 720 kJ/kg, 20 kg of batteries could support a CO_2 production rate of about 2 kg per night. This would mean that the hopper could charge its tanks and fly every 21 sols, resulting in an average travel rate of 48 m/sol. This may seem much slower than projected MSL rates, but this means that the hopper will have 21 sols at each site to search for promising samples and conduct science. Over the 800 sols of the sample return mission the hopper can travel over 36 km and thoroughly investigate many sites with varying geography. It would be possible for the gashopper, upon returning to the base, to recharge its CO_2 tanks more rapidly by tapping into the power supplied by the RTG aboard the lander, improving its rate of travel.

For comparison, MSL's MMRTG produces about 2.5 kW-hr/sol for its 900 kg mass [39], while the Mars Exploration Rovers produced about 0.6 kW-hr/sol [43] for its 174 kg mass [44]. At about 350 kg, the Mars gashopper requires 1 kW-hr/sol for all rover and science operations. The gashopper needs to produce about 4 kW-hr/sol for CO_2 production alone. Bringing the total energy production needs to 5 kW-hr/sol.

The heating of the pebble bed can be achieved in two ways, electric heating powered by solar arrays, or radioisotope heating. Radioisotope heating is preferred since it will provide consistent heat generation throughout the year, and waste heat can be used to warm electronics and pressurize the CO_2 propellant. Solar arrays can still be used to provide power to heat the pebble bed, but with a significant array already in use for freezing CO_2, a further increase in size may be difficult to deploy and retract before and after each flight. Williams et al [28] proposed using 4.22 kg of a 50:50 blend of PuO_2 and Am_2O_3 sintered with a high specific heat, high melting point material such as boron carbide or silicon carbide to form small pebbles. The radioisotope blend can supply heat to be stored in the high heat capacity material, while the high heat capacity material would be utilized to provide sufficient heat to operate the CO_2 rocket engine. A small tube can be routed from the main tank, through the radioisotope core, to provide heated CO_2 to the RCS system. Figure 19 shows the layout of the CO_2 rocket.

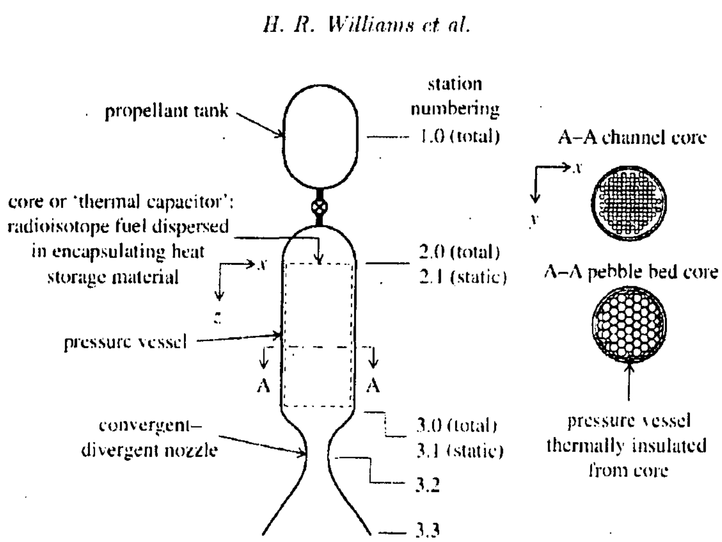


Figure 19: Radioisotope thermal rocket from Williams et al [28].

Once the gashopper has landed, it reverts to a rover operational mode for precise maneuvers in the vicinity of the landing site. The gashopper will be equipped with cameras, and remote sensing equipment in order to navigate and search for suitable samples. The guidance of the gashopper will be managed from Earth. The gashopper will be capable of scooping fine material, grinding rocks, and picking up small rocks. The sample material will be stored and shipped back to Earth in small sample containers. Each container will be sterilized on Earth and sealed to prevent intrusion of foreign material until it is opened by the gashopper. The gashopper carries small sample containers so that soil samples can be gathered every time it lands, and larger containers for small rocks of interest. Once the gashopper retrieves a sample and deposits it in the lander, it will once again be sealed and not opened again until it reaches Earth. The sample containers would be stored in a holding case aboard the lander, where the total sample load can be weighed, and then transferred to the MAV once it is ready for the return trip to Earth. The gashopper would then retrieve a new sample container from the lander and head off to gather another sample. Since the gashopper can operate as a stand-alone system it can continue to operate and conduct field research after its primary sample retrieval mission is completed. The gashopper can then travel to very remote and difficult areas to perform science until the end of its usable life.

C&DH

For the Mars sample return mission communications have a two-fold purpose. Researchers on Earth must be able to send commands to the autonomous base to control events and they must also be able to collect scientific data and perform health checks on the subsystems. This requires two communications with the base itself for signal uplink and downlink. Secondly, the autonomous base must be able to transmit instructions and receive data from the rest of the systems including the hopper, balloons, and launch vehicle. Terrestrial communications can be accomplished using current technologies, such as the Deep Space Network (DSN). DSN has the capability to communicate with the Robotic Base from Earth at various ground stations.

The system requirements for communications with the Earth are included in Table 10:

Command and Data Handling Requirements
Telemetry and tracking
Commands
Data Handling
Health checks
Clock, bit synchronization, and timing

Table 10: Necessary tasks for Mars surface base communications system

Telemetry, tracking, and command (TT&C) interfaces with all of the subsystems of the Mars base and is essential for mission success. Minimum command and data handling signals operate at a bit rate of approximately 100 kbps with a typical bit error rate of 1×10^{-6} on the uplink and 1×10^{-5} on the downlink to the Earth [45]. This can be accomplished using the DSN system using its S-band capabilities. DSN is capable of a user channel with a bit rate ranging from 1 bps to 2 kbps uplink and 6.6 Mbps to 8 Mbps downlink. DSN downlink capabilities adhere to the Space Ground Link Subsystem (SGLS) standards outlined in Table 11 below [45].

DSN Capabilities	Uplink	Downlink
	S-band	S-band
	2.03 – 2.12 GHz	2.20 – 2.30 GHz
	FSK	PCM

Table 11 – Space Ground Link Subsystem standards for TT&C packages

where FSK is Frequency Shift Keying and PCM is Phase Shift Keying, both forms of carrier signal for digital communications. A typical S-band command signal will contain a synchronization code, address bits (to direct the command to the subsystem), the actual command, and error checks to try and prevent boggled communications.

Much of the capacity of a deep space telecom package is controlled by severe mass, power and size constraints. The general desired trend is to get the highest performance out of the smallest package possible because electrical power is very limited and must be shared with other critical subsystems. Smaller more power efficient telecom packages reduce the integration and launch costs for space payloads. For the Martian surface base this constraint is somewhat relaxed, because the nuclear and radioisotope generators used by the individual subsystems provide ample power for telecommunications. Uplink and downlink can be accomplished with the Martian surface base using existing technologies with characteristics outlined in Table 12 [45]:

Combined Telemetry and Command System Physical Characteristics		
	Size	6,000 – 9,000 cm^3
	Mass	4.5 – 6.5 kg
	Power	13 – 18 W

Table 12: Nominal physical characteristics of the telemetry and command system

An additional challenge is the DSN system moving out of transmission view of the Mars surface base. Accommodating this would require dedicated ROM for data storage until communications can be established.

All communications to the other deployed surface systems will first be transmitted to the autonomous base as the primary communications node, linked with one or more satellites in Martian orbit. Communications with Mars orbiters and deployed surface systems is via UHF in the 400MHz range similar to the communication protocols utilized by the Mars Reconnaissance Orbiter and the MER rovers. These commands will then be disseminated to the appropriate recipient, hence the address bits in the command signal. To maintain the simplest system possible, communications between the autonomous base and the other systems deployed on the surface will utilize the same telecom frequencies and hardware. The autonomous base must be able to transmit and receive signals from weather balloon systems, collection hoppers, deployed rovers and the launch vehicle. This goal can be accomplished via the techniques outlined above. The additional benefit of maintaining homogeneity in the telecom system is risk reduction since common systems can be interchanged.

THERMAL PROTECTION SYSTEM

The thermal protection system will be required to maintain the thermal operating environment for the duration of interplanetary transit, EDL, and surface operations. The S/C bus will be cold biased with active electrical heaters to maintain the temperature of critical components such as batteries and electronics. The total allocated mass for the thermal subsystem is 162 kg.

MARS ASCENT VEHICLE

Pressurant gas is required in order to sustain the propulsion system. That gas is stored at a Mars ambient temperature of 210 K and a pressure of 2000 psi (13.8 MPa), which is near the lower average limit for pressure fed systems [46]. The mass of pressurant gas can be estimated as follows:

$$m_g = \frac{P_p V_p}{R T_g} \frac{\gamma}{\left(1 - P_p / P_g\right)} \tag{4}$$

where m_g = mass of pressurant gas (kg), P_p = propellant pressure (Pa), V_p = propellant volume (m^3), R = ideal gas constant for the pressurant gas, T_g = gas storage temperature (K), P_g = gas storage pressure (Pa), and γ = specific heat ratio of pressurant gas.

Nitrogen (N_2) and argon (Ar) gas pressurant options were considered, with the added benefit that both could be extracted from the Mars atmosphere. The estimated mass required for the nitrogen system is 35.8 kg, while an argon system required 60.9 kg. An ideal gas model can be employed to estimate the volume required for the pressurant tank, with the results summarized in Table 13:

Gas	V (m^3)	M_{gas} (kg)
N_2	0.24	35.8
Ar	0.29	60.9

Table 13: Comparison of pressurant gases based on mass and volume

While the volumes are similar, mass savings dictates the use of Nitrogen, which can be stored for the trip to Mars.

Potential tank materials were RZ5 Magnesium, 6061 T6 Aluminum, and Kevlar 49. RZ5 Magnesium has a density of 1840 kg/m^3, with a yield strength of 218 MPa (31.6 ksi). Aluminum has a density of 2700 kg/m^3 and a yield strength of 276 MPa (40 ksi) while the Kevlar has a density of 1380 kg/m^3, and a yield strength of 1379 MPa (200 ksi) [47]. Using the tank mass equation and using a factor of safety of 1.5 results in the following estimated masses as illustrated in Table 14.

Material	Pressurant Tank	Propellant Tank
Aluminum	76.2 kg	45.3 kg
Magnesium	65.8 kg	39.1 kg
Kevlar 49	7.8 kg	4.6 kg

Table 14: Mass trade study for pressurant and propellant tanks

From the above analysis Kevlar 49 provides superior performance with an initial tankage mass of 12.4 kg. The Kevlar has an additional benefit because it does not require any seam welds.

Reliable ignition is essential to a successful mission. This is especially true for motors that must be ignited autonomously away from the Earth. The ignition system must produce an environment within the combustion chamber that assures ignition. To this end, several designs have been developed and used in other systems for different operating environments and applications. A few of these ignition systems are: *pyrotechnic devices, spark plugs, monopropellants,* and *hypergolic devices.* A review of the available literature revealed characteristics, advantages, and limitations of each [46; 47].

Hypergolic devices have been utilized successfully to start the Atlas, Delta, H-1, F-1, and Thor engines. In addition, the hypergols' lower melting temperature of 180 K (92.9°C) precludes some of the low temperature storage difficulties of liquids such as hydrazine. Having a boiling point of 366.2 K (93°C) places the operating temperatures of hypergolics within the ambient temperature range typical of the environment of Mars. A 15% by weight triethylaluminum - 85% by weight triethylboron hypergolic slug-type igniter was chosen for the present Martian sample return launch vehicle design.

A great deal of experimental work on the topic of liquid jet impingement and break up is available in the literature. Much of what makes up the topic of propellant mixing and atomization is still an empirical subject backed up by extensive testing and refinement, especially as it pertains to the injector design [46]. Several incarnations of basic injector designs exist that have been used in liquid rocket applications. Of these, the most common designs are: *like doublet impinging*; *unlike doublet impinging*; *triplet impinging*; *shower head*; *hollow post and sleeve*; and *variable area concentric tube*. Impinging type injectors have become the most commonly prescribed designs, in part due to their ease of manufacture and operation [48]. For this reason, a like (fuel on fuel and oxidizer on oxidizer) doublet impinging injector has been chosen for this Martian surface launch vehicle design.

Attitude (or Thrust vector) control is essential in maintaining orientation of the launch vehicle during ascent. In addition to following the prescribed trajectory the attitude control system must also respond to abrupt changes in the flight path due to external influences. These changes can be caused by aerodynamic/wind loading, and thrust misalignment with respect to the launch vehicle center of gravity. Typically, control systems use either mechanical actuators or propellant flow regulation [47]. The design of the Martian surface launch vehicle requires multiple motors for a single stage, which requires an attitude control solution capable of manipulating the exhaust nozzles.

The current Martian surface motor design is capable of producing thrust levels up to 1200 N (271 lb_f). Maximum throttling for this scheme can reduce the thrust from two of the operating motors to 1023 N (230 lb_f). This approach has a distinct advantage because the only associated hardware requirements are variable flow injector units. While simple, the direct throttling approach can produce combustion instabilities. Fluctuations in propellant flow rate coupled with the lower chamber pressure could produce chugging ($f < 500$ Hz) instabilities [49]. While most low level frequency coupling can be avoided by machining and installation of damping devices in the combustion chamber, this could also add cost and complexity to the design. In addition, extensive testing will be required to avoid any other possible detrimental coupling mechanisms could.

Although actuators add non-propulsive mass, they allow the motors to operate at 100% thrust for the full duration of the propellant burn, avoiding instabilities from propellant mass flow rate fluctuations. A common actuator driven TVC method utilizes gimbals [47]. An example of successful implementation of gimballing is the Space Shuttle Main Engine [46]. Through the use of two linear (hydraulic, pneumatic, or electrical) actuators operating orthogonally to one another, thrust vectors can be diverted in any direction around the full 360° circle with respect to the vehicle line of flight. Typically, maximum slew angles are on the order of ±12° [46]. Due to the inherent stresses of transferring the thrust force from the engine to the main structure of the launch vehicle gimbals are usually constructed of high strength materials such as titanium alloys, as was the case with the Space Shuttle. On the basis of reliable performance, gimbal thrust vector control has been selected for this Martian surface launch vehicle design. The thrust vector gimbal design for the proposed system is depicted in Figure 20.

The *In situ* production of methane and oxygen from Martian resources will likely yield propellant that cannot be subjected to the same levels of quality control as terrestrial propellants. In theory, hydrogen and oxygen are separated completely by electrolysis at the cathode and anode. However, in practice this is not the entirely true because of the presence of a liquid water interface. The electrolyzed gases surrounding the cathode and anode will therefore be saturated with water vapor. That water can be removed via condensation, but that method does not remove all of the water, and multistage condenser systems add complexity and mass. Eventually a point of diminishing returns is attained and no further water molecules can be removed from the saturated mixture. The presence of the water molecules can cause thrust fluctuations, particularly when ice particles temporarily clog the orifice plate passages. Coupling this possibly random disturbance with further flow metering could induce instabilities and decrease the motors efficiency further.

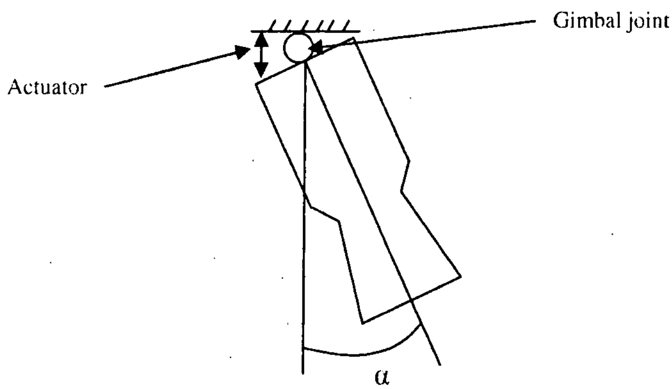


Figure 20: Simplified view of gimbal thrust vector control

While thrust vectoring is adequate for the power-on portion of the launch, it cannot provide attitude control for the entirety of the return mission. Provision has been made for this in that excess nitrogen from the gas pressurant system can be used in a cold gas thruster configuration. The current pressurant system is sized for two times the pressurant gas necessary for delivering propellant to the thrust chamber. At 2000 psi (13.8 MPa) this should serve as an adequate reserve for a simple four way pointing attitude control system. Additionally, the balloon radar system can pull double duty and serve as a tracking system for the launch vehicle to add redundancy to the system.

From a systems perspective the launch vehicle is broken down into two sub-tiers. Tier 1 describes the top level subsystems of the launch vehicle and includes the Engines, Attitude Control, and Structures. Tier 2 describes requirements for components of the subsystems and includes: Ignition, Combustion Chamber, Injector, Pressure Feed System, Nozzle, Propellant Tanks, and Structural Members. This system is shown schematically in the product breakdown structure. Requirements for these individual systems are detailed in the Appendix.

INTERFACES

The interfaces considered for this system are shown in Figure 21. Interfaces for the MABL system include the mechanical, electrical, and power interfaces between it and the S/C bus to which it is attached supplying the power and control; the mechanical piping interfaces between it and the ISPP system which supplies inflation gas and associated electrical interfaces with the ISPP for sensor feedback on inflation gas; electrical and mechanical and thermal interfaces between it and the thermal protection system which provides environmental control; a communication interface between it and the Command and Data Handling System, and mechanical and electrical interfaces between it and the WBFS and HBFS balloons which it inflates and deploys. The WBFS and HBFS also have communication links to the C&DH system and the HBFS has a communication link to a Mars orbiter. The ISPP provides power to the S/C Bus and a communication interface with the C&DH system for data relay. It also has mechanical and electrical interfaces to the thermal protection system for environmental control, and mechanical and electrical interfaces with the MAV to which it provides propellant. In addition to the ISPP interfaces, the MAV also has mechanical, electrical, and power interfaces with the S/C Bus from which it receives power; a thermal interface with the thermal protection system for environmental control, and communication links between the C&DH and orbiters for data relay. The gashopper includes mechanical, electrical, and power interfaces to the S/C Bus for surface transit; communication links between it and the S/C Bus C&DH system and a Mars orbiter; a thermal interface between it and the thermal protection system for environmental control; and a mechanical interface between it and the MAV for transfer of samples. In addition to the interfaces to all of the sub-systems, the C&DH system also has a communication link to the DSN for data and command relay.

S/C Bus	M, E, P		M, E, P	M, E, P	M	M	M, E, P		
	Balloon Launch System	M E	M, E		C	M, T			
		Balloons			C			C	
			ISPP		C	M, T	M, E	.	
				Gas Hopper	C	T	M	C	
					C&DH (Bus)	C	C	C	C
						Thermal Mgmt (Bus)	T		
							MAV	C	C
								Orbiting S/C	
									DSN

M - Mechanical
E - Electrical
C - Comm
P - Power
T - Thermal

Figure 21: Interface Control Chart

SYSTEM LIFE CYCLE

The life cycle of the proposed mission varies with respect to the system component. For example, without any damage or failure, the balloon systems can have a life cycle of years. This is also true for the CO_2 hopper and ISPP plant. As a result, it can be expected that the system can operate successfully well beyond the duration of the mission. This ability may be extremely beneficial and crucial in order to fulfill the mission requirements in the event that the desired production rate is interrupted and/or delayed (i.e. water is not extracted at the needed rate). It can also be very beneficial for powering and/or fueling rovers/hoppers when it is desired to continue to collect samples up until the next earth return opportunity as opposed to being forced to cease collections after a given time period. Also, the possibility of multiple sample return missions can be considered. However, for the purposes of this analysis, it is assumed that the total system life cycle will span the length of the minimum mission time, which starts at Earth departure and ends once the sample has been returned to Earth. This proposed Mars sample return mission will have an approximate length of 1355 days from Earth departure to Earth return. It will take 260 days to travel to and from Mars. After arrival on Mars, five days have been allotted to properly land and unload equipment as well as run system checks. The CO_2 hopper will become fully operational immediately after unloading and without failure or damage, can continue to successfully operate and collect samples for the duration of the mission. Thirty days have been allotted to allow the ISPP system to run system checks and get all components operational. During this time, however, the ISPP excavation rovers can immediately begin scouting for water and begin extraction operations and/or needed site preparation once the desired extraction site has been chosen. The ISPP plant is assumed to operate on an 800 day production cycle. Only 400 days of production are needed to fully fuel the MAV, which will be then ready for departure at the next available launch window. The remaining fuel produced will be used to fuel the hoppers from the balloon payloads. The balloons will be constantly deployed as the needed amounts of Hydrogen are produced and all 28 balloons should be deployed before the end of the ISPP production cycle. Figure 22 shows the baseline mission timeline.

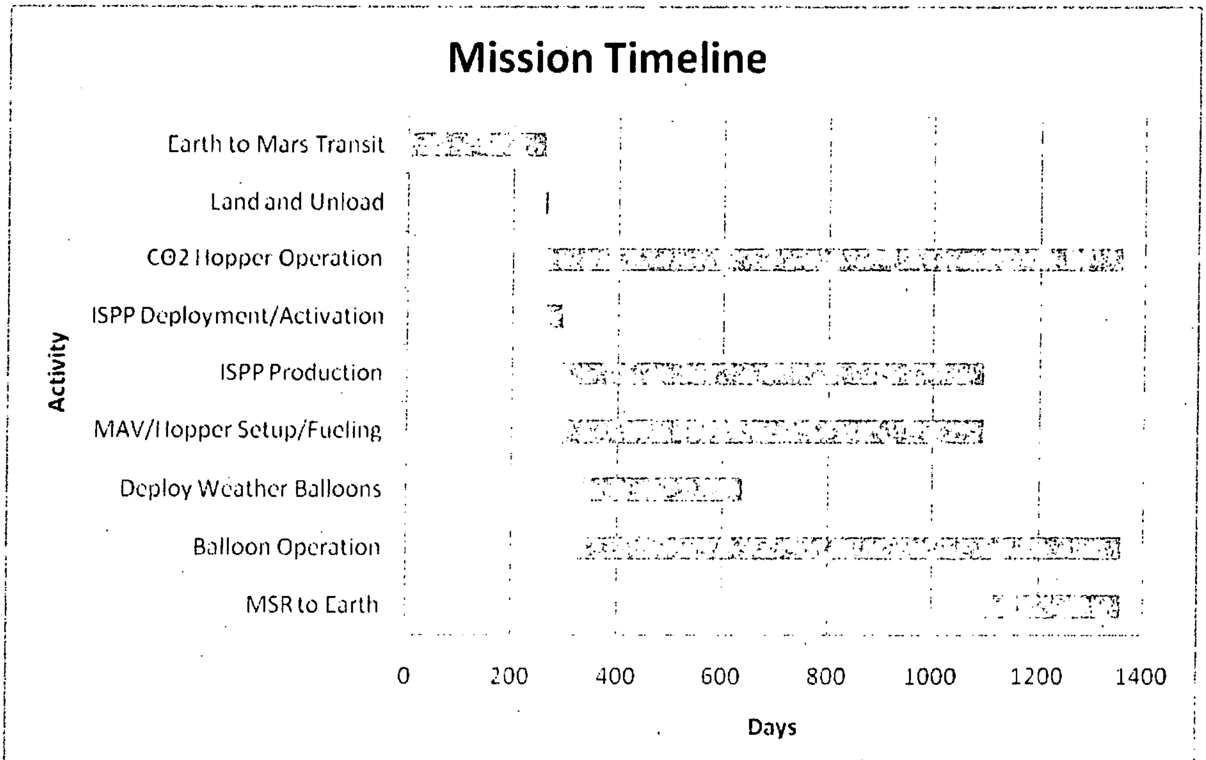


Figure 22: Mission Timeline

COST ANALYSIS

A budget cost analysis was performed using NASA JSC's Spacecraft/Vehicle Level Cost Model (SVLCM) and Advanced Missions Cost Model (AMCM), resulting in estimates for Design, Development, Test, and Evaluation (DDT&E) cost and Life Cycle Cost (LCC) [50]. The SVLCM model is an on-online cost model derived from the NASA/Air Force Cost Model (NAFCOM) database developed for quick turnaround, ROM cost estimating. The AMCM model is an online ROM cost model for the development and production cost of spacecraft.
All models and costs were adjusted to FY11 dollars using the NASA New Start Index Inflation Calculator. The budget costs are summarized in Table 15.

	Cost ($mil FY11)	Cost Model
DDT&E	2,086	SVLCM
LCC	7,618	AMCM

Table 15: Cost Summary

RISK ASSESMENT

There are a few mission critical risks, that should a malfunction occur with the system, loss of mission can occur. The most obvious of these would be a failure of the launch vehicle, but since this risk is out of the hands of mission planners, it will not be considered. Next would be any number of issues that could arise en route to Mars such as: power failure, incorrect trajectory correction, software malfunctions, micrometeorite damage, etc. These issues are handled to the best degree possible with hardened electronics, software testing, backup systems, and other appropriate environmental protection. The next mission critical risk is the process of entry, decent and landing, where failure of components can result in a high-speed collision with the surface of mars, causing a premature end of mission. Appropriate design margins, backup systems, and rigorous testing and simulation will enable successful EDL.

Once safely on the surface of Mars, assuming communication with the lander has been maintained, a failure of any particular component will not necessarily result in the complete loss of the mission. The most important mission-critical objective of surface operations is the acquisition of water for propellant production. Without water, sample return and balloon launches will not be possible, although some science can still be done at the site, and possibly from the independently operating gashopper as well. This risk is mitigated as much as possible by careful site selection based on data from previous missions regarding the availability of water at certain sites on Mars. If the water ice proves too difficult to extract from the underlying strata, it can severely slow the process of water collection, thus two rovers will be employed to increase the rate of production, and ensure system redundancy should one rover fail. If propellant production still falls short of the amount required to return to Earth by the time an Earth return launch window opens, the ISPP plant can remain in operation until the next window opens, the following Martian year. The ISPP plant utilizes power produced by radioactive decay; there is currently a shortage of Plutonium that can be used for NASA missions, and plenty of opposition to the use of nuclear power in space. Should such a situation remain during the timeframe of this mission, solar power can be utilized. A landing site has been selected that has a large flat terrain profile that would suit the deployment of a large solar array on the surface, in addition to an abundance of solar energy and access to water ice.

Sample collection is another critical component of mission success. There are several ways that samples can be collected on this mission, but primarily by the gashopper and long-range balloon sorties. There are a few obvious risks associated with the gashopper design; most noticeably the frequent flight and landing of the system increases the possibility of a crash. This can occur due to a system malfunction mid-flight such as: reaction control system failure, ground detecting radar failure, improper landing site characterization, etc. Just as in the case of EDL, appropriate design margins, backup systems, and rigorous testing and simulation are required. Adequate protection of thrusters guards against dust, which can cause the mechanisms to become clogged rendered inoperable. Pre-flight checks must be performed to ensure that all systems are working properly and that surface measurements of atmospheric conditions are within flight margins. Should the hopper not be able to fly, surface roving is still an option. Should a major malfunction occur with the gashopper, resulting in the loss of the vehicle, the ISPP rovers can still be used to gather samples from the landing site for return. This is feasible since the rovers are already equipped with coring drills and can retrieve core samples for return. They will simply gather more surface and core samples from the immediate landing site in case of a gashopper failure. Upon return of the gashopper to the lander, the risk of a collision between the lander and the gashopper is present. This risk is mitigated simply by allowing for a "no-fly zone" around the lander, causing the gashopper to land some distance away and rove to the lander to return samples.

Malfunctions that can occur with the MAV in flight can result in failure to return sample material to Earth, and the subsequent failure of the sample return mission objective. Contamination of the propellant can cause the ascent engine to prematurely shut down and can result from water ice, the risk of a loss of vehicle due to this problem can be reduced with thorough testing of the engine on Earth at various levels of contamination to ensure adequate performance. The MAV may not achieve sufficient delta V for a return to Earth due to uncertainties with propellant mass, specific impulse, and high winds causing too much fuel to be used in course correction. Upper level winds before a launch can be determined by the launch of a weather balloon from the balloon system, which should allow mission control to determine if a launch is 'go' or 'no-go'. The MAV will be housed inside of the lander to ensure adequate protection from the elements during the 400 days it is inactive on the surface of Mars. This will ensure that components have not become jammed due to dust intrusion, or failure of critical electronics due to large amplitude temperature fluctuations. The MAV will have redundancy in code execution and error checking to protect against a guidance computer fault in mid-flight.

Failures in the balloon system, such as failure of balloons to properly inflate, balloons becoming stuck in the launcher, and data collection errors, are largely overcome by redundant systems, sound engineering design, and thorough testing and simulation. A risk that must be dealt with on Mars is the potential of impurity of the hydrogen made on Mars. Impurity of the hydrogen can result in improper lift of the balloon system and the inability to obtain data from higher altitude regions of the atmosphere. Quality control of the hydrogen processing will be required in-situ on Mars to ensure the proper purity of hydrogen, and design margins are included to ensure proper balloon performance given impurity in the lifting gas.

CONCLUSIONS

A sustainable ISRU based sample return and exploration mission such as the one proposed has the potential of returning a great deal of information on the climate of Mars, as well as sample materials that scientists on Earth will be able to investigate in greater detail than if they were on Mars. The development and implementation of the technologies required for this mission would also be required of a manned mission to Mars. The landing of heavy payloads, ISRU propellant production, and subsequent return to Earth can be viewed as a robotic dress rehearsal of a manned mission to Mars. Both the large quantity of science return and validation of ISRU fuel production on Mars will lead to intra agency partnership within NASA between planetary science and manned exploration, and act as a strategic enabler of mission funding. In one mission, some of the greatest questions surrounding Mars can be answered, while acting as a springboard for further human exploration.

REFERENCES

[1] R. L. Ash, *et al.*, "Planetary Exploration: Evolution of the 'human agent' paradigm."

[2] Clark, I.G. *et al.*, "Supersonic Inflatable Aerodynamic Decelerators for Use on Future Robotic Missions to Mars", *Journal of Spacecraft and Rockets*, vol. 46, no. 2, 2009.

[3] D. Beaty, *et al.*, "Findings of the Mars Special Regions Science Analysis Group," *Astrobiology*, vol. 6, p. 677, 2006.

[4] W. V. Boynton, *et al.*, "Distribution of Hydrogen in the Near Surface of Mars: Evidence for Subsurface Ice Deposits," *SCIENCE*, vol. 297, pp. 81-85, July 5, 2002.

[5] Zurek, R. W., "Diurnal Tide in the Martian Atmosphere", *Journal of the Atmospheric 6Sciences*, vol. 33, pp. 321-337, 1976.

[6] Tillman, James E. *et al.*, "The Martian Annual Atmospheric Pressure Cycle: Years Without Great Dust Storms", *Journal of Geophysical Research*, vol. 98, no. E6, pp. 10,963-10,971, 1993 1998.

[7] Davies, Donlad W., "The Relative Humidity of Mar's Atmosphere", *Journal of Geophysical Research*, vol. 84, pp. 8335-8340, 1979.

[8] Sinclair, P.C., "General characteristics of dust devils", *Journal of Applied Meteorology*, vol. 8, pp. 32-45, 1969.

[9] Stanzel, Christina *et al.,* "Dust devil speeds, directions of motion and general characteristics observed by the Mars Express High Resolution Stereo Camera." *Icarus*, vol. 197, pp. 39-51, 2008.

[10] Savijärvi, Hannu; *et al.*, "The Martian slope winds and the nocturnal PBL Jet", *Journal of the Atmospheric Sciences*, vol. 50, pp. 77-88, 1993.

[11] Justh, Hilary L. *et* al., "Global reference atmospheric models, including thermospheres, for Mars, Venus and Earth." *Collection of Technical Papers – AIAA/AAS Astrodynamics Specialist Conference*, vol. 2, pp. 988-992, 2006.

[12] Justus, C.G., *et al.*, "Mars-GRAM 2000: A Mars Atmospheric Model for Engineering Applications", *Advances in Space Research*, vol. 29, pp. 193-202, 2002.

[13] Jones, Jack A. *et al.*, "Balloons for Controlled Roving/Landing on Mars", *Acta Astronautica*, vol. 45, pp.293-300, 1999.

[14] Smalley, J. H., "Balloon Design Considerations", *Scientific Ballooning Handbook, NCAR Technical Note*, NCAR-TN/IA-99, 1975.

[15] Rand, J. L. *et al.*, "Superpressure Balloon Design", *Advances in Space Research*, vol. 17, pp.5-13. 1996.

[16] Letrenne, G. *et al.*, "French Long Duration Balloon Activity: The InfraRed Montgolfiere (MIR) - The Superpressure Balloon (BPS)", presented at the AIAA International Balloon Technology Conference, Norfolk, VA. 1999.
[17] Smith, Michael S. *et al.*, "Development of the Elastica Shape for Pressurized Balloons.", Japan Society for Aeronautical and Space Sciences and ISTS, 2002.
[18] Calladine, C.R.. *Stability of the Endeavour Balloon. Buckling of Structures.* pp133–149, Elsevier Science Publishers, 1988.
[19] Smith, M. S.*et al.*, "Optimum Design for Superpressure Balloons", *Advances in Space Research*, vol. 33, pp. 1688-1693, 2004.
[20] Rand, J. L. *et al.*, "An Ultra Lightweight Superpressure Balloon Material", presented at the AIAA International Balloon Technology Conference, Norfolk, VA, 1999.
[21] Hari, A. M. *et al.*, "Aspects of Atmospheric Science and Instrumentation for Martian Missions", *Advances in Space Research*, vol. 16, pp. (6)15-(6)22. 1995.
[22] Saito, Y., *et al.*, "Development of a 2.8 lm film for scientific balloons", *Advances in Space Research*, vol. 37, pp. 2026-2032, 2006.
[23] Saito, Y., *et* al., "High Altitude Balloons with Ultra Thin Polyethylene Films", *Advances in Space Research*, vol. 30, pp. 1159-1165, 2002.
[24] Yamagami, T. *et al.*, "Development of the highest altitude balloon", *Advances in Space Research*, vol. 33, pp. 1653-1659, 2004.
[25] Wright, Henry S. *et al.*, "Measurements From an Aerial Vehicle: A New Tool for Planetary Exploration", presented at the Instruments, Science, and Methods for Geospace and Planetary Remote Sensing Conference, Honolulu, HI, 2004.
[26] Greeley, R. *et al.*, "The Mars Aerial Platform Mission Concept", presented at the 34th Aerospace Sciences Meeting, Reno, NV, 1996.
[27] Cutts, James A., *et al.*, "Martian Aerobot Missions: First Two Generations", presented at the IEEE Aerospace 2001Conference, Big Sky, MT, 2001.
[28] Williams, H.R., Ambrosi, R.M., & Bannister, N.P. 2010 A Mars hopping vehicle propelled by a radioisotope thermal rocket: thermofluid design and materials selection. *Proc. R. Soc. A* (doi:10.1098/rspa.2010.0438)
[29] Nock, K.T., *et al.*, "Mars 2001 Aerobot/Balloon System Overview", presented at the AIAA International Balloon Technology Conference, San Francisco, CA, 1997.
[30] Smith, I. S. *et al.*, "The Mars 2001 Balloon Design", presented at the AIAA International Balloon Technology Conference, San Francisco, CA, 1997.
[31] Ash, R., "Ballon Concepts for Scientific Investigation of Mars and Jupiter", 1979.
[32] D. Thunnissen, *et al.*, "A 2007 Mars Sample Return Mission Utilizing In-Situ Propellant Production," presented at the 37th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, 1999.
[33] R. L. Ash, *et al.*, "Feasibility of rocket propellant production on Mars," *Acta Astronautica,* vol. 5, pp. 705-724, September 1978.
[34] K. R. Sridhar, *et al.*, "Combined H2O/CO2 Solid Oxide Electrolysis for Mars In Situ Resource Utilization," *Journal of Propulsion and Power*, vol. 20, pp. 892-901, 2004.
[35] NASA. (2005, January 25, 2011). *Mars Astrobiology Research and Technology Experiment*. Available: http://marte.arc.nasa.gov/index.html
[36] M. J. L. Turner, *Expedition Mars*. Chichester, UK: Praxis Publishing, 2004.

[37] P. Mueller and T. Durrant, "Cryogenic propellant liquefaction and storage for a precursor to a human Mars mission," *Cryogenics*, vol. 39, pp. 1021-1028, 1999.
[38] W. H. Tam, *et al.*, "Conceptual Design of Space Efficient Tanks," *American Institute of Aeronautics and Astronautics*, 2006.
[39] **OPPORTUNITY UPDATE: Opportunity Hits the Road Again** - *sols 2512-2519, February 16-23, 2011: http://marsrovers.jpl.nasa.gov/mission/status.html*
[40] NASA Facts – Mars Science Laboratory, September 2010
[41] Zubrin, R., Frankie, B., Snyder, G., Chew, G., Birnbaum, B., Caviezel, M., Speith, D., Tarzian, F., Martin, A. "Mars Gashopper." Final Report on NASA Contract No.: NAS3-00074, June 2000.
[42] Private correspondence with Dr. Robert L Ash
[43] Mars Exploration Mission: Technology, http://marsrovers.nasa.gov/technology/bb_power.html, retrieved March 2011
[44] NASA Facts – Mars Exploration Rovers, October 2004
[45] Larson, Wiley J., and James Richard. Wertz. *Space Mission Analysis and Design*. El Segundo, CA: Microcosm, 2006.
[46] Sutton, George Paul., and Oscar Biblarz. *Rocket Propulsion Elements*. New York: John Wiley & Sons, 2001.
[47] Fortescue, Peter W., John Stark, and Graham Swinerd. *Spacecraft Systems Engineering*. New York: J. Wiley, 2003.
[48] Huzel, Dieter K., and David H. Huang. *Modern Engineering for Design of Liquid Propellant Rocket Engines*. Washington, DC: American Institute of Aeronautics and Astronautics, 1992.
[49] Ryan, H. M., W. E. Anderson, S. Pal, and R. J. Santoro, "Atomization Characteristics of Impinging Liquid Jets", presented at the 31st Aerospace Sciences Meeting & Exhibit, Reno, NV, 1993.
[50] "NASA Cost Estimating Website." National Aeronautics and Space Administration. March 2006 <http://cost.jsc.nasa.gov/models.htm>.

APPENDIX

APPENDIX A: Mission Level Requirements and Verification Criteria

1. Mars Robotic Base Resistance to Temperature

The Mars Robotic Base shall withstand maximum and minimum temperatures experienced during the mission profile.

Rationale: This requirement ensures the thermal properties of the autonomous weather balloon system are sufficient to withstand maximum and minimum mission profile temperatures such that operational integrity is maintained.

Verification Success Criteria:
Mars Robotic Base Thermal Protection shall be verified by Analysis. An analysis shall be performed to predict temperatures during mission stages. Verification shall be considered successful when the analysis shows the predicted temperatures are enveloped by the operational temperatures used in the analysis to calculate margins of safety.

2. Mars Robotic Base Resistance to Natural Environments

The Mars Robotic Base shall meet all functional and performance requirements within the range of environmental experienced during the mission profile.

Rationale: This requirement establishes maximum exposure time to the natural environment that the Mars Robotic Base may experience. This period includes on-pad, launch, transit, EDL, and Mars surface. Exposure to natural environments for the necessary time duration should not invalidate the design performance or operational capability of the Mars Robotic Base. Operational procedures can be used to supplement element design capability, as necessary, to meet the natural environments.

Verification Success Criteria:
The Mars Robotic Base resistance to natural environments shall be verified by analysis. An analysis shall be performed to verify that the Mars Robotic Base meets the functional and performance requirements defined within the range of environmental conditions experienced. Verification shall be considered successful when the analysis shows that the Mars Robotic Base can meet all functional and performance requirements defined within the range of environmental conditions specified.

3. Mars Robotic Base Resistance to Induced Environments

The Mars Robotic Base shall meet the requirements during and after cumulative exposure to the induced environments encountered during mission operations.

Rationale: This requirement ensures the properties of the Mars Robotic Base are sufficient to withstand induced environments throughout the mission profile.

Verification Success Criteria:
Mars Robotic Base resistance to induced environments shall be verified by Analysis and Test. An analysis shall be performed to verify the Mars Robotic Base for all induced environments. A test shall be performed to verify that the Mars Robotic Base can meet the requirements during and after exposure to the induced environments encountered during mission operations. Verification shall be considered successful when the analysis and test confirm the Mars Robotic Base meets the requirements during and after exposure to the induced environments encountered during mission.

4. Mars Robotic Base System Access

The Mars Robotic Base shall provide access for servicing at the launch site.

Rationale: This requirement ensures that access for servicing is possible during all phases of assembly and integration, ground operations, and on-Pad operations.

Verification Success Criteria:
Mars Robotic Base accessibility shall be verified by Analysis. An analysis shall be performed using drawings and/or CAD models of internal volume, access points, and associated remove/replace operations, and human anthropometric data. A demonstration may be performed using a volumetrically representative mockup to simulate a representative access operation. Verification shall be considered successful when the analysis shows that the Mars Robotic Base provides access for servicing.

5. Mars Robotic Base Electromagnetic Environmental Effects (E3) Control

Mars Robotic Base shall route avionics and instrumentation lines such that Electromagnetic Environmental Effects (E3) are minimized.

Rationale: This requirement ensures that the Mars Robotic Base is compatible with Electromagnetic Environmental Effects (E3) Control requirements, in order to meet operational and performance requirements.

Verification Success Criteria:
Electromagnetic Effects, Induced Electromagnetic Environment Compatibility shall be verified by Analysis, Inspection, and Test. An analysis shall be performed to verify that the Mars Robotic Base is in compliance with the Electromagnetic Environmental Effects (E3) requirements while in the presence of the external electromagnetic environment. An inspection shall be performed of the drawings to verify that the design is in compliance. A test shall be performed to verify that the operational performance requirements are attainable while meeting the applicable E3 compatibility requirements. Verification shall be considered successful when

the analysis, inspection, and test show that the Mars Robotic Base is in compliance with Electromagnetic Environmental Effects (E3) Control requirements while in the presence of the external electromagnetic environment.

6. Mars Robotic Base Resistance to Corrosion

The Mars Robotic Base shall be corrosion resistant.

Rationale: This requirement ensures that corrosion build-up will not occur on any Mars Robotic Base hardware.

Verification Success Criteria:
Mars Robotic Base Corrosion Resistance shall be verified by Analysis and Inspection. An analysis shall be performed to verify that the Mars Robotic Base comply with the provisions of NASA-STD-6016, Standard Material and Processes Requirements for Spacecraft. An inspection shall be performed to show that the Mars Robotic Base comply with the provisions of NASA-STD-6016. Verification shall be considered successful when the analysis and inspection show that the Mars Robotic Base meets the provisions of NASA-STD-6016, Standard Material and Processes Requirements for Spacecraft.

7. Mars Robotic Base Contamination Control

The Mars Robotic Base shall comply with Contamination Control Requirements.

Rationale: This requirement ensures that the Mars Robotic Base is qualitatively verified to be free of all particulate and non-particulate material visible to the normal unaided eye. The Mars Robotic Base will also be appropriately protected through prepackaging prior to installation.

Verification Success Criteria:
Cleanliness Requirements shall be verified by Analysis and Inspection. An analysis shall be performed to verify that the Mars Robotic Base is in compliance with Contamination Control Requirements. An inspection shall be performed to verify that the Mars Robotic Base is in compliance with Contamination Control Requirements. Verification shall be considered successful when the analysis and inspection show that the Mars Robotic Base is in compliance with Contamination Control Requirements.

8. Mars Robotic Base Interface

The Mars Robotic Base shall interface with adjacent components.

Rationale: This requirement ensures that features necessary to interface with adjacent Launch Vehicle components are included in the Mars Robotic Base design and that the interface prevents damage and does not negatively impact performance of adjacent components.

Verification Success Criteria:
Interface Requirements shall be verified by Analysis and Inspection. An analysis shall be performed using drawings and/or CAD models. A demonstration may be performed using a volumetrically representative mock-up. An inspection shall be performed to verify that the Mars Robotic Base interfaces with adjacent components. Verification shall be considered successful when the analysis and inspection show that the Mars Robotic Base interface with adjacent components.

9. Mars Robotic Base Mass

The Mars Robotic Base shall have a mass no greater than 8000 kg

Rationale: This requirement ensures that the mass of the Mars Robotic Base will have minimal negative effect on the overall cost and implementation of functional requirements.

Verification Success Criteria:
Mass Requirements shall be verified by Analysis and Testing. An analysis shall be performed using drawings and/or CAD models. Testing shall be performed to verify that the Mars Robotic Base mass does not exceed 8000 kg. Verification shall be considered successful when the analysis and testing show that the Mars Robotic Base mass is within limits.

10. Mars Robotic Base Power

The Mars Base shall operate at a power no greater than 3 kW.

Rationale: This requirement ensures that the power demand of the Mars Robotic Base will have minimal negative effect on the overall power of a Mars lander.

Verification Success Criteria:
Power Requirements shall be verified by Analysis and Testing. An analysis shall be performed using engineering models. Testing shall be performed to verify that the Mars Robotic Base power does not exceed 3 kW. Verification shall be considered successful when the analysis and testing show that the Mars Autonomous Balloon Launch System power is within limits.

11. Mars Robotic Base Weather Balloon Requirement

The Mars Robotic Base shall be capable of launching up to 25 weather balloons capable of atmospheric measurements of temperature, pressure, humidity, and wind up to 20km.

Rationale: This requirement sets the minimum acceptable number of launches for the system to meet the desired number of atmospheric measurements for the desired vertical atmospheric profile.

Verification Success Criteria:
The Requirement to launch up to 25 weather balloons shall be verified by Analysis. An analysis shall be performed using drawings and/or models. Verification shall be considered successful when the analysis shows that the Mars Robotic Base is capable of launching up to 25 weather balloons each capable of atmospheric measurements of temperature, pressure, humidity, and wind to 20km.

12. Mars Robotic Base Heavy Payload Balloon Requirement

The Mars Robotic Base shall be capable of launching up to 3 heavy science balloons capable of carrying 35kg payloads to 10km for a duration of 7 days.

Rationale: This requirement sets the minimum acceptable number of launches for the system to meet the desired number of heavy payload flights.

Verification Success Criteria:
The Requirement to launch up to 3 heavy payload balloons shall be verified by Analysis. An analysis shall be performed using drawings and/or models. Verification shall be considered successful when the analysis shows that the Mars Robotic Base is capable of launching up to 3 heavy payload balloons.

13. Mars Robotic Base ISRU

The Mars Robotic Base shall produce the required propellant and inflation gas for MAV and balloon use.

Rationale: This requirement ensures the minimum mass of propellant and inflation gas are produced to ensure successful completion of the sample return and balloon missions.

Verification Success Criteria:
The Requirement to produce sufficient propellant and inflation gas shall be verified by Analysis. An analysis shall be performed using models. Verification shall be considered successful when the analysis shows that the Mars Robotic Base is capable producing sufficient propellant and inflation gas.

14. Mars Robotic Base Autonomy

The Mars Robotic Base shall be fully autonomous and self sufficient and capable of performing necessary functions to complete the mission without the aid of ground operators.

Rationale: This requirement ensures that the Mars Robotic Base is capable of handling operational situations necessary to complete the mission without continuous observation and control from Earth ground station.

Verification Success Criteria:
Mars Robotic Base Autonomy shall be verified by Analysis and Test. An analysis shall be performed to verify the Mars Robotic Base is autonomous and self-sufficient. Tests shall be performed to confirm that the Mars Robotic Base can meet the autonomy requirement for mission operations. Verification shall be considered successful when the analysis and tests confirm the Mars Robotic Base meets the requirements for autonomy.

15. Mars Robotic Base Sample Return

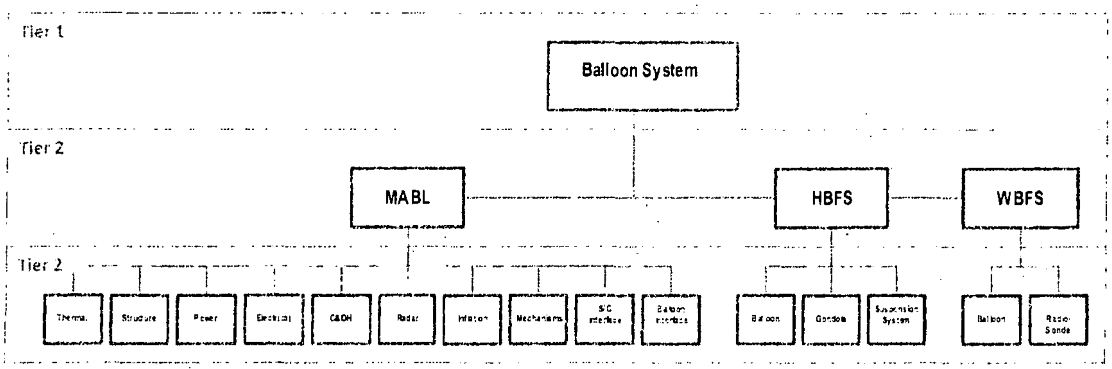
The Mars Robotic Base shall have the capability to gather and return 50 kg worth of sample material from an area greater than could be covered by the MSL rover.

Rationale: This requirement sets the scientific objective of the sample return mission and also defines that the coverage area of the samples shall be greater than that of the MSL rover.

Verification Success Criteria:
Mars Robotic Base Sample Return capability shall be verified by Analysis and Test. An analysis shall be performed using models. Tests shall be performed to confirm the Mars Robotic Base has the capability to gather and return 50kg of samples from an area greater than could be covered by MSL. Verification shall be considered successful when the analysis and tests confirm the Mars Robotic Base meets the requirement for Sample Return.

APPENDIX B-1: Balloon System Product Hierarchy

Balloon System Product Hierarchy



APPENDIX B-2: Balloon System Tier 1 Requirements and Verification Criteria Matrix

TITLE	REQUIREMNT	RATIONALE	VERIFICATION SUCCESS CRITERIA
Balloon System Resistance to Temperature	The Balloon System shall withstand maximum and minimum temperatures experienced during the mission profile.	This requirement ensures the thermal properties of the autonomous weather balloon system are sufficient to withstand maximum and minimum mission profile temperatures such that operational integrity is maintained.	Balloon System Thermal Protection shall be verified by Analysis. An analysis shall be performed to predict temperatures during mission stages. Verification shall be considered successful when the analysis shows the predicted temperatures are enveloped by the operational temperatures used in the analysis to calculate margins of safety.
Balloon System Resistance to Natural Environments	The Balloon System shall meet all functional and performance requirements defined within the within the range of environmental experienced during the mission profile.	This requirement establishes maximum exposure time to the natural environment that the Balloon System may experience. This period includes on-pad, launch, transit, EDL, and Mars surface. Exposure to natural environments for the necessary time duration should not invalidate the design performance or operational capability of the Balloon System. Operational procedures can be used to supplement element design capability, as necessary, to meet the natural environments.	The Balloon System shall be verified by analysis. An analysis shall be performed to verify that the Balloon System meets the functional and performance requirements defined within the within the range of environmental experienced during the mission profile. Verification shall be considered successful when the analysis shows that the Balloon System can meet all functional and performance requirements defined within the range of environmental conditions specified.
Balloon System Resistance to Induced Environments	The Balloon System shall meet the requirements during and after cumulative exposure to the induced environments encountered during mission operations.	This requirement ensures the properties of the Balloon System are sufficient to withstand induced environments throughout the mission profile.	Balloon System resistance to induced environments shall be verified by Analysis and Test. An analysis shall be performed to verify the Balloon System for all induced environments. A test shall be performed to verify that the Balloon System can meet the requirements during and after exposure to the induced environments encountered during mission operations. Verification shall be considered successful when the analysis and test confirm the Balloon System meet the requirements during and after exposure to the induced environments encountered during mission.

TIER I			
TITLE	**REQUIREMNT**	**RATIONALE**	**VERIFICATION SUCCESS CRITERIA**
Balloon System Electromagnetic Environmental Effects (E3) Control	Balloon System shall route avionics and instrumentation lines such that Electromagnetic Environmental Effects (E3) are minimized.	This requirement ensures that the Balloon System is compatible with Electromagnetic Environmental Effects (E3) Control requirements, in order to meet operational and performance requirements.	Electromagnetic Effects, Induced Electromagnetic Environment Compatibility shall be verified by Analysis, Inspection, and Test. An analysis shall be performed to verify that the Balloon System is in compliance with the Electromagnetic Environmental Effects (E3) requirements while in the presence of the external electromagnetic environment. An inspection shall be performed of the drawings to verify that the design is in compliance. A test shall be performed to verify that the operational performance requirements are attainable while meeting the applicable E3 compatibility requirements. Verification shall be considered successful when the analysis, inspection, and test show that the Balloon System is in compliance with Electromagnetic Environmental Effects (E3) Control requirements while in the presence of the external electromagnetic environment.
Balloon System Resistance to Corrosion	The Balloon System shall be corrosion resistant.	This requirement ensures that corrosion build-up will not occur on any Balloon System hardware.	Balloon System Corrosion Resistance shall be verified by Analysis and Inspection. An analysis shall be performed to verify that the Balloon System comply with the provisions of NASA-STD-6016, Standard Material and Processes Requirements for Spacecraft. An inspection shall be performed to show that the Balloon System comply with the provisions of NASA-STD-6016. Verification shall be considered successful when the analysis and inspection show that the Balloon System meet the provisions of NASA-STD-6016, Standard Material and Processes Requirements for Spacecraft.
Balloon System Contamination Control	The Balloon System shall comply with Contamination Control Requirements Document.	This requirement ensures that the Balloon System is qualitatively verified to be free of all particulate and non-particulate material visible to the normal unaided eye. The Balloon System will also be appropriately protected through prepackaging prior to installation.	Cleanliness Requirements shall be verified by Analysis and Inspection. An analysis shall be performed to verify that the Balloon System is in compliance with Contamination Control Requirements Document. An inspection shall be performed to verify that the Balloon System is in compliance with Contamination Control Requirements Document. Verification shall be considered successful when the analysis and inspection show that the Balloon System is in compliance with Contamination Control Requirements Document.
Balloon System Interface	The Balloon System shall interface with adjacent components.	This requirement ensures that features necessary to interface with adjacent S/C bus components are included in the Balloon System design and that the interface prevents damage and does not negatively impact performance of adjacent components. This does not on refer to physically adjacent components but also to componets which made need to be communicated with for instance.	Interface Requirements shall be verified by Analysis and Inspection. An analysis shall be performed using drawings and/or CAD models. A demonstration may be performed using a volumetrically representative mock-up. An inspection shall be performed to verify that the Balloon System interfaces with adjacent components. Verification shall be considered successful when the analysis and inspection show that the Balloon System interface with adjacent components.
Balloon System Mass	The Balloon System shall have a mass no greater than 2500 kg.	This requirement ensures that the mass of the Balloon System will have minimal negative effect on the overall mass of a Mars lander.	Mass Requirements shall be verified by Analysis and Testing. An analysis shall be performed using drawings and/or CAD models. Testing shall be performed to verify that the Balloon System mass does not exceed 2500 kg. Verification shall be considered successful when the analysis and testing show that the Balloon System mass is within limits.
Balloon System Weather Balloon Launch Requirement	The Balloon System shall be capable of launching up to 25 weather balloons.	This requirement sets the minimum acceptable number of launches for the system to meet the desired number of atmospheric measurements.	The Requirement to launch up to 25 weather balloons shall be verified by Analysis. An analysis shall be performed using drawings and/or CAD models. Verification shall be considered successful when the analysis shows that the Balloon System is capable of launching up to 25 (TBR) weather balloons.

TIER 1			
TITLE	REQUIREMENT	RATIONALE	VERIFICATION SUCCESS CRITERIA
Balloon System Heavy Payload Balloon Launch Requirement	The Balloon System shall be capable of launching up to 3 weather balloons.	This requirement sets the minimum acceptable number of launches for the system to meet the desired number of heavy payload flights.	The Requirement to launch up to 3 heavy payload balloons shall be verified by Analysis. An analysis shall be performed using drawings and/or CAD models. Verification shall be considered successful when the analysis shows that the Balloon System is capable of launching up to 3 heavy payload balloons.
Balloon System Balloon Payload Requirement	The Balloon System shall be capable of launching weather balloons with payloads up to 150g and heavy payload balloons with payloads up to 50kg (TBR).	This requirement sets the minimum payload requirements for the weather balloon and heavy payload balloon.	The Requirement to provide weather balloons that can lift up to 150g and heavy payload balloons to lift up to 50kg shall be verified by Analysis. An analysis shall be performed using drawings and/or computer models. Verification shall be considered successful when the analysis shows that the Balloon System is capable of launching weather balloons with payloads up to 150g and heavy payload balloons with payloads up to 50kg.
Balloon System Weather Balloon Altitude Requirement	The Balloon System shall be capable of flying weather balloons to a Mars atmosphere altitude of 20 km.	This requirement sets the minimum acceptable altitude for the system to meet the desired atmospheric profile corridor.	The Requirement to fly weather balloons up to 20 km shall be verified by Analysis. An analysis shall be performed using engineering models. Verification shall be considered successful when the analysis shows that the Balloon System is capable of flying weather balloons up to 20 km.
Balloon System Heavy Payload Balloon Altitude Requirement	The Balloon System shall be capable of flying heavy payload balloons to a Mars atmosphere altitude of 10 km.	This requirement sets the minimum acceptable altitude for the system to meet the desired heavy payload flight corridor.	The Requirement to fly heavy payload balloons up to 10 km shall be verified by Analysis. An analysis shall be performed using engineering models. Verification shall be considered successful when the analysis shows that the Balloon System is capable of flying heavy payload balloons up to 10 km.
Balloon System Atmospheric Measurement Requirement	The Balloon System shall be capable of measuring in situ temperature, pressure, humidity, and wind speed.	This requirement defines the requried atmospheric measurements.	The Atmospheric Measurement Requirement shall be verified by Analysis and Inspection. An analysis shall be performed using drawings and/or CAD models. An Inspection shall be performed to verify that the Autonomous Weather Balloon Launch System is capable of measuring temperature, pressure, humidity, and wind speed. Verification shall be considered successful when the analysis and inspection show that the Autonomous Weather Balloon Launch System is capable of measuring temperature, pressure, humidity, and wind speed.
Balloon System Sample Return Requirement	Each Heavy Payload Balloon shall be capable of collecting a 2kg sysem and returning it to the vicinity of the lander.	This requirement expands the scope of sample collection to a planetary scale.	The Requirement to up to 2 kg samples shall be verified by Analysis. An analysis shall be performed using engineering models. Verification shall be considered successful when the analysis shows that the Heavy Payload Balloon Systems is capable of returning 2kg samples to the lander.

APPENDIX B-3: Balloon System Tier 2 Requirements and Verification Criteria Matrix

TIER I (LAUNCH SYSTEM / BALLOON SYSTEM)

TITLE	REQUIREMNT	RATIONALE	VERIFICATION SUCCESS CRITERIA
Balloon Launch Sub-System Resistance to Temperature	The Balloon Launch Sub-System shall withstand maximum and minimum temperatures experienced during the mission profile.	This requirement ensures the thermal properties of the autonomous weather balloon system are sufficient to withstand maximum and minimum mission profile temperatures such that operational integrity is maintained	Balloon Launch Sub-System Thermal Protection shall be verified by Analysis. An analysis shall be performed to predict temperatures during mission stages. Verification shall be considered successful when the analysis shows the predicted temperatures are enveloped by the operational temperatures used in the analysis to calculate margins of safety.
Balloon Launch Sub-System Resistance to Natural Environments	The Balloon Launch Sub-System shall meet all functional and performance requirements defined within the within the range of environmental experienced during the mission profile.	This requirement establishes maximum exposure time to the natural environment that the Balloon Launch Sub-System may experience. This period includes on-pad, launch, transit, EDL and Mars surface. Exposure to natural environments for the necessary time duration should not invalidate the design performance or operational capability of the Balloon Launch Sub-System. Operational procedures can be used to supplement element design capability, as necessary, to meet the natural environments.	The Balloon Launch Sub-System shall be verified by analysis. An analysis shall be performed to verify that the Balloon Launch Sub-System meets the functional and performance requirements defined within the within the range of environmental experienced during the mission profile. Verification shall be considered successful when the analysis shows that the Balloon Launch Sub-System can meet all functional and performance requirements defined within the range of environmental conditions specified.
Balloon Launch Sub-System Resistance to Induced Environments	The Balloon Launch Sub System shall meet the requirements during and after cumulative exposure to the induced environments encountered during mission operations.	This requirement ensures the properties of the Balloon Launch Sub-System are sufficient to withstand induced environments throughout the mission profile.	Balloon Launch Sub-System resistance to induced environments shall be verified by Analysis and Test. An analysis shall be performed to verify the Mars Autonomous Balloon Launch System for all induced environments. A test shall be performed to verify that the Balloon Launch Sub-System can meet the requirements during and after cumulative exposure to the induced environments encountered during mission operations. Verification shall be considered successful when the analysis and test confirm the Balloon Launch Sub System meet the requirements during and after exposure to the induced environments encountered during mission.
Balloon Launch Sub-System Electromagnetic Environmental Effects (E3) Control	Balloon Launch Sub-System shall route avionics and instrumentation lines such that Electromagnetic Environmental Effects (E3) are minimized.	This requirement ensures that the Balloon Launch Sub-System is compatible with Electromagnetic Environmental Effects (E3) Control requirements, in order to meet operational and performance requirements.	Electromagnetic Effects. Induced Electromagnetic Environment Compatibility shall be verified by Analysis, Inspection, and Test. An analysis shall be performed to verify that the Balloon Launch Sub-System is in compliance with the Electromagnetic Environmental Effects (E3) requirements while in the presence of the external electromagnetic environment. An inspection shall be performed of the drawings to verify that the design is in compliance. A test shall be performed to verify that the operational performance requirements are attainable while meeting the applicable E3 compatibility requirements. Verification shall be considered successful when the analysis, inspection, and test show that the Balloon Launch Sub-System is in compliance with Electromagnetic Environmental Effects (E3) Control requirements while in the presence of the external electromagnetic environment.
Balloon Launch Sub-System Resistance to Corrosion	The Balloon Launch Sub-System shall be corrosion resistant.	This requirement ensures that corrosion build-up will not occur on any Balloon Launch Sub-System hardware.	Balloon Launch Sub-System Corrosion Resistance shall be verified by Analysis and Inspection. An analysis shall be performed to verify that the Balloon Launch Sub-System comply with the provisions of NASA-STD-6016, Standard Material and Processes Requirements for Spacecraft. An inspection shall be performed to show that the Balloon Launch Sub-System comply with the provisions of NASA STD-6016. Verification shall be considered successful when the analysis and inspection show that the Balloon Launch Sub-System meet the provisions of NASA-STD-6016, Standard Material and Processes Requirements for Spacecraft.
Balloon Launch Sub-System Contamination Control	The Balloon Launch Sub-System shall comply with Contamination Control Requirements Document.	This requirement ensures that the Balloon Launch Sub-System is qualitatively verified to be free of all particulate and non-particulate material visible to the normal unaided eye. The Balloon Launch Sub-System will also be *appropriately protected through prepackaging prior to* installation.	Cleanliness Requirements shall be verified by Analysis and Inspection. An analysis shall be performed to verify that the Balloon Launch Sub-System is in compliance with Contamination Control Requirements Document. An inspection shall be performed to verify that the Balloon Launch Sub-System is in compliance with Contamination Control Requirements Document. Verification shall be considered successful when the analysis and inspection show that the Balloon Launch Sub-System is in compliance with Contamination Control Requirements Document.
Balloon Launch Sub-System S/C Bus Interface	The Balloon Launch Sub-System shall interface with adjacent S/C Bus components.	This requirement ensures that features necessary for the launcher to interface with adjacent S/C Bus components components are included in the Balloon Launch Sub-System design and that the interface prevents damage and does not negatively impact performance of adjacent components.	Interface Requirements shall be verified by Analysis and Inspection. An analysis shall be performed using drawings and/or CAD models. A demonstration may be performed using a volumetrically representative mock-up. An inspection shall be performed to verify that the Balloon Launch Sub-System interfaces with adjacent S/C Bus components. Verification shall be considered successful when the analysis and inspection show that the Balloon Launch Sub-System interface with adjacent S/C Bus components.
Balloon Launch Sub-System Balloon Sub-System Interface	The Balloon Launch Sub-System shall interface with adjacent Balloon Sub-System components	This requirement ensures that features necessary for the launcher to interface with adjacent Balloon Sub-System components are included in the Balloon Launch Sub-System design and that the interface prevents damage and does not negatively impact performance of adjacent components.	Interface Requirements shall be verified by Analysis and Inspection. An analysis shall be performed using drawings and/or CAD models. A demonstration may be performed using a volumetrically representative mock-up. An inspection shall be performed to verify that the Balloon Launch Sub-System interfaces with adjacent Balloon Sub-System components. Verification shall be considered successful when the analysis and inspection show that the Balloon Launch Sub-System interface with adjacent components.

TIER 1 (LAUNCH SYSTEM / BALLOON SYSTEM)

TITLE	REQUIREMNT	RATIONALE	VERIFICATION SUCCESS CRITERIA
Balloon Launch Sub-System Balloon Balloon Damage During Launch	The Balloon Launch Sub-System shall not damage the Balloon Sub-System during launch in contact is made between the balloon and the launcher.	This requirement ensures that features necessary to minimize damage to the balloon if the balloon and launcher inadvertantly contact each other during launch	Damage minimization requirements shall be verified by Analysis and Demonstration. An analysis shall be performed using drawings and/or CAD models. A demonstration may be performed using a representative mock-up of similar materials. Verification shall be considered successful when the analysis and inspection show that the Balloon Launch Sub-System will not damage the Balloon Sub-System during launch
Balloon Launch Sub-System Mass	The Balloon Launch Sub-System shall have a mass no greater than 2000 kg.	This requirement ensures that the mass of the Balloon Launch Sub-System will have minimal negative effect on the overall mass of a Mars lander and will not detract from the mass allocation to the Balloon Sub-System	Mass Requirements shall be verified by Analysis and Testing. An analysis shall be performed using drawings and/or CAD models. Testing shall be performed to verify that the Balloon Launch Sub-System mass does not exceed 2000 kg. Verification shall be considered successful when the analysis and testing show that the Balloon Launch Sub-System mass is within limits.
Balloon Launch Sub-System Weather Balloon Launch Requirement	The Balloon Launch Sub-System shall be capable of launching up to 25 weather balloons.	This requirement sets the minimum acceptable number of launches for the system to meet the desired number of atmospheric measurements.	The Requirement to launch up to 24 weather balloons shall be verified by Analysis. An analysis shall be performed using drawings and/or CAD models. Verification shall be considered successful when the analysis shows that the Balloon Launch Sub-System is capable of launching up to 25 weather balloons.
Balloon Launch Sub-System Weather Balloon Storage Requirement	The Balloon Launch Sub-System shall be capable of storing up to 25 weather balloons.	This requirement sets the minimum acceptable number of weather balloons the Balloon Launch Sub-System must be able to store.	The Requirement to store up to 25 weather balloons shall be verified by Analysis. An analysis shall be performed using drawings and/or CAD models. Verification shall be considered successful when the analysis shows that the Balloon Launch Sub-System is capable of storing up to 25 weather balloons.
Balloon Launch Sub-System Heavy Payload Balloon Launch Requirement	The Balloon Launch Sub-System shall be capable of launching up to 3 heavy payload balloons.	This requirement sets the minimum acceptable number of launches for the system to meet the desired number of heavy payload flights.	The Requirement to launch up to 3 heavy payload balloons shall be verified by Analysis. An analysis shall be performed using drawings and/or CAD models. Verification shall be considered successful when the analysis shows that the Balloon Launch Sub-System is capable of launching up to 3 heavy payload balloons.
Balloon Launch Sub-System Heavy Payload Balloon Storage Requirement	The Balloon Launch Sub-System shall be capable of storing up to 3 heavy payload balloons.	This requirement sets the minimum acceptable number of heavy payload balloons the Balloon Launch Sub-System must be able to store.	The Requirement to store up to 6 heavy payload balloons shall be verified by Analysis. An analysis shall be performed using drawings and/or CAD models. Verification shall be considered successful when the analysis shows that the Balloon Launch Sub-System is capable of storing up to 3 heavy payload balloons.
Balloon Launch Sub-System Balloon Payload Requirement	The Balloon Launch Sub-System shall be capable of launching weather balloons with payloads up to 200g (TBR) and heavy payload balloons with payloads up to 100kg (TBR).	This requirement sets the minimum payload launch requirements for the weather balloon and heavy payload balloon.	The Requirement to provide weather balloons that can lift up to 200g (TBR) and heavy payload balloons to lift up to 100kg (TBR) shall be verified by Analysis. An analysis shall be performed using drawings and/or computer models. Verification shall be considered successful when the analysis shows that the Balloon Launch Sub-System is capable of launching weather balloons with payloads up to 200g (TBR) and heavy payload balloons with payloads up to 100kg (TBR).
Balloon Launch Sub-System Weather Balloon Inflation Gas Requirement	The Balloon Launch Sub-System shall be capable of providing sufficient lifting gas to fly weather balloons to a Mars atmosphere altitude of 20 km.	This requirement sets the mass of inflation gas to meet the minimum weather balloon altitude requirement.	The Requirement to provide sufficient lifting gas to fly weather balloons up to 20 km shall be verified by Analysis. An analysis shall be performed using engineering models. Verification shall be considered successful when the analysis shows that the Balloon Launch Sub-System is capable of providing sufficient lifting gas to fly weather balloons up to 20 km.
Balloon Launch Sub-System Heavy Payload Balloon Inflation Gas Requirement	The Balloon Launch Sub-System shall be capable of providing sufficient lifting gas to fly heavy payload balloons to a Mars atmosphere altitude of 10 km.	This requirement sets the mass of inflation gas to meet the minimum heavy payload balloon altitude requirement.	The Requirement to provide sufficient lifting gas to fly heavy payload balloons up to 10 km shall be verified by Analysis. An analysis shall be performed using engineering models. Verification shall be considered successful when the analysis shows that the Balloon Launch Sub-System is capable of providing sufficient lifting gas to fly heavy payload balloons up to 10 km.

TIER 1 (LAUNCH SYSTEM / BALLOON SYSTEM)

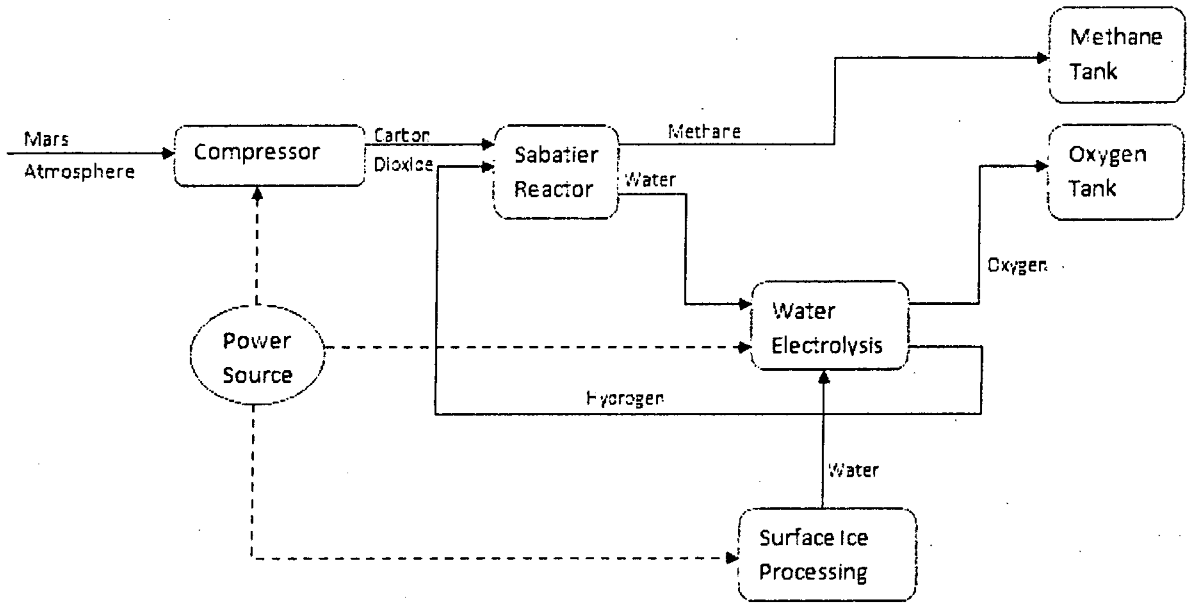
TITLE	REQUIREMNT	RATIONALE	VERIFICATION SUCCESS CRITERIA
Balloon Sub-System Resistance to Temperature	Balloon Sub-System shall withstand maximum and minimum temperatures experienced during the mission profile.	This requirement ensures the thermal properties of the autonomous weather balloon system are sufficient to withstand maximum and minimum mission profile temperatures such that operational integrity is maintained.	Balloon Sub-System Thermal Protection shall be verified by Analysis. An analysis shall be performed to predict temperatures during mission stages. Verification shall be considered successful when the analysis shows the predicted temperatures are enveloped by the operational temperatures used in the analysis to calculate margins of safety.
Balloon Sub-System Resistance to Natural Environments	The Balloon Sub-System shall meet all functional and performance requirements defined within the within the range of environmental experienced during the mission profile.	This requirement establishes maximum exposure time to the natural environment that the Balloon Sub-System may experience. This period includes on-pad, launch, transit, EDL, Mars surface, and Mars flight. Exposure to natural environments for the necessary time duration should not invalidate the design performance or operational capability of the Balloon Sub-System. Operational procedures can be used to supplement element design capability, as necessary, to meet the natural environments.	The Balloon Sub-System shall be verified by analysis. An analysis shall be performed to verify that the Balloon Sub-System meets the functional and performance requirements defined within the within the range of environmental experienced during the mission profile. Verification shall be considered successful when the analysis shows that the Balloon Sub-System can meet all functional and performance requirements defined within the range of environmental conditions specified.
Balloon Sub-System Resistance to Induced Environments	The Balloon Sub-System shall meet the requirements during and after cumulative exposure to the induced environments encountered during mission operations.	This requirement ensures the properties of the Balloon Sub-System are sufficient to withstand induced environments throughout the mission profile.	Balloon Sub-System resistance to induced environments shall be verified by Analysis and Test. An analysis shall be performed to verify the Balloon Sub-System for all induced environments. A test shall be performed to verify that the Balloon Sub-System can meet the requirements during and after cumulative exposure to the induced environments encountered during mission operations. Verification shall be considered successful when the analysis and test confirm the Balloon Sub-System meets the requirements during and after exposure to the induced environments encountered during mission
Balloon Sub-System Resistance to Corrosion	The Balloon Sub-System shall be corrosion resistant.	This requirement ensures that corrosion build-up will not occur on any Balloon Sub-System hardware.	Balloon Sub-System Corrosion Resistance shall be verified by Analysis and Inspection. An analysis shall be performed to verify that the Balloon Sub-System comply with the provisions of NASA-STD-6016, Standard Material and Processes Requirements for Spacecraft. An inspection shall be performed to show that the Balloon Sub-System comply with the provisions of NASA-STD-6016. Verification shall be considered successful when the analysis and inspection show that the Balloon Sub-System meet the provisions of NASA-STD-6016, Standard Material and Processes Requirements
Balloon Sub-System Contamination Control	The Balloon Sub-System shall comply with Contamination Control Requirements Document.	This requirement ensures that the Balloon Sub-System is qualitatively verified to be free of all particulate and non-particulate material visible to the normal unaided eye. The Balloon Sub-System will also be appropriately protected through prepackaging prior to installation.	Cleanliness Requirements shall be verified by Analysis and Inspection. An analysis shall be performed to verify that the Balloon Sub-System is in compliance with Contamination Control Requirements Document. An inspection shall be performed to verify that the Balloon Sub-System is in compliance with Contamination Control Requirements Document. Verification shall be considered successful when the analysis and inspection show that the Balloon Sub-System is in compliance with Contamination Control Requirements Document.
Balloon Sub-System Interface	The Balloon Sub-System shall interface with adjacent components.	This requirement ensures that features necessary to interface with adjacent launcher components are included in the Balloon Sub-System design and that the interface prevents damage and does not negatively impact performance of adjacent components. In addition, the requirement ensures that the communication protocol between the transmitter and receiver on the launcher sub-system and/or orbiter do not conflict.	Interface Requirements shall be verified by Analysis and Inspection. An analysis shall be performed using drawings and/or CAD models. A demonstration may be performed using a volumetrically representative mock-up. An inspection shall be performed to verify that the Balloon Sub-System interfaces with adjacent components. Verification shall be considered successful when the analysis and inspection show that the Balloon Sub-System interface with adjacent components.

TIER 1 (LAUNCH SYSTEM / BALLOON SYSTEM)

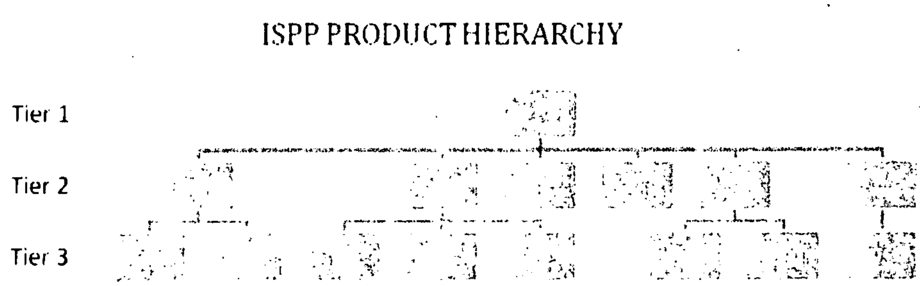
TITLE	REQUIREMNT	RATIONALE	VERIFICATION SUCCESS CRITERIA
Balloon Sub-System Mass	The Balloon Sub-System shall have a mass no greater than 500 kg	This requirement ensures that the mass of the Balloon Sub-System will have minimal negative effect on the overall mass of the Mars Autonomous Balloon Launch System.	Mass Requirements shall be verified by Analysis and Testing. An analysis shall be performed using drawings and/or CAD models. Testing shall be performed to verify that the Balloon Sub-System mass does not exceed 500 kg. Verification shall be considered successful when the analysis and testing show that the Balloon Sub-System mass is within limits.
Balloon Sub-System Payload Requirement	The Balloon Sub-System shall include weather balloons capable of carrying payloads up to 150 g and heavy payload balloons capable of carrying payloads up to 50 kg (TBR).	This requirement sets the minimum payload requirements for the weather balloon and heavy payload balloon.	The Requirement to provide weather balloons that can lift up to 150 g and heavy payload balloons to lift up to 50 kg shall be verified by Analysis. An analysis shall be performed using drawings and/or computer models. Verification shall be considered successful when the analysis shows that the Balloon Sub-System is capable of launching weather balloons with payloads up to 150 g and heavy payload balloons with payloads up to 50 kg.
Balloon Sub-System Weather Balloon Altitude Requirement	The Balloon Sub-System shall include weahter balloons capable of flying to a Mars atmosphere altitude of 20 km.	This requirement sets the minimum acceptable altitude for the system to meet the desired atmospheric profile corridor.	The Requirement for weather balloons capable of flying up to 20 km shall be verified by Analysis. An analysis shall be performed using engineering models. Verification shall be considered successful when the analysis shows that the Balloon Sub-System includes weather balloons capable of flying up to 20 km.
Balloon Sub-System Heavy Payload Balloon Altitude Requirement	The Balloon Sub-System shall include heavy payload balloons capable of flying to a Mars atmosphere altitude of 10 km.	This requirement sets the minimum acceptable altitude for the system to meet the desired heavy payload flight corridor.	The Requirement for heavy payload balloons capable of flying up to 10 km shall be verified by Analysis. An analysis shall be performed using engineering models. Verification shall be considered successful when the analysis shows that the Balloon Sub-System includes heavy payload balloons capable of flying up to 10 km.
Balloon Sub-System Atmospheric Measurement Requirement	The Balloon Sub-System shall be capable of measuring in situ temperature, pressure, humidity, and wind speed.	This requirement defines the requried atmospheric measurements.	The Atmospheric Measurement Requirement shall be verified by Analysis and Inspection. An analysis shall be performed using drawings and/or CAD models. An Inspection shall be performed to verify that the Balloon Sub-System is capable of measuring temperature, pressure, humidity, and wind speed. Verification shall be considered successful when the analysis and inspection show that the Balloon Sub-System is capable of measuring temperature, pressure, humidity, and wind speed.
Balloon Sub-System Sample Return Requirement	Each Heavy Payload Balloon shall be capable of collecting a 2kg sysem and returning it to the vicinity of the lander.	This requirement expands the scope of sample collection to a planetary scale.	The Requirement to up to 2 kg samples shall be verified by Analysis. An analysis shall be performed using engineering models. Verification shall be considered successful when the analysis shows that the Heavy Payload Balloon Systems is capable of returning 2kg samples to the lander.

TIER 1 (LAUNCH SYSTEM / BALLOON SYSTEM)			
TITLE	**REQUIREMNT**	**RATIONALE**	**VERIFICATION SUCCESS CRITERIA**
Balloon Sub-System Mass	The Balloon Sub-System shall have a mass no greater than 500 kg	This requirement ensures that the mass of the Balloon Sub-System will have minimal negative effect on the overall mass of the Mars Autonomous Balloon Luanch System.	Mass Requirements shall be verified by Analysis and Testing. An analysis shall be performed using drawings and/or CAD models. Testing shall be performed to verify that the Balloon Sub-System mass does not exceed 500 kg. Verification shall be considered successful when the analysis and testing show that the Balloon Sub-System mass is within limits.
Balloon Sub-System Payload Requirement	The Balloon Sub-System shall include weather balloons capable of carrying payloads up to 150 g and heavy payload balloons capable of carrying payloads up to 50 kg (TBR).	This requirement sets the minimum payload requirements for the weather balloon and heavy payload balloon.	The Requirement to provide weather balloons that can lift up to 150 g and heavy payload balloons to lift up to 50 kg shall be verified by Analysis. An analysis shall be performed using drawings and/or computer models. Verification shall be considered successful when the analysis shows that the Balloon Sub-System is capable of launching weather balloons with payloads up to 150 g and heavy payload balloons with payloads up to 50 kg.
Balloon Sub-System Weather Balloon Altitude Requirement	The Balloon Sub-System shall include weahter balloons capable of flying to a Mars atmosphere altitude of 20 km.	This requirement sets the minimum acceptable altitude for the system to meet the desired atmospheric profile corridor.	The Requirement for weather balloons capable of flying up to 20 km shall be verified by Analysis. An analysis shall be performed using engineering models. Verification shall be considered successful when the analysis shows that the Balloon Sub-System includes weather balloons capable of flying up to 20 km.
Balloon Sub-System Heavy Payload Balloon Altitude Requirement	The Balloon Sub-System shall include heavy payload balloons capable of flying to a Mars atmosphere altitude of 10 km.	This requirement sets the minimum acceptable altitude for the system to meet the desired heavy payload flight corridor.	The Requirement for heavy payload balloons capable of flying up to 10 km shall be verified by Analysis. An analysis shall be performed using engineering models. Verification shall be considered successful when the analysis shows that the Balloon Sub-System includes heavy payload balloons capable of flying up to 10 km.
Balloon Sub-System Atmospheric Measurement Requirement	The Balloon Sub-System shall be capable of measuring in situ temperature, pressure, humidity, and wind speed.	This requirement defines the requried atmospheric measurements.	The Atmospheric Measurement Requirement shall be verified by Analysis and Inspection. An analysis shall be performed using drawings and/or CAD models. An Inspection shall be performed to verify that the Balloon Sub-System is capable of measuring temperature, pressure, humidity, and wind speed. Verification shall be considered successful when the analysis and inspection show that the Balloon Sub-System is capable of measuring temperature, pressure, humidity, and wind speed.
Balloon Sub-System Sample Return Requirement	Each Heavy Payload Balloon shall be capable of collecting a 2kg sysem and returning it to the vicinity of the lander.	This requirement expands the scope of sample collection to a planetary scale.	The Requirement to up to 2 kg samples shall be verified by Analysis. An analysis shall be performed using engineering models. Verification shall be considered successful when the analysis shows that the Heavy Payload Balloon Systems is capable of returning 2kg samples to the lander.

APPENDIX C-1: ISPP Functional Flow Block Diagram



APPENDIX C-2: ISPP Product Hierarchy



APPENDIX C-3: ISPP Tier 1 Requirements and Verification Criteria Matrix

TIER 1

SYSTEM	REQUIREMNT	RATIONALE	VERIFICATION SUCCESS CRITERIA
ISPP PLANT	The ISPP plant shall produce the required propellant and Hydrogen for MAV and balloon use.	To fulfill its functional purpose and ensure a successful MSR.	The system shall go through testing on Earth in a facility with Mars like conditions to test the production rate and quality of the system.
ISPP PLANT	The ISPP plant shall operate under the harsh Martian environmental conditions without fault.	To ensure successful operation under the natural Martian environmental conditions.	The system shall go through testing on Earth in a facility with Mars like conditions to test its ability to operate under Martian conditions, including simulated low temperatures, low pressures, high winds and dust storms.
ISPP PLANT	The operation of the ISPP plant shall not dramatically disturb or damage the natural Martian environment.	To ensure the protection of the Martian environment.	The system shall go through analysis to ensure that all parts of the system are below contamination risk levels.
ISPP PLANT	The ISPP plant shall be fully autonomous and self-sufficient.	To ensure complete system operation without the direct presence of humans.	The system shall go through testing on Earth in a facility with Mars like conditions to test the autonomy of the system.
ISPP PLANT	The excess Hydrogen supply shall interface with the balloon refueling system.	To provide Hydrogen fuel to power the weather balloons on Mars.	The system shall go through testing on Earth in a facility with Mars like conditions to test the transfer of hydrogen to the balloon refuling system.
ISPP PLANT	The methane and oxygen supply shall interface with the MAV refueling systems.	To provide needed propellant to the MAV for its return to Earth.	The system shall go through testing on Earth in a facility with Mars like conditions to test the transfer of methane and oxygen to the MAV refuling system.

APPENDIX C-4: ISPP Tier 2 Requirements and Verification Criteria Matrix

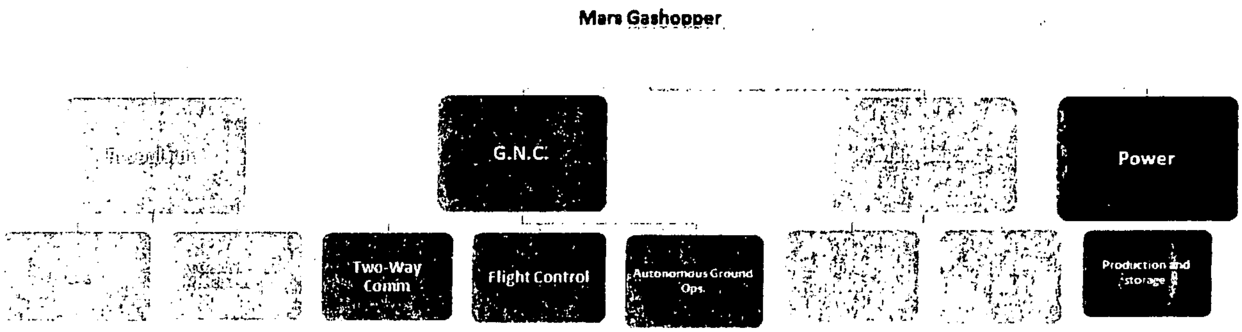
TIER 2

SYSTEM	REQUIREMNT	RATIONALE	VERIFICATION SUCCESS CRITERIA
CO2 EXTRACTION	5.5kg of CO2 shall be extracted and pressurized to 101kPa, using 634W of power each day.	To fulfill its functional purpose and ensure a successful MSR.	The system shall go through testing on Earth in a facility with Mars like conditions to test the production rate and quality of the system.
CO2 EXTRACTION	The CO2 extraction process shall operate under the harsh Martian environmental conditions without fault.	To ensure successful operation under the natural Martian environmental conditions.	The system shall go through testing on Earth in a facility with Mars like conditions to test its ability to operate under Martian conditions, including simulated low temperatures, low pressures, high winds and dust storms.
CO2 EXTRACTION	The operation of the CO2 extraction process shall not dramatically disturb or damage the natural Martian environment.	To ensure the protection of the Martian environment.	The system shall go through analysis to ensure that all parts of the system are below contamination risk levels.
CO2 EXTRACTION	The CO2 extraction process shall be fully autonomous and self-sufficient.	To ensure complete system operation without the direct presence of humans.	The system shall go through testing on Earth in a facility with Mars like conditions to test the autonomy of the system.
SURFACE ICE PROCESSING PLANT	The surface ice processing plant shall extract 9kg of ice from the Martian surface and melt it down to usable H20 using 700W of power each day.	To fulfill its functional purpose and ensure a successful MSR.	The system shall go through testing on Earth in a facility with Mars like conditions to test the production rate and quality of the system.
SURFACE ICE PROCESSING PLANT	The surface ice processing plant shall operate under the harsh Martian environmental conditions without fault.	To ensure successful operation under the natural Martian environmental conditions.	The system shall go through testing on Earth in a facility with Mars like conditions to test its ability to operate under Martian conditions, including simulated low temperatures, low pressures, high winds and dust storms.
SURFACE ICE PROCESSING PLANT	The operation of the surface ice processing plant shall not dramatically disturb or damage the natural Martian environment.	To ensure the protection of the Martian environment.	The system shall go through analysis to ensure that all parts of the system are below contamination risk levels.
SURFACE ICE PROCESSING PLANT	The surface ice processing plant shall be fully autonomous and self-sufficient.	To ensure complete system operation without the direct presence of humans.	The system shall go through testing on Earth in a facility with Mars like conditions to test the autonomy of the system.
WATER ELECTROLYSIS CELL	The water electrolysis cell shall convert 9kg of H2O into 1kg of Hydrogen and 16kg of Oxygen using 1.875kW of power each day.	To fulfill its functional purpose and ensure a successful MSR.	The system shall go through testing on Earth in a facility with Mars like conditions to test the production rate and quality of the system.
WATER ELECTROLYSIS CELL	The water electrolysis cell shall operate under the harsh Martian environmental conditions without fault.	To ensure successful operation under the natural Martian environmental conditions.	The system shall go through testing on Earth in a facility with Mars like conditions to test its ability to operate under Martian conditions, including simulated low temperatures, low pressures, high winds and dust storms.
WATER ELECTROLYSIS CELL	The operation of the water electrolysis cell shall not dramatically disturb or damage the natural Martian environment.	To ensure the protection of the Martian environment.	The system shall go through analysis to ensure that all parts of the system are below contamination risk levels.
WATER ELECTROLYSIS CELL	The water electrolysis cell shall be fully autonomous and self-sufficient.	To ensure complete system operation without the direct presence of humans.	The system shall go through testing on Earth in a facility with Mars like conditions to test the autonomy of the system.
WATER ELECTROLYSIS CELL	The excess Hydrogen supply shall interface with the balloon refueling system.	To provide Hydrogen fuel to power the weather balloons on Mars.	The system shall go through testing on Earth in a facility with Mars like conditions to test the transfer of hydrogen to the balloon refuling system.

TIER 2

SYSTEM	REQUIREMNT	RATIONALE	VERIFICATION SUCCESS CRITERIA
SABATIER REACTOR	The Sabatier reactor shall convert 1kg of Hydrogen and 5.5kg of CO2 into 4.5kg of H2O and 2kg of Methane each day.	To fulfill its functional purpose and ensure a successful MSR.	The system shall go through testing on Earth in a facility with Mars like conditions to test the production rate and quality of the system.
SABATIER REACTOR	The Sabatier reactor shall operate under the harsh Martian environmental conditions without fault.	To ensure successful operation under the natural Martian environmental conditions.	The system shall go through testing on Earth in a facility with Mars like conditions to test its ability to operate under Martian conditions, including simulated low temperatures, low pressures, high winds and dust storms.
SABATIER REACTOR	The operation of the Sabatier reactor shall not dramatically disturb or damage the natural Martian environment.	To ensure the protection of the Martian environment.	The system shall go through analysis to ensure that all parts of the system are below contamination risk levels.
SABATIER REACTOR	The Sabatier reactor shall be fully autonomous and self-sufficient.	To ensure complete system operation without the direct presence of humans.	The system shall go through testing on Earth in a facility with Mars like conditions to test the autonomy of the system.
CRYOGENIC PROPLELLANT STORAGE	The cryogenic propellant storage system shall cool, liquefy, and store up to 40,000kg of methane and oxygen propellant at 95K using 550W of power.	To fulfill its functional purpose and ensure a successful MSR.	The system shall go through testing on Earth in a facility with Mars like conditions to test the production rate and quality of the system.
CRYOGENIC PROPLELLANT STORAGE	The cryogenic propellant storage system shall operate under the harsh Martian environmental conditions without fault.	To ensure successful operation under the natural Martian environmental conditions.	The system shall go through testing on Earth in a facility with Mars like conditions to test its ability to operate under Martian conditions, including simulated low temperatures, low pressures, high winds and dust storms.
CRYOGENIC PROPLELLANT STORAGE	The operation of the cryogenic propellant storage system shall not dramatically disturb or damage the natural Martian environment.	To ensure the protection of the Martian environment.	The system shall go through analysis to ensure that all parts of the system are below contamination risk levels.
CRYOGENIC PROPLELLANT STORAGE	The cryogenic propellant storage system shall be fully autonomous and self-sufficient.	To ensure complete system operation without the direct presence of humans.	The system shall go through testing on Earth in a facility with Mars like conditions to test the autonomy of the system.
CRYOGENIC PROPLELLANT STORAGE	The methane and oxygen supply shall interface with the MAV refueling systems.	To provide needed propellant to the MAV for its return to Earth.	The system shall go through testing on Earth in a facility with Mars like conditions to test the transfer of methane and oxygen to the MAV refuling system.

APPENDIX D-1: Gas Hopper Product Hierarchy

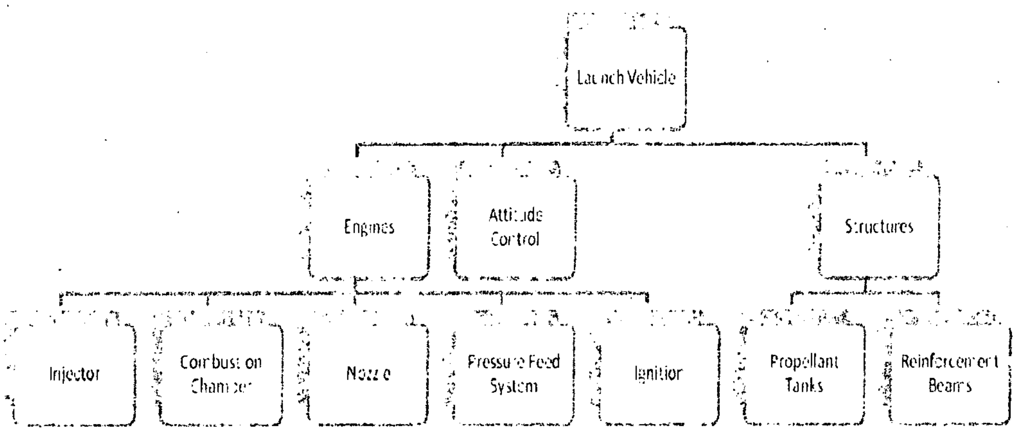


APPENDIX D-2: Gas Hopper Tier 1 Requirements and Verification Criteria Matrix

Tier 1			
Title	Requirement	Rationale	Verification Success Criteria
Gashopper Mobility Rate	Gashopper should must have a range that exceeps that of current rovers	Current MSR mission design relies on MSL style rover for sample retreival. the Gashopper design should traverse terrain at a faster rate to be an attractive option.	Gashopper can rapidly explore areas on Mars that are inaccesible to rovers
Flight Control System	Gashopper should be able to maintain proper attitude in ballistic flight and reorient for landing	Gashopper must be able to land properly on its wheels to ensure survival after a hop	Flight Control System should ensure vehicle stability while aloft under numerous potential scenarios including wind and RCS thruster failure.
Gashopper Power Production	Gashopper should be capable of producing 5 kW-h of power each sol.	Gashopper should produce sufficient power to operate the CO2 acquisition, pressureization, Flight Control System, and surface operations	Gashopper can produce at least 5 kW-h of energy in a single sol despite solar panel degradation and dust coverage
Gashopper Roving Ability	Gashopper should be able to rove on the surface after hops to locate and obtain samples of interest	It is very unlikely that the gashopper will land close enough to a potential sample of interest to retreive it	Gashopper has roving ability similar to that of current rover technology.
Sample Identification	Gashopper should have sufficient equipment onboard to detect samples that are of scientific interest to a MSR mission	Potential samples must be pre-screened in-situ to deem their worthiness of a return flight to Earth	Gashopper can identify scientifically interesting samples for subsequent collection.
Sample Retrieval and Storage	Gashopper must have a way of obtaining samples and storing them onboard	The purpose of the Gashopper is to bring samples back to the MAV	Pick up rock/soil, and store in container
Communications	Gashopper must have the ability to communicate with ground operators to receive orders and to relay status/data	Selection of samples must be made by science team members and therefore commands for the Gashopper to retrieve certain samples must be sent to the Gashopper	Gashopper can communicate with lander, orbiter, and Earth under most environmental scenarios.
Weather Station	Gashopper should be able to determine local weather conditions	Local weather conditions wil be critical pre hop to determine the possibility of landing at a particular site	Gashopper is able to determine the surface level winds
Component Resistance to Temperature	Mars Gashopper should withstand minimum mars temperatures	Hopper and all components should survive the cold temperatures on Mars	Temperature extreames do not affect the overall operation of the gashopper
Dust Protection	Effects of Martian dust should minimally affect the hopper	Martian dust can potentially jam or seize mechanisms, and thrusters, measures should be taken to seal the hopper from dust intrusion	Components do not become clogged with dust that can potentially endanger the mission.

APPENDIX E-1: MAV Product Hierarchy

MARS ASCENT VEHIVLE PRODUCT HEIRARCHY



APPENDIX E-2: MAV Tier 1 Requirements and Verification Criteria Matrix

Tier 1			
Title	**Requirement**	**Rationale**	**Verification Success Criteria**
Engines	The engines shall provide thrust levels adequate to attain the acceleration necessary for Mars orbital insertion or escape velocity	The engines must provide the impetus to accelerate the launch vehicle and surface sample to a high enough speed to return the sample either to orbit or Earth	Engine performance shall be deemed acceptable upon instrumented test stand verification of its performance
Attitude Control	The attitude control system shall provide gimbaling of individual engines on each stage of up to $\pm 12^{\circ}$	To maintain correct heading during ascent phase of vehicle launch is critical for mission success	Attitude control system success shall be verified by using previously proven heritage components, and rigorous testing testing through computer models and simulations
Structures	The launch vehicle structures shall provide the support necessary to maintain all of the launch vehicle components in their prescribed orientations without failure/yielding	The launch vehicle structure holds the individual components in the positions they need to be and transfers loads from the engines to the remaining portions of the vehicle, and must be able to handle these loads and accelerations	Structural component shall be considered successful through analysis and sound engineering design

APPENDIX E-3: MAV Tier 2 Requirements and Verification Criteria Matrix

Tier 2			
Title	**Requirement**	**Rationale**	**Verification Success Criteria**
Ignitor	The ignitor shall provide reliable ignition of the oxidizer and fuel mixture	The ignitor must be able to initiate the combustion process reliably and autonomously	Ignitor success shall be demonstrated by analysis and completion of testing prior to launch that demonstrates the ability of the ignitor to initiate combustion
Combustion Chamber	The combustion chamber shall be designed to withstand and contain the main combustion reaction, subject to variable pressure and heating	The combustion chamber must be able to withstand the operational environment of combustion, such that thrust may be produced and sustained	A successful design shall be verified by analysis, sound engineering design, and completion of pre-installation pressure testing and cylcling
Injector	The injector shall deliver propellants to the combustion chamber at the desired pressure, inlet velocity, and incidence angle	Injectors provide the final interface between the combustion reactions and the propellant feed system. As such the injector must allow for the proper mass flow and atomization of propellants	A successful injector shall be shown through proper analysis along with cold- and hot-flow testing to allow adequate mass flow and liquid droplet formation and atomization
Pressure Feed System	The pressure feed system shall provide the correct pressure to the stored propellant such that they arrive at the combustion chamber at the design pressure	Combustion chamber propellant is dependent on the ability of the propellant feed system to impart the correct pressure onto the propellant within the propellant tanks	Performance of the pressure feed components and overall system shall be verified through cold-flow testing
Nozzle	The nozzle shall provide the appropriate exhaust gas expansion to the desired exit pressure while maintaining structural rigidity and integrety	In order for the engine to produce the maximum thrust possible the exhaust nozzle must expand the combustion gases down to the assigned pressure while not succumbing to environmental stresses such as heat and pressure	The nozzle shall be shown to be adequate for the operational environment through instrumented test stand firings
Propellant Tanks	Propellant tanks shall provide for the storage of propellant without yielding or failure under launch loads or internal pressure	Tanks for the propellant must maintain structural integrity throughout the duration of the engine burn	Propellant tanks shall be deemed adequate through sound engineering design and test bench pressure cylcing and testing
Structural Members	Individual structural members shall be sized such that they can adequately transfer launch loads while not yielding	The launch loads of the engines are transferred to the entire launch vehicle, which must be held intact by individual structural members including supports and stiffeners	Structural component shall be considered successful through analysis and sound engineering design
Gimbals	Gimbals shall provide for appropriated thrust vector control of the engines without mechanical failure	The gimbals must transfer thrust forces from the engines and also support the engines at the desired angle	Gimbals shall be verified through sound engineering design