Systems Engineering and Technology Considerations of a Mars Ascent Vehicle

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Abstract— A Mars Ascent Vehicle (MAV) systems engineering study is underway to define the driving requirements, system architecture, major risks, and required technology developments to support the launch of a rock core sample to a specified delivery orbit for later retrieval and return to Earth. The proposed MAV would essentially be a small-scale launch vehicle, the first of its kind to be launched autonomously from another planet. The MAV would be a flight element of the proposed Mars Sample Return (MSR) campaign architecture, which currently assumes a 2018 launch of the sample caching mission and a 2024 (Earth) launch date of the MAV and lander, with arrival on Mars in 2025. After 9 months on the surface the MAV would be erected and launched to a specified delivery orbit. In the delivery orbit it would release its payload, a 5 kg sphere containing the rock core sample. An orbiter would rendezvous and capture the payload, returning it to Earth a year later.

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1. INTRODUCTION

A Mars Sample Return Mission is proposed as the next phase and milestone in the National Aeronautics and Space Administration (NASA) and European Space Agency's (ESA) exploration of Mars. The ability to bring back a representative sample and analyze it in Earth-based laboratories would potentially provide a quantum leap in our understanding of Mars geology, history, and climate, and potentially the identification of extra-terrestrial life. After decades of mission concept studies, NASA's In Space Propulsion Program is now investing in the technologies that would enable such a campaign.

The current Mars Sample Return (MSR) campaign architecture is shown in Figure 1. The campaign would begin with the delivery of a proposed caching rover in 2018, which falls under the domain of the Exomars program. In 2022 a second element, the proposed Mars orbiting spacecraft would be sent to provide for telecom coverage and a return trip to Earth. In the 2024 time frame a lander with Mars Ascent vehicle (MAV) would be the third element, sent in a Mars Science laboratory (MSL) like aeroshell, landing on the surface of Mars in 2025 (Figure 2). The MAV/lander combination would reside on the surface of Mars for 9 months in order to obtain the cached sample and await the next optimum trajectory to return to Earth. In 2026 the MAV would lift off from the surface of Mars with the surface sample and rendezvous with the orbiter. A portion of the orbiter would then carry the sample back to Earth for an Earth landing and sample retrieval in 2027.

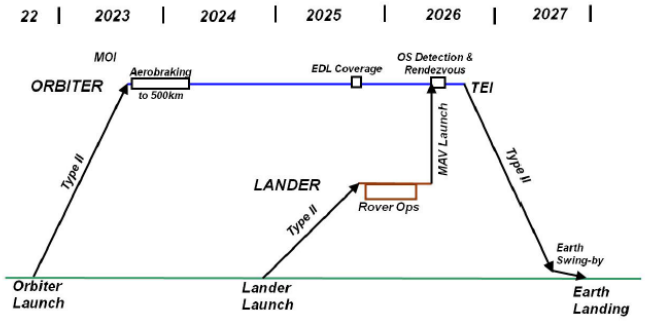

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Figure 1. Current Mars Sample Return Campaign Architecture [1].

This multi-decade architecture relies on a combination of existing and new technologies to achieve the proposed campaign objectives in a feasible time frame and budget. MSR campaign planning has identified many technology challenges and gaps to meet current campaign requirements. One major technology challenge is the development of the MAV rocket. To date, an autonomous rocket launch on another planet has never been performed. The only comparative example is the Apollo program, which had humans in the loop. Additionally, there are several imposed constraints based on the MSR architecture existing technology suite and baselined launch opportunity. They impose tight constraints on mass, volume, delivery orbit, and survivability, as summarized in Table 1. It should be noted that the MAV delivered mass must include the support systems to thermally insulate it on the surface, interface it with the lander, and erect the rocket for the launch from the surface.

Table 1. Projected MSR interface constraints [1].

Parameter	Constraint
Volumetric	2.85m x0.7 m diameter
Delivered Mass	360 kg
Surface Life	90 sols
Power Source	Ultraflex solar arrays
Thermal Control	Passive and electric heaters
Delivery Orbit	500 km

In 2011, under a National Research Announcement (NRA), the In-Space Propulsion (ISP) program initiated a MAV propulsion technology development program with private industrial partners. Phase I of the program focused on MAV system definition. Phase II and Phase III are planned follow-on efforts to further develop MAV component and propulsion system development. The work described in this paper describes the efforts of the Phase 1 Northrop Grumman Jet Propulsion Laboratory team, in the development of a novel two-stage liquid MAV system.

Based on the phase I effort, a summary of the proposed MAV systems architecture will be presented including driving requirements, reliability assessment, and unique systems engineering considerations for MAV. A review of a candidate conceptual design will be presented for the MAV surface system including the erection mechanism, ground-launch platform, igloo, and thermal maintenance system. More detail on the rocket design can be found in reference [2].

2. SYSTEMS ARCHITECTURE

Driving Requirements

Driving requirements for MAV fall into 5 phases

- Cruise
- Entry, descent, and landing (EDL)
- Surface operations
- Ascent
- Orbital operations (same as cruise)

These are further decomposed into thermal, load, interface, and telecom. The driving requirements for each phase are summarized in Table 2. The driving requirements are largely driven by the MSL EDL phase. Specifically, the MSL entry vehicle (EV) internal geometry is the source of the volumetric and mass constraint. The driving load case for the MAV corresponds to the maximum deceleration load during Mars atmospheric entry of the MSL EV. The thermal environment would be limited to +20C to protect the scientific integrity of the surface sample. The minimum temperature is driven by existing (off-the-shelf) avionics hardware qualification range.

The concept of operations would require phasing of all campaign phases to determine the worst case thermal environment.

Table 2. MAV Driving Requirements [1].

Phase	Cruise	EDL	Surface	Launch
Load (g's)	N/A	<15	0.3	<15
Max Temp (C)	<20			
Min Temp (C)	>-46			
Life	<9 mo	<1hr	<9 mo	<1 hr
Telecom	N/A	N/A	UHF	UHF
Delivery Orbit	460-580 km altitude 45 deg inclination			
Landing Site	15 deg S to 25 deg N +/- 5 deg ground slope			
Reliability	No Single Points of Failure (SPF's)			

2. MAV BASELINE DESIGN

The baseline MAV design, on which this systems engineering study was conducted, consists of 5 major subsystems that include a first stage and second stage main propulsion system, attitude control system (ACS), primary and secondary structure, avionics, nose cone, and the orbiting sample (OS) container and release mechanism, as illustrated in Figure 2 [2].

The main propulsion system design is a two-stage bipropellant liquid chemical rocket. The main engines are of a common design, but at a scale to optimize the thrust for

the respective phase of the trajectory in which they would be in use.

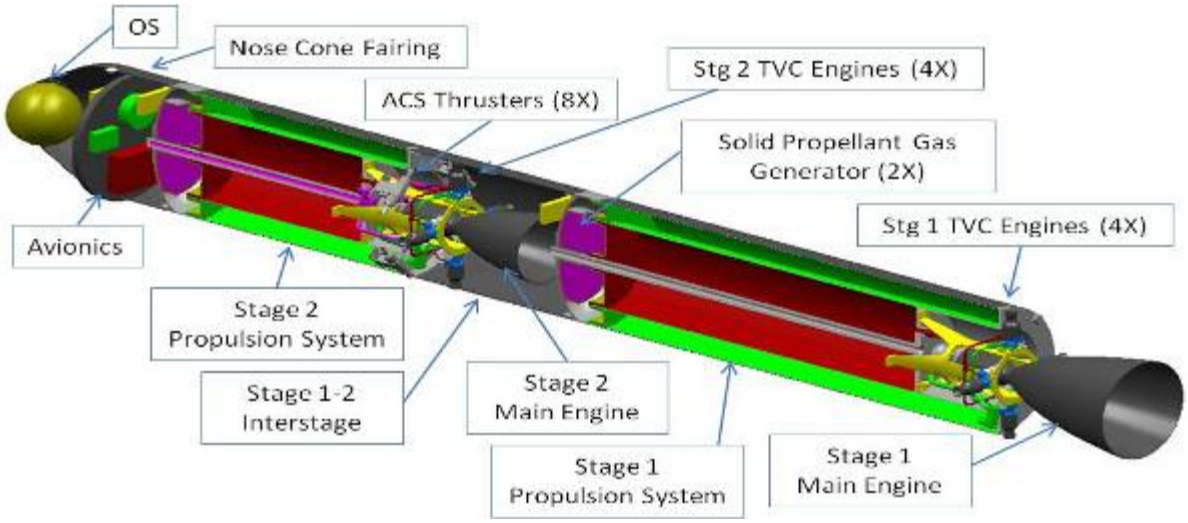

Figure 2. MAV rocket baseline conceptual design.

The first stage would use a restartable engine, providing 5.3 kN of thrust as compared to stage 2 which would provide 2.7 kN.

Commonality between the stages would include the injectors, valves, ablative chamber. Thrust vector control (TVC) would be provided by four smaller engines (445N) of a similar design but operating in pulse mode. Attitude control would be provided by eight 4.4N thrusters to be used to provide roll control during flight and enable vernier attitude control during coast and orbit insertion. The propulsion system would be supplied by coaxial propellant tanks and in line pressure regulators [2].

An interstage would be used to structurally attach the first and second stages and enable separation during ascent from the Martian surface. The interstage and stage specific structure would be fabricated from composite and aluminum separation rings. A linear shape charge would provide the mechanical separation.

The nose cone or fairing would be conical in shape with a blunted nose and fabricated from composite. A single avionics subsystem would be located in the nose cone and be used for both phases of flight. It consists of a primary battery, UHF transmitter, helical antenna, inertial measurement unit (IMU), star tracker, and flight computer. The nose cone would also house the OS sphere.

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Based on the phase I effort, a summary of the proposed MAV systems architecture will be presented, including driving requirements, concept of operations, support systems, conceptual design, reliability assessment, and unique systems engineering considerations for MAV. Driving systems requirements will be presented in the context of lander interfaces, surface support systems, mission design, and concept of operations. Mission performance drivers will be reviewed including landed versus liftoff mass, complexity, landing site accessibility, launch period flexibility, and retrieval orbit accuracy. Key system architecture trades will also be presented including system redundancy, propulsion system type, geometry, navigation, planetary protection, and landing site accommodation. A review of technology options and a candidate conceptual design will be presented for the MAV surface system, including the erection mechanism, ground-launch platform, thermal maintenance system, and telecommunications architecture. Finally, a review of the system level risks will be presented in terms of the Mars environment effects (weather, topography, ground stability), plume impingement aerodynamics and contamination during lift-off, planetary protection, and on-orbit delivery/divert.

2. Support Systems Design

The support systems for the MAV are the launch restraint, erection mechanism, launch tube, and thermal control system. The driving requirements are shown in Table 2 with the addition of a landing site ground slope of +/5 deg. The conceptual design of these systems is described in this section.

Launch Restraint

In order to reach the Mars surface safely, the MAV must be restrained for launch/EDL in three locations. Even though these locations were chosen as the most rigid points on the vehicle, it would not be possible to hold a single point at each location without causing large stress concentrations. In order to distribute the load more evenly, a cradle and strap design was chosen for the two fore interfaces, and the erector interface was designed to provide radial constraint at aft interface.

The cradles would be made of thin-walled titanium and lined with thermal isolation material in order to minimize heat loss from the MAV. The straps would be thin titanium strips which have a relatively long thermal condition path.

Prior to erection, the launch restraints must be released. In order to accommodate this, the straps would be released and subsequently pulled away by the thermal enclosure, called the "igloo", to be discussed later. If the straps and release devices release their strain energy too quickly, there would be a risk of damage to the MAV or the igloo. In order to mitigate this, a latch has been added which would decouple the energy in the release device from the system, and absorb a portion of the energy from the strap. In order to reduce shock in this area, a thermally actuated Frangibolt actuator was chosen for the release device over a more traditional pyrotechnic separation nut.

Elevation Mechanism

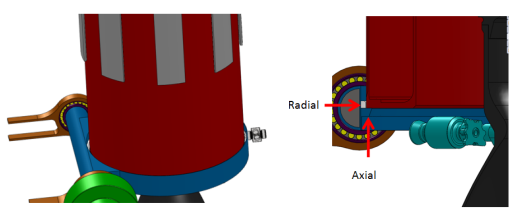

Figure 4. Conceptual design of the erector mechanism.

The elevation mechanism was chosen to be a 1-axis rotator, similar to that used by the MER lander petal [3]. Since the nozzle is not designed to take structural loads, the interface must be shifted to the base of Stage 1. Shifting the pivot point forward may create a potential problem since it would force the aft end of the MAV to travel below the top plane of the lander platform during elevation. The current work assumes that the platform would be elevated.

The erector bearings must constrain the erector radially and axially. In order to accomplish this, the current design uses a pair of angular contact bearings mounted face-to-face and adjacent to the actuator, and one cylindrical roller bearing on the opposite side of the pivot. The pair of angular contact bearings would be preloaded against each other to provide both axial and radial constraints, whereas the cylindrical bearing would be allowed to "float", and only provide a radial constraint. This would allow the system to expand and contract thermally without inducing unintended clamping loads on the bearings.

The erector pivot would connect the primary actuator to the MAV. It has been designed to carry loads directly from the MAV to the erector without impacting the launch tube. For this reason, the launch tube can be kept as light as possible. The pivot would consist of a hollow titanium torque tube which would be attached to a cup interface that restrains the base of the MAV. A Teflon ring would be bonded to the inside of the cup to provide radial alignment and support, and the MAV would simply rest on the bottom of the cup. A pyrotechnic pin puller would add an additional axial restraint to prevent the MAV from sliding forward prior to elevation.

Launch Tube Design

The launch tube's primary function would be to provide guidance for the MAV during lift-off. Additionally, unless the igloo is to be extended over the launch tube, the launch tube must also provide adequate thermal insulation to the areas it covers. The proposed concept would use a sandwiched composite cylinder which would provide excellent strength to weight properties, while the free space created by the Nomex honeycomb core would provide effective insulation. The cylinder has been sized to accommodate the loads and dynamics of a 30º off nominal launch, for added conservatism. Launch guidance would be achieved by Teflon pads which would be bonded to the inside walls of the cylinder.

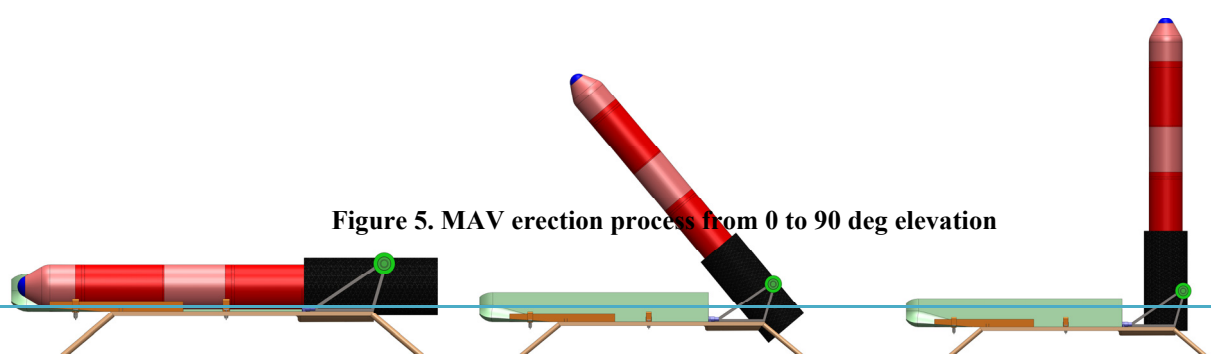

Figure 5. MAV erection process from 0 to 90 deg elevation

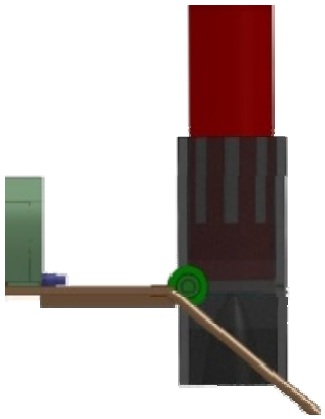

Figure 6. Conceptual design of the launch tube.

Thermal Control System

The MAV thermal control system (TCS) design consists of passive and active elements. The igloo would be a cylindrical structure that surrounds the MAV and provide passive thermal control during the long duration surface stay. The MAV would have an active TCS inside of the vehicle which consists of electrical heaters. They are both described in more detail below.

Igloo

The thermal system of the Igloo containment structure is being designed to minimize heater power required for non-operating survival of the MAV systems during the worst case cold environmental conditions. The Igloo would be an aluminum honeycomb structure that covers the MAV (Figure 7). The surface properties of the Igloo are designed to absorb heat from the sun during the day and minimize heat loss during the night. This would be accomplished by using a solar absorption coefficient (α) that is high compared to the surface emissivity (ε). For this study, a α/ε ratio of 2:1 was used, where nominally $\alpha = 0.5$ and $\varepsilon = 0.25$. These surface properties may be achieved using a combination of coatings in a striping pattern.

The interior surface of the Igloo should have a low emissivity $\varepsilon = 0.1$ to minimize heat transfer by thermal radiation to the MAV. Gas conduction would be the primary method of heating the MAV during the daytime. The Igloo would not contain any physical insulation. Rather, a gas gap between the Igloo and the MAV would serve as the insulating layer. The gas gap would be 5 cm thick and take advantage of the low thermal conductivity of the carbon dioxide atmosphere on Mars. The MSL rover uses the same thermal isolation method between its electronics boxes and the chassis walls.

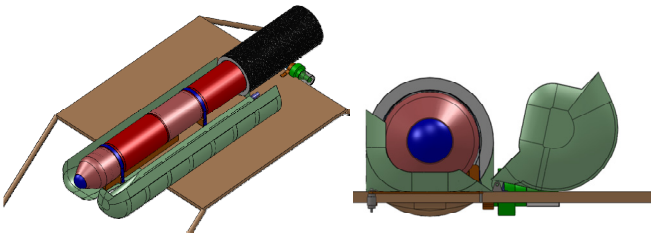

Figure 7. Igloo conceptual design, showing open position just prior to launch or during OS insertion.

MAV Active TCS

The MAV active TCS is being designed to survive a minimum storage temperature of -46°C. The TCS would consist of two different kinds of heater circuits. One would be used for warm-up and another for survival heating. Warm-up heater power would be minimized by cold biasing the MAV operating conditions to -30 to -40°C. The propulsion could then be optimized to operate in this temperature range, although the system may also be designed to operate at higher temperatures (at lower performance).

The cold biased operating temperature of the MAV dictates the need for cooling the MAV in the hot environmental case prior to launch. The MAV external surface would use a α/ε ratio of 1:1 where the solar absorptance $\alpha = 0.2$ would provide low solar heating during the day and $\varepsilon = 0.2$ would reduce thermal radiation losses at night. The main heat loss mechanism would be by convection to the atmosphere. While this strategy slows down the cooling rate in the hot case, it would prevent cooling too rapidly in the cold case.

The MAV/ thermal control system would feature technology that has flown on many previous missions. For example, Platinum Resistance Thermometers (PRTs), Kapton film heaters for warm up and survival heaters on propellant tanks, the battery, avionics and actuator mechanisms, and mechanical thermostats to separately control survival heaters and warm up heaters. Heater power would be supplied to the MAV from the Lander battery/solar array system. A representative power budget is shown in Table 3.

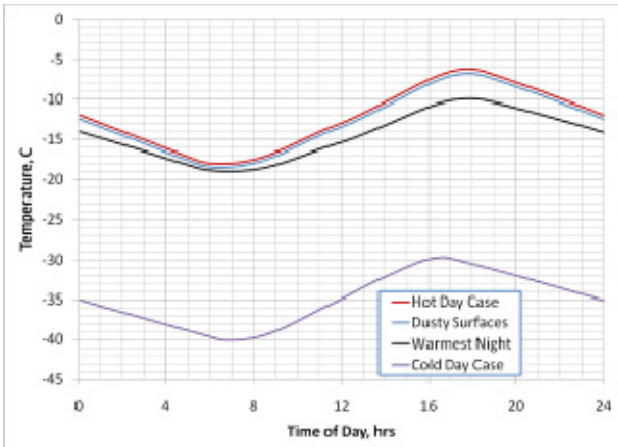

Figure 8. Thermal Environments for the MAV Concept.

Surface Storage Thermal Performance

Three different environmental conditions were used to model to the temperature profile and heater power requirements of the MAV on Mars. The conditions included (1) the Worst Case Cold, (2) the Worst Case Hot and (3) the Warmest Night [1].

In the hot cases, the thermal analysis determined the temperature profile of the lumped MAV system on (1) a nominally clear day with clean surfaces, (2) a nominally clear day with dusty surfaces and (3) a day with high Tau (dust in the sky) which creates the warmest night (this case assumes clean surfaces since the dust hasn't settled on them yet). The dusty surfaces differ from clean surfaces by increasing the solar absorptivity from 0.5 to 0.7 and the emissivity from 0.25 to 0.5. These values are estimated to be typical of increases in surface properties observed on the Mars Exploration Rovers (MER). The change in surface properties was made only on the upward facing surface of the Igloo. The properties of the side surfaces were not changed. No electrical heating of the MAV at night would be required for the hot case.

In the cold case the thermal analysis determined the power required to maintain the MAV above the minimum allowable storage temperature -46°C with 6°C of margin. A continuous heat load of 12 Watts was sufficient to maintain the MAV above -40°C in the cold case. This is about 290 W-hrs/sol of energy. Figure 8 also shows the temperature profile for the three hot case conditions and the cold case condition. Additional heating may be required to maintain electronics or the battery above different minimum allowable storage temperatures, but this was not included in the analysis.

Warm Up Thermal Performance

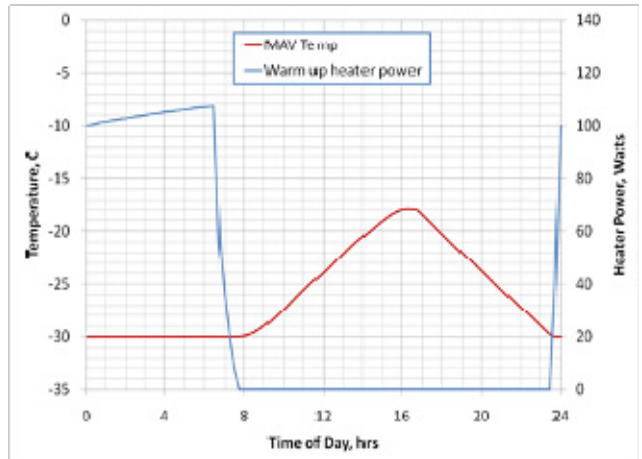

Figure 9. Estimated MAV temperature during the launch window for the cold case.

The MAV propulsion system is being designed to operate with a cold-biased starting condition which would reduce Lander mass because it could use a smaller power system. In the worst cold case, the MAV would be maintained within the operating temperature range of -30 to -40°C. Prior to launch, the Igloo would be opened and the MAV would be erected into launch position. The launch window could be maximized by preheating the MAV to -30°C or higher prior to opening the Igloo.

The estimated heating power required to maintain the MAV at -30°C is shown in Figure 9. The estimated temperature of the MAV is also shown which increases above -30°C during the daytime due to solar heating. The warm-up heaters would be shut off when the temperature rises above -30°C. The total energy required for warm-up is estimated to be about 740 Watt-hours. Higher operating temperature ranges would require more warm-up energy and larger power system mass, as summarized in Table 3.

Table 3. Energy/Mass Estimates for Alternative MAV Operating Temperature Ranges

Operating Temp Range, °C	Energy Watt-hrs/Sol	Power System Mass, kg
-10 to -20	1720	37
-20 to -30	1200	26
-30 to -40	740	16

Baseline Launch Window Thermal Performance

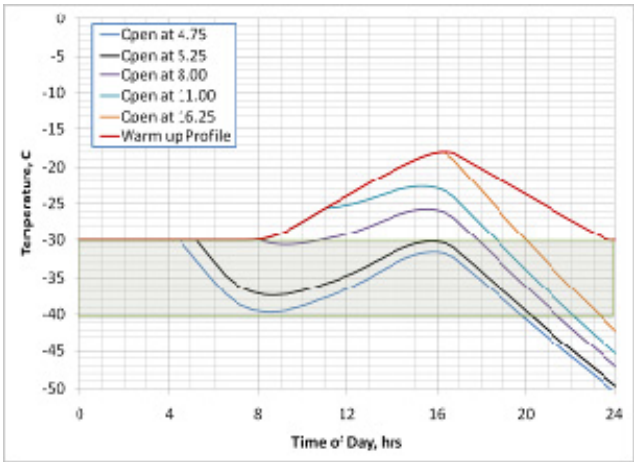

Figure 10. Estimated MAV temperature during the launch window for the cold case.

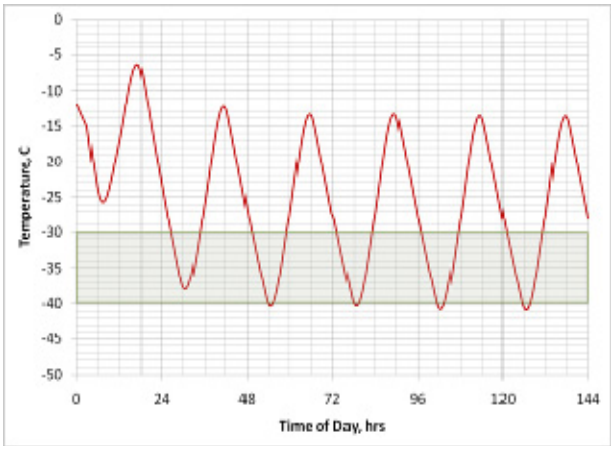

Figure 11. Estimated MAV temperature during the launch window for the hot case. Note the temperature cycling on the heaters required to bring to the cold-bias temperature.

The duration of the MAV launch window would vary with the environmental conditions prior to launch. Several cases were analyzed for the cold environment and the hot environment. The operating temperature range used in this analysis is from -30° to 40°C. In the cold case shown in Figure 10, the duration of the window would depend upon the time of day in which the Igloo is opened and the MAV is erected into launch position. The red line in Figure 11 shows the estimated temperature profile of the MAV when heated to -30°C. The legend indicates the different times of day the Igloo would be opened. The operating temperature range is shown in the gray band on the figure. The longest launch window would occur when the igloo is opened around 4:45 AM local solar time. The MAV would cool down to -40°C by sunrise; then solar heating would keep the MAV in the operating temperature range until 19:30 hours. If the Igloo is opened after sunrise, the MAV would warm up above the -30°C operating temperature and would not be within operating temperature range until well after sunset. If the launch is not accomplished within the window, the MAV must be re-stowed in the Igloo and reheated back up to the operating temperature range.

The launch window in the hot case would occur on a daily basis as shown in Figure 11. The time the Igloo is opened does not affect the launch window duration because the launch window would open up during the nighttime hours. The operating window would be approximately from 1:00 AM to 11:00 AM local solar time. In general, it would take about a day for the MAV to cool enough to reach the operating temperature.

2. Reliability Assessment

System Reliability

The MAV system reliability requirements are driven by the need to eliminate single points of failure and yet still fit within the mass and volumetric constraints described previously. Many challenges were encountered in the attempt to implement component redundancy. Most prominent factors impacting redundancy include: 1) physical limitations of the MAV envelope, 2) compounded MAV mass growth associated with additional inert component mass, and 3) quantifying increased reliability benefits during the quiescent and "active" life of the MAV mission.

The proposed MAV system would utilize the following philosophy to ensure mission success:

1. Level-2 parts
2. Stress testing of all equipment
3. Enhanced Burn in requirements
4. Large design and environmental test margin
5. Comprehensive quantitative reliability analyses
6. Independent review of all analyses

In the Phase 1, a preliminary reliability trade study was conducted, specifically to assess the benefits and costs of single, dual, and selective redundancy avionics architecture. The results are summarized in Table 4.

Table 4. Results from a system redundancy trade relative to the baseline.

Architecture	Cost Impact ($M)	Mass Impact (%)
Single	-30	-3%
Dual	+10	+1%
Selective	Baseline	Baseline

Prior NASA mission avionics architectures were reviewed and a qualitative assessment of the reliability of proposed parts / hardware for MAV was conducted. In our initial trade, single string was found to be the most mass and cost effective approach for the MAV for the following reasons:

1. Short operational lifetime requirement(<1 day)

2. Cross-strapping and switching may reduce overall system reliability
3. Flight-proven mitigations to mitigate SPF's in the avionics subsystem
4. Failures are typically at the part level
    a. Cassini and Voyager have statistically demonstrated parts failure rate post burn in and meets most mission failure rate requirements [4]
5. Reliability models are based on true life test data and therefore are quantitative
6. Increasing burn-in and operating hours would mitigate infant mortality issues at the part level
7. Engage in a robust reliability test campaign

A full system reliability analysis was not performed in the Phase 1, as it was not in scope. Therefore, to ensure a robust design, selective redundancy was base-lined. All components critical to mission success (i.e., achieving orbit) were selected to be dual string. The UHF post-Mars-launch telecom system was selected to be single string (Table 5).

Table 5. Proposed MAV selective redundancy approach [2].

Single	Dual
UHF antenna Electra-lite Radio Telemetry Encoder	Flight Computer Interface Electronics Power Electronics Batteries IMU

From a historical perspective the proposed MAV would achieve system reliability in excess of many NASA planetary exploration spacecraft. For example:, Gravity Recovery and Interior Laboratory (GRAIL), Mars Exploration Rovers (MER), Wide-field Infrared Survey Explorer (WISE), and Mars Pathfinder (MPF) all utilized single string avionics architectures. A full listing is included in Table 6. These are all missions of national priority that had/have an operational lifetime requirement of greater than 3 years. All those that have launched have operated without incident in excess of their design lifetimes, and often by a significant margin. Similarly, the Huygen's probe and Galileo spacecraft, with a mission lifetime in excess of 6 years and subject to harsh radiation environment of the Jovian system, utilized only selective redundancy. Therefore, MAV with an expected operational lifetime of less than one day (dormant life of 3 years), would be in family and in fact more robust, as compared to prior NASA missions.

Another feature to note is that regardless of the avionics architecture selected, the MAV system would be "cold" redundant. Hot redundancy during planetary entry has never been used on a NASA robotic craft. "Hot" redundancy during the ascent/descent process would require three active strings which would not be feasible due to fault-protection complexity, the short timeline, and a prohibitive mass and cost impact. NASA's space shuttle program was the only avionics architecture that has utilized "hot-swap" during planetary ascent/descent process (which required 3-strings and a human in the loop).

In future phases the team will construct a quantitative reliability model and calculate mission failure rate for several configurations, including dual string, dual string with switching / cross strapping, single string, and selective. This analysis will enable the team to determine key reliability risks in MAV system, burn-in requirements to mitigate infant mortality, and operational testing (number of cycles) to provide statistical reliability. Following these analyses an architecture would be selected and the reliability model refined.

Table 6. Example of NASA missions and payloads that have used single string avionics architectures [5][6][7][8].

Spacecraft	Operational Life (years)	Launch Date
GRAIL	+3	2011
MER (A/B)	+8	2003/2004
MPF	+2	1996
WISE	1	2009
Deep Space 1	+3	1998
Stardust	+6	1999
Stardust-NEXT	+12	1999
*Deep Impact (Impactor)	+2	2005
*Wide Field Planetary Camera (WFPC1)	+3	1990 (Hubble)
*WFPC2	+3	1993 (STS-61)

2. Systems Considerations Unique to MAV

Dust Deposition

Dust storms are a way of "life" on Mars with increasing deposition thickness with time. Without an active means to brush away the dust, solar array performance would degrade. An example of this phenomenon from MER is shown in Figure 12. Deposition rate is seasonal, location specific, and would present a large unknown to the MAV surface mission. As a result, sufficient margin of the solar power available and/or a means to actively clear away dust, would need to be traded.

Figure 12. A year of dust deposited on the Spirit rover.

Plume Impingement during initial ascent

The Mars surface environment during launch is outside of the typical experience base of terrestrial launch vehicles. The low background pressure on Mars would cause the engine plumes to expand and interact with the surface, markedly differently than is does on Earth, where the plumes are more collimated and surface impingement pressure significantly lower. On Mars this interaction could induce an aerodynamic contamination and erosive environment that would not be represented by a ground-based static engine testing or a surface launch test on Earth. An example of this effect is shown in Figure 13, where the Phoenix Lander retro-propulsive engines eroded the Martian surface beneath the lander to such an extent that it is visible from space [9]. A risk assessment would need to be performed for the MAV, to evaluate the impact of this environment on vehicles aerodynamics, launch site stability, vehicle contamination, and erosion implications.

Landing Site on Mars

In case it would not feasible for the nozzle of MAV to rotate below the top plane of the lander platform, there are several options to modify the current design. Most simply, the pivot point could be moved to a position that would no longer result in downward motion. If space could be negotiated inside the entry vehicle at the aft end of the MAV, the pivot could be
moved horizontally along the platform until it is located below the base of the nozzle. Structure would need to be added in order to connect this pivot point to the base of Stage 1, and it is estimated that this structure would add 2-3kg to the total mass of the erector.

5. CONCLUSIONS

A Phase I MAV study conducted a thorough investigation, trade studies and analysis of a suitable MAV that would meet or exceed NASA's current proposed MSR campaign requirements. The results yielded a novel MAV baseline design based on liquid propellan**ts,** and a support system design that would minimize mass and volume. The study uncovered several mission benefits and challenges, to be explored further in a Phase 2 effort.

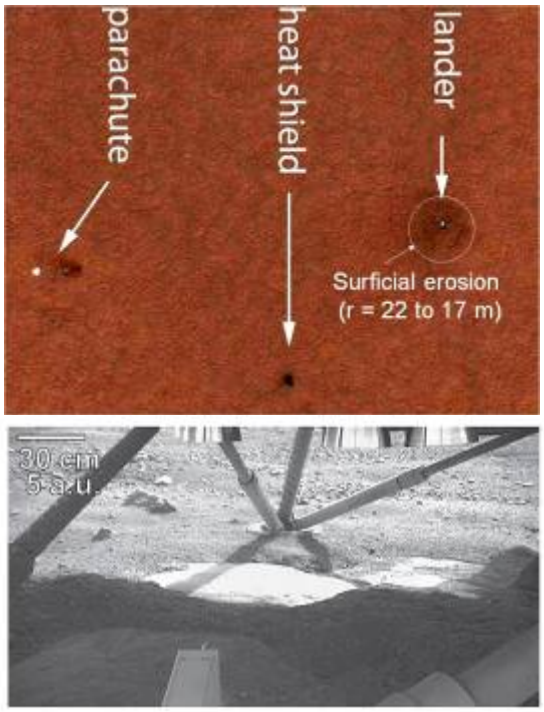

Figure 13. (Top) Effect of engine plume impingement directly above the surface on Mars was seen from space during the Phoenix retro-propulsive landing event. (Bottom) It also eroded away the surface layer of soil exposing the ice below the lander [9].

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