Drivers, Developments and Options Under Consideration for a Mars Ascent Vehicle

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***Abstract*—** The NASA Mars Exploration Program has invested technology funds over the last couple of years to advance design concepts for a Mars Ascent Vehicle (MAV) and technologies that may be enhancing or enabling for various architectures to be pursued. A Mars Ascent Vehicle would fly on a potential future Mars Lander mission to recover and return the samples to be acquired by the Mars 2020 rover, or another future mission, to a retrievable orbit. Resembling a terrestrial Surface to Air Missile (SAM), the propulsion options considered for the MAV concept span the range from two stage solid rocket motors to monoprops, biprops and hybrids. This paper will highlight the driving constraints and performance requirements and the subsequent trades that would ultimately drive the selection of a chosen approach.

TABLE OF CONTENTS

1. INTRODUCTION

To support a Mars Sample Return (MSR) endeavor, one of the more challenging and new elements of this effort would be the delivery of the collected samples to a Mars orbit where they could be captured by a spacecraft and subsequently returned. While no easy feat, landing on Mars has been performed many times over the last several decades and is becoming relatively well understood. The reverse process conversely has never been done before, and provides some key technical challenges that vary from packaging and configuration, to long term storage on Mars, to flight regimes never experienced on Mars. To design such a vehicle requires a good understanding of the design constraints, the areas of uncertainty, potential areas of growth, as well as being an active participant in the evolution of elements for which the MAV must interface, such as the Orbiting Sample (OS) and the Sample Return Lander (SRL).

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2. DELIVERY TO MARS

The first set of design requirements comes from the need to get a MAV to Mars. In so doing, the MAV must be designed to survive the typical launch, cruise and EDL environments. Fortunately, it is likely that the recent launch of the Mars Science Laboratory (MSL, aka Curiosity) is expected to be a good analog for the mission that would take a MAV to Mars. The MAV team is using the design environments from the Environmental Requirements Document (ERD) from MSL and the Mars 2020 mission for this purpose. Mars 2020, which will gather samples of Mars that could be returned by a future lander mission, is a “build to print” reflight of the MSL system. There are potential deviations from this reference baseline to be aware of however, as there is a strong probability that a future SRL mission may in fact be required to put down more landed mass than MSL or M2020 and may require a new, larger delivery system as a result. As a general rule, if the same delivery architecture is chosen (blunt body entry vehicle, parachute deceleration and sky crane terminal phase) then loads will be comparable or less than those for the smaller delivery system. This ensures the MAV design is robust to changes of this type. However, if an alternate architecture is pursued, such as an all Supersonic Retro-Propulsion (SRP) approach under consideration, then this may need to be revisited.

Using the MSL/M2020 analog environments[1] as the source of design requirements, the key launch loads are identified in the following tables.

Table 1 Key Terrestrial Launch Loads for MAV[1]

Launch Quasi-static	+6.4/-2G in Z, +/-2.2G in X-Y**
Frequency, Hz	Acceleration Spectral Density Level*
20 - 40	+ 6 dB/oct
40 - 450	0.08 g^2/Hz
450 - 2000	- 6 dB/oct
Overall	7.9 g_{rms}
*Qualification levels and require 2 min/axis ** MAV is assumed mounted in the X-Y plane, Z loads are transverse to the MAV primary axis	

A Mass Acceleration Curve (MAC) is also commonly used as an early design criteria, and the MAV fits into the mass range for which this is applicable. The MAV in a stowed, launch condition would be required to survive with appropriate margins the following MAC.

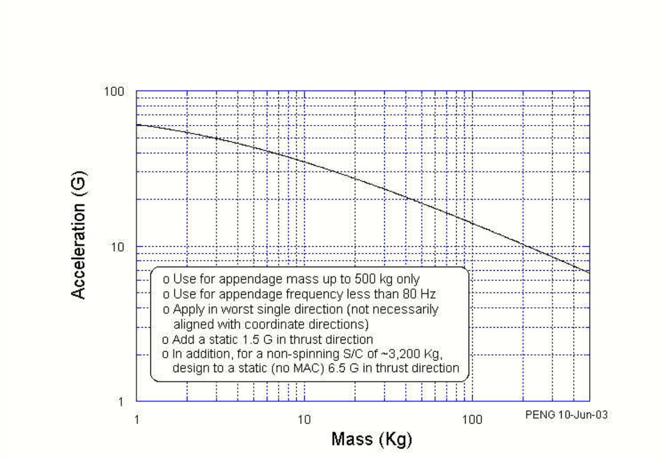


Figure 1 Mass Acceleration Curve adopted for MSR project elements[1]

Launch Acoustics is another design load for launch, and must also be applied to a MAV. For Earth Launch the expected levels are presented in the Table below.

Table 2 Terrestrial Launch Acoustic environment for MAV[1]

One-third Octave Band Center Frequency, Hz	Flight Acceptance Level, dB	Qualification / Protoflight Level, dB	Test Tolerances, dB
31.5	124.5	127.5	+5, -3
40	127.0	130.0	+5, -3
50	128.5	131.5	+5, -3
63	129.5	132.5	+/- 3
80	130.0	133.0	+/- 3
100	130.5	133.5	+/- 3
125	130.5	133.5	+/- 3
160	130.0	133.0	+/- 3
200	129.5	132.5	+/- 3
250	129.0	132.0	+/- 3
315	128.0	131.0	+/- 3
400	127.0	130.0	+/- 3
500	125.5	128.5	+/- 3
630	124.5	127.5	+/- 3
800	123.0	126.0	+/- 3
1000	121.5	124.5	+/- 3
1250	120.0	123.0	+/- 3
1600	118.0	121.0	+/- 3
2000	116.5	119.5	+/- 3
2500	115.0	118.0	+/- 3
3150	113.0	116.0	+/- 3
4000	111.5	114.5	+/- 3
5000	109.5	112.5	+/- 3
6300	107.5	110.5	+/- 3
8000	106.0	109.0	+/- 3
10000	104.0	107.0	+/- 3
Overall SPL (dB)	140.3	143.3	+/- 1
Duration	FA = 60 Seconds	Qual =120 Seconds PF = 60 Seconds	N/A

Throughout Cruise, the thermal environment will be maintained above the AFT limits of the Rover and descent system hardware. If an RTG is used for the lander, relatively warm temperatures will be experienced. This is not a driving environment for a MAV.

Landing on Mars exposes the MAV to the EDL loads. These in fact are likely to be the design drivers for some of the MAV structural aspects. There are three main periods during EDL where loads are experienced[1]:

1) Entry deceleration up to 15 G's in the Z axis (transverse to the MAV) and up to 1 G in X-Y
2) Parachute deployment up to 10 G's in the Z axis
3) Touchdown with up to 5G's and up to 116 rad/sec^2 angular acceleration

Several shock events will also occur between cruise stage separation, parachute firing, heatshield separation, backshell separation, rover mobility system deployment and rover stowed element releases after landing. Maximum expected shock levels at the MAV for these events is allocated as:

Table 3 Stowed MAV pyrotechnic shock levels for design purposes[1]

100	30 g
100 - 1,600	+ 10.0 dB / Oct.
1,600 - 10,000	3,000 g

Packaging

In addition to the environments that a MAV must be designed to, there is also challenging packaging requirements that must be met. Initial MAV accommodation studies were also performed assuming a MSL/M2020 configuration for the descent system. Both a platform lander and mobile MAV rover are options (will be discussed in more detail later), however the mobile MAV system drives the packaging more than the platform option and so was considered the reference for establishing these allocation values.

With the assumption that a Rover would be configured appropriately, and that a new location could be obtained for the terminal descent radar system, a MAV could occupy the following volumetric space when aligned with the Rover axis.

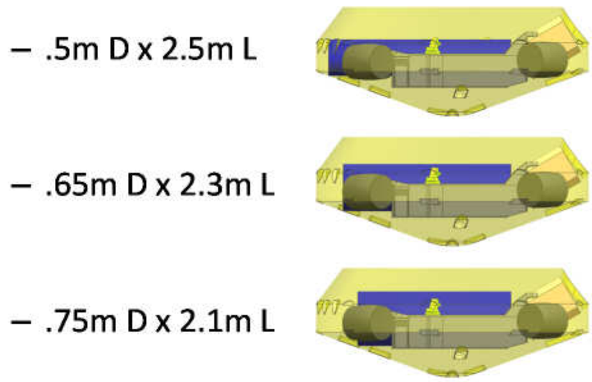


Figure 2 Rover packaging study for MAV based on MSL/M2020 4.5m aeroshell descent system

Given that this volume must enclose both the MAV and whatever launch and thermal control system a MAV requires, the maximum diameter of the combination must be considered. Initial MAV designs have been targeting a 38 cm diameter (set by the diameter of the Star 15 solid rocket motor assumed in previous MAV studies), so with the addition of 10 cm per side for these functions, a 0.6m diameter has been held as a target system diameter. This suggests a maximum MAV length of approximately 2.1 m after accounting for thermal and packaging clearances required axially as well. As we shall see later, this is one of the most challenging requirements for a MAV, and may be a key driver in deviating from the reference MSL/M2020 delivery system.

Delivered Mass

Several studies have been performed that examine the maximum possible landed mass that the MSL system could deliver to the surface of Mars with modest changes to the design (addition of a larger parachute is considered a modest change as room exists to package it already). There are several items that factor into the amount of mass a delivery system can put on the surface. Some of the key factors are associated with the arrival velocity, seasonally driven atmospheric conditions, and landing site elevation. There is no clear approved date for an SRL mission that would deliver the MAV, so the range of launch – arrival space spans from 2020 through the early 2040’s. As can be seen, L-A conditions essentially repeat in a ~ 15 year cycle. The landing site elevation is currently unknown, but will be driven by the M2020 mission, by definition as they will be collecting and preparing the samples to be returned. Based on the chosen launch year, a range of delivered masses appears to be viable, the upper end of those in the 1200 kg range. Looking at the expected mass of an SRL rover, and comparing to MSL and M20220 Rover mass predictions, a working value of 900 kg has been allocated for the Rover and 300 kg for the MAV system (MAV plus launch and thermal support systems).

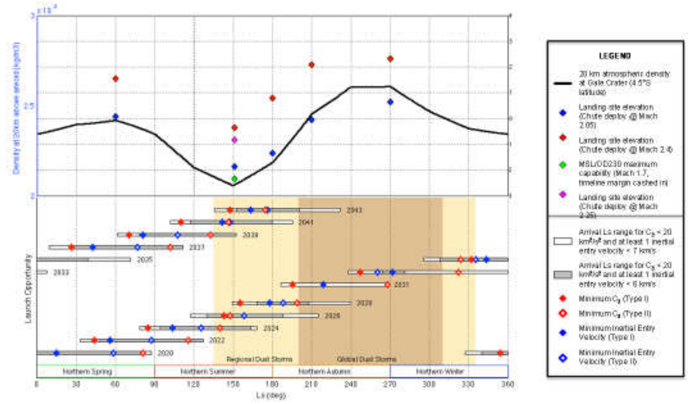


Figure 3 Delivered mass capability of the MSL descent system through early 2040[2]

For both the packaging and the delivered mass constraints, the values will change for a new descent system. There are several factors under consideration now (outside of MAV) that may be leading to the development of a larger 4.7m aeroshell and descent system. No packaging studies have been performed for this system as of yet, but initial parametric studies suggest it may be capable of delivering up to 1500 kg to the surface. This might provide up to 400-500 kg for a MAV system. With the MAV as the central packaging driver for a new lander / descent system design, MAV available volumes may reach ~ 0.7m in diameter and over 3m in length. With the current payload growth, and potential mass liens on the MAV, relief in both of these directions may be required over the initial MSL based allocations.

3. MAV SURVIVAL ON MARS

Getting to Mars is only one half of the problem. Looking again at the range of Launch – Arrival space that the MAV may be landed in, some cases landed very close to the start of or even during the Martian winter. During that period there may be limited SRL operations, and thus the MAV would be expected to survive throughout the winter conditions before use. This can be achieved in two ways.

First, the Lander could provide sufficient power to keep a MAV warm (above its Allowable Flight Temperatures, AFT) throughout winter. The MAV thermal control system would obviously be designed to keep this at a minimum, but even with 10 cm of insulation on all sides the lander power requirements can be excessive. Keeping a MAV above -40C could require between 500 and 800 Whr per sol. This is true even in dust storm or other non-optimal power production cases, as well as lander safe mode conditions. If the lander is solar powered, the MAV might require as much as half the lander daily power.

Second, the MAV could be designed to survive lower storage temperatures. If the MAV could go to -50C, -60C or even as low as -100C, then little to no additional lander energy would be required to sustain it. As a result, MAV design options being investigated are all targeting as low a reasonable non-operating temperature as is possible. For solid rocket motors, this will be driven by the particular propellant combination chosen. Typically -40C, some combinations can potentially go as low as -60C[3], but for the MAV application this would have to be demonstrated and qualified. For the liquids, MMH has the lowest freezing point of the normal fuels used (-51C), and MON-25 has a freezing point of -55C. This would suggest a liquid might nominally be allowed to reach -46C. For a hybrid, this would be driven by the freezing point of the oxidizer, and again using MON-25 would set its AFT at -50C[7,8].

In all cases, the MAV must be able to launch at the worst case hot period on Mars as well. During the summer MAV bulk average temperatures might reach close to -20C. Therefore, it was decided to set the MAV operational point at -20C across all MAV options. In cases where the MAV bulk average temperature was lower than this, heat energy would be applied to pre-condition it to this temperature prior to launch. This also helps to constrain the range of operating performance conditions the MAV must be tested on Earth to.

Open Lander Options

There are two main architectures under consideration for the SRL mission concept. One would use a platform (stationary) lander to deposit both a MAV and a fetch rover onto the surface. The other would utilize a larger, MSL-class rover to support the MAV and traverse with it attached.

The platform lander option would be a solar powered fixed lander. It would include a MER class fetch rover that would drive to collect the samples deposited by the M2020 rover, then return to the fixed lander and transfer those samples to the MAV loading system. The MAV would be loaded, erected and then prepared for launch. This approach may be the lightest landed mass concept (further study required), and might also provide good packaging options for a MAV. It might also provide for a good teaming arrangement whereby one participant provides the platform, one provides a MAV, one provides the fetch rover, and one is responsible for the delivery system. Conversely, if this were by a single provider, it is likely the most expensive option, requiring two complete landed systems that must operate autonomously and also communicate back to Earth for up to a full Mars year. This particular option would also require the longest surface operations, as the rover must make a multi-kilometer round trip. This, combined with the potential for limited or no operations during winter is the source of the MAV survival requirement of one full Mars year.

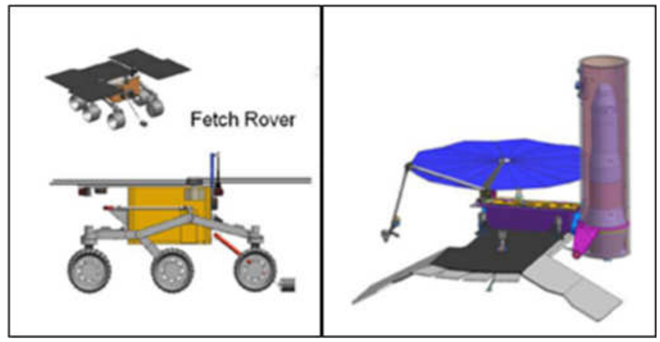


Figure 4 Fetch Rover and Platform concept

The concept of a large, MSL class rover carrying the MAV with it is called the mobile-MAV architecture. In this case, a large rover houses the MAV system onboard for landing and subsequent surface operations. This option could be either solar or Radioisotope Thermal Generator (RTG) powered (both MSL and M2020 were RTG powered). This approach has the benefit of only requiring a one-way trip to collect samples, thus reducing surface mission duration. It also has the robustness aspect in that if at anytime the rover were to get stuck or suffer some other form of disability, the MAV could be launched with whatever samples it had collected up to that point.

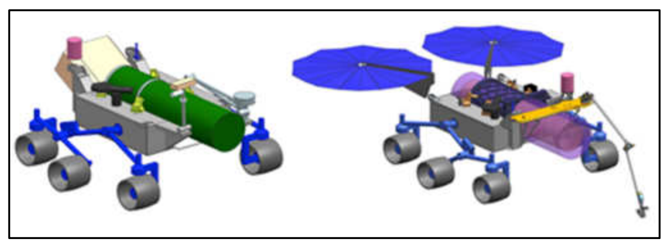


Figure 5 Mobile MAV concept, showing RTG and Solar Powered options

In this scenario, the MAV and the mobility system compete for the potentially limited on board energy available. This must be factored into to mission planning studies as during the Spring and Fall, and especially in the winter, MAV heating requirements may limit the amount of daily driving possible. If an RTG were chosen as the power system, the waste heat from the RTG could be circulated through the MAV launch tube (doubling as an RTG radiator) and the MAV would easily maintain AFT limits with no electrical power required at all. In fact, initial estimates are that should an RTG be used for any form of the lander, the MAV system temperature could be maintained above 14C at all times! This would allow propellant choices that are “off the shelf,” including the use of hydrazine for Reaction Control (RCS) if desired (freezing point at 2C) and also reduce substantially the MAV development and testing costs by not requiring cryogenic test conditions.

The Benefits of Nuclear Power

This is a good segue to discuss what an RTG could contribute to the design of a MAV system. If it could be confirmed today that the SRL lander would use an RTG as its baseline power, it might change several of the design choices that each of the MAV options are considering. It would also have a substantial impact on the development, testing and qualification costs of any MAV by eliminating the need for cryogenic testing.

For the Solids, realizing higher temperatures might allow them to utilize an HTPB binder instead of the CTPB binder they are currently using to get some performance improvement[3]. It might also allow the use of the flex seal nozzle approach instead of the trapped ball. The flex seal has significantly more heritage in motors of this class[4,5,6], and is likely less susceptible to slag build up during the burn. It might also allow for the use of hydrazine for RCS, increasing the control authority without significant mass increases, moving back to a core burner option with shorter burn times (this will be discussed in more detail later).

For liquids, this would allow the use of either MMH and MON-3 or potentially even hydrazine and MON-3 for the main engine. There are numerous engines using these combinations already available in or near the class needed for a MAV and would reduce the development cost and risk of obtaining this engine. Furthermore, there are more facilities equipped to handle MON-3 test and operations than there are that can handle MON-25. The use of a hydrazine-based engine also allows for straightforward use of hydrazine-based RCS thrusters, which are the typical work horse of the space sector.

Similarly for the hybrid, the ability to utilize MON-3 instead of MON-25 allows for lower cost development and testing. Fuel formulations could be tailored to optimize performance at higher temperature ranges and not need to demonstrate low temperature survival.

Launch and Thermal Support Systems

One way to reduce the Gross Liftoff Mass (GLOM) of the MAV is to utilize a support structure external to it to take the loads during launch and EDL. In these events, the MAV is exposed to large lateral forces, and is generally most robust to axial loads only. In particular the 15Gs that would otherwise cause substantial bending of the MAV could be supported by a strong back or other superstructure to prevent it. It is also desirable to control the exhaust gases during ignition and initial liftoff to limit rover damage and rover motion until the MAV is clear and under its own power. Both of these drivers lead to a launch tube, as is typical of terrestrial launch systems of this class.

The launch tube would be locked in place during Earth launch and EDL, and released after landing. It would be erected in preparation for launch (as shown in Figure 7). The MAV would be suspended in the launch tube with one or more sabots as depicted in Figure 6. Further design work is required to evaluate the loads imparted into the MAV and optimal placement of the sabots while not negatively affecting the inflight aerodynamics of the vehicle. The sabots must also maintain a positive preload through a range of temperatures going from up to +50 C at earth launch through as low as -80C (or whatever the low AFT of the MAV becomes). They also must separate cleanly after the MAV exits the tube. Aerodynamic features can be applied to the sabots to ensure they separate with adequate force.

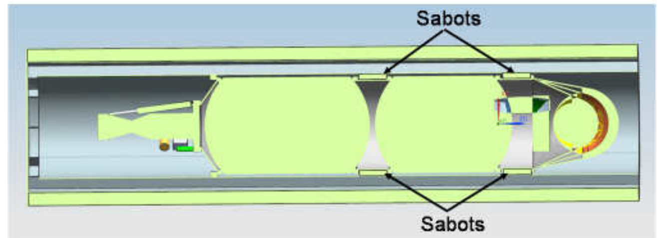


Figure 6 Example of MAV supported inside a launch tube by sabots

The launch tube itself would be structural, but it must also serve as an insulator to keep the MAV at its safe survival temperatures. The obvious way to do this is to include as an outer covering the desired amount of thermal insulation adhered to the tube. This outer covering could be from 2 up to 6 or 8 cm thick, depending on the amount of insulation needed for a given MAV. This could be achieved by using simple standoffs around the tube holding a light weight aluminized mylar covering, or might be achieved using a layer of aerogel coated with an outer surface. Both would be painted with a high α/ε coating to maximize temperatures. The two ends of the tube would keep the same standoff distances and be closed out with simple mylar covers. This design is robust to multiple launch opportunities and can maintain the MAV at launch temperatures indefinitely. This provides robustness to situations where the orbiter is not ready or has a problem, the lander does not pass internal checks, or the MAV does not report ready for launch for some reason. This is not possible with a deployable clamshell thermal enclosure concept that would be jettisoned before MAV erection (as in previous studies) where the MAV must be erected and launched shortly after cover removal before it drops in temperature below flight limits since it is now directly exposed to Mars.

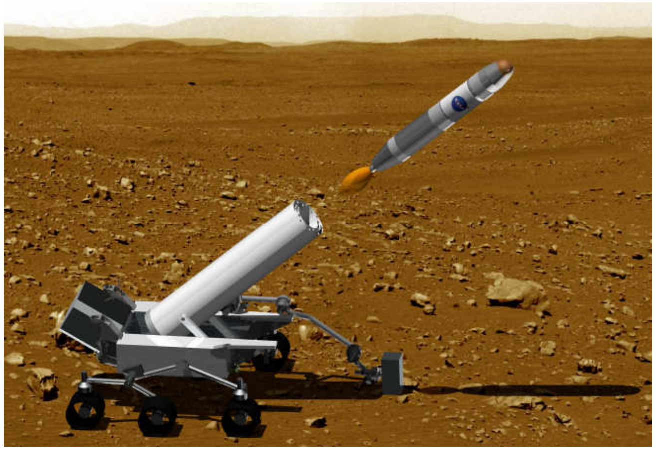


Figure 7 MAV concept launched from an erected launch tube

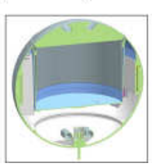
In the event that lander survival becomes important, the outer tube could become structural and exhaust gases could be ducted out the front and away from the lander. This is not uncommon for terrestrial missile systems (called Hot Launch), but would add mass. Alternatively, a gas generator could be used to pop the MAV out of the launch tube, and then airlight the main engine. This is also done with various launch systems (called Cold Launch)[8].

Payload

One of the last external, and one of the primary drivers, of the MAV size is the amount of Payload that must be delivered to orbit. Over the last two decades of MSR studies and pre-project efforts, the OS has ranged in estimate from 3.6 kg to 5 kg. In 2014 the MAV efforts assumed 30% margin on the 5kg target and used 6.65 kg as the maximum payload mass. This value covered the maximum predicted value estimated from an earlier design study that assumed every sample was loaded into its own dedicated drill bit (as opposed to each tube being swapped in and out of a fixed drill bit).

Characteristic	31-Sleeves	37-Sleeves	31-Bits	37-Bits
Cache Mass (w/ sample)	1.66kg (Ti)	1.98kg (Ti)	1.99kg	2.36kg
Cache Dimensions	10.55cm X 9.8cm	11.69cm X 9.8cm	16.2cm X 10cm	17.2cm X 10cm
OS Diameter	19.37cm	20.33cm	24.24cm	25.13cm
OS Mass (w/o Cache) PBE	2.34kg	2.52kg	3.27kg	3.46kg
OS Mass (w/ cache) PBE	4.50kg	5.09kg	5.86kg	6.53kg

- NOTE: No redesigns for wider caches, only direct scaling. There are possibilities for re-packaging for different cache dimension ratios.



Key Finding: OS mass driven more strongly by cache diameter/aspect ratio than mass, per se

Figure 8 Results of OS study performed in 2012

Since this time, the Mars 2020 project has officially begun, and detailed design work of the sample caching and storing system (SCS) has begun. Taking Planetary Protection and sample cleanliness issues into consideration, the tube sizes have grown considerably. Added elements include handling fixtures introduced on one end of the tube, an offset cam feature at the other end for sample core break off, and tube plugging and sealing hardware. These design changes have resulted in a tube that is over 100% larger than any previous study. This design effort has not yet reached PDR, and thus additional growth beyond this level is probable.

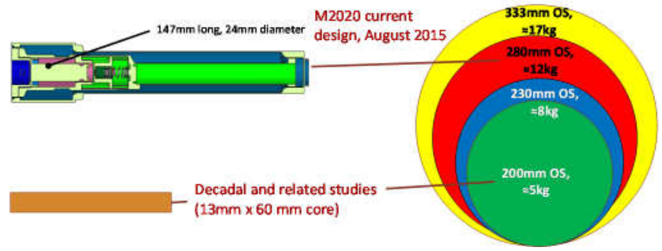


Figure 9 Comparison of historical sample tube size to present M2020 derived size and resulting OS size and mass

4. MAV Design Options for Flight

Now we deviate from external design constraints and issues to ones directly affecting the design of the MAV itself. There are several phases of flight to be considered. Each has its own unique issues and will be addresses separately.

Launch

At the time of launch, the MAV must obtain accurate initial position, attitude and time data. This can be obtained from the Lander, or potentially internally depending on which has the best IMU's and can read launch erection system encoders. A series of Go-No-Go checks would be performed by both the lander and the MAV prior to a launch commit. At that time, ignition would be triggered at the predetermined time to coordinate MAV flight with the tracking SRO orbiter to ensure both telecommunications coverage and potentially optical tracking as a backup method.

The choice of MAV propulsion system is a key feature of the size, mass and accuracy with which the payload can be injected into a correct orbit. These also affect the type of trajectory flown, and the size and total impulse needed of the RCS system during flight.

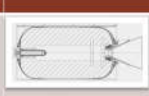
Solid Rocket Motors

Historically, the approach chosen for a MAV has been to use solid rocket motors in either a 2 or 3 stage configuration. A minimum of two burns is necessary to put the payload into a 10+ year stable orbit. For a solid, that can be achieved with either a two-stage system using two rocket motors, one on each stage, OR, more complex approaches have considered a complex fuel grain design that uses a first burn grain bonded to a fixed delay and then a second burn grain affixed to that. The latter case is not unlike a hobby rocket motor that uses a delay before firing the final charge that deploys a parachute. Due to variability in atmospheric conditions and winds, plus the inherent variability in the stage 1 motor burn, the ability to optimally start the 2nd engine burn at the appropriate time increases the probability of putting the OS into a safe orbit.

Solid rocket motors also generally burn in very short durations at very high thrust levels. For a missile this is generally a good thing. For a MAV, it is less desirable. Initial design work for a first stage solid based on a Star 15 motor resulted in an action time of only 17 seconds. At the time of burnout, the vehicle would be well in excess of Mach 5 and less than 10 km in altitude, with substantial atmosphere remaining to coast through. During the primary burn the Thrust Vector Control (TVC) provided by gimbaling the main engine provided ample control authority to maintain the vehicles attitude. However, through detailed aerodynamic analysis at Langley Research Center (LaRC), at the time of MECO, the vehicle was at maximum dynamic pressure and was not dynamically stable[10]. It would immediately start to tumble. This is not a desirable flight condition when hypersonic.

To address this, estimates were made to assess the size of the Reaction Control Systems (RCS) needed to maintain attitude until sufficiently outside the appreciable atmosphere. Due to the short length of the MAV, and thus the short moment arm available to it, it was estimated that 100 lbf class motors would be required! These would blow the mass fraction of a solid motor out of any reasonable competitive range, and drive the GLOM of a solid-based MAV to significantly higher values than previously estimated. Trades were made to fly the MAV in slightly less optimal trajectories but with the goal of hitting a lower dynamic pressure at MECO, thus reducing the size of RCS thrusters required. This it turns out was very effective, however it would require the motor to reduce its thrust and increase burn times.

Table 4 Comparison of first stage solid motors over time[15]

	Concept 1	Concept 2	Concept 3	Concept 4
Model		 *Modifications to Motor Insulation		
Isp(s)	278.4	276.4	283.8	293.3
Total Mass(kg)	123.1	119.2	133.4	141.4
Prop Mass(kg)	102.3	100.9	104.6	106.5
Burn Time(s)	19	19	119	70
Propellant	TP-H-3062 (16% Al)	TP-H-3062	TP-H-3544 (21% Al)	TP-H-3062 (16% Al)
Motor Grain	CP Grain	CP Grain	End Burning	End Burning
Nozzle	Reversed Trapped Ball Nozzle	No changes	Smaller Throat. Insulator Thickness Increased Due to Burn Time	Tungsten Throat Insert. Insulator Thickness Increase for Positive Margins
Igniter	Head End Igniter	Same	Aft-End Igniter	Same (Dual)

For a solid this is achieved by switching from a core burner to an end burner. The solid propulsion team at MSFC began work on designs that could achieve this. With the increased burn times, the design of the trapped ball nozzle became even more difficult. The size and mass of the thermal liner within the case also grew significantly, out weighing the casing itself. The result was a motor design that closed, but at a somewhat higher than desired dry mass. Future trades returning to the core burner and trading the addition of deployable stability features (fins, flares, etc) should be considered in the future to see if any better mass performance can be achieved.

Liquid Rocket Engines

Liquid bipropellant rocket engines have been used since the 1950s and offer excellent performance. Historically for relatively small applications (small meaning low total delivered impulse), they did not compare well to monopropellant systems due to the additional dry mass they require. For a MAV, which is delivering approximately 4 km/s of dV, these are certainly within the competitive range. Two versions of this are considered: one is classically regulated and the other is pump fed. The pressure regulated version is commonly found on GTO transfer stages or on deep space missions used to perform an orbit injection maneuver upon arrival at their destination planet. Pump fed systems are typical of suborbital or orbital launch systems. In the latter case, the pumps are generally turbo pump driven.

The regulated version of a MAV would be straightforward today, with the development of a new engine using the MMH and MON-25 (cold temperature propellant combination). Engines exist in this thrust class but with MMH/MON-3, or with this propellant combination but at much lower thrust levels. This development would be straightforward, but is likely to be modestly expensive. The RCS system would be driven directly off the pressurant system.

The pump fed version utilizes a new type of electrically driven pump. With the advent of 3D manufacturing very small rotors can be made with good precision for this purpose. Several companies are demonstrating the use of these for rocket engine operations. The combination of a pump and the requisite battery mass, plus a separate RCS system, trades well against a pressure fed system whose tanks must be sized to operate at higher pressures, and includes a complete He pressurization storage and delivery system. For the MAV size and payload delivery requirements, the pump fed system offers both GLOM and packaging savings over the regulated version. It will however require additional development and qualification funding. It too requires a new MMH/MON-25 engine. It is possible that the same engine could be used for either system in the event that the pumps did not reach a desired TRL level at the needed time, however this would potentially reduce limit the benefits that could be achieved with a pump that might be able to reach higher chamber pressures.

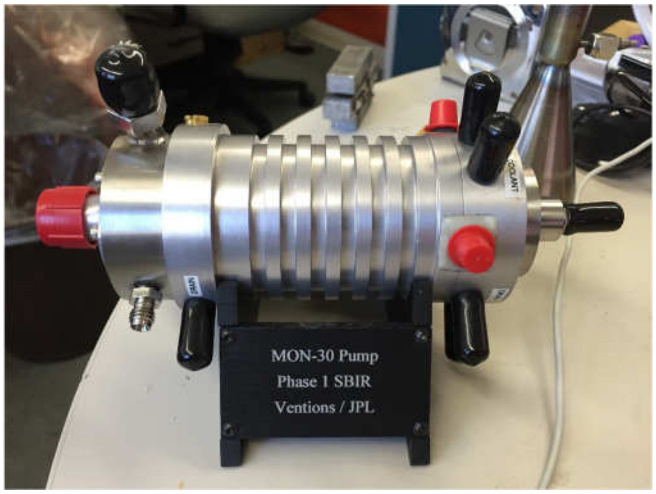


Figure 10 Electrically driven pump developed for a MAV application

Hybrid Rocket Engines

Hybrid rockets have also been tested for decades. Historically these have used HTTB or PMMA based fuels as propellants, often with significant Al particulate added (up to 25%) to increase regression rates[11,12]. Hybrids have been used as safe versions of hobby rocket motors, and have been used as launch system motors for numerous vehicles including the current Virgin Galactic Spaceship Two. More recently, Universities have started to look at paraffin based fuels as an alternative, and these have emerged with some highly beneficial properties.[13]

Unlike the HTTB fuels, which evolve material through pyrolysis, the paraffin based fuels are considered liquefying, in that they evolve in liquid form from a melt layer and thus can regress at higher rates than the previous fuels, and more efficiently. Both systems require good mixing of the fuel and oxidizer for high system efficiency and performance (driving a length to diameter ratio for hybrids). [14]

Hybrids have the benefit of terminating on command by simply closing the oxidizer valve. This helps for improved injection accuracy and control. They are also restartable making them excellent candidates for a SSTO MAV. Their Isp is better than the liquid bipropellant combinations under consideration as well. They can be throttled over a large range of Ox/Fuel ratios as well, unlike a bipropellant engine. This makes them safer and less costly to develop and optimize (don't have to rebuild as many test stands due to catastrophic failures). Their pressurant system can also be used to supply the RCS system, similar to the regulated biprop. A future trade will explore whether the pumps have sufficient benefit to the regulated system for this application as well.

Current estimates of Hybrid solutions show them to be the lightest of all MAV options evaluated. They are also the most flexible, due to the high performance and restartable nature. They are also the least mature. The new fuels have been tested across a range of temperatures, and to date appear to have good properties. They will need to be tested and thermally cycled extensively to ensure long term storage and survival characteristics. Ignition systems or hypergolic additives need to be developed and tested as well across the range of MAV restart conditions. Nozzle survivability and performance will be another challenge, similar to that faced by the solids. There is a bit of work ahead for the hybrids, but the payoff appears today to be compelling.

5. Parametric Studies

Given this set of propulsion options to choose from, each was developed to a point where a scaling model could be applied and validated against detailed Mass Equipment Lists (MELs). This model captured fixed dry masses plus variable dry masses that were a range of propellant mass to be flown. For every MAV, a fixed cold gas RCS system was applied. Later optimizations for a given MAV would look at combining this with the propulsion system built in elements (pressurant system). In addition, a set of subcases were derived that covered the range of potential payload, avionics and telecom hardware that might be considered. Some of the hardware is the same for all MAVs (such as prop drive electronics, TVC drive electronics, wrap around antennas, payload support and release mechanism, etc) and these are included in the fixed mass for each. Then the items that might vary were separated and estimated. These ranged as follows.

Table 5 Range of secondary masses used for parametric studies

Payload	6.65 kg *(smallest possible)*	25 kg *(includes PP BTC HW)*
Avionics	5.4 kg *(JPL Sphinx plus MEMs IMUs)*	15.5 kg *(fully redundant RAD 750 suite with LN 200)*
Telecom	1.45 kg *(JPL IRIS or tactical radio)*	4.2 kg *(Electra Lite)*

This set of variable mass has a large permutation range over which it covers. As such, 6 subcases were developed with varied combinations of assumptions that cover this range. The subcases were identified as:

Table 6 Range of variable mass permutations used for parametric analysis

Subcase	Payload Mass	Avionics Mass	Telecom Mass
1	6.65	5.385	1.45
2	10	5.875	2.04
3	14	5.875	4.2
4	14	15.5	2.04
5	20	15.5	4.2
6	25	15.5	4.2

In addition to the MAV mass scaling algorithms developed, a model of the launch /erector system was built that scaled as a function of MAV mass and MAV length. There were multiple versions considered, and the lightest weight version was chosen (slider-erector). The erector was assumed to be oriented vertically (zero azimuth and 90 degree orientation) at the time of launch. Trajectories are iterated until convergence meeting all constraints, and MAV and Launch system mass and dimensions are outputs.

All scaling algorithms are included in a 3-DOF trajectory optimizer. All runs were originated at the equator and targeted a 400 km orbit inclined at 45 degrees. Trajectories were constrained to have a MECO dynamic pressure of < 2000 Pa (to keep within the fixed RCS control authority). For improved accuracy, for each MAV configuration and Payload, appropriate aero coefficients were obtained from Missile DATCOM. A subset of cases were compared between Missile DATCOM and LaRC predicts for validation. Agreement was close enough for this stage of evaluation. Later 6-DOF runs would use the reference trajectories from these runs as a basis and then monte carlos would be run to look at dispersions.

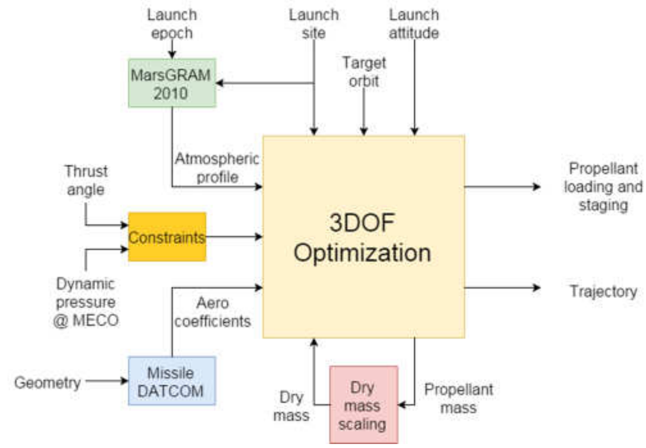


Figure 11 Process used for Parametric analysis and subsequent 6-DOF runs

6. Parametric Results

The first item of interest as a product of this effort is the GLOM of the various MAV design choices and how they vary with increasing dry mass to be lofted.

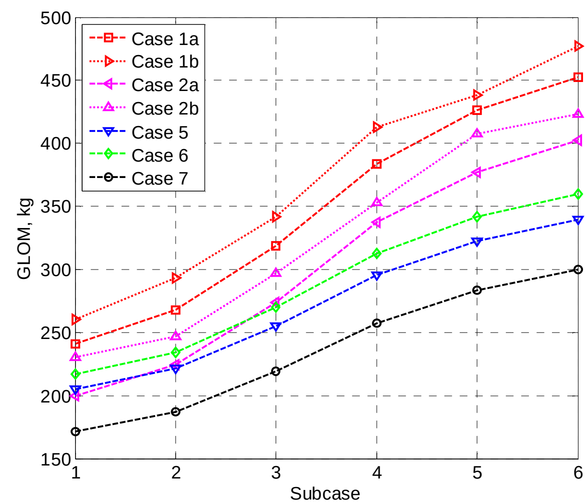


Figure 12 Parametric Results for all MAV options across range of subcases

Some observations of these results indicate that the hybrid is predicted to be the lightest option across all options, and is less sensitive to dry mass growth than the other options. The solids appear to be the most sensitive. This is not completely surprising given the Isp difference between the options, but is also a function of the total dV required by each system. It turns out that an SSTO requires less total dV to reach the target orbit than does a TSTO option. This is a result of the optimizer trying to maximize the use of the 2nd stage to "buy back" the additional dry mass required of that configuration (ie: two engines instead of one, two TVC systems, separation hardware, etc).

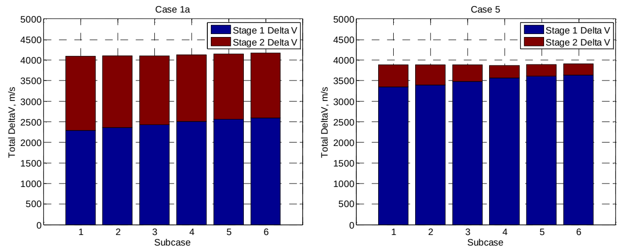


Figure 13 Total dV for the 2-stage solid vs the pump fed liquid

What is also clear is that it is unlikely for any MAV to be less than 200 kg. Unlike some previous studies that suggested low end MAV's might be achievable in the ~150 kg range, once all aerodynamic, flight path constraints and RCS system impacts are accounted for, plus the fact that the Payloads are much heavier than previously assumed, reasonable MAV masses are more likely to land in the 250-300 kg range. This does not yet include the support system hardware.

In addition to GLOM, total MAV mass is the combination of MAV and MAV launch support systems. The results of the support system mass across the range of subcases based on the lightest weight sliding erector are as follows.

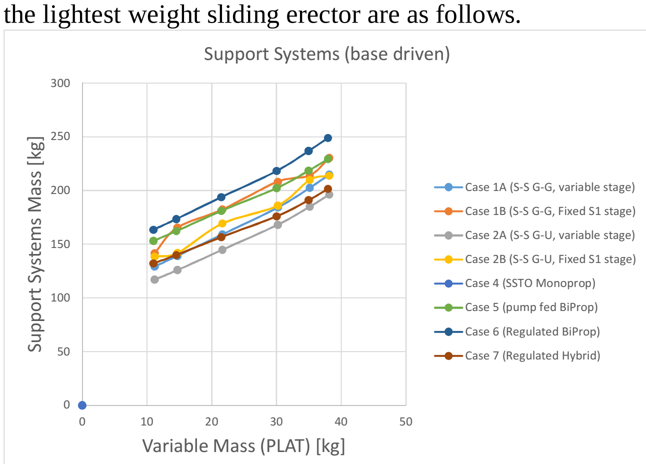


Figure 14 Launch erector and thermal system mass as a function of subcase

According to these results, a support system mass is expected to be in the 150-200 kg range. Combined with the MAV GLOM that suggests a total MAV system mass between 400 and 500 kg. The maturity of the MAV support system is less than that of the MAVs themselves, and effort over the next year is going to focus on reducing this value. It may be possible to reduce the support system by half its current value through a combination of improved design maturity, reduced requirements, and reduced robustness. The tailoring of a launch support system for a given MAV will also be investigated to see if further reductions can be achieved.

Another key factor in MAV selection is packaging, and whether the MAV is going to fit into the Aeroshell or not. With the constraint of holding MAV diameter to a maximum of 38 cm, the following stack height results were obtained.

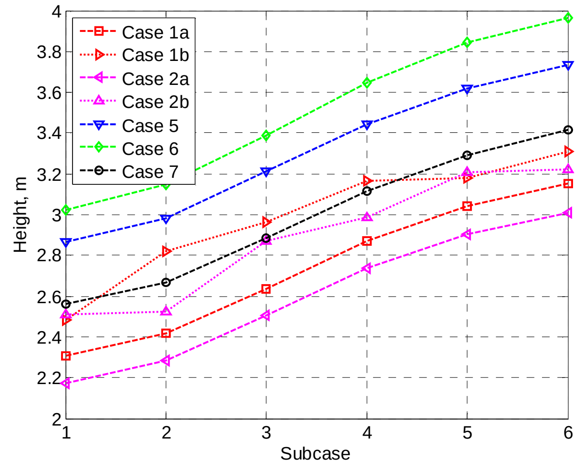


Figure 15 Stack height for all MAVs as a function of dry mass growth

Here we see that the two stage solids appear to be the shortest packaging, with the hybrids at the upper end of their range, while the liquids are longer. The liquids are driven primarily by the inclusion of the pressurant system and lower propellant densities. In any case, it is equally obvious that no MAV is likely going to be able to stay inside the MSL based volumetric allocations. Without a complete redesign of the Rover, a mobile-MAV inside the MSL aeroshell is unlikely. A platform lander may be possible, but packaging studies have not been performed for that concept yet.

Some sensitivity analyses were also run to look at impacts to changes in orbit altitude and inclination, as well as off nominal azimuth and erector inclinations. SSTO's readily handle altitude change with an impact of only a few kg per 100 km, TSTOs are 25% worse. SSTO's however cost more for large inclination changes, requiring approximately 5% GLOM for an additional 40 deg change, while the TSTO only requires about half that for an additional 40 deg change, a result of more dV being imparted by the TSTO on the second burn near apoapse making changes in inclination more efficient. The SSTO's with their lower T/W ratio have almost negligible impact for azimuth or launch inclination error, while TSTO's are slightly more impacted but still relatively robust to this.

One more aspect of the vehicle flight path to consider is the total downrange as a function of time. With the intent of keeping the orbiter communications robust but potentially also using the lander as a backup communications pathway, it is interesting to observe the varied performance in the trajectories.

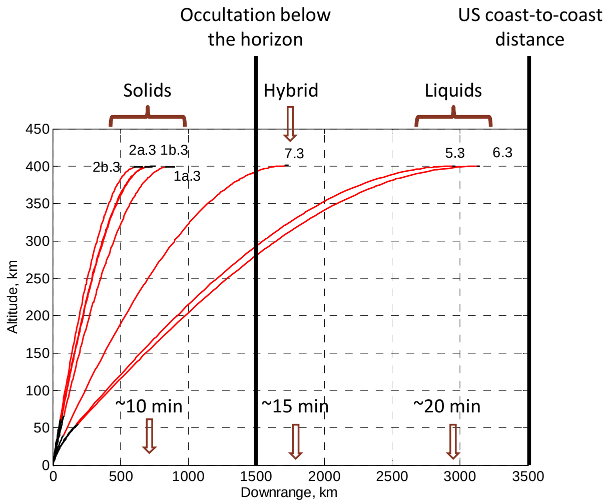


Figure 16 Total downrange distance vs altitude for each MAV option

One can see that except for the TSTO solids, the lander is not a viable secondary communications link for the whole flight.

7. Remaining Work

A Figure of Merit scoring approach was also applied to the MAV comparisons, but was not presented here. Initial scoring suggested the hybrid as a substantial leader, with the liquids following, then a drop to the solids. This is in part due to the mass being a major factor in the scoring process. In the future, leading to a MAV concept downselect, this process will be employed with a set of FOM's concurred by all stakeholders.

The launch erector and thermal control system designs need to be matured and reduced where possible. This area has grown in mass substantially over previous estimates and would have a noticeable impact on the total MAV system mass that a future lander must accommodate.

Further optimization trades remain for each of the MAV options and will be explored over the next year. Those include:

Solids	Spinning 2nd stage viable?	Alternative TVC options	Core burner vs passive stability
Liquids	Combined vs separate pumps for Fu/Ox	RCS combined with pressurant system	
Hybrids	Hypergolic fuel additive vs pyrogenic ignitor	Trapped ball vs LITVC	RCS combined with pressurant system

In addition, work will continue to evaluate delivery systems and the establishment of hard constraints and requirements that a MAV must satisfy. Work has just started on the development of a 4.7 m aeroshell concept and requisite descent system, and packaging and mass delivery values should be obtained. Work with sponsors will help to establish the need for MAV to have redundant avionics and potentially other redundant features not currently included.

Lastly, continued technology development investments in some of the key hybrid and liquid pump systems will be pursued. The objective of the current Mars Program technology focus for MAV is to bring the liquid and hybrid systems to a comparable level of maturity as the solids to enable a more well-informed downselect at a future date.

Acknowledgements

The author would like to thank the Mars Program Office for allowing me to lead this exciting and challenging endeavor. I would also like to heartfully thank all the hard work and long hours put into the MAV by all study participants.(Part of) the research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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BIOGRAPHY

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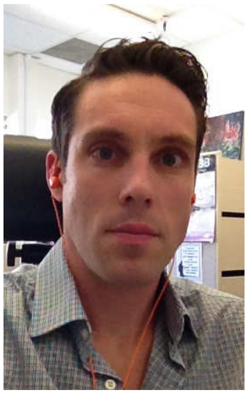

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