Mars Ascent Vehicle (MAV) Solid Motor Technology Plans

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Abstract— **Recent trades have taken place on solid propulsion options to support a potential Mars Sample Retrieval Campaign. Mass and dimensional requirements for a Mars Ascent Vehicle (MAV) are being assessed. One MAV vehicle concept would utilize a solid propulsion system. Key challenges to designing a solid propulsion system for MAV include low temperatures beyond common tactical and space requirements, performance, planetary protection, mass limits, and thrust vector control system. Two solutions are addressed, a modified commercial commercially available system, and an optimum new concept.**

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1. INTRODUCTION

The Mars Ascent Vehicle (MAV) vehicle would launch samples off a potential Mars Sample Retrieval (MSR) campaign being considered by Jet Propulsion Laboratory (JPL). The MSR is an effort to return Mars samples to earth for scientific study. MSR is currently envisioned as utilizing a series of three Earth launches. The first launch consists of a rover that collects Mars soil samples and deposits them at one location (Mars 2020). The second and third launches, potentially in 2026, would deliver the MAV as part of a Sample Retrieval Lander (SRL) and the Earth Return Orbiter (ERO). The MAV descends to the Mars surface onboard a lander. The SRL will retrieve the samples and insert them into the MAV. A potential concept for the lander is shown in Figure 1. The MAV vehicle will be housed in a thermal enclosure. The sample payload is stowed in the Orbiting Samples (OS) at the front of the vehicle. Once the MAV is loaded it will be thermally conditioned and the launch enclosure oriented for launch.

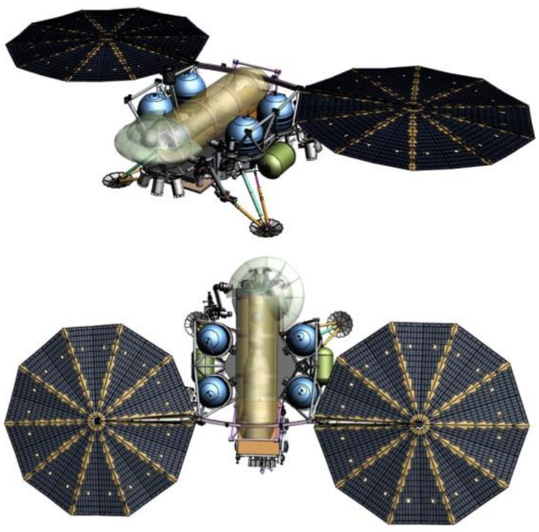

Figure 1 MAV Lander Concept

The MAV will be launched to a specified orbit where the OS can be transferred to the Earth Return Orbiter (ERO) for transit back to earth. The Earth Entry Vehicle (EEV) will house the OS and return them to Earth, where the samples will be taken for scientific study. An overview of the Mars Sample Return Campaign is shown in Figure 2[1].

This paper describes the current development of a two-stage solid motor MAV. The paper describes the ongoing effort to design the first and second stage solid motors for this concept. Once complete the performance parameters will be traded against other concepts to down select the propulsion system for the MAV.

2. SOLID CHALLENGES

Consideration of a MAV vehicle has been ongoing for many years through different efforts. Configurations have changed with various propulsion systems considered. Since 1998 the derived solutions have been mass driven solid solutions as shown in Figure 3.

Most information available was from the 2014-2016 efforts[2]. This was examined[3] for clues to sensitivities and possible considerations that might otherwise be overlooked. Trades that were examined are discussed in the following sections.

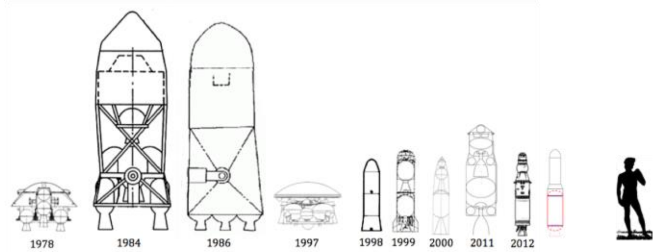

Figure 3 MAV Concept History

Propellant Capability and Loading

Special considerations are low temperature and vacuum environments while meeting performance targets. Including off-loading (not cast fully with propellent) options into the design was seen as advantageous considering firm requirements had not yet been established.

Case Material

Various metallics and composites were considered for case materials. These were graded in a weighted scale of significant properties Table 1. In this trade, metals surpassed other materials including composites with structural interfaces, cold temperatures, Technical Readiness Level (TRL) being the significant difference. The overall reliability of metals was also considered superior. Of these metal options, Titanium was selected. Several commercially available space motors of similar size also use titanium cases.

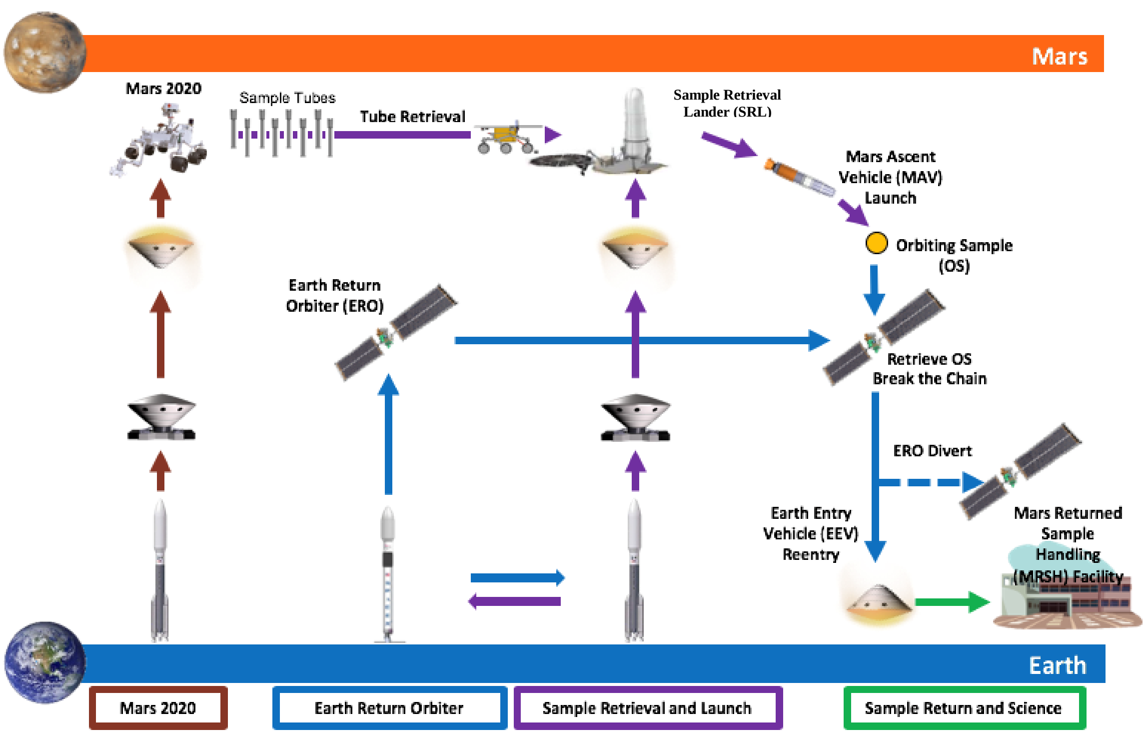

Figure 2 Mars Sample Return Campaign

Table 1 Case Material Trade

Figures of Merit	Weights	Composite	Titanium	Steel	Aluminum	DMLS / Printing	Printed Plastic
Strength / Mass	5	5	5	3	4	4	3
Storage Prop. Stress	3	5	4	3	3	5	5
Temp. Cycle Fracture	4	4	5	5	5	3	2
Mfg. Lead Time	1	3	4	4	4	5	5
Ease of Acquisition	1	4	5	5	5	2	3
TRL	4	4	5	5	5	3	2
Dev Costs	2	3	4	4	4	5	5
Production Costs	1	4	4	4	4	5	5
Cold Environment Data	5	4	5	5	5	2	2
Interface with TVC, etc.	4	2	5	5	5	5	5
Interface with Stages	4	3	5	5	5	5	5
	34	129	163	150	155	131	119

Guided versus Unguided Second Stage

Previous work noted an advantage to an un-guided system. The baseline architecture includes a guided second stage with thrust vector control (TVC). An open trade is considering a spin-stabilized unguided second stage. This would reduce overall Gross Lift Off Mass (GLOM) by eliminating upper stage TVC and moving the bulk of the avionics and reaction control system (RCS) to the first stage. However, it would lead to decreased orbital accuracy. The trade must include assessing the capability of the ERO to accommodate a less accurate orbit.

Cost of Tailoring

Requirements are typically not set during development; therefore, a concept must remain flexible to encompass possibilities. This often results in a cost-performance trade. A qualitative measure of design change cost was coalesced using industry coating methodologies. The independent variables considered included: changes to the case length, expansion ratio, and propellant loading and is given in Table 2

Observations from this study were that adding propellant mass had a higher cost than off-loading. This suggests that the solid concept should encompass the maximum range of possible requirements for propellant loading to minimize the program cost of change.

3. Mission Assumptions

Currently the missions design is in architecture space meaning things are in flux and balances on-going between systems in capability, schedule and recourses. As a result, firm requirements cannot be established. In lieu of

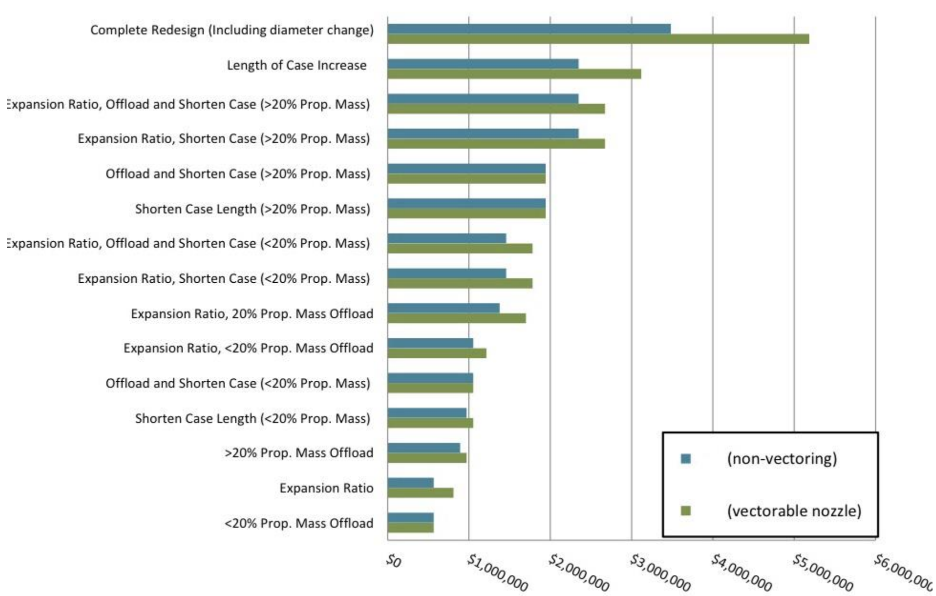

Table 2 Solid Design Modification Cost

requirements assumptions have been made[4]. These are listed in Table 3.

Table 3 Key Design Assumptions

Assumption	Value
Maximum GLOM (kg)	400.0
Maximum Vehicle Length (m)	3.0
Vehicle Diameter (m)	0.57
Payload Length Length (m)	0.5
Altitude (m)	343,000.0
Maximum Angle of Attack (degrees)	4.0
Launch PBMT (□C)	-20 (+/-2)
Storage Temperature Min/Max (□C)	-70/40

Mass, length and diameter assumptions are driven by the lander. Length must be shared with the MAV Payload Assembly (MPA) which is the payload and contains the OS.

Lander decent capability is highly developed and azimuth can be controlled to approximately half a degree. The landing site for Mars 202 is being selected through a series of workshops which engage the scientific community. Three potential option still exist, so conservative launch altitudes were chosen. The assumed orbital altitude insures the OS will be injected into a stable orbit with which the ERO is capable of rendezvousing (>30 km).

Still, orbital requirements are in flux. Altitude is assumed but the eccentricity assumption will likely be a solution of the motor design, or vice versa. It is expected that some assumptions, such as eccentricity, will be optimized and these results negotiated with other systems, such as the ERO in this case, to be addressed in its design.

The MAV will experience thermal environments at the Cape (40 °C) and minimums of the diurnals cycles of Mars (-70 °C). The MAV will be located in a thermal enclosure, possibly mylar sheets, that will allow thermal conditioning prior to launch. To reduce performance dispersions operational temperatures are 20 °C within plus or minus 2 °C.

Maximum shock load events are parachute snatch during EDL (15g) and OS impact on earth (10,000g). Acceleration limits for the MAV are likely a derived solution based on structures versus mass.

Final velocity is a solution for that altitude orbit. Guidance Navigation and Control (GNC) determined the delta-v split between the stages

4. DESIGN METHODOLOGY

Cost and schedule are drivers. Therefore, a Commercial Off-The-Shelf (COTS) solution would be advantageous. However, a COTS solution is unlikely match the requirements enough for the mission planned, so would require modification. With this in mind, two design solutions are being investigated: a modified COTS solution, and an optimized solution to meet the Gross Lift-Off Mass (GLOM) limit of 400 kg. It is possible available COTS systems and I_{sp} values are not sufficient to meet the mass goals. In that case optimum trajectories will be designed and the GLOM stated for consideration.

At this early point in the project, with only the Table 3 assumptions as constraints, all other variables are considered open. The modified COTS philosophy above suggests reasonable jumping-off points for some parameters. One known driver is the extreme low temperature required (-70 °C), which is outside the normal operating range for in-space motors. Therefore, careful consideration will be given to propellant selection.

Motors for each stage and solution will be sized using trajectory analysis provided by GNC. GNC will provide thrust shape and propellent mass required for the desired delta-v for each stage. The motor grain, case and nozzle will then be selected.

A grain shape and nozzle will be designed to meet the GNC recommendations and modeled. This will be fed back to GNC for trajectory and to analysis to close the design loop.

Thermal and structural analysis of the propellant grain, case and nozzle will be performed after initial sizing is complete. This is planned to be iterated with resulting design modifications until the system closes analytically. To increase the likelihood of adequate initial design choices, correlations were developed from both existing motors surveyed and physics principles to make initial estimates. This is expected to ease the transition from mass estimating relationships to designed part masses and reduce the number of iterations required.

Finally, a qualification effort will be examined. In this program considerations such as cost, schedule and risk will be balanced with program objectives. The number of ground and flight tests will be discussed as will the risk associated with changes to these numbers.

5. OPTIMUM STAGE 1 AND 2 DESIGN

Initial Sizing

The preliminary trajectory for the two-stage solid MAV concept is like two nearly impulsive (instantaneous) burns separated by a long coast (Figure 4). The first stage puts the vehicle into a highly elliptical orbit with an apoapsis at the desired altitude of the circular orbit, but with a negative periapsis. Once the vehicle has coasted up to nearly apogee, the second stage fires to circularize the orbit.

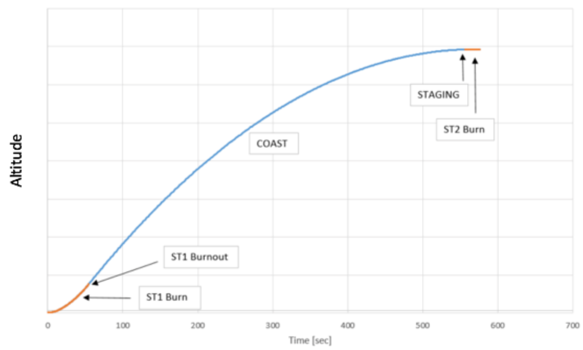

Figure 4 MAV Trajectory

Currently two key influences need to be examined, one for each stage. In first stage, the atmosphere, though much less dense than Earth's, becomes important. First stage trajectories are often a balance between high initial acceleration to overcome gravity losses and "throttling" back to limit maximum dynamic pressure (Max Q). The MAV ascent trajectory is no exception. Furthermore, the MAV must use the attitude control system (ACS) to maintain control after motor burnout. The dynamic pressure at motor burnout (Burnout Q) and its subsequent decay will drive the amount of ACS propellant required, especially if the vehicle is not near neutral aerodynamic stability. Therefore, while a typical motor of this size may burn for 20-30 seconds. Longer-burning motors are favored for the first stage in order to reduce burnout Q (Figure 5).

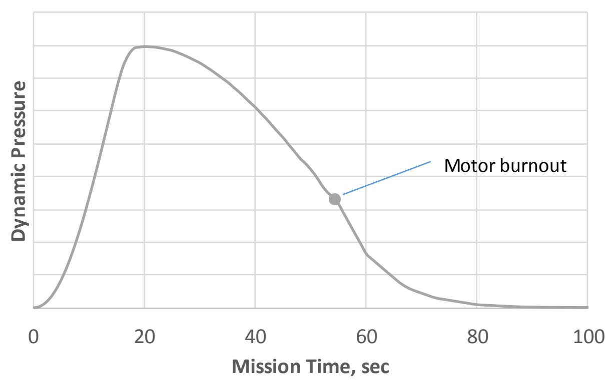

Figure 5 Example Dynamic Pressure

In the second stage the major concern is the extent to which variations compound to affect the final orbit. GNC and propulsion each performed trade studies and found that the impulse-conserving burn time variation due to solid rocket propellant burn rate variation caused very little variation in orbit. However, I_{sp} variation of the upper stage led to a variation of tens of km in apoapsis or periapsis variation. Further work, including guidance laws, will refine these estimates in future analysis cycles.

Propellent Mass Fraction Estimation

Non-dimensional relationships can provide both convenience and instruction[5]. One way to communicate the relationship between propellant and inert masses of a motor is the Propellant Mass Fraction (pmf) which is the ratio of propellant mass to total motor mass. This is distinct from stage inert mass, because it does not include auxiliary hardware such as ACS, avionics, separation systems, etc., whose masses are not related directly to motor size. Figure 6 shows this ratio for historic solid rocket motors[6] similar in size. Note that large motors approach a threshold pmf independent of propellant mass. This holds true despite data scatter due to material choices, technology levels, and other specifics of application. However, for motor masses smaller than a few hundred kilograms, the propellant mass fraction begins to drop off significantly. Any optimization should consider this behavior when varying propellant masses and estimating respective inert masses.

A convenient way to represent this is to define the inert fraction, f_i, as the ratio of inert mass to propellant mass. The shape of the data is well-fit by assuming inert mass as proportional to diameter and propellant mass, m_p. Approximating this yields the following equations.

$$f_i = f_{i_{min}} + C_{ref}\left(\frac{m_{p_{ref}}}{m_p}\right)^{\frac{2}{3}}$$

$$pmf = \frac{1}{1+f_i}$$

The intercept $f_{i_{min}}$ represents the minimum inert fraction, or the limit as propellant mass goes to infinity. The slope C_{ref} paired with a reference propellant mass $m_{p_{ref}}$ drives the location of the inflection. Depending on the trade space data can be selected to fit a broad range of options, or a relevant subset. Figure 6 shows curves that fit well with upper stage motors of similar size with a similar boost-sustain profile. The boost-sustain trend is necessarily lower because of the desired long burn time. The internal insulation masses are higher for this case due to the longer burn time and the required end-burning geometry.

This curve is updated for the MAV design to include necessary modifications to the motor and capture the development risk. For the upper stage, Thrust Vector Control (TVC) was accounted for separately in the stage parts list, but other factors need to be considered. For example integrating the motor with the interstage and payload adapter will likely increase volume more than required for the propellant load, so a 10% offload was assumed. A 25% Mass Growth Allowance (MGA) was included due to little design similarity to other systems. For the first stage motor, additional TVC mass was added for the increased size. Since the motor is expected to be an approximate scaled version of the referenced boost-sustain motor, only a 15% MGA was covered in this correlation. The results of these adjustments are shown in Figure 7.

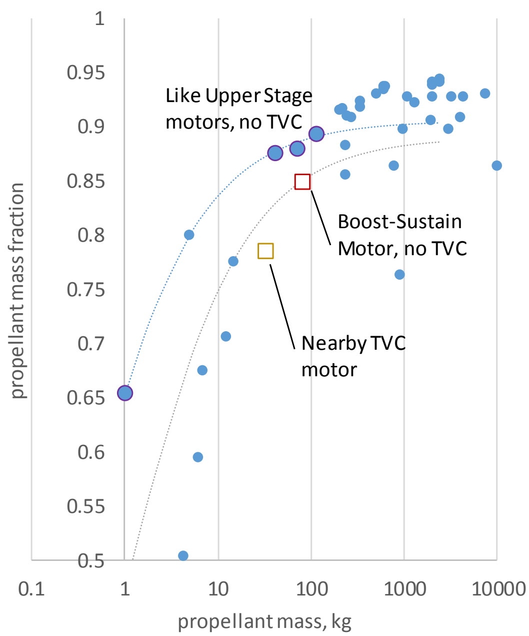

Figure 6 Solid Rocket Motors' Mass Scaling

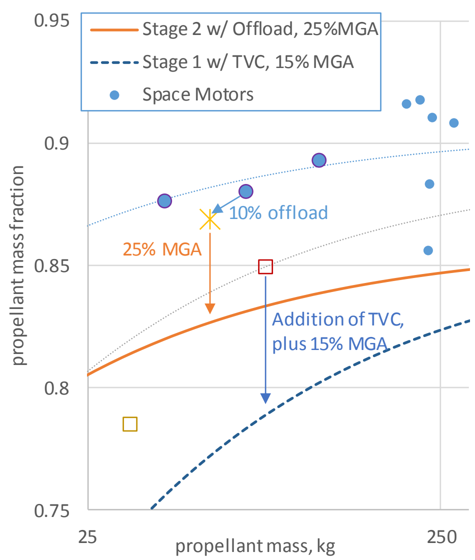

Figure 7 Mass Scaling Adjustments

Optimization Solutions

Initial sizing established a starting point and then an I_{sp} was assigned to each stage that reflected the range of current COTS products (points in Figure 9). From these a minimum GLOM was derived that met orbital assumptions. Propellent mass was allowed to vary which would eventually be converted to a case length. The resultant thrust profile is considered to be the modified COTS solution with a GLOM of 419 kg. (Figure 8) Although this is higher than the 400 kg assumption limit it is useful programmatically both for capability and comparison to other options. The GLOM was then limited to 400 kg with I_{sp} allowed to float up along the trend (line in Figure 9). This second set of thrust curves composes the optimum solution. (Figure 10) The I_{sp} and GLOM for these analyses are given in Table 4. Mass savings created with each design cycle could allow I_{sp} to be reduced for both cases.

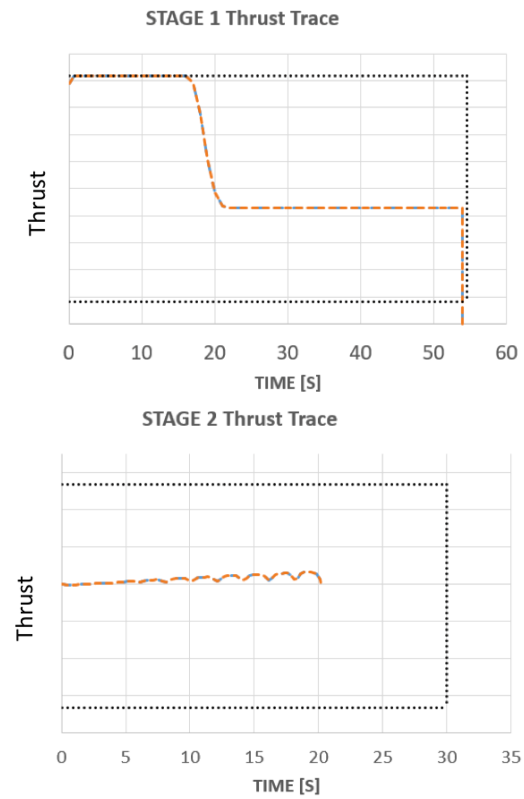

Figure 8 Modified COTS Solution Thrust

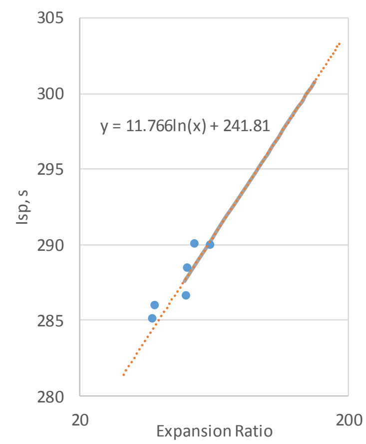

Figure 9 I_{sp} Data and Estimating Relationship

affect I_{sp} such a nozzle gimble type, and nozzle contour are beginning to be considered now.

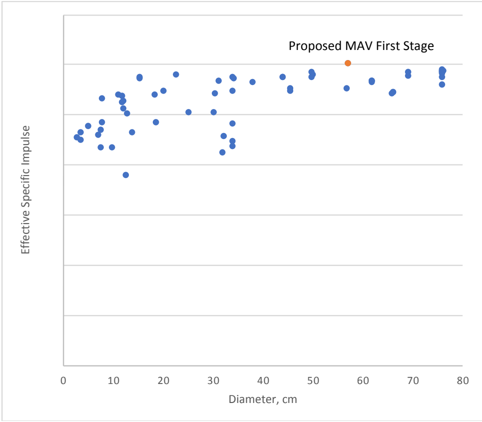

Figure 11 COTS I_{sp} vs. Diameter

The proposed solutions appear optimal from a trajectory standpoint accounting for steering losses. Other dispersions such as motor performance and atmospheric conditions are not accounted for. These would require additional impulse to negotiate. To meet mission objectives with reasonable design risk, levels one of the following four options need to be accomplished.

- Reduce Inert mass
  - non-propulsion mass (payload, avionics, etc.)
  - Increase mass fraction
- Increased I_{sp}
- Reduce altitude
- Increase GLOM

The next steps in the solid MAV design will be to complete detailed designs of the propellant, liner, case and nozzle geometry, conduct nozzle I_{sp} analysis, and trade the mass and I_{sp} due to nozzle expansion ratio and length. The optimization will then be updated.

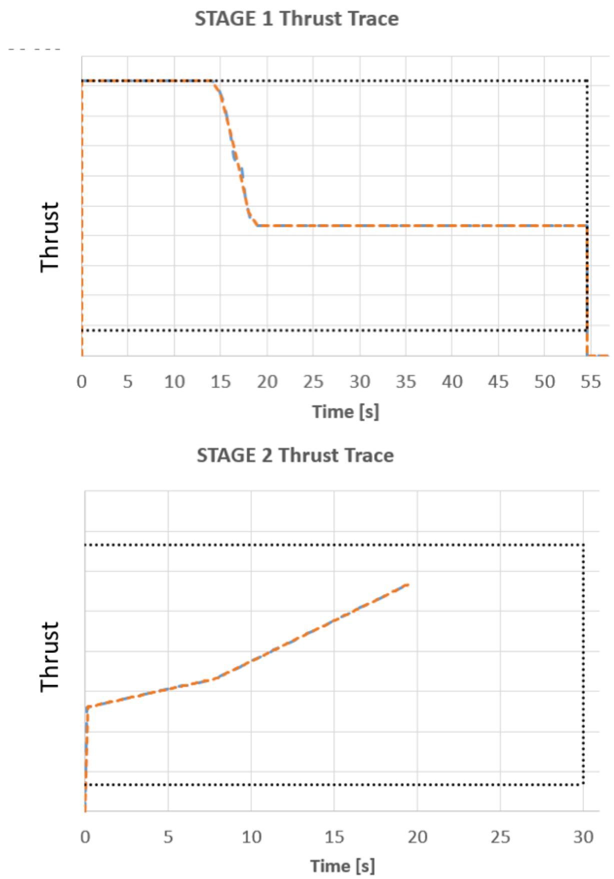

Figure 10 Optimum Solution Thrust

Table 4 GNC Solutions

Parameter	Isp, sec		GLOM, kg
Stage	1	2	
Modified COTS	288	291	419
Optimum	300	293	399

The optimum configuration requires higher I_{sp} values than the modified COTS. These higher values are challenging increase risk in the design effort. A survey of similar sized motors, shown in Figure 11, show the target I_{sp} values for the optimum (400 kg) solution are higher than that is currently available. It is possible to achieve some increase in performance with a larger nozzle expansion. However, mass vs. length trades have not been completed. Other factors that

6. Propellent Mission Capability

A solid MAV needs to be a two-stage rocket. Based on mission requirements, each stage may incorporate different propellant compositions as well as attendant insulation and liner systems.

Temperature exposure capability, specific impulse (I_{sp}), vacuum stability, and planetary protection methodologies will be important factors in propellant selection that will be derived through a trade study.

Thermal Environments

The motor(s) will be subjected to the cold of space and then the variable thermal conditions of Mars's surface for a significant fraction of its solar year. During that time, the motor will experience temperature diurnals and resulting thermal cycling with each Sol (Martian day). The mission is currently looking at a non-operational temperature range spanning from -70 °C to +40 °C. During actual motor operation, Propellant Mean Bulk Temperature (PMBT) will be raised to a level bracketing from -22 °C to -18 °C. Such temperature extremes will require propellant(s) with good low temperature mechanical properties and grain geometries designed to minimize and accommodate stresses and strains resulting from thermal cycling and motor operation.

Density-Impulse

Due to mass constraints on the lander, the MAV has a challenging GLOM. Achieving desired altitude during flight to orbit will require attainment of sufficient energy by maximizing the density-impulse, which is the product of the propellant's density and its vacuum specific impulse (I_{vac}). Propellant candidates presently being considered are based on either Carboxyl-Terminated Polybutadiene (CTPB) or Hydroxyl-Terminated (HTPB) binder systems with aluminum powder fuel and Ammonium Perchlorate (AP) oxidizer as their solids' constituents. Total solids currently range from 86% to 89%.

Off-Gassing

Propellent selection is driven by the requirement to minimize off-gassing in the vacuum of space, and on the Martian surface. Some plasticizers (e.g., Dioctyl Adipate (DOA)) off-gas, which result in propellent mass loss and affects propellant mechanical properties with subsequent consequences. Off-gassing can also obstruct instrumentation. CTPB-based propellants do not typically contain plasticizer though HTPB-based propellants can. Propellant systems currently under consideration are non-plasticized.

Planetary Protection

Planetary protection is both a stringent and a significant rconsideration[7]. Requirements are stringent to prevent contamination of Mars and the samples obtained from it, as well as insuring the planet's pristineness. Evidence of non-terrestrial life could be irretrievably lost if Earthly biological contamination inadvertently interacted with a Martian life form. This could also jeopardize future missions to evaluate the planet. Protection against biological contamination is therefore paramount.

While no selection has been made, there are three main planetary protection approaches under consideration[8]:

1) Bio-Reduction
2) Bio-Barrier
3) End-of-Mission procedures

Bio-Reduction—This method can consist of heat sterilization, use of biocides, or radiation exposure. Heat sterilization bears special mention and involves heating a motor to a specified temperature above 105 °C for a specified amount of time (not including ramp times up to and down from the targeted temperature). This method is designated Dry Heat Microbial Reduction (DHMR), and was used on both Viking Lander Capsules (VLC-1 and VLC-2) that launched in 1975 and landed on the surface of Mars. DHMR ages polymeric materials (e.g. propellant, liner, insulation) and can subsequently have detrimental effects on material properties[9,10]. Additionally, high temperature exposure can decrease AP particle size by crystal breakdown, resulting in an increased propellant burn rate. This occurs due to an increase in the bulk material's total surface area resulting in an increase in chamber pressure and therefore a change to the motor ballistic properties. Should DHMR be employed, it will be desired to stay below 135 °C to avoid chemical changes to the propellant's AP crystals.

Bio-Barriers—These barriers are meant to protect an already sterilized vehicle. While certain components of a solid rocket motor's propellant and liner subsystems (oxidizers, bonding agents, cure agents) or processing aids (solvents) used to manufacture them vary in levels of toxicity, they probably cannot be considered as biocides or sterilants. A number of materials (alcohols, phenolic compounds, aldehydes, peroxides) can serve as biocides, though their applicability is more suitable for surface treatments or hardware sterilization and will not have any effect on reducing the volumetric burden. Use of vacuum hydrogen peroxide exposure is an example of a surface treatment, though it should not be applied to propellant[11]. Certain other gaseous agents, however, may have applicability to solid rocket motor propellant. Incorporation of ethylene oxide into propellant during its manufacturing process, and then removal of the same under vacuum has previously been shown to not adversely affect either propellant mechanical or ballistic properties. Though personal protective equipment must be utilized by propellant operators due to ethylene oxide's toxicity, further work in this area may be warranted.

End-of-Mission Procedures—Mission events such as ensuring that a solid motor fires by use of redundant ignition systems could be used to ensure sterilization[12]. Motor operation in effect would be a self-sterilizing event for the Propellant-Liner-Insulation (PLI) system with a chamber temperature in the range of 5,000 °F (over half the surface temperature of the Sun).

Manufacturability

Finally, propellant and motor manufacturability are of special consideration for the program. Constraints will be placed on this by planetary protection as well as other mission requirements, with specific processes and procedures needing to be performed during various production phases. Addressing these concerns from a propellant standpoint will require suitable rheology (flow characteristics that affect propellant processing), end-of-mix viscosity, pot life, and working life (time to gel point). These parameters as well as others previously noted are being examined in current propellant trade studies.

7. NOZZLE AND CONTROLS

Nozzle

While COTS and modified COTS designs likely utilize existing nozzle designs the optimum solution will be more of a challenge. Early design suggests that required performance is in the 300 I_{sp} range, above typical motor designs in the same size class. This will require challenging design solutions. The use of refractory metals or carbon-carbon may be needed to result in a lower eroding throat. These require special consideration in configuration and would influence system reliability and cost.

Thrust Vector Control

Thrust Vector Control in the optimum solution must take in to account the atypical assumptions namely low temperature. Since operational temperature is -20 °C slag from an aluminized propellant could foul the workings of the TVC systems. Flex bearings and trapped ball concepts were considered.

TVC systems based on flex bearings are typically heavier than trapped ball-based systems. Elastomers used in these concepts have higher shear forces at low temperatures, which increases stiffness. While the elastomer will increase nozzle mass only a portion of the elastomer contributes to the moving inertia. Stiffness is the dominate factor increasing nozzle torques, which would require a heavier actuator system. Trapped ball systems are typically lighter and have lower torques than flex bearing systems, making them more attractive in terms of total (nozzle and actuator) mass. However, stiction, the frictional force to overcome at the beginning of motion, introduces a nonlinearity into the control scheme that can be significant with trapped-ball concepts.

For the MAV TVC two trapped ball concepts are being considered with different locations of the splitline, or where the moveable section and stationary section meet. The splitline is a sliding surface that must maintain a positive pressure seal across a high thermal gradient in a high vibration environment. The location of the splitline can be in the subsonic or supersonic region of a convergent-divergent nozzle, or it can be in the low-subsonic region of a submerged nozzle.

If lubricants are used, they must resist freezing and increasing nozzle torque to levels that drive actuator mass.

A low-subsonic splitline trapped ball introduces very little loss of nozzle performance since the entire nozzle can be made to move inside the chamber. However, aluminized propellants create slag that collects in the aft region of a solid motor; in the low-subsonic region of a submerged nozzle. This could potentially cause problems with nozzle actuation. Slag freezing on the initially very cold internal parts can effectively lock the nozzle in position.

On the other hand, locating the splitline in the supersonic region impacts nozzle performance that decrease the effective Isp due to the shock and expansion structures created within the divergent region. Additionally, aerodynamic side-loads within the nozzle will add to actuation torque in proportion to the thrust vector angle, similar to a spring force. Trajectory analysis suggests this will be minimal since the thrust vector angles are expected to remain less than 2 degrees. Another consideration is shock instability and the high frequency acoustic vibration that the supersonic splitline could create, but the likelihood and impact of this are both thought to be low.

While the supersonic splitline considerations do not exist for low-subsonic splitline concepts, there are advantages of the supersonic splitline design. One is the smaller moving mass reduces inertial loads. Another is the fact that the splitline, which can be angled aft, would be in a location with higher gas velocities across the exposed surfaces than a subsonic or low-subsonic design. This could avoid entrainment of alumina slag and fouling.

Currently a trapped ball supersonic splitline appears to be more attractive in terms of mass and reliability. Further trades will be made for mass and reliability with factors previously discussed.

Reaction Control System

RCS will correct roll of the MAV vehicle during the stage 1 powered flight (Figure 4) At first stage burn out the vehicle coasts. At this time RCS will control six degrees of freedom, stabilizing the vehicle until second stage initiation. RCS will control roll during stage 2 burn and may be used to perform vehicle separation or deorbit maneuverers that have yet to be defined.

Selection of an RCS system is trading between a cold gas blow down system and hydrazine monopropellant system. After completion of the solid motor design and the actual thrust traces will be fed back to GNC for conversion into a sequence of guidance commands. This information will be considered, along with dispersions for motor operation and trajectory to define the total impulse needed for RCS. This will likely be an iterative process. Trades for RCS type will include mass, thruster size requirements, and volume.

8. Qualification Effort

Due to the scale of the Mars Sample Return mission and the unique mission requirements it is important to ensure the MAV solid rocket motors, and all of the related systems, perform as expected. During the Mars Sample Return mission, the solid rocket motors are subjected to various harsh conditions. Testing will occur in mission like environments.

The MAV motors must survive the launch from earth, journey to Mars, Mars Entry, Descent, and Landing (EDL), several months on Mars, and finally ascent from Mars. Therefore, the motors will be put through various environmental conditions such as shock, vibrations, aging, and thermal cycling. In addition to the various environment conditions the motors must pass through planetary protection measures. Therefore, established planetary protection procedures must be implemented throughout the qualification process.

One of the most challenging aspects of the mission is the thermal cycling and temperature requirements. Although the temperatures on Mars changes daily and seasonally during the lander's dormancy, the vehicle will be heated to -20 ± 2 °C prior to launch. Therefore, it will be important to qualify the motor at this operation temperature. Key challenges moving forward will be the selection and characterization of the propellant and motor materials to be used.

Elements of the motor will be tested and qualified individually as well as qualified with the motor as a system. Multiple static tests will be conducted and sub-system components will be tested in applicable environments.

A set number of qualification motors will be built and tested in a single lot. Risk is reduced as a greater number of motors are fired[13]. Table 5 shows the risk as a function of the number of sub-scale tests, full-scale motor tests, and flight tests. Restrictions to the number of motor tests are cost and schedule. Sub-scale testing can be utilized in lieu of a full-scale test in some cases to reduce risk with a lower cost. Some motor components are better suited for sub-scale testing than others.

In addition to static tests, a flight test program has also been proposed. The flight tests could consist of a balloon system to take the MAV test vehicle to an altitude, at which it can be tested under conditions that best replicate Mars lower atmospheric pressures. Flight tests will engage key operations of the flight system such as staging, RCS, TVC, and avionics. Flight tests sequence would move towards a more representative flight vehicle, increasing the intricacy of the vehicle with each flight.

The qualification flight tests will be important risk reducing tests, but come at a large impact to cost and schedule. Although the flight tests are meant to simulate mission conditions, there will still be numerous structures and systems that will be unique to the flight test operations. One of the first challenges moving forward will be to mature tasks and a schedule that incorporates all of the necessary risk reducing activities within the given time remaining before the 2026 launch. The qualification of the solid rocket motors will be a balance among development motor static tests, qualification motor static tests, and flight tests.

Initial estimates of a qualification length are approximately two years. Flight hardware will potentially be required in 2024 allowing 3 years of further development.

The lowest risk qualification includes a total of 12 full scale tests; 3 will be developmental motors, 3 static test qualification motors, and 5 flight test qualification motors.

9. Future Work

Design of a solid motor MAV in the current iteration has just begun. Further refinement and evolution are needed. A solution for a COTS design remains. The modified COTS, and optimum design thrust traces will be fed back to GNC for updated performance predictions to work towards minimizing GLOM.

All aspects of this effort as discussed in the previous sections will need to be completed. A short-term result will be a Master Equipment List (MEL) which will contain the mass of all components. This will be fed to the Vehicle

OPTION	SUB-SCALE TESTING			FULL-SCALE TESTING				LIKELIHOOD X CONSEQUENCE	FINAL RISK SCORE
	PLANETARY PROTECTION	THERMAL CYCLING	COLD-SOAK	PLANETARY PROTECTION	THERMAL CYCLING	COLD-SOAK	FLIGHT TEST OR FLIGHT-LIKE TEST		
1	X	X	X	3 DMs + 8 QMs	3 DMs + 8 QMs	3 DMs + 8 QMs	5 QMs	1X2	3
2	2X	2X	2X	3 DMs + 6 QMs	3 DMs + 6 QMs	3 DMs + 6 QMs	4 QMs	2X2	6
3	3X	3X	3X	3 DMs + 4 QMs	3 DMs + 4 QMs	3 DMs + 4 QMs	3 QMs	3X2	9
4	X	X	X	3 DMs + 4 QMs	3 DMs + 4 QMs	3 DMs + 4 QMs	3 QMs	3X2	9
5	2X	2X	2X	3 DMs + 3 QMs	3 DMs + 3 QMs	3 DMs + 3 QMs	2 QMs	2X3	11
6	3X	3X	3X	2 DMs + 2 QMs	2 DMs + 2 QMs	2 DMs + 2 QMs	1 QM	2X4	14

Table 5 Qualification Risk vs. Test Quantity

system all with performance parameters to update the current MAV vehicle design iteration.

10. Conclusions

Work has begun on design of a solid motor configuration concept for a potential MAV. Motors are being sized based on optimized trajectories and manufacturable designs. Two different solution methodologies are being considered: modified COTS, and optimum.

Many of the currently known mission boundaries are being investigated including environmental loads and planetary protection practices.

Initial work has suggested that current assumptions for GLOM are close to the theoretical limits allowed leaving little room for margin. Changes in inert mass, I_{sp}, GLOM, or orbit altitude appear warranted.

Current estimates for launch are 2026 with hardware delivery in 2024. Early estimations of qualification will require two years. Two design cycles of this solid motor system are planned to be completed by spring of 2019.

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13. BIOGRAPHY

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