Mars Ascent Vehicle – Payload?, Spacecraft?, Launch Vehicle? – A Systems Approach to MAV

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Abstract

Significant effort has been expended over the past few years in order to examine propulsion technologies for an eventual robotic Mars Ascent Vehicle (MAV). The recent emphasis on studies for an overall sample return campaign, and specifically the Sample Return Lander (SRL) includes the full slate of systems required to implement a MAV. Depending on your point of view, the MAV is a major SRL flight system payload, a Mars Surface Spacecraft, or a Launch Vehicle. We will examine the MAV from these three perspectives in order to tease out the key architectural trades required to be completed prior to the start of a project Phase A activity.

Keywords: (maximum 6 keywords)
Mars, Propulsion, Architecture, Vehicle

Nomenclature

None

Acronyms/Abbreviations

Computer Aided Design (CAD)
Composite Overwrap Pressure Vessel (COPV)
Carboxyl-terminated polybutadiene (CTPB)
Design Anaylsis Cycle (DAC)
Degrees of Freedom (DOF)
Electrical, Electronic and Electromechanical (EEE)
Earth Return Orbiter (ERO)
Entry, Descent and Landing (EDL)
Gross Lift Off Mass (GLOM)
Ground rules and assumptions (GRA)
Guidance, Navigation and Control (GN&C)
Inertial Measurement Unit (IMU)
Liquid Injection Thrust Vector Control (LITVC)
Main Engine Cut-off (MECO)
Mars Ascent Vehicle (MAV)
Mars Retrieval Lander
Mars Sample Return (MSR)
Master Equipment List (MEL)
Mixed Oxides of Nitrogen (MON)
Multilayer Insulation (MLI)
Platinum Resistance Thermometers (PRT)
Preliminary Architecture Assessment (PAA)
Reaction Control System (RCS)
Real-Time Executive for Multiprocessor Systems (RTEMS)
Orbiting Sample (OS)
Sample Return Lander (SRL)
Semi major Axis (SMA)
Spray On Foam Insulation (SOFI)
Specific Impulse (ISP)
Solid Rocket Motor (SRM)
Technology Readiness Level (TRL)
Thermal Control System (TCS)
Thermal Protection System (TPS)
Thrust Vector Control (LITVC)
Volts Direct Current (VDC)

1. Introduction

The Mars Ascent Vehicle (MAV) is one element of a potential Mars Sample Return (MSR) campaign, with the purpose of launching a sample from the surface of Mars to a designated orbit around the red planet, where it will be returned to Earth. The MSR campaign, along with the Mars 2020 mission, is designed to address several high-priority science goals for Mars exploration.

Mars 2020, set to launch in July of 2020, is a rover with a drill that can collect core samples of the most promising rocks and soils and set them aside in a sample tube “cache” on the surface of Mars. These sample tubes will stay on the surface until the Sample Return Lander (SRL) mission collects them for return.

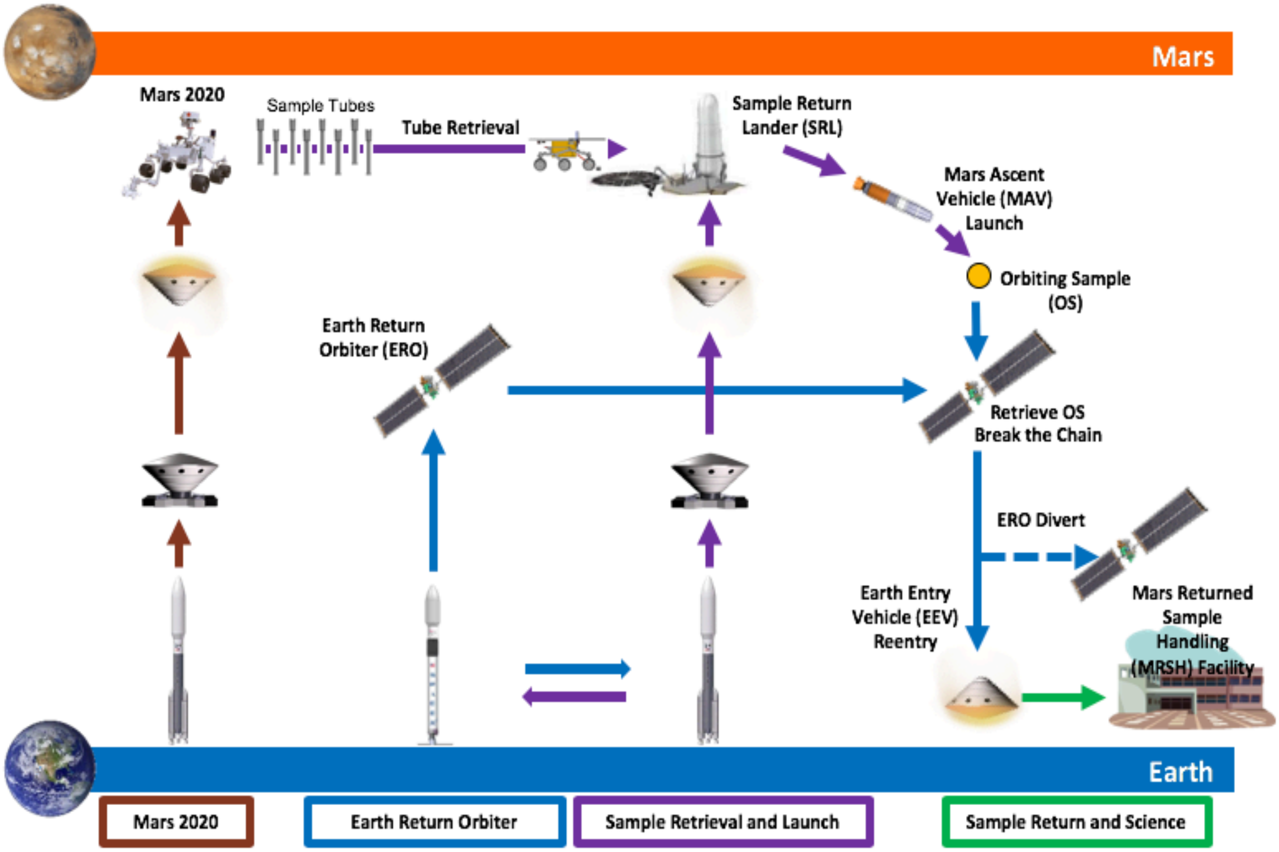


Fig. 1. MSR Mission Scenario

The second and third launches, potentially as early as 2026, would deliver the Sample Return Lander and the Earth Return Orbiter (ERO). These missions would use robotic systems and the MAV to collect and send samples of rocks, soil, and atmosphere to Earth for detailed chemistry and physical analysis.

To support the MSR formulation study, a Prelimary Architecture Study (PAA) was performed for MAV as a conceptual design activity meant to design, analyze, and compare multiple design configurations in parallel to meet a set of common engineering requirements. Potential design and programmatic issues have been identified. Specifically for MAV, there are two vehicle concepts: a solid propulsion system or a hybrid propulsion system. The goal of the study was to design a vehicle for each propulsion system to meet the SRL ground rules and assumptions, then assess if there were discriminators for each configuration.

The PAA study was kicked off on February 19, 2019. Several checkpoints were provided to JPL management along the way. The study officially ended with a peer review at MSFC on July 16, 2019. As the PAA only addresses technical conceptual design, analysis, and risks, the cost and schedule will be added for the MAV decision package. As the study progressed, however, it was determined that the two MAV vehicles would be analysed for different requirements due to the time limits of the study.

2. Mars Ascent Vehicle

The MAV mission objectives are to receive the sample tubes inside OS on the Mars surface, launch OS to a predefined Mars orbit, and release OS into Mars orbit.

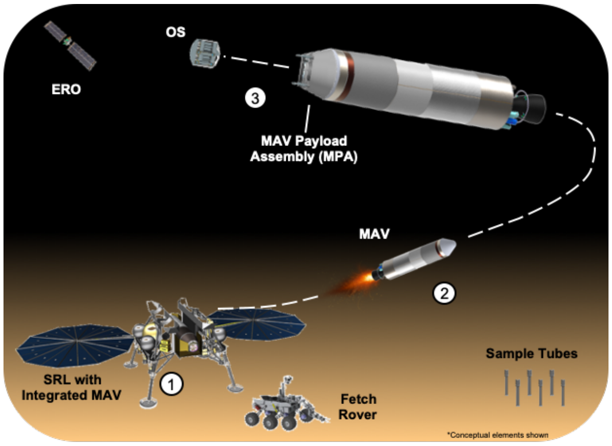


Fig. 2. MAV Objectives

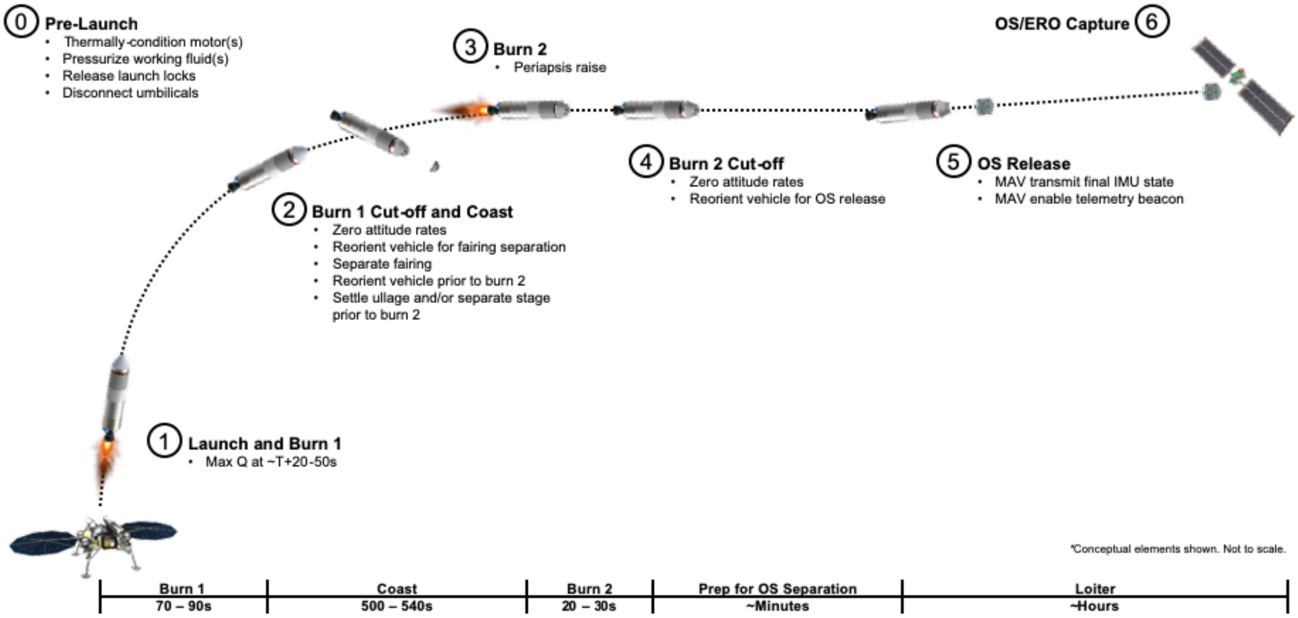


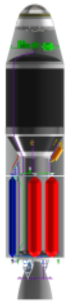
Fig. 3. Need caption.

The SRL will place the lander with MAV and a Fetch Rover in close proximity to the Mars 2020 sample cache. The MAV will be dormant and supported by SRL for several months during the sample retrieval activities. Once launch operations begin, the SRL will perform initialization of the MAV systems and conditions prior to launch of the MAV. The flight operations are a two stage burn with a long coast.

Packaging of the MAV, handling during preparations for Earth-launch, managing EDL conditions, managing Mars surface conditions, establishing the initial state of the MAV prior to Mars-launch, and supporting the MAV during ignition and launch are all major activities that can place driving requirements on the MAV itself.

2.1 Vehicle Architecture (Hybrid vs Solid)

The two MAV vehicle concepts to be studied are a single-stage hybrid motor vehicle and a two-stage solid motor vehicle.



Single-Stage Hybrid Motor Vehicle
- Storable, pressure-fed liquid oxidizer
- Solid fuel
- Liquid Injection Thrust Vector Control (LITVC)
- Cold-gas Roll Control System (RCS)
- Hypergolic ignition

Two-Stage Solid Motor Vehicle
- Solid motors for both stages
- Pyrotechnic stage separation
- Electrical-mechanical Thrust Vector Control (TVC)
- Monopropellant RCS
- Solid igniters

Fig. 4. MAV vehicle concepts

Each concept studied was designed iteratively with an initial design phase, 3-degrees-of-freedom analysis, a second design phase, 6-degrees-of-freedon analysis, and a final design phase. The output for each concept will include an integrated CAD model, master equipment list (MEL), and power profile. Driving requirements, estimated performance values for key subsystems, descriptions, and results of analyses for each subsystem and additional design documentation are other requests of the program.

In order for the MAV to be successful, this multi-faceted systems analysis must be incorporated into the SRL and MSR design analysis.

MSR imposed several ground rules and assumptions on MAV for the PAA. Mission ground rules and assumptions (GRA) assumes the earliest earth launch window is 2026 and return Mars samples in 2031. Mission Class is B Plus. The MAV will launch from the Jezero Crater site located at 18.85 degrees. The MAV driving requirements are the quality of the final orbit of OS, and volume and mass constraints to fit onto the Sample Retrieval Lander. The quality of the final orbit of OS is:

- Lower bound 300 km (hard value)
- Upper bound 375 km (soft value)
- Target orbit 343 x 343 km ± 25 deg inclination

The MAV volume and mass constraints are:

- Height 2.8 meters
- Diameter 0.57 meters
- Target gross lift-off mass 400 kg

2.1.1MAV-Solid Vehicle Architecture

2.1.1.1 Introduction to Solid Propulsion

The MAV-Solid architecture consists of two stages, with both stages based on the typical solid rocket propulsion design. A generic single-stage solid rocket propulsion design is illustrated below for reference.

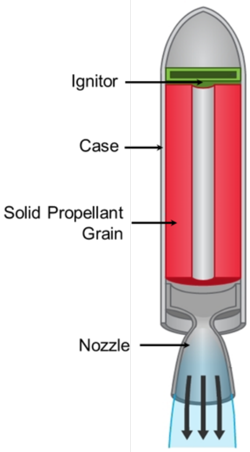


Fig. 5. Generic solid vehicle concept

The fuel and oxidizer propellant are premixed into a solid propellant that is stored inside the rocket motor pressure vessel. Upon ignition, the solid propellant is burned until it is exhausted. After the first stage is expended, it is separated from the rest of the vehicle, and the second stage motor is ignited to achieve its final orbit. The thrust direction of the expelled propellant—also known as the thrust vector—is actively controlled by a thrust vector control (TVC) system by gimbaling the nozzle.

The technical benefits of a solid rocket propulsion design are largely due to its simple nature and minimal to no moving parts required. Because this technogloy has been around for decades with proven flight records, it has a very high technology readiness level (TRL) and is readily available for real and direct applications. Challenges with this design option, however, include an inability to actively throttle or shut down the solid rocket motor once lit; although advanced—albeit lower TRL—technologies can make up for these shortcomings. Another drawback with the solid rocket motor design is the relatively low ISP compared to their liquid or hybrid counterparts.

2.1.1.2 MAV-Solid General Specifications

The general dimensions and major subsystems of the MAV-Solid architecture, as well as a list of the architecture's performance and design characteristics, are illustrated below:

Vehicle Performance:

- Gross lift-off mass: 394 kg
- 1st stage propellant mass: 216 kg
- 2nd stage propellant mass: 54 kg
- Payload (30 sample tubes): 16 kg
- Nominal orbit: 351 x 349 km

Propulsion:

- Motor grain (both stages): CTPB TP-H-3062
- 1st stage avg ISP: 293 s
- 1st stage burn time: 75.9 s
- 1st stage avg thrust: 9854 N
- 2nd stage avg ISP: 282 s
- 2nd stage burn time: 24.5 s
- 2nd stage avg thrust: 6937 N
- RCS propellant: hydrazine

Avionics:

- Voltage system: 24 VDC
- Total battery energy: 269 Wh
- Transmitters: 1x downlink

Materials: Mostly metallic, excepting the composite overwrap pressure vessel (COPV) first-stage motor pressure vessel.

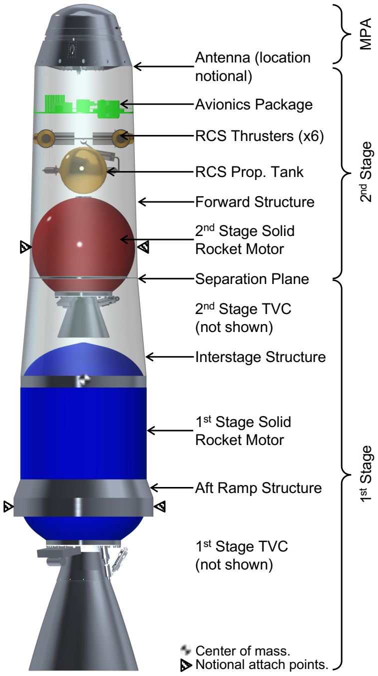


Fig. 6. MAV solid vehicle concept layour

2.1.1.3 MAV-Solid Thermal Design

The MAV-Solid incorporates high TRL thermal control system (TCS) components to maintain the vehicle temperatures during operational and non-operational/stowed stages of flight. The TCS employed includes active and passive thermal control technologies.

Active thermal control is used for maintaining the MAV temperatures above the minimum while on the Martian surface. Subsystems such as the reaction control system (RCS) hydrazine, solid rocket motor grains, and the avionics have minimum temperatures that must be maintained in order to preserve their functionality and quality. For the MAV-Solid architecture, 16 heater control zones were designed, each with their own active thermal systems. High TRL solutions studied for active TCS included polyimide heaters, line heaters, and platinum resistance thermometers (PRTs). Heater power would be provided by the SRL. For motor warm-up on the Martian surface prior to launch, it was estimated to take between 2 to 12 sols to warm the SRMs to flight temperatures, depending on the heater power used. Following are photos of select representatives of the different active thermal control technologies referenced.

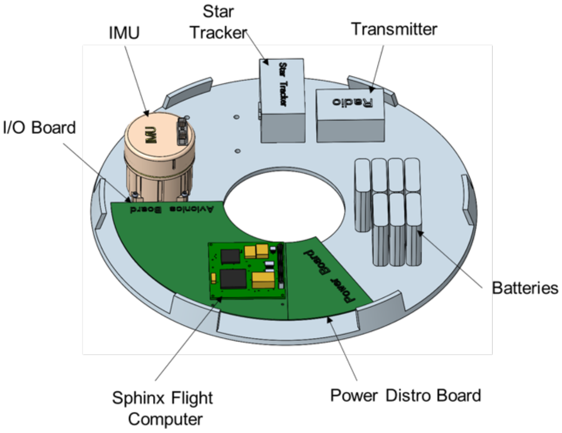

Line Heaters
Single Element Polyimide patch/strip Heaters
PRT Sensors

Fig. 7. Thermal control components

Passive thermal control is used for protecting the vehicle from high heat sources (e.g. radiant and conductive heat from the nozzle and nozzle plume during flight) and for retaining heat during non-operational phases of the mission. Multilayer insulation (MLI), possibly comprising high TRL aluminized Kapton, aluminized Mylar, Dacron netting, Nomex threads, and aluminized polyimide tape were studied. Traditional thermal protection system (TPS) technologies, including spray-on foam insulation (SOFI) and P50 cork, were also studied for use for the RCS hydrazine tank and lines, and insulating the MAV-Solid base area, respectively. Lastly, the MAV vehicle, while stowed in the SRL, will be surrounded by two layers of CO2, each layer being 5-cm thick. This is to reduce radiant and convective heat loss from the MAV to the interior of the SRL.

2.1.1.4 MAV- Solid Avionics Design

The objectives of the MAV-Solid avionics are to maintain communication with other vehicle elements of the mission, determine MAV positioning, and provide power to MAV subsystems that need it to function. Major avionics components include the flight computer, batteries, inertial measurement unit (IMU), transmitter, star tracker, beacon, cables/wires and wire harnesses, electrical boards, and the avionics shelf/plate on which the majority of the avionics hardware is mounted. Following is an illustration of the major avionics components and their notional arrangement on the MAV-Solid avionics plate.



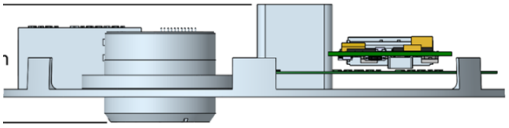


Fig. 8. MAV solid avionics layout concept

The Sphinx Flight Computer was notionally selected as the MAV-Solid's flight computer. Its pairing with the Core Flight System framework and the Real-Time Executive for Multiprocessor Systems (RTEMS) operating system was studied. The Honeywell HG5700 IMU, Blue Canyon Technologies Nano Star Tracker, ISIS TRXVU Transceiver, and SAFT 176065 battery and similar designs were also studied for use as part of the avionics package.

Due to the extremely short mission duration and mass constraints, EEE Parts qualifications will be subject to significant up-screening where grade 2 parts are not available.

2.1.1.5 MAV-Solid Propulsion Design

The MAV-Solid architecture consists of two stages, with each stage having its own solid rocket motor (SRM). They are illustrated below.

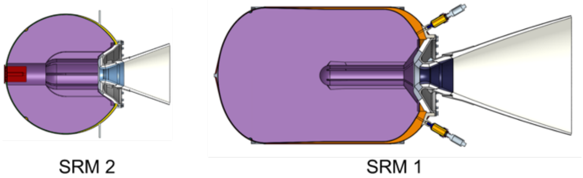


Fig. 9. MAV solid motors 1 and 2 concepts

Both motors use the same grain: CTPB TP-H-3062. The grain is a high TRL that is also used on previous Mars missions, including the Mars Exploration Rovers and Mars Pathfinder.

Both motors include separate, traditional electro-mechanical actuators similar to the ASAS 13-30V for thrust vector control up to 5 degrees from the exhaust centreline. The TVC system would be powered by thermal batteries, separate from the main avionics batteries. In order to facilitate nozzle gimballing, a supersonic splitline design was incorporated into the nozzle for both SRM 1 and 2. An illustration of this technology is shown below.

Fig. 10. MAV solid motor nozzle concept

For the MAV-Solid attitude and reaction control, the study assessed the use of both hydrazine-based and nitrogen cold gas-based systems. Ultimately, a hydrazine system was selected due to the high performance and lower propellant mass required. The MAV-Solid design incorporated two groups of three thrusters each, providing pitch, roll, and yaw command. The blowdown hydrazine tank includes a rolling metal diaphragm to contain and separate the hydrazine and the nitrogen pressurant. Below is an illustration of the notional MAV-Solid RCS design.

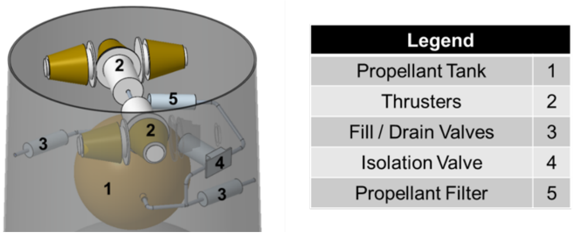


Fig. 11. MAV RCS layout concept

2.1.1.6 MAV-Solid Structures

The MAV-Solid architecture study included designing the vehicle's primary structures and notional specifications for a separation system. The primary structure includes the forward structure, interstage, and aft ramp, as illustrated below.

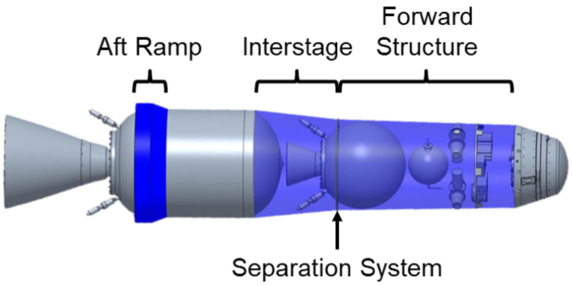


Fig. 12. MAV solid structures concept

The primary structure notionally has a monocoque construction and is flanged at the major interfaces. Strength and buckling analyses were completed assuming factors of safety yield of 1.25 and ultimate of 2.0. The loads assessment was primarly driven and enveloped by the –15 gs Mars entry, descent, and landing (EDL) environment case. A mass growth allowance of 19% and 17% was assigned to the first and second stage structures, respectively. All structural elements were assumed to be metallic.

2.1.1.7 MAV-Solid GN&C Flight Performance

Below illustrates the nominal MAV-Solid flight plan.

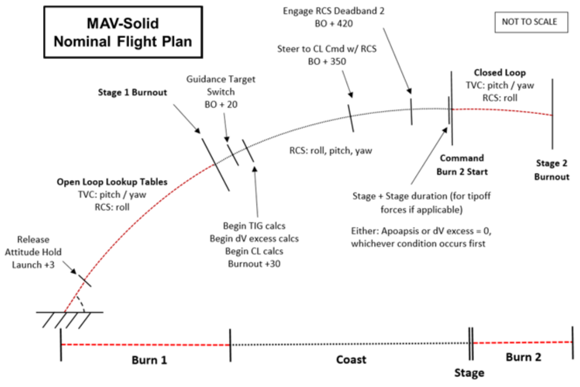


Fig. 13. MAV solid vehicle nominal flight plan

The nominal and select dispersed trajectory cases were run and analyzed. Nominally, the MAV-Hybrid's flight duration is roughly 546 seconds, including 446 seconds of coast. Because the MAV-Solid architecture used SRMs, the targeted orbits could not be optimized through the use of motor throttling or commanded cutoff. Thus, the MAV-Solid trajectory was designed so that it targeted above the ideal orbit altitude in order to maintain the minimum periapsis of 300 km, including when performance parameters like ISP, payload mass, launch angle, and azimuth were selectively dispersed. This meant exceeding the maximum-allowable apoapsis soft requirement of 375 km. However, other energy management techniques were used to achieve a more precise orbit, including "deoptimizing" the second stage flight to lower the apoapsis to compensate for dispersed cases involving an overperforming first stage flight.

Out of 44 manually-dispersed cases ran, only two failed to meet the apoapsis soft requirement. However, a number of cases failed to remain within the maximum semi-major axis (SMA) variability. Furthermore, a complete Monte Carlo analysis was not conducted for the study, which may reveal other requirement exceedances. Lastly, guidance and position knowledge error are highly dependent on the IMU solution chosen and may result in higher or lower target orbit accuracy and precision. Thus, further trajectory dispersion analysis work is recommended to verify that the MAV-Solid architecture solution can indeed meet all orbital requirements within an acceptable level of confidence.

2.1.2 MAV-Hybrid Vehicle Architecture

2.1.2.1 Introduction to Hybrid Propulsion

The MAV-Hybrid architecture consists of a single stage to orbit. A generic hybrid rocket propulsion design is illustrated below for reference.

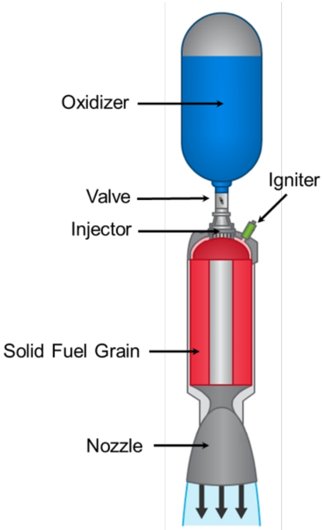


Fig. 14. Generic hybrid vehicle concept

For the MAV-Hybrid, the oxidizer is a liquid and the fuel is a solid grain. The oxidizer flow is controlled by a valve. During flight, the valve is open and the oxidizer flows into the combustion chamber located inside the solid fuel casing. Upon ignition, the solid fuel and flowing liquid oxidizer are combusted. When the vehicle completes its first burn, the propulsion power is stopped by closing the oxidizer valve, thus starving the combustion and extinguishing thrust. After a period of quiescent cruising and once apoapsis is reached, the motor is ignited again, the oxidizer valve is opened once more, and the solid fuel grain is burned to achieve thrust for the vehicle to attain its final orbit. In the MAV-Hybrid design, the thrust direction of the expelled propellant—also known as the thrust vector—is actively controlled by a liquid injection thrust vector control (LITVC) system by directly injecting oxidizer into the nozzle to redirect the flow of the plume and thus the reacting thrust vector onto the vehicle.

The technical benefits of a hybrid rocket propulsion design are largely due to its ability to throttle and cut off combustion and thrust. Furthermore, assembling the vehicle and ground operations can occur wthout exposing personnel to hazardous materials or risk proximity to explosive material until just before encapsulation. Lastly, hybrids afford higher ISP performance than solid rocket propulsion. However, hybrid propulsion systems require additional complexity and more moving parts. Their TRL is also lower than solids due to their inherently complex combustion characteristics, starts and restarts, less-than-common proliferation in industry, and other design and operational challenges.

2.1.2.2 MAV-Hybrid General Specifications

The following diagram illustrates the general dimensions and major subsystems of the MAV-Hybrid architecture, as well as a list of the architecture's performance and design characteristics:

Vehicle Performance:

- Gross lift-off mass: 396 kg
- Usable propellant mass: 288 kg
- Payload (20 sample tubes): 14 kg
- Nominal orbit: 352 x 352 km

Propulsion:

- Hybrid motor grain: SP7A
- Liquid oxidizer: MON-25
- Avg ISP: 310 s
- 1st burn time: 93.3 s
- 2nd burn time: 27.9 s
- Avg thrust: 7229 N
- RCS propellant: cold gas helium

Avionics:

- Voltage system: 24 VDC
- Total battery energy: 323 Wh
- Transmitters: 1x downlink

Materials: Primary structure composite excepting aluminium aft deck, and COPV tanks and motor case.

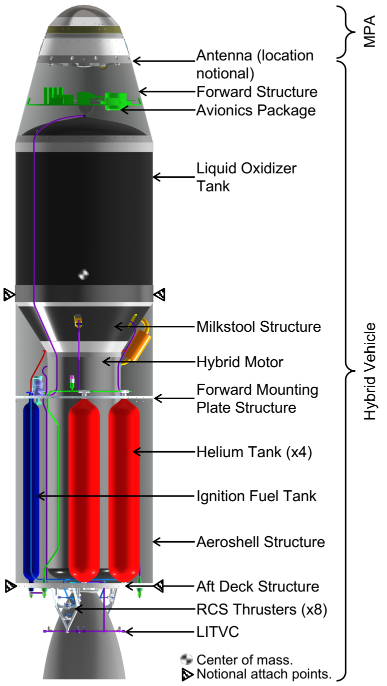


Fig. 15. MAV hybrid vehicle concept layout

2.1.2.3 MAV-Hybrid Thermal Design

Much of the same notional components and designs selected for analysis in the MAV-Solid thermal case were also applied for the MAV-Hybrid architecture, and the reader is directed to the respective MAV-Solid thermal section for additional details. The exception in similarity is an additional heat control zone, bringing the total to seventeen for the MAV-Hybrid design. For motor warm-up on the Martian surface prior to launch, it was estimated to take between 2 to 8 sols, depending on the heater power used.

2.1.2.4 MAV-Hybrid Avionics Design

Like the thermal design, the design of the MAV-Hybrid avionics is also similar to the MAV-Solid. Unlike the MAV-Solid, however, the MAV-Hybrid avionics batteries are also responsible for providing power to the vehicle's LITVC system. Following is an illustration of the major avionics components and their notional arrangement on the MAV-Hybrid avionics plate.

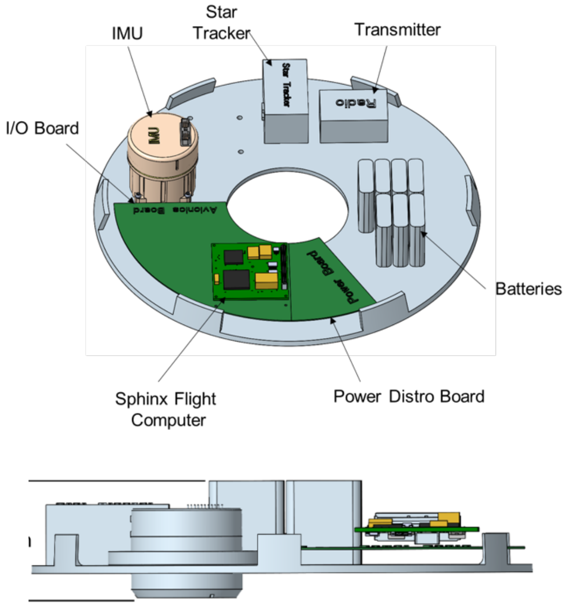


Fig. 16. MAV hybrid avionics layout concept

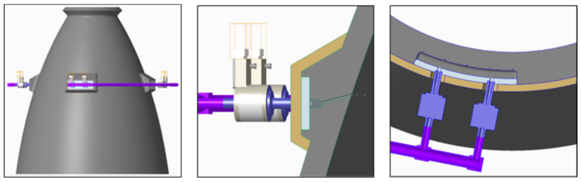
The Sphinx Flight Computer was also notionally selected as the MAV-Hybrid's flight computer. Just like the MAV-Solid, it's paired with the Core Flight System framework and the RTEMS operating system. The Honeywell HG5700 IMU, Blue Canyon Technologies Nano Star Tracker, ISIS TRXVU Transceiver, and SAFT 176065 battery and similar designs were also studied for use as part of the avionics package.

2.1.2.5 MAV-Hybrid Propulsion Design

The MAV-Hybrid architecture consists of a single stage. The main hybrid propulsion elements include the pressurant gas, liquid oxidizer, main oxidizer valve, solid fuel motor, LITVC, RCS, and nozzle.

Helium is used to pressurize the oxidizer tank. MON-25 is the oxidizer, and the hybrid motor grain is SP7A.

Thrust vector control is achieved through the use of a liquid injection TVC system. This works by injecting oxidizer directly into the flow field of the combustion products in the nozzle, causing a boundary layer separation and asymmetrical thrust vector. The design study included eight total LITVC valves controlling four liquid injection ports. The use of an LITVC solution was selected due to the high degree of mass savings compared to the traditional electro-mechanical TVC system, with the tradeoff being a lower TRL and more complex system. This notional design offers an effective/equivalent gimbal angle of 2.2 degrees from the exhaust centreline. The LITVC does not have its own independent power supply and would instead be powered by the MAV main batteries. An illustration of the LITVC valves and port installed on the nozzle is shown below.


LITVC Valves Supplied MON-25 Through Common Manifold

Preliminary Design Of Dual Valve LITVC Port

LITVC Flow Path Through Downstream Manifold

Fig. 17. MAV hybrid nozzle concept

For the MAV-Hybrid attitude and reaction control, the study assessed the use of helium cold gas-based systems. The helium is tapped off of the same supply as the oxidizer pressurant supply. The MAV-Hybrid design incorporated two groups of three 6 N thrusters each, providing pitch, roll, and yaw command. Two additional thrusters—each with 0.5 N of thrust—provide ullage settling acceleration for reignition of the motor for the second burn. The RCS design is illustrated below.

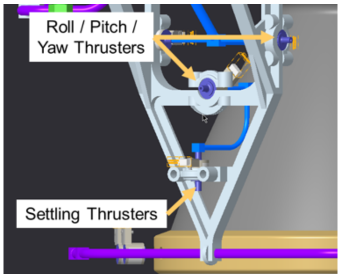


Fig. 18. MAV bybrid TVC concept

2.1.2.6 MAV-Hybrid Structures

The MAV-Hybrid architecture study included designing the vehicle's primary structures. The primary structures include the forward structure, milkstool, and aeroshell, as illustrated in the following figure.

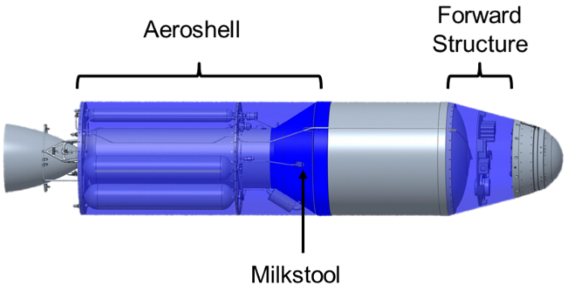


Fig. 19. MAV hybrid structures concept

The primary structure notionally has a monocoque construction with no stiffening elements. Like the MAV-Solid, strength and buckling analyses were completed assuming factors of safety yield of 1.25 and ultimate of 2.0. The MAV-Hybrid loads assessment were also primarily driven and enveloped by the –15 gs Mars EDL environment case. A mass growth allowance of 15% was assigned to vehicle structures. The forward structure and aeroshell were assumed to be composite, and the milkstool structure was assumed to be composite honeycomb.

2.1.2.7 MAV-Hybrid GN&C Flight Performance

Below illustrates the nominal MAV-Hybrid flight plan.

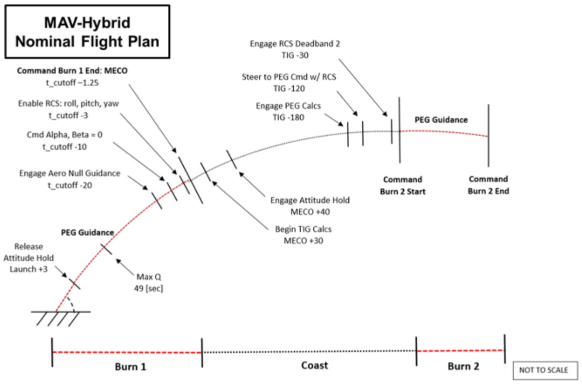


Fig. 20. MAV hybrid nominal flight plan

The nominal and select dispersed trajectory cases were run and analyzed. Nominally, the MAV-Hybrid's flight duration is roughly 658 seconds, including 537 seconds of coast. In all cases, the MAV-Hybrid achieved a desired orbit within the minimum and maximum periapsis and apoapsis, respectively, as well as within the maximum allowable eccentricity; however, like the MAV-Solid, several cases showed the MAV-Hybrid exceeded the max semi-major axis variability. Furthermore, due to an initially forward-dominant CM, the analysis showed some limited instability during the first burn flight. The RCS compensated for the instability with excessive RCS use, but the given cases run did not necessarily bound the maximum possible RCS consumption and would need to be studied further.

Out of 40 manually-dispersed cases ran, thirteen cases showed some level of instability after main engine cutoff. Like the MAV-Solid, a complete Monte Carlo analysis was not conducted for the study, which may reveal other requirement exceedances. Lastly, guidance and position knowledge error are highly dependent on the IMU solution chosen and may result in higher or lower target orbit accuracy and precision. Thus, further trajectory dispersion analysis work is recommended to verify that the MAV-Hybrid architecture solution can indeed meet all orbital requirements within an acceptable level of confidence.

2.1.3 Architecture Comparisons

Performance: The PAA analysis showed the solid vehicle successfully delivers a 16-kg/30-sample tube payload to orbit. While the hybrid vehicle successfully delivers a 14-kg/20-sample tube payload to orbit.

Physical size: Both vehicles meet the length and diameter requirements, although the hybrid vehicle is 10 cm longer than the solid vehicle. The hybrid vehicle features are mostly uniform while the solid vehicle diameter tapers.

Mass: After the PAA analysis, each vehicle was updated with the latest mass estimates and mass growth allowance percentage. The predicted solid vehicle mass is below the 400-kg limit while the predicted hybrid vehicle mass is slightly above the 400-kg limit.

Power: Power for both vehicles was assessed during the PAA. There is minimal difference regarding the two systems; i.e. 16.46 W-Hrs for the Hybrid and 23.34 W-Hrs for the Solid. The reason for this difference is the solid vehicle uses a hydrazine reaction control system (RCS) after first burn during the long coast; therefore, the RCS thruster heaters, thruster valves, and catalyst bed require power so the hydrazine does not freeze during these maneuvers. Hydrazine freezes at 2-degrees C.

Lander integration: There are no significant differences between the two vehicles with respect to SRL integration; however, the solid vehicle has more lander attach points available.

Inherent Reliability: The solid vehicle design has a higher inherent reliability because of the history of solid motors. The lower reliability of the hybrid design was driven primarily by the lower TRL of components involved and lack of heritage in the ignition schemes. Future testing and analysis cycles can raise hybrid TRL, resulting in higher inherent reliability. At this point in the MAV development, there was significant uncertainty introduced into the reliability analysis with the assumptions made. There is no clear discriminator in the reliability numbers of failure scenarios at this time.

Risk Comparison: Both vehicle designs have risks and challenges associated with the design, development, assembly, test, and mission. The solid and hybrid vehicles share common technical risks and challenges associated with mass growth, ground processing, long-term storage, external interfaces, and planetary protection. Risks only associated with the hybrid vehicle are primarily associated with the propulsion system's low maturity and the development efforts required to advance the technology. Although the solid vehicle does not require an extensive development effort, its risks include development of its nozzle and TVC, operational risks that involve handling of live propellant, and separation events introducing dynamics into the vehicle. Although both have considerable technical risks to resolve, programmatic risks tend to favor the solid vehicle due to the extensive development required to mature the hybrid vehicle design.

4. Conclusions

The goal of the PAA study was to design a vehicle for each propulsion system to meet the SRL ground rules and assumptions, and to assess if there were discriminators for each configuration. From the assessement, each vehicle is capable of delivering the vehicle specific payload mass to orbit within the size and weight constraints.

The hybrid vehicle successfully delivers a 14-kg/20-sample tube payload to orbit. The initial 6DOF analysis showed size and weight constraints were met under nominal conditions. However, later analysis determined that an increase mass was necessary, but due to the time limitations of the study, was not factored into the 6DOF results. Even though trajectory closes for initial 6DOF, it may not necessarily close for updated mass and ISP. This will need to be assessed in the first Design Analysis Cycle (DAC). Target orbit was achieved in most dispersed cases; however, stability issues arise in some runs towards MECO. The hybrid engine is capable of shutdown in the event of excess propellant. Further studies will expand upon design and increase maturity if this vehicle is selected as the MAV baseline.

The solid vehicle successfully delivers a 16-kg/30-sample tube payload to orbit. The mission design constraints for size and weight were met under nominal conditions. The target orbit was achieved with most 6DOF dispersions. The “soft” limits were exceeded in some cases. Energy management maneuvers may be necessary under certain conditions. Further studies will expand upon design and increase maturity if this vehicle is selected as the MAV baseline.

The PAA analysis has greatly advanced the technical knowledge of the MAV vehicle options for technical and risk figures on merit. Development costs and schedule, along with analysis of recent test results, will be incorporated into decision packages and presented to the MSR community.

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References

None