Mars Ascent Vehicle (MAV) Concept - Launch System Development

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***Abstract*— A Mars Ascent Vehicle (MAV) would be one component of potential Mars Sample Return (MSR) and would have to launch from the surface of Mars into orbit about Mars with a soil sample. A MAV is a small lightweight rocket that must survive various environmental conditions, including powered ascent through the Martian atmosphere. A concept for the MAV system design includes a launch tube mounted on top of a mobile rover or a stationary lander. The launch tube must thermally insulate the MAV on the surface of Mars, and then guide the MAV during the initial portion of the launch. A mechanical erector system is also necessary for moving the MAV and launch tube from a stowed configuration to a launch configuration. The launch system would have to perform these tasks while also meeting many design constraints. This paper is a systems engineering perspective that will examine the current development of the launch system including design concepts, design trades, driving issues, and analyses performed. Design trades include different launch configurations that would prevent rover or lander tip-over, as well as re-contact between the MAV and the launch tube. Additional trades include options for guiding the MAV out of the launch tube, whether using launch rails or sabots, and finding a reliable but simple mechanical erector system. Analyses include investigating the impact of ignition overpressure based on launch configuration, launch loads and sensitivities to the launch system design, and Entry, Descent and Landing loads. The key considerations for these design trades are overall system mass, size, and reliability.**

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I. BACKGROUND

The scientific community has advocated for the return of samples from Mars for several decades. The 2011 planetary science "Decadal Survey" by the National Academy of Sciences emphasized the high priority for NASA of making significant progress on this task in the subsequent decade. A robotic Mars Sample Return (MSR) campaign would be a major milestone for the worldwide scientific community, giving scientists the ability to perform detailed chemical and physical analysis on Martian rocks and soil.

The potential MSR campaign could consist of the Mars 2020 rover mission, a Sample Return Orbiter (SRO) mission, and a Sample Retrieval and Launch (SRL) mission. The SRL mission would be composed of a mobile rover with a Mars Ascent Vehicle (MAV), or a lander and fetch rover with the MAV on the lander. A MAV is a rocket used to insert the Martian sample into orbit about Mars for orbiter rendezvous.

In the current concept, the MAV would be a two-stage or Single-Stage-To-Orbit (SSTO) rocket that must operate in the Martian environment during launch from the surface. A launch tube would most likely be used to transport and erect the MAV on top of a mobile rover or lander. This mission concept is unique because it would be the first time that a rocket has been launched from the surface of Mars.

This paper presents a conceptual design of the launch system that resulted from recent development work. This

design in no way reflects an actual or future mission design. The goal of this effort was to develop a legitimate design for a launch system for this mission that covers the design and analysis of all necessary components.

II. Major Assumptions

1) MAV Characteristics

For this study, the MAV was an SSTO hybrid engine rocket. The MAV had a length of 2.8 meters and a major diameter of 50 cm, as shown in Figure 1. The MAV had a Gross-Lift-Off-Mass of 290 kg and a dry mass of 68 kg.

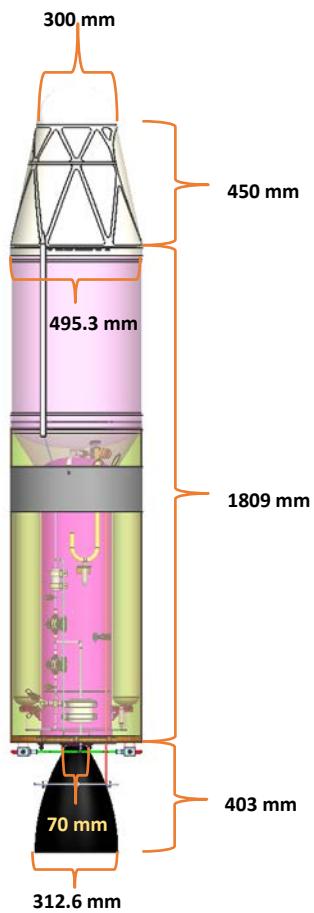

Figure 1. Current MAV Configuration with Dimensions

2) Host Characteristics

In this study, the rover or lander that the MAV launch system is connected to will be referred to as the "host." In this design development, there were not many assumptions made about the host. Instead, based on the launch system design, requirements were developed for the host to accommodate the launch system.

III. Environments

The MAV would be exposed to a variety of extreme environmental stresses throughout its mission duration. These include mechanical vibration, thermal stresses, and dynamic loads. There are several driving cases that define the design requirements for the MAV and launch system.

1) Earth Launch

The Earth launch would be the bounding random vibration environment for the MAV. This vibration environment will be determined by analysis and by using the mass acceleration curve of the launch vehicle. This will determine the structural requirements for the primary and secondary structures on the MAV and launch system.

2) Mars EDL

Mars Entry, Descent, and Landing (EDL) is a process of managed energy dissipation. The central challenge is to remove the kinetic energy of planetary arrival and prepare for a managed impact with the surface. During this development it was assumed that the MAV will have a similar EDL architecture to that of the Mars Science Laboratory (MSL).

The MSL EDL sequence of events was composed of various segments: Final Approach, EDL start, Exo-Atmospheric, Entry, Parachute Descent, Powered Descent, Skycrane, and Flyaway. From these events the driving load cases were obtained for the MAV and launch system.

The highest axial acceleration occurred during the Entry phase and was 15 G's. The "axial direction" is parallel and opposite of the velocity vector during Entry. In order to produce a conservative analysis, this 15 G acceleration will be assumed to occur in all directions.

These environments will affect the MAV and launch system primary structure design.

3) Mars Surface Ops

After EDL, the MAV would experience two Earth years of Mars surface operations. Although no mechanical loads are expected during this time, the MAV would experience extreme temperatures, ranging from -115°C at night to 50°C during the day. The MAV would be required to keep its avionics and propulsion components within required temperature ranges. This requirement falls on the launch system. Also, the launch system must be designed such that thermal expansion of any components due to the temperature swings during any phase of the mission do not create excessive stresses in the structure of the MAV.

4) Mars Launch

The last stage in the MAV mission cycle would be the Mars launch. Since this paper focuses on launch system development,

it is only the beginning of the launch process that will be of concern.

The major stresses on the MAV during this phase would come from the friction between the MAV and the launch tube before exiting the launch tube (from either sabots or guide rails), back-pressure from the engine exhaust, and any thermal stresses from the reflection of the engine exhaust off of the ground.

Other potential issues for this part of the mission would be host tip-over or MAV re-contact. Host tip-over refers to the host moving during the launch, and leads to unexpected stresses on the MAV. MAV re-contact refers to the possibility of unexpected contact of the aft end, or nozzle, of the MAV with the launch tube prior to exiting the tube.

These are complicated environments that require high fidelity analysis in order to characterize the design.

IV. DESIGN

A. Launch Methods

While the concept of launching a rocket from a mobile platform is a rare mission objective in the space community this is very common in the defense industry. For this reason, research was performed with respect to launch tube methods, platforms, and designs. When describing these systems, the word rocket will be interchangeable with the word missile. There are three main launch methods for mobile missile launch systems. These are open-backed, closed tube with venting, or cold launch.

Open-backed missile systems consist of a launch tube where the aft end is open so that the exhaust of the missile exits out of the back of the launch tube. With this method the launch tube does not have to withstand large pressures, and the vehicle or person holding the launch tube does not have to withstand a reaction force similar to the rocket thrust magnitude.

Closed launch tubes with venting can be designed in various ways but the most common design ducts the exhaust out of the front of the launch tube. An example of the Titan launcher is shown in Figure 2. This launch method is most common in aircraft carriers and silo launches. A drawback of this method is that the reaction force on the launch tube is two times the thrust magnitude of the rocket. Lateral venting is also possible, but challenging to design. There is more information available about open-backed launch tubes than closed tubes with venting.

Cold launch is when the rocket engine does not ignite until after it exits the launch tube. The rocket is ejected from the launch tube by a different method. Ejecting methods include using cold gas, hot gas, pneumatic launch, or others. For this method the launch tube tends to experience lower pressures than the other two methods. This method also protects the vehicle or user from the plume of the rocket at the beginning of launch. For these reasons this launch method is common in shoulder launched missile systems. This is also common for very large missiles such as the Russian S-400 and also for submarine missile launch systems.

One significant aspect of this study is that there was no requirement for host survivability, meaning there was no concern for the exhaust of the rocket damaging the host. Because of this, an open-backed launch tube was chosen. This method takes away many unpredictable dynamics that come into play for the other two methods.

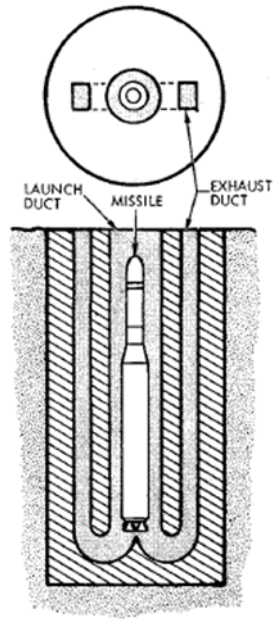

Figure 2: Example Ducted Launch System

B. Research

The research presented in this paper started with a general literature search focused on understanding the loads and flow processes within different launch tubes. There was a significant amount of declassified research on open-backed launch tubes, though detailed analysis on ducted launch tubes were not available. Most research was focused on specific missile launching systems but there were some common practices that made it possible to study general processes with simple experiments.

The pressures caused by a stationary rocket inside a launch tube is equivalent to the pressures experienced during the actual launch [1]. Experimental data with cold gas flowing through the nozzle and launch tube geometry has been shown to present resulting flow models and pressures that correlate reasonably well with the actual launch behavior [2].

All of the rocket launch systems studied were underexpanded flows. This means that the ambient pressure is lower than the rocket nozzle exit pressure. Thus at the nozzle exit there would be a Prandtl-Meyer expansion fan. When this comes into contact with the launch tube wall an impingement shock occurs against that wall. The location of this first impingement shock is the point of maximum pressure inside that launch tube [3] [4].

Ref [5] shows two different flow behaviors for two different shock strengths in an open-backed launch tube. This model does not include an obturator ring. An obturator ring is an object that blocks the engine exhaust from going upstream through the annular gap between the rocket and launch tube. Parameters such as nozzle geometry and engine stagnation pressure decide the strength of that impingement shock. When the flow exits the nozzle, it carries some of that air in the annular gap and forms

a shear layer at the plume boundary. When that impingement shock is weak, a certain fraction of that air has enough momentum to pass through the impingement shock. The fraction of air that doesn't have the necessary momentum forms a separation "bubble" between the rocket and launch tube wall. This creates an ejector type flow [5]. If the impingement shock is strong enough, then a fraction of the flow does not have enough momentum to pass through the pressure gradient of the impingement shock. Instead the flow is turned upstream into the annular gap, known as blow-by flow. Blow-by flow can cause unbalanced forces on the rocket and should be avoided [5].

Certain dimensional parameters can be established for open-backed launch tubes in order to obtain desired flow characteristics and low pressures inside the launch tube, such as the launch tube length. [3].

The launch tube dimensional ratios can have an effect on the stability of the flow in the launch tube. Certain nozzle throat to launch tube exit area ratios, along with launch tube diameter to annular gap distance ratios, allow for stable flow conditions [6].

The launch tube diameter is inversely proportional to the pressures experienced inside the launch tube. Even small changes in launch tube diameter can significantly effect maximum pressures [5].

Lastly a grid was found to be useful in "spreading" the plume of the rocket in the launch tube. This is particularly implemented to lower the peak pressures on the petals that open at the back of some launch tubes [7].

C. Thermal Limitations

One major limitation with the launch tube is that the launch tube must also act as a thermal isolator for the MAV. Past design studies had chosen a thermal igloo that covered the MAV during operations prior to launch, then it was released when the MAV was erected. This meant that it did not have to withstand launch loads, but the MAV would have to be launched very quickly once erected.

By using a launch tube that also thermally insulates the MAV, the MAV would not have to undergo erecting and launch operations in an urgent manner. After a trade study it was decided to baseline a two-inch CO_2 gap between the MAV and the launch tube as insulation. This is the most lightweight and efficient method.

D. Guidance Trade Study

The MAV must maintain alignment within the launch tube during the initial phase of launch. Since the MAV design looks to minimize mass and complexity it would not be ideal to have the outer mold line of the MAV directly contact the inner edge of the launch tube, since this would lead to stronger and heavier skin on the MAV. Instead there are other common methods used, such as sabots or guide rails.

A sabot is a device that is used to aid a projectile in maintaining a precise position while being launched or fired from a barrel or launch tube. This is common in both missile systems and firearms.

Figure 3 and 4 show an initial concept for both the launch rails and the sabot method.

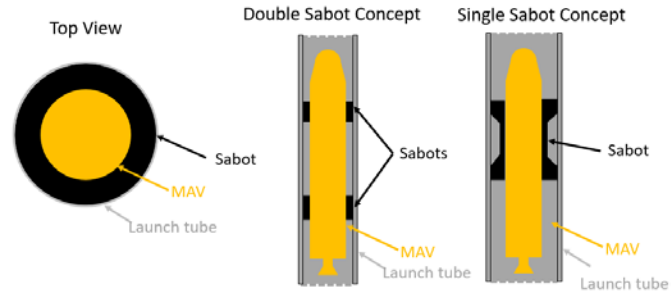

Figure 3: Sabot Concept

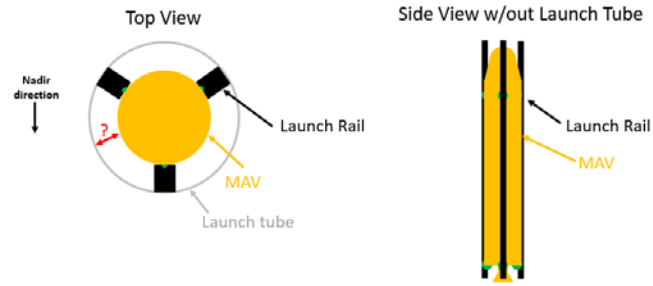

Figure 4: Launch Rail Concept

For the sabot concept, each sabot would be segmented and not attached to the MAV or launch tube. Because they would only be held in place by friction, once the MAV exited the tube these sabots would fall away.

One benefit of this sabot concept is that there is the possibility of very little modification to the MAV itself if they are friction fit to the MAV and launch tube. The increased surface area contact with the MAV is also a benefit, since this would distribute the load on the MAV during Mars EDL loads. Another benefit is that the sabot could act as an obturator ring.

There are a few drawbacks as well for the sabot concept. In this setup, there is a distinct thermal short between the MAV and launch tube, and thermal control is a major driver of the launch system. This concept would make it necessary for the entire launch tube to be designed for structural loading cases, such as EDL, whereas the launch rail concept could possibly have the launch rails take most loads and the rest would be very thin skin. Also, it would be much more difficult to control any coefficient of thermal expansion (CTE) differences between the launch tube, sabot, and MAV. This would lead to more stress between these components and would make it difficult to predict and test the initial guidance out of the rocket while on Earth.

For the guide rail concept, the rails always remain in the launch tube and do not move. There are mechanical components that attach to the MAV and simply slide through the rails. These mechanical attachments could be designed to fall away or eject from the MAV after it exits the launch tube.

For the guide rail concept, one major benefit is that the thermal design is decoupled from the initial guidance design. This leaves minimal thermal shorts from the launch tube to the MAV. This method is also more common for larger missile

systems and is easier to characterize, predict, and test. As mentioned previously, an advantage to this concept is the possibility of making the rest of the launch tube (skin connecting the rails) thin and non-structural, thus low-mass.

Downsides to the guide rail concept are that it leads to point loads on the MAV during Earth launch and Mars EDL, and there is no obturator ring to prevent blow-by-flow.

The initial trade study led to moving forward with the guide rail concept.

E. Guide Rail Design

Most of the guide rails used on Earth for missile and rocket launches are simple structures with minimal interaction with the vehicle. The MAV would use the guide rail not only for Mars launch, but also as its primary locking structure to keep the MAV attached to the launch system throughout the mission. Therefore, it was important to evaluate the guide rail not as a simple structure, but as a linear separation mechanism.

The MSL EDL design had a linear separation mechanism that was used to separate the descent stage (used for Powered Descent) from the backshell (used during Parachute Descent). The mechanism was needed to prevent the descent stage from re-contacting the backshell. The mechanism consisted of 3 structurally stiff rails equally spaced 120 degrees apart around the backshell, with 3 rollers in contact with those rails. This provided kinematic constraints in 5 degrees of freedom (all except for the translational degree of freedom aligned with the rails), minimizing risk of jamming. The symmetry made the analysis of the structure simple.

This mechanism was directly adapted to the MAV guide rail design, as shown in Figure 5. Three rails attached around the launch tube provide a minimal mass structure to support the MAV. It creates the kinematic separation environment much like the MSL backshell separation mechanism. The rollers are attached to the MAV, but will be radially ejected after exiting the launch tube using a separation spring so the rollers do not cause aerodynamic interference for the MAV during ascent. Additional rollers may be placed in multiple points along the MAV axially so that they can be used to provide structural support during Earth launch, EDL, and surface operations.

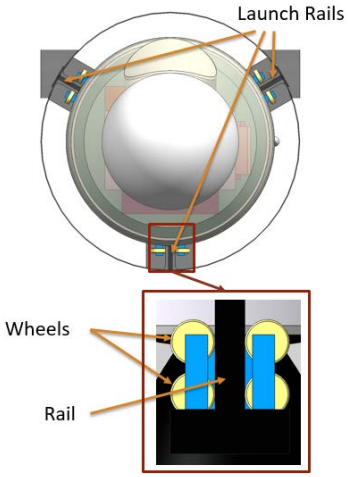

Figure 5: Rail Guide Design

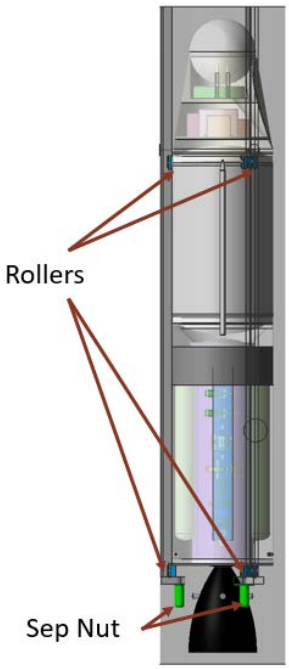

Figure 6: Launch Rail Hold-down Design

Finally, a separation mechanism (currently a separation nut) is used to hold the MAV in the final degree of freedom until being released prior to launch. Figure 6 shows the current configuration of the guide rail design.

F. Sample Insertion / White Room

The current plan for the sample insertion into the Orbiting Sample (OS), that is at the forward end of the MAV, is to use a canister to carry all of the sample tubes into the MAV. This means that only a single actuator event would be needed, instead of a repeating the insertion event multiple times. The reasoning for this was to minimize the possibility of mechanism failure, but also to minimize MAV exposure to the Martian environment.

Since the launch tube would also be a thermal barrier as well as an atmospheric barrier, it would be used to protect the MAV and the OS from the Martian environment, particularly thermal and contamination/dust. Sample insertion into the OS would necessarily breach this seal, and thus it is best to minimize the number and duration of these breaches in order to keep the MAV/OS from getting contaminated by Martian dust, and to minimize heat loss.

To conduct this canister insertion, a “white room” mechanism was proposed to satisfy the desired requirements. The “white room” is a mechanism consisting of linear actuator and rotational actuator. The “white room” would seal the mechanism and the canister insertion path from the Mars environment, only exposing the sample tube open side of the canister to the Martian environment. When all of the sample tubes have been loaded into the canister by the robotic arm, the “white room” would close a door around the exposed surface of the canister, rotate the canister, and linearly insert the canister

into the OS on top of the MAV. This effectively prevents any exposure of the MAV to the outside environment. The name "white room" was used as a reference to the clean room that Apollo astronauts were in before they boarded a spacecraft.

G. Mechanical Erector design

A mechanical erector system would be needed to raise the MAV from a stowed position to its launch angle. Several different options were considered, including a single rotational mechanical actuator at the base of the launch system, a pulley and sliding base mechanism that would raise the MAV by pulling its base closer to a strut, and a 4 bar linkage system.

Conceptual designs were developed for all options, and a mass trade study was conducted over the design space. The single actuator mechanism was selected due to its simplicity, comparatively lower mass against other options, and its flight heritage from other actuators like the MER petal actuator.

The location of the actuator was moved more towards to the center of gravity of the launch system in order to lower the torque requirement on the actuator, and thus lower the mas of the actuator. The launch tube is now hinged around its center, and would be erected with the bottom portion of the launch system coming below the host base plate and close to the Martian surface.

V. ACKNOWLEDGMENT

This effort was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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