An Efficient Approach for Mars Sample Return Using Emerging Commercial Capabilities

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ABSTRACT

Mars Sample Return is the highest priority science mission for the next decade as recommended by the 2011 Decadal Survey of Planetary Science [1]. This article presents the results of a feasibility study for a Mars Sample Return mission that efficiently uses emerging commercial capabilities expected to be available in the near future. The motivation of our study was the recognition that emerging commercial capabilities might be used to perform Mars Sample Return with an Earth-direct architecture, and that this may offer a desirable simpler and lower cost approach. The objective of the study was to determine whether these capabilities can be used to optimize the number of mission systems and launches required to return the samples, with the goal of achieving the desired simplicity.

All of the major element required for the Mars Sample Return mission are described. Mission system elements were analyzed with either direct techniques or by using parametric mass estimating relationships. The analysis shows the feasibility of a complete and closed Mars Sample Return mission design based on the following scenario: A SpaceX Falcon Heavy launch vehicle places a modified version of a SpaceX Dragon capsule, referred to as "Red Dragon", onto a Trans Mars Injection trajectory. The capsule carries all the hardware needed to return to Earth Orbit samples collected by a prior mission, such as the planned NASA Mars 2020 sample collection rover. The payload includes a fully fueled Mars Ascent Vehicle; a fueled Earth Return Vehicle, support equipment, and a mechanism to transfer samples from the sample cache system onboard the rover to the Earth Return Vehicle. The Red Dragon descends to land on the surface of Mars using Supersonic Retropropulsion. After collected samples are transferred to the Earth Return Vehicle, the single-stage Mars Ascent Vehicle launches the Earth Return Vehicle from the surface of Mars to a Mars phasing orbit. After a brief phasing period, the Earth Return Vehicle performs a Trans Earth Injection burn. Once near Earth, the Earth Return Vehicle performs Earth and lunar swing-bys and is placed into a Lunar Trailing Orbit - an Earth orbit, at lunar distance. A retrieval mission then performs a rendezvous with the Earth Return Vehicle, retrieves the sample container, and breaks the chain of contact with Mars by transferring the sample into a sterile and secure container. With the sample contained, the retrieving spacecraft makes a controlled Earth re-entry preventing any unintended release of Martian materials into the Earth's biosphere. The mission can start in any one of three Earth to Mars launch opportunities, beginning in 2022.

KEY WORDS

Red Dragon	SpaceX
Commercial	Mars Sample Return
Supersonic Retropropulsion	Mars Entry, Descent, and Landing

1. INTRODUCTION

1.1. Mars Sample Return

Mars Sample Return (MSR) has been identified as the highest priority planetary science mission in the 2011 Decadal Survey of Planetary Science, the guiding document for the United States Planetary Science Program [1]. MSR has been studied extensively within the last three decades and several mission designs have been proposed [2 – 6]. Those earlier mission designs have been large and complex, with many elements and systems, and multiple launches, implying a high cost. This article reports on a study that examined the use of an emerging suite of commercial capabilities to reduce the number of elements, systems, and launches and therefore the mission complexity compared to the previous approaches [2 - 6]. A description of emerging commercial capability is provided in Section 1.2.

Mars Sample Return is intrinsically a complex mission as it requires Entry Descent and Landing (EDL) through atmosphere and onto the surface; surface mobility to collect the samples; a rocket powered Mars Ascent Vehicle (MAV) capable of launching the samples into space from the Martian surface; transportation of the sample back to the vicinity of Earth; and EDL of the sample at Earth in a controlled manner to minimize the risk of planetary back contamination at Earth. The 2011 Decadal Survey [1] is supported by a mission architecture [2 – 4] that involves three Mars launches, carrying 14 mission elements. We refer to this architecture as the "Decadal Survey architecture". This Decadal Survey architecture includes the following:

- Launch Vehicles
  - ✓ Three Atlas V or Falcon 9 class launch vehicles.

- Mission Elements
  - ✓ Two cruise stages.
  - ✓ Two entry vehicles.
  - ✓ Two sky cranes.
  - ✓ Two differently designed, rovers.
  - ✓ One orbiter.
  - ✓ One Earth Return Vehicle (ERV).
  - ✓ One Earth Entry Vehicle (EEV).
  - ✓ One Mars Ascent Vehicle (MAV).
  - ✓ One thermal protection "igloo" for the MAV.
  - ✓ One landing pallet for the MAV and fetch rover.

In the first mission [2], a sample collection rover lands using the same "sky crane" landing system as the Curiosity Rover. The second mission [3] sends a Mars orbiter with an ERV and an EEV to Mars. The combined spacecraft wait in Mars orbit to perform the end steps of the third mission. The third mission [4] begins by dispatching a MAV and a fetch rover to be landed on Mars. The fetch rover drives to where the cache was left by the sample collection rover, picks them up and delivers them to the MAV. The fetch process takes up to six months and a traverse of up to 12 km. The MAV then delivers the sample canister, with minimal spacecraft support functions, into Mars Orbit. The waiting Mars orbiter performs a Mars Orbit Rendezvous with the sample canister, and captures it with a basket. The sample canister is them placed in into a sterile container housed within the EEV. The ERV carries the propulsion system to send the EEV from Mars orbit back to Earth. Near Earth, the ERV releases the EEV where it performs a passive EDL while safely containing the sample.

In addition to the previous MSR mission studies mentioned earlier, [2 – 6], other prior work has questioned the use of Mars Orbit rendezvous and suggested that a direct to Earth approach be considered [7 - 8]. In particular, in [7], it is suggested that in order to break out of the much used box defined by legacy mission approaches, the development of alternative systems would be required. The emerging commercial capabilities of Red Dragon and the Falcon Heavy, can meet this need.

It is to be noted that although the Decadal Survey architecture was not approved as a whole due to cost concerns, the Mars 2020 rover will be tasked with performing sample collection functions in addition to the primary science mission. This startup of MSR activities was actually assumed by the worked described in this article.

The motivation of our study was the recognition that emerging commercial capabilities might be used to perform MSR with an Earth-direct architecture, and that this may offer a simpler and lower cost approach. We examined whether a suitably modified SpaceX Dragon capsule, referred to as a "Red Dragon" could perform the cruise, entry, descent, and landing functions in place of a dedicated cruise stage, an aeroshell, a sky crane, and a landed platform as used in the Decadal Survey Architecture [2 – 4]. We evaluated the landed mass capability of a Red Dragon to determine that it allows a MAV-ERV stack with the capability of launching the sample directly towards earth, without the need for Mars orbit operations.

This article presents a new MSR architecture based on the emerging capabilities under development by SpaceX. We refer to this new MSR architecture as the "Red Dragon MSR architecture". The original sampling intent of the planetary science community is preserved in the Red Dragon MSR architecture. We show that it is possible to take advantage of the Mars 2020 sample collection rover that has already started development. In keeping with the desire to lower the complexity and cost of the MSR program, we assumed that the Mars 2020 rover could be used to deliver the samples to the sample return vehicles. The Red Dragon MSR architecture was analyzed as starting in any one of three consecutive Earth to Mars launch opportunities, beginning in 2022. The 2022 opportunity is the preferred option since the shortest mission extension, approximately of 12 months, will be required for the 2020 rover. The Red Dragon MSR architecture covers a complete mission with all required elements. Mass closure is achieved when it is shown that the mass of elements needed to perform the Earth direct mission fit within the mass that can be landed on Mars.

1.2. Emerging Commercial Capabilities

The use of the capabilities that have been emerging from recent commercial space activities is key to the Red Dragon MSR architecture. The use of fewer elements makes this architecture an efficient approach. SpaceX is used as an example but there are others that are attempting to reduce the cost of spaceflight as well. There is no endorsement of any particular commercial organization by NASA. There is also no endorsement of this work by any particular commercial organization.

SpaceX is a much different type of organization than the aerospace industry has seen in the past. They operate in a more efficient manner than the aerospace industry or large customers such as NASA.

Within a time period just under a decade, the Dragon capsule and Falcon 9 launch vehicle have emerged as a commercial source of cargo delivery services to the International Space Station (ISS) to fill the gap left by the retirement of the Space Shuttle. Commercial, in this sense, refers to the fact that NASA can now contract for cargo delivery services to ISS. A similar approach will be used for human missions to the ISS. Both capabilities are implementations of U.S. Space Exploration policy as administered by the NASA Commercial Crew and Cargo Program Office

(C3PO) [9 - 10]. The Red Dragon MSR architecture described in this article is built on this commercial premise.

1.3. Article Overview

We first describe the MSR Concept of Operations (ConOps) in Section 2, from Earth launch until return of the recovered samples to Earth. In Section 3, the methodology used to perform the study, including data sources; major engineering tools, and internal checks is provided. Appendix A provides a summary of key data assumptions. Section 4 provides information related to the design and operation of the Red Dragon MSR architecture elements. A description of the interfaces between the Red Dragon MSR architecture and the Mars 2020 rover is provided in Section 5. Planetary Protection issues are addressed in Section 6. In Section 7, a discussion of the results and related topics is included. Section 8 is the conclusion while Section 9 recommends potential future work.

2. Concept of Operations

Figure 1 illustrates the MSR mission concept of operations. The mission starts with a launch of a SpaceX Falcon Heavy (FH) (first development flight expected in late 2015). The FH carries a modified version of a SpaceX Dragon capsule, the "Red Dragon", plus a service module or trunk. The Red Dragon capsule is a SpaceX Dragon capsule that has been modified to carry all the necessary hardware to return samples collected on Mars. The return system elements include a MAV and an ERV. Also included are an augmented propellant tank system for Red Dragon, systems that support the MAV-ERV stack; and a robotic arm, described in Sections 4.6 and 5, to transfer the sample cache from a rover to the ERV. For design purposes, the configuration of the sample cache for the Mars 2020 rover was used, and as that mission was not yet fully designed at the start of the study, we assumed that the cache would be placed in a location on the rover that could be accessed by an arm extending from the capsule. Red Dragon is sent on a Trans Mars Injection (TMI) trajectory by the FH upper stage. The mission continues with an interplanetary cruise of approximately 10 to 13 months, depending on opportunity.
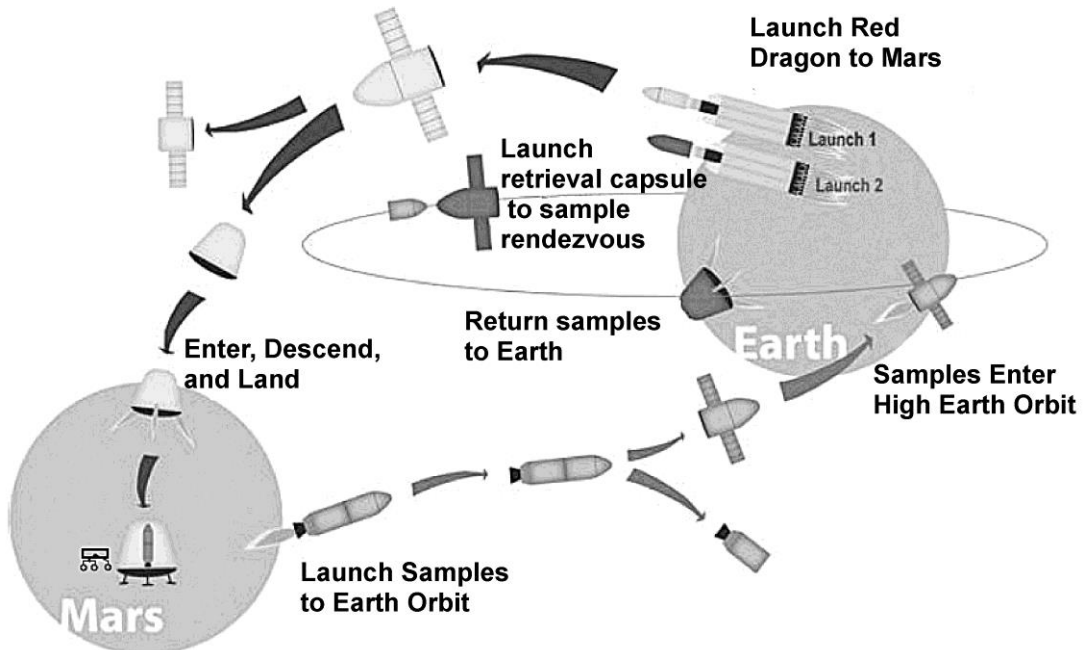

Fig 1. MSR Concept of Operations

Upon arrival at Mars, Red Dragon performs a direct entry followed by a non-traditional Entry, Descent, and Landing (EDL) using a lifting trajectory with bank angle modulation and Supersonic Retropropulsion (SRP). Parachute braking or descent is not performed. Additional details for the EDL are provided below in Section 4.2

Sample transfer from the rover requires that the rover drive up to Red Dragon so the sample can be transferred to the ERV via the robotic arm. The samples must be transferred to the MAV within approximately 10 months of landing. Red Dragon is assumed to be able to land anywhere the 2020 rover can land because of the bank angle modulation technique. Red Dragon is also assumed to be able to land ahead of the rover's projected path; close enough to allow for sample recovery to occur in time for launch. The MAV launches the ERV from the surface of Mars to a short term phasing orbit. The MAV uses a storable liquid, pump-fed bi-propellant propulsion system. After the brief phasing period, the ERV, which also uses a storable bi-propellant system, performs a Trans Earth Injection (TEI) burn. The unique return interplanetary cruise towards Earth lasts approximately 10 to 12 months, depending on opportunity. Once near Earth, the ERV performs swing-by maneuvers at Earth and the moon in order to enter into a Lunar Trailing Orbit (LTO) – a high Earth orbit, at lunar distance and inclined to the plane of the Earth-moon system. Later, a sample retrieval mission is launched. This mission could also use a Dragon capsule. This mission performs a rendezvous with the ERV in the LTO. The retrieving capsule can be operated telerobotically or by an on-board crew. The retrieval of the sample container from the ERV will break the chain of contact with Mars as required by COSPAR Planetary Protection policy for Category V, restricted Earth return missions [11] and NASA Procedural Requirement (NPR) 8020.12D [12]. This will be accomplished by using an arm to transfer the sample container into a suitably clean and secure container. With the sample cache contained and secured, the retrieving capsule makes a controlled Earth re-entry preventing any unintended release of pristine Martian materials into the Earth's biosphere.

The direct Mars to Earth approach is enabled by the ability of the Red Dragon to deliver a high performance MAV to the surface of Mars.

3. Study Methodology

The study described in this article was conducted in 2013 [13] by a team of engineers at NASA's Ames Research Center (see acknowledgements), led by the co-authors of this report. Only publicly available information on the properties of SpaceX hardware such as the Falcon Heavy and the Dragon capsule were used. There was no direct contact with SpaceX Corp. and they did not contribute to the analysis, so our study represents an independent assessment of how these systems can be used. The study team investigated the major architecture elements needed for sample return to understand the ramification of each option. Engineering assessments and assumptions were made for all of the architecture elements required to perform the MSR mission on the surface and in-space. In parallel with this effort, engineering analyses based on publicly available data were used for the elements needed to launch, deliver, land, and return the mission elements. Periodic cross checks between the two efforts were used to drive the study to mass closure using appropriate contingencies.

For the special problems associated with design of the MAV the standard aerospace analysis tools CBAERO, CART3D, and POST2 were used in conjunction with a database of previous United States aerospace mission hardware. For the EDL analysis, CBAERO and POST2 was used.

Trajectories for transit to Mars and back were selected for consistency with Earth and Mars launch capabilities including the Falcon Heavy launch vehicle. In addition an integrated Mars

return stack that included the custom designed MAV and ERV was optimized. The design for all mission elements utilized design heritage and technology within the current state of the art.

At the conclusion of the study, a closed architecture did, in fact, result. Mission closure means that mass and volume of all the mission elements fit with the mass and volume that can be landed. The elements must be designed in sufficient detail to have a confident estimate of their mass and volume. A summary of key data assumptions used in the study is provided in Appendix A.

4. Architecture Element and Operation Description

This section describes design and operation of six elements of the Red Dragon MSR architecture.

4.1. Earth Launch

For the Earth launch operation, an assessment of payload mass versus launch energy for the three opportunities occurring in 2022, 2024, and 2026 was made. Definitive C3 curves for the FH are not yet available; however, an analysis of FH by Tito et al [14] provided sufficient information for this study. The resulting payload mass versus launch energy curve is shown in Fig. 2.

Earth Launch mass is less than 11 mt, which is within the estimated FH capability for launch opportunities in 2022, 2024, and 2026. The highest C3 of 13.2 km2/sec2, occurring in

Fig. 2. Derived Falcon Heavy Performance, using the methods from [14].

2022 opportunity, was used in the analysis. The C3 for the 2026 opportunity is significantly less. A representation of the launch mass breakdown is shown in Fig. 3.
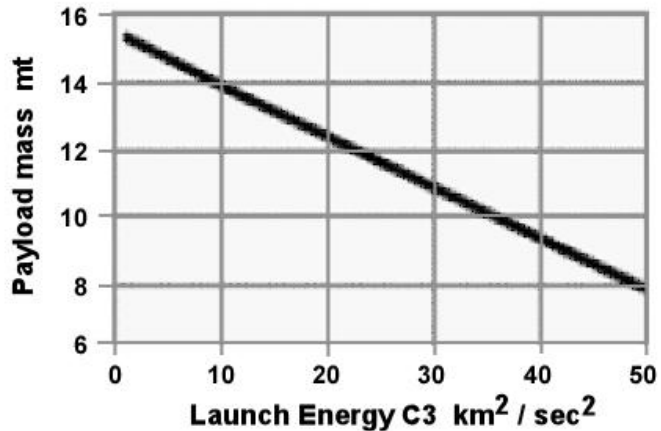
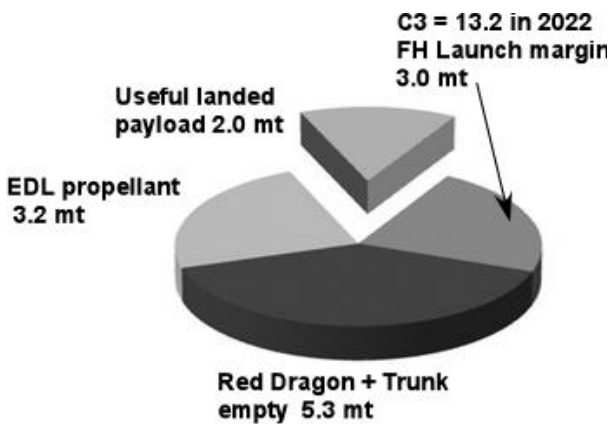### 4.2. Entry, Descent, and Landing

Fig. 3. MSR Launch Mass Representation

The critical EDL is performed by Red Dragon, using a lifting trajectory with bank angle modulation [15]. The EDL challenges to be faced using a propulsive approach have also been addressed computationally in detail by Braun and Manning [16]. Supersonic Retropropulsion, in particular, has been extensively investigated [17 -20], and is in fact utilized during Falcon 9 first stage booster recovery attempts [21].

The analysis of the EDL included a determination of propellant mass fractions for entry, terminal descent, and hazard avoidance. An assessment of the effect of

the entry conditions on the thermal protection system (TPS), currently in use for Dragon missions, was also performed using CBAERO and indicated a non-stressing condition.

The selected entry trajectory type, resulting from a POST2 analysis, depicted in Fig. 4, utilizes a sophisticated bank-angle control strategy. In this strategy, the capsule enters the atmosphere with a lift-downward angle of attack. This causes the capsule to proceed to greater depth

Fig. 4. Entry Trajectory

into the atmosphere, more quickly. Immediately prior to the inflection point in the trajectory, the capsule banks 180 deg. around the velocity vector to achieve a lift-up configuration. This maneuver creates a nearly constant altitude flight path. The result is a significant decrease in both the altitude and the vertical velocity component at the time propulsive deceleration begins, which acts to minimize the propellant mass fraction used for terminal descent. This entry strategy requires active flying of the capsule with reference to the density altitude of the atmosphere, as compared to the passive deceleration of the capsule, as used in more traditional approaches. This technique not only constrains the vertical component of the trajectory but allows for precision control of the horizontal component (i.e. targeting control) as well.

Red Dragon's SuperDraco thrusters perform the final braking, terminal landing, and hazard avoidance burns. No parachutes are utilized in this approach.

Total entry masses between 7 and 10 mt were considered with closure occurring between 9 and 10 mt. The entry mass accounts for all of the elements needed to perform the MSR mission including the Red Dragon capsule, MAV, the ERV, mission unique support equipment, and the total propellant to perform the entry and landing operations. A useful payload of 2 mt is provided and includes the MAV, ERV, and support equipment. A representation of the useful mass breakdown is shown in Fig. 5. These data are derived from an entry at Mars Ls = 180 deg. and a landing altitude of − 4.0 km (MOLA datum). Entries at Ls = 270 deg. and altitudes up to 0 km were also analyzed.

In summary, EDL using Red Dragon in a lifting trajectory, decelerating aerodynamically and with SRP can soft land a vehicle mass of 6,600 kg, including 2,000 kg of useful payload mass, onto the Martian surface.
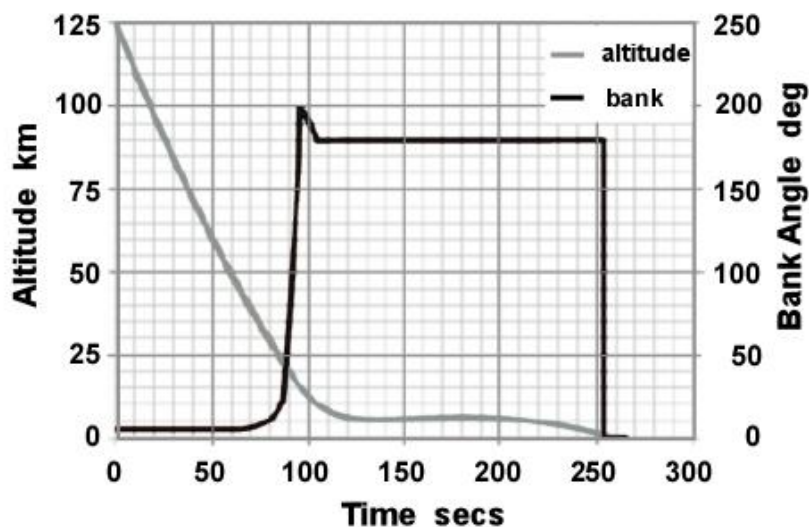
4.3. Red Dragon Capsule

The Red Dragon capsule is envisioned to be a modified version of the SpaceX Dragon capsule currently in service as a Space Station cargo re-supply and return vehicle, and soon to be used for crew launch and return. Red Dragon will need features such as landing legs and SuperDraco thrusters already planned for crew return.

Modifications to the standard Dragon capsule in order for it to become a Red Dragon suitable for MSR are described next.

Fig. 5. Red Dragon Useful Mass Representation

4.3.1. Interior Structure

Interior modifications to the Dragon to incorporate and structurally support the MAV within a launch tube will be required. Attachments to existing hard points will be needed, as shown in Fig. 6. The MAV is mounted to the containment shell by trunnions at the top, for axial loads, and snubbers at the bottom, for lateral loads, The MAV structure is in axial tension during Earth launch and Mars entry. At Mars ignition, the trunnions release to launch the MAV. While a complete structural evaluation will be needed, comparing anticipated MSR loads to load cases required for human rating lends confidence in the capability of Red Dragon to perform the MSR mission.

4.3.2. Additional Propellant Capacity

The standard Dragon carries propellant in the lower bays. For the MSR EDL, including terminal descent and hazard avoidance, additional propellant is required. Figure 7 indicates the location of the additional propellant in supplementary tanks in the cabin section. The cabin volume allows this configuration, which will be the arrangement for any high mass implementation of Red Dragon.
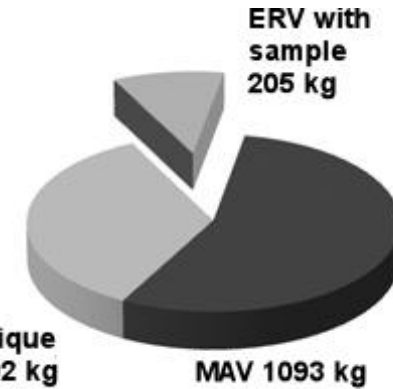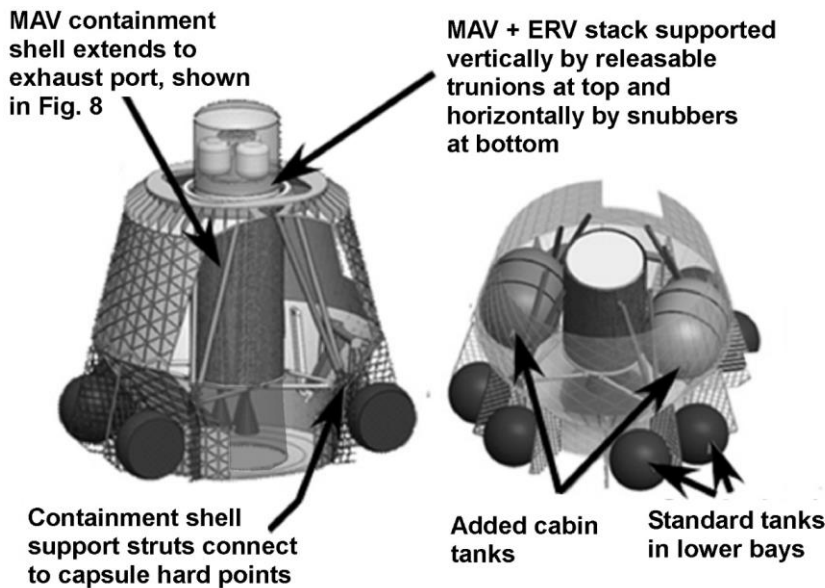

Fig. 6. MAV Mounted in Red Dragon

Fig. 7. EDL Propellant Tank Arrangement

4.3.3. Exhaust Venting for Mars Ascent Vehicle Launch

A MAV launch exhaust venting scheme will need to be incorporated into Red Dragon. Several possibilities were investigated. One option is the utilization of existing hatch and window openings requiring complex internal ducting. Another option is a "missile silo" type vertical vent annulus that requires turning vanes at the base of the MAV. A more direct, and selected, approach utilizes a hatch in the heat shield that opens post-landing, directly below the MAV. Figure. 8 shows the condition after the hatch has opened. The MAV is mounted such that the rocket nozzles are as low as feasible, with the containment shell extending to the lower floor of Red Dragon (inner face of the heat shield carrying structure). A port in the heat shield is considered feasible since entry heating is low. Dragon Version 2.0 uses heat shield ports for the landing legs. There is also precedent for heat shield hatches, from such items as Space Shuttle landing gear and umbilical doors

4.4. Mars Ascent Vehicle

The MAV was sized to fit within the volume of Red Dragon. A set of Mass Estimating Relations (MERs) capturing all subsystems were developed for this class of vehicle, and integrated into a vehicle synthesis code for computing mass and volume, and performing vehicle closure to meet mission requirements. Best practices and State-of-the-Art and traditional aerospace technologies were used. A dry mass growth allowance of 30% was used.

An optimized ΔV split between the MAV and the ERV and an estimated mass for the full sample container was utilized in a parametric design approach. Details on the MAV design are given in [22]. Design iterations were framed within a set of assumptions and ground rules based on best practices and experience for the conceptual design phase. The propulsion for the MAV that produced most favorable results is a pump fed, storable propellant system. A pressure fed system was considered but not selected due to higher tank mass. The analysis of the MAV was integrated with the parallel design of the ERV described in Section 4.5. The MAV plus ERV stack was optimized over several iterations and convergence was achieved. Table 1 details the components of the optimized ΔV assignment for the MAV.

Table 1. MAV Design ΔV Budget Distribution

Trajectory Component	MAV ΔV, m/sec
Orbital	3,299
Aero Drag Loss	4.0
Gravity Loss	400
Thrust Vectoring Loss	327
Atmospheric Loss	1.1
Coriolis Loss	0
Inclination Loss (due east from N/S Lat. 45)	70
Subtotal	4,101
3.6% Reserve	149
Total ΔV	4,250

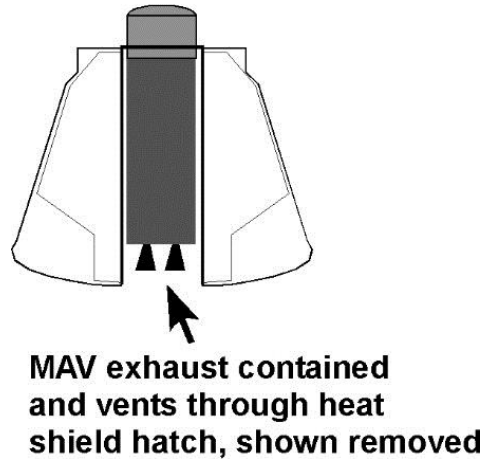MAV exhaust contained and vents through heat shield hatch, shown removed

Fig. 8. MAV Exhaust Venting Approach

Load bearing structures, including forward and aft compartments, and inter-tank, were assumed to be high temperature thermo-plastic composites, skin-stringer stiffened semi-monocoque construction. Design loads consistent with Earth launch, Mars entry, and Mars launch cases as well

as the mounting scheme described in Section 4.3.1, were used to size the load bearing structure, with a safety factor of 1.4 on loads and a knock-down factor of 0.80 on stiffness. Non-load bearing aeroshell structure was assumed to be min-gauge (5 plies) thermo-plastic. Secondary structure mass was assumed to be 10% of primary structure.

Propellant tanks were also assumed to be high temperature thermo-plastic composites with a liner, and were sized using historical weight trends. A 20% reduction in tank mass was used to account for composite construction, as opposed to metal tanks used in the historical correlation for tank weights. A factor of safety of 2.0 was used for tank internal pressure. A 5% ullage volume was assumed for all propellant tanks. For hypergolic propellants, a low ullage pressure of .0345 MPa was used. Because of low tank pressure, hypergolic tanks were assumed to have a dome eccentricity of 0.90 (relatively "flat" domes) to improve overall vehicle packing efficiency.

Rocket engine performance was computed assuming chemical equilibrium for the hypergolic propellants. Based on preliminary ascent trajectory optimizations, a liftoff thrust-to-weight ratio of 2.5 was used. Propellant oxidizer-to-fuel ratio was optimized for maximum performance. Startup propellant for engine startup period was also provided. [22]

4.5. Earth Return Vehicle

The ERV drives the Red Dragon MSR architecture since its mass travels the farthest, being carried down to and lifted off of the surface of Mars. For this reason the ERV is worthy of a significant amount of design consideration. In addition, the ERV is a strong candidate for the application of maturing small spacecraft techniques. For these reasons, the ERV was defined by two separate approaches. The optimized ΔV split with the MAV was used in both of these design

Table 2. ERV Design ΔV Budget Distribution

Trajectory Component	ERV ΔV, m/sec
Circularization at Mars Phasing Orbit	37
TEI	2,114
TEI Gravity Loss	21
Mid-course	75
Earth Fly-by	641
Earth Fly-by Gravity Loss	1
Moon Fly-by	0
Circularization at Earth Lunar Trailing Orbit	25
Disposal to Heliocentric orbit	25
Subtotal	2,939
7.2% Reserve	211
Total ΔV	3,150

Table 3. ERV Parametric Design Mass Budget

Category	Mass - kg
ERV dry	50
27% mass growth allowance	13.5
Subtotal dry	63.5
Sample container + sampler	8.5
Subtotal dry + container + sample	72
Propellant	133
Total ERV wet as payload to the MAV	205

approaches. A parametric approach, similar to that used for the MAV was compared to a "bottoms up" design using commercially available, off the shelf, components (COTS). The COTS design includes a pressure-fed propulsion system reducing development risks associated with small engines that require multiple starts and tanks that can be jettisoned. Table 2 details the components of the optimized ΔV assignment for the ERV. Table 3 indicates the results of the parametric design for the ERV and Table 4 provides data for the "COTS design.

Subsystem	Component (units)	Mass		Subsystem	Component (units)	Mass
ADACS	Star Tracker (1)	0.80		Thermal	Coatings (1)	0.13
	IMU (1)	0.98			Heaters (12)	1.40
	Sun Sensor (4)	0.05			MLI (1)	0.04
	RWA (4)	3.6			Temp. Sensors (6)	0.39
C&DH	Integrated Avionics. (1)	6.9			Thermoelectric Cooler (1)	0.13
Power	Battery Pack (3)	6.24		Propulsion	Fixed tank (2)s	4.0
	Solar Array (1)	1.59			Jettisoned tanks (2)	9.2
Structure	Dust Cove (1)r	0.91			Fixed valves / filters (2)	2.7
	Fasteners, Hinges, Latches (1)	3.90			Jettisoned valves / filters (2)	2.7
	Cabling (1)	2.60			Main thruster (1)	6.8
	Second. Structure (1)	0.44			Vernier thrusters (6)	3.5
	Prim. Structure. (1)	4.39			Structure (1)	2.0
Telecomm	LGA (2)	0.21			Jettison mechanism (1)	1.3
	HGA (1)	1.6		Payload	Sample Container – 50% mass growth (1)	4.0
	Transponder, XS (2)	7.8			Samples with 20% mass growth (1)	0.60
	Diplexers (3)	1.4		Subtotal dry		82
				Propellant		129
				Total wet		211

Table 4. ERV Bottoms Up COTS Design Mass Budget – kg incl. 30% growth unless note

4.6. Sample Transfer Operations

The desired cached sample, has a mass of 500 g in accordance with MEPAG guidelines [23]. Figure 9a illustrates the operation of a sample retrieval from a rover via a robotic arm fitted to Red Dragon. Use of the robotic arm would require the opening the side hatch port in order to capture and transfer the sample to the ERV. The arm would also have the capability to capture a grab sample in the event that the cache could not be transferred. Planning for the analysis of such a grab sample would have to carefully define protocols for separating the contamination introduced by thruster exhaust.

After the sample has been stowed on the ERV, the MAV launches the ERV and sample into a temporary phasing orbit. The ERV then injects into a cruise towards Earth. Once near Earth, the ERV performs Earth and lunar swing-bys and enters into a Lunar Trailing Orbit (LTO) – a high earth orbit at lunar distance, but inclined to the plane of the Earth-moon system.

We envision that a later mission can retrieve the sample container as shown schematically in Fig. 9b. This mission was not designed in detail during the study. Optionally, a Dragon or Orion capsule, operated by a crew or robotically, can perform a rendezvous with the ERV. The arm is then used to transfer the sample container from the ERV to a sealed volume in the nose of the capsule.

The mission then performs a controlled reentry. The sealed volume containing the sample must be capable of surviving a worst case reentry accident without compromising the seal. This is a planetary protection requirement for the mission and can be implemented with more confidence by performing the rendezvous and transfer nearer to Earth than at Mars.

The arm is a new design [24] and is shown in Fig. 9c. The sample collection, retrieval and storage concepts were based on the guidelines in the Decadal Survey architecture [1 - 4], and MEPAG [23] for 500 g of samples. The samples are contained within a 31-tube cache canister [25]. The arm must also opportunity during an in-space rendezvous. The arm mass is 40 kg.

A 7 DOF jointed robot arm with extendable segment for compact storage provides a 3-meter reach enabling the sample container to be removed from the rover (2.5 m away) and placed into a magnesium alloy thermos flask sample canister kept cool with a TEC chip. The robot arm has a coupling effector for the cache retrieval and a spoon effector to obtain any grab samples.
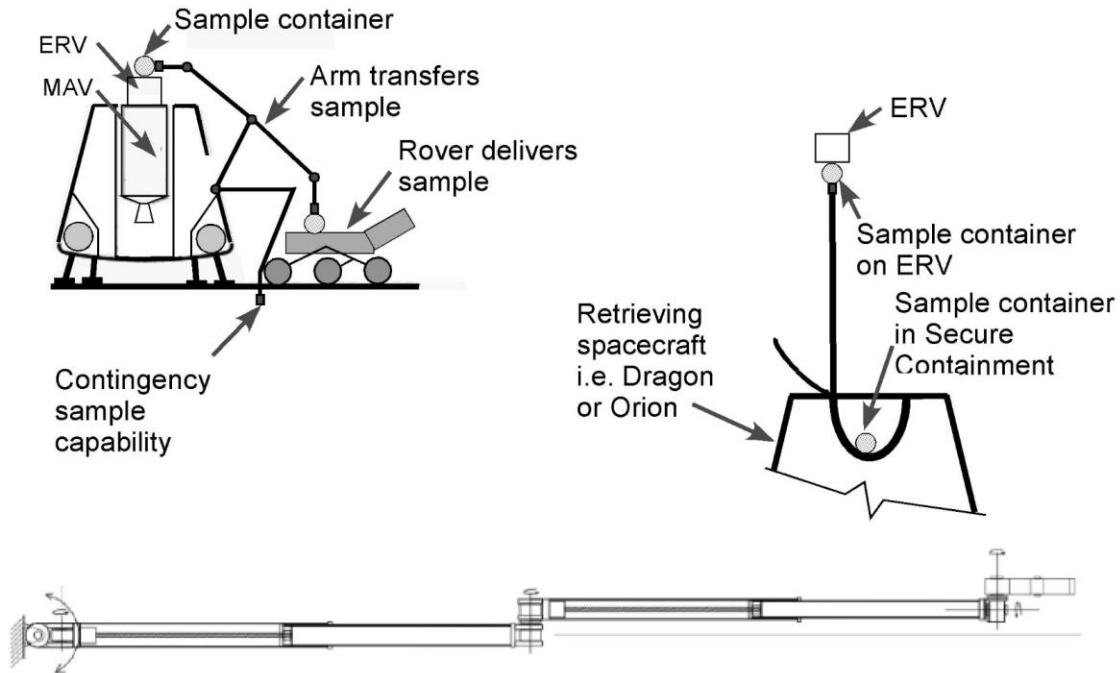

Fig. 9a. Rover to Red Dragon Sample Transfer, upper left, **Fig. 9b.** LTO Sample Retrieval, middle right, and **Fig. 9c.** Sample Transfer Arm design, lower.

5. Interface to Mars 2020 Rover Mission

In order to fulfill the scientific requirements for samples that were identified in the Decadal Survey [1 – 4] and MEPAG [23], a capable rover mission to collect samples must precede the sample return mission. Development of the Mars 2020 rover mission is now underway to collect samples for return as defined in the Report of the Mars 2020 Science Definition Team [26]. The major elements of the Mars 2020 rover mission include the same elements that were part of the current Mars Science Laboratory (MSL) mission: 1) Atlas V class launch vehicle, 2) Cruise Stage, 3) Entry Aero shell, 4) Sky Crane, and 5) Rover. Of these elements only the rover has a direct interface with the Red Dragon MSR architecture described in this article. Our study assumed that the sample container is delivered to Red Dragon by the rover. It is therefore necessary for the Red Dragon MSR mission to be launched soon after the Mars 2020 rover. The 2022 launch opportunity was evaluated and is feasible, as are the following 2 opportunities.

It will be necessary for Red Dragon to land close to the projected exploration path of the rover, subject to a safe standoff distance, in order to minimize any rover diversion. Red Dragon can land at any of the sites described for the 2020 rover by the Science Definition Team report [26]. The rover would be required to drive up to a point within reach of the robotic arm mounted in Red

Dragon described in Section 4.6 and shown in Figs. 9a and 9c. The rover sample container must be within reach of the robotic arm which then transfers it to the ERV at the top of Red Dragon.

Mission success of both the Mars 2020 rover mission and the Red Dragon MSR mission architecture, should a decision be made to implement it, depends upon close co-operation between both projects. Section 7.1 discusses potential modification that could be made to the Red Dragon MSR architecture in order to accommodate the development of the Mars 2020 rover design life cycle.

6. Planetary Protection

All missions to Mars—whether one way or round trip – must comply with International and NASA Planetary Protection policy [11 - 12] rooted in the Outer Space Treaty [27]. Policies addressing both forward and backward contamination concerns are updated over time by the Committee on Space Research (COSPAR) to reflect advances in scientific knowledge, new technologies and practical experiences.

This proposed Red Dragon MSR architecture will be impacted by several Planetary Protection policy provisions that span across the various mission elements and include concerns about both forward and backward contamination. The Red Dragon must provide outbound forward contamination controls that meet requirements for pre-launch cleanliness and bio load reduction for flight hardware. Controls to address backward contamination must also be in place. Controls must be provided for the sample container; transfer of the container to the ERV, and a final transfer of the sample container to the retrieving capsule or EEV, as appropriate. Both the flight hardware that has been on Mars as well as pristine Martian material returned from Mars will have to be contained. These impacts, are as follows:

- The exterior surfaces of Red Dragon will be exposed to the terrestrial environment during processing and launch. These surfaces will also be exposed to the space environment while in transit to Mars. The landing legs and exhaust gas venting system, including entrained material, will also require special attention. These considerations will be addressed in determining Planetary Protection requirements associated with forward contamination controls.

- The interior surfaces of Red Dragon, including encapsulated and embedded surfaces will need to comply with appropriate pre-launch Planetary Protection cleanliness requirements based on the landing location.

- The sample handling robotic arm end effectors used for obtaining grab samples and for the transfer of the sample container from the Martian surface to the ERV, will need to be sterilized. A separate in-space sample transfer arm, if used, will also require attention.

- The exterior of the sample container delivered by the 2020 rover will be exposed to Mars material and will need to be suitably contained.

- The exterior surfaces of the ERV will be exposed to Mars materials. After sample transfer the ERV will be disposed to a heliocentric orbit and will not impact the moon.

The retrieval and containment strategy for the transfer in the LTO, shown in Fig. 9b, provides secure, secondary isolation and containment for the sample. No Martian material will be allowed to touch the outer surfaces of the retrieving capsule. In the event of a capsule failure, the secure containment will prevent introduction of Martian material into the Earth's biosphere.

7. Discussion

By comparison with the Decadal Survey architecture [2 - 4], summarized in Section 1.1, the Red Dragon MSR architecture is significantly simpler. There are two Mars launches instead of

three. In both cases, the first launch is the sample collection mission. NASA has already selected a mission to be launched in 2020 for the sample collection activity. The second Mars launch brings Red Dragon with a MAV-ERV spacecraft stack to Mars capable of carrying the sample container back to Earth Orbit. Then a third mission to Earth Orbit is required to capture the sample, contain it securely, and bring it to Earth's surface. While there are still a total of three launches in the Red Dragon MSR architecture, only two of them are to Mars. We believe that rendezvous and repackaging of the sample in the LTO is fundamentally simpler than a Mars Orbital mission to accomplish essentially the same task. A simplification is to use the 2020 Sample Collection rover to bring the samples to the MAV, rather than having a separate fetch rover. While there is enough mass and volume available for the MAV and ERV, a fetch rover cannot be accommodated. The lack of a fetch rover and the direct to Earth transfer are the main departures between the Red Dragon MSR architecture and the Decadal Survey architecture [2 – 4]. In Section 7.1, we do discuss including a fetch rover as a means of accommodating recent developments for the Mars 2020 rover.

7.1. Potential Changes to the Red Dragon MSR Architecture

An alternative form of caching, described as "adaptive caching" is currently under consideration for the Mars 2020 rover [28]. This new approach was brought forth after the work described in this article was performed. Using the "adaptive caching" approach, sample tubes are not placed in a single container and carried along with the 2020 rover. Instead, individual tubes are left on the surface in documented locations. A follow-on rover, similar to the fetch rover concept proposed earlier [4], but with extended capabilities to place the tubes in a container, will be necessary to retrieve the samples of interest. By including a fetch rover, Red Dragon can only carry a less capable MAV, similar to one previously proposed [4]. In this case, the MAV places an orbiting sample satellite into Mars orbit. A Mars orbiter, similar to the one proposed earlier [3], will also be necessary. Such an orbiter, with multiple functions and capabilities, has recently been advocated [29].

As can be seen, the alternate approach does return to the Mars orbit rendezvous paradigm, giving up some simplicity; however, the landing capabilities of Red Dragon can still be utilized. The fetch rover is traded against MAV capability. However, if Red Dragon is used, even this modification is simpler than the Decadal Survey architecture [2 - 4].

Red Dragon turns out to be a capable and adaptable vehicle, and can accommodate changes to Mars 2020 rover mission operations.

7.2. Other Options for Earth Return

The architecture could be further simplified if the sample can be brought directly back to the Earth's surface, without a stop in LTO. Our study team evaluated this option and found that use of conventional thermal protection system on the Earth Entry Vehicle (EEV) would too massive to close the currently defined Red Dragon MSR architecture. The advanced entry systems and Thermal Protection System, (TPS) technologies currently being investigated by NASA in the Adaptable, Deployable Entry Technology and Placement (ADEPT) program [30 - 31], have the potential to reduce mass. A direct entry approach would also require a strategy to meet the Planetary Protection requirements, i.e. any materials that have been in the Mars environment can't be exposed to the Earth environment in an uncontrolled manner. Future work is required to evaluate the feasibility of a direct entry option.

7.3. Alternate MAV Propellant Options

The baseline propellant for the MAV is storable hypergolic propellants (NTO / MMH). Designs and trade studies were also conducted for alternate propellant types for the MAV [22]. These included LOX / RP-1 and LOX / Liquid CH4. For the alternate propellant designs, LOX would be manufactured on Mars, using in-situ resources. The fuel would be brought from Earth, emulating the strategy described in the current human exploration of Mars architecture [32]. Workable MAV designs were produced and some mass savings were achieved; however, even the generous volume of Red Dragon has limits. Red Dragon does not provide enough volume to package the MAV-ERV stack, mission unique support equipment, EDL propellant, and the ISRU equipment. In addition, the TRL of the ISRU process was not deemed sufficiently high enough to support a timely MSR mission implementation.

7.4. Other Commercial Missions to Mars

It is possible that using some or all of the capabilities described in this article, commercial contracting for the delivery of Mars missions, in a manner similar to the method for cargo and crew delivery to ISS, can be utilized. This would introduce efficiencies to Mars exploration as the need for more missions to prepare for human exploration are defined.

7.5. Importance as a Precursor to Human Exploration Missions

The EDL technique to be used by Red Dragon is very similar to the types of EDL techniques that have been projected for human exploration missions. Such missions, as described in the current human exploration of Mars architecture [32], require entry masses that far exceed the capabilities of traditional parachute systems. A propulsive type EDL, as described for Red Dragon, will be required to support human exploration class payloads. It is possible that a system such as ADEPT [30 – 31] or the Low-Density Supersonic Decelerator (LDSD) [33], could be combined with a propulsive EDL system.

Consider a series of missions consisting of the Red Dragon MSR mission, as well as other investigation missions that prepare for human exploration. This series could not only directly enable investigations necessary to plan future human Mars missions, but also perform precursor flight tests for those future activities.

8. Summary and Conclusions

The results of this study show that a sample from Mars can be returned within the next decade using commercial capabilities, and that these capabilities can be used to substantially reduce the complexity and number of mission elements required to return the samples. The deliverable mass afforded by the Falcon Heavy and Red Dragon combination reduces complexity compared to previous complex and costly campaign proposals. It is implicit that cost reductions flow from reduced mission complexity as well as business practices that lower production costs. A minimum-energy transfer to Mars is possible in the 2022 opportunity using a Falcon Heavy capable of throwing ~ 13 mt to Mars. Launch energy for the 2024 and 2026 are lower. EDL using Red Dragon in a lifting trajectory, decelerating aerodynamically and with SRP can soft land a vehicle mass of 6,600 kg, including 2,000 kg of useful payload mass, onto the Martian surface. Assumed modifications to Red Dragon include a sample transfer and storage system with grab sample capability; additional propellant tanks within the capsule; structural supports for the MAV; and exhaust venting to accommodate the launch of the MAV. A set of Mass Estimating Relations (MERs) capturing all subsystems were developed for this class of vehicle, and integrated into a vehicle synthesis code for computing mass and volume, and performing vehicle closure to meet

mission requirements. The propulsion for the MAV that produced most favorable results is a pump fed, storable propellant system. An Earth Return Vehicle was designed that can achieve Earth orbit, without requiring the infusion of advanced technology. The ERV employs pressure-fed engines, reducing development risks associated with small engines that require multiple starts. The analyses of the MAV was integrated with the parallel design of the ERV.

Recalling the number of elements required for the Decadal Survey Architecture, we can draw a comparison to the Red Dragon MSR architecture. The Red Dragon approach, *when combined with the Mars 2020 rover mission,* would use three launch vehicles plus eight mission elements as follows:

- Launch Vehicles
  - ✓ *One Atlas V for the Mars 2020 rover.*
  - ✓ One Falcon Heavy for Red Dragon to Mars.
  - ✓ One Falcon Heavy for the recovery mission in the LTO.

- Mission Elements
  - ✓ *One cruise stage for the Mars 2020 rover*
  - ✓ *One entry vehicle for the Mars 2020 rover.*
  - ✓ *One sky crane for the Mars 2020 rover.*
  - ✓ *One Mars 2020 rover*

  - ✓ One Red Dragon to Mars.
  - ✓ One MAV.
  - ✓ One ERV.
  - ✓ One standard Dragon for the recovery mission in the LTO.

The emergence of a commercial capability such as Red Dragon, is the type of development that can allow movement out of the constraining box of legacy approaches to Mars Sample Return.

9. Recommendations for Future Work

The following items of future work are recommended:

- Verification of assumptions against actual values.

- Performance of a cost estimate.

- Additional evaluation of the direct Earth entry approach, addressing Planetary Protection considerations.

- Consideration of how a Red Dragon EDL, using SRP, could be used as a precursor to test capabilities for crewed mission as contemplated in [32].

- Updates to address operational changes for the Mars 2020 rove related to sample handling and other features.

- Definition of other mission applications for Red Dragon.

APPENIDX A: Summary of Key Data

The assumed data noted were obtained from publicly available sources and analyzed independently by NASA, Ames Research Center. All research and analysis work was performed with no assistance from any commercial organization.

Tables A-1, A-2, and A-3 and Figs. A-1 and A-2 present the key data assumptions and results for the Red Dragon Capsule.

Table A-1 Assumed Red Dragon Capsule and Trunk Data

Item	CBE kg	Contingency kg	MEV kg
Basic Red Dragon capsule with empty propellant tanks	4,200	420	4,620
Red Dragon trunk with power system	500	150	650
Total Basic Red Dragon Capsule and Trunk	4,700	570	5,270

Table A-2 Maximum Entry Conditions

FP entry mass kg	max g-load	FP entry angle deg.	Max J/cm^2	Max W/cm^2	L/D
9,800	10	-14	2,738	118	0.20

Table A-3 Assumed SuperDraco Performance

Isp sec	Thrust for 8 units kN	Throttle setting	Cant angle outward deg.
265.7	534	80%	20
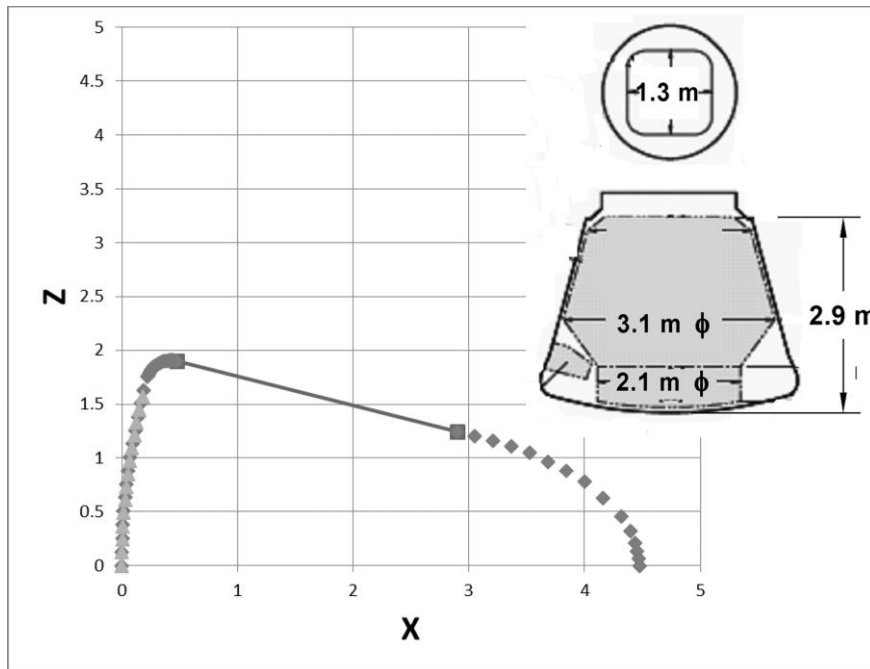
Fig. A-1 Assumed Red Dragon Outer Mold Line - m

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