Mars Sample Return Using Commercial Capabilities: Mission Architecture Overview

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Mars Sample Return (MSR) is the highest priority science mission for the next decade as recommended by the recent Decadal Survey of Planetary Science. This paper presents an overview of a feasibility study for a MSR mission. The objective of the study was to determine whether emerging commercial capabilities can be used to reduce the number of mission systems and launches required to return the samples, with the goal of reducing mission cost. The major element required for the MSR mission are described and include an integration of the emerging commercial capabilities with small spacecraft design techniques; new utilizations of traditional aerospace technologies; and recent technological developments.

We report the feasibility of a complete and closed MSR mission design using the following scenario that covers three synodic launch opportunities, beginning with the 2022 opportunity: A Falcon Heavy injects a SpaceX Red Dragon capsule and trunk onto a Trans Mars Injection (TMI) trajectory. The capsule is modified to carry all the hardware needed to return samples collected on Mars including a Mars Ascent Vehicle (MAV); an Earth Return Vehicle (ERV); and hardware to transfer a sample collected in a previously landed rover mission to the ERV. The Red Dragon descends to land on the surface of Mars using Supersonic Retro Propulsion (SRP). After previously collected samples are transferred to the ERV, the single-stage MAV launches the ERV from the surface of Mars to a Mars phasing orbit. The MAV uses a storable liquid, pump fed bi-propellant propulsion system. After a brief phasing period, the ERV, which also uses a storable bi-propellant system, performs a Trans Earth Injection (TEI) burn. Once near Earth the ERV performs Earth and lunar swing-bys and is placed into a Lunar Trailing Orbit (LTO0 - an Earth orbit, at lunar distance. A later mission, using a Dragon and launched by a Falcon Heavy, performs a rendezvous with the ERV in the lunar trailing orbit, retrieves the sample container and breaks the chain of contact with Mars by transferring the sample into a sterile and secure

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container. With the sample contained, the retrieving spacecraft, makes a controlled Earth re-entry preventing any unintended release of pristine Martian materials into the Earth's biosphere. Other capsule type vehicles and associated launchers may be applicable.

The analysis methods employed standard and specialized aerospace engineering tools. Mission system elements were analyzed with either direct techniques or by using parametric mass estimating relationships (MERs). The architecture was iterated until overall mission convergence was achieved on at least one path. Subsystems analyzed in this study include support structures, power system, nose fairing, thermal insulation, actuation devices, MAV exhaust venting, and GN&C. Best practice application of loads, mass growth contingencies, and resource margins were used. For Falcon Heavy capabilities and Dragon subsystems we utilized publically available data from SpaceX; published analyses from other sources; as well as our own engineering and aerodynamic estimates.

Earth Launch mass is under 11 mt, which is within the estimated capability of a Falcon Heavy, with margin. Total entry masses between 7 and 10 mt were considered with closure occurring between 9 and 10 mt. Propellant mass fractions for each major phase of the EDL - Entry, Terminal Descent, and Hazard Avoidance - have been derived. An assessment of the entry conditions on the thermal protection system (TPS), currently in use for Dragon missions, has been made. And shows no significant stressors. A useful mass of 2.0 mt is provided and includes mass growth allowances for the MAV, the ERV, and mission unique equipment.

We also report on alternate propellant options for the MAV and options for the ERV, including propulsion systems; crewed versus robotic retrieval mission; as well as direct Earth entry.

International Planetary Protection Policies as well as verifiable means of compliance will have a large impact on any MSR mission design. We identify areas within our architecture where such impacts occur.

This work shows that emerging commercial capabilities can be used to effectively integrated into a mission to achieve an important planetary science objective.

Nomenclature

abbrev.	full name		abbrev.	full name
COSPAR	Committee on Space Research		MER	Mass Estimating Relationship
C3	launch energy, km^2/sec^2		MOLA	Mars Orbiter Laser Altimeter
COTS	Commercial, Off the Shelf		MON3	Storable propellant oxidizer
DoD	Department of Defense		MEPAG	Mars Exploration Program Analysis Group
EDE	Earth Direct Entry		MSL	Mars Science Laboratory
EDL	Entry, Descent, and Landing		MSR	Mars Sample Return
EEV	Earth Entry Vehicle		NOFB	Nitrous Oxide Fuel Blend
ERV	Earth Return Vehicle		mt	metric tonne (1000 kg)
FH	Falcon Heavy		S/C	Spacecraft
GLOM	Gross Lift Off Mass		SDT	Report of the Mars 2020 Science Definition Team
Isp	Specific Impulse, secs.		SRP	Supersonic Retro Propulsion
ISRU	*In-situ* Resource Utilization		TMI	Trans Mars Injection
LCH_4	Liquid Methane		TPS	Thermal Protection System
LOX	Liquid Oxygen		ΔV	Delta Velocity or delta-V
LTO	Lunar Trailing Orbit			
MAV	Mars Ascent Vehicle			

I. Introduction

MARS Sample Return (MSR) has been identified as the highest priority planetary science mission for the next decade by the most recent version of the Decadal Survey of Planetary Science[1]. MSR has been the subject of several studies within the last three decades[2 – 6]. Proposed missions resulting from those studies have been large, complex, and by extension, costly. This paper provides an overview of the results of a study of a new MSR architecture. This new architecture leverages the use of emerging commercial capabilities in order to reduce the complexity and cost of previous approaches.

The objective of the study was to determine whether emerging commercial capabilities can be integrated into to such a mission. The premises of the study is that commercial capabilities can be more efficient than previously described systems, and by using fewer systems and fewer or less extensive launches, overall mission cost can be reduced. The original sampling intent of the planetary science community is preserved in the new architecture. The architecture is applicable and feasible within three consecutive synodic launch opportunities, beginning in 2022. The earliest opportunity is particularly relevant since the proposed Mars 2020 rover mission will be tasked with sample gathering for future retrieval. The architecture covers a complete mission with all required elements and achieves mass closure.

II. MSR Mission Concept of Operations

The MSR mission is illustrated in Fig. 1 and begins with the launch of a SpaceX Falcon Heavy (FH) (currently underdevelopment). The payload for the FH is a modified version of a SpaceX Dragon capsule, designated as "Red Dragon", along with a trunk. The Red Dragon capsule is modified to carry all the hardware needed to return samples collected on Mars. These elements include a Mars Ascent Vehicle (MAV) and an Earth Return Vehicle (ERV). Also included are systesm to support the MAV / ERV and the hardware needed to transfer a sample collected by 2020 rover mission to the ERV. 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. The launch and cruise operations are similar to traditional Mars missions.

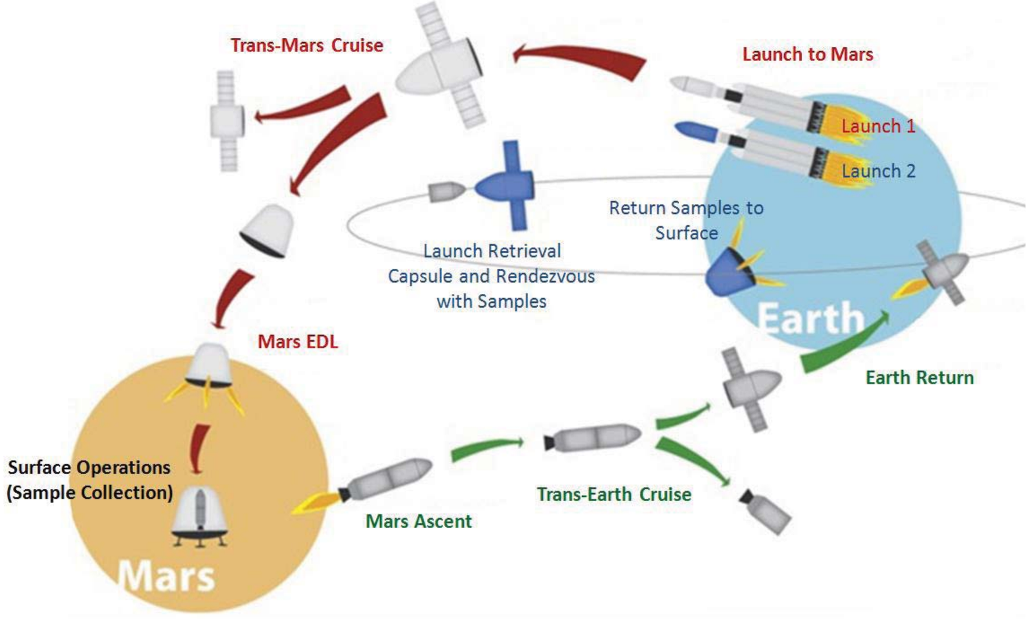

Figure 1. Mars Sample Return Mission Architecure Diagram

Upon arrival at Mars, Red Dragon performs a direct entry followed by a non-traditional EDL using a lifting trajectory with bank angle modulation and Supersonic Retro Propulsion (SRP). Parachute braking or descent is not performed.

After previously collected samples are transferred to the ERV, the single-stage 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 Earth and lunar swing-bys and enters into a, Lunar Trailing Orbit (LTO) – a high Earth orbit, at lunar distance and inclined to the plane of the Earth-moon system. A later mission, possibly a capsule type vehicle such Dragon, performs a rendezvous with the ERV in the LTO. The retrieval of the sample container from the ERV must breaks the chain of contact with Mars by transferring the sample into a sterile and secure container.

This retrieval option can also be performed with other comibnations of capsule and launch vehicle can be either crewed or robotic. With the sample contained, the retrieving spacecraft, makes a controlled Earth re-entry preventing any unintended release of pristine Martian materials into the Earth's biosphere. The retrieving spacecraft will follow a course to the moon that is similar to an Apollo profile but will perform a swing-by to match the ERV oribt. The return can either be performed propulsively, for a crewed case, or by another lunar swing-by in a robotic case.

A return option in which an Earth Entry Vehicle (EEV) performs an Earth Direct Entry (EDE) with the sample is also a possibility. This approach is similar to one used in the MSR Orbiter Mission study [3] . The EEV in that study is too massive to fit within the architecture reported here. The application of advanced entry systems and Thermal Protection System, (TPS) technologies currently within NASA's portfolio, may provide sufficient mass reductions – provided that Planetary Protection reliabilities can be achieved.

The direct Mars to Earth approach defines the key concept of this architecture. The Red Dragon enables the architecture by providing the required Mars landing capability. On the other hand the ERV balances the architecture by being the element that travels the furthest and carries the sample.

III. Study Methodology

To ensure feasibility, the MSR study team investigated a prioritized listing of elements to understand ramification of the architecture options. Trajectory detailing transit to Mars and back have been reconciled with Earth and Mars launch capabilities. These capabilities include an Earth launch vehicle under development, Falcon Heavy, as well as a custom designed MAV that utilizes design heritage and technology within the current state of the art. An assessment of launch mass versus launch energy for the three opportunities was used. A parametric assessment of the MAV was made based on an extensive database of aerospace technology, linking standard, aerospace engineering tools. The TRL of actual components that can be used in the MAV is high. Some elements are currently in use for DoD applications. The Earth Return Vehicle (ERV), the element that drives overall mission performance, was scrutinized by two separate approaches. A parametric approach, similar to that used for the MAV was compared to a "bottoms up" design using COTS components. The MAV plus ERV stack was optimized over several iterations and convergence was achieved. While the MAV was assessed parametrically, the ERV was assessed both parametrically and "bottoms up". Supporting, mission equipment such as the sample collection and transfer system and internal structures were conceptually designed to yield a sensible comprehensive understanding of the system. The critical Entry Descent and Landing (EDL) portion, performed propulsively by Red Dragon, using a lifting trajectory with bank angle modulation, was examined and is described in a forthcoming paper[7].

Mass rollups for all elements of the selected family of options produce an architecture that closes using storable propellant for the MAV.

As a means to sample the alternative architectural space, other options such as Earth Direct Entry (EDE) and Mars *in-situ* resource utilization (ISRU) were concurrently studied. Although mass savings can be achieved by using ISRU, power requirements and development lead time for the ISRU processing equipment are both high. For the EDE case, an EEV similar to that used in the MSR Orbiter Mission study[3] is too massive requiring additional development work as stated earlier.

IV. Architecture Element Description

The major hardware items required for the MSR mission are described in this section and include an integration of hardware derived from emerging commercial capabilities; maturation of small spacecraft design techniques; new utilizations of traditional aerospace technologies, and the application of recent technological developments. Also described in this section are the EDL approach; options and approaches for the ERV; propellant options for the MAV; and interfaces to the Mars 2020 Rover mission.

A. Falcon Heavy

The Launch vehicle for the Red Dragon MSR mission will be the Falcon Heavy, currently under development by SpaceX. Performance of the Falcon Heavy has been derived by others[8] and is shown in Fig. 2. The first flight of the Falcon Heavy has not yet occurred, however, SpaceX has made steady progress in the development of their Falcon 9 line. The Falcon Heavy Launch Vehicle is an example of an emerging commercial capability. Earth Launch mass is less than 11 mt, which is within the estimated capability of a Falcon Heavy, for launch opportunities in 2022, 2024, and 2026. The highest C3 from these opportunities, 13.2 km^2/sec^2, was used. The C3 for the 2026 opportunity is significantly less. Launch margins vary between 22% and 27%. A representation of the launch mass is shown in Fig. 3.

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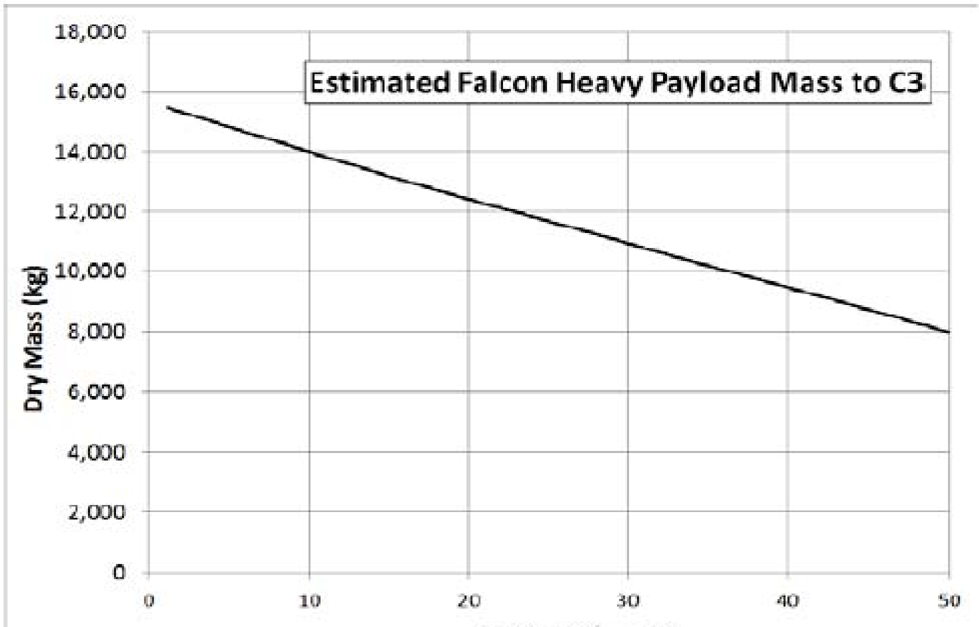

Figure 2. Derived Falcon Heavy Launch Performance[8]

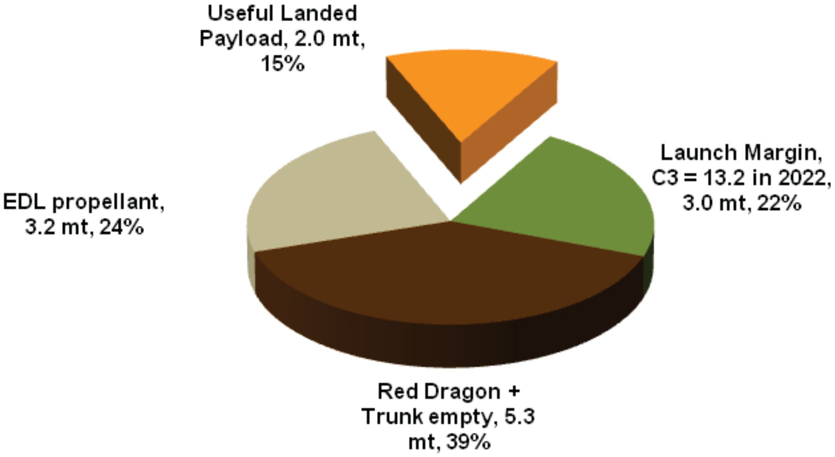

Figure 3. MSR Launch Mass Representation

B. Red Dragon Capsule

The Red Dragon capsule will be a modified version of the Dragon capsule currently in service as a cargo re-supply and return vehicle. Dragon will be upgraded by SpaceX to carry crew and eventually perform ground landings. The Dragon capsule is another example of an emerging commercial capability. Two of the SpaceX upgrades are applicable to the MSR mission: 1) Addition of Super Draco thruster for launch orbit and possible ground landing assist. 2) Landing legs for ground landing. It is anticipated that these legs will extend through ports in the Dragon heat shield.

There will have to be additional modifications to the standard Dragon capsule in order for it to become a Red Dragon suitable for MSR. Important modifications are listed in Table 1.

Table 1. Red Dragon MSR Modifications

No.	MODIFICATION ITEMS
1	Interior modifications to the Dragon to incorporate and structurally support the MAV within a launch tube will be required. It is anticipated that attachments to existing hard points can be made, as shown in Fig. 4. A complete structural evaluation will also need to be made, however, comparing anticipated MSR loads to load cases required for human rating lends confidence in the capability of Red Dragon to perform the MSR mission.
2	Additional tanks will be required to carry the propellant required for the complete EDL process, including terminal descent and hazard avoidance. A possible tank arrangement scheme is shown in Fig. 5.
3	An 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 that requires complex ducting. Another option is a "missile silo" type vertical vent annulus that requires turning vanes at the base of the MAV. A more direct approach utilizes a port or hatch in the heat shield, directly below the MAV, as shown in Fig. 6 was selected. Entry heating is low and it has been mentioned that landing leg ports will be introduced by SpaceX. There is also precedent for heat shield hatches, from such items as Space Shuttle landing gear and umbilical doors.
4	A robotic arm will be installed along with a mechanism for opening the Red Dragon side hatch. These mechanisms will be required to obtain a contingency sample as well as to transfer the sample container from the rover to the ERV at the top of Red Dragon.

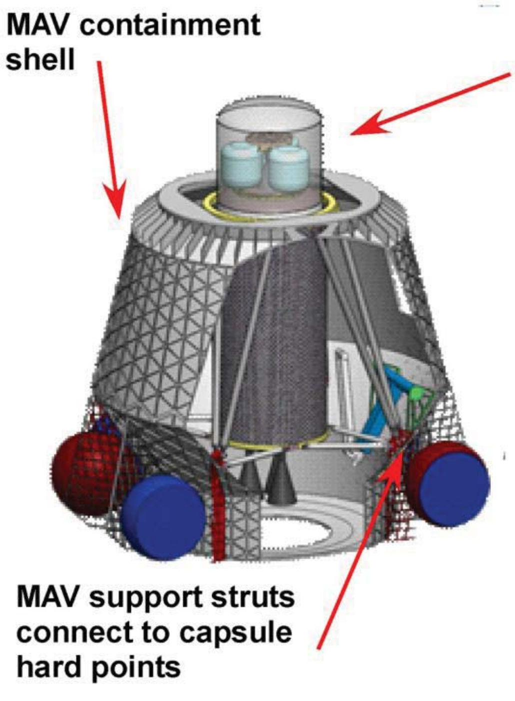

Figure 4.MAV Mounted in Red Dragon

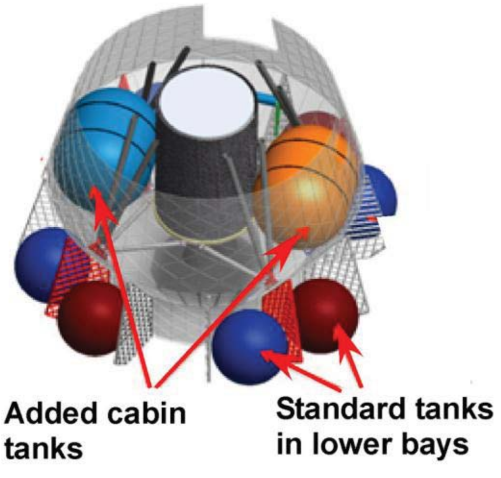

Figure 5. EDL Propellant Tank Arrangement

C. EDL Approach

The analysis of the EDL approach for Red Dragon, included a determination of propellant mass fractions for entry, terminal descent, and hazard avoidance. The propellant quantity will require mission unique tanks as part of the support equipment package. An assessment of the effect of the entry conditions on the thermal protection system (TPS), currently in use for Dragon missions, has also been performed and indicated a non-stressing condition. Details of the EDL approach are described in a forthcoming paper[7] and are summarized here. The Red Dragon will utilize a lifting trajectory, combined with bank angle modulation in order to fly the entry and landing trajectory until the point that retro propulsion can be utilized. The Super Draco thrusters will perform the final braking, terminal landing, and hazard avoidance. No parachutes are utilized in this approach. This is an example of an application of recent technological developments. Total entry masses between 7 and 10 mt were considered with closure occurring between 9 and 10 mt. The entry mass includes 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, the ERV, and the support equipment. A representation of the entry and landed mass is shown in Fig. 7.

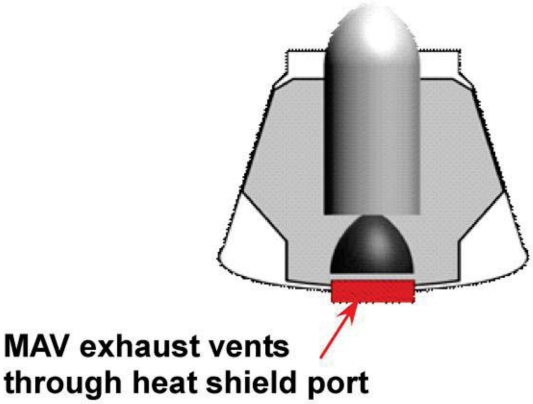

Figure 6. MAV Exhaust Venting Approach

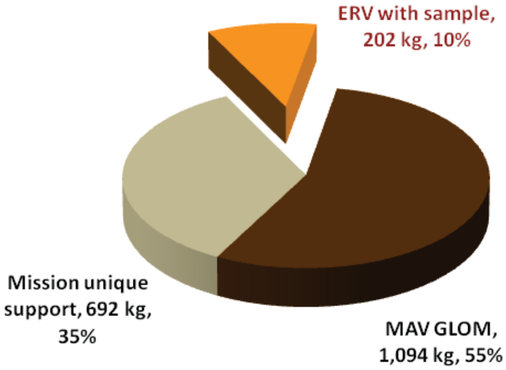

Figure 7. Red Dragon Entry Mass Representation

D. Earth Return Vehicle and Retrieval Options

The ERV balances the architecture since its mass travels the farthest, including a decent to and ascent from Mars, therefore 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. In the baseline MSR architecture, the ERV has several functions.

The ERV receives a the sample from a rover, and after it is launched into a temporary phasing orbit, inject 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 later mission, retrieves the sample container as shown in Fig. 8. In this approach, a Dragon or Orion capsule, operated by a crew or robotically, performs a rendezvous with the ERV and uses a arm to transfer the sample container to a sealed volume in the nose of the capsule. The capsule then performs an Earth re-entry. In this baseline, the ERV propulsion system includes standard MON3 and pump fed main thrusters. ERV alternatives are listed in Table 2.

After assessing the possible alternatives, no conclusive decision was reached for option 1. Options 2 and 3 are now considered part of the baseline. Option 4 was rejected since NOFB has not yet been flight tested. Option 5 has not yet been accepted within the baseline due to the high mass of the EEV. An effort to significantly lighten the EEV, as future work described in Section VI, may allow EDE to be reconsidered along with Planetary Protection Policy implications associated with sample container handling.

During the early portion of the MSR study the ERV mass was defined by a coupled set of Mass Estimation Relationships (MERs). Such a parametric

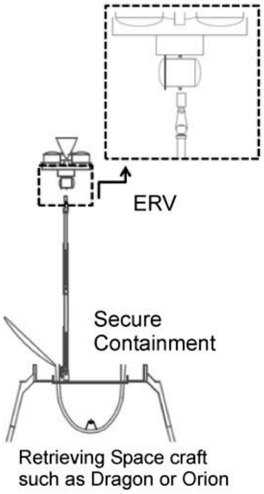

Figure 8. LTO Sample Retrieval

approach treats the masses (and sometimes volumes) of all the significant subsystems (thrusters, tanks, structure, etc.) as idealized, analytic functions. The MERs predict the mass of a future system based on an historical database of previous systems of an analogous nature. The original baseline described earlier and a ΔV budget distribution is as presented in Table 3. The budget giving the highest total, for the 2026 opportunity, was used. The total for the 2022 opportunity is slightly less. ΔV reserves for ascent propellants and the ERV trajectory are also provided. The parametric design masse budget for the ERV is summarized in Table 4.

Give the critical balancing nature of the ERV, a later, bottoms-up estimate was performed using actual COTS components to meet performance requirements. This bottoms-up approach utilized alternative options 2 and 3, described in Table 2. The bottoms-up MEL is shown in Table 5. Option 5, EDE as described in Table 2, is not included since it does not provide a closed architecture. A separate breakdown for jettisoned elements, option 2, is provide. By comparing Tables 4 and 5 it can be seen that the bottoms-up mass is slightly greater than the parametric mass but we conclude that the architecture remains closed. The bottoms up design accounts for a sample container design. The mass allocation of 500 g for the sample follows MEPAG guidelines[9].

Table 2. ERV Options

No.	ERV OPTION ITEMS
1	The retrieving spacecraft can be either A crewed or robotic mission and using spacecraft under development such as a Dragon or Orion capsule. An arm is used to bring the sample into a sealed chamber. In this study, both options were defined, however, no conclusive choisce has been made. Robotic operations are inherently less expensive. On the other hand, the expense of the crewed option provides contingency capability and as well as an opportunity to operate in cis-lunar space.
2	The propulsion system for the ERV can include a set of tanks that can be jettisoned, in a 1 and ½ stage approach.
3	Main thrusters can be pressure fed to reduce development risks associated with small engines that require the multiple burns shown in Table 3.
4	Use Nitrous Oxide Fuel Blend (NOFB) rather than propellant with MON 3oxidixer in a pressure fed configuration. NOFB is a single part blend of fuel and oxidizer. Propulsion system mass savings are possible due to the reduction in the number of tanks and amount of plumbing. NOFB can be transported and handled without undue precautions or hazards. NOFB has not yet been space tested.
5	Instead of operations in LTO, the ERV will deploy an Earth Entry Vehicle (EEV) that carries the sample in an Earth Direct Entry maneuver (EDE). Within the study, this approach was initially modeled as the superposition of the EEV as defined in the MSR Orbiter Mission study[3] on the ERV. The use of EDE will eliminate the need for launch and operation of a retrieval spacecraft.

E. Mars Ascent Vehicle

The function of the MAV is to launch its payload, the ER,V from the surface of Mars to a temporary phasing orbit. The Mars Ascent vehicle was designed as a single stage to orbit. The initial launch point was 0 m MOLA altitude, 0º Latitude and 0º Longitude. Trajectory heading was due East. The latitude range of the landing / launch site was later expanded to +/- 45 degrees. The MAV was sized for each value of total ΔV and assumed payload mass using a set of assumptions and ground rules. These values were consistent with the results of other portions of the work and were tracked and updated through the course of the study. The ΔV budget distribution for the MAV is presented in Table 6. These assumptions are based on best practices and experience for the conceptual design phase. The results for this portion of the MSR study showed the technical feasibility of MSR stack consisting of a single stage MAV and with the ERV as its payload. The ERV was described in the previous section. A set of MERs at the subsystem level 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. These MERs included the expected elements such as structures, power system, propulsion system, nose fairing, thermal insulation, actuation devices, guidance and communication. Best practices were and State-of-the-Art and traditional aerospace technologies were used . A dry mass growth allowance of 30% was used for all dry mass elements.

Preliminary analysis of Red Dragon indicated that the capsule could land up to +2000 kg at terrain elevations between -0 and – 4 km MOLA elevation. Available Red Dragon internal volume allocated to the MAV and ERV, is approximately1.2 m diameter and 4+ m length. The MAV could not reach the full 2000 kg limit; however, since mass for support equipment was needed.

Table 3. ERV Design ΔV Budget Distribution

Trajectory Component	ERV ΔV, m/s
Circularization at Mars Phasing Orbit	37
TEI	2114
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	**2939**
7.2% Reserve	211
Total ΔV	**3150**

Table 4. 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**

Table 5. ERV Bottoms Up COTS Design Mass Budget – kg

incl 30% growth unless noted and incorporates opions 2 & 3 from Table 2

Subsystem	Component (units)	Mass
ADACS	Star Tracker (1)	0.80
	IMU (1)	0.98
	Sun Sensor (4)	0.05
	RWA (4)	3.6
C&DH	Integrated Avion. (1)	6.9
Power	Battery Pack (3)	6.24
	Solar Array (1)	1.59
Structure	Dust Cove (1)r	0.91
	Fasteners, Hinges, Latches (1)	3.90
	Cabling (1)	2.60
	Second. Struct (1)	0.44
	Prim. Struct. (1)	4.39
Telecomm	LGA (2)	0.21
	HGA (1)	1.6
	Transpond, XS (2)	7.8
	Diplexers (3)	1.4
Thermal	Coatings (1)	0.13
	Heaters (12)	1.40
	MLI (1)	0.04
	Temp. Sensors (6)	0.39
	Thermoelectric Cooler (1)	0.13
Propulsion	Fixed tank (2)s	4.0
	Jettisoned tanks (2)	9.2
	Fixed valves / filters (2)	2.7
	Jettisoned valves / filters (2)	2.7
	Main thruster (1)	6.8
	Vernier thrusters (6)	3.5
	Structure (1)	2.0
	Jettison mech (1)	1.3
Payload	Sample Container – 50% mass growth (1)	4.0
	Sample – 20% mass growth (1) [11]	0.60
Subtotal dry		**82**
Propellant		**129**
Total wet		**211**

A feasible MAV/ERV design has been demonstrated with gross liftoff mass of 1300 kg. The MAV overall body length and diameter are compatible with the Red Dragon. A set of design and trade studies, as listed in Table 7 have been completed using multiple iterations. From these studies a baseline configuration was defined and sensitivity studies about the baseline design were performed. A description of a representative subset of this data is included in Table 8. Full documentation will be available in a forthcoming NASA Technical Memorandum[10]. A combined mass and dimension statements for the MAV / ERV stack is provided in Table 9. Overall dimensions are given in Table 10. The entry mass for the MAV, ERVV and support equipment is shown in Fig. 7.

Table 6. MAV Design ΔV Budget Distribution

Trajectory Component	MAV ΔV, m/s
Orbital	3299
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	**4101**
3.6% Reserve	149
Total ΔV	**4250**

Table 7. MAV Design &Trade Studies

No.	MAV STUDY ITEMS
1	Fore body shape.
2	Propellant tank configuration – intertank space versus nested tanks.
3	Propellant feed – pumped versus pressure..
4	Propellant type – storable versus cryogenic (LOX manufactured on Mars using ISRU techniques).
5	Oxygen / Fuel ratio
6	Number of engines – 1 to 3
7	Engine chamber pressure
8	Engine nozzle expansion ratio
9	Isp

Table 8. Representative MAV DATA

No.	MAV DATA ITEMS
1	Design and analysis methods used for each of the technical areas based on Engineering-level MER's derived from historical data for each of the major subsystem.
2	Higher fidelity codes used, as needed, to supplement the engineering methods
3	Aerodynamics and aero-thermodynamics where computed using CBAERO and CART3D.
4	Ascent was optimized with defined aerodynamics and data from The Mars GRAM atmospheric model, using the POST2 trajectory code. Table 6 presents the velocity loss breakdown for the ascent trajectory to 100km X 250km.
5	Aero loss, thrust vectoring loss, and atmospheric loss are all small. .
6	Rocket engine performance predicted using a quasi-one dimensional nozzle flow, for a pump-fed, engine, including appropriate thermodynamic and chemical performance as adjusted by comparison to a known reference engine.
7	Nested tank configuration was selected to reduce overall vehicle length
8	General arrangement for the baseline MAV configuration and the internal tank design are shown in Fig. 9.

Table 9. ERV & MAV Combined Stack Mass Statement

Category	Mass - kg
MAV dry	106
30% mass growth allowance	32
Subtotal MAV dry	**138**
ERV wet as payload to the MAV	205
Subtotal MAV dry + ERV wet	**343**
MAV propellant, including residuals	955
GLOM	**1298**

Table 10. ERV & MAV Overall Dimensions

Category	Dimension - m
Length	2.80
Diameter	1.02

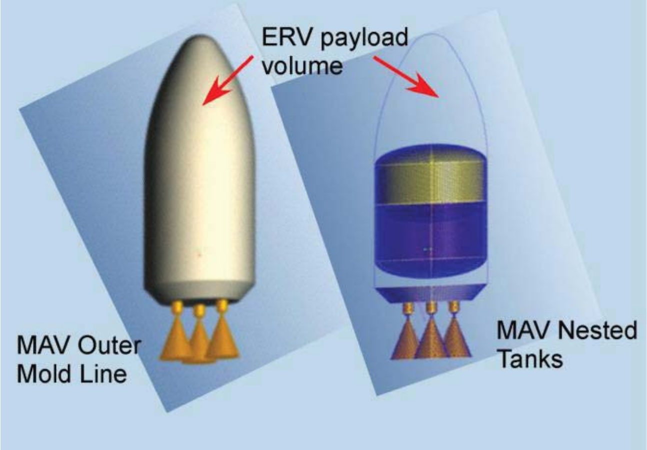

Figure 9. General MAV Arrangment

F. 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. These included LOX / RP-1 and LOX Liquid CH_4/. 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 Mars Human Reference Mission Architecture[11]. Workable MAV designs were produced and 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.

G. Interface to Mars 2020 Rover Mission

The major elements of the Mars 2020 Rover mission are presumed to 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 MSR architecture described in this paper. The rover will be tasked with collecting and caching samples as defined in the Report of the Mars 2020 Science Definition Team [12] (SDT). It is assumed that the sample container will be 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 is feasible.

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 diversion, Red Dragon can land at any of the sites described in the SDT[12]. The rover will have to be able to drive up to within reach of the arm on Red Dragon. The rover must be able to present the sample container in a manner that can be transferred to the ERV at the top of Red Dragon. This interaction is depicted in Fig. 10

For total mission success of both the Mars 2020 rover mission and an MSR mission launched in 2022, planning and development must be coordinated starting early in the life cycle of each, mission considering the time lag between the two.

V. Planetary Protection Policy Considerations

International Planetary Protection Policy is governed by an International Treaty[13] that has been ratified by the United States. Specific implementation requirements have been developed by COSPAR[14]. This MSR architecture will be impacted by several Planetary Protection Policy provisions that span across the various mission elements. Both the pristine Martian material returned from Mars as well as flight hardware that has been on Mars will have to be contained. Important Planetary Protection impacts for this MSR mission, have been identified. These impacts, along with critical factors, are summarized in Table 12. A forthcoming paper[15] will address the end-to-end requirements for Planetary Protection in a MSR mission in more depth.

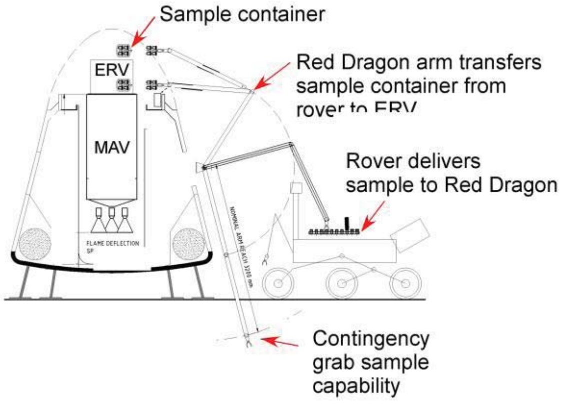

Figure 10. Rover to Red Dragon Sample Transfer

Table 12. Planetary Protection Considerations for MSR

No.	PLANETARY PROTECTION IMPACT ITEMS
1	The exterior surfaces of Red Dragon will be exposed to the terrestrial environment during processing and launch. These surfaces will also be exposed the space environment while in transit to Mars.
2	The interior surfaces of Red Dragon will need to be sterilized .
3	The sample handling robotic arm grab sample end effector will need to be sterilized.
4	The exterior of the sample container delivered by the 2020 rover will be exposed to Mars material and will need to be contained whether it is retrieved in a LTO or is returned via EDE.
5	The exterior surfaces of the ERV will be exposed to Mars materials. If the ERV is operated in the LTO mode, it will be disposed to a heliocentric orbit. If the ERV is operated in the EDE mode, it will fly-by the Earth after the EEV is targeted to Earth entry, and remain on its hyperbolic orbit. In neither case will the ERV enter the Earth's biosphere or impact the moon.
6	The interior surfaces of the EEV, if the EDE mode is used, will be sealed and contained after the sample container is loaded onboard.
7	The exterior surfaces of the EEV, if the EDE mode is used, will be exposed to Mars. Protecting all of the exterior surfaces, including the sample container loading port, will be a problem area.

Items 5 and 7 will provide the largest Planetary Protection challenges and methods to address them may drive large portions of the architecture – for example, the decision to utilize the LTO or the EDE option As described earlier, LTO requires another Earth centric mission, but EDE requires the development of containment and sample container transfer mechanisms; advanced TPS technology (currently in NASA's portfolio); and structures technology to ensure that the chain of contact between Mars and Earth is broken.

Fig. 8 illustrates both the retrieval and containment strategy for LTO that was studied. For EDE, several notional containment schemes were postulated but not studied in depth. These schemes include coatings and mechanisms for loading the sample container into the EEV. These schemes are not yet mature and will need to be addressed as part an overall EEV study.

VI. Conclusion and Major Findings

A MSR mission in the 2022 opportunity that retrieve samples collected by the Mars 2020 rover is feasible with the use of emerging commercial technologies integrated with other types of techniques derived from traditional and new sources. The Major Findings in Table 12 provide key points. The significance of the work is that it opens the door to the efficient achievement of an important planetary science objective at a lower complexity level and by extension, a potentially lower cost than previously considered.

Table 12. Major Findings Support the Application of Commercial Capabilities for MSR

No.	MAJOR FINDING
1	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 requirements for the 2024 and 2026 opportunities are lower.
2	EDL using Red Dragon in a lifting trajectory, decelerating aerodynamically and with supersonic retro-propulsion can soft land a vehicle mass of 6,600 kg, including 2,000 kg of useful payload mass, onto the Martian surface.
3	The payload is a fully fueled Earth return launch system capable of launching a small (5 kg) payload directly to Earth. Also included is a sample transfer and storage system with grab sample capability as well as structural supports and exhaust venting to accommodate the launch vehicle. Vehicle health systems are also included.
4	The LTO recovery option can be designed within the ERV mass and volume goals, with confidence and without requiring the infusion of advanced technology. An EDE mission option can be designed within the ERV mass and volume goals, if an EEV probe mass ≤ 20 kg can be achieved. This design goal may be achievable with the infusion of advanced entry systems configurations and TPS currently within NASA's technology development portfolio.
5	Employing propellant tanks that are jettisoned can produce useful mass savings for the ERV, and thus the entire architecture.
6	Employing pressure fed engines for the ERV reduces development risks associated with small engines that require multiple starts.
7	The ERV along with the LTO and EDE recovery options are high priorities for future study.
8	Planetary Protection policy, as determined by international agreements, will influence sample transfers and sample recovery processes. High reliability requirements are key drivers.
9	The use of ISRU in the same way as described in potential human exploration missions is not feasible within the earliest of the opportunities examined. High volume, high power – requiring a nuclear power plant, and low equipment TRL work against this option.
10	A MSR mission in the 2022 opportunity that retrieve samples collected by Mars 2020 rover is feasible by integrating emerging commercial capabilites with other esisting and new types of capabilities.

VII. Future Work

Moving forward, Table 13 shows recommended future work. If this MSR option advances to the point where it is acted upon, initiation of joint mission planning between the Mars 2020 Rover project and this potential MSR project should begin at the earliest possible date.

Disclaimer

The work described in this paper was performed internally by NASA's Ames Research Center using information in the public domain and without the assistance of any commercial organization. There is no endorsements of any particular commercial organization by NASA. There is also no endorsement of this work by any particular commercial organization.

Table 13. Recommended Future work

#	FUTURE WORK TASK	TASK SCOPE
1	Mission Cost Estimate and Explore Partnership Opportunities	Determine a realistic engineering cost estimate, and determine partnership opportunities
2	CFD Study of Supersonic Retro-propulsion	Mission specific application of Supersonic Retro Propulsion
3	Earth Return Vehicle design studies – technical elements equivalent to pre ϕ A study.	Define and Document a study that defines a full set of mission and spacecraft requirements and provides a preliminary design using COTS components with appropriate margins and growth allowances.
4	Detailed study of a lighter weight EEV to allow reconsideration of EDE.	Application of current Thermal Protection System technology and addressing containent and high reliabilityentry requirements imposed by Planetary Protection Policy[14]. Trade study of EEV development versus the cost of a LTO retrieval mission.
5	Detailed study of Mars Ascent Vehicle (MAV).	Application of current technology from DoD programs.

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