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Mars Molniya Orbit Atmospheric Resource Mining

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Abstract

Landing on Mars is extremely difficult [1] and is considered one of NASA's biggest technical challenges on the journey to Mars. Science magazine [2] reported the following about the NASA Mars Science Lab (MSL) Mission:

> "Not only will NASA have to slow the most massive load ever delivered to another planet's surface from hypervelocity bullet speeds to a dead stop, all in the usual "7 minutes of terror." But NASA is also attempting to deliver Curiosity to the surface of Mars more precisely than any mission before, within a 20-kilometer-long ellipse some 240 million kilometers from Earth. Both feats are essential to NASA's long-term goals at Mars: returning samples of Martian rock and sending humans to the Red Planet."

As a result of the thin Mars atmosphere, this challenge is exacerbated as the payload mass is increased. This NASA Innovative Advanced Concepts (NIAC) project has studied one of the top challenges for landing large payloads and humans on Mars by using advanced atmospheric In-Situ Resource Utilization (ISRU) methods that have never been tried or studied before. The proposed Mars Molniya Orbit Atmospheric Resource Mining concept mission architecture changes the paradigm of Mars landings for a wide range of vehicle classes to make the Earth-Mars round-trip travel robust, affordable, and ultimately routine for cargo and crew, therefore enabling the expansion of human civilization to Mars.

Keywords: Mars; Entry, Descent & Landing (EDL); In-Situ Resource Utilization (ISRU)

Acronyms/Abbreviations

Entry, Descent & Landing (EDL),
In-Situ Resource Utilization (ISRU)
magnetohydrodynamic (MHD)
Mars Ascent Vehicle (MAV)
Mars Descent Ascent Vehcle (MDAV)
NASA Innovative Advanced Concepts (NIAC)
Resource Collector Vehicle (RCV)
Single Stage Reusable Lander (SSRL)
solid oxide electrolysis (SOE)
supersonic retro-propulsion (SRP)

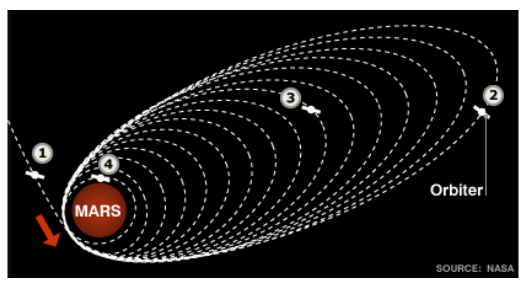

Figure 1. A representative decaying highly elliptic Molniya orbit around Mars.

1. Introduction

In situ resource utilization (ISRU) on the surface of Mars has been proposed and studied for making rocket propellants, in order to fuel a Mars Ascent Vehicle (MAV) [3, 4], but using ISRU in Mars orbit to make propellants for supersonic retropropulsion (SRP)-enabled Entry, Descent and landing (EDL) is a new concept, which creates an unprecedented association of ISRU, including energy harvesting, and EDL.

Molniya is the Russian word for *lightning*, and in this study, a highly elliptical Mars orbit is referred to as a *Mars Molniya orbit* because of the high velocities encountered at periapsis (Figure 1). Our calculations and modeling indicate that the scooping velocities achieved at periapsis will range from 3.57 km/s to 4.5 km/s. Similar orbits are used in Earth applications, but we are not constraining ourselves to the definition of an Earth Molniya orbit. Typically during aerobraking, kinetic energy is converted into heat energy and wasted, but in this concept, the heat and associated plasma are transformed into magnetohydrodynamic (MHD) electricity generation, heat transfer, and thermal storage for endothermic chemical ISRU solid oxide electrolysis (SOE) processes, and the high velocity of the spacecraft is used for hypersonic ram compression of atmospheric gases for storing and making liquid O_2 oxidizer for SRP-assisted EDL.

1.1 Background

From 1956 to 1963, S.T. Demetriades proposed three methods of atmospheric gas accumulation: (1) by means of a satellite moving in a 120 km low Earth orbit, (2) by accumulating propellants on the surface of a planet, or (3) by gathering and exploiting interstellar matter. He called this concept the PROpulsive Fluid ACcumulator system (PROFAC). Wilkes and Klinkman revived the idea in 2007 [5]. In 2007, B. Palaszewski proposed atmospheric mining in the outer solar system (AMOSS) because of the abundance of valuable resources such as hydrogen and helium 3 for potential use in nuclear power and propulsion systems [6]. The primary targets considered by Palaszewski were Uranus and Neptune.

Demetriades' proposal was further refined by C. Jones and A. Wilhite in 2010 in the Propellant Harvesting of Atmospheric Resources in Orbit (PHARO) concept, describing multiple collection vehicles that would accumulate propellant gases approximately 120 km above Earth, and later transfer them to a higher orbit [7]. In 2015, D. Arney et al. published a paper at the AIAA Space Forum titled, "Sustainable Human presence on Mars Using ISRU and a Reusable Lander," [8] which defined a Mars SSRL vehicle using O_2 and CH_4 propellants made on the surface of Mars.

Our NIAC study draws from these previous efforts to show, for the first time, that atmospheric mining of CO_2 and ISRU processing on orbit and on the surface of Mars is a potential solution for developing and operating a large reusable Mars Descent Ascent Vehcle (MDAV) / Single Stage Reusable Lander (SSRL).

2. Description and Benefit of the Concept

2.1 Description of Orbital Resource Mining and Resource Utilization

By using ISRU, propellant and logistics items do not have to be transported from Earth, which makes self-sustainment and independence possible for the pioneering Martian astronaut crews.

This NIAC Phase I study has expanded the possibilities of ISRU at Mars, not only in using propellant made on the surface, but also in using propellant and electrical energy generated on orbit via plasma-harnessing MHD, scooping and ram-compressing the 95% CO_2 Martian atmosphere, and by using indigenous resources on the surface of Mars (CO_2, H_2O). This system can carry four crew members and cargo up to 20 metric tons (t) of landed mass.

By combining the atmospheric orbital ISRU with surface ISRU (CO_2 and H_2O), an Earth-independent MDAV/SSRL with large landed-mass payloads may be possible, which dramatically changes the possibilities for mission designers and crews operating at Mars. The technical descriptions of the required element concepts and their associated technologies are described in the following sections of this report. This concept is at a technology readiness level (TRL) of TRL 2, which means that substantial work is required to advance it to a more detailed level of technical analysis. The goal of this study was to establish the architectural and technical feasibility of this concept through ideation, modeling, and analysis.

2.2 Architectural Advantages of Orbital Resource Mining and Resource Utilization

While it is possible to execute a human mission to Mars through using existing technologies and transporting the propellants through the Earth's deep gravity well all the way to the surface of Mars, a substantial penalty is paid for doing so, as the *gear ratio* for landing 1 kg of mass on Mars requires 10.5 kg to 17 kg to be launched to low Earth orbit (LEO) [9]. Under our approach, transporting propellants from Earth will no longer be necessary in order to be able to land and launch from the surface of Mars. This results in fewer vehicles being launched from Earth and means that smaller propulsion stages are needed to reach Trans Mars Injection (TMI). It also produces a substantial recurring cost savings (billions of dollars) and flexibility in scheduling Mars landings and launches, since the propellant does not have to be sent within a constrained launch window (every 26 months). By using the SSRL, multiple Mars launches and landings could be possible within the typical 18-month Mars visit in a conjunction-class mission. In addition, an abort to Mars orbit and operations from orbit would be possible in the event of a catastrophe on the surface.

The method for achieving this derives from harnessing local resources at Mars. NASA has considered the surface component of this approach before, in a study performed in the 2000's and published as the *Mars Design Reference Architecture 5.0*, [3]. The study considered an ISRU system that would have already been deployed on the surface of Mars, with an estimated mass of approximately 1 t, and 400 kg of imported hydrogen. It was estimated that the surface ISRU plant could produce 25 t of O_2 for an ascent vehicle, 2 t of O_2 for crew consumption, and 133 kg of nitrogen/argon buffer gas, and as a by-product, could produce water for crew use. The power requirements were estimated to be between 24 kWe and 30 kWe.

By making propellants at Mars and using them for SRP with a deployable aerobrake, it is also possible to scale up the Mars landed payload mass from the 1 t that is possible today, to 20 t in the future. This would enable human missions that are not possible with existing EDL systems, such as the Mars sky crane system developed by the NASA Jet Propulsion Lab.

Our NIAC Phase I work has shown that it is potentially feasible to use a new Mars EDL and launch system that uses not only surface ISRU (as previously proposed), but also atmospheric ISRU where O_2 is extracted from CO_2 on orbit. This means that the propellant oxidizer doesn't have to be launched through the Mars gravity well for an MDAV/SSRL as proposed by others [10]. This new Mars transportation system is made possible by purposefully infusing energy sources into the architecture. Combining the use of MHD to generate and store large amounts of electrical power in orbit with the use of fission-based power units on the surface is a key innovation that enables the energetic balance to be sustained.

Preliminary estimates indicate that the launch mass of an atmospheric resource collector vehicle (RCV) could pay for itself in two descent/ascent missions in terms of the O_2 propellant produced. All missions after that provide net gains in O_2 propellant by avoiding the requirement for transportation of O_2 propellant from Earth or the Mars surface. Further work is needed in the future to work out specifics, and our team will use the following three published architectures to benchmark and compare our results:

- *Human Exploration of Mars, NASA Design Reference Architecture 5.0* (Drake, 2010)
- Jet Propulsion Lab, *A Minimal Architecture for Human Journeys to Mars* (Price, 2015)
- NASA Langley Research Center, *Sustaining Human Presence on Mars Using ISRU and a Reusable Lander* (Arney, 2015)

3. Mission Architecture and Concepts of Operation

3.1 Ground Rules and Assumptions

The overarching goal of the mission architecture—which provides context to this study—is to enable multiple landings of large payloads and crew vehicles (>= 20 t payloads) on the surface of Mars to sustain the long-term presence of humans on the planet. The objective achieved in Phase I was to provide a system-level technical solution toward the goal of using the acquisition of Mars atmospheric CO_2 during orbital operations and processing the CO_2 into propellant for the landing phase. Two case studies were done: one was an unmanned Mars Sample Return (MSR) and the other was a reference four-crew surface mission. The use of ISRU in orbital operations at Mars provides a potential way to obtain propellant for the EDL of large vehicles at Mars. By successfully using ISRU, we can decrease the launch mass required from Earth and contribute to the sustainability of human exploration of Mars. Ultimately, making optimal use of accessible resources within the Mars planetary system will lead to Mars missions becoming logistically independent from Earth.

3.1.1 Ground Rules **–** The team adopted the overall ground rule that the solution would leverage any assets currently in use by NASA or in development by NASA's Exploration Systems Development (ESD) Division for the Evolvable Mars Campaign (EMC) and other campaign architectures, as well as those developed by academic institutions and private space companies whose aim is to land large vehicles on Mars. New concepts and systems were developed to meet the NIAC Phase I objective. This ground rule aims at maximizing compatibility of the mission concept with existing NASA assets and engage participation of non-NASA developers and stakeholders.

The scope of the Phase I NIAC mission concept was focused on the operations in the Mars system that enable four crew members to descend to the Mars surface, ascend from the Mars surface, and rendezvous with an Earth-Mars transportation system. This focus enabled us to study solutions based on new paradigms in the Mars system while adopting reasonable assumptions for the architecture of the system for transportation from Earth launch to arrival in the vicinity of Mars. Robotic precursor missions such as MSR were included to test capabilities and validate technologies at the destination before launching a crew in order to reduce the risk in reliance on these systems.

3.1.2 Assumptions **–** The mission architecture is founded on the following assumptions.

The current NASA Mars timeline for sending humans to Mars system and return them safely to Earth by the mid-2030s was adopted. It is based on the 2010 National Space Policy of the United States of America.

The Space Launch System is used as the baseline for Earth launches with cadences adopted by EMC studies: 1 per year from 2021 through 2027, then 2 per year starting in 2028. The transition between the 105 t payload capability of SLS Block 1B to the 130 t capability of SLS Block 2B is assumed to be set for 2028. In future work, we propose to examine the potential use of other heavy-lift launch vehicles for transporting cargo and unmanned spacecraft to the Mars system.

The launch vehicle stacks for the Mars missions will be assembled in high Earth orbit (HEO) for rendezvous with the crew vehicles and additional required elements (e.g., limited life in-space propulsion orbital elements) based on EMC studies showing that HEO is an appropriate location for departure and return in an efficient trans-Mars injection orbit.

Our mission architecture uses the Orion crew capsule, the vehicle that NASA plans to use for performing tasks such as delivering a crew from Earth to the HEO staging area and returning the crew from the staging area to Earth at mission end. Because Orion was selected for such tasks independent of architecture or trajectory, in future work we intend to perform a system trade with commercial or partner crew excursion vehicles (e.g., SpaceX), if enough data is available, to verify that this is the optimal selection for this specific mission architecture.

The in-space transportation system used for crew travel between Earth and Mars will be based on chemical propulsion to reduce the transit time for crew and make in-space transportation compatible with emerging concepts of propellant depots in the Earth-Moon system. Only conjunction-class trajectories between Earth and Mars are considered, and a maximum round-trip duration of 1100 days is assumed, including a 300-500 day surface stay. In future work, we intend to perform a system trade between chemical propulsion, solar-electric propulsion, and nuclear propulsion from Earth to Mars to assess costs, development timelines, and synergistic impacts on the architecture.

In the Mars vicinity, the architecture will use a Mars 1-Sol orbit (~250 × 33,000 km) as a waypoint en route to other orbital and surface destinations because it supports arrivals and departures for Earth-Mars trajectories. Low Mars orbit (LMO) is defined as a 250 km circular orbit. In future work, we intend to trade the 1-Sol option with 5-Sol orbits (~200 × 60,000 km) for timeline efficiency and overall capability. A single long-duration surface site located within ±30° of the Martian equator will be targeted so that the infrastructure required for a sustained human presence can be efficiently put into place. The delivered infrastructure will include modular 10 kWe nuclear power systems for continuous high-specific power generation.

4 Mission Design

The concepts of operation for trade studies have been developed as follows:

a. ISRU/Mars Sample Return demonstration mission – 100 kg delivered to Earth
   (1) All propellants are brought from Earth – reference case without ISRU
   (2) Mars surface ISRU is used to make propellants for an expendable Mars Ascent Vehicle (MAV) – no orbital atmospheric mining is used. Supersonic retropropulsion (SRP) is proven while landing the ISRU equipment and MAV.
   (3) Mars Molniya Orbit Atmospheric Mining is used (and proven) to acquire carbon dioxide and make oxygen for SRP lander propulsion, and surface ISRU is used to make propellants for the MAV.

b. Mission architecture for landing human crews on the surface of Mars
   (1) All propellants are brought from Earth – reference case without ISRU
   (2) Mars surface ISRU is used to make propellants for a reusable MDAV/SSRL – no orbital atmospheric mining is used.
   (3) Mars Molniya Orbit Atmospheric Mining is used to acquire carbon dioxide and make oxygen for lander propulsion, and surface ISRU is used to make propellants (LO_2/ CH_4) for the MDAV/SSRL. The MDAV/SSRL carries enough CH_4 fuel into orbit to enable landing on Mars again from a high Mars orbit (HMO) – which has a period of 1 Sol and is a highly elliptical orbit.

Please reference Appendix A for acronyms and representative graphics of the mission architectures.

Please reference Appendix B for a list of all the mission elements and their estimated masses.

5 Analysis Methods and Modeling

This section explains the analytic computer models that were developed to assess feasibility of this concept. The modeling and associated results are described in detail below. The work was divided between all the team members by subject matter expertise. The advanced nature of this work benefited greatly from the government and academic alliance that was formed between NASA and Georgia Tech graduate researchers. Engineering simulations based on physics principles, in addition to proven NASA computer models, were used to ensure an accurate assessment of the component performance within the uncertainty of the low TRL level. The emphasis was on determining the critical variables, their relationships, sensitivity, and ultimately, the feasibility of the concept. Closing the mission case for an MDAV/SSRL using ISRU on orbit and on the surface was the primary goal of Phase I. Other orbital resource mining applications and simulations were deferred to a future study.

5.1 Astrodynamics Model

The astrodynamics of all architectural spacecraft was modeled by using fundamental physics equations modeled in “Matlab” software. The fundamental laws of astrodynamics—Newton’s law of universal gravitation, Newton’s laws of motion, and Kepler’s laws—were used to determine the required change in velocity (ΔV) while Tsiolkovsky's rocket equation was used to determine propellant masses required. Subsequently, parametric modeling with typical existing spacecraft mass fractions (80%–90% propellant) was used to determine the propulsive stages estimated masses. This data was then used to inform our mission architecture concepts of operations (ConOps), including generating launch vehicle payload stacks and launch manifests. The calculated ΔV is summarized in Table 1 for each mission segment.

Mission Segment	ΔV (km/s)	Propellant Required (t) per event	Notes
LEO to HEO	2.46	29-94	CPS H_2/O_2, Highly Elliptical Orbit 407 × >40,000 km
Dock Elements	0.1	1.2	CH_4/O_2
TMI	0.65	17.2	CH_4/O_2, Depart from HEO, TMI burn at perigee
Mars Aerocapture	0.9	Negligible – Aerocapture	Heat Shield RCV & MDAV/SSRL
Mars Aerobraking	1.3	Negligible – Aerobrake	Heat Shield RCV
Raise Periapsis	0.01	Negligible	Raise orbit out of atmosphere
Mars EDL & SRP	4.0	8.5	SSRL Aero decel. & CH_4/O_2 SRP
Mars Ascent to LMO	4.2	110.9	CH_4/O_2, MDAV + CH_4 for EDL
Mars LMO to HMO	1.32	11.3	CH_4/O_2, MDAV + CH_4 for EDL
TEI	1.45	21.9	CH_4/O_2
Earth Capture to HEO	0.80	10.9	CH_4/O_2
Dock with CTV	0.1	1.2	CH_4/O_2
HEO orient and burn for EDL	.092	0.7	Orion

Table 1. Mission Segment Delta V

5.2 Mars Atmospheric Resource Mining Model

5.2.1 Aerobraking and Atmospheric Resource Mining Simulation Algorithm

An aerobraking simulation was developed to assess the effects of the Resource Collector Vehicle (RCV) design on the oxidizer ingestion during the aerobraking campaign. This simulation, along with the EDL and ISRU simulations, was used to determine closure of the overall vehicle architecture.

The aerobraking simulation is composed of two parts, an atmospheric trajectory calculator that determines the state parameters during a single pass through the atmosphere and a wrapper function which propagates and tabulates the orbit and vehicle state between successive passes, starting from the initial highly elliptical orbit and ending with the circular parking orbit.

For a given atmospheric periapsis target, which is assumed to be constant for each pass, and atmospheric interface altitude, a geometric trajectory was constructed in order to determine the average altitude during the atmospheric pass. This geometric trajectory started at the atmospheric interface, passed through the periapsis altitude at its closest approach, and proceeded symmetrically back to the atmospheric interface altitude. The approximate average pass altitude and distance traveled during the pass were determined from the trajectory. The calculation of the approximate average altitude and distance traveled therefore neglected the effects of drag and changing inertia throughout the pass. A second calculation was performed to determine the minimum velocity necessary at the periapsis altitude to attain the final circular orbit altitude. These two parameters were used in the atmospheric trajectory calculator and trajectory propagating functions.

The atmospheric trajectory calculator assumes that the entire pass occurs at the average altitude and with a constant vehicle state. Therefore, all atmospheric parameters, vehicle mass, and vehicle velocity are constant throughout the maneuver. The CO_2 mass flux, MHD power generated, and drag force are all determined by the average altitude, and vehicle and entry state and are integrated based on the atmospheric pass distance to determine total CO_2 ingestion mass, MHD energy available, and change in velocity. The trajectory propagator takes the output from the atmospheric trajectory calculator and applies the vehicle and trajectory state updates, including the added vehicle mass and reduction in velocity, approximating the pass as occurring instantaneously at the trajectory periapsis. The subsequent orbit is calculated based on the updated velocity and the trajectory is propagated to the next pass. When the updated periapsis velocity drops below the velocity required to reach the terminal circular orbit, the simulation stops. Total CO_2 capture is converted to equivalent oxidizer capture based on the overall conversion efficiency of 20% by mass. Total MHD energy stored is based on the MHD power profile and the battery storage system power and energy density.

5.2.2 Assumptions

The following assumptions were used for the modeling algorithm:

a. Passes behave as discrete events.
b. Atmospheric pass parameters calculated are based on the average aerobraking altitude; all are constant during a single pass.
c. Average aerobraking altitude calculations are based on a symmetric entry/exit profile (no deceleration during pass).
d. All atmospheric pass effects are calculated, summed, and applied instantaneously at the orbit periapsis.
e. Start is in a highly elliptic orbit. Atmosphere model: MarsGRAM at median density state https://software.nasa.gov/software/MFS-33158-1
f. Initial orbit: 250 km altitude (periapsis) × 33,793 km altitude (apoapsis)
g. Final orbit: 250 km altitude, circular

Mission Phase	Action
1. RCV stack enters initial orbit	Systems checkout; initial aerobrake orbit entered.
2. Periapsis-lowering burn	Use thruster to lower periapsis to target altitude.
3. Scooping drag near periapsis	With each pass through the atmosphere, the scooping drag reduces the orbit energy and lowers the orbit apoapsis.
4. Apoapsis burns to control periapsis	Apoapsis burns will be made as necessary to adjust periapsis altitude to counter secular orbit disturbances and maintain periapsis altitude within the target window (~79 km).
5. Periapsis-raising burns	As the apoapsis altitude nears the desired level, several apoapsis burns will raise the periapsis out of the atmosphere, therefore stopping the aerobraking (~250 km).
6. Final circular orbit	Thruster burns will now set the RCV stack at the desired orbital parameters (250 km × 250 km).

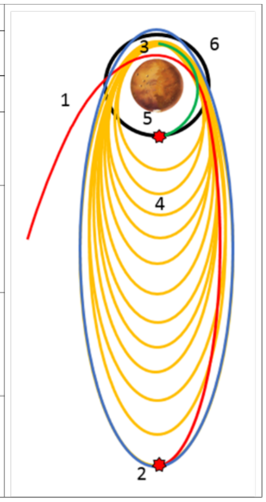

Table 2. Mars atmospheric scooping concept of operations

Parameter	Value	Notes
Aerobraking target altitude (h_periapsis)	80 km	Optimized to enable max CO_2 ingestion
Inlet area (Ain)	24 m²	Adjusted to meet oxidizer ingestion requirements
RCV stack mass (mVeh)	21 t	Based on sizing requirements of vehicle and subsystems, also adjusted to meet ingestion requirements
Hypersonic drag coefficient (Cd)	1.6	Based on heritage data
RCV diameter (Dia)	5.5 m	Based on subsystem packaging requirements and rocket shroud packaging requirements
Atmospheric interface altitude (h_atm)	120 km	Standard value used in Mars EDL modeling

Table 3. Mars Sample Return Mission RCV Parameters

Parameter	Value	Description
Aerobraking target altitude (h_periapsis)	79 km	Optimized to enable max CO_2 ingestion
Inlet area (Ain)	80 m²	Adjusted to meet oxidizer ingestion requirements
RCV stack mass (mVeh)	84 t	Based on sizing requirements of vehicle and subsystems, also adjusted to meet ingestion requirements
Hypersonic drag coefficient (Cd)	1.6	Based on heritage data
RCV diameter (Dia)	10 m	Based on subsystem packaging requirements and rocket shroud packaging requirements
Atmospheric interface altitude (h_atm)	120 km	Standard value used in Mars EDL modeling

Table 4. Human Mars Mission RCV Parameters

5.2.3 Algorithm Characteristics

All parameter updates (velocity, CO_2 mass ingested, vehicle mass, MHD energy stored) are assumed to act instantaneously at the periapsis altitude, and subsequent orbit is determined based on new velocity. When subsequent periapsis velocity after the pass is less than the required velocity for the circular orbit, integration is stopped at the previous iteration.

The total atmospheric CO_2 oxidizer feedstock capture mass is determined based on 20% conversion efficiency of CO_2 ingestion mass as calculated by using SOE chemistry and a multiplicative efficiency stack up. The MHD energy storage battery mass and percent energy storage is determined based on MHD power profile and energy/power density of different storage options.

5.2.4 Discussion

Many simulation parameters are a function of the initial and final orbits and, as a result, are fixed. Analysis indicated that four parameters primarily affect the oxidizer ingestion: *the periapsis altitude*, *inlet area of scooping nozzle*, *RCV total mass*, and *RCV diameter*.

Through various studies and iterative modeling, the inlet area was found to be the dominant factor contributing to oxidizer acquisition and storage capability. This was found to be true as long as the inlet diameter is less than the vehicle diameter; however, for an inlet area greater than the vehicle diameter, the increased drag (and shorter trajectory) negates instantaneous collection benefits. This also was linked to a constraint imposed by the diameter of the launch vehicle shroud. For this study, a maximum heavy-lift launch vehicle diameter of 10 meters (m) was assumed, which coincided with optimal atmospheric scooping characteristics. Some concepts under consideration had inflatable scooping nozzles that exceeded a 10 m RCV bus diameter, but the modeling indicated that this was not desirable because of excessive drag.

If the inlet area and the RCV bus diameter are jointly varied, it does not significantly impact oxidizer ingestion because the improved collection is balanced by increased drag. The RCV bus diameter is limited on the low end by subsystem packaging and on the high end by packaging in a launch vehicle fairing.

The periapsis altitude of the Molniya orbital resource mining scooping passes has the following effects on ingested CO_2:

a. A higher altitude results in less drag and increased number of passes.

b. A lower altitude results in higher atmospheric density and more CO_2 oxidizer feedstock collected per pass.

These competing effects result in the existence of an altitude of maximum collection potential.

The RCV stack mass affects CO_2 ingestion because of the effects of momentum transfer: A higher stack mass decreases deceleration because of atmospheric drag and CO_2 ingestion and allows for a longer trajectory through the atmosphere.

For the MSR case, the RPSCL lander required the production of 1.78 t of O_2, which meant that, with efficiency considerations, 8.76 t of CO_2 would have to be ingested during the scooping passes through the atmosphere. The periapsis of the decaying elliptical orbits was set at 80 km altitude for optimum atmospheric density, and a periapsis raise maneuver resulted in a 250 km × 250 km circular LMO staging orbit prior to EDL. The RCV stack in the MSR case consisted of the RPSCL, ISRU, SPP, SCR, and RCV weighing 21 t, which was required for atmospheric momentum exchange for scooping and compression of the atmospheric gases.

The modeling and simulation results were also used to determine the configuration and design of the human mission RCV stack element concepts. The RCV stack consists of the RCV, MDAV/SSRL, and MTCS stages. Although the team initially tried to reduce the size of the stack in an alternative ConOps, the modeling indicated that a higher mass was needed to achieve

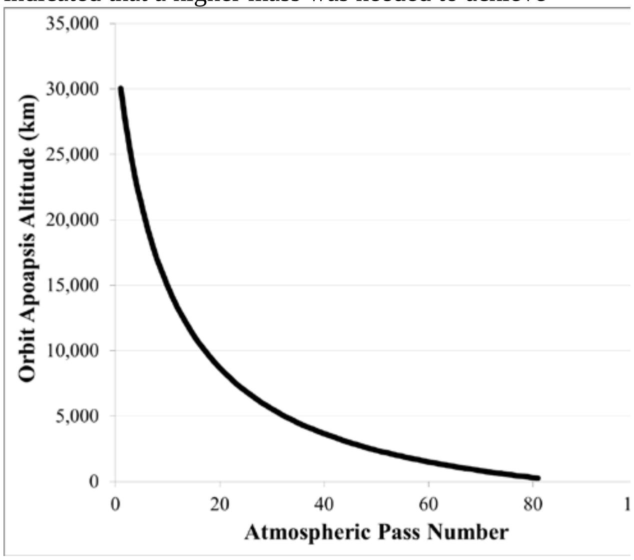

Fig. 2. Decaying elliptical orbits during aerobraking maneuver. (Target is a final altitude of 250 km.)

efficient momentum exchange. As a result, the MDAV/SSRL and MTCS are not de-mated prior to orbital scooping passes. Higher mass can also be achieved by putting more electrical storage capacity batteries on board, which provides a convenient and useful variable for achieving any required RCV stack mass. This stack scooping method provides several benefits, including eliminating separate MDAV/SSRL aerobraking, and avoiding a rendezvous and docking operation between the RCV and the MDAV/SSRL in circular Mars orbit. The O_2 that is made on orbit can be directly transferred from the mated RCV to the MDAV/SSRL prior to separation for EDL.

After 80 periapsis scooping passes, the full-scale human mission version of the RCV has captured ~35 t of CO_2, which will then be processed via SOE in circular LMO to produce ~7 t of O_2 for EDL propulsion use.

A risk that must be considered is the seasonal fluctuations and overall uncertainty in the Mars atmosphere. These variations are attributed to many factors, including dust storms and other weather phenomena, and may cause unexpected conditions that must be compensated for. Our team used the state-of-the-art Mars atmosphere database (MarsGRAM), which has been used by NASA when designing Mars missions, to best account for these considerations in the scooping calculations.

5.3 *Mars Atmospheric Orbital ISRU Model*

One of the primary innovations of this NIAC concept is that it features the production of O_2 on orbit to be used as oxidizer by the SSRL vehicle during its EDL phase to the Mars surface under supersonic retropropulsion (SRP).

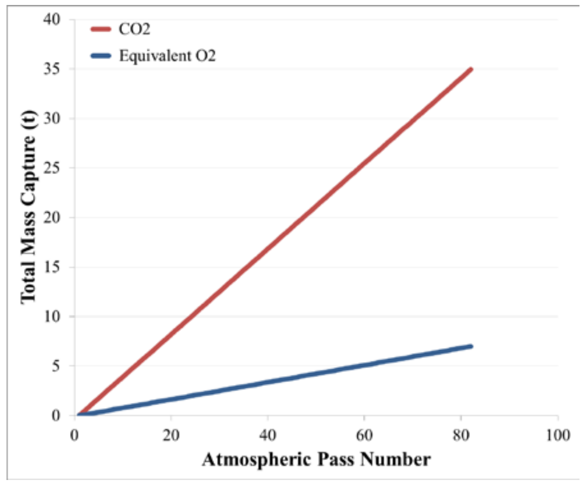

Fig. 3. Mars orbital resource mining capability.

This production is made possible by capturing atmospheric CO_2 via ram compression during successive orbital flight passes in the upper Martian atmosphere between the altitudes of 120 km (entry point) and 80 km (periapsis.) The acquired gas feedstock can be processed into O_2 on board the RCV by a limited number of chemical methods applicable according to the availability of certain reagents, and an energy source. Thermochemical splitting of CO_2 (thermolysis) was considered since the following simple reaction (Equation 1) can be potentially performed by concentrated sunlight, which can be obtained readily in space operations.

5.4 *Solid-Oxide Electrolysis (SOE)*

The on-board generation of electrical energy by MHD on the RCV led to the selection of SOE as a method of oxygen production since it relies exclusively on electrical energy to achieve the conversion of CO_2 collected from the upper Martian atmosphere into O_2 according to reaction (Equation 1):

$$\mathbf{2CO_2\ (+\ energy) \rightarrow 2CO + O_2} \qquad \mathbf{(1)}$$

Other technologies require the use of chemical reducing agents such as hydrogen (Sabatier process) in addition to electrolysis. The solid oxide electrolysis cell (SOEC) technology has also advanced significantly and has been modeled and developed experimentally for Mars surface mission demonstrations such as the MIP experiment initially planned on the Mars Phoenix lander in 2001 (TRL 8) and more recently the Mars Atmosphere Resource Verification INsitu (MARVIN) experiment [11] and the Mars Oxygen ISRU Experiment (MOXIE) experiment for the NASA Mars 2020 mission. In Phase I, we adapted a modeling tool based on SOEC technology developed since 2001 to estimate cell performance parameters.

Because SOE technology uses a cell and stack approach similar to fuel cells, production operations are easily scalable to different production rates. A SOE cell uses an electrolyte made of a nonporous ceramic oxide, such as YSZ, which conducts oxygen ions at elevated temperatures (750 °C to 850 °C).

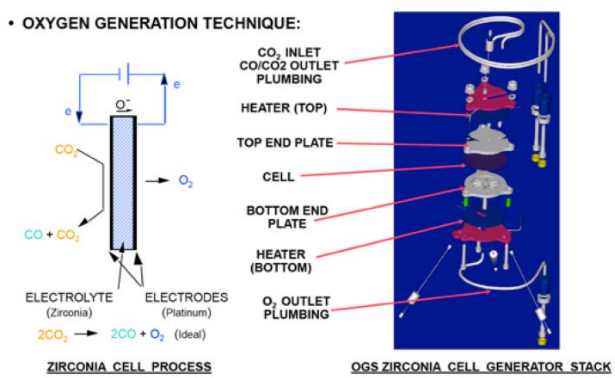

Fig. 4. SOEC cell design for MIP experiment (2001).

5.5 Entry, Descent & Landing (EDL) Model

5.5.1 EDL Simulation

The EDL concept used in this study consists of a blunt body aerodynamic deceleration vehicle that enters following a deorbit burn from the circular 250 km × 250 km LMO. Since it would be prohibitive, in terms of propellant required, to do a full propulsive deceleration burn to the Mars surface, aerodynamic deceleration must be used. The diameter of the aerodynamic decelerator directly affects the performance of the vehicle's EDL characteristics. A larger area decelerator will allow for lower peak heat rate and peak deceleration. Analysis and a literature review indicated that typical Mars entry vehicles employ a blunt body, sphere-cone forebody ranging in diameter from 12 to 20 m. Since a large, heavy lift rocket shroud is not anticipated to be more than 10 to 12 m in diameter, a deployable decelerator must be used. Although an inflatable heat shield is an option in single-use vehicles, reusability considerations indicate that a deployable and furling decelerator system poses less risk. Such a system is presented in this paper. In this study, a 21 m diameter deployable heat shield was used in the modeling analysis described in the following paragraphs.

A trajectory simulation was developed to calculate the entry, descent, and landing (EDL) sequence of the MDAV/SSRL. A three-degree-of-freedom trajectory was implemented in the NASA software, Program to Optimize Simulated Trajectories 2 (POST2), which integrates the equations of motion starting from initial atmospheric interface through hypersonic aerodynamic deceleration and propulsive descent and landing (*https://post2.larc.nasa.gov/).*

The RCV aerodynamic and propulsive performance parameters were based on literature values of a blunt body entry vehicle with liquid methane—liquid oxygen propulsion [8]. During hypersonic deceleration, bank angle modulation was used to control the lifting trajectory until propulsive initiation. Upon propulsive initiation, the vehicle flies a powered, ballistic trajectory at full thrust until the planet-relative velocity is nullified. Propellant mass was converged upon to ensure the entry vehicle is able to thrust for the entire powered descent phase and land with no residual propellant. The structural mass of the vehicle was not determined a priori and instead scales with the propellant mass based on sizing ratios derived from literature data [8]. The propulsive initiation conditions were also optimized to achieve a soft landing, attaining 0 m/s relative velocity at 0 m altitude. Favorable propulsive initiation conditions, which minimize the required propellant mass, were found through adjustment of the hypersonic bank angle profile within a genetic algorithm optimizer. The bank profile was subject to certain constraints, which reject trajectories that exceed the maximum *g*-force limits for human payloads. Figure 5 is an example of the EDL trajectory.

Through iterative analysis methods, a feasible MDAV/SSRL configuration with a landed payload mass of 20 t was achieved. This vehicle used a 21 m diameter deployable/furling decelerator during the hypersonic deceleration phases in order to reach valid propulsive initiation conditions.. Closure may be possible with smaller diameter decelerators, which will be the subject of further investigation and analysis in future studies.

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Closure may be possible with smaller diameter decelerators, which will be the subject of further investigation and analysis in the future.

Since parachutes do not scale to the large lander sizes required for human-class missions, retropropulsion was used in the final stages of the EDL sequence, with all propellants being produced at Mars. The CH_4 fuel is made on the surface and transported to orbit in the MDAV/SSRL and the O_2 oxidizer is made on orbit in the RCV and subsequently transferred to the MDAV/SSRL. A reusable propulsion system must be developed that is able to deep throttle while also attaining a long life cycle without required maintenance. Such an engine does not exist today and must be developed.

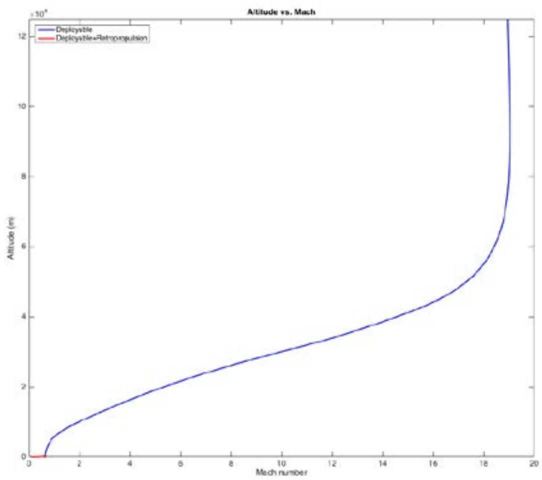

Fig. 5. SSRP EDL Altitude vs. Mach number of the entry vehicle during EDL.

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With a projected MDAV/SSRL mass of 38 t (including 20 t of payload) and approximately 8.5 t of propellant required for EDL, the total MDAV/SSRL mass during EDL is 46.5 t. Engine thrust for retropropulsive descent and landing is based on a 3 Earth G's thrust-to-weight. This is planned to be accomplished with four 353 kN rocket engines. The engines must be throttled to 10 % at landing, which would require some further technology development.

5.6 Mars Surface ISRU Model

The ISRU surface infrastructure is comprised of all systems needed for the production of the MDAV/SSRL fuel CH_4 and oxidizer O_2 during a predefined production time of 500 days in our Phase I work. These system elements were modeled based on previous work done for the EMC coordinated and led by one of the authors of this study, R. Mueller.

These systems are summarized in Table 5 below. The concept of operations of the surface ISRU is identical in both the MSR and the human mission case.

Mars Sample Return – Payloads	**Mass (kg)**	**Source**
ISRU production systems	429	Model
Excavator (RASSOR x1)	100	Model
Surface Power Plant	3340	EMC
Rover & Cargo deployment system	1200	EMC
Rover Sampling mechanism	100	MSL
Rover Science Instruments	75	MSL
Sample Container	30	Estimate
Samples collected	100	Estimate
Total	5274	
20% Margin	1054.8	
Total w/margin	**6428.8**	

Table 5. ISRU Surface Systems

The MSR case is designed to be a demonstration and validation mission, with one ISRU module being placed on the surface of Mars to be operated for 500 days. In the subsequent human mission, three ISRU modules will be sent.

5.7 Spacecraft Concepts and CAD Models

The results from all mission architectural trades and technical analysis were used to develop concepts for propulsive transfer stages, mission spacecraft and surface payloads. The focus of this study was on the Mars segment of the missions. In Phase I, standard and available propulsion technology was assumed for Earth-to-Mars transportation. In future work, other more exotic propulsion stages may be considered such as nuclear thermal propulsion (NTP) and/or dual mode NTP with nuclear electric propulsion (NEP). Other examples of options are hybrid solar electric propulsion (SEP).

The modeling work and associated mission simulations pointed toward a large stack for the RCV of 10 m diameter with a mass of 84 t operating at 79 km periapsis scooping altitude to achieve the propellant oxidizer requirements for a human-mission class with an MDAV/SSRL having a 20 t landed payload capacity. The RCV stack artistic concept is shown in Figure 6.

Note that the stack consists of the RCV at the front, with the MDAV/SSRL docked to it and an alignment and structural interface cylinder acting as an aerodynamic fairing as well.

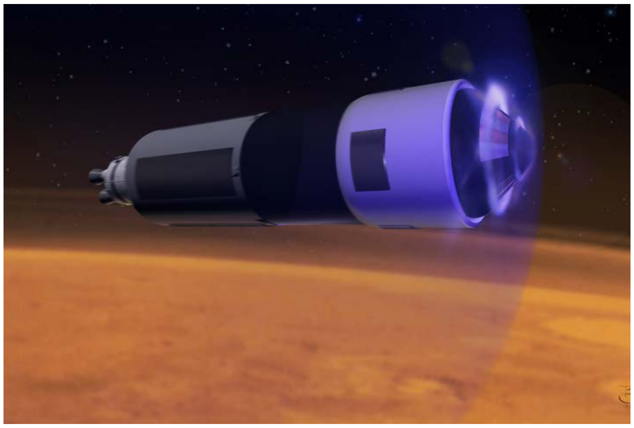

Fig. 6. NIAC Mars Atmospheric Gas Resources Collector Vehicle (RCV) stack concept during an aerobraking CO_2 collection pass in the upper atmosphere.

Behind the MDAV/SSRL, an MTCS pushes the stack with propellants for TMI and Mars EDL brought from Earth in the first mission. In subsequent missions, no propellant is needed (other than for the RCS), since it is only used as ballast to achieve the mass required for orbital resource mining. After the surface mission has been completed, the MDAV/SSRL launches the crew directly to HMO into a Mars Molniya orbit to restart the Conops sequence. Propellants for this launch are made on the surface of Mars via the ISRU methods previously described.

5.8 Concept Technology Descriptions and Technical Details to Support Feasibility

In Phase I, two mission case studies were evaluated: a demonstrator Mars sample return (MSR) vehicle and a full-scale human MDAV/SSRL capable of transporting a crew of four to the surface and back to LMO. The amount of propellant required to perform retropropulsive EDL was calculated for both cases. The MSR mission has a landed payload mass of 6.4 t, consisting of ISRU equipment, fission power plants, an excavator and a sample collection rover, which requires 1.8 t of O_2 produced on orbit for EDL. The human-scale mission has a landed payload mass of 20 t per lander, consisting of a crew cabin with cargo in one lander version, and just cargo in the other version, while using the same lander platform and EDL system. The transportation system was analyzed to assess the functional allocations, interfaces, and element divisions to enable in-orbit O_2 production. Our assessment of the concept of operations concluded that the RCV will be mated with the MDAV/SSRL during orbital collection of CO_2 and O_2 production, then transfer the O_2 to the MDAV/SSRL prior to its separation and departure for a Mars surface taxi trip, while the RCV remains in orbit. The concept evolved to include the Mars Transport Cryogenic Stage (MTCS), which propels mission elements between Earth and Mars via the Atmospheric Mining stack, as shown in Figure 7. This evolution was driven by the requirement for the high momentum exchange needed for the collection vehicle to achieve a number of atmospheric passes sufficient to collect enough CO_2 and generate onboard electrical power. In a future study, the stack concept will be evaluated in detail in terms of operational limits, risks, and viability of the associated technologies.

Once the spacecraft oxidizer has been made on orbit and stored, then it becomes possible to use retropropulsion to decelerate the spacecraft, even at supersonic speeds, thereby replacing conventional parachutes in the EDL, which do not scale well on Mars when the landed mass is above approximately 1,000 to 2,000 kg. The *in situ* production of sufficient propellants that do not have to be transported from Earth enables the descent to be controlled by MDAV/SSRL aerodynamic deceleration, followed by supersonic retropropulsion to enable a precision landing.

This innovative Mars transportation system will allow all the elements to be deployed in a pioneering Mars station without sending a new lander from Earth each time, resulting in cost savings, independence, and mission flexibility.

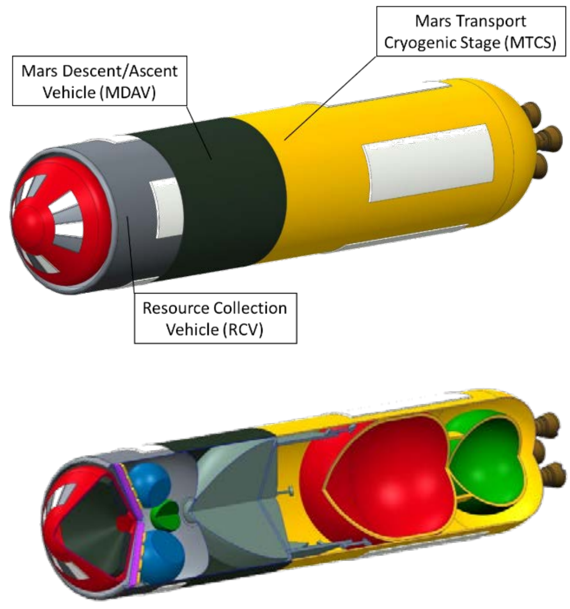

Fig. 7. Mars atmospheric resource mining stack

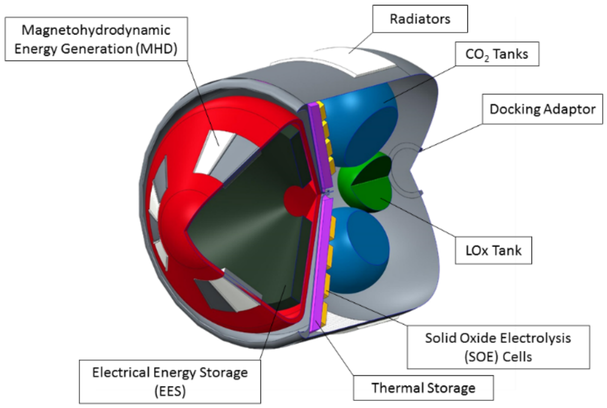

Fig. 8. Resource Collector Vehicle with major systems.

5.9 Spacecraft Systems and Operations

The RCV is designed to make use of the upper Martian atmosphere to produce two critical products: electrical energy and oxygen for EDL SRP. In Phase I, the RCV concept vehicle was studied for use in two mission scenarios: an unmanned Mars Sample Return (MSR) mission and a reference human landing mission.

The spacecraft systems are designed to achieve the collection and compression of CO_2 atmospheric gases at high Mars altitude (79 km) and high velocities at periapsis ranging from 3.57 km/s to 4.5 km/s. In addition, it is capable of the generation of electrical energy (MHD) and its storage (EES), the storage and use of CO_2 in SOE to produce oxygen, and the liquefaction, storage, and delivery of oxygen to the MDAV/SSRL vehicle docked with the RCV. The MDAV/SSRL vehicle uses the oxidizer to perform EDL with SRP. The RCV also has a deployable augmented SEP system using solar power and the ESS which boosts itself and the MTCS back to HMO for a re-set of orbital mining operations.

5.10 Hypersonic Aeroshell Coupled with CO2 Collection

The collection of gas and MHD energy occurs at hypersonic speeds within the continuum regime, requiring design guidance from hypersonic heat shield profiles with collection adaptations. Consequently, the critical aerodynamic heating loads can be reduced by using shapes with higher pressure drag and a blunted design. Likewise, to maintain a controlled aerobraking and atmospheric dipping maneuver, the vehicle profile should also act to stabilize the spacecraft as it transitions from a free molecular to continuum flow regime.

The Viking mission pioneered the use of the 70° sphere-cone to handle the hypersonic entry conditions at Mars. All subsequent missions to Mars have used sphere-cone designs, with cone half-angles between 45° and 70° to accommodate requirements for packaging, heating, drag, and stability. The Deep Space 2 mission used a 45° sphere-cone, because of a desire for reduced drag and a higher entry velocity. Our design aims to take advantage of this heritage geometry—a sphere-cone design that is guided by hypersonic aerodynamics. Furthermore, a desire for reduced drag has influenced the choice for a steeper half-angle, similar to that used for the Deep Space 2 mission vehicle. In future work, a detailed analysis of vehicle aerodynamics will serve to further refine this design to accommodate the heating and structural constraints, while achieving our desired aerobraking maneuver objectives. The high-temperature boundary layer will also inform the specific geometry of the flow capture inlet in the detailed design.

5.11 RCV Geometry Justification

The resource collection vehicle has the objective of generating oxidizer from CO2 collected in the Martian atmosphere using electrical energy supplied by MHD generation. The collection of gas and MHD energy occur at hypersonic speeds within the continuum regime, placing specific requirements on the shape of the aeroshell of the vehicle to endure thermal and structural loading. Considering these extreme conditions, the design of the collection structure must be guided by hypersonic heat shield profiles with adaptations for CO2 gas and MHD collection. Under these conditions, the aerodynamic heating can be reduced by using shapes with higher pressure drag and a blunted design [15].

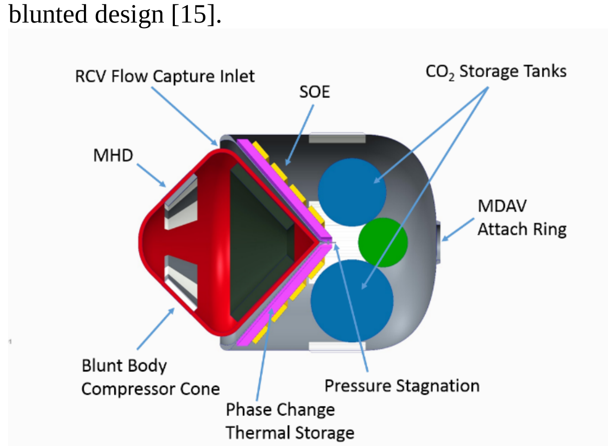

Fig. 9. Cross section side view of RCV compressor cone and RCV.

5.12 RCV Flow Capture Inlet

The concept for the RCV flow capture inlet (FCI) is that there is an annular gap between the outer edge of the sphere-cone heat shield/aeroshell and the inner edge of the RCV bus fairing. The aerodynamics of the blunt body create a shock wave and associated gas and plasma flow that will be channeled into the FCI at supersonic velocity. A converging annular cone cavity will further compress the incoming gases through momentum exchange from the high speed/high mass of the RCV stack. At the apex of the FCI cone cavity, a stagnation pressure will occur, at which point a check valve captures the high pressure CO_2 atmosphere gases in a previously evacuated capture tank. Subsequently the CO_2 is pumped into a storage tank, liquefied and the capture tank is reset with vacuum for the next scoping pass. As a point of reference, storing this carbon dioxide in liquid form would require approximately 1.5 megajoules per kilogram [16], so with our large surplus of MHD energy this seems very feasible. This design is a concept and further work is required to validate it, including computational fluid dynamics (CFD) modeling and other analysis such as structural, thermal, and mechanical considerations.

5.13 Heat Transfer and Storage

Because the kinetic energy interaction with the atmosphere creates frictional heat, and large amounts of energy are converted into heat because of friction with the Mars atmosphere, there is an opportunity to use this heat for beneficial applications. The SOE system needs to run at 800–900 °C, but most of the SOE processing will happen after the scooping operations. In order to avoid the inefficiencies of converting heat energy to electrical, storing it in batteries and then converting it back to heat while in a circular LMO, the heat is stored in a phase-changing material such as a molten salt or liquid metal in order to release it for SOE operations in LMO. The phase-changing material can be packaged at the bottom of the blunt body sphere, which will be next to the SOE stacks that can be mounted on a bulkhead for a direct conduction path to the SOE stacks via conductive metal plates. The heat can be channeled from the front of the blunt body to the phase-changing material via heat pipes. By storing heat energy in this way, heat from the electrical battery system will be off-loaded and overall system efficiencies will increase. Further work is required in future work to validate and expand on this concept.

5.14 Magnetohydrodynamic (MHD) Energy Generation

The high kinetic energy of a spacecraft entering an atmosphere, which is traditionally converted into the heat of reentry during friction with the atmosphere, constitutes an energy resource. This rapid deceleration at hypersonic speeds results in the thermal ionization of the atmospheric gas in the shock layer. Numerous free electrons created in this process can be subjected to a magnetic field and their sustained collective motion used to generate an electric field. MHD systems are designed to create the magnetic field and collect the electrical energy generated (Fig. 10).

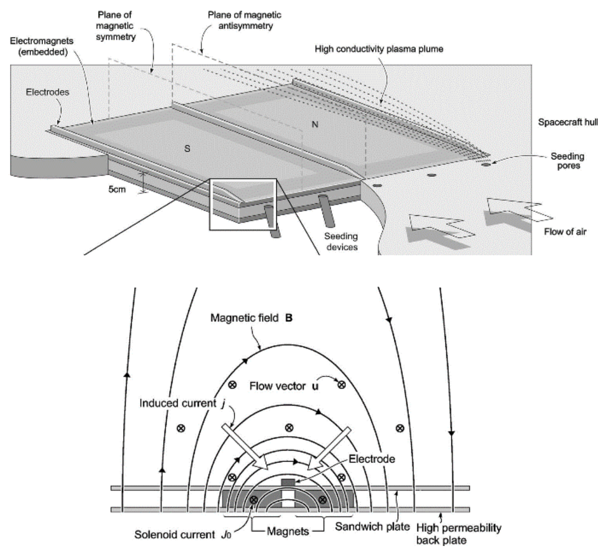

Fig. 10. MHD concept design for spacecraft skin mounted on blunt body cone. Isometric view includes optional alkali metal seeding devices to increase plasma conductivity. Side view shows gas flow, magnetic field, and collected current.

In Phase I, the energy produced by MHD was calculated using a model tool developed by Ali et al. to determine the values of key variables during each orbital pass through the Martian atmosphere. The total energy available via MHD energy generation is the integration of the power available for an MHD generator along a given trajectory. To calculate this power generation profile, it is necessary to identify the relevant physical interactions occurring along a given trajectory.

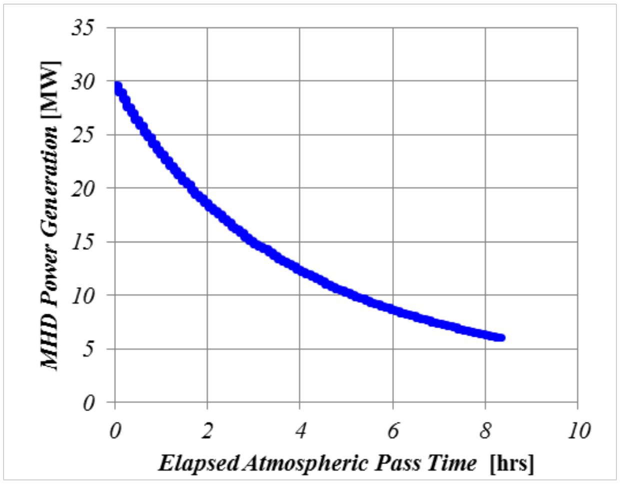

Fig 11. MHD power generation capability during atmospheric passes.

For a Faraday-type MHD generator, the generated power behaves according to the following scaling law:

$$P \propto \sigma_e u^2 B^2 A_c L_i \qquad (2)$$

Where P is the generator power output, σe is the scalar electrical conductivity, u is the local flow velocity, B is the magnetic field strength, A_c is the generator interaction area, and L_i is the generator length [16].

In reality, an open-channel Faraday-type MHD energy generator may be unsuitable for planetary entry applications because of the need to allow the high-temperature entry plasma to flow through the vehicle. However, the basic physics of Equation 2 applies to a non-flow through external MHD energy generator design applicable to planetary entry vehicles and thus may be used in this analysis [12]. For the purposes of this analysis, the magnetic field strength will be assumed in all cases to be a constant 0.2 T as studied in previous investigations [12,13] The generator area is assumed to be 1 square meter in all cases, with a characteristic length of 1 meter in order to change its scale up and down in the model. These MHD external generator plates are mounted on the front of the blunt body cone section where a high plasma flow field is expected. In future work, our project will work synergistically with H. Ali's doctoral research at Georgia Tech on experimental performance assessments of MHD energy generation for planetary entry applications. Our work will advance the state-of-the-art of MHD modeling to evaluate its practical limits in our application. We will also perform a mass and power trade between the integration of one fission surface power (FSP) equivalent unit on board an RCV vs. the MHD + electrical storage. Risks and costs will be evaluated for both systems, including radiation shielding requirements needed on board in proximity to the MDAV/SSRL.

All RCV technologies were derived from the first-order principle and evaluated for feasibility: heat storage phase-change material, RAM compression, CO_2 liquefaction, O_2 liquefaction and storage, propellant transfer, automated AR&D, high-temperature non-ablating materials, GN&C, control authority, and reusability. More work is required to increase fidelity of the analysis and related conclusions.

5.15 Mars Descent & Ascent Vehicle/Single-Stage Reusable Lander

5.15.1 Spacecraft Systems and Operations

The MDAV/SSRL is designed to execute multiple landings and launches at Mars during a given campaign; it is intended to serve as a safe and reliable Mars transportation element to ferry cargo and crew to and from the Mars surface. The MDAV/SSRL is initially docked with the RCV in the atmospheric mining stack through a docking hatch at top of the MDAV/SSRL ogive fairing. The docking port also provides a propellant-transfer capability from the RCV via umbilical plate connectors. The ogive structure is designed to perform as a launch fairing during a Mars launch as well as an Earth launch on a heavy-lift launcher payload stack.

In principle, the spacecraft systems are designed to achieve maximum reusability through the use of a deployable carbon-fiber polymer matrix composite material aerodynamic deceleration non-ablating system, followed by SRP. An accordion-style webbing is deployed between aerobrake petals made from high-temperature carbon fiber as a 3D woven cloth with battens (Figure 13).

The retropropulsion engines are stored behind bay trapdoors while the trapdoors are also deployed as thrust vectoring surfaces for protection of the lander structures from ejecta and cratering during terminal phase landing. In the landing configuration, the webbing forms a skirt to protect other surface infrastructure elements from ejecta. The structure of the morphing aerobrake system becomes the landing gear with six legs spanning very wide to provide stability and straddle the blast erosion area

Fig.12. Stowed configuration for launch from Earth.

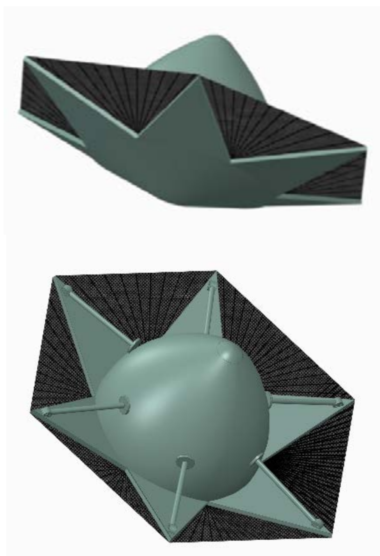

Fig. 13. MDAV/SSRL decelerating aerodynamically at Mars with recessed SRP engines (top and bottom isometric views)

This MDAV/SSRL concept solves the landing gear protrusion issue, and creates an innovative aerobrake while using the legs as structural braces. By incorporating the landing gear, aerobrake and engine blast protection functions all into one system, significant mass savings and risk reduction could be achieved.

Once the MDAV/SSRL has landed, then cargo unloading is an issue on most Mars lander concepts due to the height of the lander. In our concept the landing gear can rotate to provide a “kneel down” capability for cargo offloading. The propellant tanks are packaged above the cargo bay so that the cargo can roll out onto the surface with the aid of a lightweight deployable ramp, which can be supported by the aerobrake petal structures, eliminating additional mass.

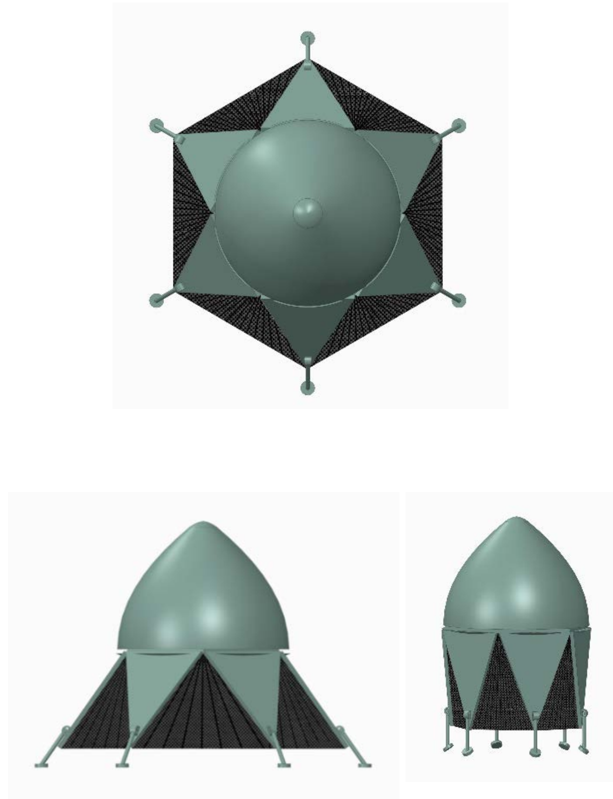

Fig.14. Configuration for landing at Mars (top and left) and for ascent from Mars after launch (right).

During Mars launch the entire aerobrake/skirt system can be vectored to a vertical configuration to allow a streamlined launch to take place. While Phase I only included first-concept analysis focused mainly on mass and volume of the MDAV/SSRL, our future work will develop the MDAV/SSRL systems based on expected performance, adherence to design standards, and ability to integrate with the other elements.

6.0 Phase I Study Results

While ISRU has been proposed on the surface of Mars, using atmospheric mining of resources while in orbit is a new and innovative concept. This study has examined the case for a reusable Mars space transportation system that can repeatedly launch and land on Mars, without ever relying on transportation of propellant from Earth by using propellant and electrical energy generated on orbit via plasma-harnessing, scooping, and ram-compressing the 95% CO_2 Martian atmosphere, and by using indigenous resources on the surface of Mars (CO_2, H_2O) as well for the launch and landing mission segments. The concept was investigated in the context of an enabling architecture with an associated concept of operations, mission elements, and technologies needed.

In this NIAC Phase I project we showed that a 4-crew reusable Mars lander human class mission can be supplied with LO_2 in Mars orbit prior to executing a supersonic retro-propulsive EDL to the surface. A Resource Collector Vehicle (RCV) performing 81 orbital scooping passes into the upper Martian atmosphere, with each atmospheric scoop varying in duration from 7.1 minutes to 5.3 minutes, can ingest approximately 431 kg of CO2 per scoop and compress it via a hypersonic ram compression system. The total amount of CO2 captured and stored is about 34,939 kg. The use of solid oxide electrolysis and a conservative calculation of efficiency losses results in the on-board production of O2 at an estimated 20% of the captured CO2 mass - resulting in 6,986 kg O2 for EDL propulsion to provide thrust for de-orbit, re-orient for entry, supersonic retro-propulsion (SRP) and propulsive precision landing. A concept has been developed and the scooping analysis indicates feasibility, but more detailed analysis and design scaling of technologies is required in future work to optimize it and work out details of the aerodynamics and compression thermodynamics. After the CO_2 has been captured, then it is processed into O_2 using solid oxide electrolysis, while in orbit. Subsequently the O_2 is used with CH_4 (that is brought from Earth on the first mission and then from the surface of Mars in subsequent missions) as propellants to enable EDL with SRP. Once landed, the MDAV is re-fueled with propellants made by surface ISRU systems and it launches directly to HMO, and then repeats the cycle. The RCV stack is raised independently from LMO to HMO via an onboard deployable augmented Solar Electric Propulsion (SEP) system. A crew exchange occurs at HMO every 26 months as a sustainable pioneering presence on Mars becomes reality.

An alternative trade was considered whereby the MDAV launches to LMO and does a rendezvous with the RCV and MTCS. Propellant brought from Mars on the MDAV was considered for the MDAV+RCV+MTCS stack LMO to HMO burn, but transporting this propellant through the ΔV of 4.2 km/s creates a large launch propellant penalty, which made the MDAV size prohibitive, so this method was rejected. A new way was found to raise the RCV + MTCS from LMO to HMO without using propellant from the surface of Mars. There is excess MHD electrical energy created during aerobraking, so if the energy can be stored, it could be used to augment a deployable SEP system that is part of the RCV. AT LMO the SEP is then used to boost the RCV + MTCS back to HMO, while the MDAV proceeds directly to HMO with less propellant requirements, so that it is feasible to bring the crew to the Crew Transit Vehicle (CTV) for a return to Earth without an intermediate docking manoeuvre, which decreases risk to the crew.

A variety of new technologies are required such as MHD electrical energy generation and storage, EES-augmented SEP, heat storage and release and deployable decelerators.

Future efforts will focus on detailed analysis of the proposed technology concepts and other mission architectures. Our results will be benchmarked against these previous studies to show the relative benefits:

- Human exploration of Mars, NASA Design Reference Architecture 5.0 (Drake et al, 2010)
- Jet Propulsion Lab, “A Minimal Architecture for Human Journeys to Mars” (Price, 2015)
- NASA Langley Research Center, “Sustaining Human Presence on Mars Using ISRU and a Reusable Lander” (Arney, 2015)

A successful collaboration between NASA KSC Swamp Works and Georgia Tech has created a team of experts that have developed a set of computer models that allow rapid simulations of various concepts and ideas. This systems model will be the basis for solving the challenges identified in Phase I. The “unknown unknowns” have been identified and are now “known unknowns,” therefore forming a solid basis for further investigation in future work.

7.0 Conclusions

Mars Molniya Orbit Atmospheric Resource Mining was investigated in this NIAC Phase I project, in order to determine if it is feasible at all. Our NASA KSC Swamp Works/Georgia Tech Aerospace Department team has examined the case for a reusable Mars space transportation system that can repeatedly launch and land on Mars, without ever relying on transportation of propellant from Earth after the initial bootstrapping mission. This space transportation system uses propellant and electrical energy generated on orbit via plasma-harnessing, scooping, and ram-compressing the 95% CO_2 Martian atmosphere, and also uses indigenous resources on the surface of Mars (CO_2, H_2O) for the launch and landing mission segments.

The study considered the space missions that would be required to implement this system, and an associated space mission architecture was generated and tested by analysis. It shows that the concept can support a pioneering presence by humans on Mars with precursor robots deployed to prepare the ISRU aspects and robotic surface systems to keep the astronauts safe by autonomously making propellant from local resources in the atmosphere and regolith, for the journey home.

In Phase I of this NIAC study, two major applications for Mars Molniya Orbit Atmospheric Mining mission architecture concepts were studied. Both mission concepts are aligned with NASA's top priorities for Mars exploration in the next three decades:

- A path for further architecture and technology development and eventual implementation is proposed by proving this technology as part of an **ISRU/Mars Sample Return (MSR) demonstration mission**.
- The eventual goal for this revolutionary and breakthrough space mission architecture is to enable **landing humans (4 crew) on the surface of Mars with all associated equipment** needed to allow them to survive and thrive. This will require landing very large vehicles, from 20 t to 60 t in mass. A breakthrough method is required to make this technically and economically feasible.

Other solar system destinations and related space transportation systems have been deferred to future phases of the study. It is likely that the same orbital resource mining architecture being developed for Mars in this study could also be viable at other outer Solar System destinations.

The mission elements can all be delivered to Mars using the existing and projected SLS rocket in the 70 t payload version for a Mars sample return mission and the 105 t payload version for the human-class missions. The number of launches needed are comparable to other human Mars mission studies, and less total mass is needed than in the NASA Mars DRA 5.0 reference architecture. The RCV vehicle is projected to achieve a full payback in terms of mass transported from Earth after two missions by making O_2 propellant on orbit, which eliminates the transportation stages and extra Earth launch operations and associated risk. After that, an Earth-independent Mars descent/ascent system for crew and cargo will be available at no further cost for transportation of mass from Earth. By amortizing the costs over the subsequent missions, substantial cost savings and mission flexibility can be achieved.

New technologies and mission design are required to make this concept feasible, such as HEO departures that use a lunar-gravity assist, aerocapture at Mars, atmospheric ram compression at hypersonic speeds, magnetohydrodynamic electricity generation and storage, large-scale solid oxide electrolysis to make O_2 from CO_2, phase-changing thermal storage materials, zero boiloff cryogenic storage, advanced deployable aerodynamic decelerator systems, novel lander configurations and designs, 10% throttling CH_4/O_2 rocket engines, supersonic retropropulsion, autonomous excavation and propellant production on the Mars surface, automated propellant loading systems, augmented solar electric propulsion systems, and automated rendezvous and docking. These are just some of the technologies needed; others are identified in our NIAC Phase I report and associated technology roadmap [14].

In conclusion, our study has shown that a novel architecture using Mars Molniya Orbit Atmospheric Resource Mining is potentially feasible. This could enable an Earth-independent and pioneering, permanent human presence on Mars by providing a reusable, single-stage-to-orbit transportation system. It will allow cargo and crew to be routinely delivered to and from Mars without transporting propellants from Earth, therefore reducing the massive logistics burden facing human mission to Mars and giving flexibility to operations at Mars.

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The work performed during Phase I revealed many interdependent connections between the overall architecture, the local architectures at Mars, and the systems that build them; and it and quickly became a multidisciplinary study rich in questions about multi-physics phenomena, chemical and energetic processes, as well as flight dynamics and more. Consequently, the association of NASA personnel and academic personnel at Georgia Tech was fully used to involve graduate students and young researchers in the study. Several face-to-face meetings were organized on the campus of Georgia Tech to stimulate concept brainstorming and rapid iterations of elements in the architecture. Doctoral candidates Keir Goneiya and Hisham Ali became full partners in the project and provided state-of-the-art expertise on orbital mechanics, aerobraking, EDL, and MHD and associated systems. Their contributions were guided by Co-I Prof. Bobby Braun, who is their doctoral advisor, and Co-I Dr. Brandon Sforzo, who also contributed his expert knowledge in hypersonic dynamics and atmospheric entry phenomena.

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NASA Innovative Advanced Concepts

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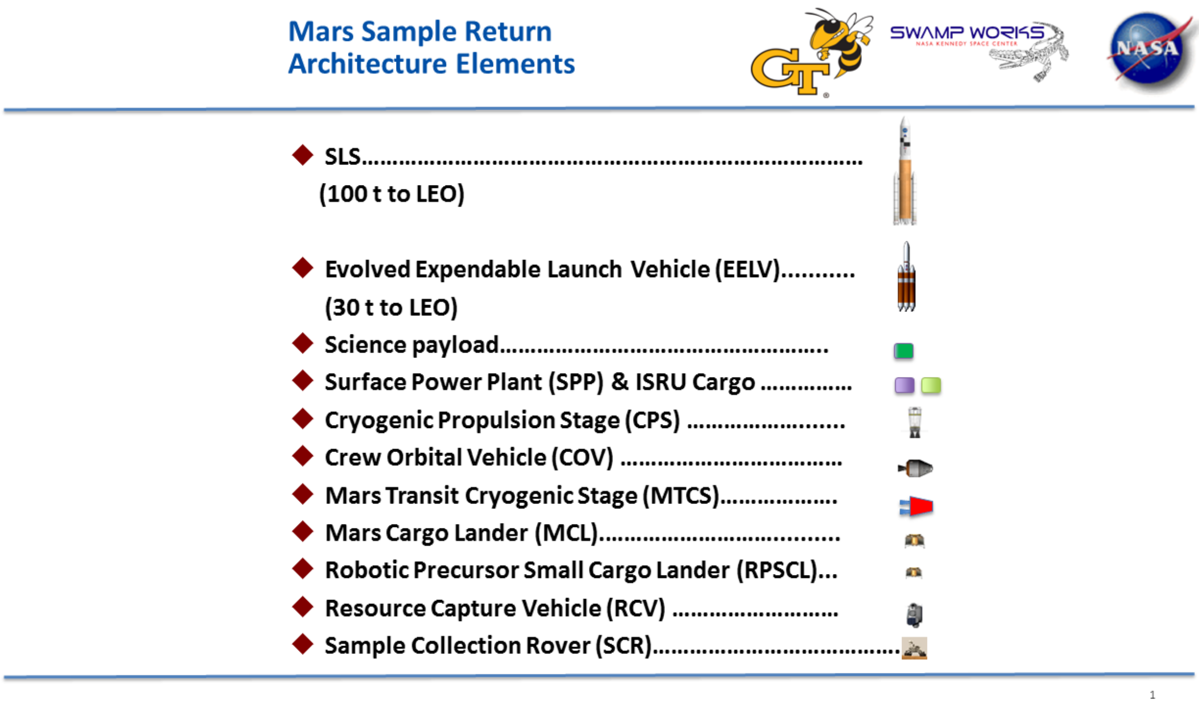
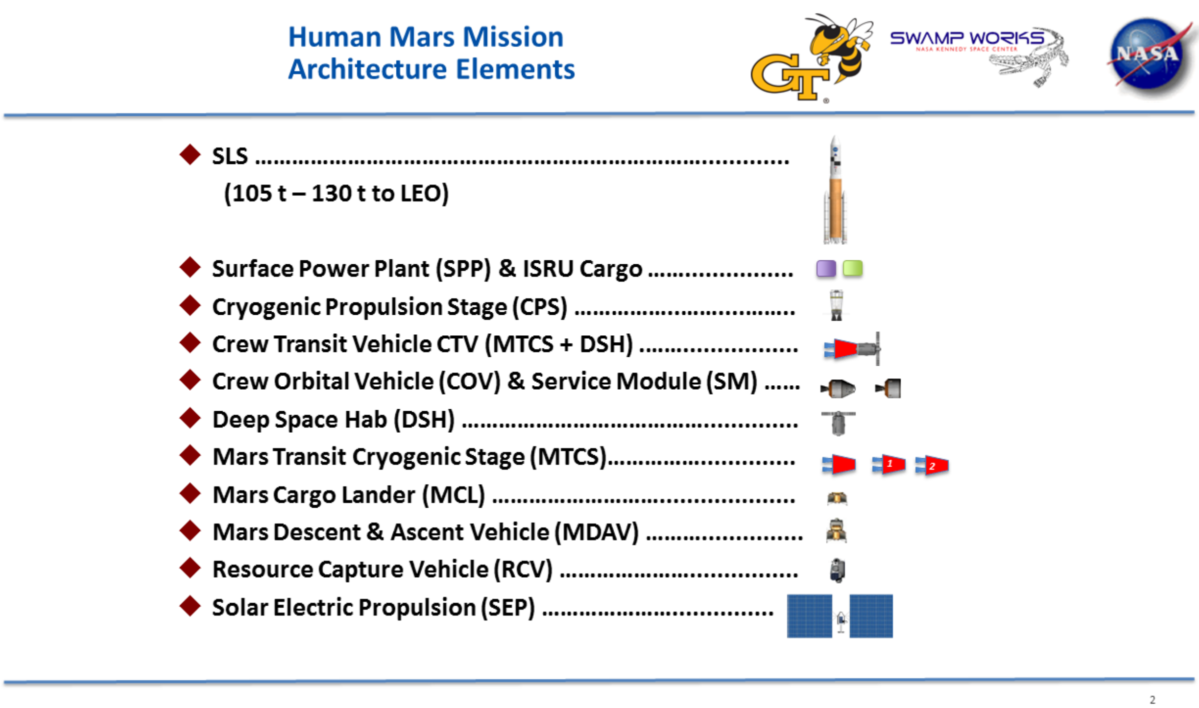
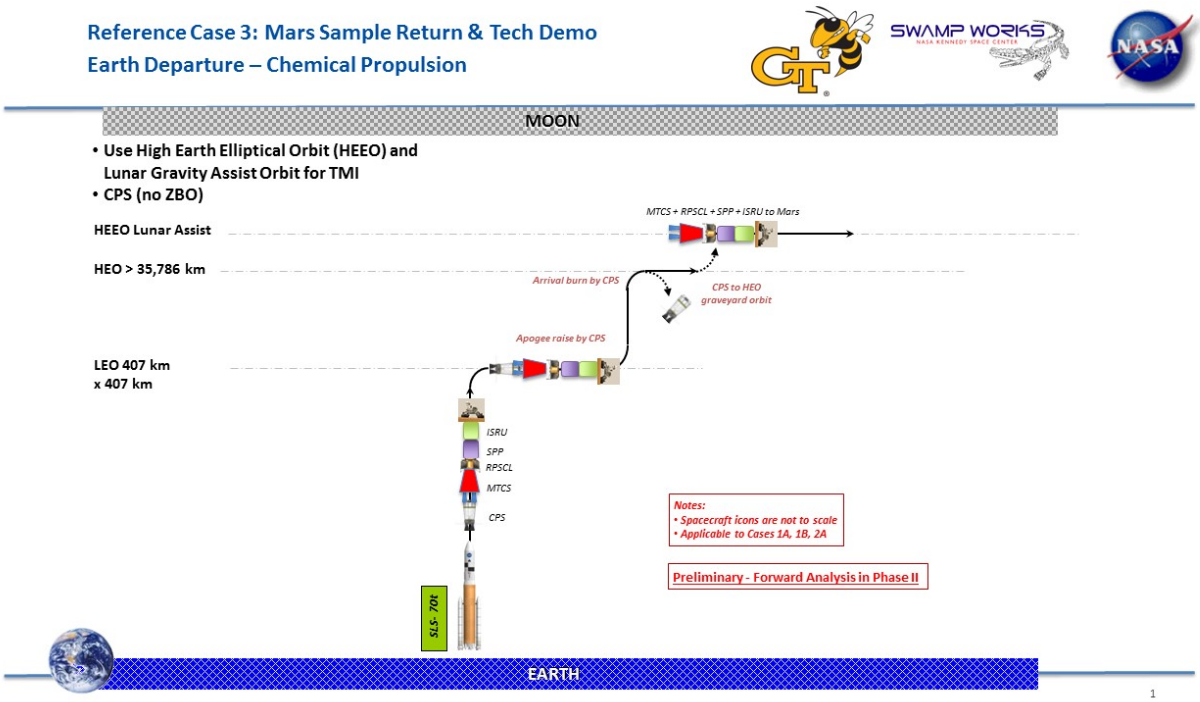
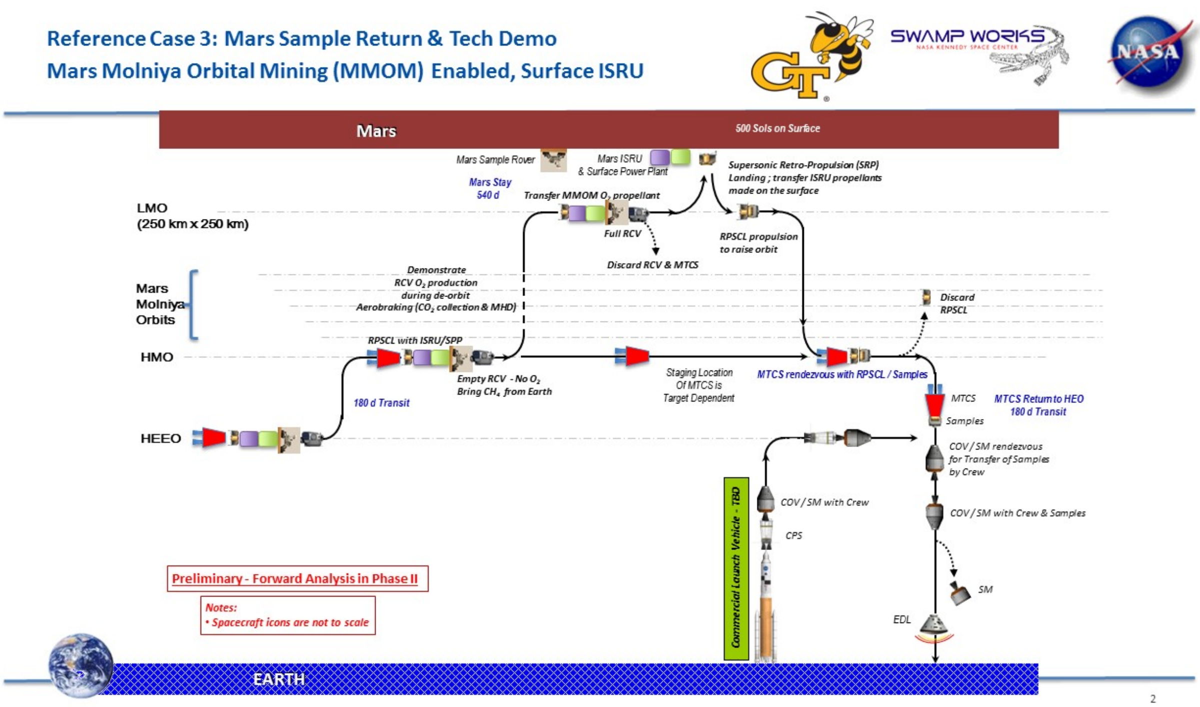
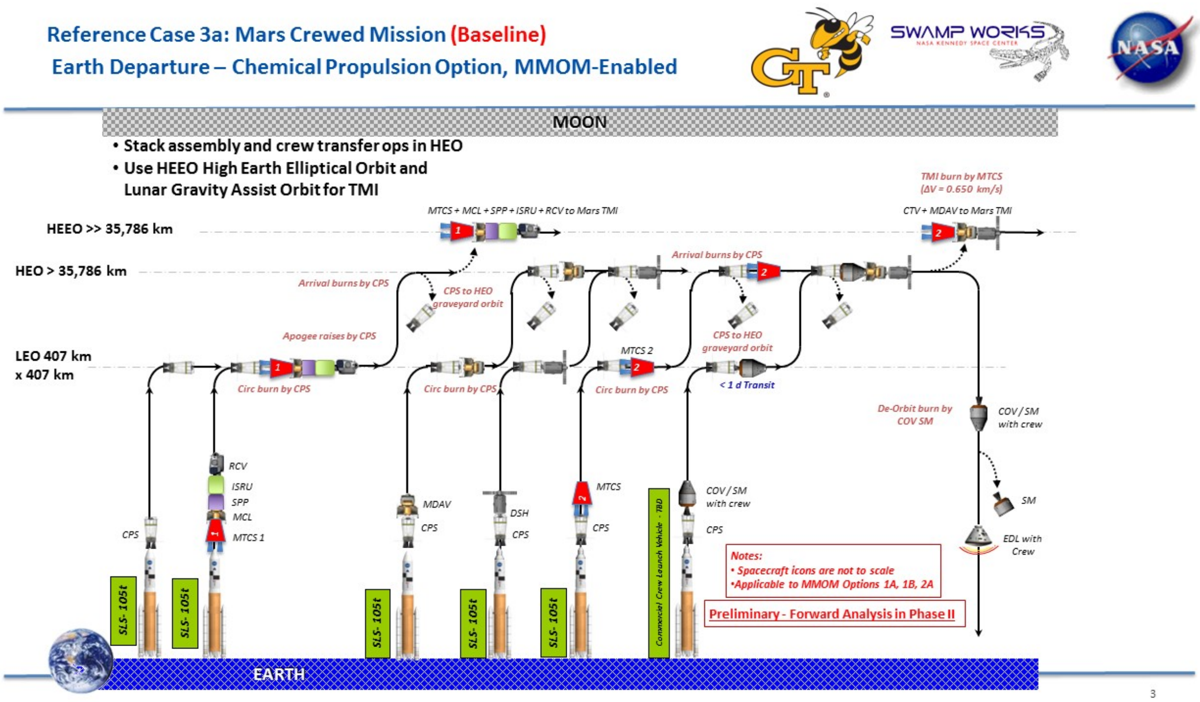
Appendix A: Mission Architecture Graphic Representation

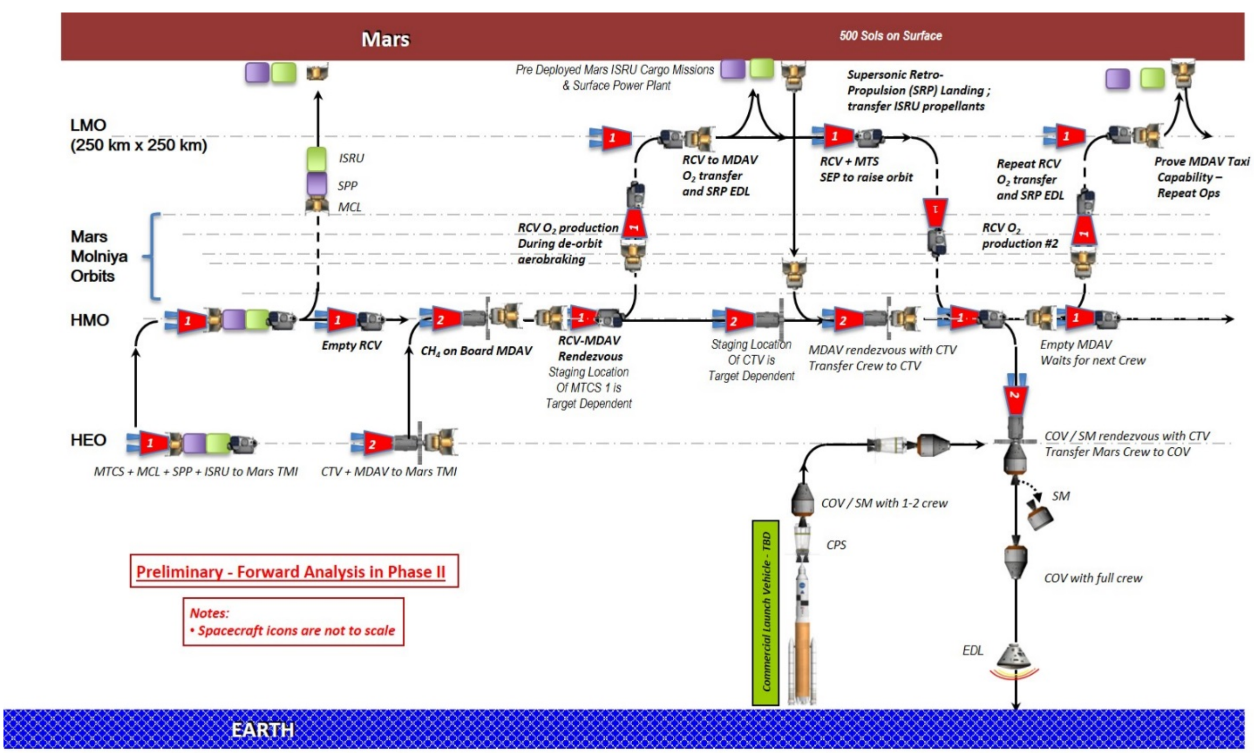





Reference Case 3: Mars Sample Return & Tech Demo
Earth Departure – Chemical Propulsion
MOON
• Use High Earth Elliptical Orbit (HEEO) and Lunar Gravity Assist Orbit for TMI
• CPS (no ZBO)
HEEO Lunar Assist
MTCS + RPSCL + SPP + ISRU to Mars
HEO > 35,786 km
Arrival burn by CPS
CPS to HEO graveyard orbit
Apogee raise by CPS
LEO 407 km x 407 km
ISRU
SPP
RPSCL
MTCS
CPS
SLS- 70t
Notes:
• Spacecraft icons are not to scale
• Applicable to Cases 1A, 1B, 2A
Preliminary - Forward Analysis in Phase II
EARTH
1


Reference Case 3: Mars Sample Return & Tech Demo
Mars Molniya Orbital Mining (MMOM) Enabled, Surface ISRU
Mars
500 Sols on Surface
Mars Sample Rover
Mars ISRU & Surface Power Plant
Mars Stay 540 d
Transfer MMOM O2 propellant
Supersonic Retro-Propulsion (SRP) Landing ; transfer ISRU propellants made on the surface
LMO (250 km x 250 km)
Full RCV
RPSCL propulsion to raise orbit
Discard RCV & MTCS
Demonstrate RCV O2 production during de-orbit Aerobraking (CO2 collection & MHD)
Mars Molniya Orbits
Discard RPSCL
RPSCL with ISRU/SPP
HMO
Empty RCV - No O2 Bring CH4 from Earth
Staging Location Of MTCS is Target Dependent
MTCS rendezvous with RPSCL / Samples
180 d Transit
MTCS
MTCS Return to HEO 180 d Transit
Samples
HEEO
COV / SM rendezvous for Transfer of Samples by Crew
COV / SM with Crew
COV / SM with Crew & Samples
CPS
Commercial Launch Vehicle - TBD
SM
EDL
Preliminary - Forward Analysis in Phase II
Notes:
• Spacecraft icons are not to scale
EARTH
2


Reference Case 3a: Mars Crewed Mission (Baseline)
Earth Departure – Chemical Propulsion Option, MMOM-Enabled
MOON
• Stack assembly and crew transfer ops in HEO
• Use HEEO High Earth Elliptical Orbit and Lunar Gravity Assist Orbit for TMI
HEEO >> 35,786 km
HEO > 35,786 km
LEO 407 km x 407 km
MTCS + MCL + SPP + ISRU + RCV to Mars TMI
CTV + MDAV to Mars TMI
TMI burn by MTCS (ΔV = 0.650 km/s)
Arrival burns by CPS
CPS to HEO graveyard orbit
Apogee raises by CPS
Circ burn by CPS
< 1 d Transit
De-Orbit burn by COV SM
COV / SM with crew
SM
EDL with Crew
RCV
ISRU
SPP
MCL
MTCS 1
MDAV
DSH
MTCS
CPS
SLS- 105t
Commercial Crew Launch Vehicle - TBD
Notes:
• Spacecraft icons are not to scale
•Applicable to MMOM Options 1A, 1B, 2A
Preliminary - Forward Analysis in Phase II
EARTH
3


Mars
500 Sols on Surface
Pre Deployed Mars ISRU Cargo Missions & Surface Power Plant
Supersonic Retro-Propulsion (SRP) Landing ; transfer ISRU propellants
LMO (250 km x 250 km)
ISRU
SPP
MCL
RCV to MDAV O2 transfer and SRP EDL
RCV + MTS SEP to raise orbit
Repeat RCV O2 transfer and SRP EDL
Prove MDAV Taxi Capability – Repeat Ops
Mars Molniya Orbits
RCV O2 production During de-orbit aerobraking
RCV O2 production #2
HMO
Empty RCV
CH4 on Board MDAV
RCV-MDAV Rendezvous
Staging Location Of MTCS 1 is Target Dependent
Staging Location Of CTV is Target Dependent
MDAV rendezvous with CTV Transfer Crew to CTV
Empty MDAV Waits for next Crew
HEO
MTCS + MCL + SPP + ISRU to Mars TMI
CTV + MDAV to Mars TMI
COV / SM rendezvous with CTV Transfer Mars Crew to COV
COV / SM with 1-2 crew
CPS
SM
COV with full crew
EDL
Commercial Launch Vehicle - TBD
Preliminary - Forward Analysis in Phase II
Notes:
• Spacecraft icons are not to scale
EARTH

Appendix B:

The estimated masses in Table B-1 were used to inform the reference case concepts of operations shown in Appendix A, based on parametric design, analysis, NASA missions, studies, and reference papers.

Table B-1. Elements, mass, and origins for the Mars Molniya Atmospheric Resource Mining Architecture.

Element	Mass (t)	Notes
CPS – Cryogenic Propulsion Stage	10	Dry mass, parametric design
CTV – Crew Transit Vehicle (MTCS + DSH)	47	Dry mass, EMC
MDAV/SSRL	22	MCL with crew cabin, parametric design, Ref: Hercules
COV with SM	25.8	EMC/Orion
DSH – Deep Space Habitat	43	EMC
MTCS – Mars Transit Cryogenic Stage	4	Dry mass, parametric design
MCL – Mars Cargo Lander	18.1	Ref: Hercules Lander (Arney et al.)
SPP – Surface Power Plant, 10 kWe unit	1.5	EMC
ISRU – 1 module	0.6	EMC
SP – Science Payload	0.1	MSR mission
RPSCL – Robotic Precursor Small Cargo Lander	1.9	MSR mission
RCV – Resource Collector Vehicle stack (Human)	84	RCV+MDAV+MTCS dry mass
RCV – Resource Collector Vehicle (Human)	58	Dry mass, atm. mining model
RCV – Resource Collector Vehicle stack (MSR)	21	RCV+ RPSCL+Payload dry mass
RCV – Resource Collector Vehicle (MSR)	12.4	Dry mass, atm. mining model
SCR – Sample Collection Rover	1	MSR mission
COV SM – Service Module	15.5	EMC/Orion
Mars Samples	0.1	MSR mission
Total Payload RPSCL	6.4	MSR mission