Development of a surface cryogenic propellant transfer concept for Martian operations

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Abstract. NASA is currently evaluating architectures to support human missions to Mars. A multitude of concepts are being traded and associated sensitivities are being analyzed. Mars Ascent Vehicle (MAV) propellant supply is a key consideration. Mass constraints for the Mars descent system and in-space transportation present significant architectural challenges that may preclude landing a fully fueled MAV for crew use. In such a case, to ensure the ability of the crewed mission to meet its objectives, propellant should be supplied to the MAV prior to the arrival of the crewed mission from Earth. A concept to robotically transfer liquid oxygen from a separate storage tanker across the surface to the MAV is proposed. This concept makes use of an unpressurized rover and is optimized to maximize the amount of propellant conveyed per trip.

1. Introduction

NASA is considering a number of options for sending a crewed mission to Mars and returning that crew safely to Earth. A critical element of any architecture is the Mars Ascent Vehicle (MAV), which is used to return the crew to Martian orbit at the end of their surface mission. A cryogenic propulsion system for the MAV, baselined to use liquid methane (LCH4) and liquid oxygen (LOX) is considered. Constraints to landed mass capability arising from Mars descent system and the in-space transportation architecture may preclude landing a fully-fueled MAV, instead landing the MAV with its full methane load and only a partial oxygen load. The MAV would need to be fully supplied with propellant prior to crew arrival. This creates an opportunity for the in-situ resource utilization (ISRU) production of oxygen to supply the MAV [1], however, while oxygen production was recently demonstrated by the Mars Oxygen ISRU Experiment (MOXIE) on the Perseverance rover [2], the ability to produce liquid oxygen at scale remains an open question. Pre-positioning the remaining required LOX on a separate lander from Earth and transporting it robotically across the surface to the MAV is an alternative. A notional Cryogenic Surface Propellant Transfer Package (CSPTP) is described here. Goals of the study: characterize and minimize commodity losses during transfer of propellant from lander to MAV, characterize and minimize dry mass required to accomplish propellant transfers, identify all system interfaces and touch points with other architectural components.
2. Assumptions
Given assumptions used to bound the capabilities of the CSPTP are as follows:

- 15,000 kg of usable propellant must be transferred to the MAV.
- Management of the LOX payload while in transit from Earth to Mars, while onboard the landing system, and after being loaded into the MAV is beyond the scope of this document. Commodity management is only considered through all stages of transfer between lander and MAV.
- For the purposes of this evaluation, it was assumed that LOX would be loaded at Earth at normal boiling point (90 K, ~1 bar), with no special conditioning.
- The descent system carrying the propellant and the MAV will be approximately one kilometer from each other. This is to avoid damaging an already present lander with blast debris liberated from the surface by the descent engines as a new lander arrives.
- Unpressurized rover payloads cannot exceed a footprint of 2.91 m x 1.84 m and cannot exceed a total mass of 2200 kg.

3. Design concept
Three landings at the chosen crew landing site will be required to support the crewed Mars mission. The first (which, for the purpose of this paper, will be called “Lander 1”) will land a power unit, an unpressurized rover, the CSPTP and the propellant required for the MAV, in addition to cargo offloading and other equipment. The second landing will consist primarily of the MAV and other equipment, particularly that required for EVAs. It is after this second landing that the propellant transfer operation must take place. Once the propellant transfer operation is complete, the third landing will bring the crew, their pressurized rover, and other associated cargo. A notional representation of the propellant transfer operation is shown in Figure 1.

Conceptually, the CSPTP is a skid of propellant transfer equipment that is carried on top of the unpressurized rover between “Lander 1” and the MAV. The CSPTP must function both independently and have the capability to establish physical, electrical and power interfaces with the unpressurized rover and with both “Lander 1” and the MAV as needed.

The propellant transfer equipment aboard the CSPTP would consist of a vacuum-jacketed LOX tank, vacuum-jacketed 1-inch transfer piping, and redundant 1-inch vacuum-jacketed flexhose for mating. Redundant control and vent/relief valving would be used as required. In order to minimize losses, the tank would be equipped with a cryocooler to minimize boiloff while in transit.
In consideration of notional relative elevations of the tankage between “Lander 1” and the CSPTP, it was determined that LOX could be supplied to the CSPTP via gravity feed. This is desirable as a simple, low-power transfer mechanism. If needed, the “Lander 1” tank could be equipped with a small heater to vaporize enough oxygen to avoid creating a vacuum in the ullage of the “Lander 1” tank.

Pumps are baselined for use to transfer LOX from the CSPTP to the MAV. This is partially in consideration of the relative elevation between the CSPTP and the MAV tanks and partially to ensure that the CSPTP tank has a low maximum allowable working pressure and thus requires a minimal wall thickness to save dry mass.

A pressurization system on the CSPTP tank will be required to maintain pump net positive suction pressure. Commonly, a gaseous helium system would be utilized for this purpose. However, a helium system would require an additional tank, tubing, and prelaunch servicing of an additional commodity. This would result in additional operational complexity as well as additional dry mass of the CSPTP system, reducing the amount of LOX that could be carried per trip. Instead, a small amount of LOX will be routed through a heater to create pressurant gas.

Other ancillary equipment to enable the transfer process, including pressure and temperature sensors, tank liquid level sensors, and check and relief valves will be required as well. All of these will need to be rated for cryogenic usage and of high reliability. It is also expected that the tanker package will require cameras that to aid in the mating/demating operation.

4. Operations concept
The distance over which the propellant transfer would take place was originally characterized as “no more than” one kilometer, as depicted in Figure 2, however, it was noted that unforeseen adverse ground conditions such as soft sand or difficult rocks might necessitate rerouting the rover. A “dry run” was proposed, with the rover driving the empty CSPTP between “Lander 1” and the MAV to establish a workable route that could be traversed quickly when the CSPTP was loaded with propellant. In order to take operational advantage of this dry run and further increase the amount of mass available for LOX in a given transfer operation, the pumps and their associated piping and equipment would be consolidated into a separate skid that would be semi-permanently mated to the MAV and left behind, to be removed upon overall completion of the transfer operation.

Figure 2. Notional landing site configuration [3]
After establishing a route with the “dry run”, the rover would return to “Lander 1” and mate with the transfer system. Once the CSPTP is loaded, the rover would demate and then traverse the route back to the MAV. At the MAV, the CSPTP will mate with the pump skid and offload LOX to the MAV. When the transfer is complete, the CSPTP will demate and the rover will return to “Lander 1”. It is estimated that each traverse will take two hours, one way. This process will repeat until the MAV is fully loaded with LOX. Then the pump skid will be demated and the overall CSPTP removed to a safe location on the surface. This overall transfer operation is expected to be completed with a high degree of autonomy, with minimal intervention from control stations on Earth.

An initial mass estimate predicts a dry mass for the mobile element of the CSPTP of approximately 640 kg, leaving 1560 kg available for LOX payload per trip. Transfer losses such as chilldown and leak checks as well as residuals and unrecoverable trapped volumes are estimated to consume up to 200 kg of that payload. This translates to 11 trips being required to complete the propellant transfer operation. The losses of propellant during transfer also means that approximately 18,000 kg of LOX will need to be landed in order to successfully transfer 15,000 kg to the MAV.

5. Developmental needs

5.1 Umbilicals & dust tolerance
Reliability of the umbilical connection between the CSPTP and each lander is vital. Failure to complete a connection or excessive leakage at a completed connection may result in an insufficiently loaded MAV, resulting in the loss of the ability to execute a crewed surface mission. The mass estimate given above indicates that a total of 23 mating actions can be expected to take place over the course of the transfer operation. These umbilicals must be able to reliably and autonomously connect the LOX transfer line, as well as any needed power and data connections, while being able to compensate for misalignment between the mating surfaces. The umbilicals must also be able to account for the dust prevalent in the Martian environment, through some combination of exclusion, tolerance, or removal. This is in order to prevent a failed umbilical connection due to dust accumulation in the mating cavity, resulting in leakage and possible loss of mission. Previous work on a Dust Tolerant Automated Umbilical, first conducted by Moon/Chariot Rover and Mars Pathfinder, may be of use for this purpose.

5.2 Cryocoolers & heat rejection
The CSPTP cryocooler is important to minimize or possibly eliminate propellant loss due to heat leak while in transit. Due to challenging mass, volume, and power constraints current Commercial Off-The-Shelf (COTS) units may not meet mission requirements or could require modifications. Therefore, it may be necessary to pursue bespoke units that are optimized for the unique application and Martian environment. Some key aspects to consider for a purpose-built unit are:

1. Choosing the correct refrigeration cycle and refrigerant for the situation
   a. AC-type (i.e. Stirling, Gifford-McMahon, pulse tube), or DC-type (i.e. Reverse-Brayton, vapor-compression, Joule-Thompson)
   b. Isothermal or sensible heat removal (Preliminary estimate 160W)
   c. Maximize efficiency and heat removal for the temperature range and environment

2. Optimizing the integration strategy for coupling the cryocooler to the load
   a. Typically driven by the type of cycle and/or machine chosen but is equally important to the overall efficiency and electrical power requirements because of integration losses. These losses should be minimized to the most practical extent possible, especially when the available power is limited.
   b. A remotely located, flow-through-type cold heat exchanger packaged inside or connected to the refrigerated region, with external interfaces to the rest of the refrigerator; or cold-finger type solid heat exchanger (usually copper) integral to the cryocooler itself, with a relatively short regenerator separating the warm and cold ends
(cold-finger type can be flow-through type by virtue of an additional flow loop to transport heat from the refrigerated region to the cold-finger, but requires additional hardware and increases complexity).

3. **Reliability of the system**
   a. Reduce overall system complexity (fewer components, novel packaging concepts, etc.)
   b. Minimize refrigerant leak points
   c. Autonomous control of cold power to prevent freezing or ullage collapse

Effectively rejecting the cryocooler waste heat to the Martian environment is vital. On Earth this is accomplished in a variety of ways, commonly using water chiller/circulator units, but the ambient Martian environment complicates matters due to its low-pressure atmosphere (~5 torr), which substantially retards the convective heat transfer mechanism primarily utilized in terrestrial systems to ultimately reject waste heat to the ambient environment. Additionally, integration of the cryocooler and heat rejection hardware is much more critical for space applications such as the CSPTP than for Earth-based systems due to physical constraints. Little work has been done to-date regarding design and optimization of waste heat rejection methods on Mars, and even less specifically related to cryogenic refrigeration. This presents a risk for current design and planning efforts, but also an opportunity for immediate technology development.

5.3 **Cryogenic pumps**
Commercial Off-The-Shelf cryogenic pumps designed for liquid oxygen service have a power requirement on the order of kilowatts. Smaller COTS pumps with adequate flowrate capabilities are available that operate at a maximum of 0.5 kW, however, are only rated for water service. Flight qualification of a high reliability, lightweight, low-power liquid oxygen pump would be necessary.

5.4 **Autonomous operations**
Propellant transfer operations will need to be conducted autonomously, as communications latency with Earth-based ground control is likely to exceed what would be needed for timely command and response. Autonomously controlled cryogenic propellant transfer has been demonstrated on ground-based systems for nominal conditions, however, automated recovery from a fault condition is still limited. Most faults require operator intervention. For this reason, autonomous system health monitoring, fault isolation, and recovery will need to be matured to a high degree of reliability in order to assure success of the transfer operation and overall mission success.

5.5 **Risk reduction**
A number of other design considerations exist as well, ranging from other aspects of survival in the Martian environment to fault tolerance to activity scheduling to ensure adequate time is available to complete the transfer operation when the rover may be used for other site setup tasks to prepare for crew arrival. In addition, design and operational coordination with the lander carrying the liquid oxygen payload, the MAV, and the rover will be critical for the successful transfer of propellant.

6. **Interfaces**
Liquid oxygen will be transferred to and from the CSPTP via a 1-inch quick disconnect that connects to a corresponding interface plate on “Lander 1” and an interface plate on the pump skid. The pump skid will mate to the MAV via another 1-inch quick disconnect. These disconnect interfaces will also feature power and data connections to enable operations. It is estimated that these interface plates will be no more than one meter off of the ground. Figure 3 shows a notional umbilical mate concept.
Power would be provided to the CSPTP via external sources, either the rover itself or the landers at either end of the traverse. Initial estimates are that 0.5 kW will be necessary in transit, mostly due to the cryocooler, peaking to 0.7 kW during mating operations. Once mated, the architecture is estimated to draw up to 3.2 kW to complete the transfer process. As noted, power and data connections between the CSPTP and each lander will be via the interface plates, however, a separate power and data connection will need to be coordinated with the unpressurized rover to support operations while in transit.

Further anticipated touch points for the CSPTP are given in Table 1.

Table 1. CSPTP Touch Points

| Lander          | Assumption                                      | MAV          | Assumption | Rover          | Assumption | Other                    | Assumption |
|-----------------|-------------------------------------------------|--------------|------------|----------------|------------|--------------------------|------------|
| QD location     | 1 m (h) x 1 m (l)                               | QD location  | 1 m (h) x 1 m (l) | Mass Capacity | 2,200 kg   | Commodity to be transferred | LOX        |
| QD diameter     | 25mm/6.4mm                                     | QD diameter  | 25mm/6.4mm | Available Footprint | 2.91 m (l) x 1.84 m (w) x 4.1 m (h) | Travel distance between Lander and MAV | 2 km      |
| QD mating surface (male or female) | TBD                                            | QD mating surface (male or female) | TBD          | Power Available during transit (cooler, instrumentation, etc.) | Developing subsystem requirement | Fault tolerance | Dual |
| Supply tank outlet height | 4 m                                           | Receiver tank inlet height | 4 m         | Maximum duration of travel between Lander/MAV | 2 hours one way | Method of transferring skid elements on/off of rover | Jack stands |
| Power availability | 5 kW                                           | Power availability | 5 kW        | Camera availability | TBD        | Ambient temp max/min | 310 K - 150 K |
| Landers | Assumption | MAV | Assumption | Rover | Assumption | Other | Assumption |
|---------|------------|-----|------------|-------|------------|-------|------------|
| Supply tank instrumentation | TBD | Receiver tank instrumentation | TBD | Dust mitigation requirements / accommodations (for QD interfaces) |
| (pressure, liquid level, temperature, leak detection, etc.) | | | | |
| Supply tank liquid transfer and vent valve configurations | TBD | Receiver tank liquid transfer and vent valve configurations | TBD | System remote control latency |
| | | | | TBD |
| Supply tank MAWP | TBD | Receiver tank MAWP | TBD | Local automated control software conops |
| | | | | TBD |
| Supply tank Min Press rating | TBD | Receiver tank Min Press rating | TBD | Total transfer time available |
| | | | | 12 months |
| Supply tank cooling/heating capacity | TBD | Receiver tank cooling/heating capacity | TBD | CO2 de-icing considerations |
| | | | | TBD |
| Supply tank quiescent liquid state | LOX: ~1 bar, 90K | Receiver tank quiescent liquid state | LOX: ~1 bar, 90K | Nuclear power supply thermal effects |
| | | | | TBD |
| Supply tank size (commodity mass available) | TBD | MAV tank mass requirement | ~15,000 kg LOX |
| Camera availability | TBD | Camera Availability | TBD |
| Filter/purity requirement | TBD | Filter/purity requirement | TBD |
| Available Helium Supply | None | Available Helium Supply | None |
| Supply Tank Pressurization methodology | Autogenous | Receiver tank pressurization methodology | Autogenous |
| How many tanks need to be drained | 1 | How many tanks need to be filled | TBD |

7. Conclusion
Landing a separate payload of cryogenic propellant and transferring that propellant to a waiting Mars Ascent Vehicle is a possible method for enabling crewed surface exploration of Mars. While similar in some ways to the delivery of liquefied gases from a vendor that commonly takes place at NASA launch facilities, key differences exist. Minimization of commodity losses and overall system dry mass is essential. Furthermore, the ability to conduct such a delivery autonomously is a complex technological
challenge. Early identification and maturation of technologies necessary to accomplish these goals in order to integrate them with the overall mission architecture are critical to the success of a crewed mission to the Red Planet.

8. References
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