Development of a Two-Stage Mars Ascent Vehicle Using In-Situ Propellant Production

Laurel Paxton* David Vaughan†

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

Mars Sample Return (MSR) and Mars In-Situ Resource Utilization (ISRU) present two main challenges for the advancement of Mars science. MSR would demonstrate Mars lift-off capability, while ISRU would test the ability to produce fuel and oxidizer using Martian resources, a crucial step for future human missions. A two-stage Mars Ascent Vehicle (MAV) concept was developed to support sample return as well as in-situ propellant production. The MAV would be powered by a solid rocket first stage and a LOX-propane second stage. A liquid second-stage provides higher orbit insertion reliability than a solid second stage as well as a degree of complexity eventually required for manned missions. Propane in particular offers comparable performance to methane without requiring cryogenic storage. The total MAV mass would be 119.9 kg to carry an 11 kg payload to orbit. The feasibility of in-situ fuel and oxidizer production was also examined. Two potential schemes were evaluated for production capability, size and power requirements. The schemes examined utilize CO2 and water as starting blocks to produce LOX and a propane blend. The infrastructure required to fuel and launch the MAV was also explored.

Nomenclature

CBE	Current Best Estimate
DME	Dimethyl Ether
ISP	Specific Impulse
$ISPP$	In-Situ Propellant Production
$ISRU$	In-Situ Resource Utilization
LOX	Liquid Oxygen
LPG	Liquified Petroleum Gas
MAV	Mars Ascent Vehicle
MEL	Mass Equipment List
MSR	Mars Sample Return
OF	Oxidizer-Fuel Ratio
$SOEC$	Solid Oxide Electrolysis Cell
TRL	Technology Reliance Level

I. Introduction

In the coming decades, two key technologies of are of primary interest to Mars science: Mars Sample Return (MSR) and In-Situ Resource Utilization (ISRU). MSR endeavors to retrieve a sample from the Martian surface and return it to Earth for study. Earth laboratories are better able than rovers to analyze Martian rocks and soil: sample return would likely yield unique scientific insight. It would also allow to demonstrate the ability to lift-off from Mars, which has never been done. This is a large hurdle for human missions to Mars, since return vehicles would be a key part of any exploration framework. Similarly, In-Situ Resource Utilization is critical for sustained human development on Mars. It is impractical for future

*JPL Summer Intern: Propulsion and Fluid Flight Systems, Princeton University AIAA Member.

†Group Supervisor: Propulsion and Fluid Flight Systems.

settlements to rely on propellant shipments; ISRU would allow self-sustainability. In the near-term, in-situ fuel production would help reduce Earth lift-off and Mars landing weights. Earth lift-off without MAV propellant allows the propulsion system to preclude heavy, complex redundancy systems.

A. Mission Profile

To address MSR and ISRU goals, a potential Mars Ascent Vehicle (MAV) was designed to lift a sample to Mars orbit. The vehicle would use two stages to achieve a delta V of 3.5 km/s and an orbit of 500 km. At this velocity, the sample would remain in a stable parking orbit to await a retrieval vehicle from Earth. As the sample must remain in stable parking orbit for a potentially long duration of time, the accuracy of orbital insertion must be high.

The second stage of the MAV would be fueled by propellants produced on the Martian surface. The propellants would be produced over an approximate 400 day mission and then transferred to the MAV for lift-off. This mission framework accomplishes two major Mars science goals in relatively compressed time frame. This paper details the design of the MAV second-stage and considers several options for in-situ processes to provide the required propellant.

II. MAV Design

A. Initial Design Formulation

The two-stage design was chosen to allow comparison with a previously suggested benchmark that utilized solid fuel motors for both first and second stages. The proposed design utilizes a similar solid rocket first stage with a liquid bipropellant second stage. A liquid second-stage provides higher orbit insertion reliability than a solid second stage. This is important, because the sample must attain a stable orbit to allow retrieval. The liquid stage also provides a degree of complexity that will eventually be required for manned missions.

The motor will be thrust-vector controlled. The MAV contains an interstage module with a telecom subassembly and a spin stabilization system. Spin thrusters will stabilize the second stage at 300 RPM before separation.

B. Propellant Selection and Characterization

Liquid oxygen and propane (C_3H_8) were chosen for the second-stage propellants. LOX-propane has a good Isp of 360 s and remains liquid over a wide range of temperatures. Propane offers several advantages over methane. With comparable Isp to methane, it does not need to be stored cryogenically and has a lower atmospheric freezing point.[1] Thus, propane reduces the power overhead required for Martian storage, is less susceptible to temperature fluctuations, and has a higher bulk density, which reduces MAV and ISPP system mass.

In addition, propane also provides raw material for plastic production. Propane can be refined to generate propylene (C_3H_6). Propylene chains form polypropylene, which is used in a wide variety of useful plastics, from tubing to clothing. Plastic production is crucial to the sustainability of a manned presence on Mars, given its ubiquity in industrial and commericial products. Specifically, polypropylene can be used in 3-D printers. This property is particularly important, as 3-D printing can be used to print neccessary parts. Methane, on the other hand, is extremely difficult to refine into plastics. The table below shows a comparison of LOX, propane and methane fluid properties.[2]

Table 1. Propellant Fluid Properties

	LOX	Propane	Methane
Freezing Point (K)	54.4	83	90.5
Boiling Point (K)	90	231	111.4

The LOX-propane system was then characterized using NASA's CEA code. CEA is a program which calculates chemical equilibrium product concentrations from any set of reactants and determines thermodynamic and transport properties for the product mixture.[3] The optimal oxidizer/fuel ratio (O/F) was determined by examining the Isp variation over a range of operating conditions. The Isp peaked at an O/F of 2.9. There was relatively little shift in the O/F for increased chamber pressure as illustrated at right.

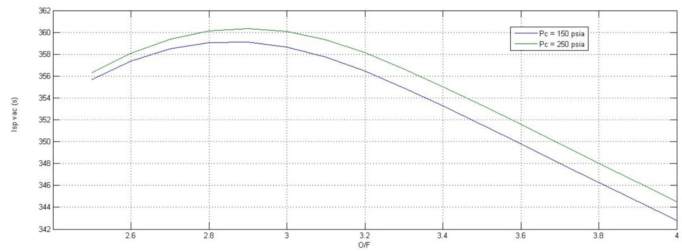

Figure 1. Chamber Pressure Comparison

Therefore, for second stage operation, a chamber pressure of 150 psia was deemed sufficient. The theoretical Isp was 359.7 s, and the expected Isp (including a 95% efficiency assumption) was 342 s.

Using the Isp and O/F ratio, the Tsiolkovsky rocket equation was used to determine the system delta V and required propellant mass. To begin the iterative process, a first stage total mass of 86.5 kg and a second stage burnout mass of 15 kg was assumed. This included 11 kg allotted for the orbital sample and avionics, with an additional 4 kg for the propulsion feed system. This feed system mas was later adjusted and is discussed further in this paper. With these initial assumptions, the propellant mass was calculated at 7.73 kg. With an O/F of 2.9, the required propellant was calculated to be 1.98 kg of propane and 5.75 kg of LOX.

C. Vehicle Configuration

Using initial propellant mass sizing, the vehicle configuration could be established. The initial propellant mass sizing corresponded to a propellant volume of 367 in^3 and 266 in^3, for LOX and propane respectively. As both LOX and propane densities change considerabely for non-standard conditions, new densities were calculated for the tank operating conditions.[4] These calculated densities were used to determine propellant volume. Assuming a tank pressure of 250 psi, a spherical tank of mass 1.5 kg was chosen to hold both propellants.

There are two options to pressurize the propellant tanks: a helium pressurization system or use of the propellant vapor pressure in a self-pressurizing system. In a self-pressurizing system, the propellants are warmed to increase the vapor pressure to the desired tank pressurization. The system then functions as a simple blowdown engine. Self-pressurization is attractive for its simplicity: reducing the complexity of the system reduces mass and increases reliability. Such systems have been tested with LOX-propane: AirLaunch developed a LOX-propane self-pressurized second stage as a DARPA program.[5] Tanks will drop in pressure approximately 60% over the period of operation.[6] Such a pressure drop is not necessarily a concern if starting from a sufficient pressurization. However, SPS has difficulties in flow and thermal control as well as a low Technology Reliance Level (TRL). Two-phase flow can develop in the propellant lines, reducing engine performance and causing damage. Heat flow between propane and LOX tank must be managed, as the propane is heated to a temperature approximately 200 K greater than the LOX.[7] Excess heat from the propane tank could causes excess pressurization in the LOX system. A helium pressurization system, on the other hand, would result in a higher TRL though with increased mass penalty. For such a small system, helium pressurization would be a more realistic option for near-term implementation.

Using a helium blowdown system, a propulsion block diagram was created (shown in Figure 2). From the block diagram, a Mass Equipment List (MEL) was created to asses the second stage

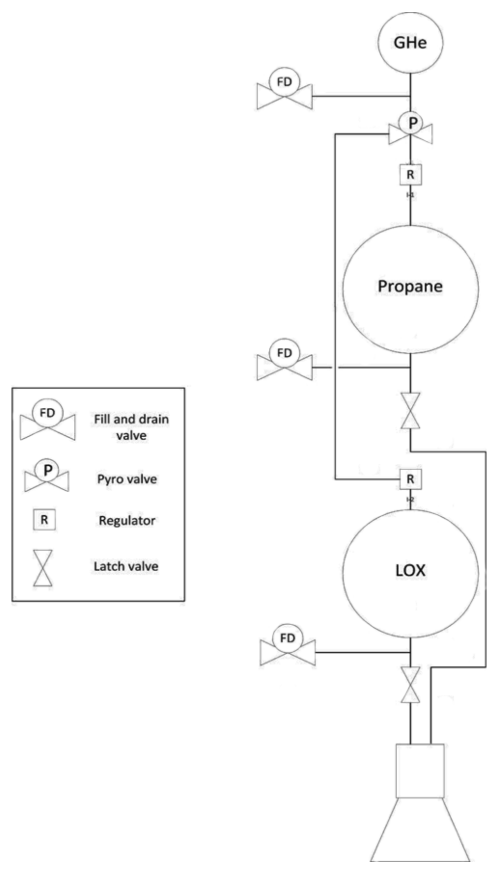

Figure 2. Propulsion Block Diagram

mass. The MEL is included in Figure 3. Using the new feedsystem mass, the required propellant mass was re-calculated to be 10.29 kg of LOX and 3.55 kg of propane.

Stage 2 Parameters	
	CBE (kg)
LOX	10.29
Propane	3.55
Burnout mass:	20.48
Feedsystem:	9.53
Tanks (2)	3
Pyro valve	0.15
Nozzle	1.56
Latch valves (2)	0.3
Regulators (2)	1
He tank (loaded)	0.48
Piping, instrum.	3.04
Payload (includes structure, avionics)	10.95
Total 2nd stage	**34.32**

Figure 3. LOX-Propane Stage 2 Parameters

D. Baseline Comparison

Figure 4 presents a comparison between the all-solid baseline MAV and the part liquid MAV using LOX-propane. As expected, the part-liquid MAV is slightly heavier but not excessively. The liquid MAV is not unreasonably heavy so as to remove it from consideration. These numbers are estimates, and, given further development, the part-liquid mass estimate might decrease. Given the orbital insertion accuracy requirement, the liquid stage presents a competetive alternative to an all-solid MAV. Additionally, a part liquid MAV presents an attractive option to test in-situ propellant production, which would not be possible with an all-solid MAV.

	Mass CBE (kg)	CBE + 43% (kg)
Part Liquid MAV:	119.9	171.5
All Solid Baseline:	105.9	150.8

Figure 4. Baseline MAV Comparison

III. In-Situ Resource Utilization

In-situ resource utilization uses Martian resources to create required mission materials. This paper focuses, in particular, on the use of an In-Situ Propellant Production system (ISPP) to produce liquid oxygen and propane. Gaseous oxygen production through the Sabatier reaction has been used on the ISS for many years, but off-Earth LOX production has never been tested. Little work has been conducted on creating a combined LOX-propane ISPP system.

Martian temepratures and pressures present a unique challenge for propellant production. Mars temperature averages at around -55 deg C (218 K) with diurnal temperature swings of 100 K. In addition, Mars pressure is about 0.09 psi, extremely low compared to Earth pressure of 14.7 psi. As most in-situ processes have precise temperature and pressure requirements (usually both high temperature and high pressure), infastructure must be designed to pressurize, heat and store reactants.

The two main options for a LOX-propane combined cycle are discussed in the following section. Each option begins with Martian CO_2 and water. Initially, water will most likely be transported from Earth. Water supply is not discussed in this paper. Since each process utilizes pressurized Martian CO_2 , the CO_2 must be gathered from the atmosphere and pressurized. This can be done through use of a sorption compressor.[8]

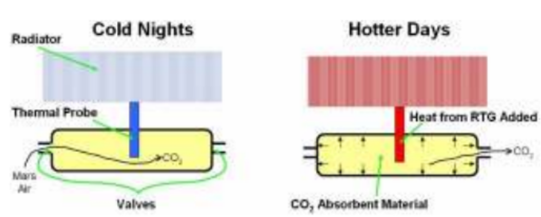

Figure 5. Mars Sorption Compressor

The sorption compressor utilizes the day-night temperature swings of the Martian surface to compress CO_2 gathered through a sorption bed. A sorption compressor was developed at JPL for the 2001 Mars Surveyor mission but requires further development.[9] As Martian dust could damage the sorption bed, a dust filter will be required. This filters out dust particles to allow a flow of mostly CO_2 through the device. The sorption compressor has been sized at roughly 1 kg and the dust filter at 0.5 kg.

A. Option 1: Solid Oxide Electrolysis Cell (SOEC) with Fischer-Tropsch (F-T) Reactor

The first option is to use a solid oxide electrolysis cell in conjunction with a Fischer-Tropsch reactor. This sequence reacts Martian CO_2 with water to produce liquid oxygen and propane. There are two key components required: a solid oxide electrolysis cell (SOEC) and a Fischer-Tropsch reactor. The SOEC uses electrochemical potential to complete a desired chemical reaction. SOECs have most commonly been used in the electrolysis of water to produce hydrogen and oxygen. Water-CO_2 co-electrolysis is beginning to be studied as a more desirable alternative, as the reaction does not cause as much wear on the cell.[10] The co-electrolysis process produces a stream of pure oxygen and a stream of hydrogen, carbon monoxide and residual water.[11]

The carbon monoxide-hydrogen stream (a syngas stream) is then fed to a Fischer-Tropsch reactor. The Fischer-Tropsch process was first pioneered in Germany in the 1920s, as a response to dwindling fuel reserves. The process passes carbon monoxide and hydrogen gas over a catalyst bed to produce liquid hydrocarbons.[12] The process later became industrialized in South Africa and more recently, in Saudi Arabia. As a result, much of the research on the process has been focused towards producing long hydrocarbon chains (C5+) at industrial scales.

	Temperature	Pressure
SOEC	500-800 C	1 bar
Fischer-Tropsch Reactor	300-800 C	10-60 bar

Figure 6. Fischer-Tropsch Operating Conditions

Hydrocarbon selection is determined by the type of catalyst used and the operating conditions of the reactor. To select for moderate length hydrocarbons, a cobalt-based catalyst should be used. Use of a cobalt catalyst also allows for more flexibility in the allowable ratio of hydrogen to carbon monoxide. For propane production in a cobalt reactor, the hydrogen-carbon monoxide ratio should be approximately 1.9. Reactors typically operate between 300 and 800 degrees C, and at a pressure of 10 to 60 bar.[13] Higher temperatures favor an undesirably low rate of methane production, though it leads to higher reaction times and conversion rates. Higher pressures also reduce methane production. The SOEC operates at a pressure of 1 bar and at temperatures of 500 to 800 deg C.

There are several benefits to the use of the Fischer-Tropsch process. Due to its longevity and current industrial use, the process has been well-documented. The process also results in liquid hydrocarbons, eliminating the need for liquefaction equipment. Also, once started, the reaction is largely self-sustaining, though there are large power draws on startup, which could pose problems in the case of non-continuous operation. Catalyst and experimental unit are not optimized for propane production, as much of the current production is focused on long chain hydrocarbons. Process work is geared towards large-scale industrial units, as small-scale units are not marketable. Furthermore, the high pressures required by the reactor are incur large mass and power penalties.[14] Therefore, while the Fischer-Tropsch process is promising route for hydrocarbon production, much work must be done to classify the reaction and required hardware for Martian operation.

B. Option 2: SOEC with Dimethyl-Ether (DME) and LPG Reactor

The second option also uses a SOEC, but instead of a single Fischer-Tropsch reactor, combines a dimethyl ether (DME) reactor and a liquefied petroleum gas (LPG) reactor. This option also utilizes Martian CO_2 and water to produce liquid oxygen and propane. There are three key components: a SOEC, a DME reactor, and an LPG reactor. The SOEC is utilized as in Option 1: it processes water and carbon dioxide to produce syngas. This syngas stream then passes to the DME reactor, which produces dimethyl ether (C_2H_6O). The produced dimethyl ether then passes into an LPG reactor which produces a hydrocarbon mix including propane. Unlike the Fischer-Tropsch process, the DME reactor requires an H2-CO ratio of 1.[15] This ratio is easier to obtain from the SOEC, simplifying operation. The DME-LPG process was recently explored by Ma, Ge, Xu (Dalian National Laboratory, China) directed towards optimizing propane production. The DME process uses a Cu-Zn-Al/ZSM-5 catalyst at a temperature of 250 deg C and 3 Mpa. The LPG process uses a Pd-Y catalyst at a temperature of 405 deg C and 1 Mpa.[16] This temperature-pressure ratio produces a hydrocarbon stream of 55% propane. The process diagram is shown below.

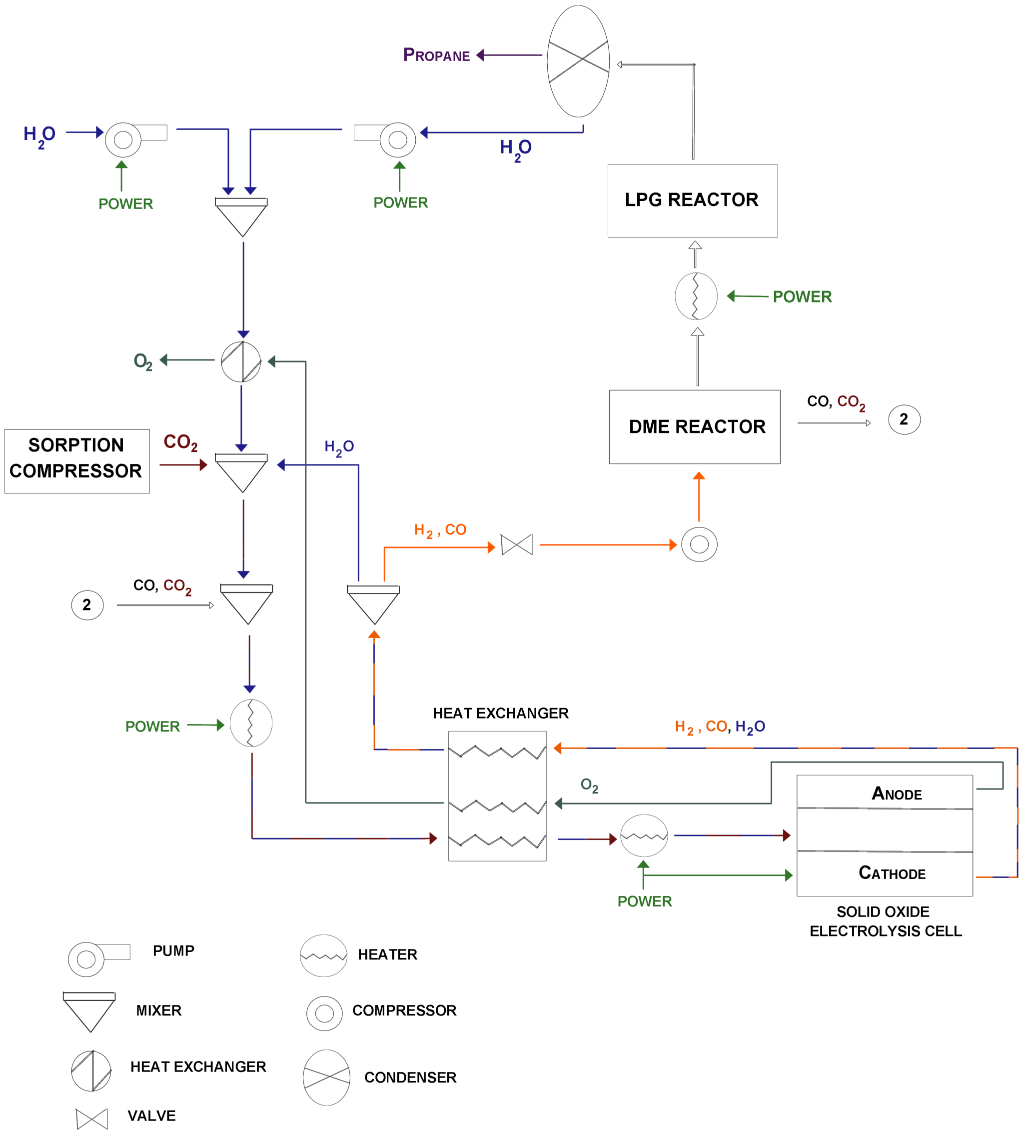

Figure 7. SOEC-DME-LPG Process Diagram

Option 2 is an attractive option for its reduced temperature and pressure requirements. This reduces the need for additional compressors and heaters, which incur heavy mass and power penalties. As the availability of power is a major concern for surface operation, processes requiring less power are better. Moreover, as a suitable catalyst has already been developed, the process is better suited for propane production than the Fischer-Tropsch process. However, work on this combined process is very recent. More research will be needed to identify potential flaws.

	Temperature	Pressure
SOEC	500-800 C	1 bar
DME Reactor	250 C	30 bar
LPG Reactor	405 C	20 bar

Figure 8. DME-LPG Operating Conditions

The 55% propane hydrocarbon stream was analyzed using CEA to determine the Isp effects of using such a mixture. Studies on the DME-LPG process described the full hydrcarbon fuel product: this full content was encoded into the CEA analysis. Though the change is small, the ISP actually improves when using mixed hydrocarbons. Storage conditions and engine operation may change with this as well.

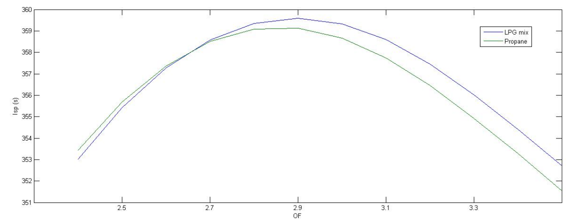

Figure 9. LPG-Propane Comparison

C. Process Mass Breakdown and Comparison

Option 1: SOEC-FT	Unit Mass (kg)	Option 2: SOEC-DME-LPG	Unit Mass (kg)
Sorption compressor	0.96	Sorption compressor	0.96
Dust filter	0.5	Dust filter	0.5
Mixer (4)	0.5	Mixer (4)	0.5
Heat exchanger (2)	0.5	Heat exchanger (2)	0.5
Large exchanger	7	Large exchanger	7
SOEC	15	SOEC	15
Compressor	9	Compressor	9
Condenser	0.7	Condenser	0.7
Crycooler	6	Crycooler	6
Holding tanks (4)	10	Holding tanks (5)	10
Fischer-Tropsch reactor	2	DME reactor	2
Piping, valves	8.4	LPG reactor	2
		Piping, valves	9.6
Total	**92.5**	**Total**	**105.7**

Figure 10. Process Mass Comparison

As shown in the figure above, both systems are about 100 kg. The DME-LPG process appears slightly heavier, but this estimate accounts for an extra holding tank between the two processes. The DME-LPG process operating conditions make it a good candidate for surface implementation.

As shown in Figure 8, the ISPP is not a trivial system. The network of mixers, pumps and heat exchangers must be properly designed to reduce mass. This system must be thoroughly tested to determine reliability under Mars conditions.

D. Infastructure: Storage, Fueling and Power

The power required to operate the in-situ process was also assessed. Operating the full in-situ process continuously will require about one kilowatt.[17] However, this kind of power is not available on Mars: power availiability for the Mars Science Laboratory was estimated at 100 Watts. An all-solar power source such as the one carried by the Phoenix Lander could potentially provide 300-400 Watts. With lower power, the ISPP system would need to be run in stages. Holding tanks would be added between processes, so that one process could be run, the results stored and then the system shut down for power conservation.

An important consideration for in-situ fuel production is the ability to store fuels on the surface of Mars. Temperatures and pressures are below Earth ambient, so some pressure and temperature control will be required to maintain the propellants' liquid state.

Liquid	Pressurization	Temperature Control
Water	None	> 273 K
Propane	> 8.7 psi	None
Oxygen	> 1.4 psi	~ 70 K

Figure 11. Liquid Storage Requirements

Propane is a superior choice for storability. No temperature maintenance is required: it needs moderate pressurization of above 8.7 psi for liquid state. Water requires temperature management but no pressurization. Liquid oxygen, as a cryogen, will require cooling but relatively little pressurization.

Propellant must also be transferred from the holding tanks to the MAV. This can be accomplished using a pressure differential. As the propane will be pressurized, that pressure can be used to push the fuel into the lower pressure tanks. Prior to fuel transfer, the LOX cryocooler will be turned off, allowing the liquid's pressure and temperature to rise. This pressure differential can be used to push the LOX into the MAV tanks. However, with this temperature and pressure rise, some of the LOX will be lost due to boil-off. These boil-off losses must be accounted for in the propellant production process: excess propellant must be manufactured to balance this.

1. Automatic Disconnect Mechanism

Once fuel has been transferred to the MAV, the fuel lines must be disconnected. This needs to be accomplished by an automatic disconnect mechanism. The mechanism would close the fuel/MAV lines and seperate itself from the craft. Automatic disconnects were developed for use with the Space Shuttle, as the external fuel tank had to be separated from the Shuttle. Such a disconnect is shown in the figure at right.[18]

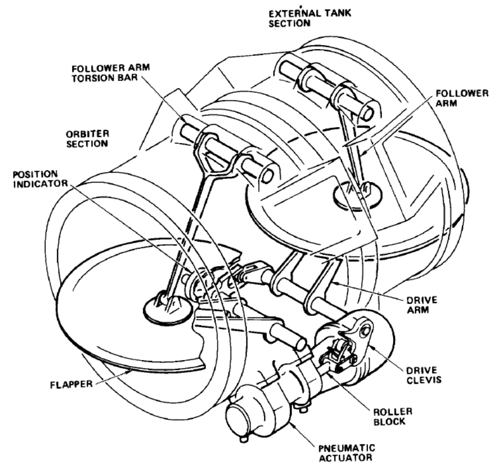

Figure 12. Space Shuttle Automatic Disconnect

However, the Space Shuttle disconnect is a large and complex mechanism, with documented reliability issues. The disconnect operates on a 17 inch diameter line. An ascent vehicle would likely use lines of 1/2 in diameter, thus the disconnect would need to be correspondingly scaled. There are also no existing automatic disconnect systems for such small lines. Further, issues with the Shuttle disconnect mechanism should be resolved before pursuing this route. The use of metal flapper valves as the closing valve was neccessary given the cryogenic nature of the propellants. However, a metal-metal seal is difficult to seal properly, as it is sensitive to temperature fluctuations, abrasion and external movement. The use of smaller lines may resolve this issue.

IV. Future Work and Conclusion

A. Future Work

Future work is needed to develop the ISPP system and the infrastructure required to support its implementation. The SOEC-DME-LPG process must be further developed and tested for robustness. The process must be tested for a long-term (400 day) mission. Concerns have been raised regarding the longevity of the process catalysts: long-term testing will determine if catalyst depletion is an issue. System power requirements must also be studied. These power requirements are the main limitation for the implementation of an ISPP on Mars, since the available power is low. Due to high power requirements, the system may need to operate intermitently. Reactor start-up and shutdown conditions and power requirements therefore must be studied. If non-continuous operation will affect system performance, alternative power supplies should be explored for continuous operation. Fuel cells are a potential alternative, as they can be powered using the propane product produced in the ISPP system.

The fueling of the MAV must be also be addressed. A scaled Space Shuttle automatic disconnect is an option, but given the issues in past operation and difficulties of Mars surface operation, a reliable disconnect mechanism should be developed.

B. Conclusion

To support Mars Sample Return and Mars In-Situ Resource Utilization, a two-stage Mars Ascent Vehicle concept was developed to lift a sample into Mars orbit using propellant produced on Mars. This study analyzed the use of a two-stage MAV with a solid rocket first stage and liquid biprop second stage. The liquid biprop stage would provide additional orbital accuracy, which is desirable for caching the sample in a long-term stable orbit. The MAV would use a LOX-propane engine, since propane has performance comparable to methane and can be stored easier on Mars. A propulsion block diagram and mass equipment list were developed to help size the second stage. The total ascent vehicle was sized at 119.9 kg for a worst case 11 kg payload. The part-liquid MAV is therefore comparable in mass to the all-solid configuration.

This paper also discusses the production of propellant on Mars. The current state of work on in-situ propellant production was also explored. As propane is not commonly used as a rocket propellant, little information was available for in-situ production systems. Two options were then developed for an in-situ propellant production system (ISPP). Both options react Martian CO_2 and water to produce liquid oxygen and liquid propane. A solid oxide electrolysis cell reacts CO_2 and water to produce oxygen and a syngas stream. The syngas stream can be processed using a Fischer-Tropsch reactor or a two-step dimethyl ether-liquified petroleum gas reactor. The DME-LPG process has more feasible operating temperatures and pressures: this is crucial, as increased temperatures and pressures drastically increase mass and power requirements. An estimate of the mass required for both in-situ processes was calculated. Both mass estimates were comparable. The infrastructure required for MAV fueling and propellant storage was also examined.

Areas for future work were identified, such as an automatic fueling disconnect mechanism and the power-required for an ISPP system. This study focused on a comprehensive analysis of mission parameters: keeping a systems perspective to analyze mass AND power required for successful completion. While much work remains, the results of this study are promising and show that further work is merited.

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