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Feasibility of a single port Hybrid Propulsion system for a Mars Ascent Vehicle ☆

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ABSTRACT

Developments in hybrid propellants over the last decade make the hybrid motor a viable candidate and possibly an enabling technology for a Mars Ascent Vehicle (MAV) as part of a Mars Sample Return (MSR) campaign. Fast regression rate fuels such as paraffin allow for single port hybrid designs that overcome the disadvantages associated with classical hybrid fuels. Additionally, paraffin has a both a weak and low glass transition temperature, making it an ideal candidate for a Mars application. Nytrox, a high performance oxidizer made of a mixture of nitrous oxide and oxygen, can be chosen to match the temperatures on Mars. The hybrid MAV can survive the harsh Martian environment with minimal or no thermal conditioning and it can meet the design challenges posed by coordinating with the other aspects of MSR.

1. Introduction

A Mars Sample Return (MSR) campaign is the next major step in Mars science [1]. Returning samples from Mars allows scientists to conduct tests that would not be possible *in situ*. These include tests that require complex sample preparation or instrumentation that is not suitable for Mars (e.g. it is too large, has a high power requirement, is high maintenance or requires complex procedures). Also, returned samples can be analyzed by a larger and more diverse group of instruments [1].

The current MSR architecture breaks the campaign into three main objectives: collecting and caching samples, retrieving the samples and launching them into Mars orbit, and returning the samples to Earth. While there are many challenges within this campaign the focus of this paper will be the Mars Ascent Vehicle (MAV), for getting the samples into Mars orbit, which has been identified as the highest system technology risk [2]. The risk is greatly heightened by the desired low mass MAV and long storage time in Mars' cold and highly variable environment.

The MAV will remain on the Martian surface for a year or more in order to coordinate with the other elements of the MSR campaign. Environmental conditions on Mars are design drivers and have forced previous industry studies to include a substantial amount of thermal control requiring up to about 30 kg of additional mass [3]. Diurnal temperature variations have been determined to be about $\pm 50\,C^{\circ}$ with annual temperature extremes from -111 to $24\,C^{\circ}$ [4].

NASA's current architecture requires the MAV to return the 5 kg, 16 cm diameter sample container to a greater than 400 km circular orbit at an inclination angle of $30^{\circ} \pm 0.2^{\circ}$. Although there is no fundamental mass requirement, a gross lift-off mass of less than 300 kg is a reasonable goal. There is a strong desire to reduce thermal conditioning required throughout the mission in order to reduce both mass at Earth launch and Mars Entry Descent

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and Landing (EDL). Additionally, decreasing the required thermal control has the desirable effect of reducing the system complexity.

The MAV is constrained by current EDL system technology to fit within a 3 m by 0.6 m envelope. This assumes a Mars Science Laboratory (MSL) sky crane-type lander, which is the current state-of-the-art technology. A mass requirement will also evolve from this EDL system, since it can only lower about one metric ton to the Martian surface. Using technology that will have flown to Mars before MSR will contribute significantly to risk reduction.

1.1. Baseline MAV design

In 2001, a study was conducted to evaluate propulsion options for the MAV. Three propulsion systems were selected: a liquid, a solid and a gel solution. The current baseline design for the MAV was chosen from this study. It is a two-stage solid rocket, based on a modified (stretched) ATK Star 17A first stage and a commercial off the shelf (COTS) Star 13A second stage [3]. Both the liquid and the solid incorporate COTS parts. While this is desirable for technological readiness level (TRL) considerations, it forces the designs to be non-optimal. The liquid bipropellant design did not fit within the geometric constraints and weighed over 100 kg more than the other two options. Gel systems would require a substantial development program. Additionally, the company responsible for the gelled design lost interest in the technology. All three designs required a substantial thermal protection system, termed the "igloo."

2. Hybrid rockets

Hybrid rockets generally consist of a solid fuel and liquid oxidizer (though the opposite is also possible). The liquid oxidizer is vaporized and passed over the solid fuel. An igniter is used to evaporate some of the fuel and initiate combustion. Once a diffusion flame is established, the process is self-sustaining and will continue as long as a combustible mixture exists. Since the fuel and the oxidizer are separated the system is inert, leading to enhanced safety and a high tolerance to cracks and debonding in the fuel grain. Most hybrid propellants (including those discussed here) are non-toxic, non-hazardous to manufacture and can be stored for long periods of time without the risk of decreased performance. Hybrid motors can be throttled for thrust tailoring and impulse management, perform in-flight motor shutdown and restart, and incorporate non-destructive mission abort modes, all of which will be crucial for the MAV.

The hybrid concept is not a new one. The first rocket tested by Russia was a hybrid (GRID-9) in 1933. However, the concept has never been widely used for large-scale applications because classical hybrids suffer from one main disadvantage: the low regression (or burning) rate associated with the evaporative–diffusive nature of the combustion process of conventional polymeric fuels such as hydroxyl-terminated polybutadiene (HTPB). Increasing the available burning area through multi-port grain designs is generally used to compensate for the low burning rate. Fig. 1 shows an example of a multi-port hybrid fuel grain. The requirement for multiple ports leads to complex grain geometries requiring web supports, poor fuel grain structural integrity (especially at the end of the burn), low volumetric loading, a large unburned fuel sliver fraction (5–10%), uneven burning of individual ports and the requirement for either a substantial pre-combustion chamber or individual injectors for each port in order to achieve even burning. Additionally, as the size of the hybrid increases, so does the number of ports required.

2.1. Liquefying hybrid fuels

In the late 1990s a new class of high regression rate paraffin-based fuels was discovered at Stanford University [6]. The high regression rate of these fuels is due to a droplet entrainment mass transfer mechanism that adds to the conventional evaporation mass transfer [7,8]. These fuels produce a very thin, low viscosity, low surface tension liquid layer on the fuel surface when they burn. The instability of this layer, illustrated in Fig. 2, is driven by

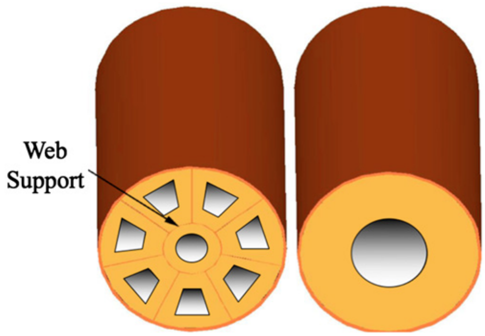

Fig. 1. Hybrid rocket fuel grains [5]. On the left is an HTPB-based 7+1 wagon wheel multi-port design. On the right is a paraffin-based single circular port.

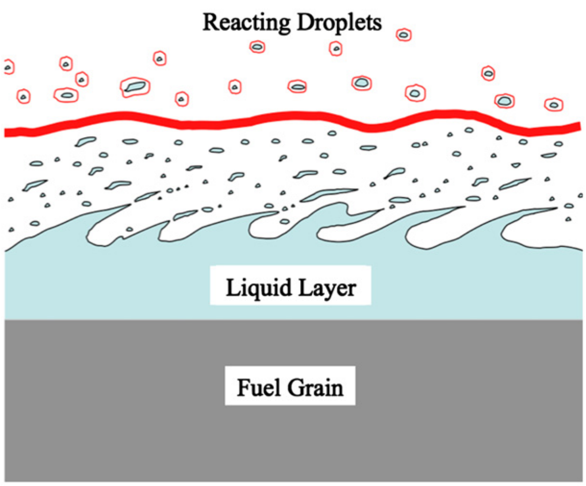

Fig. 2. Liquid layer entrainment [5]. The roll wave and entrained fuel droplets are in blue. The diffusion flame is the red line and reacting droplets are circled in red. Flow is from left to right.

the oxidizer gas flow in the port. Droplets of fuel lift-off and entrain in the gas stream, which greatly increases the overall fuel mass transfer rate. These fuels burn fast enough to enable desired thrust levels to be produced in a single port design. Note that not all fuels that form a melt layer at the fuel surface will entrain. For example, high-density polyethelene (HDPE), a conventional hybrid fuel, forms a melt layer that is too viscous to permit droplet entrainment. Further development of this fuel technology is currently being carried out by Space Propulsion Group, Inc. (SPG) a small company in Sunnyvale, California.

The regression rates of paraffin-based fuels are generally 3–4 times higher than conventional hybrid fuels (e.g. HTPB). At oxidizer mass fluxes typical of commercial applications, space-time averaged regression rates of up to 4.7 mm/s are measured for these fuels with a corresponding instantaneous regression rate at the beginning of burn of 8.4 mm/s [9]. To our knowledge this is the highest reported regression rate for any inert fuel. The fast burn rate allows for a simple single circular port grain design and results in significantly improved volumetric fuel loading and significantly increased fuel utilization (typically more than 97%).

This hybrid fuel also enjoys the added flexibility of having an adjustable regression rate. Slight alterations in additive concentration can change this rate by more than a factor of two. This is a critical virtue that can be quite beneficial in designing efficient hybrid systems with mission flexibility. Casting hybrid fuel grains is a relatively simple process that can be carried out at a small-scale facility. The fuel composition needed for a given mission including structural additives is melted and then cooled and solidified into the required grain size and shape using a centrifugal casting process designed to produce crack-free and void-free grains. No polymerization reactions are involved nor are curing agents required. The scrap pieces of fuel can be re-melted and reused. Because of its fundamental inertness, deterioration in storage is not an issue and its safe handling property is especially important in shipping where no special precautions are needed, resulting in appreciable cost savings.

Paraffin waxes are hydrophobic, making them an ideal binder for metal, metal hydride or dense organic additives (e.g. aluminum powder). This enables the hybrid to achieve a specific impulse (Isp) and density advantage over a comparable hydrocarbon-fueled liquid system. An important, but subtle, effect of aluminum addition to the fuel is that it tends to shift the combustion to a lower oxidizer to fuel (O/F) ratio. Therefore, for the same total propellant mass there is a larger proportion of the denser solid propellant. This reduces the tank size required for the liquid oxidizer and leads to a less massive system overall, thus producing a better-performing system.

2.2. Nytrox

Nytrox is a mixture that combines the high vapor pressure of dissolved oxygen with the high density of refrigerated nitrous oxide to produce a safe, non-toxic, partially self-pressurizing oxidizer with high density and good Isp performance [10,11]. Refrigeration temperatures are between -80 and 0 C° enabling the use of composite pressure vessels. As increasing amounts of oxygen are dissolved in liquid nitrous oxide at a given temperature, the mixture vapor pressure increases from about 2 to 12 MPa [11]. At a given temperature, the liquid density remains relatively constant with pressure as long as the pressure is not close to the critical value at that temperature. This feature gives the designer the flexibility of selecting the system pressure without significantly affecting the density of the liquid oxidizer. The freezing point of Nytrox, while not yet determined, is expected to be at least as low as that of pure nitrous oxide (-90.8 C°). Nytrox temperatures can be perfectly matched to the surface temperature on Mars eliminating the need for any temperature conditioning for the oxidizer.

For the Mars Ascent Vehicle application, it would be desirable to make the Nytrox mixture fairly close to the launch date. Several sols should be sufficient to establish an equilibrium mixture. Initially only N_2O will be stored in the oxidizer tanks until a few sols prior to launch. The oxidizer tank volume is selected for a maximum storage temperature of -10 C° at which the density of N_2O is 953 kg/m^3. A few sols prior to launch, gaseous oxygen will be transferred from the pressurization tanks to the main oxidizer tanks in order to make equilibrium Nytrox. There is a mass penalty to pressurizing the system with gaseous oxygen instead of helium, predominantly due to their molecular weights. However, the ΔV advantage realized by combusting the oxygen, as opposed to expelling cold helium, outweighs the increased system mass. The Nytrox mixture has several advantages over its individual components. It has improved Isp performance compared to N_2O. A Nytrox system is also much safer than a pure N_2O system because the ullage gas of the Nytrox system has a large O_2 concentration, making N_2O decomposition virtually impossible [11].

The only thermal conditioning necessary for the system would be to insure that the temperature of nitrous oxide does not cause the self-pressurizing oxidizer to exceed the design pressure of the oxidizer tank. A thermal conditioning system on the launch pad may be necessary to keep the oxidizer at -10 C°. While it is possible to store the oxidizer at higher temperatures, the weight and volumetric penalties incurred by large increases would be substantial.

2.3. O/F shift

The Nytrox system will require some pressurization during the course of the burn to maintain the design oxidizer flow rate. Choosing oxygen as the pressurant has an interesting system benefit that enables nearly complete utilization of the tank ullage and pressurant to produce thrust. The ideal O/F ratio for paraffin burning with nitrous oxide is much higher than for paraffin burning with oxygen. As the oxidizer tank empties during the course of a burn there is a transition from liquid flow of a mixture that is mostly nitrous oxide to gas flow of a mixture that is mostly oxygen. The transition is also marked by a sudden decrease in the oxidizer mass flow rate with a corresponding decrease in the motor O/F ratio. Coincidentally the new O/F is well matched to the ideal value for oxygen and the paraffin will continue to burn until nearly all of the pressurant is depleted. This greatly improves the structural mass fraction and the delivered Isp of the system compared to using an inert pressurant. The liquid to gas phase transition is shown in Fig. 3 for paraffin with 40% aluminum loading and a Nytrox mixture of 15% oxygen by mass in the liquid phase and 65% by mass in the gas phase. This system is representative of the MAV design in [4]. While the system is designed for peak operation during liquid phase flow, there is actually a boost in Isp during gas phase flow because of this effect. The red diamonds in Fig. 3 depict the operating O/F shifting from peak (O/F=3.7) during the liquid phase flow to a higher, though slightly off peak, Isp (O/F=2.2) for the gas phase flow. Gas phase combustion of 80% of the oxygen pressurant has been demonstrated in motor testing by SPG.

2.4. Repackaging capability

The hybrid approach provides greater flexibility in packaging the MAV within the geometric envelope imposed by the lander compared to a solid. Fig. 4 shows two possible configurations of a hybrid MAV fit into the current JPL "strawman" lander system (based on the MSL sky crane). The oxidizer and/or pressurant tanks can be placed either in line with or around the combustion chamber to fit into strict geometric and center of gravity constraints. For this specific application, placing the low pressure oxidizer tanks around the combustion chamber adds a great deal of flexibility to the packaging in the lander. In Fig. 4, the gold ball represents the payload, the pressurant is green, the oxidizer is blue, the combustion chamber containing the solid fuel is red and the nozzles are gray. The multiple colors that make up the lander's volume represent the complex geometry, full of sloped edges and cuts.

2.5. Comparison to other propulsion systems

Table 1 gives a comparison of chemical propulsion systems. Advantages and disadvantages of paraffin-based hybrids (which will be discussed in the next section), liquids, solids and gelled systems are presented. It is important to note that while solids have low system complexity, they are not tolerant to cracks or debonding. This could lead to an explosion and a catastrophic system failure. Liquids are more complex because they require a feed system and either a pressurization system or pumps. However, like hybrids they can be throttled and can perform non-destructive mission abort modes.

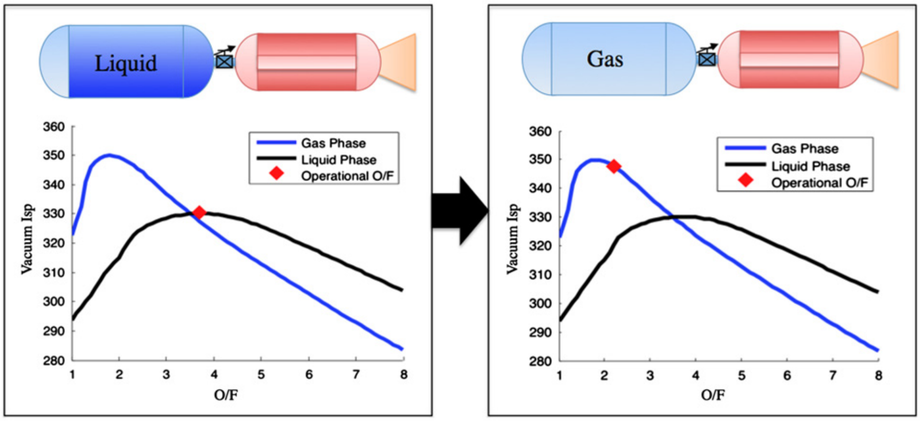

Fig. 3. O/F shift as the oxidizer shifts from liquid to gas flow. The red diamonds show the shift in operational O/F as the flow changes from liquid to gas phase. The fuel/oxidizer combination is representative of that used for the MAV design in [4]. The oxidizer is a Nytrox mixture with 15% oxygen by mass dissolved in the liquid phase and 65% oxygen by mass in the gas phase. The fuel is paraffin with 40% aluminum.

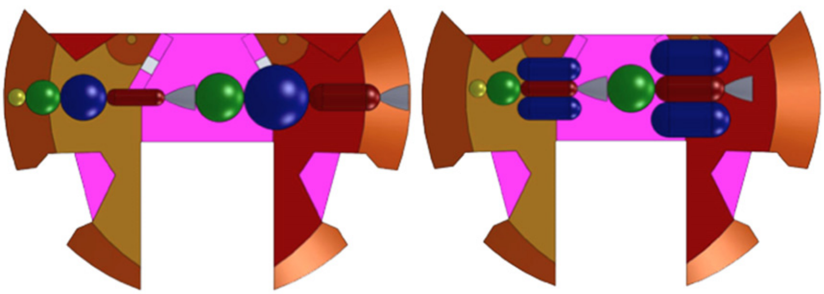

Fig. 4. Repackaging capability of hybrid MAV. Design fit into the volume available from the strawman lander system. CAD of strawman lander system provided by Richard Mattingly, JPL. In each arrangement, the payload is to the far left. The next spherical tank contains the pressurant. In the figure on the left, the oxidizer tank is the largest sphere, followed by the combustion chamber and the nozzle. In the figure on the right, the combustion chamber is flanked by two cylindrical oxidizer tanks and followed by the nozzle. The same configuration is repeated for the first and second stages in each figure. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

Table 1
Comparison of chemical propulsion systems.

	Hybrid: Paraffin/Nytrox	Liquid: Bipropellant	Solid	Gel
Thermal: storage	No heating required	Heating required	Heating required	Heating required
Thermal: operations	No heating required	100% of the propellants must be heated	100% of propellants must be heated	100% of propellants must be heated
Tolerance to debonding and cracks	Highly tolerant	N/A	Not tolerant can cause catastrophic failure	N/A
Pressurization requirements	Only one pressurant required	Both propellants must be pressurized	N/A	High pressures required
Systems complexity	Moderate	High	Low	High
Utilization of propellants	Excellent, pressurant is also propellant	Good	Good	Poor
Throttling	Simple design, only one liquid	Complex design	Very difficult/impossible	Requires complex design
Stop/restart capability	Yes	Yes	No	Yes
Propellant density	Moderate to high	Low to moderate	Very high	Low to moderate

3. The Mars environment

Mars presents a harsh, variable and low temperature environment for the MAV to overcome. Previous designs, including the baseline solid, required substantial thermal protection, which adds up to about 30 kg to the system. Hybrid fuel grains enjoy a reduced sensitivity to cracking, debonding, imperfections and environmental temperature compared to solids. Therefore, it is possible to design a hybrid MAV that requires minimal or no thermal control.

The launch site has not yet been determined, so the temperature profile from the most extreme of the four MSL candidate sites is used as representative of possible MAV site. Holden Crater was determined to have the most extreme temperature profile with yearly minimum and maximum surface temperatures of -111 and $+24\,\mathrm{C}^{\circ}$, respectively [4]. Using the same temperature profile, the average temperature over a Martian year was found to be about $-60\,\mathrm{C}^{\circ}$. If the diurnal cycling is removed, the minimum annual temperature is about $-90\,\mathrm{C}^{\circ}$ and the maximum is $-10\,\mathrm{C}^{\circ}$. This site is not nearest to the 30° north latitude currently being considered by NASA, but is a worst-case example.

The temperatures on Mars drove the fuel/oxidizer choice for the MAV. The glass transition temperature of paraffin is known to be quite low, about $-108\,\mathrm{C}^{\circ}$ and much lower than conventional polymeric hybrid fuels such as HTPB, which has a glass transition temperature of about $-70\,\mathrm{C}^{\circ}$ [4]. Additionally, paraffin is highly crystalline. Therefore, the glass transition is actually quite weak and the fuel grain is expected to recover from departures below this temperature. It would be necessary to insure that the MAV does not launch below the glass transition temperature. However, this would be fairly easy to accomplish using the natural temperature variations on Mars. For example, since there are currently no launch time requirements on the MAV, launch could simply be postponed for several hours (or less) until the temperature of the grain is above the transition temperature. In contrast to a solid, there is essentially no effect of propellant temperature on fuel regression rate or motor performance.

Using a mixture of refrigerated nitrous oxide and oxygen allows the designer to take advantage of the Martian environment. The temperature of the Nytrox can be chosen to match the expected temperature on Mars. Without thermal control, this may require a short wait to ensure the oxidizer is cold enough. Performance increases inversely with temperature for this oxidizer due to an increase in oxygen concentration, therefore lower temperatures could be tolerated.

3.1. Planetary protection

Planetary protection for both Earth and Mars will be crucial aspects of MSR. For the MAV, it will be important to consider the effect of the rocket on the Martian environment. A hybrid MAV does not pose any threats to the environment on Mars. The major products of combustion for a paraffin-based/Nytrox hybrid are CO_2, H_2O and N_2, all of which are already present there.

4. The hybrid MAV

For a paraffin/Nytrox hybrid MAV, it is expected that no temperature conditioning will be required, either for the oxidizer or the fuel during the long storage period or for the orbital launch operation. The hybrid design enables each component of the MAV propulsion system to survive an extended period of time (more than one year) on the surface of Mars without thermal control. This will reduce the overall mass by approximately 30 kg.

4.1. Paraffin/Nytrox60 MAV

A design for a two-stage hybrid MAV has been presented in [4]. The pressure-fed hybrid rocket propulsion system was based on Nytrox60 (Nytrox at $-60\,C^{\circ}$) oxidizer and paraffin-based fuel with 40% aluminum loading by mass. The hybrid design with pressurant combustion maintains both a performance advantage and reduced complexity compared to a small pump fed system. The addition of aluminum increases the performance of the system through a slight increase in Isp and a decrease in the required O/F ratio. Nytrox60 was chosen because the average temperature on Mars is approximately $-60\,C^{\circ}$. Future plans call for a study of the effect of oxidizer temperature on the MAV performance.

The payload was taken to be 36 kg comprised of a 5 kg orbiting sample (OS) plus 31 kg, which includes the OS interface and separation mechanisms, avionics (Attitude Control System (ACS), Command and Data Handling (C&DH), power), telecommunications, cabling, thermal control, structure, a reaction control system, plus an additional 3 kg [4]. It should be noted that each of the payload components have contingencies folded into their masses; therefore, it is likely the additional 3 kg could be translated into extra payload. Of the 5 kg science payload, only 500 g are the actual samples, so this additional mass could make a huge impact on the amount of samples able to be returned. Based on discussions with JPL personnel, the mass allocated for telecommunications is sufficient to include a system capable of transferring high fidelity data to determine root causes of decreased performance or failure.

The fuel for the proposed design is composed of 60% paraffin-based matrix and 40% aluminum powder (2 μm). The mean molecular composition of the grade of paraffin used is $C_{32}H_{66}$ (melting point $60\,C^{\circ}$). Additives are included to tailor the yield strength and regression rate to the desired levels. The gas phase combustion contribution to the total impulse is around 3.8% for both stages. Given the present uncertainty in drag losses, the variety of alternative lander sites still under consideration and the still unknown amount of thrust vectoring that may be required, ΔV used in the preliminary two-stage design is taken to be a relatively conservative 4375 m/sec, for a 500 km orbit.

Table 2 presents the design results for the hybrid MAV compared to the quasi-baseline solid system. The baseline system was recalculated to get the same payload into the orbit assumed by [4].

Table 2
Hybrid MAV design results [4].

MAV system	Two-stage solid	40% margin hybrid	20% margin hybrid
Stage 1			
Mass (kg)	215.6	145.89	128.86
Structural coefficient	0.170	0.189	0.167
Initial nozzle area ratio	60.7	45	45
Avg. nozzle area ratio	53.2	40.1	40.0
Max. chamber pressure (MPa)	4.83	1.72	1.72
Delivered Isp (m/sec)	2813	2952	2951
Thrust (kN)	16.01	8.213	7.464
ΔV (m/sec)	2530	1675	1675
Stage 2			
Mass (kg)	86.2	91.37	83.57
Structural coefficient	0.175	0.169	0.147
Initial nozzle area ratio	49.8	50	50
Avg. nozzle area ratio	41.0	41.9	41.7
Max. chamber pressure (MPa)	6.45	1.38	1.38
Delivered Isp (m/sec)	2813	2977	2976
Thrust (kN)	5.874	3.827	3.593
ΔV (m/sec)	1845	2700	2700
Total ideal ΔV (m/sec)	4375	4375	4375
Maximum diameter (m)	0.442	0.541	0.524
Vehicle length (m)	2.56	3.829	3.747
Payload mass (kg)	36	36	36
Gross lift-off mass (kg)	301.8	273.3	248.4
Erection system (kg)	30	30	30
Igloo mass (kg)	30	0	0
System total mass (kg)	361.8	303.3	278.4

5. TRL level

The paraffin-based hybrid is presently at a technology readiness level of 5. Stanford and SPG researchers have conducted well over 600 tests with a variety of paraffin-based fuel formulations [5]. It has been shown that these fuels provide reliable ignition and stable combustion over the entire range of mass fluxes tested (5–80 gm/cm^2 sec) and with a variety of oxidizers. Sub-scale motor tests (900 N thrust class) with Nytrox oxidizers have been conducted by SPG. High combustion efficiencies ($>95\%$ c* efficiency) and good motor stability at low oxidizer temperatures are attainable. The Nytrox mixture was made and maintained at low temperatures without trouble. Deep throttling has been demonstrated (up to 3:1) and it was confirmed that Nytrox has efficient and stable combustion in the gas phase. The combustion efficiencies in the gas phase are measured to be better than 90% even for the relatively small-scale motor used in the testing.

The regression rate behavior observed over a wide range of motor sizes can be predicted quite well indicating that the dependence of the regression rate on grain length is relatively weak and small-scale tests can be used to infer the behavior of larger motors [5]. This result is extremely useful for developing the correct fuel formulation for a given mission. High combustion efficiencies are possible and c* efficiencies of 96–97% have been achieved in ground tests using N_2O as well as LOx. The fuel exhibited excellent structural integrity over the range of chamber pressures used (1–7 MPa).

The development cost of the two-stage hybrid is expected to be less than competing systems. For example, the propellants are inert; therefore, fuel grain fabrication and handling will be greatly simplified compared to a solid. The reduced development cost could free up funds to support a realistic flight test of the MAV system with balloon launch to simulate the thermal and atmospheric density environment.

6. Conclusion

In the past, hybrid rockets have been considered to have all the problems of both liquids and solids without the benefits. Today, the opposite is true. Hybrid rockets using liquefying fuels such as paraffin combine the benefits of their parent systems and help negate the major disadvantages inherent to the liquid and solid systems.

The MAV is a complex new problem that can be made lighter and more robust with new hybrid technologies. The design for a Mars Ascent Vehicle using a paraffin-based fuel and Nytrox oxidizer meets all the requirements of the mission [4]. These two key new technologies: liquefying hybrid fuels (such as paraffin) and Nytrox oxidizers can be combined to design high energy, operationally flexible, low cost, safe, non-toxic and environmentally friendly hybrid propulsion systems that can be stored and operated at the temperatures encountered on Mars.

Hybrids are ideal for mission flexibility since they can be actively throttled with a relatively small impact on the system performance. Easy throttling and shutdown capability of hybrid systems is an important virtue especially for planetary ascent missions for which the propulsion system operation takes place following a long storage period in the spaceship and on the planet surface under adverse environmental conditions. It is expected that the technology developed for the hybrid MAV could also be used for ascent vehicles on other non-terrestrial bodies (the moon, etc.) and for in-space propulsion. We hope that this research will be a catalyst for new ideas for planetary ascent missions and in-space propulsion.

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