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Propulsion system options for a Potential Sample Return Lander(SRL) for Mars

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Abstract

A potential Mars Sample Return (MSR) campaign would be very unique challenge and has been the focus of technology development and planning efforts at JPL for several decades. The latest mission concept study focuses on a potential Sample Return Lander (SRL). The potential SRL examined several propulsion system approaches using monopropellant and bi-propellants for the terminal descent phase. A ranking was developed based on a mathematical optimization program. This paper focuses on the evaluations conducted for these system options. Historically, monopropellant and bi-propellant propulsion systems are usually considered for this application; this study took a fresh look at both conventional State of the Art (SOA) pressure fed mono-propellant and bi-propellant propulsion system and augmenting the system using small Electrically Driven Pumps (EDP) for both these propulsion systems.

1. Introduction

The most recent notional Mars Sample Return (MSR) [1] architecture, shown in Figure 1, is designed to return soil/rock/gas samples, collected on the Martian surface, back to Earth. MSR could consist of a combination of three separate missions. The first mission would cache samples for retrieval. NASA's Mars 2020 rover is planning to collect samples that could be returned in the future. The second segment would consist of an orbiter carrying an Earth return vehicle combined with a potential SRL. The SRL would then contain a sample collection rover. In one option, a small rover would collect the samples from the previous mission and return to the fixed lander. The samples collected by the rover would be loaded into the forward payload area of the potential MAV, which would then be erected into a vertical position for launch. The conceptual MAV would then be launched to transport the science samples from the Martian surface to a low circular orbit for rendezvous with the orbiting Earth Return Vehicle (ERV).

Key to this potential MSR approach would be the successful landing of the SRL. The current estimated mass of the SRL is potentially larger than any previous payload to land on the surface of Mars. The basis of the previous landings was derived from the successful Viking landing. The typical sequence of events is shown in Figure 1. This sequence was built around 3 key phases,

heatshield, supersonic deployment of a parachute and powered descent for terminal descent. The recent (2011) Mars Science Laboratory mission used the same three approaches but used the sky crane maneuver for the powered descent phase. This allowed the large MSL rover, named Curiosity, to be directly deployed on the surface. Mechanisms and ramps to allow the rover to disembark a static, propulsive style lander are no longer required. After delivery of the rover to the surface, the descent stage performs one last maneuver to fly away and crash at a prescribed distance from the landing site. For the potential Sample Return Lander, the mass of the descent stage with a sample fetch rover, fixed lander and Mars Ascent Vehicle (MAV)[2,3] is expected to exceed the current capability of the supersonic deployed parachute. This study looks at a variation of terminal descent delta-V from where the parachute is used to values where it is not part of the sequence of events and the powered descent is achieved using only the propulsion system. This parachuteless approach is referred to as the supersonic retro-propulsion (SRP) phase. This paper discusses propulsion systems using conventional parachutes and with SRP approaches so that the spectrum of potential SRL delta-V can be examined.

The Viking and MSL missions used a monopropellant, hydrazine, for the powered descent phase. M2020 will also use the same propellant and propulsion system as MSL.

Figure 2 shows a historical comparison for monopropellant and storable bi-propellant propulsion systems. As the payload increases even the lower complexity and corresponding propulsion dry mass benefit of a monopropellant system combined with low specific impulse (Isp) results in a steep increase in propulsion wet mass with increased payload. The advantage of a bi-propellant propulsion system can easily be seen. The higher Isp associated with a bi-propellant system even with the associated complexity and corresponding increased propulsion dry mass results in a less steep curve of wet mass with increasing payload mass. It should be noted that even MSL and M2020 should have used a bi-propellant option. The schedule and cost risk for these missions and the deviation from Viking heritage resulted in an acceptable, slightly non-optimum, system performance.

For higher terminal descent delta-V the continued use of a heritage propulsion system could be used but the parachute limitations drive the propulsion system to a pure propulsion option.

Details of the various propulsion configurations considered during the study are shown in Table 1.

A mathematical model of the propulsion system was generated to examine the trade space with respect to delta-V required. The pressure fed monopropellant results in the heaviest mass. An Electrically Driven Pump Fed (EDPF) option provides a noticeable reduction in system mass. For bi-propellant options the model indicates that at delta-V's less than 560 m/sec conventional pressure fed bi-propellant system has the lightest system mass. As this increases the EDPF option for a bi-propellant system results in the lightest mass. This conclusion is driven by the slight enhanced Isp, however the primary reason is the reduced pressurization gas and propulsion drymass. However, it should be noted that it is the highest schedule risk and cost due to the low technology readiness level.

2. Monopropellant and Bi-propellant Technology Description

Storable monopropellant and bi-propellant rocket propulsion has been a mainstay for over 60 years for a variety of in-space spacecraft applications. Most of the spacecraft systems for low earth orbit, geostationary and planetary missions to date have used SOA pressure-fed systems. Common bi-propellants used are Monomethyl Hydrazine (MMH) and

Nitrogen Tetroxide (NTO) for the main engine propulsion system. For monopropellant systems hydrazine has been used extensively for main and for attitude control systems (ACS). A variety of cold/hot gas propellants are often used for ACS as well. In addition, bi-propellant systems with hydrazine and NTO have also been used to reduce system complexity and propulsion drymass by combining the ACS function in with the main propulsion function.

Typical spacecraft main bi-propellant engine size has remained less than 890N (200 lbf). This has been driven primarily by requirements for industry to satisfy commercial spacecraft needs. Planetary missions are a small subset of the commercial market and as such do not warrant industry developing one-off engines with minimal commercial use. Larger engines had been developed; for example, the Apollo program in the 1960's and early 70's developed the lunar lander engine [reference 4 and 5] (40kN for descent engine and 16kN for ascent engine). But with no subsequent commercial need or application for this class of engine, there has been very little impetus to develop engines in the 2.5kN to 25 kN class. The few that have been produced over the years were usually pressure-fed engines with fairly large expansion ratios to provide increased performance. Only one pump-fed engine of any note was developed, XLR132 [6]. This engine was a turbine-driven pump system with a fairly large area ratio nozzle. Larger thrust engines >>25kN have been developed for launch vehicles. Again, these are turbine driven pump fed propulsion systems. They are also have cryogenic propellants and have very limited applicability for near term in-space applications for SRP and planetary ascent needs where long term storage of cryogens will need to be developed and demonstrated.

Monopropellant engines primarily using hydrazine have been a mainstay for the in-space propulsion systems. They provide a wide range of thrust levels from fractions of a newton up to 100's of newtons. This makes them very versatile over a wide range of needs from small delta-V maneuvers to larger delta-V maneuvers. Almost all systems are pressure fed systems using either simple blowdown or regulated pressure control.

A more detailed breakdown of pressure-fed and pump-fed storable monopropellant and bi-propellant systems will be described in the next two sections.

2.1 Conventional pressure fed Monopropellant and Bi-propellant description for SRL

A conventional pressure fed monopropellant system offers a fairly simple configuration with inherent low dry mass. Due to hydrazine being extensively used throughout the spacecraft industry, a wide range of qualified engines and components exist. The Technology Readiness Level (TRL) is almost always >6. This extensive heritage has resulted in monopropellant hydrazine being used at JPL for a number of descent missions.

A conventional SOA pressure-fed bi-propellant system offers a reliable but fairly complex configuration compared to monopropellant propulsion systems. The complexity of these systems is driven purely by the need for two propellants and consequently the increased number of components required. Various valves, filters, regulators and other components do not pose a technology challenge for the thrust levels used to date on conventional spacecraft. For SOA pressure fed bi-propellant systems the TRL of individual components are typically high (TRL>6). This is a direct result of pressure-fed systems being the current SOA. They have been used on a number of robotic missions over the past several decades. Missions such as Cassini [7] and Juno are good examples of recent outer planet missions using storable bipropellants with a pressure-fed propulsion system. Multiple

commercial spacecraft for geosynchronous operation have also used pressure-fed bi-propellant propulsion systems for orbit transfer from low-Earth orbit (LEO) to geosynchronous orbit (GEO).

For the expected thrust requirements for SRL the propellant flowrates would be much higher than SOA. As a consequence, feed system components will also need delta development but the cost and technology risk are considered low to medium.

The engine for potential SRL applications would be a new development. It has several constraints that need to be satisfied.

These are: steady state thrust, throttle capability and available volume. Thrust and throttle capability will be discussed in the next section.

The volume constraint however is unique for SRP and has not normally been a strong driver for most propulsion systems. For SRP the propulsion system has to be enclosed within the aeroshell. The need to minimize volume but maximize performance is a unique challenge and will also be discussed in a subsequent section.

2.1.1 SRL Thrust, and Throttle capability

The thrust for a potential SRL descent phase has to meet the need for initial high thrust to provide the rapid deceleration required. As the vehicle continues to decelerate the thrust needs to be reduced so that at or just prior to touchdown the thrust to weight of 1 is met.

This can be accomplished using several throttling approaches. The approach used for this study was to distribute the initial thrust between N engines. N was either 12, 16 and 20. The engines were then distributed around the outer diameter of the aeroshell. The rationale for this was to place the engines in groups of 3, 4 and 5 at 90 deg locations. The throttle capability is then achieved using an approach used on MSL where the maximum throttle capability used for each engine is only 50%. This is then combined with shutdown of engines in groups of 4. This method reduces the throttle range required for each engine. This approach is a very simple robust method to obtain the desired throttle range. For an EDPF engine achieving the pump speed can be changed to reduce the flowrate and hence the thrust. For pressure fed systems it is not as simple. The supply pressure is difficult to regulate at the rate required by spacecraft Guidance Navigation and Control, GN&C. For pressure fed propulsion system the flowrate is reduced by either reducing the flowrate using cavitating throttle valves [8] or reduce the injector flow area using a pintle injector[9]. Both these approaches have successfully been used on prior spacecraft.

The thrust requirement for SRL is much higher than typical SOA pressure-fed monopropellant and bi-propellant engines. All propulsion systems evaluated during this study would require the development of new engines. This development is not anticipated to be a significant challenge. Higher thrust bi-propellant chambers have been developed and the risk for this new development is considered medium.

The following discussion details the approach to increase engine thrust for SRL. As will be seen the pump fed bi-propellant engine offers key benefits for the SRL configuration that are prohibitive for the conventional pressure fed system.

The thrust of a generic rocket propulsion system is given by equation 1, where T is thrust (N), m_e is mass flow (kg/sec), V_e is gas velocity (m/sec) at the nozzle exit plane, Ae is nozzle exit plane area (m^2) Pe is exit pressure (N/m^2) and P_0 is external pressure (N/m^2).

$$T = m_e V_e + (P_e - P_0) A_e \qquad (1)$$

Examination of this equation shows specifically the methods by which the thrust can be increased. For monopropellant and bi-propellant propulsion system the following

approaches can be employed. The most obvious would be to operate where P_0 is zero. Since this is the environmental pressure there is very little that can be done physically to change the value on Mars. Martian atmosphere is less than 10 mbar. Landing at higher altitudes lowers the ambient pressure but changes in ambient pressure of this magnitude have very minimal effect on the ability to generate thrust. The next approach is to increase mass flow (m_e). This is probably the most commonly used approach. For a conventional pressure fed bi-propellant system this is achieved by an increase in propellant tank pressure (Pt) to increase the propellant flow. The increase in propellant tank pressure however results in a propellant tank (dm_{pt}) and pressurization gas tank (dm_{pgt}) mass increase as shown in equation 2.

$$dP \times dm_{increase}/dP_{tank} = dm_{pt} + dm_{pgt} \qquad (2)$$

There are also secondary mass increases from vehicle structural changes due to these tank increases resulting from an increase in the propulsion tank pressures. These were included in the study but are second order effects compared to the propulsion system drymass increase ($dm_{increase}$).

Another common approach to increase thrust in equation 1 is to increase the nozzle exit area and hence velocity at the exit of the nozzle, V_e. This is commonly achieved by increasing the nozzle length. This results in a nozzle mass increase due to the increased conical length but for reasonable length increases can provide 1-2 % increase in Isp after taking into account the nozzle dry mass increase. SRL could have a volume constraint that is dictated by the available space within an aeroshell delivery system for Mars.

For a pressure fed propulsion system, attempts to increase the area ratio of the engine is very difficult resulting in L/D of the engine that is prohibitive for the available aeroshell volume. The EDPF bi-propellant propulsion system however has two distinct advantages that result from this architectural approach that allow increased area ratio to be incorporated. First the helium tank volume requirement is less than the pressure fed architecture due to the lower propellant tank pressure required. This provides additional volume within the aeroshell. The second is that the chamber pressure can be increased by changing the pump operating characteristics. The resulting higher chamber pressure for a fixed thrust requirement implies the throat diameter can be reduced. This allows the area ratio to be increased with a corresponding increase in Isp. All this can be achieved and still maintain reasonable L/D for the engine.

2.3 EDPF Bi-Propellant SRL Description

An EDPF bi-propellant propulsion system has not been previously used in space. For large thrust systems associated with launch vehicles, pumps have been a common solution since the early vehicle designs. The drive mechanism for these pumps are typically turbines (turbo-pumps) due to the large power demands of these high flow, high thrust systems. Scaling of large turbo-pumps down to the 2.0kN to 25kN thrust range has proved problematic and costly. Recent developments in lithium-based battery technology coupled with high power density electric motors and the use of additive manufacturing of high speed rotating components has provided an opportunity to apply EDP to this thrust class. An EDPF system offers a distinct advantage in that, unlike the conventional pressure fed bi-propellant propulsion system, the propellant tank mass (m_{pt}), pressurization tank (m_{pgt}) and pressurant gas (m_{pg}) mass are constant and independent of combustion chamber pressure and increased thrust. The mass increase for an increase in chamber pressure is simply the pump mass increase (dm_p) and battery mass increase (dm_{bat}) as shown in equation 3.

$$dm_{increase} = dm_p + dm_{bat} \quad (3)$$

The pump for an EDPF configuration would be located at the engine inlet upstream of the engine inlet valves. An assumption was made for this study that both propellants, MON3 and MMH would be driven from a single electric motor. This approach is expected to minimize pump mass. This assumption will be further investigated to ensure that safe operating conditions can be maintained throughout the operational life. The feed system is a regulated system similar to conventional pressure fed system.

2.4 RCS description for SRL

The RCS is the same for both architectures considered. This is currently envisaged as similar to the monopropellant hydrazine currently used on MSL mission.

3. Recent EDPF Technology Developments

Ventions LLC. first began work on small-scale electric pump technology for rocket engine propulsion during 2009 under a NASA JPL funded program to evaluate use of pump-fed liquid bipropellant engines for a Mars Ascent Vehicle. As part of this effort, Ventions utilized a novel fabrication methodology to realize high-speed impellers approximately 1-inch in diameter with exit blade heights as small as 0.025-inches. The program resulted in successful demonstration of a first-of-its-kind electric motor-driven centrifugal pump operating at 50,000RPM, and led to further optimization of successive generations for flight-like packaging in a compact, highly integrated form-factor, Figures 3 & 4 show examples of EDP's developed.

Most recently, Ventions successfully designed, fabricated and flight tested a 300lbf, electric pump-fed LOX / IPA engine in a 9-inch diameter sounding rocket under the DARPA ALASA (Airborne Launch Assist Space Access) Phase I Program. Similar pumps are also currently being used by Ventions in the DARPA SALVO (Small Air Launch Vehicle to Orbit) stage to pressurize two 1,000lbf LOX / RP-1 regeneratively cooled engines, and in a scaled-up version for a 4,000lbf LOX / RP-1 engine for NASA KSC launch vehicle applications. Ventions has recently been acquired by Moog LLC and is now part of their technical capability.

4. Results

A MATLAB program was developed to solve for the various parameters required in the sizing of the propulsion system. The Flow diagram is shown in Figure 5. A simple user interface allows for new configuration parameters or using an existing dataset. The code then performs an iteration looking at engine performance, mass and configuration, generates a preliminary pressure drop for the feed system. The tanks are then sized for the propellant combination being considered. The code then allows for an option for EDPF or pressure fed system. For EDPF the pump, batteries, pressurant and tank sizing are calculated. For the pressure fed option the pressurant mass and tank size are generated. The other components that make up the system are then estimated from a database of hardware to arrive at a system mass. The system is then examined to see if it has met all the required constraints. If not, the system iterates again using an E-Greedy [10] optimization routine. At completion the optimized system then is place within the configuration volume to generate a first pass 3d visualization of the propulsion system within the structure.

Two examples of inner subroutines are shown in Figures 6 and 7. These two subroutines show the tank sizing detail logic and the engine sizing detail logic.

Validation of this code was based on 4 cases

ranging over a fairly large spectrum of thrust and payload. This is shown in Figure 8.

Figure 9 shows the results of an evaluation of the 4 propulsion concepts for SRL. The four systems are monopropellant with throttle valves, an EDPF monopropellant system, SOA pressure fed bi-propellant system with throttle valves and an EDPF bi-propellant system. Figure 9 shows the system mass vs delta-V required during terminal descent over a delta-V range of 240 m/sec to 660 m/sec.

5.Discussion

Figure 9 highlights the significant decrease in system mass for an EDPF mono-propellant system. To increase performance for a mission like M2020 additional delta-V performance could be realized. This is the result of the propellant tank mass reduction and more importantly reduction in pressurization gas needed using an EDPF approach. These tank and fluid mass reductions more than offset the addition of pumps and battery packs.

For bi-propellant systems the situation is not as straight forward. At low delta-v missions, which are associated with parachute EDL scenarios like M2020 the bi-propellant system using pressure fed is the lightest solution. As the delta-V is increased the benefit pf the EDPF system results in it being the lightest solution once the delta-V increases above 560 m/sec.

The main issue associated with the EDPF monopropellant and EDPF bi-propellant propulsion systems are its lower Technology Readiness Level (TRL) compared to the conventional pressure fed monopropellant and SOA pressure fed bi-propellant propulsion system. Currently funding for EDPF system development is not planned. The EDPF bi-propellant propulsion system has two other key challenges. The first is the which any leakage and external leakage can occur. However, it does not eliminate the possibility. Several design options can be implemented to try and prevent potential battery operating parameters and the second is the use of a single shaft for the two propellant pumps.

The pump electrical power/engine configuration is currently expected to be supplied from two battery packs. Each battery pack consists of 12 lithium polymer cells. Each pack is capable of providing 125 Amps. The expected current requirement is 111 amps/pack. Pump efficiency is a key factor in the amount of power required. Recent pump testing with slightly modified impeller geometry has shown that efficiencies of 65% can be achieved at this size. Additional efforts are currently in work to increase the efficiency into the mid-70%. With this sort of efficiency, decreases in electrical power and hence battery mass required can be realized. Ventions LLC has conducted numerous ground tests using EDPF propulsion systems and the battery power and current discharge have not been an issue during any of these test campaigns. The open challenge however is to evaluate the battery current discharge under all conditions and ensure that spacecraft design principles that are currently in place for spacecraft battery systems do not prohibitively influence their use or result in excessive mass increase to provide very high margins of safety.

The other challenge is whether the EDPF configuration, for bi-propellant use, should consider a single shaft configuration. Even though this is expected to result in a minimum mass for the EDPF systems, having the fuel and oxidizer in close proximity raises a safety concern due to the possibility of seal leakage from both propellants resulting in uncontained hypergolic ignition. The short exposure time prior to launch and the short trajectory duration reduces the time during

leakage such as an inert barrier purge or redundant seals. To reduce the risk completely separate fuel and oxidizer pumps could be used. This is expected to increase

the system mass. An evaluation of options to reduce this risk is expected to be performed in subsequent studies.

6. Conclusions

An extensive study was performed by the JPL Propulsion Group during FY17 and early FY18 that evaluated several configurations for future SRL architectures. A mathematical model was developed and used to evaluate and optimize both monopropellant and bipropellant systems. SOA pressure fed systems and EDPF systems were considered. Storable pressure fed bi-propellant configurations show the lightest system mass at low delta-v terminal descent requirements. At higher, greater than 560 m/sec terminal descent delta-v requirement, the EDPF configuration starts to become the lightest system mass solution.

Acknowledgments

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Case	Propellant	Description
Monopropellant	Hydrazine	Pressure Fed , Regulated helium pressurization and N engines (3500N class) with throttle valves.
EDPF Monopropellant	Hydrazine	Pump Fed , regulated helium pressurization and N engines (3500N) class)
SOA Bi-propellant	NTO/MMH	Pressure Fed, Regulated helium pressurization and N engines with throttle valves
EDPF Bi-propellant	NTO/MMH	Pump Fed, regulated helium pressurization and N engines

Table 1. Cases considered in Study

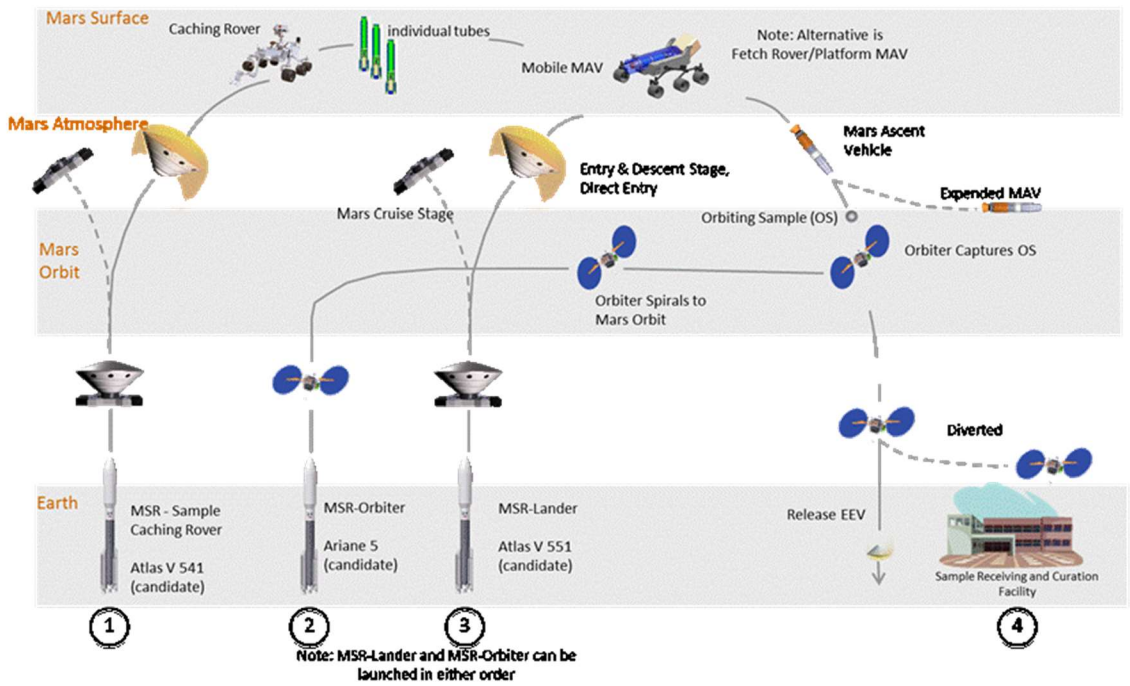

Figure 1 – A Notional three mission concept architecture approach for MSR

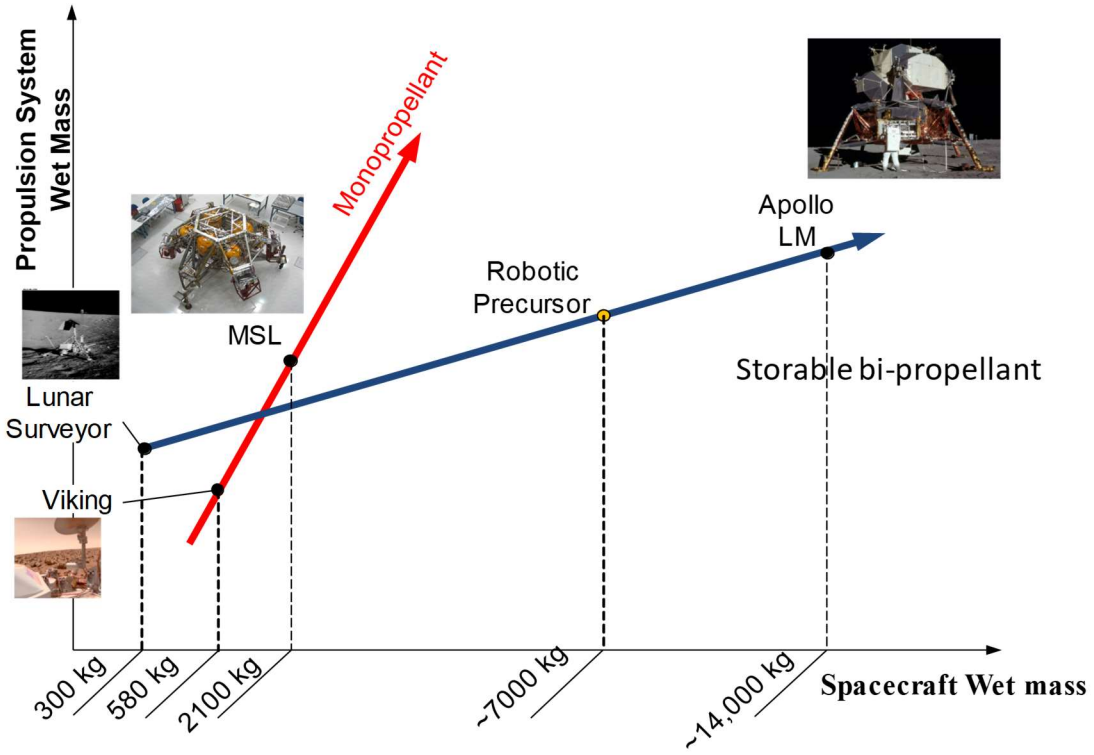

Figure 2 -Historical View of Monopropellant and Bi-propellant Propulsion Systems

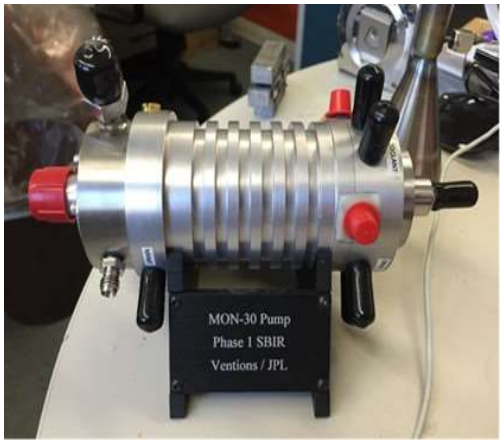

Figure 3. – Mon-30 EDPF

Figure 4. – Examples of Ventions LLC EDPF development

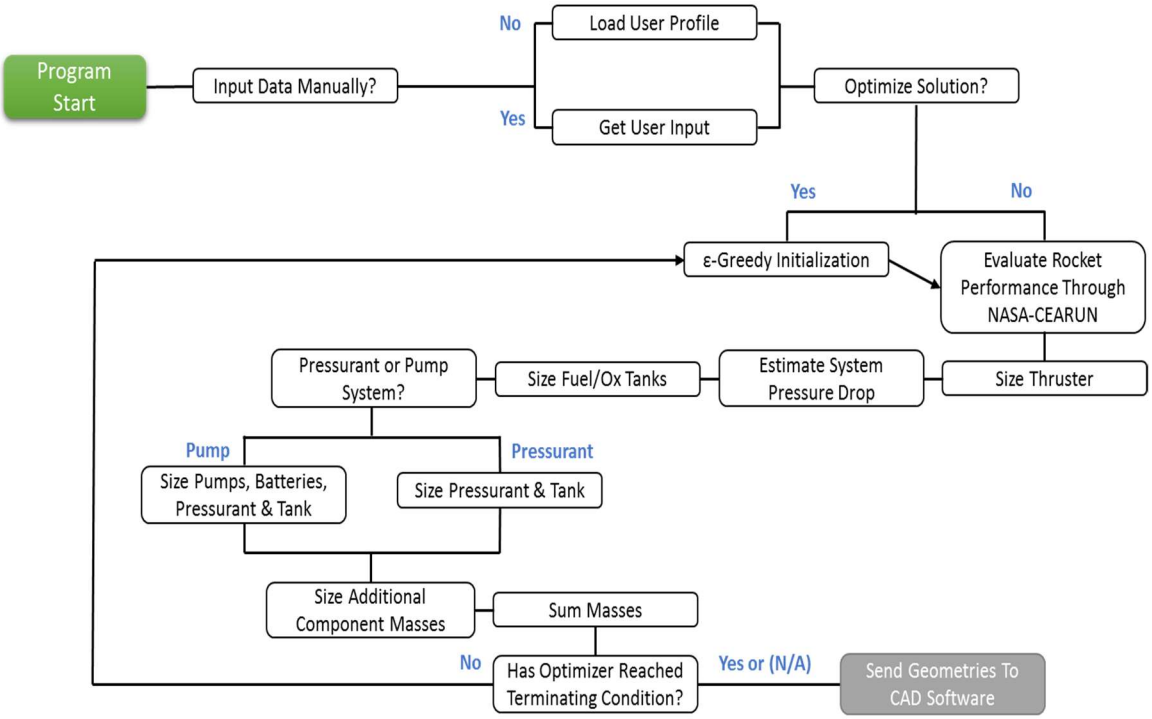

Figure 5. Mathematical model logic flow.

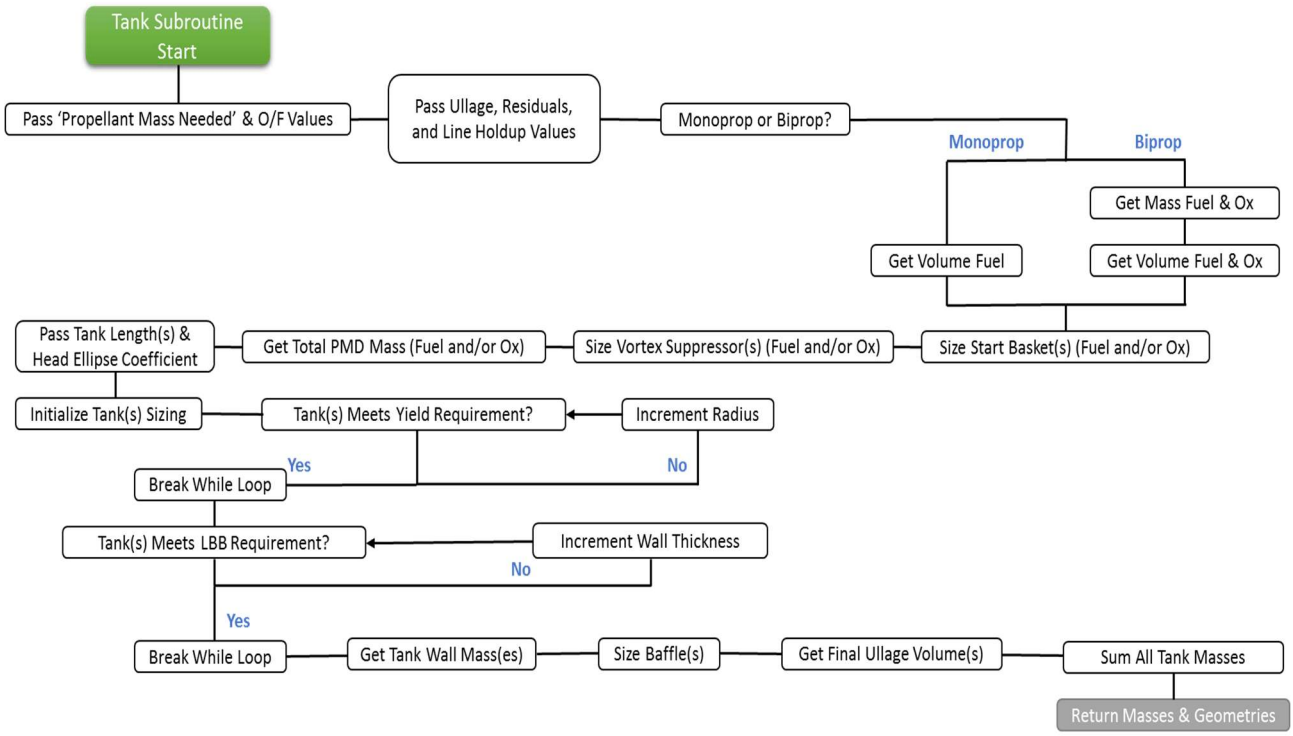

Figure 6. Details of tank sizing logic subroutine

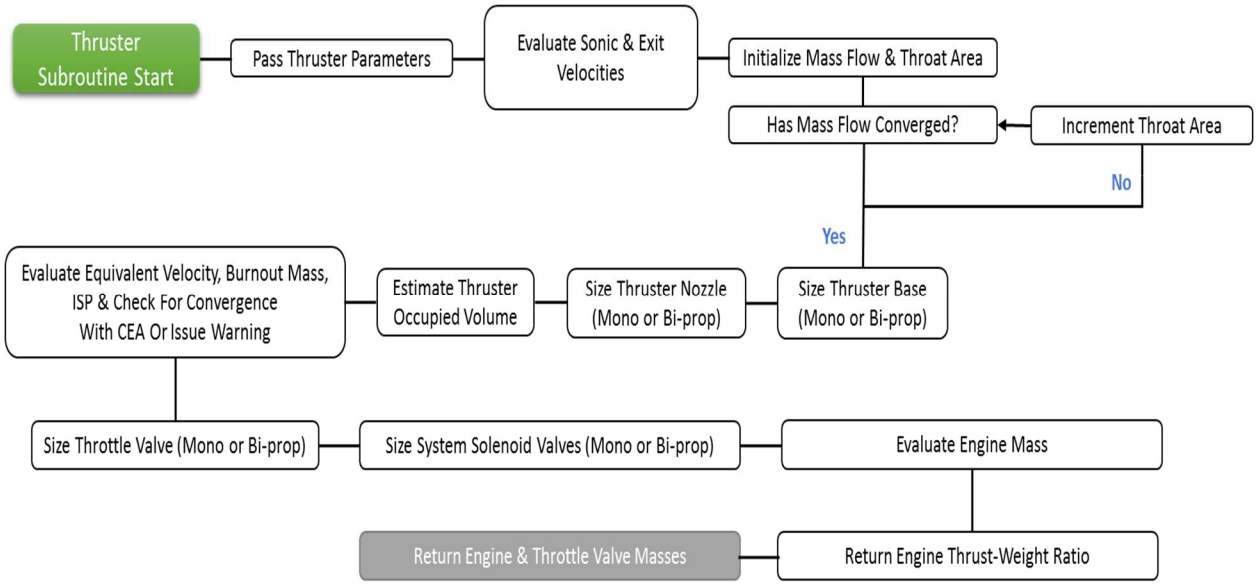

Figure 7 Detaiuls of Engine sizing subroutine

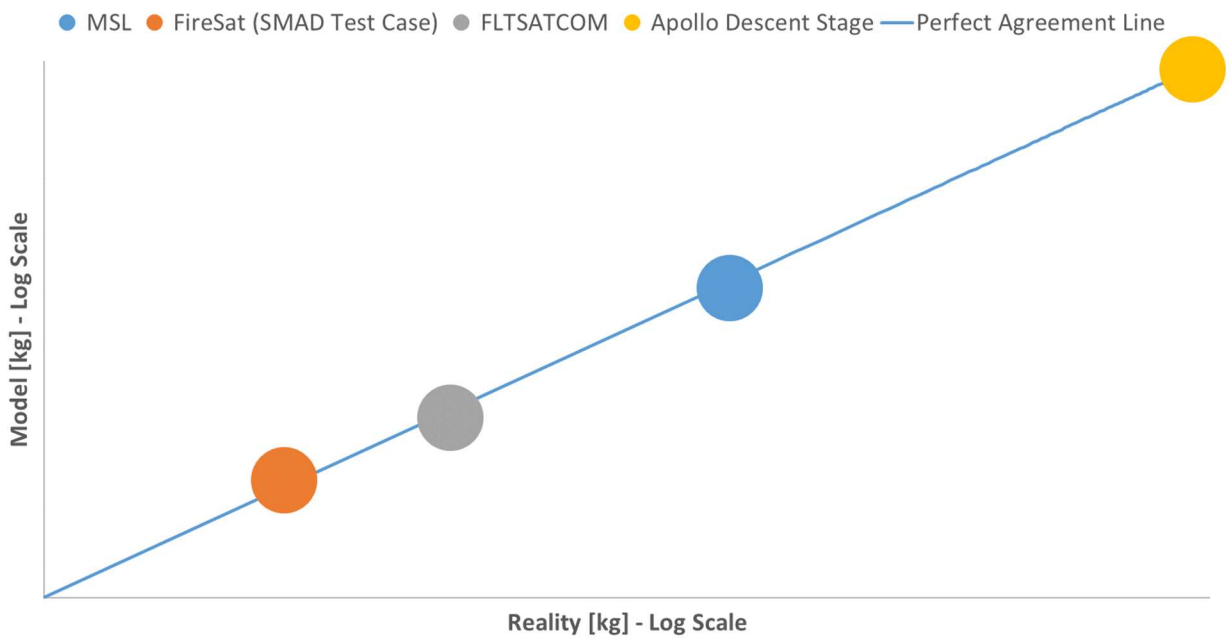

Figure 8. Comparison of model with test cases

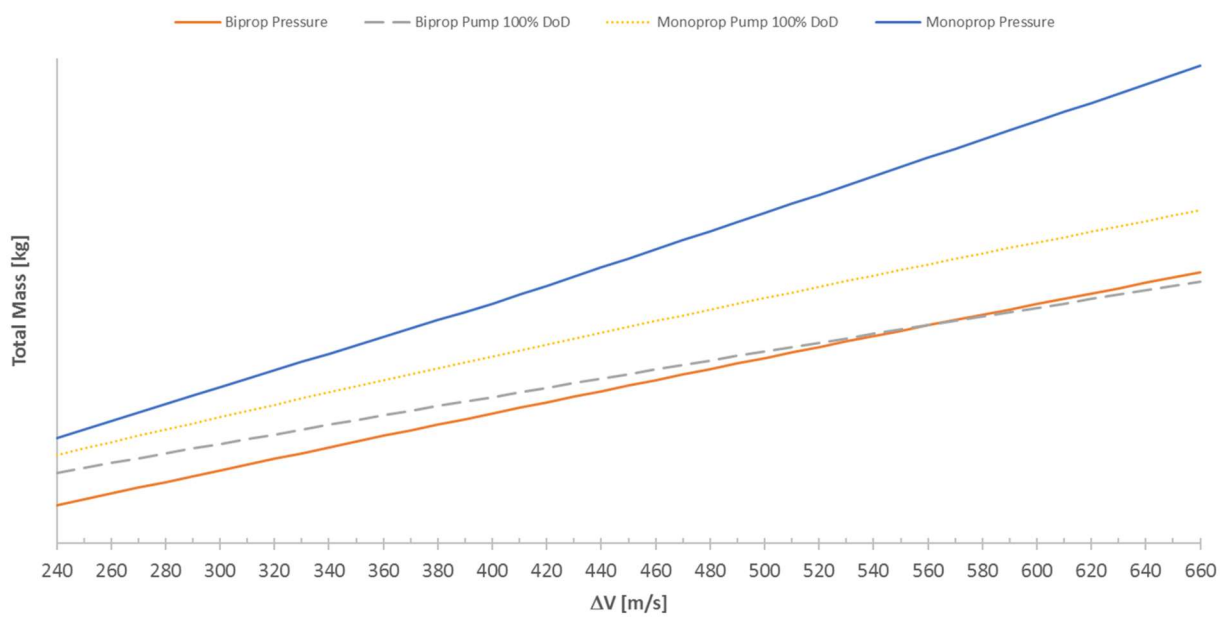

Figure 9. Results of study of System Mass against Delta-V required.