

Using Pressure-Fed Propulsion Technology to Lower Space Transportation Costs

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This paper illustrates the cost advantage of a space transportation system that uses pressure-fed technology and describes pertinent aspects of scaling the propulsion technology for light-lift through medium- and heavy-lift vehicles. Microcosm has used this approach of scaling the propulsion system to support the design and development of a number of low-cost, pressure-fed launch vehicles for various defense, scientific, and commercial applications, particularly the Scorpius[®] family of launch vehicles. The application of this innovative and low-cost propulsion approach to various pressure-fed space transportation systems, including those for thrust augmentation boosters and upper stages, will be discussed. In addition, the enabling propulsion technologies, their development status and the results of trade studies associated with deriving the optimum propulsion parameters will be discussed. The paper discusses our approach to achieving higher reliability from our simple but robust, light-weight and scalable critical technologies such as the low-cost ablative combustion chambers, all-composite propellant tanks, the High Performance Pressurization System (HPPS) that also provides for an innovative RCS/ACS systems for the upper stages, a low-cost TVC, and a GPS-based GN&C system. The results of trade studies will be presented to demonstrate our approach to providing a balance between costs and performance. Pressure-fed, liquid rockets have the potential to significantly lower the cost of delivering payload to orbit. While pressure-fed propulsion Systems result in higher stage dry mass fractions and slightly lower specific impulse, their very low costs more than offset the weight penalties, resulting in lower cost as measured by cost per pound of payload over the life cycle of the vehicle system. Therefore, for a given payload, gross weight and size of a pressure-fed, expendable vehicle will be somewhat larger than those of a pump-fed vehicle, but cost per pound of stage will be much lower. In addition, because pressure-fed stages are relatively inexpensive, more stages can be employed for the pressure-fed system, partially offsetting the effect of high dry mass fraction. Finally, pressure-fed stages are inherently more robust during manufacture and ground handling, providing another means for reducing cost. Moreover, as the vehicle is scaled up, development costs for a pressure-fed system do not rise as fast as those for a pump-fed system because of the complexity of the latter system's engine design and its cost of development. This implies that pressure-fed vehicles become more cost-effective as the propulsion systems and vehicles are scaled to progressively larger configurations.

Nomenclature

r = characteristic linear dimension of vehicle

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I. Background

FOR over 12 years, Microcosm has been involved in the design and development of low-cost, responsive pressure-fed expendable launch vehicles¹ for defense and commercial applications. The family of pressure-fed launch vehicles shown in Figure 1 includes two suborbital vehicles that have been flown successfully and other orbital vehicles in development with capabilities ranging from 700 lbm to 50,000 lbm to Low Earth Orbit (LEO) and GTO applications. While continuing with the efforts to mature the design, Microcosm has been pursuing in a parallel path the development of the enabling critical technologies² that are essential for the success of these planned pressure-fed launch vehicles. The technology effort includes the development of the high performance light-weight all-composite propellant tanks, a heated High Performance Pressurization System (HPPS), low-cost ablative engines.

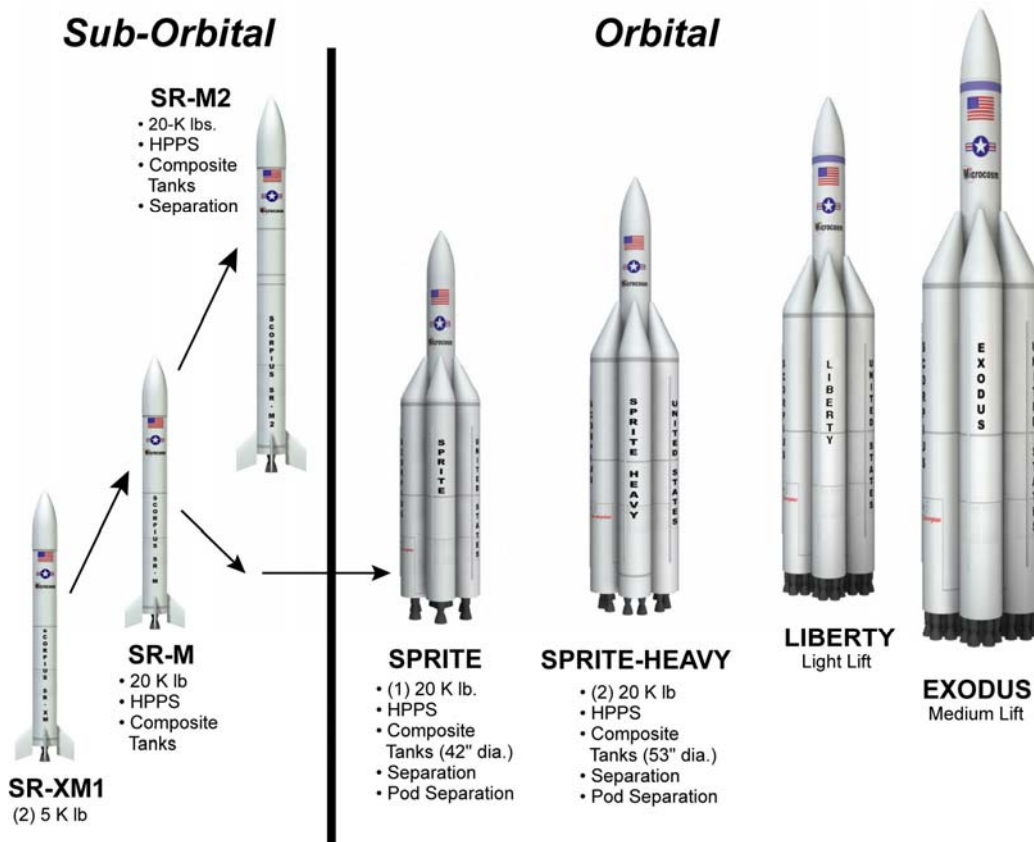


Figure 1: Microcosm's Family of Low-Cost, Pressure-Fed Launch Vehicles.

The primary objectives of the pressure-fed launcher program include:

- A factor of 5 to 10 reduction in launch cost
- Low recurring, non-recurring, facility, and operating costs
- Scalable from sub-orbital to heavy lift vehicles
- Launch on demand with weather conditions comparable to commercial airlines

Table 1 shows configuration information for both pressure-fed and conventional (pump-fed liquids and solid) launch vehicles that indicates the relative strengths of each. Data for Microcosm's pressure-fed Sprite-Heavy, Liberty, and Exodus vehicles are included. Data for Pegasus, Kosmos, and Delta are from Ref. 3. In particular, it can be seen that the pressure-fed systems have comparable specific impulses but lower propellant mass fractions, requiring higher gross weights for the same payload to LEO. The higher gross weights of the simple pressure-fed launch vehicles are accompanied by substantially lower launch costs, resulting in substantially lower specific costs

(dollars per pound of payload to LEO.) Reductions in specific life cycle costs by factors of 2 to 5 are possible when the pressure-fed approach is adopted. Launch costs and specific costs from Table 1 and for the Sprite are plotted in Figure 2 as continuous functions of payload to LEO as shown by solid lines and closed symbols. In addition, launch costs and specific costs for 3 conventional (pump-fed and solid) vehicles are shown by open symbols for comparison.

Table 1: Comparison of Pressure-Fed and Conventional (Pump-Fed Liquids and Solids) Launch Vehicles.

PAYLOAD	(lbs)	1170	1000	2900	3300	15,000	11,320
Type	(-)	Pressure	Solid	Pressure	Pump	Pressure	Pump
Name	(-)	Sprite-H	Pegasus	Liberty	Kosmos	Exodus	Delta II
Version	(-)	DS	XL	OS	3M	OS+	7920
GLOW	(lbs)	166,000	51,000	325,000	240,000	1,480,000	507,565
Payload Fraction	(%)	0.7%	2.0%	0.9%	1.4%	1.0%	2.2%
Cost	(\$M)	3.6	15	5.5	12	15.3	50
Specific cost	(\$/lb)	3077	15,000	1897	3636	1020	4417
Stages	(-)	3	3	3	2	3	3
Mass Fraction 1	(%)	83%	91%	85%	94%	87%	90%
Mass Fraction 2	(%)	82%	90%	85%	93%	86%	94%
Mass Fraction 3	(%)	80%	88%	81%	-	81%	86%
Isp1	(sec)	281	295	281	291	281	274
Isp2	(sec)	297	289	309	303	306	302
Isp3	(sec)	319	290	323	-	323	319

SCORPIUS AND CONVENTIONAL ORBITAL COST VS. PAYLOAD TO LEO

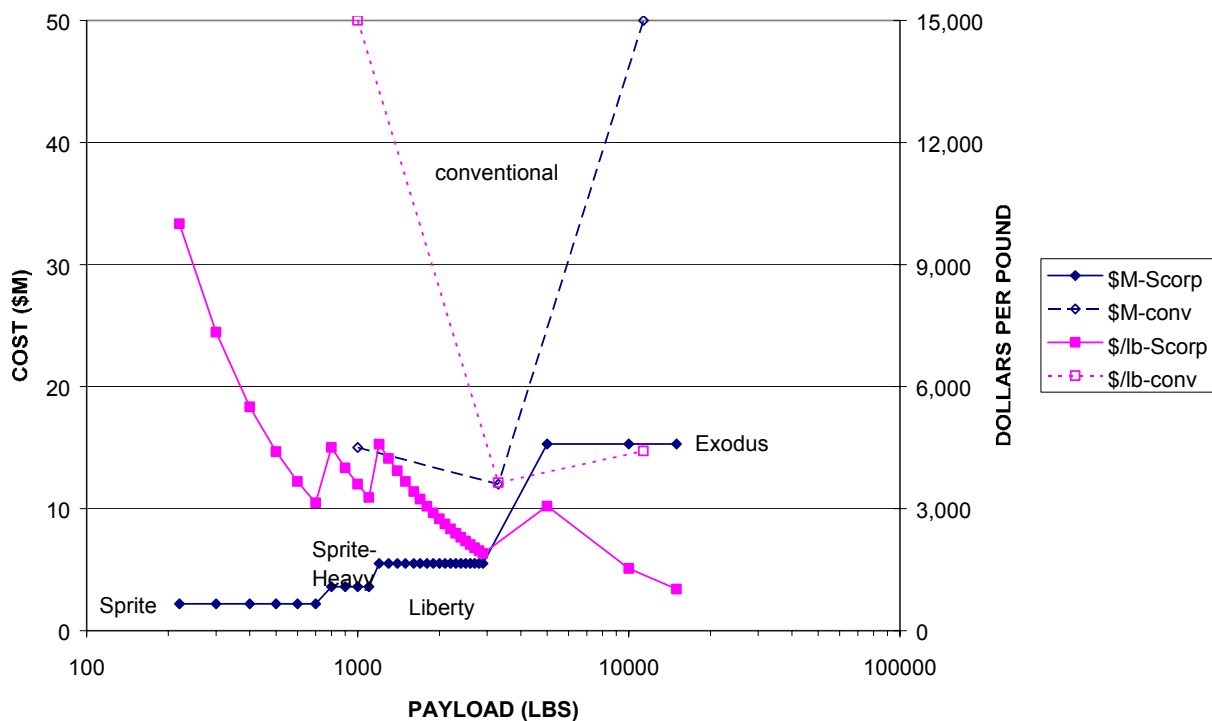


Figure 2: Scorpius® Launch Vehicle Life Cycle Costs.

Table 2 lists various characteristics of pressure-fed and pump-fed launch vehicles that illustrate the motivation for employing pressure-fed systems to reduce launch costs. In general, pressure-fed systems are simple, reliable, and robust. They are easy to operate, have good specific impulse, and are low in cost. The largest drawback of pressure-fed systems is their higher weight. However, with a moderate staging arrangement of 3 stages to LEO, the much lower developmental and recurring costs of the pressure-fed systems more than offset the somewhat higher gross weights of the pressure-fed vehicles. That the weights are only moderately higher for the lower stages of the pressure-fed vehicle is the enabling feature of the composite tanks and high performance pressurization system employed herein. A benefit of the higher gross weights of the pressure-fed systems is that the vehicles are robust during manufacture, transportation, and ground handling when, of course, they are empty of propellants. Further, the thicker tank walls yield stronger structures with more margin for flight through maximum dynamic pressure and winds aloft.

Table 2: Characteristics of Pressure-Fed and Pump-Fed Launch Vehicles.

CHARACTERISTIC	PRESSURE-FED	PUMP-FED
Complexity	Simple	Complex
Recurring cost	Inexpensive	Expensive
Specific impulse	Good	Slightly higher than pressure-fed
Development cost	Low	High
Development risk	Low	Moderate
Development schedule	Short	Long
Reliability	High	Low
Number of parts	Few	Many
Tolerances	Low	Very high
Start up / shut down	Easy and short	Difficult and long
Tank stiffness	High	Low
Handling robustness	High	Low
Cross-sectional area	High	Moderate
Failure type	Benign	Catastrophic
Weight	Heavy	Light

II. Design Approach

The substantial cost reductions provided by these launchers stem from the non-traditional design approach used. The launchers are designed as expendable rockets for low cost and simplicity rather than high performance or reuse. Where many new rocket designs use two-stage-to-Low Earth Orbit configurations driven by high performance pump-fed engines, Microcosm rockets employ a three-stage configuration using simple, very low cost, pressure-fed engines. The vehicle configuration is modular, built around scalable components and technologies. Consequently, the vehicles can be scaled up easily to accommodate larger payload needs.

Table 3 shows idealized scaling factors for the subsystems of pressure-fed launch vehicles. Values for the first stage “pods” and Stage 3 are listed. Scaling factors are important when considering the effects of increasing the payload performance by increasing the size (gross weight) of the vehicle. The table shows that when the number of stages, stage mass ratios, relative geometries, tank pressures, and expansion ratios are held fixed, the largest portion of the vehicle is scaling-neutral. For example, as a pressure vessel (tank) is increased in size at a given pressure, weight increases proportionately⁴, or weight increases with the cube of the linear dimension (“r”). Similarly, most other structures are scaling-neutral. Avionics, except for wires due to increases in lengths, tend to be constant in weight (very scaling-favorable), although additional battery weight may be required for some solenoid valves that are increased in size.

Propulsion systems, however, can be scaling-adverse in the idealized sense. As a vehicle design is scaled up in weight, the number of valves, engines, and feed lines can be increased in number, resulting in a nearly scaling-neutral procedure. For example, if gross weight is quadrupled, increasing the number of engines by four will provide the requisite thrust but the accompanying increase in weight will be proportional to the increase in gross weight, except for possible feed line length increases. On the other hand, if the engine is scaled up in thrust by a factor of four (and chamber pressure is held constant), throat area must be quadrupled since thrust is proportional to area.

Diameter is doubled. But quadrupling the throat area causes the size of the engine (and valves and feed lines) to increase by a factor of eight if all geometric proportions are fixed and flow velocity limits maintained. In other words, rather than increasing with the cube of the linear dimension (scaling-neutral), the weight of the propulsion subsystem increases with the 4.5 power of the linear dimension, which is scaling-adverse. The trends in the real weights depart from the idealized trends in that some parts of the engine such as the thickness of the ablative layer, the length of the combustion chamber upstream of the throat, and the thickness of the injector do not increase with the scale of the vehicle. Indeed, it can be seen (from Ref. 5) that specific thrust for large pump-fed engines increases somewhat with thrust level.

Table 3: Scaling Factors for Subsystems of Pressure-Fed Launch Vehicles.

COMPONENT	POD BURNOUT WEIGHT FRACTION	STAGE 3 BURNOUT WEIGHT FRACTION	IDEALIZED SCALING FACTOR	SCALING
Tanks	0.46	0.31	$\sim r^3$	Neutral
Structure	0.15	0.16	$\sim r^3$	Neutral
Propulsion	0.21	0.43	$\sim r^3$ to $r^{4.5}$	Adverse
Avionics	0.01	0.05	$\sim c$	Insensitive
Aerodyn. Loss	-	-	$\sim r^2$	Favorable
Retained fluids	0.18	0.05	$\sim r^2$ to r^3	Favorable

Microcosm’s design approach is enabled by a number of key design features including:

- Robust Three-stage Configuration Design
- Simple Pressure-fed Propulsion System
- Multiple Similar Components
- Incremental Development
- Low Complexity Production
- Efficient Operations Infrastructure

A. Robust Configuration Design

Most of these vehicles are three-stage-to-orbit designs that allow the use of high margin, moderate performance components. These components can be produced for less cost since weight is less of an issue. Additionally off-the-shelf and industrial components are more likely to be useful. These components are not only vastly lower cost than traditional “aerospace quality” parts but are usually more reliable due to their high production volumes and experience base.

Pressure-fed rocket propulsion is enabled by the emerging technology for low-cost, high-pressure composite tanks. This is one of the most critical technologies being developed in this program. This approach eliminates turbo-machinery, usually the most expensive, complex, and least reliable component in a modern rocket engine. Additionally, the pressure-fed tanks are much thicker and more robust than the thin low-pressure tanks of a conventional pump-fed rocket. This leads to a stiffer vehicle structure with fewer and less critical structural dynamic interactions

B. Simple Propulsion System

Since the propulsion system does not use turbo-pumps, it is far less costly to develop and produce. Simple low-cost ablative chambers are used, avoiding any extendable or actively cooled (regenerative) nozzles. This not only reduces engine costs by at least an order-of-magnitude, but also substantially increases reliability. Pressure-fed rockets are traditionally far more reliable than those with turbo-pumps.

The simple pressure-fed ablative-chamber approach significantly reduced the number of potential failure modes. These engines are far less sensitive to start transients, instability, and propellant quality. This reduces development cost, enables use of lower cost feed system components, and substantially improves reliability.

C. Multiple Similar Components

Microcosm's approach to vehicle architecture for Scorpius[®] and other orbital vehicle families employs six identical booster "pods" as the first stage arrayed around a single sustainer pod (Stage 2). The sustainer pod is essentially the same as the booster pod except that it incorporates a larger expansion ratio for more efficient vacuum operation. This approach greatly increases production efficiency by producing many similar small parts rather than a small quantity of both small and large parts. This enables larger production runs of the same parts to lower cost and inventory complexity.

There are also fewer components to understand and a large amount of experience gained on each flight increasing the reliability with added flight experiences. Since parts are fewer, the development and testing costs are reduced substantially.

The architecture with multiple small pods compared to a monolithic design allows the use of smaller tanks, structures, and engines thus significantly reducing the development costs and increasing the reliability.

D. Incremental Development

Microcosm's program approach is based on incremental advancement in technology as the vehicle size gets progressively larger in terms of payload capabilities. New technologies are phased in a parallel path and are phased in when they are substantiated by analyses and/or testing. Technologies are demonstrated at small scale and once the viability of their application is substantiated, steps are taken to incorporate the technology for full-scale qualification.

As an example, we matured the technology for the Tridyne based High Performance Pressurization System in a small laboratory test bed. We continued our efforts to demonstrate the flight readiness of this technology with a comprehensive test program. The development of the all-composite LOX tank had taken a similar approach. While two of the suborbital flights to date had used a metallic LOX tank, we now plan to use an all-composite, light-weight LOX tank in our next vehicle. The technology for the all-composite LOX tank was advanced incrementally starting with the successful flight demonstration of a 10-inch size LOX tank and subsequently, a 42-inch all-composite fuel tank. The all-composite LOX tank is in the final stages of qualification.

E. Low Complexity Production Infrastructure

Our low cost production infrastructure allows us to fabricate most of our critical components and subsystems in-house and thus control the costs. Our in-house production facilities are up and running for our all-composite propellant tanks and our ablative combustion chambers. Our ablative combustion chamber design has only three major parts and less than 40 parts total and requires less than 30 person-hours of touch labor for fabrication. Our low-cost, out-of-autoclave, filament-wound graphite composite fabrication process allows us to make our propellant tanks in-house at a significantly lower cost and significantly shorter production schedule compared to what is available commercially. We have also established working partnership with a number of our major subcontractors to develop low cost valves and injectors.

F. Efficient Operations Infrastructure

The use of a single, non-toxic propellant type (Jet fuel and LOX), air/road transportable components leads to an efficient operations infrastructure. The design incorporates mechanical, fluid, and electrical interfaces to facilitate efficient pre-launch and launch operations thus reducing launch-to-launch time and prelaunch processing time on the pad⁶.

Our focus is to make all flight operations as airline-like as possible. This begins with the system design, where we emphasize simple, robust designs, minimal parts counts, maximum commonality between stage hardware designs, and design for operability. This approach enhances reliability, minimizes manufacturing and integration times, allows for quick and easy repair of any hardware failures, and allows for fast, efficient flight and ground operations. The short and stout configurations of our launchers are assembled in the integration facility and towed in the vertical position to the launch pad aboard their transportable launch stand. The robust structure of our vehicles allows vertical towing at higher speeds and over rougher surfaces than is common for launchers. The short and stout design also reduces the effect of wind shear and dramatically reduces the moments of inertia, at the cost of slightly higher drag.

Nearly all of the vehicle power, data, and fluid connections will be at ground level to minimize connection times. Upper stage umbilicals will be run along a simple umbilical pole and connected to the vehicle by a technician on a cherry picker. This eliminates the need for complex and expensive gantries. For first stage propellant and pressurant fill/drain, we are examining the option of using single point connections and on-board manifolds to reduce fluid fill tasks.

III. Enabling Technologies

In parallel with the system development activity for over 12 years, Microcosm has been pursuing the development of the critical enabling technologies required for the pressure-fed launch vehicles.

A. High Pressure Composite Tank Technology

Composite tanks are clearly an enabling technology for Microcosm's pressure-fed family of orbital vehicles. Composite technology is far more important for pressure-fed rockets than for traditional pump-fed boosters where the weight advantage is far less significant. Composite tanks designed for the Scorpius[®] boosters can be three times lighter than metallic tanks. We have flown an all-composite fuel tank in our SR-XM-1 vehicle. Microcosm has produced all-composite LOX tanks using a similar process as the fuel tanks. These tanks have been cryogenically tested with increasing success. Figure 3 shows our all-composite LOX tank under cryogenic test conditions and our flight-proven all-composite fuel tank. Smaller versions built under Microcosm IR&D have flown as the main LOX tank in a 10-inch diameter rocket.



Figure 3: All-Composite LOX Tank (left) in Cryogenic Testing and Flight-Proven Fuel Tank (right).

An improved and larger version has been successfully tested above the MEOP. Further enhancement in performance is underway.

The pressurization system requires high-pressure helium bottles to store pressurant. The technology to build these tanks currently exists but the cost is too high. Additionally, the metallic liners employed cause somewhat higher than necessary weight and may preclude cryogenic operation. Near-cryogenic pressurant temperatures improve system performance. In-house fabrication of this component is preferred to control cost and availability. Our plan is to utilize the same process used for the LOX tank to the maximum extent possible, however, since they operate at ten times the pressure, we plan to make the necessary modifications as required.

B. Pressurization and RCS Technology

In a pressure-fed rocket, the pressurization system is a critical subsystem especially in terms of the total weight of hardware and pressurant that is required. In our two previous suborbital flights, we demonstrated a cold helium pressurization system. However, it weighs two to three times the weight required for the orbital launcher. Under IR&D and subsequently under two government contracts, Microcosm has demonstrated the viability of a pressurization system employing Tridyne and a catalyst bed reactor. Our analyses and testing to date indicated a reduction of the pressurization system weight by over 50% when the Tridyne based system is incorporated. The Tridyne test rig and test set up is shown in Figure 4.

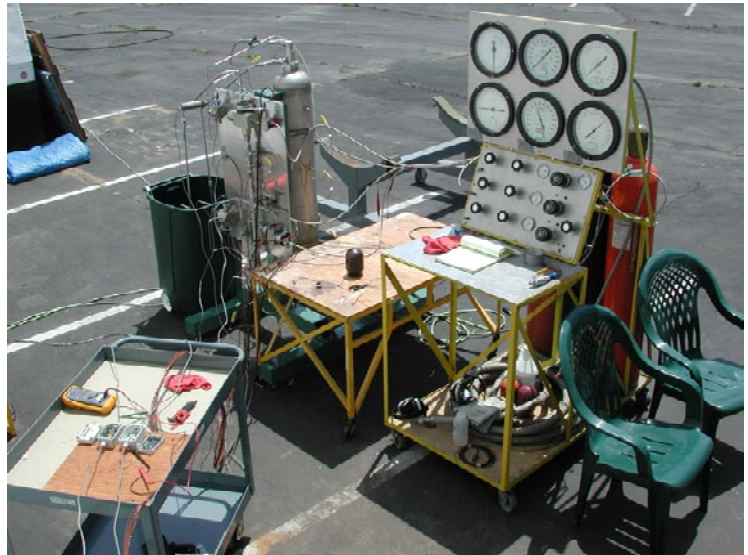


Figure 4: Tridyne Test Rig and Test Set Up.

Another technology required for our orbital vehicles is a reaction control system (RCS) for the upper stage. To meet program cost and operability goals, this subsystem should cost less and avoid the hazardous propellants used in typical hydrazine or bi-propellant thrusters. Since the performance requirements are not high, a cold gas system may be sufficient. However, with the heated helium on board for the HPPS, we are evaluating an option to integrate the RCS with the HPPS.

C. Low Cost Engine Technology

Another enabling technology for our suborbital and orbital launchers is low cost engines. Over the past 12 years, Microcosm has successfully demonstrated the low-cost engine technology that cost much lower than any other engines available in the industry. Our goals are to produce engines in direct manufacturing cost for as low as \$1 per pound of thrust. We have demonstrated chamber production costs for our flight-proven 5,000 lb-thrust of about \$4,000. Projected costs for the first generation of 20,000 lb-thrust engines are already under \$2 per pound of thrust. These costs are at least an order-of-magnitude less than traditional rocket engines. In-house production of these engines enables us to control costs and assure availability.

The general approach is to build on the successes to date in the Scorpius[®] 5,000 lb. and 20,000 lb.-thrust (vac) engines. Over the last 10 years, Microcosm successfully demonstrated the viability of its 5,000-lbf thrust engines for application in various launch vehicles including the successful SR-Sa and SR-XM-1 flights. The 5,000-lbf engine design was extrapolated to design a 20,000-lbf engine in collaboration with Schafer Corp. The 20,000-lbf injector was characterized with a workhorse metal chamber through a series of short duration hot fire tests at the Rocket Propulsion Test Facility (RPTF) in Socorro, New Mexico. The test data indicated a stable combustion with a C* (combustion efficiency) well over 96 percent. Figure 5 shows our 20,000-lbf thrust combustion chamber and a 5,000-lbf thrust engine testing at the Rocket Propulsion Test Facility at Socorro, NM. The engine development effort is continuing along with the development and qualification of the various other segments of the propulsion systems such as the feedlines and pressurization systems.

D. Low Cost Flight Systems Technology

The flights of our suborbital vehicles to date demonstrated that commercial-off-the-shelf industrial computer hardware combined with low cost avionics hardware built at Microcosm and a low cost, integrated GPS/INS are effective, low cost components for suborbital rocket avionics. For the orbital vehicles, this technology is expanded to enable the control of multiple pods and stages. The avionics for the orbital vehicles are designed so that they work reliably for a few hours in the space environment – during the launch operation and de-orbit of the upper stage.



Figure 5: 20-klbf Ablative Engine (left) and 5-klbf Engine Hot Fire Testing (right).

IV. Conclusion

The paper describes Microcosm’s approach to developing low-cost, pressure-fed launch vehicles. While the pressure-fed designs are relatively heavy compared to the traditional pump-fed designs, our enabling critical technologies for composite tanks, high performance pressurization system, and low-cost ablative engines allow us to provide pressure-fed design solutions at a significantly lower cost and higher reliability compared to the pump-fed options. Most of the critical technologies have been either qualified or are in the final stages of qualification. All these technologies are scalable and thus can be easily integrated to progressively larger vehicles to meet the evolving payload requirements of various defense and commercial programs. This approach of designing for low cost by exploiting the pressure-fed technologies has the potential to revolutionize space transportation and enable the next generation of expendable launch vehicles at greatly reduced cost.

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