4th Responsive Space Conference
RS4-2006-2002

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4th Responsive Space Conference
April 24–27, 2006
Los Angeles, CA

4th Responsive Space Conference, Los Angeles, CA, April 25–27, 2006

SYSTEMS ENGINEERING FOR RESPONSIVE LAUNCH[*]

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Abstract

In the Microcosm Responsive Launch Systems model, a key requirement is that the launch vehicle be essentially a commodity, built to inventory, and ready to go whenever needed, much like cruise missiles or rental cars. This, in turn, implies the need for low vehicle cost and minimum ground infrastructure in order to hold down the capital cost of maintaining systems in inventory, as well as minimizing the actual launch operations time. Thus, one way to achieve responsive launch is to design a low-cost system which provides a ready inventory and necessitates a brief launch operation to keep operations cost low.

This paper addresses 5 key system engineering trades and their results in the implementation of low cost, responsive launch systems:

- Propellant selection – Kerosene/LOX
- Feed system – Pressure-fed
- Number of stages to orbit – 3 stages
- Technology commonality – Common in all stages
- Launch constraints – All-weather launch

The net result of these trades is the Sprite Small Launch Vehicle, capable of putting 810 lbs into LEO for $4.2 million with a small number of launches per year. Launch can be within 8 hours from the storage condition (not on alert), within 2 hours from alert on the launch pad (indefinite hold period), and within 5 minutes when the system is on alert and fueled.

Introduction

The cost of access to low earth orbit (LEO) is high. Isakowitz[1] reported prices of American launch vehicles as shown in Table 1. While the prices listed in Table 1 are, in some cases, approximate and for years between 2000 and 2002, they do illustrate the fact that the cost of getting to orbit is high. Indeed, it could be argued that prices have escalated in recent years due to the paucity of satellites and the resulting depression of the launch market. London[2] has observed that some estimates have indicated that high launch costs are responsible for about one-half of the total cost of new satellite systems.

Table 1. Vehicle Comparison. Prices of American Launch Vehicles.

Vehicle	Payload (LBS)	Price ($M)	Specific Price ($/LB)
Pegasus XL	977	15-25	15,400-25,600
Athena I	1805	40-45	22,200-24,900
Athena II	4520	45-50	10,000-11,100
Delta II 7320	6120	~45	7400
Delta II 7920	11,150	~55	4900
Delta IV M	20,158	~75	3700
Atlas V 402	27,558	~75	2900
Atlas V 552	45,239	~110	2400
Delta IV H	52,855	148-160	2800-3000

The Scorpius® system has as its primary goal the lowering of the cost of achieving orbit. As an example, the first and smallest Scorpius® orbital vehicle, the Sprite, has a payload of 810 lbs, a price of $4.2 million, and a specific price of $5200 per lb. Such a cost regime creates both a low entry cost for achieving orbit and, due to the

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scalability of the Scorpius® architecture, a low specific cost for the range of payloads cited. For Liberty Light Lift and Exodus Medium Lift, the payloads are 3,200 and 13,000 lbs, the prices are \$7.9 and \$15.9 million, and the specific prices are \$2,400 and \$1,200 per lb, respectively. As an added benefit, given the simplicity (short time of launch operations) and low cost (built to inventory) of the Scorpius® design, the secondary goal of high responsiveness (8 hours from arrival of payload on site) is also achieved.

Low cost and responsiveness are achieved by utilizing the historical "Big Dumb Booster" approaches[3,4,5] in combination with three new enabling technologies: pressure-fed, ablative engines; composite tanks; and a high performance pressurization system.

The five key systems engineering trades addressed in this paper are vital to the implementation of a low-cost, responsive launch system:

- Propellant selection
- Feed system
- Number of stages to orbit
- Technology commonality
- Launch constraints

The first four of these trades were discussed in the previous "Big Dumb Booster" studies with conclusions that have been confirmed and adopted by Microcosm and embodied in the Scorpius® architecture. The all-weather launch feature is a side benefit of the pressure-fed design and modular architecture (short, squat profile) and has been found to minimize operations costs and cost penalties and mission gaps due to launch delays.

Propellant Selection – Kerosene/LOX

There are 3 broad categories of chemical rockets, those using liquid, solid, or "hybrid" propellants. Each broad category has its advantages and disadvantages, including those beyond[6,7,2] the ones mentioned below. One metric for propellants is specific impulse and is listed in Table 2 for several propellant types[6,7]. Note that specific impulse for a pump-fed engine system is several seconds lower than that for the chamber due to losses for driving the pump.

Table 2. Specific Impulse Comparison. Specific Impulses of Current Propellant Combinations.

PROPELLANT	SPECIFIC IMPULSE (SEC) [p_c = 1000 psi expanded to SL]
LH2/LOX	387-395
Kerosene/LOX	286-300
Hydrazine/Nitrogen Tetroxide	278-292
HTPB (solid)	260-265
Hybrid	~270
Hydrazine (monopropellant)	~220

Solid rockets (HTPB propellant) are ready to launch at a moment's notice, simple, and relatively dense, but are expensive, heavy for ground operations (always loaded with propellant), difficult to shut down, dangerous for manufacturing and ground personnel, and have a relatively high burnout mass fraction.

Liquid rockets are of two basic sub-categories, pump-fed and pressure-fed, and are currently being used in launch vehicles with three propellant combinations: kerosene/LOX, hydrogen/LOX, and hydrazine/nitrogen tetroxide. Hydrazine is used as a monopropellant in some maneuvering modules for near-orbital velocity regimes in an application similar to hydrazine rockets for spacecraft, but is not generally considered for application in the main stages of launch due to its low specific impulse. Other propellants, such as ethanol, nitric acid, and fluorine, have been used in the past or proposed, but are not now employed for various reasons, the Russian Kosmos vehicle being an exception.

Currently, only the hydrazine/nitrogen tetroxide combination is utilized for pressure-fed applications in launch vehicles and pressure-fed systems are used only in upper stages.

Liquid rockets are light and safe during ground handling, can be shut down easily, and generally have somewhat better performance (specific impulse) than solids for propellant combinations of kerosene/LOX and hydrazine/nitrogen tetroxide and much better performance for hydrogen/LOX, but are more complex and expensive in the case of pump-fed systems. Pump-fed systems have the added advantage of lower burnout mass fraction. The hydrazine /nitrogen tetroxide propellant combination has the additional advantage of being hypergolic (not requiring a separate ignition source), but the disadvantage of being toxic. The other two liquid combinations have the added disadvantage of having at least one cryogenic propellant. The hydrogen/LOX combination has poor propellant density and is more dangerous during launch operations.

While hybrid rockets, those having one liquid propellant and one solid propellant, are touted as having the best of both liquid and solid "worlds," such as easy shutdown, safety on the ground, and low cost, they also can be seen as having the worst of both "worlds": low performance, heavy on the ground, somewhat complex, and high burnout mass fraction (especially due to large propellant residuals.)

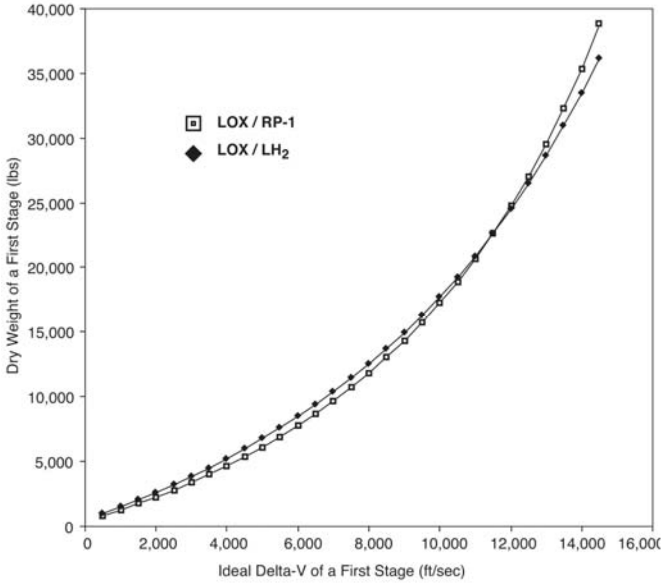
Given the effort by the U.S. government to migrate to more environmentally benign propellants, the hydrazine/nitrogen tetroxide combination is untenable for application to a new launch vehicle. The complexity, expense, and safety considerations of the hydrogen/LOX combination do not outweigh the performance advantage, especially for the first stage where propellant density (relatively high burnout mass fraction) has a significant impact on overall vehicle performance. Many studies and the historical Saturn vehicles that include the hydrogen/LOX combination as a candidate have concluded that the kerosene/LOX combination is preferred for the first stage. See, for example, Figure 1 from London[2]. The historical Atlas Centaur vehicle and the Atlas V vehicle embody this approach.

To maintain commonality among stages and to utilize the lowest cost propellant combination (both cost of propellant and cost of handling), kerosene/LOX was chosen as the propellant combination for all stages of the Scorpius® launch vehicles. This approach has also been long used in the Russian Soyuz and Ukrainian Zenit launch vehicles and is proposed for the Russian Angara launch vehicle. Specifically, Jet A, which is a type of kerosene widely used around the world, was chosen for its low cost. This combination provides good specific impulse, good propellant density, low toxicity, ease of handling, low cost, the best availability, and common use.

A side benefit of using kerosene is its availability as a hydraulic fluid for thrust vector control, since many industrial hydraulic components are compatible with it. Because of the readily available supply of high pressure kerosene in the Scorpius® launch vehicle, no auxiliary power unit or hydraulic pump is needed.

Feed System – Pressure-Fed

All current launch vehicles that use liquid propellants employ turbopumps during their lower stages. Notable pressure-fed upper stages



Assumptions: Isp of LOX / RP-1 Is 300.1, of LOX / LH_2 is 389.4. Propellant fraction of LOX / RP-1 stage is 92.5%, of LOX / LH_2 stage is 88.5%

Figure 1. Stage Dry Weight Versus Velocity (from Reference 2).

in use include Stage 2 of Delta II (really the third stage with the solid boosters present) and the EPS of the Ariane 5, both of which exploit the hydrazine/nitrogen tetroxide propellant combination. As mentioned, many spacecraft and maneuvering modules use pressure-fed systems as exemplified by the Space Shuttle's Orbital Maneuvering System (OMS) pods.

Pressure-fed systems heretofore have not been applied to the boost problem, with the apparent single exception of the 1960's era Diamant, primarily because of the high burnout mass fractions and somewhat lower specific impulses associated with pressure-fed systems. Pressure-fed systems, a familiar example of which is the neighborhood bottle rocket, offer abject simplicity (see Figure 2) and low cost at the price of heavier tankage and a significant pressurization system. Until recently, pressure-fed launch vehicles have been proposed with metallic propellant and pressurization tanks. While viable designs have been proffered with such an arrangement, the onset of composite technology in the past two decades has presented an exciting enabling technology for efficient low-cost, pressure-fed launch vehicles in the form of composite propellant and pressurization tanks.

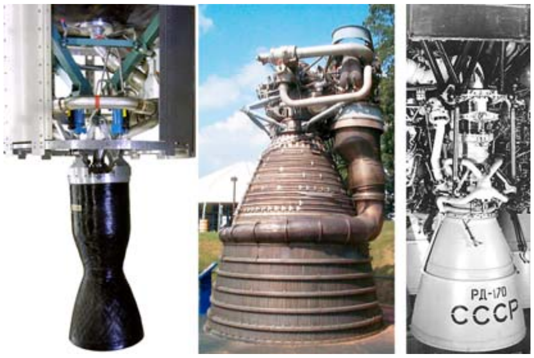


Figure 2. Engine Comparison. Simplicity of Scorpius® Pressure-fed Engine (left) vs. F-1 of Saturn V (center) and RD-170/-171/-180 of Zenit/Atlas V (right).

The strength-to-weight ratio of carbon fiber is about 10 times that of typical metallic materials such as steel and aluminum. When the necessary resin material is included in the composite structure, the strength-to-weight ratio of the composite is still 3 times that of the metallic materials. Actual, low-cost composite tank weights as depicted in Figure 3 are approximately half that of metallic tanks for the same volume and pressure. Since tank weights comprise about half the dry mass of a typical pressure-fed stage, savings of about one fourth in stage dry mass can be realized through the use of composite tanks.

Figure 3. Composite Tank Strength Demo. Composite Tanks for Pressure-fed Launch Vehicles Display High Strength.

If propellant tank weight is driven by pressure, it is proportional to pressure for a given volume. Thus, if a propellant tank for a pump-fed system operates at an ullage (tank) pressure of 25 psi, then a propellant tank for a comparable pressure-fed system operated at 500 psi would weigh 20 times as much. In addition, the pressurization tanks would weigh about 20 times as much, unless a more efficient approach, such as heated pressurization gas, is adopted. These higher tank component weights would be partially offset by the much higher weight of the pump-fed engine. The net result is that the pressure-fed system is heavier than the comparable pump-fed system for the same propellant mass and thrust level; has a somewhat lower chamber pressure and, therefore, sea-level specific impulse; but has far fewer parts, especially high temperature, tight tolerance parts; and is, thus, much less expensive than the pump-fed system and has higher potential reliability.

An interesting benefit of the pressure-fed approach is that because chamber pressures are necessarily lower than those of a pump-fed system, ablatively-cooled chambers are practical, which further reduces cost, complexity, and unreliability. Composite ablative chambers are manufactured with processes and equipment that are similar to those for composite tanks, further reducing manufacturing, tooling, and personnel costs. A further benefit accrues to ablative chambers for the kerosene/LOX propellant combination in that coking of coolant passages is avoided entirely. Low-cost chambers have the compounding benefit that developmental testing costs and schedules are greatly reduced due to the relative expendability of the chambers and their very short manufacturing times. While ablative engines are not entirely new, their application in the pressure-fed approach, especially with the composite materials and processes employed, represent a fresh, enabling technology for low-cost launch vehicles.

A key technology for any pressure-fed vehicle is the pressurization system. While the "Big Dumb Booster" approaches contemplated conventional systems using helium at ambient temperature, a weight savings of as much as a factor of two can be realized by exploiting a scheme that utilizes heated gas. This savings occurs because less pressurant gas is required to displace propellants if it is heated, which results in lower storage volume and pressurant tank weight. Thus, if an efficient, passive method of heating the pressurant can be devised, such a pressurization system becomes a third enabling technology for a pressure-fed launch vehicle with little penalty in cost, complexity, or unreliability.

As will be seen in the next section, the higher burnout mass fraction and slightly lower specific impulse for the pressure-fed launch vehicle result in a somewhat higher vehicle gross liftoff weight (GLOW) for a given payload to LEO than that for the pump-fed vehicle, but the cost is far lower because of the low cost of the individual components, integration of the vehicle, and operations.

Number of Stages to Orbit – 3 Stages

Figure 4 shows that for launch to LEO, the use of 3 rather than 2 stages greatly reduces GLOW for the idealized stage burnout mass fraction of 0.10. Moreover, the benefit of further increasing the number of stages is far less significant in this nonlinear problem. The "delta-v" of 32,879 fps is a typical ideal velocity increment for achieving low earth orbit with a low thrust-to-weight liquid launch vehicle and includes losses due to gravity, steering, atmospheric pressure, and drag. Vacuum specific impulses for this example are 286 and 319 sec for Stages 1 and 2, respectively, and 323 sec for Stages 3 and higher.

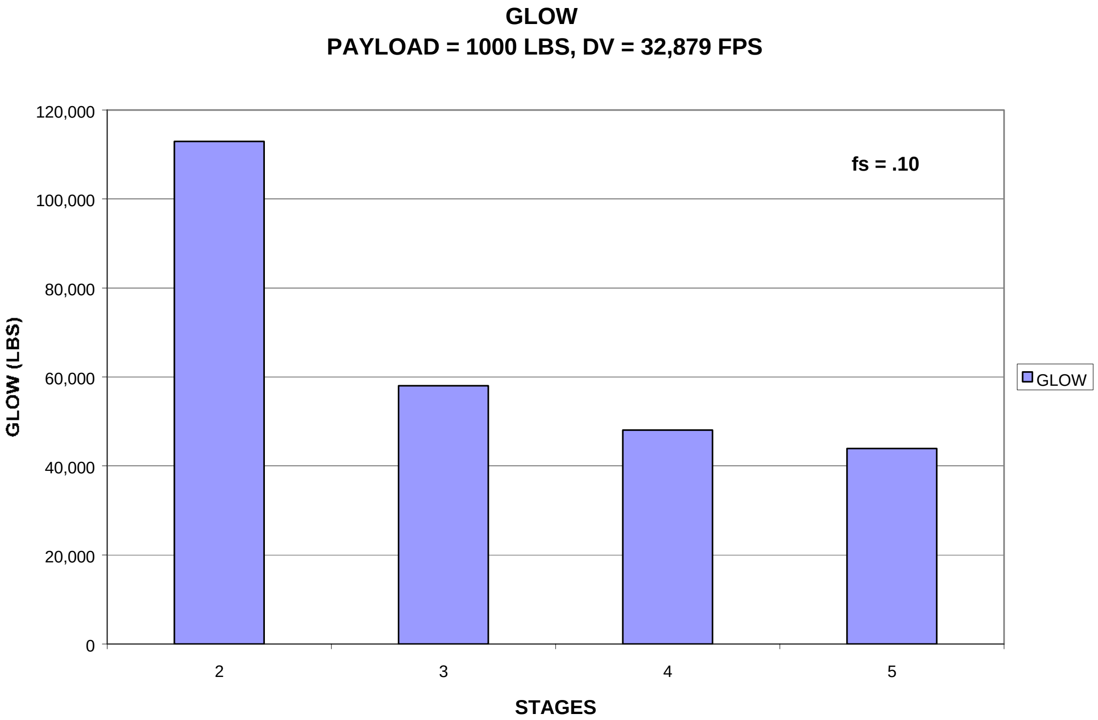


Figure 4. GLOW as a Function of Number of Stages.

Most launch vehicles employ 3 stages or high performance techniques to attain orbit. High performance techniques include

- Hydrogen/LOX propulsion, e.g., Space Shuttle (2 and a fraction stages if the OMS is included), Delta IV M (both stages utilize hydrogen; can achieve GEO),
- Very high pressure kerosene/LOX propulsion, e.g., Atlas V 402, which also employs a hydrogen/LOX upper stage (a version can achieve GTO)
- Very lightweight or "balloon" propellant tanks usually with common bulkhead, e.g., historical ICBM-class Atlas D/E ("stage and a half" to orbit) and Atlas II (two and a half stages) and historical ICBM-class Titan II and Kosmos (2 stages).

Most other vehicles and, indeed, the Atlas IIAS and other variants of Delta IV and Atlas V that employ solid booster rockets require at least 3 stages to attain low earth orbit, e.g., Delta II, Athena I, Pegasus XL, Soyuz, Proton, Ariane 5, and historical Titan IV.

Figure 5 shows GLOW as a function of the number of stages for various stage burnout mass fractions. The nonlinear nature of the problem is further illustrated in this figure where the reduction in GLOW from the 2-stage configuration to the 3-stage configuration increases as stage burnout mass fraction increases. Conversely, the figure indicates that burnout mass fraction must drop substantially to maintain GLOW when the number of stages is reduced from 3 to 2, e.g., from 0.14 for 3 stages to 0.09 for 2 stages.

Given the higher stage burnout mass fractions for pressure-fed systems, e.g., 0.16, compared with 0.08 to 0.12 for pump-fed systems, the choice of a 3-stage rather than a 2-stage architecture is obvious. Burnout mass fraction does tend to increase as the size of a stage decreases, so actual designs would show a slightly lesser difference in GLOW. However, this is partially offset by the fact that the nonlinearity of the GLOW/number of stages relationship is exacerbated by the somewhat higher ideal velocities needed for more useful orbits than the 100-NMI, 28.5-deg "standard" orbit.

Stages 1 and 2 of Scorpius® vehicles have nearly identical burnout mass fractions because they are comprised of nearly identical modules or "pods." Stage 1 is a ring of 6 "pods" that surrounds a seventh pod that is Stage 2. See Figure 6. Stage 3 is of the same technology and diameter as the pods of Stages 1 and 2, but is shorter and operates at a lower pressure.

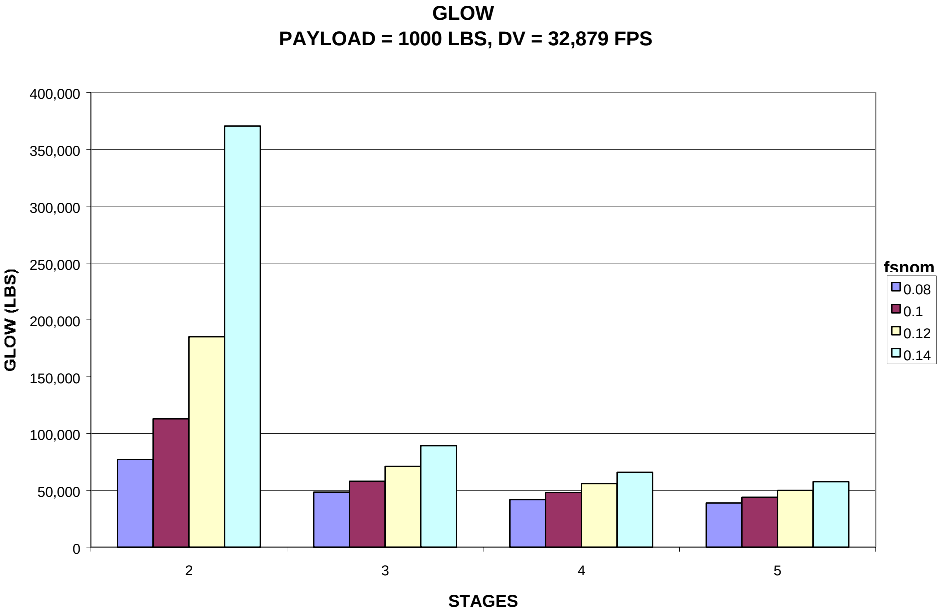


Figure 5. GLOW as a Function of Number of Stages for Different Stage Burnout Mass Fractions.

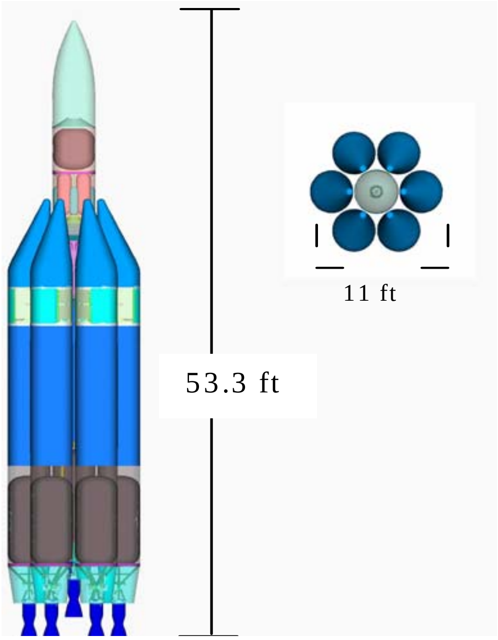


Figure 6. Scorpius® Configuration.

Another aspect of the design process that relates to the choice of the number of stages is indicated indirectly by the portion of Figure 5 that applies to three stages. It can be seen that for three stages, the GLOW increases nearly linearly with burnout mass fraction. However, it should be realized that for the range of values pertinent to a pressure-fed system, i.e., from 0.08 to 0.16, cost of manufacturing and, to some extent, operations is a highly nonlinear function of mass fraction. For a given pressure, geometry, and safety margin, costs rise dramatically as burnout mass fraction decreases below 0.12. (Indeed, this nonlinearity of cost with mass fraction is applicable to all existing American rocket types as described by London[2] where ICBM legacy vehicles were designed for minimum weight by keeping margins low and by making extraordinary efforts to decrease structural weight and increase propulsion efficiency with high chamber pressures and sophisticated turbopumps.) Therefore, cost optimized designs are those that increase GLOW (a weak determinant of cost) until the technology (a strong determinant of cost), e.g., composite tanks, becomes conventional enough to be readily available.

Technology Commonality – Common in all Stages

One way to reduce cost and increase reliability is to use the same technology in many or all of the stages of the launch vehicle. To the extent that similar or identical components can be used in multiple applications throughout the vehicle, economies of scale and reductions of part types conspire to decrease manufacturing and integration costs. Moreover, developmental testing is reduced due to the requirement for fewer designs and confidence in reliability is increased over time due the higher instances of use. Lowered cost of manufacturing and commonality in technologies contribute to the effect of creating a commodity out of the low-cost launch vehicle, such that units are built to inventory and can be available on a stand-by basis at the launch site.

This approach has been implemented to some degree in other vehicles. Saturn 5 employed the J-2 engine on both Stages 2 and 3. The Soyuz utilizes four “pods” in Stage 1 that are somewhat similar to Stage 2 as illustrated in Figure 7. Titan II and IV used the same propellant types on Stages 1 and 2, although the Titan IV had 3 different propellant combinations. The Athena II uses identical Castor 120-based stages for Stages 1 and 2. Vehicles developed after the Scorpius® vehicles such as the new Delta IV Heavy or the proposed Atlas V Heavy and Angara use “pods” (designated as common booster core, common core booster, or common rocket module) for Stages 1 and 2.

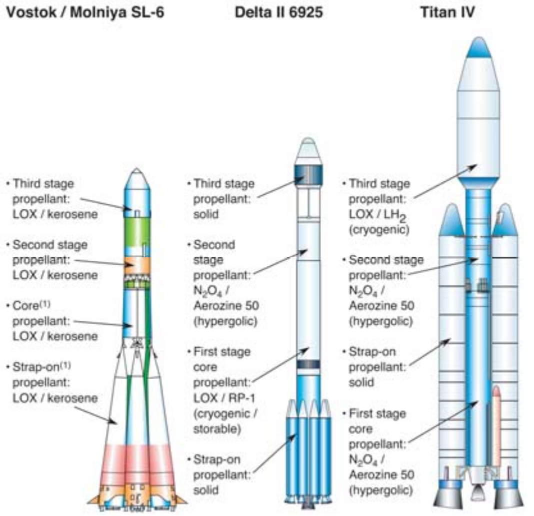


Figure 7. Commonality Comparison of Launch Vehicle Systems (from London[2]). The Vostok/Molniya SL-6 booster has significant propellant and system commonality when compared to U.S. boosters. The SL-6 uses LOX and kerosene all the way up the stack, whereas the Delta and Titan use various combinations of solid, hypergolic, and cryogenic propellants. The SL-6 uses virtually the same engine on its core vehicle as well as on each of its four strap-ons, resulting in 20 identical thrust chambers per vehicle. System commonality like that exhibited by the Russian booster can be enabling in driving down design, manufacturing and operating costs.

As mentioned, the Scorpius® design uses the kerosene/LOX propellant combination and pressure-fed propulsions systems for all stages and nearly identical pods for Stages 1 and 2. Manufacturing technologies for the tanks, engines, and structures for Stage 3 are the same as those for the “pods” of Stages 1 and 2. Avionics are located primarily on Stage 3 with common interface units, gimbal controllers, buses, and sensors on all stages.

Finally, the same architecture and technologies are used as the Scorpius® vehicles are scaled in size from the small launch vehicle (Sprite) through light lift (Liberty) to medium lift (Exodus) and larger. The use of common technologies keeps both developmental and recurring costs low, not only for a given vehicle, but across the family of vehicles.

Launch Constraints – All-Weather Launch

A side benefit of the pressure-fed approach for launch vehicles and the particular architecture of the Scorpius® vehicles is the ability to launch in all weather conditions in which the commercial aviation industry operates. Except for extreme conditions such as hurricane, tornado, severe thunderstorm, and blizzard, Scorpius® vehicles are strong enough and projected to be controllable in virtually all wind conditions. By its nature, a pressure-fed launch vehicle is composed of tanks that must withstand internal pressures that are 5 to 20 times higher than those of a pump-fed vehicle, implying that the tanks are 5 to 20 times more resistant to bending, buckling, and other loads. See Figure 3. If the intertank, stage attachment, and other load bearing structures are built in a similar manner, the vehicle can withstand higher air loads induced by wind shear aloft near the maximum dynamic pressure regime. The Scorpius® design in particular, a solid ring of pods (Stage 1) surrounding a nearly identical pod (Stage 2), creates a geometry with a lower length-to-diameter ratio than that of a monolithic arrangement, reducing the moment of inertia, reducing the bending loads, increasing stiffness beyond that attained with just the pressure-fed aspect of the system, and reducing aerodynamic disturbances. See Figure 6. Maximum TVC deflection angles are generous to accommodate the higher allowable angles of attack.

Currently, the launch operations for Scorpius® limit the launch process to ground winds of not more than 30 knots for personnel safety. Movement of the vehicle and platform on the ground is possible at over 40 knots. The vehicle itself is controllable in flight at ground wind speeds in excess of 70 knots, at which time thrust misalignment and pod-to-pod thrust variation represent larger typical disturbances than wind loads. For the worst month, 100 trials of wind profiles (with wind speeds upwards of 150 knots aloft) at a candidate launch site were examined with 6-DOF simulation with regard to controllability and aerodynamic load of a Scorpius® orbital vehicle throughout boost. All cases were shown to be well within controllability limits and q-alpha design limits, demonstrating an all-weather launch capability. Responsiveness with regard to weather is not an issue for the Scorpius system.

The all-weather capability of the Scorpius® system coupled with the ability to maintain vehicles in an “at-the-ready” inventory at the launch site due to their low cost and the short period of launch operations due to the simplicity of the design provide a truly responsive launch system. Note that the “at-the-ready” inventory, the short period of operations, and the encapsulated payload permit rapid turnaround following a launch abort on the pad whereby the stack is returned to the integration facility for replacement of the launch vehicle with a unit from inventory followed by launch in short order.

Conclusions

Virtually all American launch vehicles use 3 stages to get to usable low earth orbits or they employ high performance features, e.g., hydrogen/oxygen engines, very high chamber pressure (RD-180), or exotic structures (balloon or chemically milled isogrid tanks). This is a direct result of the rocket equation. High performance features drive up life cycle cost because of both high developmental costs and high manufacturing and operating (recurring) costs.

The Scorpius® design seeks to substantially lower the time and cost of payload delivery to usable low Earth orbits. The design strategy is to use technologies of moderate performance so as to keep developmental and recurring costs to a minimum. Minimizing cost using "conventional" propellants, e.g., kerosene/LOX, and structures and other systems that are easily manufactured and handled, i.e., of moderate weight, necessitates the use of 3 stages for the low Earth orbit mission.

The Scorpius® design uses pressure-fed systems because of their extremely low life cycle costs. Because these are heavier than moderately performing pump-fed systems, three stages are required for cost efficacy. The third stage enables a substantially lower gross weight and higher margins in the quest for low cost, especially for the pressure-fed technology. The use of three stages has the added benefit of being less sensitive to growth in dry mass.

The short, squat design and pressure-fed system provides other features that drive down cost and directly impact responsiveness. Specifically, the use of 7 nearly identical pods per vehicle allows a significant cost reduction due to learning curve even when only a small number of vehicles are built per year. The short, robust mechanical configuration allows the system to be designed for all-weather launch, the lack of which is typically a major impediment to responsive launch.

In Summary:

Scorpius® launch vehicles are designed for low-cost launch to orbit (Sprite delivers 810 lbs to LEO for $4.2 million.)

Low cost is achieved by systematically addressing the factors that affect cost: simple systems, available technology, and high margins.

Responsiveness is enabled in the Scorpius® launch vehicle system by low cost which allows for an “at-the-ready” inventory of vehicles to be used in conjunction with encapsulated payloads (as in the cases of rental cars, munitions such as cruise missiles, and container ships), simple systems and operations which allow for quick launch, and by an all-weather launch capability that eliminates weather-related delays.

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