LOW-COST LAUNCH OPPORTUNITIES PROVIDED BY THE FALCON FAMILY OF LAUNCH VEHICLES

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ABSTRACT

The Falcon family of launch vehicles, developed by Space Exploration Technologies Corporation (SpaceX), are designed to provide the world's lowest cost access to orbit. Highly reliable, low cost launch services offer considerable opportunities for risk reduction throughout the life cycle of satellite programs. The significantly lower costs of Falcon 1 and Falcon 9 as compared with other similar-class launch vehicles results in a number of new business case opportunities; which in turn presents the possibility for a paradigm shift in how the satellite industry thinks about launch services.

1. INTRODUCTION

SpaceX was founded in 2002 by Elon Musk with the goal of reducing the cost and increasing the reliability of access to space by a factor of ten. To accomplish this, SpaceX is developing a family of launch vehicles which includes the Falcon 1 and Falcon 9 to offer a full spectrum of light, medium and heavy lift capabilities. Additionally, SpaceX is developing the Dragon capsule for transport of cargo and crew to and from the International Space Station (ISS).

The Falcon family of launch vehicles has been developed from "clean sheet" designs in order to reduce dependency on legacy components and implement technology improvements wherever feasible. To reduce cost and increase reliability, SpaceX combines significant in-house manufacturing capabilities, rigorous flight-representative testing and streamlined launch operations.

SpaceX is organized with a flat hierarchy and high engineer-to-manager ratio to facilitate decision-making, rapid prototype iteration and innovation. The Falcon 1 was designed, developed and qualified in less than four years. It has since launched twice; reaching space on the second launch. Two operational launches are scheduled to occur in 2008. The first flight of the Falcon 9 is scheduled for early 2009. Figure 1 provides an overview of the current Falcon 1 and Falcon 9 configurations.

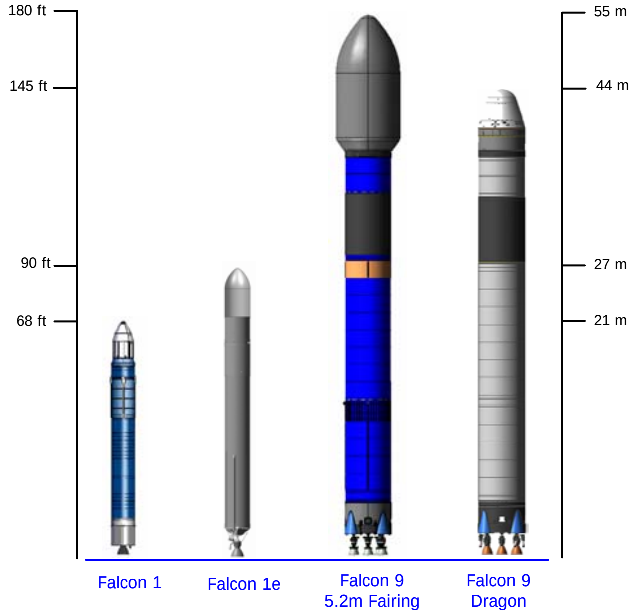

***Figure 1**. The SpaceX Falcon launch vehicle family.*

SpaceX has over 500 employees and is headquartered in southern California with a test site in Texas and launch complexes at Kwajalein, Vandenberg and Cape Canaveral.

2. FALCON 1 OVERVIEW

The Falcon 1 is designed to provide the world's lowest cost access to orbit. The vehicle is designed above all for high reliability, followed by low cost and a benign payload flight environment.

2.1. Falcon 1 Vehicle Architecture

The Falcon 1 is a two-stage, liquid oxygen (LOX) and rocket-grade kerosene (RP-1) powered launch vehicle which combines a turbopump-fed first stage powered by a SpaceX-developed Merlin engine with a pressure-fed second stage powered by a SpaceX-developed Kestrel engine.

2.1.1. First Stage

The first stage of the Falcon 1 generates 78,400 lbf (349 kN) of sea-level thrust using a single Merlin engine. The Merlin rocket engine, shown in Figure 2, was designed and developed internally at SpaceX. Like the rest of the Falcon 1, the Merlin was designed for high reliability and low cost. This was achieved by keeping the design as simple as possible and drawing on a long heritage of space-proven engines. The Merlin engine has demonstrated large margins in heat flux, mixture ratio tolerance and turbopump operating speed during ground testing, and has exceeded the performance goals set during the design phase.

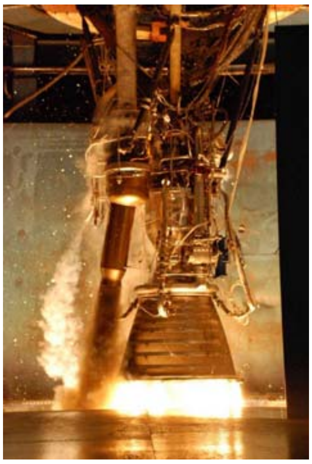

***Figure 2**. Merlin engine during test fire.*

At the heart of the Merlin engine is a low-cost pintle injector. The pintle style injector was first used in the Apollo lunar module landing engine and was chosen for the Merlin for its simplicity and robustness. The injector is resistant to acoustic instabilities, insensitive to contamination, stable over a wide range of operating conditions and has wide throttling capabilities. It is also easy and inexpensive to manufacture due to being comprised of a minimal number of parts. Propellant is fed to the engine via a single shaft, dual impeller turbopump. In order to reduce the number of subsystems in the launch vehicle, the turbopump also delivers kerosene under pressure to the hydraulic actuators used to gimbal the nozzle in pitch and yaw. This eliminates the need for a separate hydraulic power system and means that thrust vector control failure by hydraulic fluid depletion is not possible. The fuel is also used to cool the thrust chamber and nozzle. The coolant flows through hundreds of milled channels and tubes to provide cooling to the hot wall before being injected into the thrust chamber for combustion. This allows for both increased performance and reusability. Roll control during first stage flight is accomplished by gimbaling the Merlin turbopump exhaust.

The first stage of the Falcon 1 is highly mass efficient. The propellant tanks are constructed from aluminum and utilize a common dome to separate the fuel and oxidizer, minimizing mass and cost.

The tanks employ a monocoque design for mass savings and serve as the primary structure. They are structurally stable under ground loads. During flight, the tanks are pressurized to withstand the maximum flight loads. This approach provides an optimization of a fully structural-stable (but heavier) design and one that is completely dependent upon pressurization; the resulting design is operations-friendly and offers substantial weight savings. Following stage separation during flight, the first stage descends to a water landing under parachutes – for recovery, engineering evaluation and potential reuse.

2.1.2. Second Stage

The second stage of the Falcon 1 generates 7,000 lbf (31 kN) of vacuum thrust using a single Kestrel engine, which is capable of multiple on-orbit restarts. Propellant is pressure-fed to the engine via a heated helium blowdown system. Attitude control in pitch and yaw is accomplished via electro-mechanical thrust vector control (TVC) actuators; roll control and on-orbit attitude control are accomplished via cold gas helium thrusters.

The second stage is constructed from a lighter aluminum alloy for mass savings. The propellant and oxidizer tanks are separated by a common dome (similar to the design of the first stage) as shown in Figure 3.

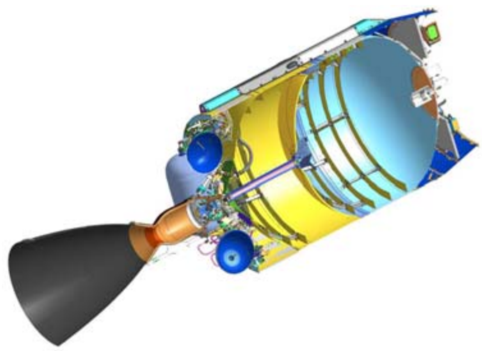

***Figure 3**. Falcon 1 second stage.*

2.2. Falcon 1 Upgrade Path

Consistent with SpaceX's corporate philosophy of rapid and continuous improvement, Falcon 1 has a planned upgrade path based upon experience from the demonstration missions. These vehicle enhancements are being implemented as block upgrades and will increase the payload capability beyond that of the original Falcon 1 configuration.

2.2.1. First Stage Upgrades

The Merlin engine employed for the first two demonstration flights of the Falcon 1 utilized an ablatively-cooled thrust chamber and nozzle. To increase reliability and allow for reuse, the chamber and nozzle have been upgraded to regeneratively-cooled designs. Because it is able to operate at higher temperatures and pressures, the regeneratively-cooled (Merlin 1C) design provides a greater level of thrust, as shown in Figure 4.

Parameter	Merlin 1A	Merlin 1C	
	Falcon 1 (Demo flights)	Falcon 1 (Interim upgrade)	Falcon 1e & Falcon 9
Sea Level Thrust (lbf)	73,000	78,400	95,000
Vacuum Thrust (lbf)	83,000	88,700	108,500
Chamber Pressure (psia)	782	825	982
Nozzle Expansion Ratio	14.5	14.5	14.5
Isp Vacuum (sec)	288.5	302.5	304.8

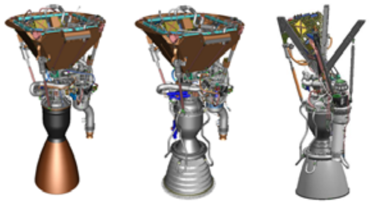

Figure 4*. Merlin engine upgrade path.*

The full thrust of the Merlin 1C engine exceeds the structural margins of the existing Falcon 1 first stage tank design, which was originally qualified based on the lower thrust of the ablatively-cooled engine. In addition, when operating at full thrust, the Merlin 1C requires an increased propellant flow rate – and thus a greater volume of propellant. Therefore, the first stage tank structure will be redesigned and qualified to meet the increased load requirements and propellant needs of the Merlin 1C engine. This full block upgrade, called the Falcon 1e (for *enhanced*) will be available beginning in the second quarter of 2010. However, as an interim upgrade, the Merlin 1C will be flown at a reduced thrust level (within the current first stage structural limits) for operational launches through early 2010.

2.2.2. Second Stage Upgrades

To address the control anomaly experienced during the second Falcon 1 demonstration flight, slosh baffles have been added to the second stage propellant and oxidizer tanks. Reliability improvements have been made to the Kestrel engine, which also allowed for some minor mass reductions. For the Falcon 1e, additional mass savings will be achieved by changing the second stage tank material to an aluminum-lithium alloy similar to that used on the Space Shuttle external tank.

2.2.3. Payload Fairing Upgrades

The Falcon 1 employs a bi-conic aluminum payload fairing with a maximum inner diameter of 54 in (1.4 m) and an internal height of 110 in (2.8 m). For mass savings and to provide increased payload volume, the payload fairing for the Falcon 1e will be a composite ogive with a maximum inner diameter of 61 in (1.55 m) and an internal height of 150 in (3.8 m). A dimensional comparison of the Falcon 1 and Falcon 1e payload fairings is provided in Fig. 5.

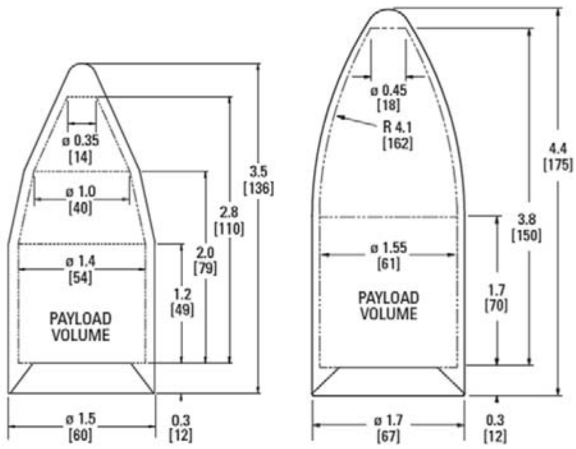

Figure 5*. Falcon 1 and Falcon 1e payload fairing dimensions.*

2.3. Falcon 1 Payload Capabilities

The Falcon 1 is capable of delivering a 925 lb (420 kg) satellite into a circular reference orbit of 185 km inclined at 9.1 degrees, as shown in Figure 6.

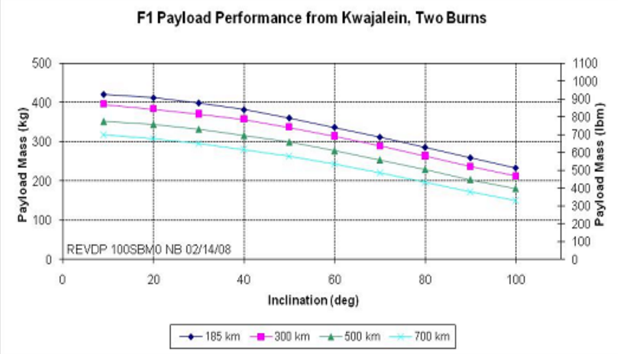

Figure 6*. Falcon 1 payload performance.*

The Falcon 1e will provide the increased payload capability shown in Figure 7, with the ability to deliver a 2,225 lb (1,010 kg) satellite into a reference orbit of 185 km inclined at 9.1 degrees.

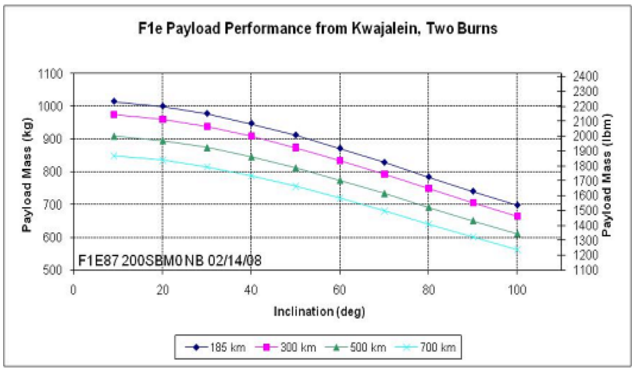

Figure 7. *Falcon 1e payload performance.*

3. FALCON 9 OVERVIEW

The Falcon 9 launch vehicle builds on the technologies and expertise developed during the design, assembly and commercial deployment of the Falcon 1. The design goal of the Falcon 9 is to produce an Evolved Expendable Launch Vehicle (EELV)–class launch capability while attaining significant improvements in reliability, cost and responsiveness over existing vehicles. Design philosophies employed during the development of the Falcon 1 launch vehicle are being similarly employed for Falcon 9. These include simplicity of architecture and the elimination or minimization of failure modes. The Falcon 9 is designed for robustness and high launch availability to enable flexible manifests and launch schedules.

3.1. Falcon 9 Vehicle Architecture

The Falcon 9 is designed to be a fully reusable, two-stage launch vehicle; powered by SpaceX-developed Merlin engines. It is the only launch vehicle in its class with first stage engine-out capability. The Falcon 9 is also designed to meet human-rated safety requirements and to launch Dragon, SpaceX's cargo and crew capsule. Overall specifications of the Falcon 9 are given in Table 1.

Table 1. *Specifications of the Falcon 9 launch vehicle.*

Falcon 9 Specifications (Block 1)	
Length	180 ft (55 m)
Width	12 ft (3.6 m)
Mass	716,000 lb (325,000 kg)
Thrust at Liftoff	855,000 lbf (3.8 MN)

3.1.1. First Stage

The Falcon 9 first stage generates 855,000 lbf (3.8 MN) of sea-level thrust using nine Merlin engines. The engines are arranged in a 3x3 grid pattern, as shown in Figure 8; the vehicle is controlled by gimbaling the engines. An aluminum thrust frame provides mounting points for the nine Merlin engines and a load path from the engines to a composite thrust skirt constructed of carbon fiber face sheets with an aluminum honeycomb core, which transfers loads from the thrust frame to the tank walls.

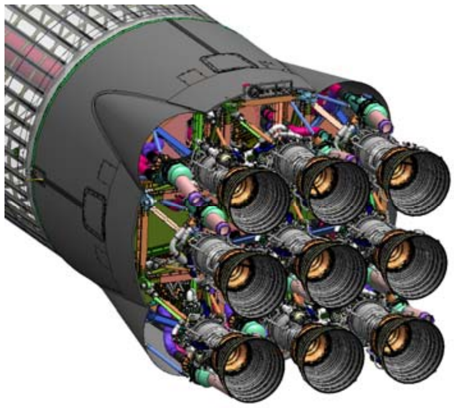

Figure 8. *Aft view of Falcon 9 first stage engine configuration.*

The first stage of the Falcon 9 is comprised of aluminum-lithium propellant tanks, the previously mentioned composite thrust skirt and aluminum thrust frame, and the engines. The tanks are constructed from an aluminum-lithium alloy that is lighter in weight than traditional aluminum while providing improved stiffness. A common dome is used to separate the fuel and oxidizer tanks, minimizing mass and cost. The tanks are produced using friction stir welding, which creates a high-quality, repeatable weld. The tanks employ a combination of monocoque and skin-and-stringer design and are used as primary load-bearing structure.

The Falcon 9 launch vehicle is designed for a 5g acceleration during flight. The typical mission profile includes limiting acceleration to the 5g maximum by shutting off two engines late in the first stage burn, leaving seven engines burning until MECO (main engine cut-off). The Falcon 9 thrust-to-weight ratio is sufficiently high that the vehicle is able to lose a single engine throughout most of the first stage burn, and multiple engines later in the burn.

Following stage separation, the first stage and attached interstage descend to a water landing under parachutes for recovery, engineering evaluation and reuse.

3.1.2. Second Stage

The Falcon 9 second stage uses a vacuum-rated Merlin engine, which provides 96,000 lbf (427 kN) of vacuum thrust and is capable of multiple on-orbit restarts. It is nearly identical to the first stage Merlin engines, except for a larger niobium alloy nozzle extension with an expansion ratio of 117:1 for optimal vacuum performance. Roll control is provided by vectoring the turbine exhaust gases through a gimbaled roll nozzle. The Merlin engine also provides throttling capability from 60 to 100 percent, which allows for both reduced payload acceleration as well as a more precise orbit injection.

The second stage tank, shown in Figure 9, is simply a shorter version of the first stage tank. By using a common architecture and materials, much of the same tooling and processes can be used; resulting in both cost savings and manufacturing and operational efficiencies. The second stage is designed to survive reentry and descend via parachute to a water landing for recovery. As a result, nearly the entire total mass of the Falcon 9 vehicle can be reused.

Figure 10. *The Dragon cargo and crew capsule.*

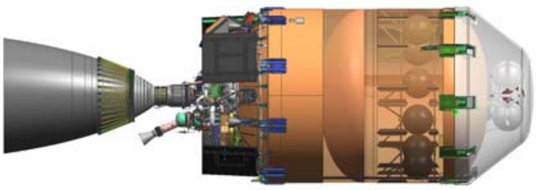

Figure 9. *Falcon 9 second stage.*

3.2. Falcon 9 Payload Capabilities

The Falcon 9 is available in two payload configurations. The first configuration uses a 17 ft (5.2 m) diameter payload fairing. The fairing is of composite construction consisting of carbon fiber face sheets with an aluminum honeycomb core. In the payload fairing configuration, the Falcon 9 is able to deliver approximately 22,000 lb (10,000 kg) to low Earth orbit (LEO) or 7,700 lb (3,500 kg) to a 28.5 degree inclined geostationary transfer orbit (GTO) from the SpaceX launch site at Cape Canaveral.

The second configuration replaces the fairing with the Dragon capsule – SpaceX's cargo and crew vehicle, shown in Figure 10. In the Dragon configuration, the Falcon 9 is capable of delivering 5,500 lb (2,500 kg) of cargo or 7 crew members to LEO. The Dragon capsule will initially be used for transport to and from the International Space Station for NASA COTS (Commercial Orbital Transportation Services) missions, but will also be offered for future use by non-ISS related commercial customers.

4. RELIABILITY AND COST

The Falcon launch vehicles have been designed to provide dramatically lower cost access to space. However, the price reductions do not come at the expense of reliability. SpaceX has pursued reliability and reduced cost hand-in-hand, and has often found the two are inextricably linked in that the lower cost, simpler choice is often the most reliable.

4.1. Reliability

Reliability has been built into the Falcon designs from the beginning. The engines, structural design, avionics and software, and launch operations concept – though slightly modified for Falcon 9, have already been proven on the Falcon 1. The Falcon 9 also has the advantage, from a reliability perspective, of having to meet human-rating requirements. The result is that safety margins for the vehicle are as high as or higher than other launch vehicles in its class. For example, portions of the Falcon 9 primary structure are designed to the NASA standard that requires a factor of safety of 1.40, instead of the traditional 1.25. In addition, the Falcon 9 design will be required to pass NASA safety reviews, arguably the most stringent in the world.

Prior to any Falcon launch vehicle leaving the launch pad, it is held down for a few seconds at full operational thrust in order to monitor the health of each engine. Due to the liquid propellant design, the launch can be terminated after ignition if any anomalies are detected.

Additionally, the large number of Merlin engines used (one for each Falcon 1 and a total of ten on each Falcon 9) coupled with the high launch rates of both vehicles means that an enormous quantity of engine firing data is able to be accumulated quickly. This allows engines which are "out-of-family" to be identified easily during ground testing and removed. Throughout the vehicle and across the company there are many other reliability improvements. The elimination of failure modes is a key design philosophy of the Falcon vehicles. Where possible, entire subsystems are eliminated (for example, there is not a separate hydraulic system for thrust vector control). Architecturally, having only two stages improves reliability by reducing the number of separation events, which have historically contributed to higher failure rates. Organizationally, SpaceX has developed a culture of quality and has implemented a rigorous quality assurance process and exhaustive test programs. An independent study by the Futron Corporation [Ref 1] concluded that the Falcon has the highest design reliability of any American launch vehicle family, as illustrated in Figure 11.

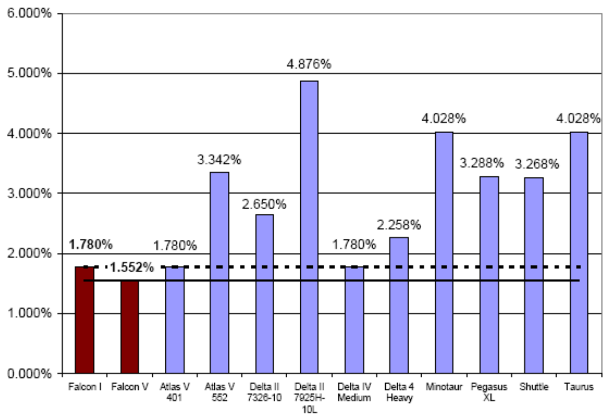

***Figure 11**. Expected failure rates due to all causes based on the historical average subsystem failure. [1]**

*Note: Falcon 9 replaces Falcon V, and has four additional engines; two of which are shut down late in flight and can provide additional engine-out capability for greater reliability.

4.2. Cost

A standard Falcon 1 costs 7.9 million dollars ($US). This price provides for complete launch services including mission integration, range fees and ancillary costs. The price of complete Falcon 1e launch services is 9.1 million dollars ($US).

Configured with a 5.2 m payload fairing, complete Falcon 9 launch services cost 37 million dollars ($US). Alternatively, mission integration for a half-bay / shared flight on a Falcon 9 is priced at 25 million dollars ($US). In the Dragon configuration, complete Falcon 9 launch services start at 75 million dollars ($US).

The low cost of the Falcon launch vehicles is not the result of a single innovation, but rather many innovations and intelligent choices made throughout the vehicle design combined with a small, flat organization and the advantage of learning from past vehicle programs. Some of the many reasons SpaceX is able to achieve lower costs are highlighted below:

Systemic reasons why SpaceX is lower cost

- Same propellants used in all stages
- Lowest cost propellant possible – liquid oxygen and rocket grade kerosene
- Only two stages for standard vehicle designs
- Tank diameters allow for low cost road transportation
- Vertically integrated to control costs
- Single Texas test site with broad test capabilities and responsive local government and community
- Truly commercial company vs. government or quasi-government heritage
- Continuous examination of production costs, starting in early design concept phase – balanced with pursuit of high reliability

Engines

- The Merlin is the simplest form of pump-fed rocket engine
- The design uses a single element pintle injector, reducing manufacturing costs and complexity
- The same engine is used on the Falcon 1 first stage and Falcon 9 first and second stages, thus providing economies of scale

Structures

- The first and second stages share a common architecture; tooling costs are reduced and only one welding line is required for each vehicle
- Common bulkhead design avoids need for intertank structures
- By using a design that requires pressurization to handle flight loads, but not ground loads, the need for machined isogrid structures is avoided
- The composite structures for each vehicle are manufactured on the same tooling mandrels

Avionics

- Systems designed in the 21st century, so are not burdened with legacy electronics hardware
- Significant number of components are designed and manufactured in-house

Launch operations

- Horizontal integration, only rotates vertical on the launch pad
- Designed for fast dispatch capability
- Highly automated countdown and checkout procedures – personnel used only to observe automated functions and intervene when needed
- “Virtual control room” allows most of the launch crew to perform functions remotely and/or only participate in necessary parts of the countdown

Overhead

- Lean operation with high engineer-to-manager ratio
- Minimal bureaucracy (e.g. purchase order are typically approved in less than 1 hour)
- All employees are granted stock options – creates an “owner mentality”
- High launch rate equates to less overhead per launch

5. NEW OPPORTUNITIES FOR SATELLITE PROGRAMS

Highly reliable, low cost launch services offer considerable opportunities for small satellite programs. However, in order for satellite providers and operators to take maximum advantage of these unique opportunities, it is necessary to alter the manner in which launch services are perceived as part of the overall program plan.

5.1. Risk Reduction

Traditionally, the high cost associated with launching any type of payload into orbit has often resulted in the desire to pack as much capability as possible onto each and every satellite bus. Thus, expensive launchers have lead to a “maximum capability per spacecraft” mentality – which in turn serves to increase the cost of the satellite. Attempting to incorporate increased payload capabilities results in a greater risk of encountering technical problems, which can require yet more funding (and/or program delays) to solve. Further, higher overall hardware costs lead to higher insurance premiums, resulting in the need for a larger initial budget; which has the potential to endanger a program before it even begins.

Alternatively, low cost launch vehicles can actually be viewed as a satellite program enabler, rather than simply one of the program’s most substantial budget line items. The significantly lower costs of the Falcon 1 and the Falcon 9, as compared with other similar-class launch vehicles, allow for considerable reductions in technical, schedule and financial risks. Because launches on Falcon vehicles consume a significantly smaller portion of a satellite program’s budget, additional resources are made available to address technical development and schedule issues, as described in Table 2.

***Table 2**. Satellite program risk reduction opportunities provided by low cost launch services.*

Program Management Area	Risk Reduction Opportunities
Financial	• Smaller budgets provide a greater chance of program approval • Money that would otherwise be devoted to the launch vehicle may be applied to other areas
Technical	• Procurement of additional hardware components • Distribution of payload capabilities between multiple spacecraft and/or launches
Schedule	• Pursue multiple technical solutions simultaneously

Additionally, as multiple launches are possible for less than what a single launch has traditionally cost, technical and schedule risk can be further reduced through the procurement of complete additional payload hardware sets – to provide increased on-orbit coverage/capability or to rapidly replace the original in the event of a launch or on-orbit failure.

5.2. Secondary Payloads as Primaries

For small satellites which would otherwise fly as secondary payloads, the Falcon 1 provides the opportunity to fly as a primary for less money than it might cost to fly as a secondary on someone else’s mission. This in turn results in a decreased risk of primary-related delays, due to fewer technical integration considerations and the elimination of the possibility for requirements conflicts.

A unique business case opportunity provided by the Falcon 1 is that of “dedicated secondary missions”, where multiple small satellites which would otherwise compete for secondary slots on a space-available basis are flown together as the primary mission. Such missions could involve payloads from either a single customer which procures the entire launch, or multiple providers. In the latter case, SpaceX is continually seeking partnerships with companies interested in fulfilling the role of “manifest agent” – to buy and re-sell the available payload mass and volume, select and integrate small/secondary satellites with compatible orbit requirements and develop suitable multi-payload adapters, as necessary.

For larger satellites, the Falcon 9 provides a similar opportunity to fly as a primary payload for less than it might cost to fly as a secondary on many other comparable launch vehicles. Alternatively, further reduced costs are possible with co-manifest/half-bay scenarios utilizing a standardized multi-payload adapter under development by SpaceX.

5.3. On-Orbit Hardware Demonstration

Finally, the Falcon 9 Dragon configuration provides a unique, economical opportunity for on-orbit technology demonstration of components requiring either a pressurized or unpressurized environment. Due to the extended on-orbit lifetime of the Dragon capsule, such scenarios provide for weeks to months of microgravity and/or space environment testing, versus durations on the order of only a few minutes typically provided by suborbital flights. Additionally, since the Dragon capsule is designed for re-entry and recovery, it is also possible to retrieve the flight hardware for evaluation or re-use.

6. CONCLUSION

The significantly lower cost of the Falcon family of launch vehicles, as compared to similar-class vehicles, will redefine the satellite launch market. Highly reliable, low cost launch services present a number of new business case opportunities – and allow for a paradigm shift in how the satellite industry thinks about launch services.

A current manifest for Falcon 1 and Falcon 9 launches is shown in Table 3.

***Table 3**. SpaceX launch manifest.*

Customer	Launch	Vehicle	Launch Site
DARPA Demo 1*	Q1 2006	Falcon 1	Kwajalein
DARPA Demo 2*	Q1 2007	Falcon 1	Kwajalein
ORS and ATSB*	Q2 2008	Falcon 1	Kwajalein
Flight 4	Q3 2008	Falcon 1	Kwajalein
US Government	Q4 2008 [t]	Falcon 9	Cape Canaveral
ATSB (Malaysia)	Q1 2009	Falcon 1	Kwajalein
MDA (Canada)	2009	Falcon 9	Cape Canaveral
Avanti (UK)	2009	Falcon 9	Cape Canaveral
NASA	2009	Falcon 9	Cape Canaveral
NASA	2009	Falcon 9	Cape Canaveral
SpaceDev (US)	2009	Falcon 1	Kwajalein
NASA	2010	Falcon 9	Cape Canaveral
MDA (Canada)	2010	Falcon 1	Kwajalein
SSC (Sweden)	2010	Falcon 1	Kwajalein
Bigelow (US)	2011	Falcon 9	Cape Canaveral

* completed

[t] hardware at launch site

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1. *Design Reliability Comparison for SpaceX Falcon Vehicles*, 2004. http://www.spacex.com/FutronDesignReliability.pdf