Launch Propulsion

Technology Assessment

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Executive Summary

Our initial project was researching innovation in rocket propulsion; we intentionally made it vague so that we could explore different areas and decide, based on the results of that research, what to focus on. Looking into methods of both launch propulsion and space propulsion, we learned that launch propulsion seemed to have most of its innovation on the business side, whereas space propulsion had more technological innovations; we decided to focus on launch propulsion.

Next we researched the current and alternative fuels and launch mechanisms (i.e. liquid/solid rockets vs. nuclear rockets, rail guns, etc.). We discovered some alternatives could potentially be disruptive, but are far too theoretical, complicated, and expensive for them to really be worth considering – especially given that traditional fuels/launch methods are very reliable and well tested (level 9 on the NASA Technology Readiness Level- Actual system 'flight proven' through successful mission operations). For example, nuclear thermal rockets are at a readiness level of 6 (System model or prototype demonstration in a relevant environment), and beam-powered drives and space elevators are at 3 (Analytical and experimental critical function and/or characteristic proof of concept).

We conducted several interviews, the most important of which were with Gwynne Shotwell, President of SpaceX, and those gained from our tour of the Air Force Research Laboratory at Edwards Air Force Base. From Ms. Shotwell we learned about small innovations that SpaceX is making in rocket engine design and implementation – she confirmed that most of the technological innovation comes in small steps that all add together, in addition to their Falcon 9 rocket harkening back to the Apollo days with a setup similar to a Saturn 5, but that there were much bigger steps in innovation on the business side. We also learned, quite surprisingly, that

SpaceX currently sees most of its competition from international companies rather than domestic (since the big "competitors" in the US cater almost solely to the government), and that she hopes to see SpaceX evenly serving US government, domestic commercial, and international evenly. Meanwhile, the AFRL focuses on conducting research, looking to understand the physics behind the very basic components of rocket engines – the effects of acoustic waves on mixing, injectors, and even radical new self-igniting propellants that may eventually be used if they can find some that are not toxic. The AFRL also conducts tests for other companies, and sometimes develops tech that they sell to manufacturers to produce so the Air Force can buy it back, but is primarily a research institute. Seeing the contrast between the "science" of AFRL and the "engineering" of SpaceX was very enlightening.

Ultimately, we concluded that we must look at innovation in rocket launch propulsion from two different angles – that of business, and that of technology. Technologically, we are seeing small steps in innovation as opposed to giant leaps, similar to what is seen in the automotive and airline industries. But private companies like SpaceX are renovating the business side (not so with government companies, since bureaucracy slows change as a whole and, as they currently hold a monopoly on their only customer's business they have little incentive to change until private companies start to disrupt that monopoly). They utilize their reliable technology in novel or rediscovered ways while making their rockets much more cost efficient, which is what will eventually change the face of the market.

Description of Technology

Solid-fuel Rockets

A solid-fuel rocket is a rocket with a motor that uses solid propellants. The propellant needs to burn very quickly but does not explode. All rockets used some form of solid or powdered propellant up until the 20th century, when liquid rockets and hybrid rockets offered more efficient and controllable alternatives. Solid rockets are still used today in model rockets, and on larger applications for their simplicity and reliability. In a Space Shuttle Solid Rocket Booster containing over a million pounds of fuel, the burn lasts about two minutes.

Advantages:

- Simplicity
- Low cost
- Safety

Disadvantages:

- Thrust cannot be controlled.
- Once ignited, the engine cannot be stopped or restarted.

Liquid Fuel Rockets

In most liquid-propellant rocket engines, a fuel and an oxidizer (for example, gasoline and liquid oxygen) are pumped into a combustion chamber. There they burn to create a high-pressure and high-velocity stream of hot gases. These gases flow through a nozzle that accelerates them further (5,000 to 10,000 mph exit velocities being typical), and then they leave the engine.

All kinds of fuel combinations get used in liquid propellant rocket engines.

- Liquid hydrogen and liquid oxygen - used in the Space Shuttle main engines
- Gasoline and liquid oxygen - used in Goddard's early rockets
- Kerosene and liquid oxygen - used on the first stage of the large Saturn V boosters in the Apollo program
- Alcohol and liquid oxygen - used in the German V2 rockets

Advantages:

- Liquid propellant rockets are the most powerful (in terms gross thrust) propulsion systems available
- They are also among the most variable, that is to say, adjustable given a large array of valves and regulators to control and augment rocket performance

Disadvantages:

- Liquid propellant rockets intricate and complex requiring thousands of piping connections carrying various cooling, fueling, or lubricating fluids
- Given the many parts, the chance of one integral function failing is large

Hybrid Rockets

A hybrid rocket propulsion system comprises propellants of two different states of matter, the most common configuration being a rocket engine composed of a solid propellant lining a combustion chamber into which a liquid or gaseous propellant is injected so as to undergo a strong exothermic reaction to produce hot gas that is emitted through a De Laval nozzle for propulsive purposes. These systems are superior to solid propulsion systems in the respects of safety, throttling, restartability, and environmental cleanliness. Current development is directed toward discovering more efficient fuels. Since the technology is well developed already, it will continue to be used until another propulsion method can be used as reliably.

Alternatives to Solid/Liquid Propulsion

Beam-Powered Rockets

Beam-powered propulsion is a class of propulsion mechanisms that use energy beamed to the spacecraft from a remote power plant. The most common designs are rocket engines where the energy is provided by a laser beam and is used to superheat the propellant.

Method of beam-powered propulsion	Advantages	Chief Roadblocks to Adoption
Thermal propulsion	• Weight reduction • Improved performance • High specific impulse • Cheap	• Not sufficient thrust for launch
Microwave-electric propulsion	• Lightweight • high power at high conversion efficiency	• Antennas need to be very large for a significant amount of power to be captured
Laser-pushed lightsail	• Absence of fuel helps avoid extremely high mass ratios	• Possible diffraction effects can cause beam to miss sail • Antennas must be extremely precise
Magnetic sail	• Less massive than a solar sail	• Mass/thrust ratio not optimal

Railgun Rockets

A railgun is an electrically powered artillery gun that accelerates a projectile along electromagnetic rails. Particular characteristics are the lack of propellant (only the projectile and the electrical energy to launch it are required), and the ability to launch projectiles much faster than firearms technology allows.

Advantages	Chief Roadblocks to Adoption
• Generate high power • No additional weight or cost due to fuel storage	• Power supply must be able to deliver extremely large currents • Rails need to withstand large repulsive forces during shooting • Excessive heat generated by friction of projectile on rails, or by electric currents flowing through rails, decreases safety of launch • Restricted to unmanned vehicle

Space Elevators

Space elevators involve traveling along a fixed structure instead of using rocket-powered space launch. The fixed structure is most often a cable that reaches from the surface of the Earth on or near the equator, up through the level of geostationary orbit, and terminating at a counterweight well above that level.

Advantages	Chief Roadblocks to Adoption
• Cost-effective alternative for launch	• Navigational hazards • Safety precautions • Passengers need to be protected from radiation by shielding • Potential impacts by space objects such as meteoroids • Need cable to maneuver out of the way of debris

Nuclear Thermal Rockets

In a nuclear thermal rocket a working fluid, usually liquid hydrogen, is heated to a high temperature in a nuclear reactor, and then expands through a rocket nozzle to create thrust. In this kind of thermal rocket, the nuclear reactor's energy replaces the chemical energy of the propellant's reactive chemicals in a chemical rocket.

Advantages	Chief Roadblocks to Adoption
• High Efficiency • Doubles or triples payload	• Failure would result in dispersal of radioactive material • Possible failure leading to uncontrolled fission

SpaceX Innovations

SpaceX's Merlin engine currently has the highest thrust to weight of any engine ever produced; in the standard Falcon 9 rocket, 9 Merlins in a 3x3 array are operated independently in the first stage --an implementation borrowing from the Saturn V of the Apollo era. A single Merlin engine powers the second stage. On this engine, according to SpaceX President Gwynne Shotwell, there are several minor innovations that improve reliability and reduce cost. Several elements cut down on the total number of moving parts, simplifying the system (e.g. using a single shaft inducer, on powering the roll control system with exhaust gas).

The skin of the rocket is made with a simple skin and stringer (a thin strip of material, to which the skin of the craft is fastened). Competitors use an iso-grid (machining down a thick sheet of aluminum), which is strong and light but wastes a lot of material.

The separation system uses an innovative pneumatically powered clamp as opposed to the standard explosive bolts, which allows for cheaper ground testing (a simple reset compared to rebuilding), and when they launch a rocket, they keep it clamped to the pad even after ignition until they confirm everything is in the green before they let it go. Shotwell calls this in particular an "operational innovation."

Summary of Interviews

Erik Antonsson (Northrop Grumman)
3:30pm April 19, 2012
Caltech GUG 101

From Mr. Antonsson, we learned that there are two very different sides to propulsion, space and launch. Launch propulsion has very little innovation on the technical side. Companies like SpaceX are not drastically innovating rocket technology, but improving the current design to lower cost. Using the current rockets we have now, air-launched rockets place satellites into orbit. Space propulsion has been rapidly innovating and developing new methods of propulsion, such as electric, solar, and nuclear.

James Polk (JPL)
12:00pm May 3, 2012
Caltech GUG202

We learned from Professor Polk that NASA has the Commercial Crew Program. Prof. Polk gave us the names of many private companies (SpaceX, Sierra Nevada, Orbital) working on launch propulsion, which we investigated. In terms of alternative methods of launch, Prof. Polk believes that currently solid- and liquid-fuel rockets are still the best option because they are very well developed. He sees methods such as rail guns, beam power, and space elevators are “crazy” ideas. The most interesting information we learned from Professor Polk was the existence of a company called Virgin Galactic. Virgin Galactic is a company which plans to provide sub-orbital spaceflights to space tourists. This new knowledge has even lead to a new project hypothesis predicting the success of space tourism.

Rob Manning (JPL)
4:00pm May 3, 2012
Caltech GUG101

From Mr. Manning, we learned that the price of launch rockets has been increasing. Due to the air force launching fewer rockets, NASA is no longer guaranteed a low launch price from the air force. Not only does NASA have to pay for the rocket but also the infrastructure maintenance. Companies like SpaceX have been developing low-cost launches to compete with the air force.

Gwynne Shotwell (SpaceX)
10:00am May 12, 2012
Conference Call

"The original goal has always been more reliable. Cost efficiency was a secondary objective. Reliability has to be there because when Elon started the company, he wanted to develop the capability and technology that would take humans to space. I think it's innovations on the operations side, on the technology side, on the business side. We've looked at all facets of launch services company and make sure we are doing things smart from a business perspective in each one of those. We want to have good penetration in every market sector. Which we've done pretty well. We've got 11% of our missions are for international governments that should go up. About 45% is domestic and international commercial. Rest is US government. I'd really like those sectors approximately equal so that if there were to be issues in any one sector due to economic or government fluctuations, I'd like to make sure we have a stable business base."

AFRL Interviews
(Ivett Leyva, Melissa Lightfoot, Alex Schumaker, Juan Rodriguez, Jeff Wegener, Steve Chambreau, Bill Hargus)
10:00am May 16, 2012
Edwards Air Force Base: Air Force Research Laboratory

We learned that AFRL is doing research in science, not engineering. They are studying the physics of nozzles and mixing of fuels. In the Cold Flow facility (Melissa Lightfoot), the only one in the country, they test the nozzles basic mixing characteristics using laser imaging. In the Hot Fire testing (Alex Schumaker), they test combustion of nozzles, focusing on injector mixing distance, wall heat transfer, and fuels. AFRL also has an acoustics lab (Ivett Leyva, Juan Rodriguez, Jeff Wegener) where they study the way the combustion is affected by acoustic fluctuations. In addition to studying nozzle characteristics, Steve Chambreau looks into mixing two stable liquids which combust on contact without external ignition, a "chemical spark". We concluded from these interviews that AFRL is looking to the basic physics of rockets rather than engineering innovations.

Science vs. Engineering: SpaceX and AFRL

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1. Can the technology be manufactured with known manufacturing processes?

The main factor behind SpaceX's philosophy is to make rocket launches reliable (and, as a consequence of that goal, cost efficient); while they are continuing to create small innovations toward their goal of human space flight, they are clearly demonstrating that their current innovations (e.g. the pneumatic clamps) can be manufactured with known processes. SpaceX's recent mission to the ISS is evidence of this.

AFRL specializes in testing the basic principles of rocket launch technology. Some of their research, like that in ionized propellants, show that they are far from creating a non-toxic self-igniting propellant. Other testing looks into nozzle acoustics, which is in and of itself not actually creating technology but testing what already exists and (maybe) how to improve it.

2. Are the critical parameters that control the new technology's function identified?

As launches still rely on the seemingly old-fashioned solid/liquid fuel rocket propulsion system, it is safe to say that all critical parameters have been identified. That being said, AFRL is conducting research into some of these parameters (how acoustics affect mixing and so on), and SpaceX is looking into how to adjust these parameters to decrease cost while increasing reliability.

3. Are the safe operating ranges known?

We have established that current rocket launch propulsion tech is quite the tried and true method compared to anything especially innovative. However, small adjustments can be made (e.g. going back to the Saturn 5 style of independent arrayed engines) to test the boundaries of these safe operating ranges. To extend beyond this basic question, SpaceX developed an innovative method of launching their rockets – clamping them onto the pad during the initial stages of ignition until they show all systems are in the green – to prevent what could have become another Vanguard explosion. This could potentially save both time and money in exploring the boundaries of these ranges.

AFRL's work in such field as acoustics is also looking into this – seeing how chaotic the injection and mixing of fuel can become due to sound waves from the rest of the system, and how that could potentially be dealt with to make rocket engines more efficient and safer.

4. Have the failure modes been evaluated?

Solid/liquid fuel rockets are well researched, so failure modes have certainly been evaluated. Alternative fuel methods (see the above section) are overly complicated and expensive compared to these, and are still low on the technical readiness scale, so it is likely their failure modes have not been evaluated. SpaceX innovations implemented on their Falcon rockets should also have their failure modes well researched and evaluated, as they are currently using these rockets for missions.

Final Hypotheses

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a) Due to a growing number of suppliers and the constant presence of only one customer, i.e. the government, competition for military contracts will increase.

From our research, we have found that the United States government is not the only customer for rocket launches. Only 44% of SpaceX launches care for the US government. SpaceX also does launches for international governments. They are currently working with Argentina, Iran and Canada. 11% of their missions are for international governments. Also, SpaceX's largest market is domestic and international commercial launches, 45% of their missions. They work mostly with telecommunications companies such as Iridium, Orv Comm, Asia Sat, Thai Com, and SES.

b) The progress in current propulsion (solid- or liquid-fuel rockets) methods is relatively slow because the technology is well developed and fulfills current requirements in launch.

Good analogies to rocket development are airplane and gasoline car development. There is progress in the technology, but it is slow and incremental. There is no giant leap happening in solid and liquid fuel rockets. From the interviews in AFRL, we learned that they are studying the fundamental physics of rocket nozzles and rocket fuels, which will improve rockets by small steps. Also, we learned from SpaceX that they have developed minor innovations, but they add up and they end up with a very reliable vehicle architecture that they can produce and operate for substantially less price than the competitors.

c) Through current solid and liquid-fuel rockets are well developed, they are still expensive; therefore, alternative methods of propulsion are being developed, which will potentially improve cost efficiency.

We researched alternatives to solid and liquid fuel rockets, such as nuclear, rail guns, space elevators, and beam-power. However, none of these options are actually in development. Many of them are still a design concept. Therefore, we were wrong to assume that alternatives are being developed to improve cost efficiency. Most of the improvements in cost efficiency have been through operational innovations with solid and liquid fuel rockets.

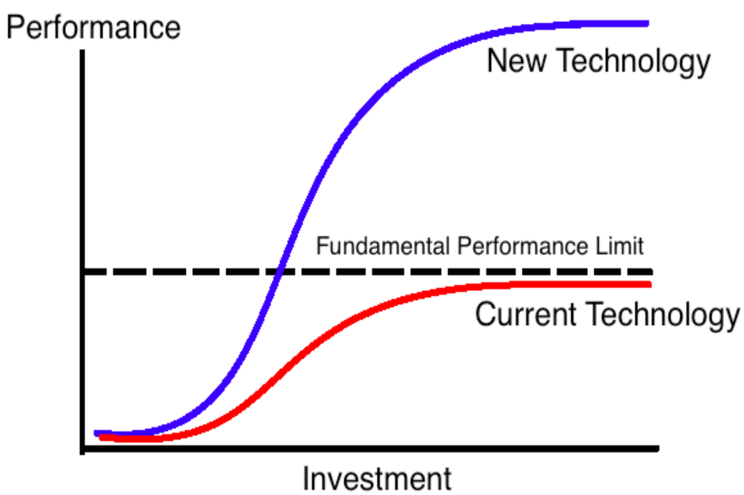
d) Due to the US government decommissioning of the space shuttle program in July 2011, thus forcing NASA to rely on the Russian space program, there is more motivation for private American companies to develop a cost-efficient way to travel to the International Space Station. Hence, there is more room for potential entrants to the market, which will undergo significant expansion.

This hypothesis was proven correct when SpaceX became the first private company to send cargo to the international space station on May 22, 2012. Also, NASA's Commercial Crew Program confirms our hypothesis. The program is intended to stimulate development of privately operated crew vehicles to low Earth orbit.

e) Space tourism remains a future endeavor. However, it can only be implemented once launch propulsion becomes more economically accessible to the general public.

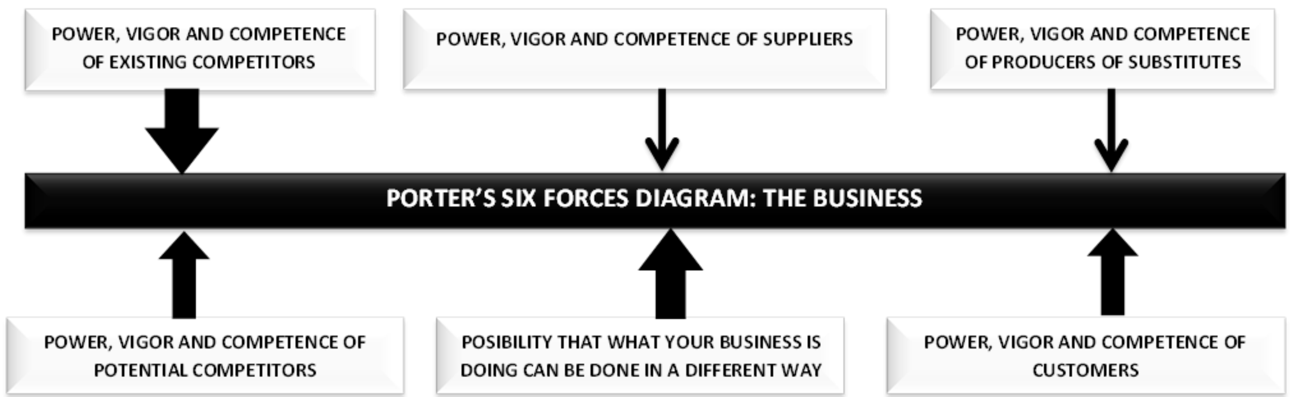
Space tourism is currently available to the wealthy through Virgin Galactic. However, their flights are only suborbital. SpaceX views this is not space tourism. Space tourism to SpaceX means traveling to a destination in outer space, not just a five-minute ride into zero-gravity, suborbital space. SpaceX is the closest to having capabilities to provide orbital human space flight on a tourist level. They believe they can have flights for tourists in low Earth orbit within ten years.

S Curve



The S-Curve figure illustrates both the evolution of a given technology, and the breakthrough event when a new, superior technology becomes viable. For a given technology, the evolution is as follows: Initial efforts result in little advancement and then the technology becomes successful. This success point, at the lower knee of the curve, is where the technology has finally demonstrated its utility. After this point significant progress and improvements are made as several embodiments are produced and the technology becomes widely established. For our project, the technology is solid and liquid propulsion methods. When it was first installed in rockets, it was a huge success because it served the purpose of defying gravity meeting market demand. Eventually, however, the physical limits of the current technology are reached, and continued efforts are resulting in little additional advancement. For solid and liquid propulsion methods, it is safe to say that the technology in use right now is at the shallow slope at the end section. To *go beyond* the limits of the S-curve for this current technology, new alternative methods must be created which will have its own S-curve. However, as we discussed previous, all the alternative methods are in the early stage of development. They are all yet to reach the steep slope portion of the S-curve.

Porter's Six Force Analysis



Porter's Six Force diagram models the launch propulsion industry as influenced by six main forces: existing competitors, suppliers, producers of substitutes, customers, potential competitors, and the possibility that alternative ways of approaching the market exist. Examining the effect each of these forces exerts on the launch propulsion business, we have reached the conclusion that the most influential market agent is existing competitors, which are typically large, well-established companies. The second most important factor that determines the development of the rocket launch business is the existence of alternative approaches to commercializing viable technologies. The fact that private companies have increasingly been entering the industry in attempts to develop innovative, cost-efficient alternatives is a proof that different perspectives on the business exist. The influence of customers comes after, since customer's choice is severely limited compared to other industries. Potential competitors are also less influential since entry barriers to the market are extremely high, and the incumbents' defense of market share would become highly aggressive if new entrants arise. Lastly, suppliers have most limited power on the launch propulsion market. The high concentration of subcontractors and large availability of substitute inputs makes them easily replaceable without significant costs.

International launch market

Commercial Launch Trends (Orbital Launches Only)
(October 2007 – September 2008)

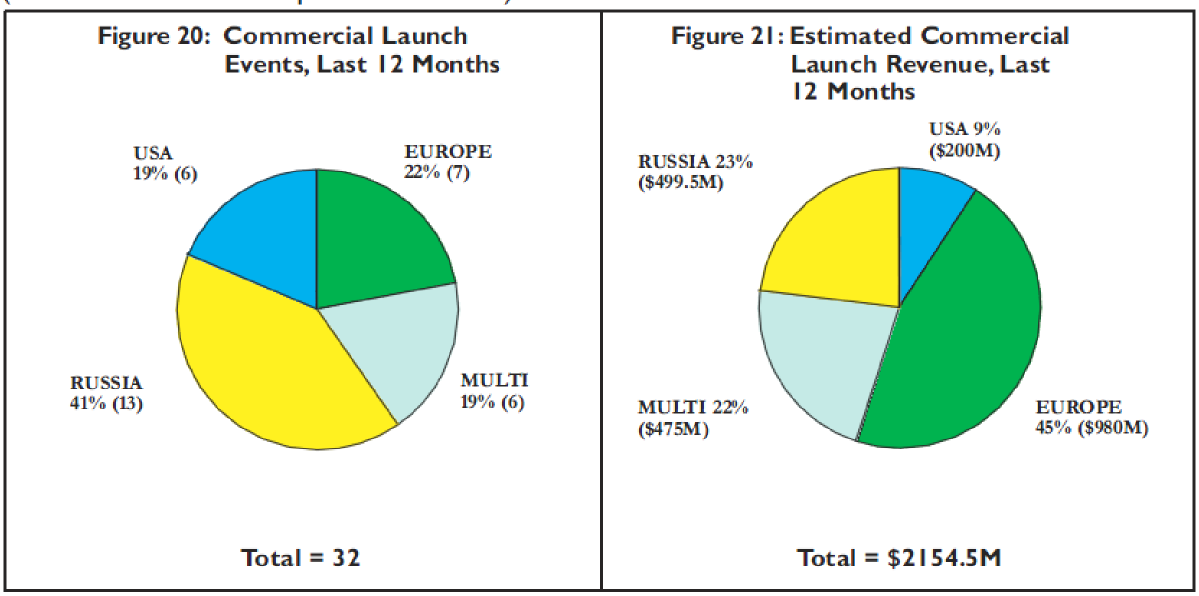
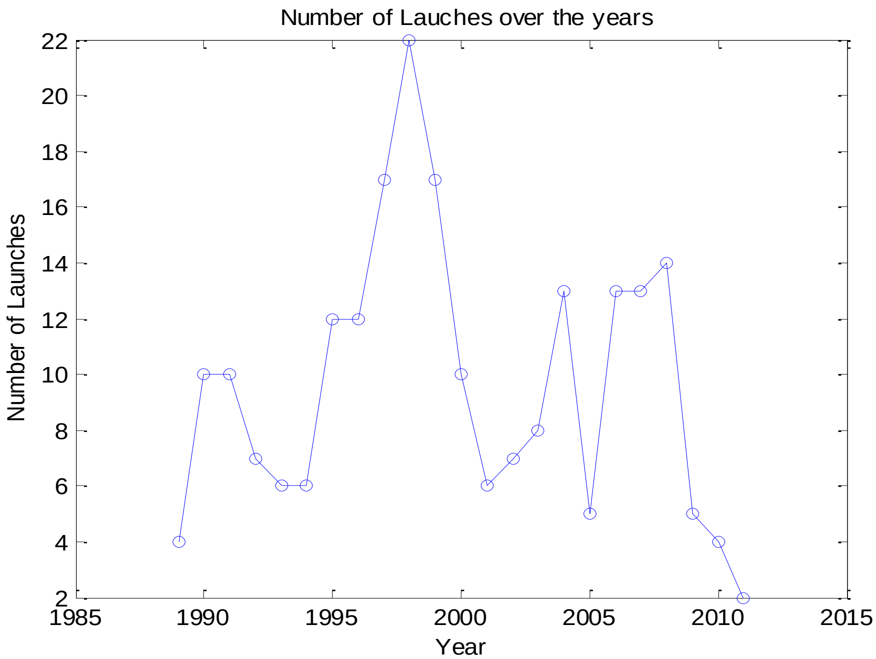


Figure 20 shows commercial orbital launch events for the period of October 2007 to September 2008 by country.

Figure 21 shows estimated commercial launch revenue for orbital launches for the period of October 2007 to September 2008 by country.

The above plot compares the number of commercial launches and the revenue generated from them for US with the rest of the world key players for the year 2007-2008. It is of immense importance here to note that the revenue generated by 6 commercial flights by US is $200 million whereas that generated by Europe for 7 commercial flights is $980. This makes $33.3 million revenue generated per flight by USA and $140 million by Europe. The reason for the revenue generated by Europe to be four times as much as USA is that European countries charge higher for each flight as the business is monopolized by certain companies. The customers paid the high price since they had no other option. Taking a closer look at USA'a launch industry, we see large fluctuations in the number of launches over the years.

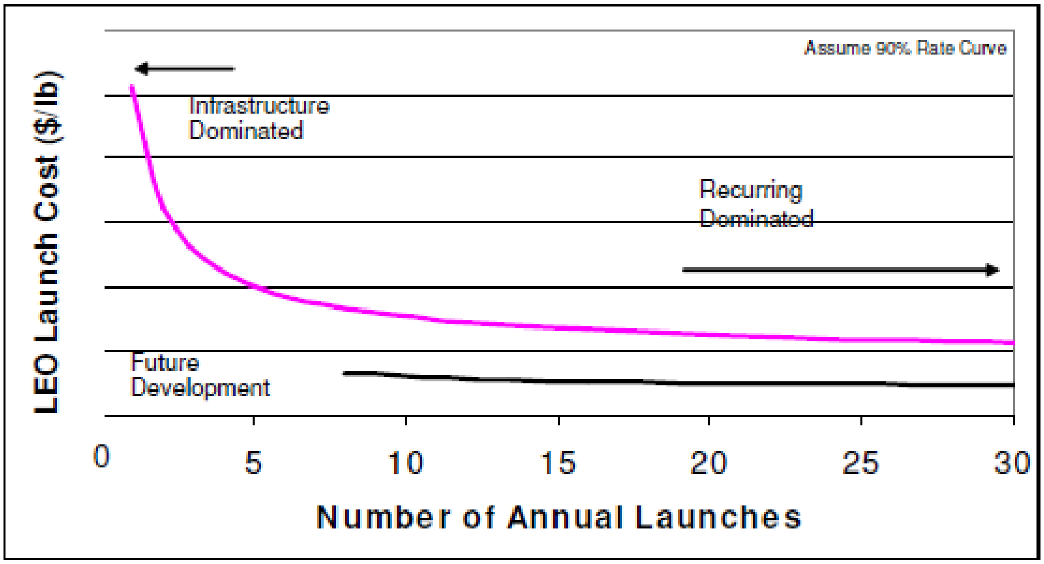
Domestic launch market



Evolution of launch propulsion technology over time

The above plot shows the number of launches starting from year 1989 to 2011. (In 2011, we had two launches and we couldn't find any data for 2012.) The number of launches in the last two decades has been fluctuating. The large variations could be explained by unstable demand and the constantly varying global political situation. Since in the past, rocket applications were primarily military and the government was the main customer, demand frequently varied according to specific political and defense needs. However, there is a decreasing general trend after 2008 and the highest number of launches has been in 1998. As the launch numbers are fluctuating, we cannot predict future launches.

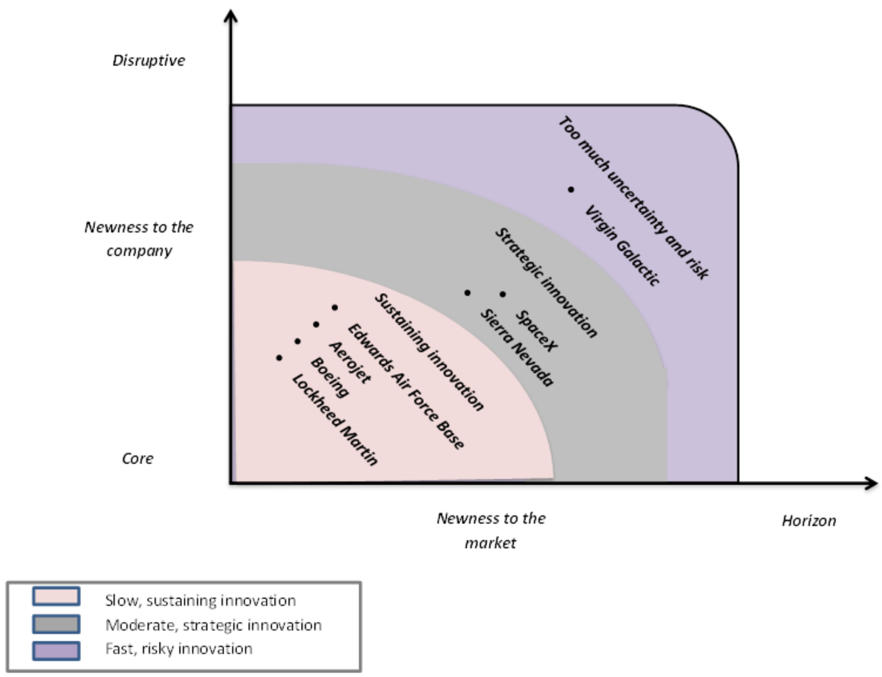
As private companies are focusing on cost reduction, the entry cost to the industry will eventually decrease. This will create an incentive for the creation of more private companies which will drive up the number of launches per year.



Due to the extremely high fixed infrastructure costs of typical launch system, rate has a very profound effect on cost of space access.

As launch rate increases fixed costs are spread over more launches and economies of scale can be realized. The launch industry is a very capital intensive business. Launching rockets requires significant infrastructure consisting of manufacture sites, integration facilities and launch sites. Similar infrastructure is required independent of launch rate. At low launch rates, the fixed infrastructure costs and the investment recuperation dominate the launch costs. The above figure illustrates the effect of rate on launch costs using representative values assuming a 90% rate cost curve. This figure shows that below ~5 launches per year the fixed costs dominate the launch cost. At rates above ~10 launches per year, vehicle costs and the ability to benefit from bulk buys of hardware tend to dominate the launch cost. Continued development may provide significant future cost reduction.

Disruptive technology?



In our attempts to evaluate whether rocket launch technology is disruptive or not, we have divided the main agents on the market in three distinctive groups. The pink-shaded area represents slow, sustaining innovation driven by specific product demands and reluctance for risky ventures. The grey-shaded area represents moderate, strategic innovation primarily driven by the need for reducing cost to performance ratio. Lastly, the purple-shaded area represents fast, risky innovation based on ideas that currently seem unrealistic, far-fetched, or overly ambitious.

Technology Projections in the Next 5-10 Years

According to our primary and secondary research findings, rocket launch technology is unlikely to change dramatically over the next decade, but rather enjoy gradual, incremental improvements. Any modification that will, for instance, result in differential increase in thrust or specific impulse, reduction of weight or improvement of fuel efficiency is desirable, but does not necessarily need to be a technology innovation; it could be a design innovation as well. The most pressing issue of the market for rocket launch propulsion is currently the need for cost-efficient solutions. There are many institutes, government-sponsored or private laboratories and companies doing research in innovative launch technology; nevertheless, conventional methods that have been used for the past several decades still prove most efficient in terms of desired performance. However, the same cannot be said about the cost of manufacturing and launch itself. Hence, the industry is in search of not so much a major breakthrough in rocket launch innovation, but rather of less costly alternative methods. The necessity to reduce cost, which in recent years has been exacerbated by the government trimming down the budged allocated for rocket manufacturing, and cutting down on sponsoring R&D in various government-funded companies, has been an incentive for many new private companies to enter the market, each of them competing on the basis of cost/performance ratio. A major portion of current launch propulsion research is thus concentrated on the major issue in the rocket launch industry: coming up with a revolutionary method for using already existing technology such that cost is significantly reduced without compromising performance. As this issue is being addressed over the next decade, an ever increasing number of private companies will have an incentive to enter the market for rocket manufacturing and launch, the private and the government sector will even out, and more commercial applications will be developed. As more competitors attempt to trim costs, rocket launch will become less costly without compromising reliability and performance. While ventures such as commercial space travel are still far-fetched, it may well be that rocket launch will be readily embraced by the commercial sector (comprised mainly of telecommunication companies) and that society becomes increasingly accustomed to commercial applications of rockets. There is a serious possibility that the government sector would “shrink” in relative terms compared to the expanding commercial sector, and private rocket launch hits not only the domestic, but also the international market. However, one should still allow enough room for surprises, as the industry is highly volatile and contingent upon certain political and economic frames.

Rewards for Developing the Technology

The main objective of developing Rocket propulsion is for scientific, security and economic interests. The most vital improvement in the rocket propulsion method would be to make it cheaper. The first advantage of that will be that the Government will have to allocate a smaller budget for launch department for the same number of flights. The second advantage is that the market for commercial launch will increase as smaller telecommunication companies will be able to afford launches and take advantage of it. As the market will be increased, there will be more revenue generated from these commercial launches. This decrease in cost would, also, be an incentive for start-up companies to enter the arena. During the past 20 years the promise of an expanding space launch market, driven by commercial demand, has encouraged numerous entrepreneurial entrants into the launch market. Startup companies such as Space X, Beal, Kistler, Rotan, etc. have invested hugely in their new launch Vehicles. Hence, with more companies in the market, competition will be encouraged resulting in a stronger, healthier, more robust launch industry, with reduced launch costs for all.

The development of a low cost launch system will, also, stimulate demand, enabling new uses of space (NASA, DoD and commercial) for the betterment of mankind. Science institutions will be more likely to invest in conducting experiments or data collection from outer space. One of the hindrances in expanding space exploration and utilization has been the high cost of access. Hence, reduction in the cost of space access through launch vehicle development will encourage advancement in scientific knowledge.

The next industry that will be improved with development of launch propulsion is the space tourism industry. With low cost of vehicles and launch methods, more people will be interested in visiting outer space. A developed space tourism industry will generate revenue and jobs for thousands of people.

Scenario

When we last left little Billy West he was strapped into his family's old stationwagon on his way to visit his aunt and uncle on the moon. His mother had already taken away his iGameX 30 minutes after getting on the interstate after he started firing holographic bullets at his annoying little sister. He zonked out an hour after that and didn't wake until they arrived at the space port. Billy failed at trying to sneak the giant can of caffeinated candy worms into his oversized pant pocket – the consequence of which was his mother prohibiting him from visiting Lunar DisneyLand (the happiest place not on earth, and probably the most overpriced) with his cousins. Not that Billy wanted to go, anyway. He did manage to steal his iGame back from his mother without her notice and sneak it past security, so he was happier than he thought he would be by this point. The family had arrived at the gate just as boarding had commenced, and Billy sulked as he looked out the window-paned walls at the giant spaceship8 connected to the even gianter White Knight 5, ominously humming at him. Finally he boarded, nearly choking as his mother pulled him down the walkway as he complained they were all going to die. He took his seat next to his father, who assured his wife that he would keep Billy in line. The flight attendant robot gave the standard safety speech – turning off electronic devices, fastening seatbelts, and so forth – and after rolling down the aisle attached itself to the back wall for takeoff. The lights dimmed, and Billy took out his iGame as the White Knight 5 headed for the runway.

"Billy, those things aren't allowed on board," his dad shunned.

"Come on, dad. It's not going to kill us. Great Grandpa Ray always told us about that stupid cell phone rule and how he never turned his off and nothing ever happened."

Mr. West rolled his eyes but did nothing.

“Just put it on mute. And no 3D.”

Billy conceded, and pulled up his favorite 2D FPS.

The mothership launched. The iGame took Billy’s mind off the nerve wracking tingling sensation shooting down his spine. But Billy didn’t know that his wireless port was still emitting a signal, looking for a computer to connect to. It connected to the SpaceShip8 main computer and caused an early detachment from the mothership. The ionized propellant rocket on SS8 fired to compensate and the ship managed to safely reenter low earth orbit. But the ship was off course and the navigation sensors had been misaligned. The pilots spoke to the Ground and decided it was not worth aiming for the moon the hard way, and there were no engineers on board who could fix it. So they had to return to earth, forced to land in Spain.

It was immediately discovered that Billy was to blame, and the West family was fined by the airline and sued by several passengers for a total of a million dollars.

Safe to say, Billy was grounded for life.

Null Result

Starting out with vague hypothesis and testing them through primary and secondary research, we concluded that rocket launch technology is improving incrementally rather than taking giant leaps in innovation. The current solid and liquid propulsion rockets are reliable and have sufficiently good performance, but their biggest disadvantage is cost. Current launch propulsion research is therefore focused primarily on alternative approaches to rocket design aimed at reducing cost. However, the basic operation principles have not changed radically for the past thirty years, which leads us to project that over the next decade, launch technology will continue to enjoy gradual, differential innovations rather than a major breakthrough. The industry is also looking into alternatives to solid- and liquid-fueled rockets such as space elevators, rail-gun rockets, beam-powered or nuclear thermal rockets, and trying to evaluate whether these ideas are viable. These technologies, if developed, tested in multiple cycles, and commercialized, could potentially become disruptive, but as of yet, they still remain unfeasible and far-fetched, either because of cost and reliability concerns, or because of insufficient performance.

Our primary research consisted of several interviews with companies of different background and concentration. Among them, the interview with SpaceX proved most illuminating on how companies approach innovation to launch technology and what their current short- and long-term goals are. SpaceX is the only company on the market aiming at active innovation for the sake of both cost reduction and performance improvement. On the other hand, the rest of the interviews on our list helped us test our starting hypothesis about the industry and modify them to conclude that rocket launch technology innovations will be mostly incremental in the near future.

Team Dynamics

Our team dynamics worked really well. We established clear roles and responsibilities at the beginning of the term which we rotate through depending on the assignment and people's availability and schedules. The main team roles are that of a leader, taking notes during each meeting, contacting people for interviews and putting together the assignment and presentation. Everybody took full responsibility for their roles and fulfilled them punctually. Moreover, we divided all the homework questions and every member of our team was good about doing her share well and on time. Our team members communicated candidly. Because of this, in case of disagreements we always reached a consensus. Everybody tried to explain their own point of view and at the same time keeps her mind open to anyone else's opinions. All members showed attitude of cooperation, mutual trust and openness in their relationship towards other members. We were, also, ready to offer and receive help and guidance if needed. All members gave helpful and constructive suggestions, advice and criticism and accepted suggestions and criticism for self-improvement without being offended. Another strong point of our team was our diverse backgrounds which gave all of our discussions a very broad perspective. We try to think out of the box by considering how a different culture would approach the same problem. All the team members showed up for the weekly meetings on time and worked hard towards a mutual goal of learning the subject matter and attaining the best possible grade.

Even with not many contacts in our field, we managed to get some crucial interviews with the professor's help. During the span of this class, we visited Edwards AFB. As the base was two hours' drive away and our interviews were early in the morning, we decided to stay there overnight. During that entire trip in the middle of the desert, our team members cooperated with each other and made the trip extremely productive.

APPENDIX A: Detailed Diagram Analysis

In our attempts to evaluate whether rocket launch technology is disruptive or not, we have divided the main agents on the market in three distinctive groups. The pink-shaded area represents slow, sustaining innovation driven by specific product demands and reluctance for risky ventures. Technological improvements are primarily motivated by the need for better performance and lower cost. Design and innovation management is more rigid, the market is primarily government-oriented. Examples of companies operating in this region are Edwards Air Force Base, Aerojet, Lockheed Martin, and Boeing, who are currently researching alternative less costly uses of existing launch technology. The grey-shaded area represents moderate, strategic innovation primarily driven by the need for reducing cost to performance ratio. Competition is cost-based, technological improvements aim at incremental reductions in cost. Product design is much more creative, and innovation management more flexibility and receptive to new ideas. The market is both commercial and government-oriented. Examples include SpaceX and Sierra Nevada who are researching creative, low-cost solutions to both the government and the commercial sector needs. Lastly, the purple-shaded area represents fast, risky innovation based on ideas that currently seem unrealistic, far-fetched, or overly ambitious. Out-of-the-box solutions to cost and performance issues are preferable and the market is currently emerging, with few agents and scarce competition. Virgin Galactic could be considered as a "disruptive" company since they are researching less-developed alternatives such as space elevators and space tourism.

Porter's Six Force diagram models the launch propulsion industry as influenced by six main forces: existing competitors, suppliers, producers of substitutes, customers, potential competitors, and the possibility that alternative ways of approaching the market exist.

Examining the effect each of these forces exerts on the launch propulsion business, we have reached the conclusion that the most influential market agent is existing competitors. There are relatively few competitors on the launch propulsion market, which are typically large, well-established companies, either government-sponsored or private. Product differentiation is relatively low; competitive advantages of different companies are based on cost-efficiency and performance rather than a unique, distinctive set of product features. Hence, the number of substitute providers overlaps with existing competitors, and is logically small, with no significant price differences among them. The switching cost to consumers from one competitor to another is extremely high, since rockets are products with a long development life-cycle and customers tend to be unwilling to change their current company preference. Exit barriers to the launch propulsion market are high as large costs are incurred should a company decide or be forced to seize operation.

The second most important factor that determines the development of the rocket launch business is the existence of alternative approaches to commercializing viable technologies. The fact that private companies have increasingly been entering the industry in attempts to develop innovative, cost-efficient alternatives is a proof that different perspectives on the business exist.

The third most influential market agent is customers. The customers-to-suppliers ratio is quite varying, depending on whether we refer to the commercial or the government sector, and on product application or intent. Customers tend to be relatively few, if not even reducing to a single major one – the government, when it comes to defense and military applications, whereas the commercial sector, comprised mainly of telecommunication companies, has a much larger customer base. What reduced the influence of customers on the business is their restricted use of multiple resources: there are a certain number of companies doing rocket manufacturing, testing and launch, and the customer's choice is severely limited compared to other industries. At the same time, the importance of the product to the buyer is crucial and is a significant investment of time, human or physical capital, and funds. This combination of conflicting factors places customers towards the bottom of the influence scale.

Potential competitors are less influential since the barriers to entry are extremely high. Significant initial capital is required to start off and economies of scale are difficult to achieve, given the slow incremental growth of the industry. Earning customer trust and loyalty is a lengthy process, and consumers' switching costs are also non-negligible. Testing the company's products on the market could also be a slow process due to the extensive product life-cycle. Capturing market share is difficult given the power of existing competitors, and government contracts would not be so easy to attract for a newly-created company. Moreover, the incumbents' defense of their market share would be highly aggressive and vigorous if potential competitors arise.

Suppliers have very limited power on the launch propulsion market, since there is high concentration of subcontractors and large availability of substitute inputs. Suppliers are very important as a whole, but individuals are not unique and could easily be replaced. The switching cost from one supplier to another is low, but the importance of the industry to the suppliers is high: hence, a rocket launch company could easily afford to change its subcontractors, while suppliers are always facing the threat of forward integration.

APPENDIX B: Detailed Interviews

Erik Antonsson (Northrop Grumman)

3:30pm April 19, 2012
Caltech GUG 101

Where do you think the rocket propulsion industry is heading?

Launch propulsion:

- Little innovation on technical side
- Some change in the economic prospect (spacex)
- Competitive business

Boeing/Lockheed:

- Don't want to do it, but gov made deal to always give them profit
- No incentive to be innovative

SpaceX:

- To make launches cheaper than united launch alliance
- smaller private company, trying to get into market
- Using medium sized rockets in arrays for thrust
- Little technological innovation
- Being smart about using what we already have
- 'Stole' people from Northrop Space Park, b/c they stopped propulsion?

Northrop: in air deployment

- Bring thingy up to commercial airspace height and launch in mid air
- Bigger planes
- Overcome earth's gravity with airplane
- Need less fuel on the rocket
- 'launch operation' innovation

In-Space propulsion:

More technological innovation

Electric propulsion:

- Boeing had something (all electric satellite)
- People already have solar panels on it
- Some telescope (JWST, northrop) uses electric to avoid pollutants

James Polk (JPL)

12:00pm May 3, 2012
Caltech GUG202

What can you tell us about current research in launch propulsion?

Private industry: developing own engines, using existing technology

SpaceX: Falcon program

Government shuttle replacement: SLS

- for launch, not too many options, need thrust
- things like electric are low thrust and need to operate in a vacuum
- crazy concepts:
- beamed power systems
- rail guns:
- decouples energy source from vehicle, more energy per unit mass, higher velocities
- NASA- kevin, grad 5-6 years ago. Caltech aero grad student, fred Culick advisor, rail gun

Are there any other companies working on launch?

- Orbital, SpaceX, Lockheed martin, Sierra Nevada
- some star-ups (3 or 4)
- Commercial Crew Program (NASA program to use commercial launch)
- Virgin Galactic: space tourism

What is the current market for launch propulsion like?

- liquid rocket engines are already pretty good
- for launch, not too many options, need thrust
- things like electric are low thrust and need to operate in a vaccum

How practical is space tourism?

- virgin, sub orbital flight
- almost ready, have customers lined up already
- tourists into orbit, that will take some time
- people have paid $20mil

What about the economic side? Worth it to invest?

- government is willing, shuttle replacement
- international market
- the money is there
- doesn't know too much about the economic side

What do you think is the future of launch propulsion in US?

- will never give up on launch
- never give up on robotic exploration
- media: "giving up on human space flight" because of canceling shuttle program. but I don't think people will give up human space flight because other countries are trying.
- other countries are trying harder than the US. china definitely. Russian is up and down. china will be big player

In US, who do you think the big players are: government or commercial?

- NASA buy commercial, NASA and concentrate on new technologies
- launch is mature industry
- not a lot of new technology, big liquid engines are pretty good
- not a lot of ideas about how to reduce the cost
- SpaceX has done a lot of innovative things in productions to reduce the cost, so theirs are relatively cheap
- NASA used to have a things to try to get a single stage into orbit, but didn't work
- needs some kind of a break through to get a dramatic reduction in price to happen
- maybe the skeptical things like beam will work?
- then will see a lot more commercial, like manufacturing and tourism

Do you have any contacts that may help us?

- ask Fred Culick

Rob Manning (JPL)

4:00pm May 3, 2012
Caltech GUG101

Cost of rockets:

- 60mil to 210mil? (Mariya says 16 to 20mil)
- Because the air force is not making as many rockets anymore.
- They don't need them as much
- Contract over between NASA and air force which guaranteed prices
- Less demand, infrastructure cost still there
- NASA has to pay for rocket and the infrastructure maintenance cost

SpaceX

- Ball clamps:
  Makes testing much cheaper
  Normally, the used stages of the rocket are separated using explosions
  SpaceX is using ball clamps, so that parts are not damaged during testing and can be reused again and again.

Smart design that is cheap.
Innovation is mostly done for lower cost

Gwynne Shotwell (President of SpaceX)

10am Saturday, May 12, 2012
Conference Call

We know you have an upcoming launch in just a couple days; we are wondering what type of launch technology that is innovative that's flying on the Falcon 9?

You know, I think there's no, as far as the Falcon 9 vehicle, I don't think there's any one particular blazing technology. The engine is probably the greatest step forward. It's an upgrade. The Merlin engine will be the highest thrust to weight engine ever produced. For a LOX-RP system it's pretty great. The majority of the technology is in the engine. On the other hand, we've got a pretty innovative way of creating a stiff but light structure. Our competitors use iso-grid where you machine down a very thick plate of aluminum. You machine it with ribs in it. It's strong and it's light. Frankly, it wastes a lot of metal in the process. You machine away a lot. So we just use a simple skin and stringer configuration. It's not particularly rocket science but a straightforward way to have an even lighter and stiffer structure and not waste resources.

You mentioned that there are big innovations in the engine. When you mean engine, as in the rockets itself?

It's called a Merlin. There are nine of them on the first stage ganged together. There's one on the second stage. That particular architecture is somewhat innovative. It hasn't been done since Saturn. The Saturn 1 and Saturn 5 have multiple engines on the back end in a configuration where you could actually loose an engine and still make mission. The Soyuz flies with, I believe, 28 thrust chambers, but they're not necessarily independent, meaning you can't lose one of them and still make mission. It's innovative in that it was a great architectural concept brought out in the 60's but no one's used it since and we've picked it up.

From our secondary research, and from what've told us, you've come up with a cheaper way to build your structures. And also we've heard that you came up with an innovative ball clamp that lowers the price of testing. It this true?

Are you talking about the separation system? It's a pneumatically powered system, which means it's resettable on the ground, so we don't us squibs or EED, explosive devices, to pop the system. Which means you can do the testing on the ground all you want because it's really just press the gas that drives it. They are minor innovations, but they add up and you end up with a very reliable vehicle architecture that we can produce and operate for substantially less price than the competitors.

Can you describe any other kind of small innovations that add up to a more reliable system?

To go back to the engine, it's a single shaft impeller inducer as opposed. Both the LOX and the RP, so that almost cut down by a factor of two on the moving parts in the engine. We leverage the exhaust gas from the gas generator to power the roll control system. Again, that's a small innovation that eliminates the need for additional parts and subsystems. We do tap a line off the pressurized RP from the pump to drive the thrust vector control system. We don't have a separate hydraulic section on the first stage to gimbal the first stage engine. That's another innovation. You can pretty much step up the rocket stage-by-stage or point-by-point and there are small innovations that drive a more reliable system. We hold down the rocket when we're operating. I've talked a little about architectural design decisions where you take an innovative approach to make the system more reliable. We took the concept of operations from aircrafts. When a pilot is ready to take off, he's at the end of the runway and he revs his engines and looks at the gauges and makes sure that everything looks right. We do the same with the rocket. We hold the rocket down on the pad, we clamp it while we light the engine for flight, and if things look good and they're trending appropriately, then we'll let it go. If they're not then we shut it down. We abort, and we figure out what went wrong. We've aborted and launched a number of times. The Falcon 1 twice and Falcon 9 once. That's an operational innovation. Not necessarily innovative in a board sense but certainly in an aerospace sense.

Everything to make it more reliable and cost efficient.

Absolutely. We're known more for low cost. Unfortunately. The key to SpaceX is to make it more reliable.

Was your original goal to make things more cost efficient?

The original goal has always been more reliable. Cost efficiency was a secondary objective. Reliability has to be there because when Elon started the company, he wanted to develop the capability and technology that would take humans to space. So you want to make sure that it's reliable or that doesn't make much of a business.

Is taking humans in space still a goal for SpaceX?

Yes, absolutely. From the beginning.

You mentioned some technologies that are already well developed that are already flying on Falcon 9. Are you working on anything that is still in the research and development area?

There's no question. We are working on a number of features to work on Falcon 9 and Falcon Heavy is in development right now. There's a lot there. Probably not a lot I'm going to want to talk about.

When you have all these different R&D projects, from the business side, how do you choose which technologies to invest in? Do you have a formal hierarchy?

No, it's really more of a best idea wins. As we're marching down the development path, if we an area that really could use some improvement, we'll go ahead and do a deep dive and determine whether that technology is worth it or not. If it's a time crunch and we still think it's worth the investment, we'll proceed down the path we originally envisioned and work off the side and see if we can't develop that technology that improves the vehicle to add in later.

Do you get a lot of ideas that just stay on paper and never make it to a prototype or any sort of testing?

I'm sure there's plenty. But I'd know if I could come up with any right now. Tons of ideas that are sitting around.

So no one makes the final call, yes or no, on the technology? It's kind of of a work together?

Depending on the level of the investment or the impact of the design decision. It could be with an engineer level all the way up to Elon. Elon all of the important design decisions.

Can you describe how involved Elon in the business and technology decisions?

He is extremely involved in both. He is fundamentally the chief designer/engineer of the company. As far as the business decisions goes, he sets strategy and it's my job to execute. He's less involved on the business side. Only because he has me. If he were to have a chief engineer, he would probably decrease some of his technical input as well. He's super involved in the technical side. And as CEO he's very involved in the business side as well.

Do you see SpaceX expanding in both government and commercial markets?

Oh yeah. We are already in both. International government, domestic government, and commercial.

Is it ok to mention a couple of your customers?

We've got a lot of manifests. NASA, the US government customer. Big customer for SpaceX. Commercial operators such as Iridium, OrvComm, Asia Sat. ThaiCom, SES. We're going to announce a new big deal for the first Falcon Heavy in the next week or so with a big commercial operator. As far as international governments go, we're working with Argentina, Iran, and Canada.

What kind of payloads are you taking up for these commercial markets?

The majority of our commercial business is telecommunications. Whether it's low earth orbit (OrvComm, Iridium) or geo operators (other customers).

What kind of competitive advantages do you have over other companies, such as Northrop, Lockheed, and Boeing?

We don't compete with Northrop. But as far as the launch vehicle side, we go strong competition in terms of internationally. Not really much competition Domestically. ULA by Boeing and Lockheed. They are cost competitive, so they barely get a commercial field. They are fundamentally a government corp. to serve the US air force and national reconnaissance. But we're working on taking that business away from them (lol).

Can you describe the international market? You say you have a lot of competitors internationally.

Co ton? Is a great launch vehicle. It does about 8 commercial launches per year. Ariane from the Ariane 5 is a fine system. It's incredibly expensive. They fly about 5 times per year for commercial. They also fly ATV almost once a year. They fly 6 times a year, maybe7 in a good year. It will compete most prominently with Falcon Heavy. Ariane 5 flies too satellites at a time, so the low earth satellites compete with Falcon 9. The upper orbit more with Falcon Heavy. Regardless, our prices on both Falcon 9 and Heavy are most less expensive.

Is it your technology that allows you to make it cheaper?

I think it's innovations on the operations side, on the technology side, on the business side. We've looked at all facets of launch services company and make sure we are doing things smart from a business perspective in each one of those. Ariane is expensive because it's a Euro government. They consider themselves commercial, but they're really not. They are more like ULA. Ariane sells for about $250mil all in flight. Whereas Atlas and Delta are about $500mil per flight. It hard to build a government system and still remain commercial. They do things so differently both in their procurement practices and the rules and regulations. Less so on the technology. Everybody assumes if it's more expensive then it more reliable. Which is garbage (lol again). If you look at cars, the most expensive cars are the least reliable. We're trying to scratch that same image on the aerospace side.

Can you explain why the American market is small, but the international market is so much more competitive?

There hasn't been a domestic competitor yet to Boeing and Lockheed. The markets are small because… nation by nation, the market is not small, US launches 10-12 satellites per year, Russian launches 4-5 in this class. It's not a small. It would be a larger market within the government is launch was cheaper. If you have a $300mil satellite and you need to put it on a 500mil launcher that's kind of stupid (lol again). Launch doesn't exist for the sake of launch. Launch exists for the sake of placing satellites in orbit and bringing data back. When your launcher exceeds the cost of your mission, you reorganize your mission and make the mission super expensive. You get this death spiral of escalation of cost. Which is why we are hampered here in the US.

Can you describe the SpaceX business model? What its goals are in the market.

We want to have good penetration in every market sector. Which we've done pretty well. We've got 11% of our missions are for international governments that should go up. About 45% is domestic and international commercial. Rest is US government. I'd really like those sectors approximately equal so that if there were to be issues in any one sector due to economic or government fluctuations, I'd like to make sure we have a stable business base.

You mentioned that SpaceX has a goal of human flight; have you ever considered space tourism?

I don't want to dis that particular market. (lol again) That's not the market we're going after right now. I think it would be very foolish to focus on a very tourist focused market before you've demonstrated sufficiently the technology. I think it would be devastating to the market and to the business if folks rushed too quickly to tourism. Just like you do dangerous things during the test phase of building an aircraft, you want to make sure you get through and prove the system is reliable before you open up the market to the public. People in space initially explore first. Then of course tourism will follow.

There are already some companies already trying to achieve space tourism such as Virgin Galactic. They do it a little differently in terms of their launch method. Do you think in the future, this is something SpaceX will look at or wait until the market has been developed before trying to cut into it?

There's a big difference between what Virgin is doing and what SpaceX is heading for. Virgin is suborbital. That is not space tourism. That's like a five-minute ride. That is not what I consider tourism. That's Disneyland. (ROFL!) The real market exists in placing destinations into orbit and sending folk there. Virgin does not have that capability; they're nowhere near that capability. SpaceX is the closest to having that capability. Orbital human space flight.

How far to you think human space flight it out in terms of years?

For demonstration and exploration, couples year. 2 or 3. As far as tourism goes, I would double that.

Really? Within ten years?

Absolutely. With low Earth orbit. Absolutely. If we're talking Mars, it's a little further off. 10 or 15 years for Mars (!!!!).

In my mind, I was thinking 20-30 years.

No, that would be sad. (Haha)

But there needs to be a market for you to pursue…

The market will develop while we are taking astronauts to space. Or while we are taking them to the ISS. And once you have a few years worth of that kind of history and heritage, then the folks will start to build the infrastructure necessary for true tourism. I'm not dissing the market at all. We need to step carefully into that market.

I was reading about your Dragon capsule and I wanted to confirm how far off are you from human testing.

We are submitting and negotiating with NASA to take this fundamentally designed for crew but currently outfitted for cargo Dragon and form that into a fully crew capable system. The only major subsystem that needs to be added is the escape system. If there were to be a problem with the rocket, you need to have an abort system to get off the rocket. We're working on that right now. A full program is in procurement process right now. We are negotiating with NASA at the end of the month for something on the order of half a billion dollars to finish that development. That would take place, crew flight, 2 years from contract award. Late 2012 for demo flight. We've been trying to make Dragon crew-capable since we've started work in 2006 on it, so it's not magic. We can't do this overnight. We've been focused on this from the beginning.

I also read that you had a NASA contract to launch another rover to Mars in 2018.

Red dragon? Right now that just kind of a concept project WE are looking at it at a very high level. And with not many resources. There is no question we are designing dragon to land on other planetary bodies.

Melissa Lightfoot (AFRL)
10:30am May 16, 2012
Edwards Air Force Base: Air Force Research Laboratory

Goal: Understand the physics of the nozzle

Cold flow facility

Gas-Centered Swirl coaxial injectors
Pressures at: 1800spi
Pressure chambers, match density ratios
Aerated spray
Only place in the country to do this
Row to tubes, mass profile

Mobile flow lab

Argonne national lab

Stephen Alex Schumaker (AFRL)
10:45am May 16, 2012
Edwards Air Force Base: Air Force Research Laboratory

Goal: Combustion "Hot fire testing"

Laboratory control engine

100's lb. thrust, higher to make measurements in the actual flame
500-800 pis chamber, low 1000psi in kerosene
Laser or camera imaging

They test three things:

injector (mixing distance), wall heat transfer, fuels

Cost of tests:

Cold flow- $15, 1-2ppl
Hot fire- $100s, 3-4 ppl

Process order:

cold flow then flame test

AFRL:

develop tech, hand out to manufactures, then buy back? Called procurement
Act as technical experts on their own tech for the manufactures

Ivett Leyva (AFRL)
11:00am May 16, 2012
Edwards Air Force Base: Air Force Research Laboratory

Goal: Test the acoustics which changes the mixing layer
Nozzels are designed to perfect mixing, but in application, nozzles are not perfect

What kind of people work here:

Rely on mechanics, plumbers, students, professional researchers
Lots of people are working together

Lab:

millions of dollars because need for accuracy
Very hard to find sensors at high pressure
Europe: facilities are the same

Research applies to what type of rockets:

Cryogenic, RS68, volcan, space shuttle main engine

Juan Rodriguez (Post Doc at AFRL)

11:15am May 16, 2012
Edwards Air Force Base: Air Force Research Laboratory

Goal: Study the atomization of the fuel in a nozzle

Physics:

Particles that are created when a liquid goes into a pressurized environment
Rocket engines reach very high pressure, where droplets no longer exists
"super critical fluid"
Play with temperature: super critical or cryogenic

Application:

one element facility, one injector
rocket engine has injector plate with many injectors

Nozzle:

coaxial jet which is standard in rocket injectors
look at heat flux, combustion instabilities, cooling effects…
the injector is one of them that we can look at
analyze the fluid mechanics of the injector, to understand the mixing of a injector

Jeff Wegener (Graduate Student at AFRL)

11:30am May 16, 2012
Edwards Air Force Base: Air Force Research Laboratory

Goal: Look at the way the combustion is affected by acoustic fluctuations

Physics:

Equations of acoustics vs equations of thermodynamics vs equations of fluids

Testing:

Test single injectors simulating liquid rocket injector
Speakers on the chamber to produce the sounds that function on psi
(really high!)
Imaging the reaction flame, we can see how the flame reacts to the pressure fluctuations
Look at different flow conditions
Use not reactive case: nitro vs nitro instead of hydro vs. oxygen (combustive)

Steve Chambreau
11:45am May 16, 2012
Edwards Air Force Base: Air Force Research Laboratory

Goal: Mix two stable liquids, you can get them to combust without external ignition when mixing "chemical spark"

Physics:

Current fuels are all molecules
Use ionic liquids instead
Less toxic, low vapor pressure, hard to put in vacuum
Ionic liquids are more like salt, very low vapor pressure
Make the ions really "big" and "greasy" so they don't have high covalent attraction
Higher isp, but low thrust, more finesse

Pros:

Can turn thruster off by turning off the injector of one or two fuels

Cons:

Two chemicals are really toxic and vaporize easily
Not safe in transportation and loading
Ignition generates a lot of heat, can decompose

Could this tech be used on something like the Virgin Galactic system?

Probably yes…

Bill Hargus
12:30am May 16, 2012
Edwards Air Force Base: Air Force Research Laboratory

Goal: electric propulsion, space craft prop

Pros:

better than chemical because you can put more energy into the propellants
lighter system, lighter thruster

Resisto-jet:

electro-thermal thruster
decrease the amount of weight by 25%

Arcjet thruster:

heats propellant via electric arc
decrease amount the weight by factor of two

Ion thruster:

Electro-static
Propellant is ionized via electron bombardment and accelerated by high voltage grids
Mercury, now xenon
Specific impulse of 10000 seconds
Thrust is prop to power/specific impulse
Less thrust proportionally

Hall Thruster Operational Principles:

Grid less electrostatic thrusters
Ions accelerated by an electric field between anode and electron cloud
Compact thruster design
Specific impulse 1800-2000 seconds

Micro Pulsed Plasma thruster:

High impedance
Convectional voltage measurements perturb charge currents

In-house micro-laser propulsion effort:

Laser plasma thruster

Solar-thermal system

Electrodynamic tether propulsion system development:

Tether 10's kilometers of length
Broke the tether

What is the innovation process?:

Ground test, modeling and simulation, fight test

Where does the money come from?:

Where there are interests, there is money
DARPA system:
program manager, crazier the idea, most likely to get funded
Small business innovative research program:
Small businesses are more nimble on their feet
National science foundation:
Sponsor universities
AFO?

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