INNOVATION IN THE DESIGN AND DEVELOPMEMT OF A COMMERCIAL FLIGHT TERMINATION SYSTEM

By

Eugene Kwak

B.S., Computer Science, State University of New York, Binghamton

M.S., Mechanical Engineering- Product Development Technology, University of Southern California

Submitted to the System Design and Management Program

In Partial Fulfillment of the Requirements for the Degree of

Master of Science in Engineering and Management

At the

Massachusetts Institute of Technology

December 2012

Signature of Author____

Eugene Kwak

System Design and Management Program

December 2012

Certified By____

Jeffrey Hoffman

Professor of the Practice of Aerospace Engineering MIT

Thesis Advisor

Accepted By____

Patrick Hale

Director- System Design and Management Program

Senior Lecturer- Engineering Systems Division

This page has been intentionally left blank

Innovation in the Design and Development of a Commercial Flight Termination System

By

Eugene Kwak

Submitted to the System Design and Management Program
In Partial Fulfillment of the Requirements for the Degree of Master of Science in Engineering and Management at the Massachusetts Institute of Technology

Abstract

With the ramp up of commercial spaceflight over the last decade with the assistance of the US Government and NASA, commercial spaceflight companies such as Space Exploration Technologies (SpaceX) and Orbital Sciences have taken significant strides in reducing the overall cost of space travel. The overall cost per launch goes far beyond the actual cost of the materials and labor associated with each launch vehicle, and must include all the political, environmental and social costs, which often amount to more than the actual cost of the vehicle itself.

The main focus of my thesis is the Flight Termination System (FTS) which is the system used to terminate the flight of the launch vehicle in the event the vehicle veers off course or experiences any anomalies, which would impede its mission and cause a threat to human assets. Because of my work as the lead engineer of the FTS system at SpaceX, this thesis will mainly cover the system used at SpaceX. The FTS system is unique in that the approval of the system is as political and social as it is technical. Systems engineering is applied throughout the process of architecting, designing, testing, and manufacturing, where all stakeholders have a part in the success of each step of the product design. The key to the success of SpaceX lies in innovation, and as this thesis outlines, the FTS system has many innovative products and processes in place, including the establishment of many key relationships with stakeholders.

This page has been intentionally left blank

Acknowledgements

I would like to take this time to thank the many people who have made this thesis possible. Dr. Jeffrey Hoffman, who serves as an inspiration to many, expressed genuine interest in working with me on my thesis and helped develop ideas which had not occurred to me before. The SDM team, especially Patrick Hale for providing me with all the resources I needed and making recommendations based on personal experiences. My cohort for pushing me to work at my absolute limit, especially in January during boot camp and job interviews.

I would also like to thank the SpaceX team with whom I had the pleasure of working with for over 5 unforgettable years and making history in the process. Finally, I would like to thank my family, friends and the Good Lord, who have sacrificed a lot of their time and resources to help me succeed in everything that I do. I owe all my success to them.

Table of Contents

The Flight Termination System -Overview

Space launches are inherently risky. However, no member of the public or launch site workforce has ever been killed (National Research Council, 2000). This is in large part due to the high reliability of the Flight Termination System used on all modern launch vehicles, ranging from the Shuttle to SpaceX's Falcon 9 launch vehicle. However, because of the rigors involved in producing a certified system, many companies tend to stay with legacy systems which are decades old, dating as far back as the Apollo missions from the 1960's. In an effort to modernize the system, there is an inherent conflict between the new technology and the requirements imposed by Range Safety to meet these requirements. Building a new system to satisfy these requirements using traditional approaches would require significant technical and financial resources. SpaceX, by employing innovative processes utilizing modern technology, was able to develop a new system while keeping the scope, schedule, and costs all within reason.

The Flight Termination System (herein known as the FTS System) is used in the event the launch vehicle either veers off course, breaks up, or heads towards a populated area, outside of its limit lines (Hadden, 2010). It is activated approximately T minus 90 minutes prior to launch at which point the system undergoes a series of tests to ensure proper functionality. It is then switched over to internal battery power during terminal count (T minus 10 minutes). The system is active throughout the course of flight from lift off until the 2nd stage cutoff as seen in Figure 1.

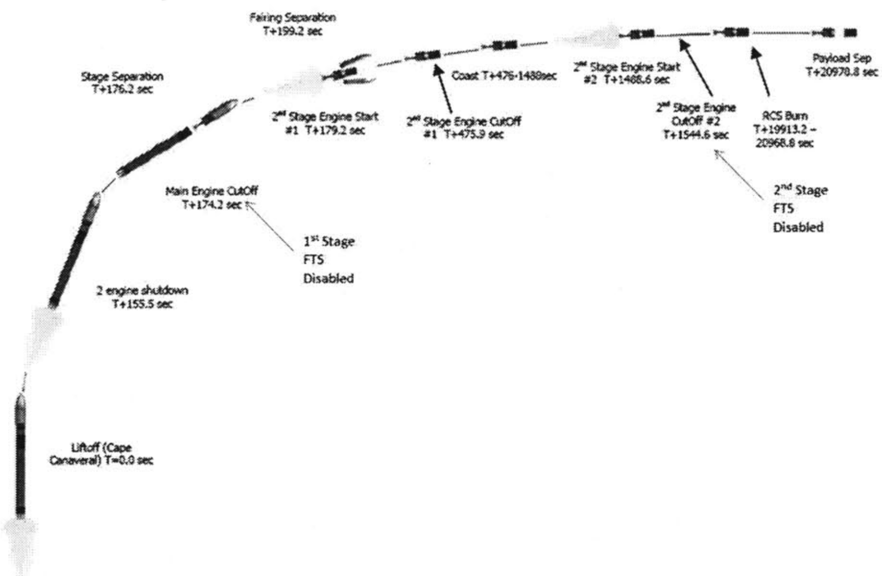

Figure 1: FTS Arming and Disarming (SpaceX, 2009)

There are 3 main subsystems to the FTS System. The **Destruct Termination System** utilizes ordnance in the form of Linear Shaped Charges (LSCs) which are initiated when a pulse from the Destruct Termination Box (DTB) receives a command from the Command Receive Decoder (CRD) to destruct the system. This initial signal is received from Range Safety during flight, if there is an anomaly which may pose a threat to human assets. This signal would be transmitted from the ground station and relayed to the UHF antenna system. The ordnance system then ruptures the fuel and LOX tanks, thereby depleting the propellant in the vehicle at a very fast rate (28ms), essentially creating a debris cloud and terminating any forward acceleration of the vehicle.

The **Thrust Termination System** shares many components with the destruct termination system. Rather than destructing the vehicle, an Arm command is sent, which closes the valves within the propulsive system. This starves the 9 Merlin engines (in the 1st stage) or 1 Merlin Vacuum (MVAC) engine in the 2nd stage of fuel, thereby terminating thrust. The choice of using thrust termination or destruct termination is based on the nature of the failure and where in flight the vehicle currently is. For example, if a vehicle fails over a large body of water or immediately off the Launchpad, the thrust terminate only option may be used. Over a populated area, the destruct option may be used since a debris cloud is deemed less of a hazard than a fully intact and fueled vehicle.

The third termination system is linked to the Destruct Termination System and is called the **Autodestruct System.** In the event the vehicle breaks apart prematurely during Maximum Dynamic Pressure (Max Q), Lanyard Pull Initiators (LPIs) are actuated, thereby initiating the explosive train, which in turn initiates the Linear Shaped Charges. At this point, the vehicle would rupture in the same way it does during standard destruct termination. Figure 2 shows a high level overview of the FTS system and its components. Figure 3 shows the listing of components associated with an FTS System. Each component must go through a series of rigorous Qualification and Acceptance tests, which tests the design and workmanship of the components respectively.

All systems utilize C band radar systems coupled with vehicle telemetry to ensure that the vehicle is on its nominal trajectory. Other innovations have been explored, including the use of GPS and Automated FTS Systems. While this new technology is promising, SpaceX has not yet fully explored these options, and therefore they will not be discussed at length in this thesis. Currently, all Arm and Destruct signals are received through UHF antennas, which are set to the same frequency and received from the ground station, operated by the Mission Flight Control Officer (MFCO). The nature of the command is based on a series of tones which either provide an Arm or Destruct command.

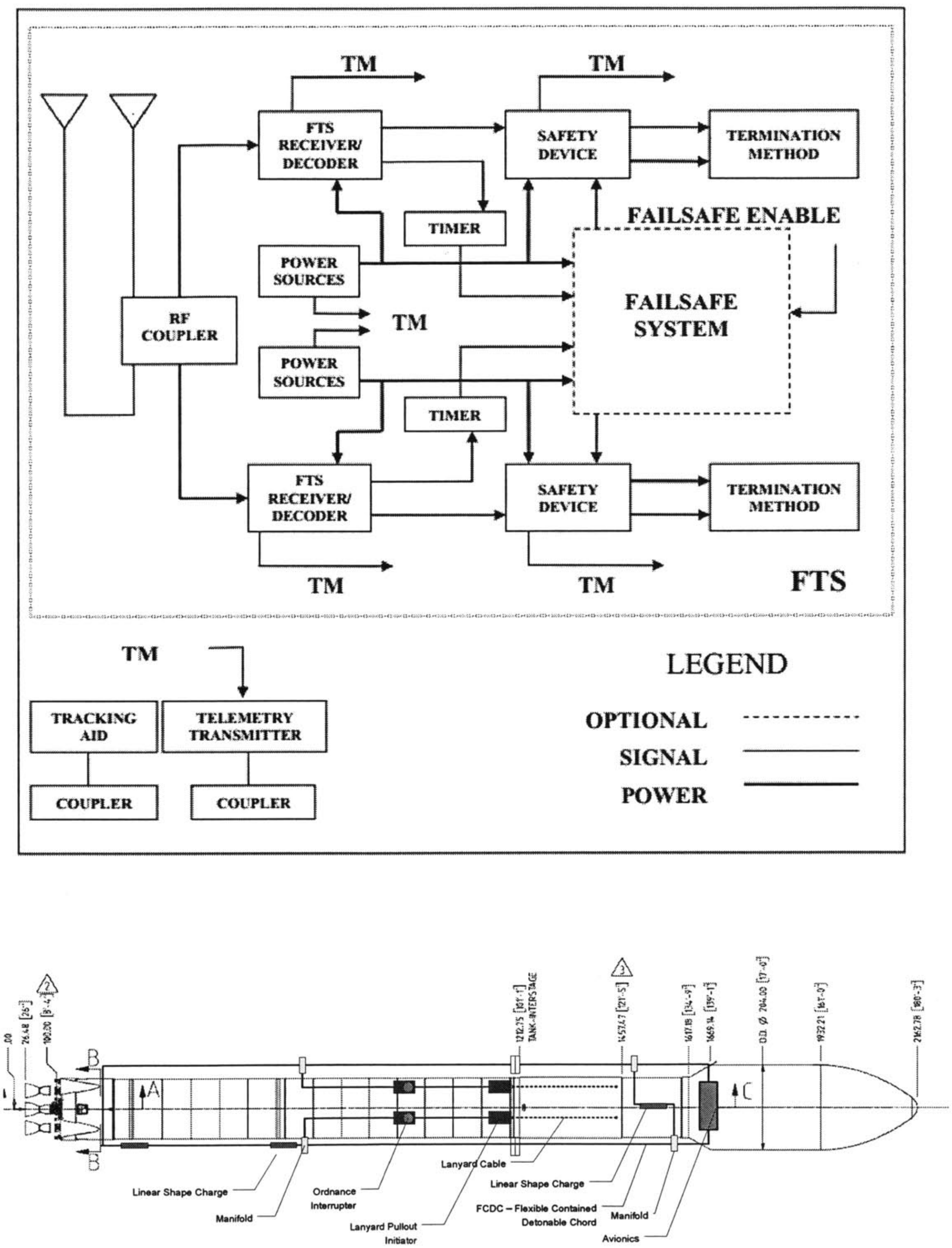

Figure 2: Overview of the FTS System (Hadden, 2010)

FTS Component List

Component	Weight [lbm]	Length ["]	Width ["]	Height ["]	Location [Name]
Command Receiver and Decoder	0.31	3.3	2.2	0.5	2nd Stage Avionics Bay
Thrust Termination Box	3.00	7.5	3.5	2	2nd Stage Avionics Bay
Flight Termination Battery	10.00	9.5	7.4	3.7	2nd Stage Avionics Bay
UHF Quadrature Hybrid	0.09	4.15	1.4	0.4	2nd Stage Avionics Bay
Antenna	1.00	8.6	6.5	0.24	2nd Stage Outer Skin
Safe & Arm	4.00	4.5	4.2	3.3	2nd Stage
Ordnance Interrupter	4.00	5.9	5	3.3	1st Stage Interstage
Linear Shape Charges	3.51	30	2.50	1.50	1st Stage Fuel Tank Bottom
Lanyard Pullout Initiator	0.80	5	1.75	1.25	1st Stage Interstage
Manifold 1 in 2 out	0.22				Several

Figure 3: FTS Component List Abbreviated (Hadden, 2010)

Workflow

Per Range requirements in ASFPC 91-710, EWR 127-1, and RCC 319, the three above systems must meet a multitude of strict technical requirements in order to be certified to fly. Per Range Safety requirements:

Scope And Compliance. This chapter contains requirements for tests and analyses that apply to all FTS systems and the components that make up each FTS system. Requests to eliminate or reduce testing shall be justified with clear and convincing evidence presented by the Range User for Space Wing Commander approval. The Space Wing Commander may delegate that authority to Range Safety for approval. (Range Safety Office, 1997)

All these requirements must take into account systems engineering, where social, political, as well as technical considerations must all be taken into account together in reaching any decision.

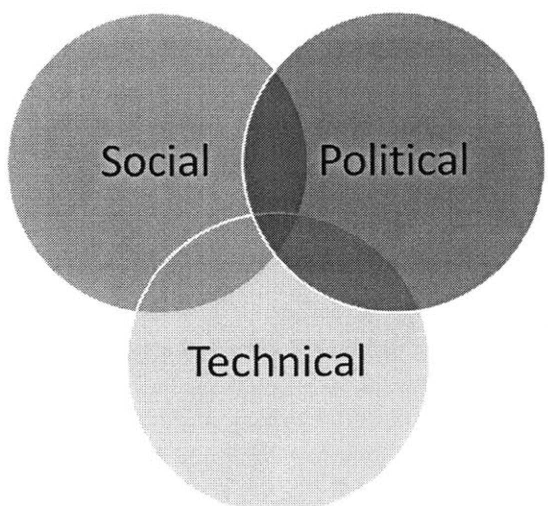

Figure 4: Key Considerations in Designing an FTS System

While taking into account the three key areas above, an FTS system will go through multiple design iterations in its product development life cycle which includes:

- Tailoring of requirements – Tailoring is the process by which a general technical requirement is specifically defined in relation to the FTS system's specification and performance parameters. For example, if an FTS Battery operates within a specific voltage range of 26 volts- 30 volts, then a requirement which may have a more general voltage rating of 28 volts - 30 volts must be modified or tailored to the specific output of the chosen battery. Rationale must also be provided as to why this voltage range is acceptable, and how it will impact the other components on the FTS system. All testing will occur within these limits plus added margin, and flight must occur within these limits. Additionally, tailoring refers to the modification or omission of requirements that do not pertain to the specific FTS system. This terminology will be used repeatedly throughout this thesis in describing processes to modify and omit requirements.
- Parts availability
- Changes to other parts of the vehicle
- Weight and form factor considerations

In a perfect world, the FTS system would follow a serial design process as seen in Figure 5, but this is never the case. Many iterations have to be reworked due to design changes, test failures, schedule changes, and additional tailoring. Figure 5 shows a high level assessment of an ideal workflow with the FTS components versus the actual experienced during the workflow.

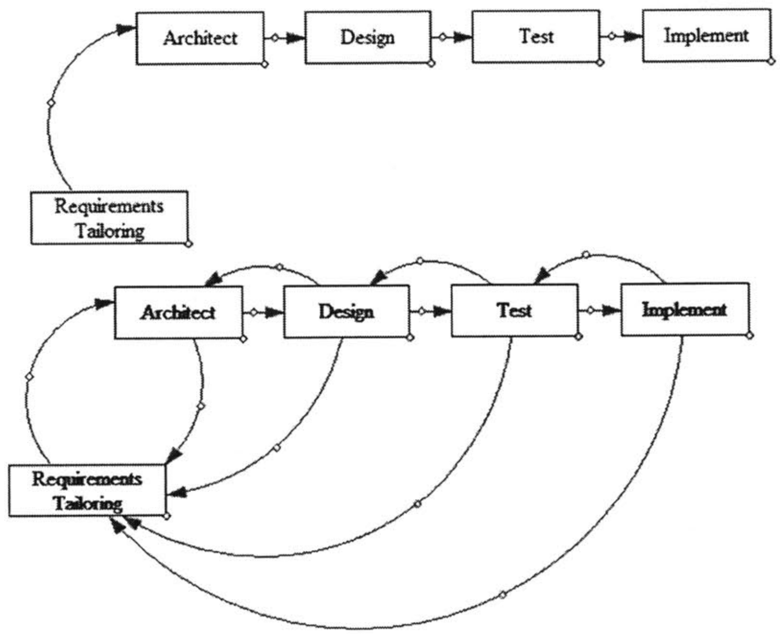

Figure 5: Ideal versus Realistic Product Life Cycle for FTS

The time to bring the FTS system online and certified is in excess of 2 years due to the many iterations required in the workflow. Unfortunately this workflow is not transparent, leading to many uncertainties about status in the product development lifecycle. This usually represents thousands of hours of labor, negotiations, and redesigns costing several millions of dollars. In an effort to streamline the FTS workflow, SpaceX took many innovative approaches to meet the requirements imposed by Range Safety. They are briefly discussed below and have more comprehensive details in the subsequent chapters.

Interaction with the Airforce, Army, FAA, and NASA for Tailoring- Range Safety is comprised of Airforce, Army, FAA, and NASA personnel, depending on which launch site you launch from. Close collaboration with each group is imperative to properly architect a system which adheres to EWR127-1, RCC 319, and AFSPC 91-710. In addition, because SpaceX utilizes multiple launch sites, it is important to keep communication open between all Range Safety personnel. This allows for one universal FTS system across multiple Ranges.

- **Commercial Parts and Tailoring-** Traditionally, FTS components have been manufactured using space rated parts. The process used to become space rated Class S or Class R parts is both time consuming and very expensive. SpaceX employed the use of commercial parts in an effort to drive down cost and have parts readily available. The process to get commercial parts certified for use on the FTS system required innovative processes to certify and also required a lot of tailoring and requirements changing in the Range Safety manuals.

- **Project Management**- Managing the different phases of the system development are key in delivering a product which meets the intent of the technical scope, the aggressive schedule, and limited cost associated with the FTS system at SpaceX. Because of the company's ambitious goals, meeting these three constraints within the Iron Triangle posed significant challenges and risks. Concurrency in testing, design, and implementation of the multiple components of the FTS system proved to be key and will be discussed in further detail.

- **Concurrent Processes on the Launch Site**- While this technically falls under Project Management, launch site operations can significantly stall a launch and put FTS on the critical path. SpaceX employed innovative ways to test which allowed for serial processes at the launch site to be curtailed through concurrent testing and installs. Typical prelaunch FTS tests cost in excess of $100,000 per test, with C-band and S-Band system tests accounting for an additional $100,000 (HIllyer, 1999)

- **Other Innovative Tools**-SpaceX has looked into other innovative tools to help reduce schedule and costs while maintaining a high level of reliability. Such tools include NVIDIA's Maximus platform, which allows for concurrent design work and simulation, which creates the opportunity to make changes realtime. This technology helped reshape the traditional workflow, allowing for a significant savings in schedule.

By noting the above key items, SpaceX has managed to keep its costs lower than its competitors while still delivering uncompromised reliability and performance. The FTS System has traditionally been known as a system which is of utmost value, but of no real use on a nominal mission. However, each flight does require such a system. Since SpaceX expects to have a whole family of vehicles utilizing the system, they are looking to make constant improvements to keep it as user friendly and as modular as possible; therefore a large part of the budget is geared towards R&D as shown in Figure 6.

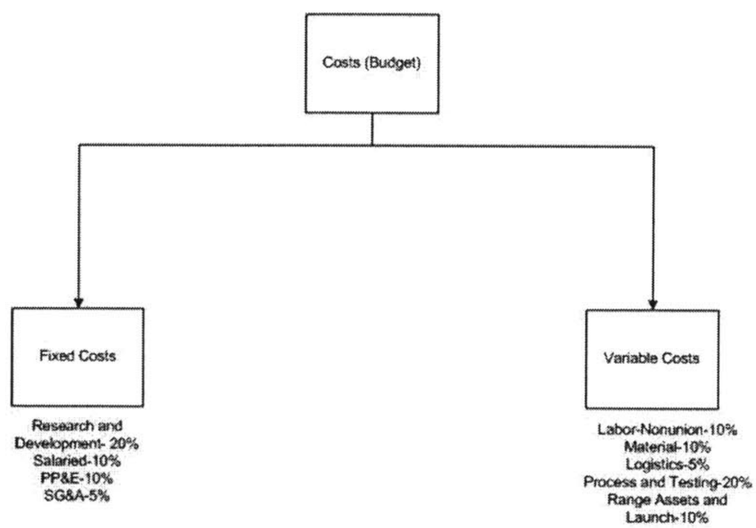

Figure 6: Approximate Cost Breakdown for FTS

Other key areas both in fixed costs and variable costs are heavily scrutinized to keep schedules moving and costs down. With the increased use of modern technology, fewer Range assets are required, and the duration of time these assets are used also decreases, thereby cutting the variable cost per launch. Many of the processes and tests are done in house at SpaceX as well, which considerably cuts the cost of testing and manufacturing. These are but a few areas SpaceX looks into for cost reduction. The highlighted points above shall be reviewed in further detail to show the type of cost savings the process innovations at SpaceX have allowed the company to enjoy.

Utilizing innovations in the above key areas, SpaceX has been able to deliver an FTS system which meets the reliability requirements of the Range Safety documentation (.999 at 95% confidence rating)(Range Safety Group, 2010), while making a modular product which may be used on the entire family of Falcon vehicles with minimal modifications. While most traditional FTS systems cost well over $10M per launch, SpaceX has a goal of significantly lower costs per launch. With such innovations employed, lower costs have become a reality with further improvements possible.

Innovation in the Interaction with Different Stakeholders- Ranges, FAA, Army, Air Force, and NASA

As discussed in the previous section, the interface between SpaceX, its vendors and the different stakeholders including the Eastern/Western Range, the FAA, Army, Air Force and NASA is absolutely vital to the architecting of the FTS system. Because each stakeholder is held liable for the nominal performance of the FTS system from their respective launch sites, each stakeholder has a set of technical requirements which the FTS system must satisfy in order to be certified to fly. With any government or military entity, there are a lot of processes in place which need to be met in order to proceed to the next step. Depending on the nature of the issue, these steps can take from one month to several years. In order for SpaceX to retain its competitive advantage, it is very important that these standardized steps be streamlined to allow for quicker turnaround. .

This problem becomes even more apparent when a Range user must fly out of more than one Range. SpaceX has launched successfully out of Kwajalein and the Eastern Range, and will soon be flying out of the Western Range in Vandenberg, Ca. These three launch sites are governed by 3 different bodies; The US Army, the 45th Space Wing, and the 30th Space Wing respectively. The FAA is involved in launches from all 3 locations as well. While the same documentation in RCC 319, AFSPC 91-710 and EWR127-1 is shared, their interpretation has not always been the same. This leads to confusion in requirements, and may result in multiple reworks in both tailoring and redesign of components. Receiving actual buyoff for any one component, let alone the entire FTS system is therefore a very challenging and costly process.

Traditionally, the FTS group discusses and modifies requirements with each Range and once the requirements are met, they may build their components and be certified to fly out of that particular Range. However, to fly out of a new Range, a serial process must be employed as shown in Figure 7.

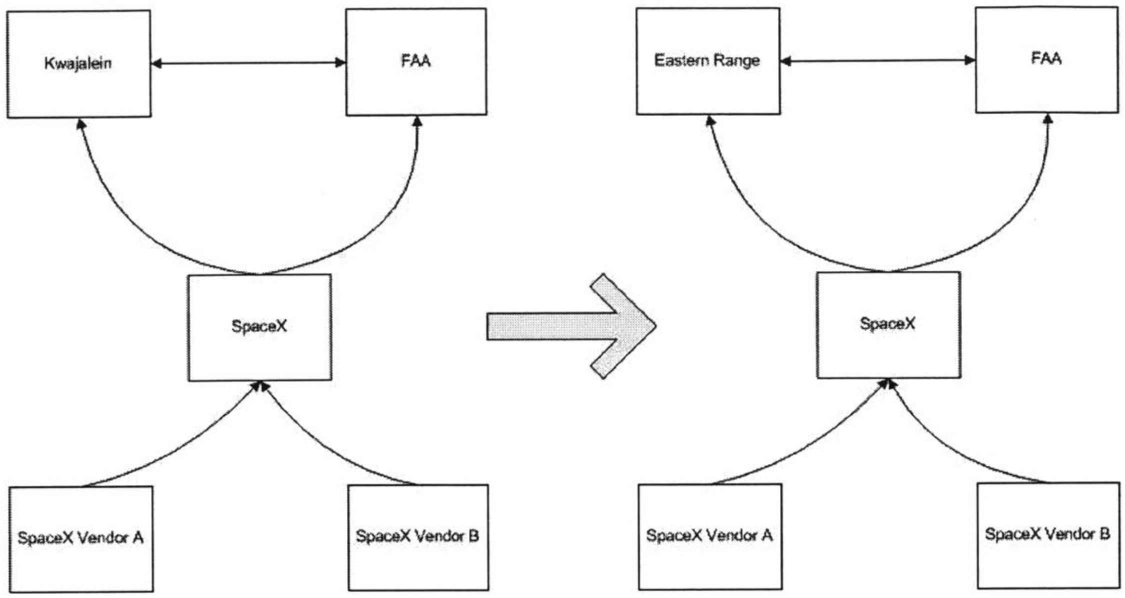

Figure 7: Serial Range Approval Process

With each FTS system taking in excess of 2 years to fully architect, design, develop, and implement, the Range tailoring process takes up a significant portion of that time. Modifying Figure 5 to account for the amount of time rework is implemented during each stage of the product development cycle, we end up with Figure 8, which shows how much time is spent in the tailoring process.

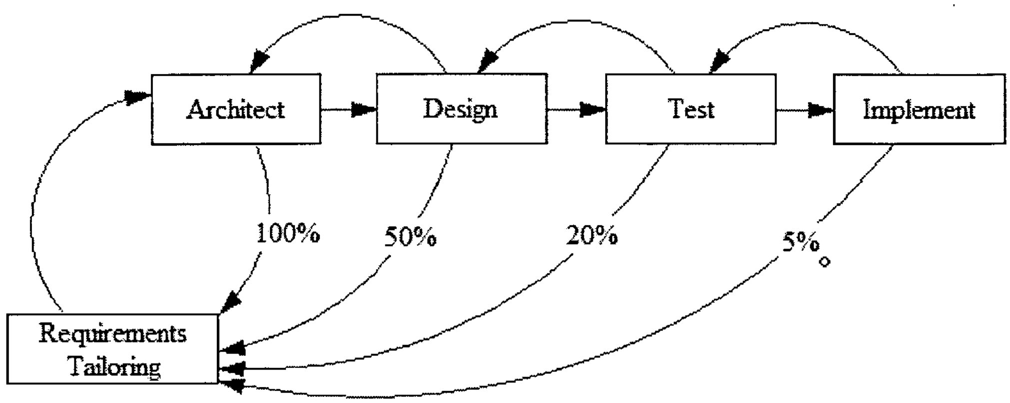

Figure 8: Amount of Tailoring Per Milestone

Note: The percentages above refer specifically to the tailoring required within each segment of the product design cycle.

Each segment above requires some modifications to the requirements and tailoring. The percentages seen are the percentage of each segment's time and resources spent in this process. To provide more detail into this, I will break down each milestone and what aspect of tailoring is involved.

- **Architecting**- The architecting stage is a close collaboration with the Range, FAA, and any other stakeholders. This process includes going over each requirement one by one, initial tailoring of requirements to meet the needs of the proposed FTS system, and how they actually plan to implement these requirements into a design. The architecting segment takes up about 40% of the entire FTS product development cycle.
- **Design**- The design work is done once the initial tailoring is done. This includes the actual CAD/CAM work, interfacing with other groups to get form factor and power constraints, as

well as investigation into the types of resources and materials which will be used. New discoveries are made during this time, which require revisiting the tailoring process, and further modify requirements as needed. Nearly half our time in the design phase requires us to revisit tailoring and make necessary changes to take into account new constraints. The design segment accounts for 25% of the total FTS product development cycle.

- **Test**- During the test phase, a new design is run through what is called Qualification testing. As quoted from RCC 319-10 (Range Safety Group, 2010)

> Qualification Tests. Qualification tests are functional tests of flight-representative hardware system or component designs. Performed during exposure to physical stress, these tests ensure the adequacy and suitability of the design to reliably operate during and after exposure to certain physical environments in excess of flight predictions by a prescribed margin. Test articles subjected to qualification testing are considered expended and shall not be used for flight termination applications.

These represent a multitude of tests including functional and environmental tests which must all be passed without issue. Qualification testing requires ample margin to account for any anomalies experienced during flight. This is usually margin on top of the margin of the acceptance tests (workmanship tests). Examples of design tests a component may have to go through are seen in Figure 9.

Test	Paragraph	Quantity Tested [5]		
		Cable X=3	Coupler X=3	Antenna X=3
Acceptance Tests	Table 4.16.1	X	X	X
Antenna Pattern	4.16.6	X	X	X
Performance Verification	4.10.4			
VSWR	4.16.2	X	X	X
Insertion Loss [1], [2], [3]	4.16.3	X	X	-
Isolation [1]	4.16.4	-	X	X
Abbreviated Antenna Pattern	4.16.7	-	-	X
Abbreviated Performance Verification	4.10.5			
VSWR[1], [2], [3]	4.16.5	-	-	X
Non-Operating Environment Tests	4.13.1			
Storage Temperature	4.13.2	X	X	X
Transportation Shock	4.13.4	X	X	X
Bench Handling Shock	4.13.5	X	X	X
Transportation Vibration	4.13.6	X	X	X
Fungus Resistance	4.13.7	1	1	1
Fine Sand	4.13.8	1	1	1
Operating Environment Tests[4]	4.14.1			
Thermal Cycling	4.14.2	X	X	X
Thermal Vacuum	4.14.3	X	-	X
Humidity	4.14.4	X	X	X
Salt Fog	4.14.5	X	X	X
Temperature/Humidity/Altitude	4.14.6	X	X	X
Acceleration	4.14.7	X	X	X
Shock	4.14.8	X	X	X
Acoustic	4.14.9	X	X	X
Sinusoidal Vibration	4.14.10	X	X	X
Random Vibration	4.14.11	X	X	X
Tensile Load	4.13.9	X	X-	X-
Internal Inspection	4.11.7	-	X	X

Figure 9: Example of a Qualification Test (Range Safety Group, 2010)

The number of tests and test units is quite staggering. Depending on the nature of the component (electrical, mechanical, ordnance, etc…) the test will vary greatly, as will the number of units required to be tested. If any unit fails testing, the unit must be reworked, rationale to proceed will have to be provided and the Range must decide if the unit must completely be redesigned or further testing is allowed. This often will require some additional tailoring to the original requirements to narrow the scope of the component and its requirement. Approximately 20% of the time of testing may require some form of retailoring. The testing segment accounts for 25% of the total FTS life cycle.

- **Implementation-** Implementation and Integration deal with the placement and test of the completed FTS components on the vehicle. Many may think that once testing of the FTS component is complete, the system is done. However, new challenges await. Actually placing the component on the vehicle with the proper torque specifications (same specifications used during testing), ensuring the voltage readings are identical to what was experienced during testing, and how the FTS behaves as a full system versus at the component level are all analyzed. Testing with the vehicle fully fueled as well as static firings give some insight into the types of temperatures and environments which are to be expected in flight. Anything "out of family" needs to be investigated and corrective actions need to take place. These corrective actions may involve retailoring, which is approximately 5% of the total effort of implementation.

We can come to approximate resource utilization just for tailoring for the four segments as seen below.

Total product development time = 2 Years (Conservative estimate)

Arch= 40% of total product development time

Design = 25% of total product development time

Testing= 25% of total product development time

Implement = 10% of total product development time

T_a= 100% of Arch time

T_d= 50% of Design time

T_t= 20% of Testing time

T_i= 5% of implementing time

Tailoring Time = (T_a*Arch) + (T_d*Design) + (T_t*Testing) + (T_i * Implement)

Tailoring Time = (1.00*292 days) + (.50 * 182.5 days) + (.20 * 182.5 days) + (.05 * 73 days)

Tailoring Time = 292 Days + 91.25 days + 36.50 days + 3.65 days

Tailoring Time = 423.4 Total days out of 730.

Based on this conservative calculation, we see that nearly 60% of the product management is in dealing with tailoring requirements, as seen in Figure 10. Of course with more experience tailoring, the amount of time tailoring should decrease by a significant amount, but it will remain a large part of the total resource allocation for the FTS system and the team. However, if the process for each Range is done in serial, then it will be a vast portion of the resources used for <u>each</u> Range. If we are able to concurrently tailor with multiple Ranges, the resource allocation can be seen as a fixed cost as opposed to a variable cost with each Range. One of the biggest issues experienced when tailoring occurs due to ambiguous requirements which can easily be interpreted differently by the Ranges. These are discussed in the next section.

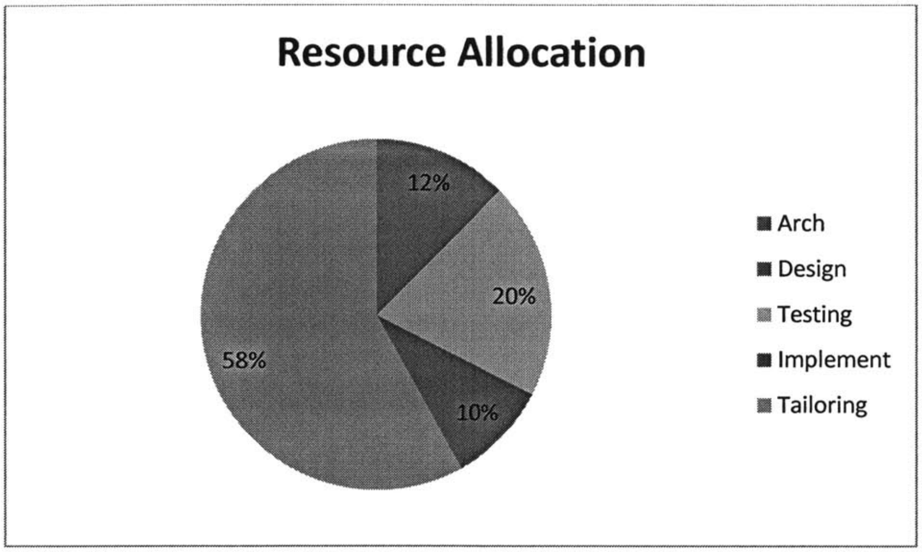

Figure 10: Resource Allocation

Ambiguity in Requirements Between Ranges

> This section applies to any component that is critical to the reliability of an FTS and is not otherwise identified by this chapter. This includes any new technology or any component that may be unique to the design of a vehicle, such as any auto-destruct box, current limiter, or timer. A miscellaneous component shall satisfy each test or analysis identified by any table of this section to demonstrate that the component satisfies all its performance specifications when subjected to each non-operating and operating environment. For any new or unique component, the Range User shall identify any additional test requirements necessary to ensure its reliability.

(Range Safety Group, 2010)

The above requirement from RCC 319-10 seems relatively straightforward. For components which do not fit into the standard framework of components used in the FTS system, they shall then satisfy the requirements from the "miscellaneous" section. However, the last sentence

For any new or unique component, the Range User shall identify any additional test requirements necessary to ensure its reliability.

keeps the requirement very open ended and ambiguous. It is requirements like the one above which impose additional tests. Often times, these additional tests are employed in the middle of existing testing, causing additional tailoring to be needed. This accounts for a percentage of the retailoring required during the testing segment. It is even more problematic when you have launch vehicles at multiple launch sites since each Range may interpret these additional tests differently and will require a totally different subset of tests. In addition, when one of the technical documents does not contain knowhow on a specific component, they are oftentimes imported from other documents.

This adds to the confusion when dealing with Ranges serially. Despite the fact that the technical documents were written jointly by all the Ranges, the nuances associated with each Range and how they deal with the requirements vary. Such is the case with Qualification test programs where requirements may be waived. An example of a repeat of testing and nullification of a tailored requirement is cited below.

The FTS Battery is the heart of the FTS system, providing power to all other components on the FTS system. Prior to building a battery pack, the cells must be screened in packs to ensure that they are within family, that is, they fall within a prescribed range of values. One Range allowed SpaceX to test the cells as a pack, which allows the cells to match properly and they were allowed to build batteries with those cells. However, another Range interpreted the requirements differently and stated the following:

Any cell unable to demonstrate consistent capacity at ambient and cold temperature shall not be used.

Any cell with out-of-family data for initial cell voltage and pulse load voltage regulation at ambient and cold temperature shall not be used.

Final Cell Matching. Cells shall be selected for each battery by matching associated performance properties of individual cells from the lot. The Range User shall provide to Range Safety for approval, the variables, criteria, and methodology used for matching cells into batteries.

(Range Safety Group, 2010)

The above set of requirements was interpreted differently by one of the Ranges. As a result, final cell matching occurred after the battery cells were screened. So essentially, the packs could not be formed during screening. This would result in out of family cells since the charging would vary slightly with each screening of the packs. While one Range wanted to test the cells matched together as a pack, another Range preferred for SpaceX to test several cells in parallel, then match them. The latter process proved extremely inconvenient and costly, and only after several months of negotiations and further tailoring of the requirements could the former process be used.

The Range User shall provide to Range Safety for approval, the variables, criteria, and methodology used for matching cells into batteries.

The above snippet from the parent requirement left a lot of ambiguity with cell selection. This would vary from Range to Range. So given a statistical sampling of cells based on their Open Circuit Voltages (OCV), the Range, using their own methodology would choose cells to group together as a pack, rather than letting SpaceX combine its own pack from the beginning of cell screening. The typical result of doing this can be seen in Figure 12, which shows an initial flat peaking of cells during a charge-discharge process. Normally this flat curve is a result of poor matching. However, with additional cycling, the cells do begin to match, as seen in the later peaks.

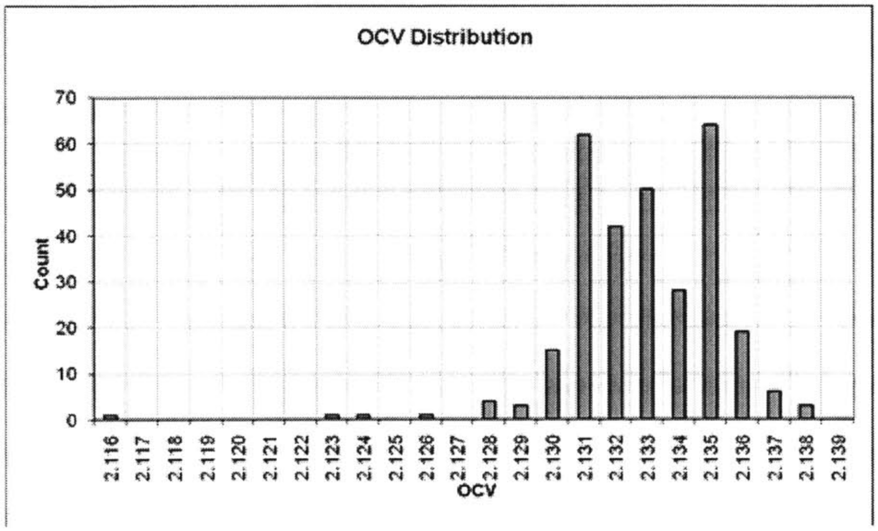

Figure 11: OCV Distribution (Kwak, 2007)

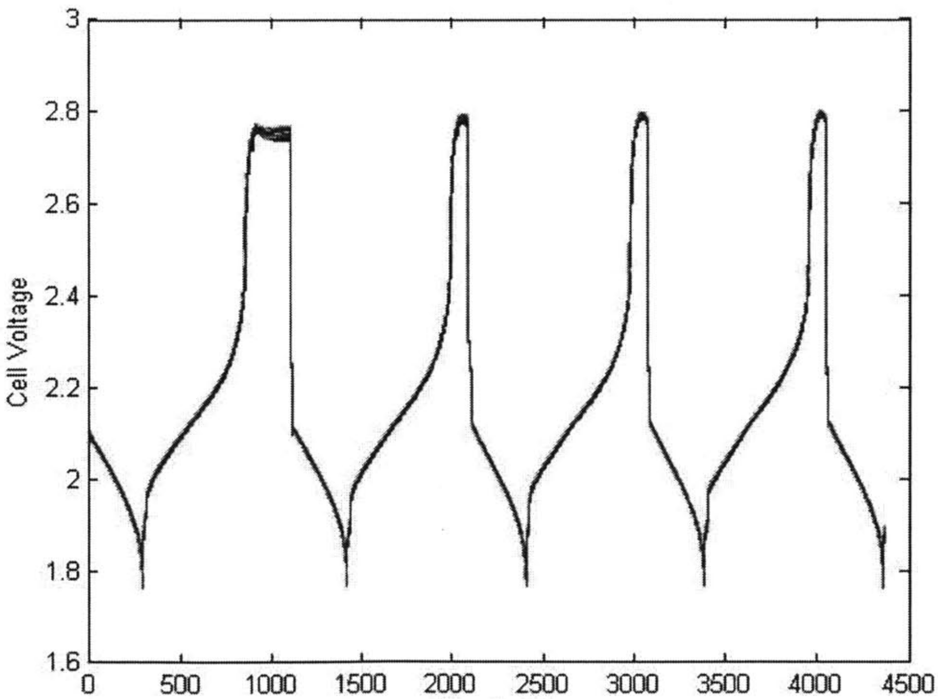

Figure 12: Cell Screening (Kwak, 2007)

While this is not disastrous, it does show that the pack formed together was not initially an optimal pack. A pack with Open Circuit Voltages (OCVs) better matched (closer) from the beginning should have been chosen to ensure that the performance was consistent throughout. The cells always performed nominally, but better matching of each pack would exhibit better performance for the battery pack as a whole. Had the discussions with the Ranges occurred concurrently as opposed to serially, this may very well have been avoided. The next chapter will go into details about concurrent Range tailoring of requirements.

Parallel Process

As the examples above shows, SpaceX needed a more efficient way to tailor requirements with multiple stakeholders. Cutting significant time with the Range tailoring process would prove to be difficult as there were several hundred requirements which needed to be met. As SpaceX became more proficient with the requirements, they could streamline the process, but there was still the issue of concurrency. As the interview with the Senior Flight Termination Systems Senior Manager in the Appendix explains, once they were able to achieve concurrency with the tailoring, a lot of time was saved and that time could be used elsewhere. Requalification of hardware for every Range would no longer need to be conducted. As he explains, each Range requires several buyoffs within, making the tailoring process a very time consuming one, where all stakeholders within a Range must come to an agreement regarding the changes. The best way to streamline this process is to have all the Ranges they wanted to fly from agree to one standard FTS system utilizing the same components.

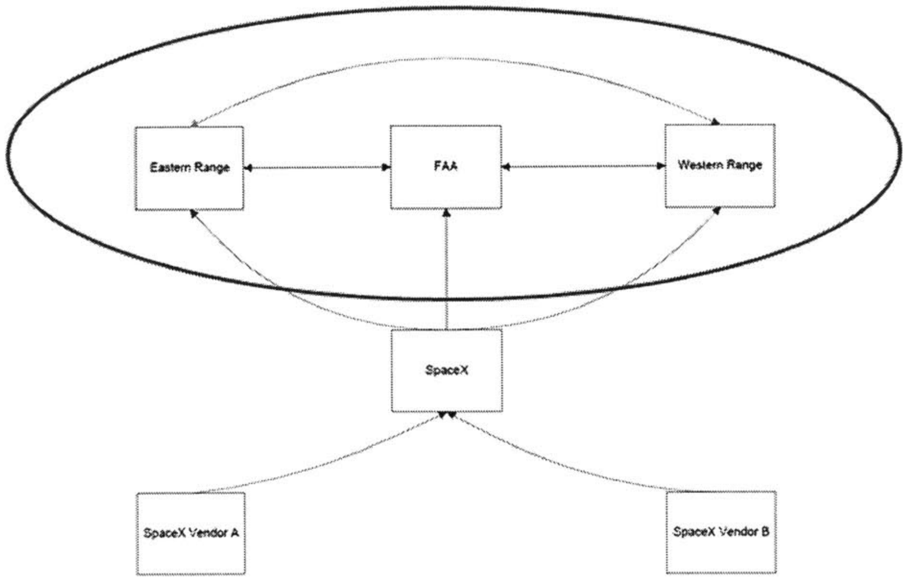

Figure 13: Concurrent Tailoring

As Figure 13 shows, SpaceX looked for innovation within a tailoring process which took up over ½ of their resources. In addition to working with their initial target Range, SpaceX would now work with future Ranges. Requirements will now be discussed in conjunction with all groups, and any ambiguity could now be discussed in detail in an open forum. As the FTS Manager mentions, each Range has its own geographical constraints and concerns. Therefore tailoring cannot overlap 100%, but greater than 90% of the requirements have been successfully met by more than one Range. Revisiting the calculations done earlier:

Range 1

Total product management time = 2 Years

Arch= 40% of total product development time

Design = 25% of total product development time

Testing= 25% of total product development time

Implement = 10% of total product development time

T_a= 100% of Arch time

T_d= 50% of Design time

T_t= 20% of Testing time

T_i= 5% of implementing time

Tailoring Time = (T_a*Arch) + (T_d*Design) + (T_t*Testing) + (T_i * Implement)

Tailoring Time = (1.00*292 days) + (.50 * 182.5 days) + (.20 * 182.5 days) + (.05 * 73 days)

Tailoring Time = 292 Days + 91.25 days + 36.50 days + 3.65 days

Tailoring Time = 423.4 Total days out of 730.

Range 2

Total product management time = 2 Years

Arch= 40% of total product development time

Design = 25% of total product development time

Testing= 25% of total product development time

Implement = 10% of total product development time

T_a= 100% * 10% of Arch time

T_d= 50% * 10% of Design time

T_t= 20% * 10% of Testing time

T_i= 5% * 10% of implementing time

Tailoring Time = (T_a*Arch) + (T_d*Design) + (T_t*Testing) + (T_i * Implement)

Tailoring Time = (.10*292 days) + (.05 * 182.5 days) + (.02 * 182.5 days) + (.005 * 73 days)

Tailoring Time = 29.2 Days + 9.125 days + 3.650 days + .365 days

Tailoring Time = 42.34 Total days out of 730.

This results in a savings of 90% of total tailoring time or 42.34/730= 5.8% of the total fixed 2 year time frame. Of course, these 2 years can now be reduced significantly and those resources can now be allocated to other tasks. In summary, cutting down on Range Tailoring is one of the biggest innovations the FTS team accomplished. Additionally, by establishing concurrent requirements tailoring with all the Ranges, each requirement and any ambiguity within had been clarified and agreed upon by all stakeholders, thereby eliminating the possibility that a requirement will be misconstrued with future FTS components. New processes and formats have been setup between SpaceX and its stakeholders through monthly meetings onsite, and reviewing all current requirements, future requirements, and any potential anomalies which may be seen during testing or flight. The establishment of this close relationship ensures that all future processes will be done concurrently. Because of the bureaucratic nature of tailoring government based technical documents to meet the needs of the FTS system, it is in the best interest of the Range user to streamline this process and concurrently deal with all the Ranges at once to avoid redundant tailoring of the documents. The following additional benefits were realized:

- Each FTS component now only needed to have one variation. For example, three different Thrust Termination Boxes for three different Ranges was not required. This resulted in cost savings for Non-recurring engineering, revisions, materials, and test.
- Having the insight of all the Ranges at once provided valuable information about the optimal way to architect the FTS system, since they were drawing on the experiences of different Range personnel from different backgrounds.
- Disagreements over a requirement were internally discussed by the Ranges. Only the end results were presented to SpaceX and discussed, allowing an agreed upon solution to be realized

Innovation Through Lead Users and the Use of Commercial Parts

The previous chapter focused on process innovation within the Range requirements tailoring. This tailoring process accounted for over 50% of the total resource usage for the FTS system. Moving into the actual components used in the FTS system, there was a lot of product innovation in designing the FTS system. This includes two main areas:

- The use of commercial parts in place of space rated parts
- Designing, building all components in house

These are two fundamental areas in product innovation which permeate the culture at SpaceX. In addition to the realized cost savings of building components in house, it also provides significant flexibility when a component needs to be redesigned "on the fly" due to changes late in the product development cycle. Another consideration is the synergies which are realized between various groups. Lead users within one group will develop a product which suits their needs and is not already developed by another group within the organization. Other users will evaluate this product, reject it, or copy and improve upon it. (Von Hippel, 2012). This happens at SpaceX on a regular basis where one group (lead user) recognizes the need for a product. Another department may see the benefits of this product and adopt it for their own uses. As needed, they proceed to make improvements to meet their specific needs, and may present the refined product back to the original group with added improvements. As Figure 14 shows, there are 3 phases of development. Phase 1 is where the need is identified. Once this need has been identified and an initial solution is implemented, it is picked up by another group who may have need for this product (application independent). Phase 3 does not apply to this specific model used at SpaceX, since the producers remain internal, and no products, outside the launch vehicle are independently sold.

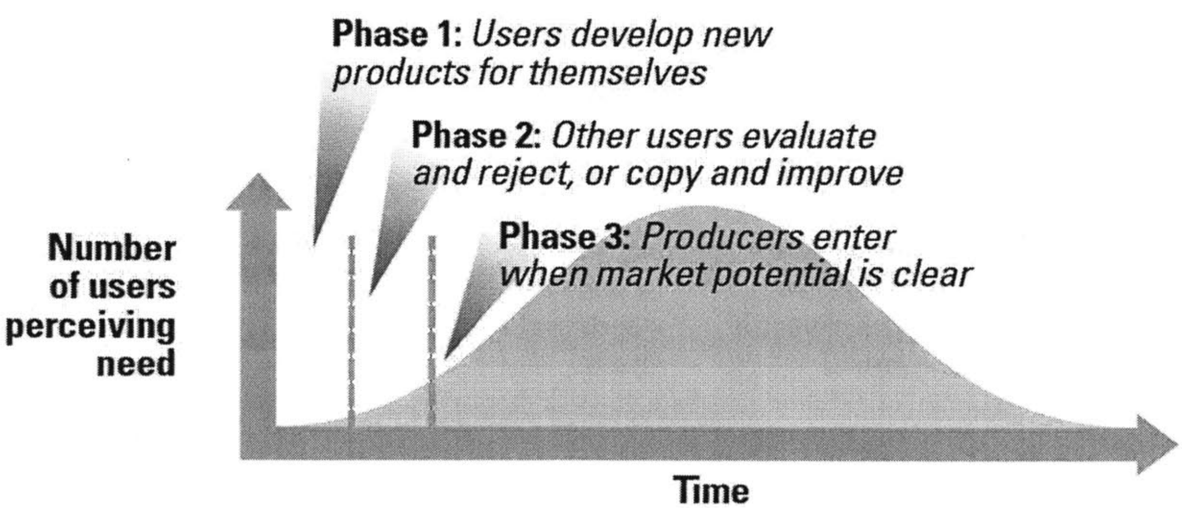

Figure 14: Lead Users and How Products are Developed (Von Hippel, 2012)

The case which will be discussed here is the FTS battery which utilized a simple lead acid cell structure. With the Avionics system needing a battery, a lead acid battery was developed by the Avionics Power Group (Lead User). They developed a simple battery consisting of 14 lead acid cell batteries in series to account for a 28 Volt system (Kwak, 2009). The design was simple and reliable, as the cells had been used in several applications outside of space. As the first revision of batteries was being completed for the Avionics group, the FTS group also needed a power system for their system. Looking for a cost effective and reliable design, they began exploring different options. Space rated batteries were available for purchase, but they were in excess of $20k per battery. Because of the small size of the company, the FTS group was able to take note of the battery being used in the Avionics group, and adopt its technology. Several revisions were made based on the technical requirements needed to meet the FTS criteria for an acceptable battery. However, the fundamental design was the same. The housings utilized the same material, the FTS battery utilized the same type of lead acid cells, just smaller, since the power requirement was less, and the internals for cell placement and security utilized the same Teflon inserts. The fully built batteries essentially were the same. The FTS group needing additional requirements for cell monitoring during testing implemented a second connector which would not be used for charging, but rather cell monitoring. Seeing this as an innovative solution, the Avionics group was able to adopt the new change as well into their system.

The shared innovations between the lead user and new group did not stop there. Because they now shared the same type of connectors, the batteries could be tested on the same software system and utilize the same hardware for charging and monitoring, with simple changes in the parameter settings. The test setups were now identical and could be used interchangeably as shown in Figure 15.

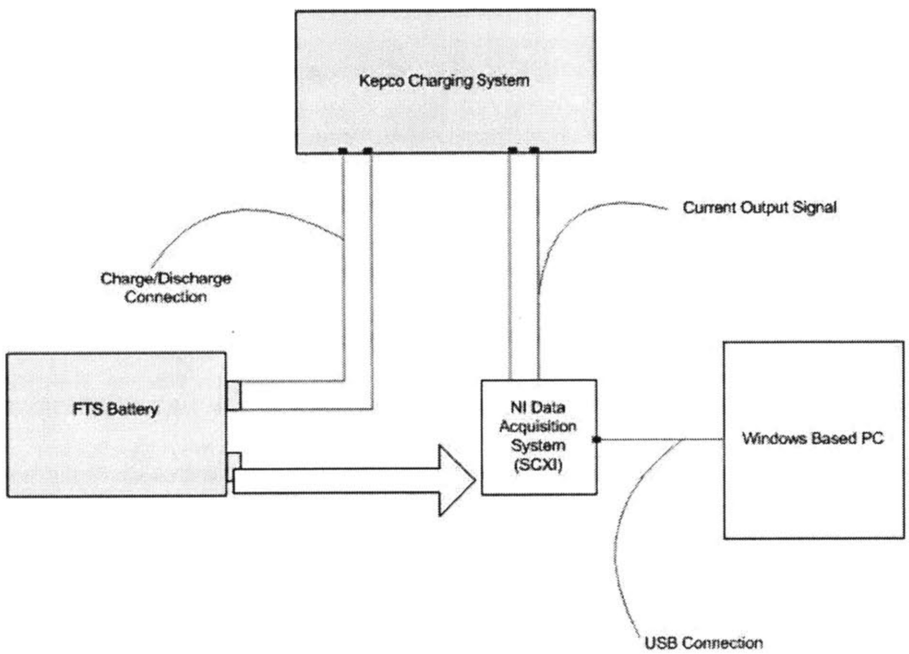

Figure 15: Test Setup (Kwak, 2007)

This back and forth between the original lead user and the new group allowed for new innovations to take place within both groups. The manufacturing processes could now be near identical, and the procured materials could be shared, which allowed for a cost benefit from economies of scale, thereby reducing overall costs. In addition, the test setups were identical and could be used interchangeably allowing for more efficient resource usage.

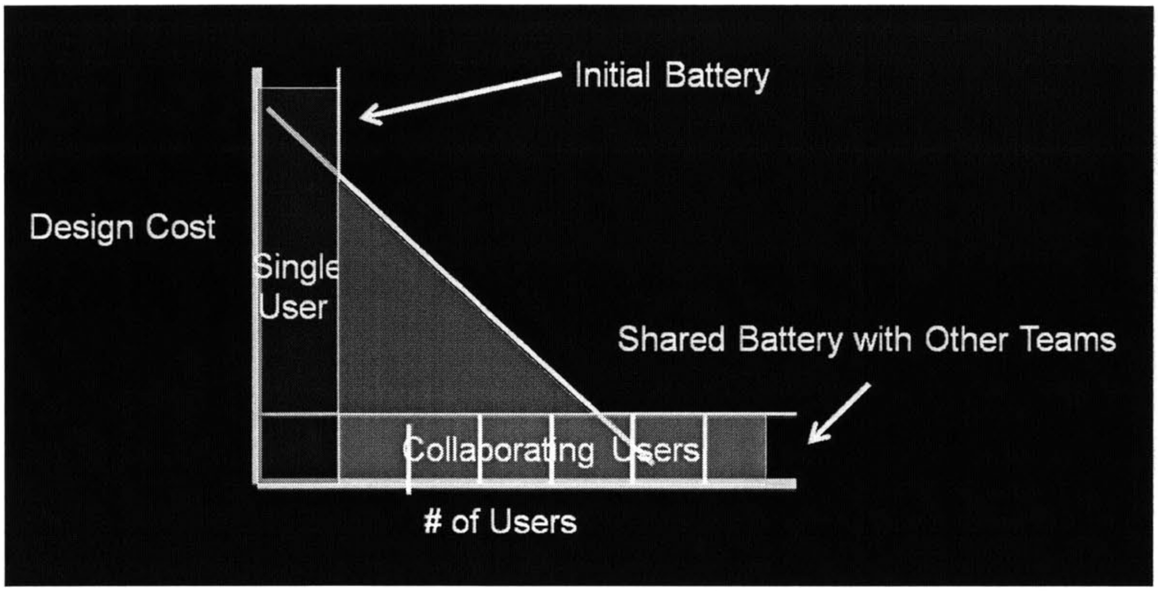

Figure 16: Benefits of multiple users (Von Hippel, 2012)

Ultimately, the Avionics battery moved to a newer lithium ion technology, since the power requirements grew with the vehicle's complexity. However, a lot of the original innovations were carried over from the original design of the lead acid battery, including the type of harnessing, connector types, monitoring software and test setups. If the FTS battery were to change technologies, it would certainly benefit from the Avionics group's move to the new technology as well.

It is important to note that that the exchange of innovation between groups is made possible only because the components were made in house. Had SpaceX been purchasing all of its Avionics and FTS components from outside vendors, a lot of the synergies between the groups would never have been realized and new innovations would have ceased to exist. This is one of the key philosophies which has made SpaceX successful. Knowledge sharing remains internal and very active within the community, thereby nurturing the sharing of ideas across different departments. The lessons learned within each group are also shared so different teams don't waste time making the same mistakes.

The Use of Commercial Parts

Many components within a traditional FTS system are legacy parts which have been through extensive qualification testing. Because the difficult part has already been done, the vendor of these certified components are able to charge a significant price per component. The benefits of economies of scale are also limited as the product is seen as a niche product, thereby commanding a pricing premium. A component which would normally cost $2k-3K per component is being sold for almost an order of magnitude more, due to the heritage and test data associated with the component. In order to make access to space more affordable, it is important to find innovations in other areas such as in manufacturing and purchasing. There are three key areas to consider when deciding to purchase a space rated part or to use commercial parts:

- Total cost per flight
- Lead time for components
- Reliability

The cost per flight is a significant factor in improving access to space. SpaceX realized this, and unless the component could not be built in house due to the lack of core competencies or special permits required to build in house, every stride was made to build the components in house using Commercial Off The Shelf Parts (COTS). Another key consideration when deciding between space rated solutions or commercial parts were the lead time for components. As mentioned in an earlier chapter, this is a huge problem for new entrants. Typically, established players are given precedence by manufacturers of space rated parts, and as a result are given preference in purchasing large orders. New entrants are essentially left with the scraps, and in many cases, could not receive parts at all. This hinders any R&D which can be done within the company, since parts were not available to test with. An example of this is the purchasing of space rated mechanical relays. Relays are abundant and can be purchased within a few days from most manufacturers. However, because space rated relays are harder to procure, their costs are significantly more and supplies are very limited. Upon doing a quick internet search for a simple relay, Figure 17 shows the cost and lead time for these relays. If an FTS component required 10 of these relays per flight, the flight would have to be delayed due to the lack of stock and the minimum 26 week lead time! Oftentimes, the lead times end up being longer than the minimum expected.

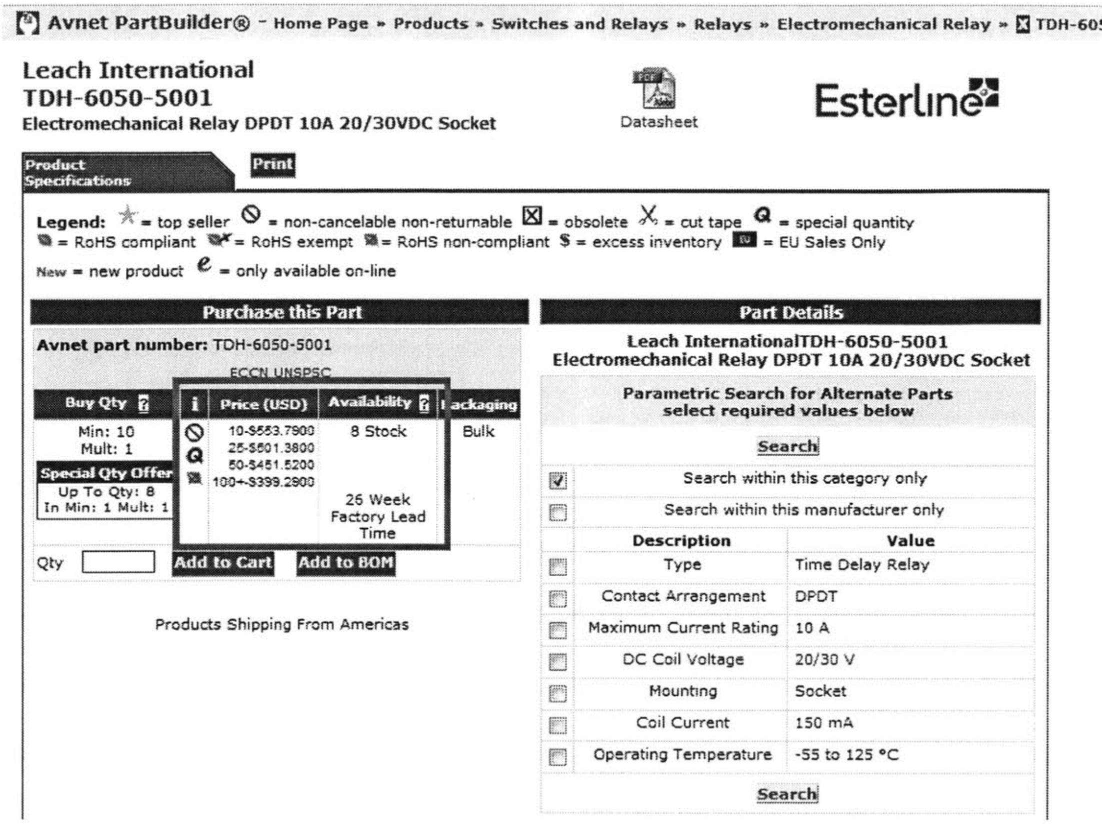

Figure 17: Internet Search for Space Rated Relays

As a result, SpaceX took an innovative approach in meeting this challenge. When evaluating the 3 above criteria, SpaceX elected to upscreen COTS components which, through testing, would prove that they have the reliability of the space rated parts, but at the same time, are fully stocked and available at any time. They are also significantly less expensive.

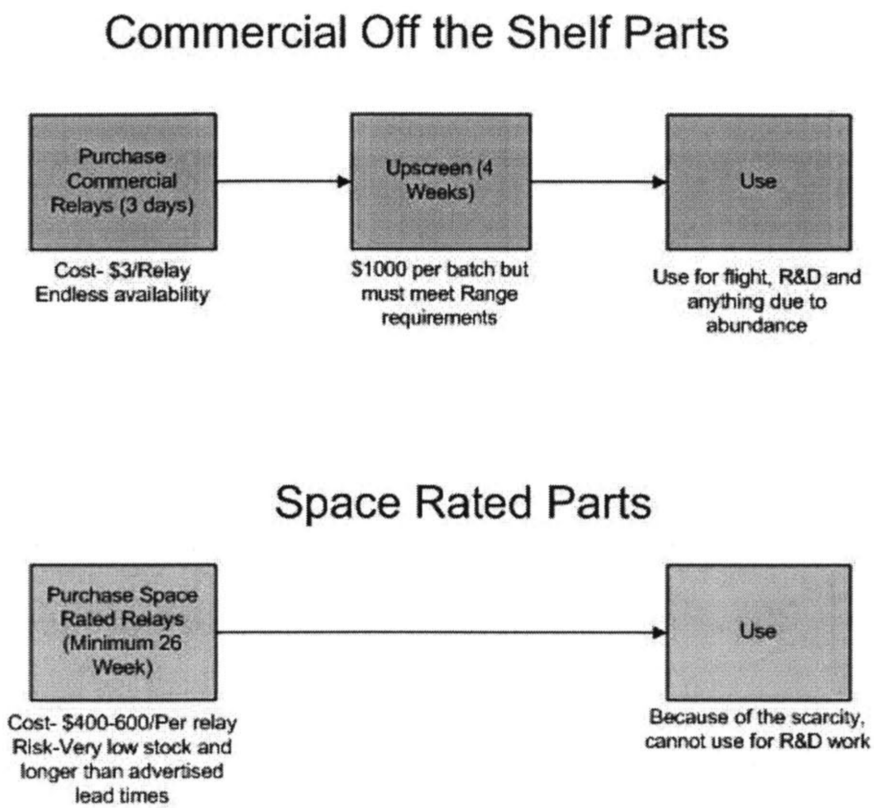

Figure 18: COTS VS Space Rated Parts Lead Time and Cost

The high-level relay flow chart in Figure 18 shows the typical comparison of taking the two approaches. As you can see, going the COTS route, the cost per relay is cheaper. Just as important is the actual lead time and assurance that the parts are always available. If an FTS component is changed at the last minute, supporting hardware must always be available. A 26+ week lead time is simply unacceptable. Next, following the Range requirements to upscreen the parts is the most challenging part of choosing to utilize COTS parts. In this simple relay example, only a few weeks and some technical rationale for tailoring are required to prove the parts are equally reliable as the space rated parts. Of course the level of complexity varies based on the component. The FTS battery will be discussed in detail in the below section, which outlines a bit more of a complicated process for using COTS parts. Finally, once these relays have been upscreened, an abundance of relays exist, allowing for multiple uses including for R&D. The cost and time savings are apparent with this method.

Following the space rated parts approach, new entrants are not guaranteed parts, nor are they guaranteed the parts in a reasonable amount of time. In addition, the cost is significantly higher than their COTS counterparts. During the time it would take to wait for space rated parts, thousands of relays can be upscreened. A large quantity can be purchased and stored. The next time these relays have to be ordered can easily be years. Also with the space rated relays, since you are limited in your supply, usage must be shrewd. By taking this innovative approach, SpaceX is able to develop multiple components and test them freely using stocked parts at a fraction of the cost and time. A core segment of SpaceX's innovation arises from this choice.

Utilizing COTS Battery Cells

The FTS Battery uses COTS cells which are purchased from a local vendor. They have batteries which have flown on several different missions and applications, both commercial and government based (Kwak, 2007). They have proven their reliability with no failures in over 3 decades. In addition, they only cost a few dollars per cell. SpaceX elected to use these cells for their battery which they developed in house, as opposed to purchasing a space rated battery which could cost in excess of $20K with lead times of up to a year or more. However, the process was not as simple as the one outlined above with the relays. Because the FTS Battery is the heart of the FTS system, many Range requirements from RCC 319-10 had to be met. As the below text from this document shows, there was a lot of compliance which had to be met.

Compliance. Any commercial lead-acid battery must satisfy each test or analysis identified by any table of this section to demonstrate that the battery satisfies all its performance specifications when subjected to each non-operating and operating environment.

(Range Safety Group, 2010)

As mentioned in the previous chapter, typical FTS systems take in excess of 2 years to qualify all the components. The FTS Battery alone can take up 25% of that time. However, the benefits of building a battery in house versus purchasing from a vendor are huge. The same synergies and benefits of in house components are realized, as mentioned in the section above. Also, SpaceX has a lot more control and flexibility with the design of the battery since it is not a fixed solution from someone else. The FTS Battery can be built taking into account other structures and requirements on the launch vehicle. Figure 19 shows the potential timeline of going the COTS route and Figure 20 shows the space rated route.

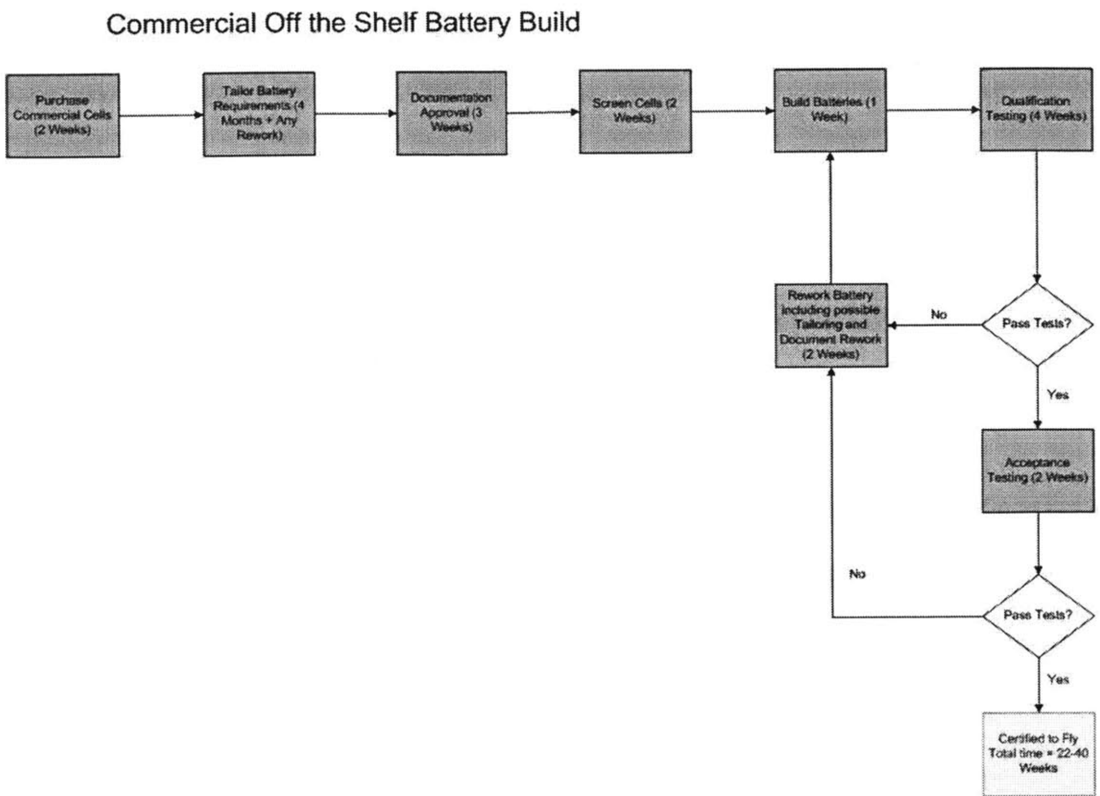

Figure 19: COTS Battery Workflow

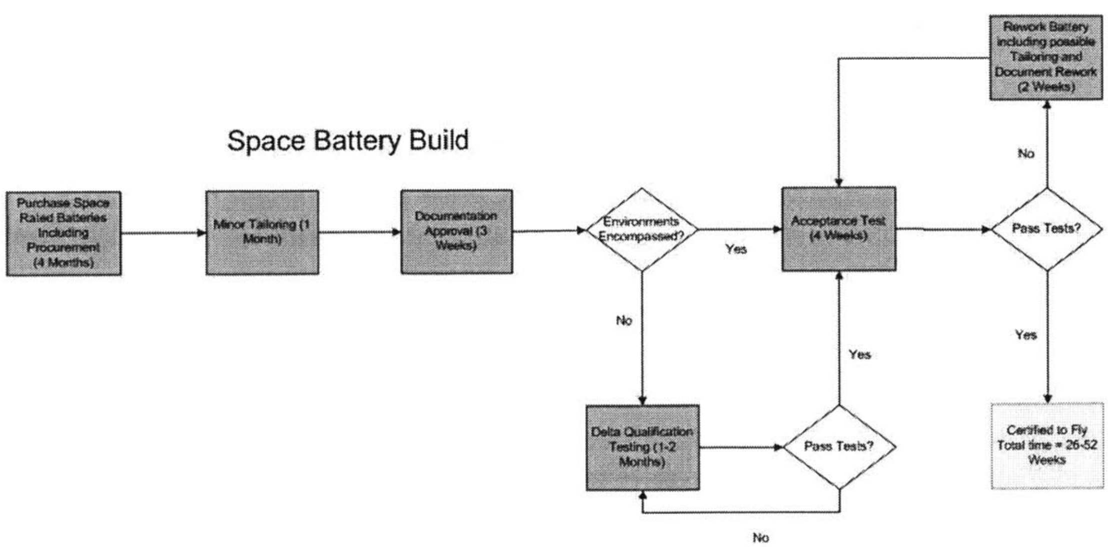

Figure 20: Space Rated Battery Workflow

While the total times do not vary by more than 30% in lead times, there are significant differences in the approaches and associated risks. With the space rated option, the process is relatively simple. Batteries are ordered from the vendor and standard project management is implemented, where documentation is wordsmithed and sent to the Range for approval. If the SpaceX environments are not totally encompassed by the heritage levels, a delta qualification is conducted to encompass all the SpaceX environments. If these levels are encompassed, then a simple Acceptance test, which verifies the workmanship is conducted. Upon successful completion of the Acceptance test, the batteries are flightworthy and certified.

With the COTS Batteries the process is a lot more involved. Several meetings with the Ranges to tailor requirements are required, along with the approval of all the documents for testing, including Screening, Qualification, Acceptance, and Build. These are all written in house as the battery requirements are being finalized. The cells are purchased from a commercial vendor and are tested with a test setup SpaceX builds. The requirements are in depth as Figure 21 shows. The cells must pass all these tests for cell screening.

TABLE 4.27-2. LEAD ACID BATTERY ACCEPTANCE TEST REQUIREMENTS		
Test (1)	**Paragraph**	**Quantity Tested**
Cell Lot Acceptance (2)	Table 4.27.1	100% of Cells
Component Examination (7)	4.11.1	
Identification Check (8)	4.11.5	100%
Visual Examination (8)	4.11.2	100%
Dimension Measurement	4.11.3	100%
Weight Measurement	4.11.4	100%
Performance Verification (2)	4.10.4	
Continuity, Isolation and Insulation Resistance (8)	4.27.11	100%
Charge Retention (8)	4.27.16	100%
Monitoring Capability (8)	4.27.12	100%
Heater Circuit Verification (8)	4.27.13	100%
Non-Reusable Venting Devices (Battery Only)	4.27.2b	Lot Sample (6)
Operating Environment Tests (5), (7)	4.15.1	
Acceptance Thermal Cycle	4.27.15	100%
Acoustic (4)	4.15.4	100%
Sinusoidal (4)	4.15.5	100%
Random Vibration (4)	4.15.6	100%
Performance Verification (7)	4.10.4	
Charge Retention (Battery)	4.27.16	100%
Electrical Performance (8)	4.27.14	100%
Continuity, Isolation and Insulation Resistance (8)	4.27.11	100%
Component Examination (7)	4.11	
Visual Examination	4.11.2	100%
Reusable Venting Devices (Battery Only)	4.27.2a	100%
Battery Case Integrity (3)	4.27.23	100%
Post Acceptance Storage (7)	4.27.17	100%

Figure 21: Cell Screening (Range Safety Group, 2010)

Once the cells have successfully completed all tests, the FTS battery needs to be built and tested in that configuration. There is some trial and error involved here, but many of the experiences of other departments (lead users), can be realized here, facilitating the process. A full Qualification program is conducted to ensure the design can handle the environment, plus margin. Upon successful completion of the Qualification testing, workmanship needs to be tested in the Acceptance testing. The batteries are certified for flight once the Acceptance tests have been completed.

Additional difficulties with choosing the COTS option arise since Range requirements in the governing documents have additional requirements to verify consistency in lots. The below requirements cite these additional concerns.

> Battery and battery flight cells shall use the same parts, materials, and processes as the qualification test unit.
>
> To be considered a "lot", non-configuration controlled (COTS) cells shall have a manufacturing code indicating that they are from a large, continuous, uninterrupted automated production run using materials from the same source.
>
> To be considered a "lot", limited production cells (non-automated production) shall be manufactured in a continuous, uninterrupted production run by personnel who are trained, qualified, and experienced in continuous production manufacturing techniques

(Range Safety Group, 2010)

It must be proven to the Range that the cells are from a continuous lot with the same lot code. Same processes and materials are used throughout the process, since this is what constitutes a lot to the Range. This includes the facilities and employees manufacturing the cells per lot. This is a requirement that many COTS manufacturers have trouble meeting. Since they are typically building in large quantities, it is hard to keep track of every lot. As a result, lots are often varied and built on multiple assembly lines. Identifying a COTS manufacturer who met these requirements was challenging and establishing good relationships with these vendors, allowed for these processes to be realized and observed.

While using COTS parts pose additional challenges, there is a lot of innovation in developing the core competencies in house which can be used to build future components. Purchasing in bulk also allows for the benefit of economies of scale and scope. Additionally, SpaceX maintains control of all the batteries which it builds, so there is never a fear of depletion of parts. Internal product innovation has led to the success and overall cost reduction per launch vehicle. When this methodology in product innovation is applied to hundreds of components across all the departments within SpaceX, the cost savings realization is huge.

Innovation in Project Management and Testing

Project Management is the discipline of planning, organizing, allocating resources, and optimizing workflow across several projects and subprojects. (Wikipedia, 2012). With the FTS system, project management was absolutely crucial in managing the three key areas of Scope, Schedule, and Cost. The major subsections of the three key areas are outlined below in Figure 22 with brief explanations of each one below.

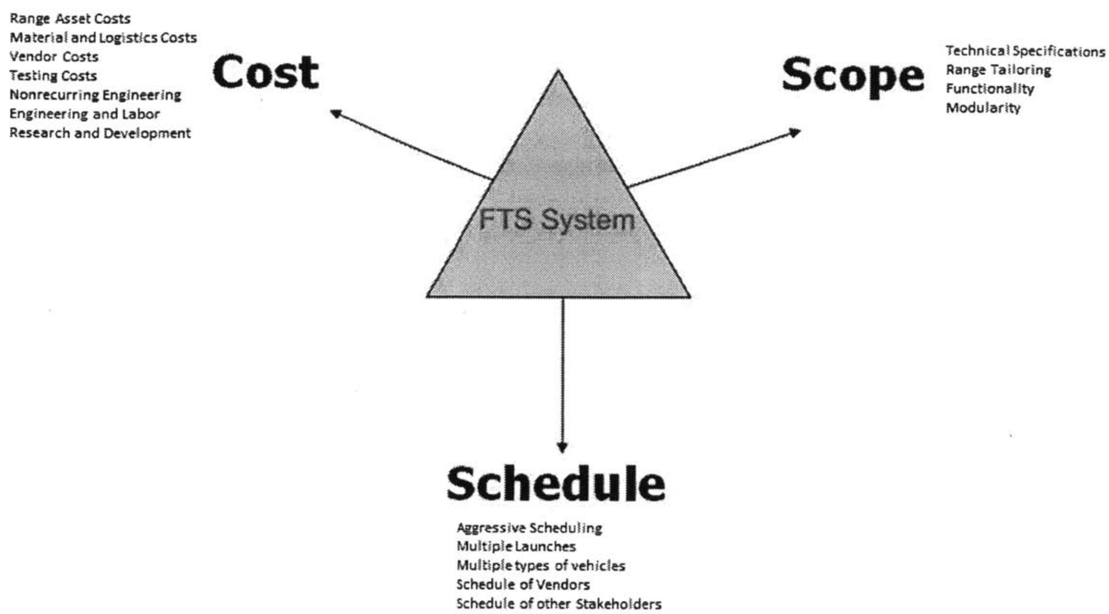

Figure 22: FTS Iron Triangle

- **Scope**-Aligning the scope is a very difficult challenge when you have multiple stakeholders, including the FAA and the various Ranges. Technical specifications have to be in line with the Range requirements tailoring and the system must perform exactly to its specifications. As described in the previous chapter, innovation was achieved in Range requirements tailoring through the consolidation of the processes and negotiations with several Ranges at once. This cut a lot of the bureaucracy associated with launching vehicles from different Range launchsites. Another aspect of scope which SpaceX has continually looked to achieve is the modularity of their test setups. All scope requirements are satisfied through testing, but streamlining how the tests are conducted is another way innovation is achieved. The later sections will discuss ways in which testing has added to the innovation at SpaceX

- **Schedule-**SpaceX operates on a very aggressive schedule, with launches occurring as quickly as 8 weeks after the prior launch. This means post flight data review, and any updates to components and documentation must be completed as efficiently as possible. In addition, with the upcoming Falcon Heavy vehicle, multiple vehicles are in development concurrently. Since not all components are built in house, working with the schedule of vendors, such as the ordnance vendors, and working the schedule for document approval from the various Ranges presents a challenge. SpaceX has noted the need for a lot of vendor and Range face time, as this social aspect of systems engineering allows for strong client relationships, where various stakeholders are willing to work at an elevated pace to help meet the needs of the aggressive schedule. This would not be possible in a situation where no client face time was pursued, rather a contract is signed, and one milestone date is given. Constant tweaking of the schedule and face time to discuss these changes is absolutely vital in meeting the schedule. One of the major ways SpaceX has been able to meet schedules is through bringing the vast majority of the testing in house to the SpaceX facility. This eliminates any wait time, and with changes on the fly, tests can quickly be conducted at a moment's notice. This will also be discussed in the testing section.

  An example of face-to-face meetings providing benefits for SpaceX involved the updating of documentation for Ordnance.

  The vendor had allocated over 100 days for the updating of documentation! This was much too much time for documentation review and acceptance, and typically at SpaceX, this was accomplished in less than a month. As a result, SpaceX worked with the vendor in bringing documentation in house. SpaceX proofread the documents, ensured that all Range requirements were met, then proceeded to meet with the Range, FAA, and the vendor to review the document and have it accepted. This was accomplished in a little over a month, saving over 2 months in the overall schedule, and freeing up resources at the vendor to continue to work on the other aspects of our program, including the actual manufacturing of the ordnance!

- **Cost-** Cost is among the most important aspects of sustaining a business. If the fixed and variable costs are too high, the company will remain unprofitable, which will eventually lead to the ceasing of operations. Costs can be segmented into several different categories. There are the Range Asset Costs which include the labor of the Range officials to review and approve documentation, tailor requirements with SpaceX, witness tests, and the use of Range facilities to launch the vehicle. This can include a lot of costly equipment such as radars, consoles, fire safety personnel, permits, to name a few. Material and logistics costs are also something which must be taken into consideration. The transport of the vehicle is costly due to permits required to transport across the country. In addition, components which are built in house must procure proper materials for prototyping and manufacturing. While these costs are significantly lower than having a vendor develop a part, they are still costs that have to be reckoned with.

  In order to remain innovative, SpaceX must also continue to do heavy research and development, which will allow for both product and process innovations moving forward to keep costs down. As mentioned, this is also a key consideration in bringing all processes in house, as it allows for the gain of core competencies among all the departments, and allows for cost synergies to be realized. Finally, testing costs, which are a major portion of total cost can be brought down through the streamlining of the testing process. Out of house vendors charge several thousands of dollars a day to test components, while having no competencies in the actual component. So if something goes wrong, they are not in the position to help with troubleshooting.

Amongst the three key areas, testing is a major contributor to the amount of resources required. With innovation in testing, the overall constraints of the iron triangle can be relieved. This next section will cover some of the measures SpaceX has taken to innovate change within traditional testing methodologies.

Innovation in Testing

Once technical requirements for a component have been agreed upon, the component spends a lot of time in the testing phase of the product development cycle. Often, reworks are required, resulting in even further required testing. Environment tests range from simple bench shock tests, where a component is dropped on a table to ensure it functions properly after the drop, to more complex tests such as pyrotechnic shock testing or thermal cycling, which can take several days or even weeks to complete. Figure 23 shows a typical Qualification Test Sequence where several environmental tests need to be run while the component is in operation mode and also when it is not.

Test	Section	Quantity Tested = 3		
		X=1	X=1	X=1
Acceptance Testing	Table 4.19-1	X	X	X
Non-Operating Environments:	4.13.1			
Storage Temperature	4.13.2	X	X	X
Transportation Shock	4.13.4	X	X	X
Bench Handling	4.13.5	X	X	X
Transportation Vibration	4.13.6	X	X	X
Fungus Resistance	4.13.7	X	X	X
Fine Sand	4.13.8	X	X	X
Operating Environment Tests	4.14.1			
Thermal Cycling (4)	4.14.2	X	X	X
Thermal Vacuum (4)	4.14.3	X	X	X
Humidity (4), (6)	4.14.4	X	X	X
Salt Fog (7)	4.14.5	X	X	X
Temperature/Humidity/Altitude (4)	4.14.6	X	X	X
Acceleration (3)	4.14.7	X	X	X
Shock (5)	4.14.8	X	X	X
Acoustic (3)	4.14.9	X	X	X
Sinusoidal Vibration (3)	4.14.10	X	X	X
Random Vibration (3)	4.14.11	X	X	X
Electromagnetic Interference and Compatibility	4.14.12	X	X	X
Explosive Atmosphere	4.14.13	X	X	
Cycle Life	4.19.13	X	X	X
External Leak Test	4.19.5	X	X	X
Pressure Cycle Life	4.19.11	X	X	X
Performance Verification:	4.10.4			
Valve Actuation Test	4.19.7	X	X	X
Component Examination:	4.11	X	X	X
Visual Examination	4.11.2	X	X	X
System Tests (8)	4.19.9		X	X
System Functional Margin (8)	4.19.6	X	X	X
Extended Stall	4.19.10	X		
Burst Test	4.19.14	X	X	

Figure 23: Typical Qualification Test Sequence (Range Safety Group 2010)

The Appendix has an interview with the Senior Director of Avionics Test and Manufacturing. He outlines some of the key areas where innovations have been made to streamline the testing process to reduce the overall schedule, cost, and scope of the FTS system.

- **Testing in house-** SpaceX has taken most of its testing in house, according to the Director of Avionics Testing and Manufacturing. Over 90% of all testing is done in house. With internal testing, it can be conducted 24/7 rather than being constrained by the testing house's hours of operation. Engineers can be there to troubleshoot immediate problems and make changes on the fly. This is not possible at a testing house. The innovation of doing everything in house means that initial fixed costs will be higher, with variable costs only being machine maintenance, labor and electricity. Because multiple components need to be tested, anytime there is a bottleneck, the queue size will grow, which in turn makes it more costly to SpaceX. As a result, SpaceX has moved these operations in house. An example of thermal chamber usage can be seen in Figure 24.

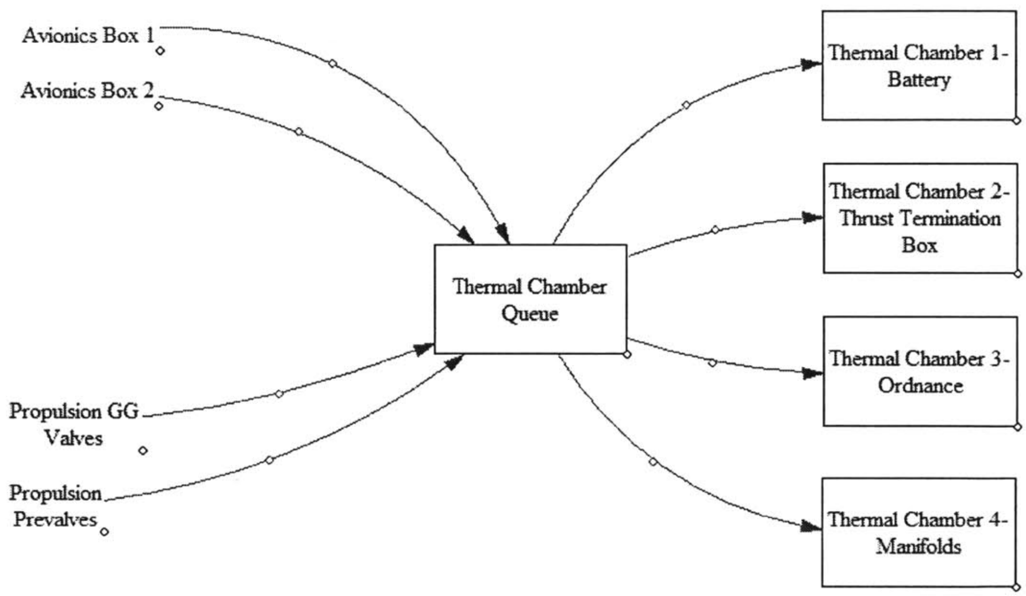

Figure 24: Cost Benefit Analysis of Thermal Chambers

In this example, we have a total of 4 components being tested and 4 components in the queue.

Assuming the thermal test follows a path similar to Figure 25, the test process will take 40 hours +

the time to setup the test. Assume the total time to be 48 hours or 2 days.

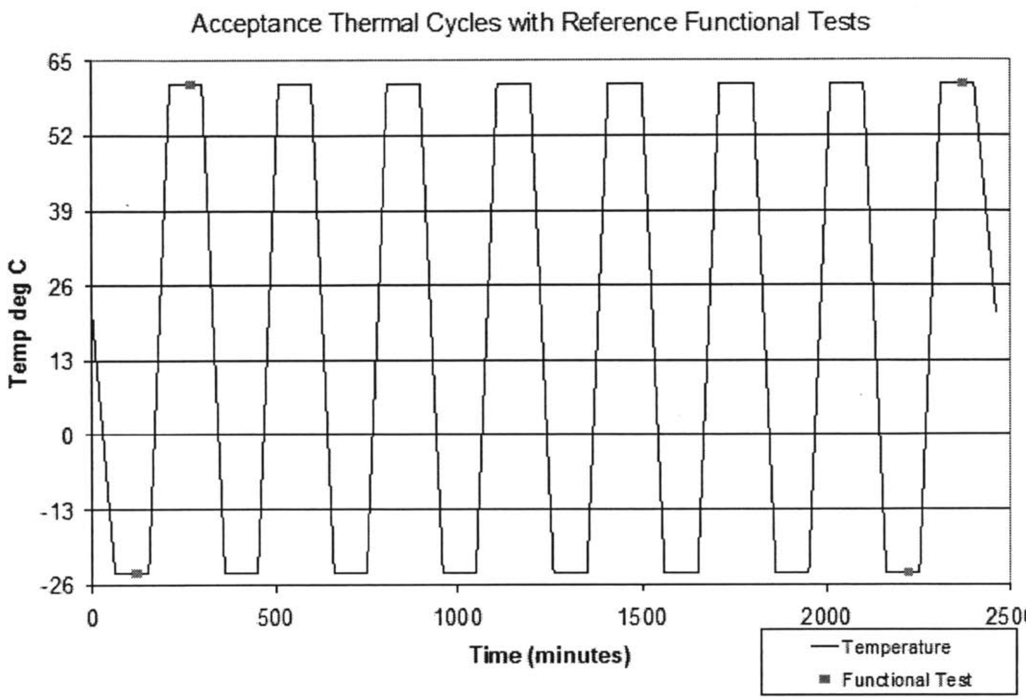

Figure 25: Thermal Cycling (Kwak, 2007)

If all testing is conducted in house, the total variable cost is the cost of labor + electricity with negligible maintenance costs, since the thermal chambers are very reliable, requiring little maintenance. With this option, all thermal chamber testing for all 8 components can be completed in 2 sets of components * 48 hours = 4 days for both sets. The total cost associated with this approach is:

(Engineering labor/ hr) * 16 (since chambers are run overnight with no supervision) + (Electricity/hr *48hrs * 4 chambers)

= ($50 *16) + ($20*48* 4) =$4,640

Multiply this value x 2 to take into account the 4 units in the queue, giving you $9,280. The fixturing and test setup are additional minimal variable costs per component type and would cost a few hundred dollars at most. A rough estimate for 8 components over a 4 day span is $10,000.

Running the same test function out of house the way most Aerospace companies do:

(Fixed daily labor rate* 4 days) + (Setup cost) + (Fixture Creation)

= (5000 * 4) + %1000 + %1000= $22,000 for 4 days

The cost delta between in house and out house is $12,000! This is 120% the variable cost of doing it in house. Now if we take into account the fixed cost of the thermal chamber plus setup of approximately $120,000, the payback period is simply

(inv cost/savings from in house) = ($120K/12k). This is roughly 10 X 4 day long thermal tests which can be recouped in less than two months!

Different tests have different levels of complexity and cost, with many tests such as pyroshock, costing more than double the cost of thermal cycling. Clearly the innovation of bringing all testing n house has huge benefits. Other benefits which are a bit less tangible include:

- Testing at any time of day
- Changes on the fly

- Issues with test equipment- More often than not, the transport of the test equipment may lead to damage of the apparatus, or may cause loose wiring. This has happened before, and it leads to potentially spurious readings or damaged hardware. These are very serious issues and they can delay testing even further.

Such competitive advantages are hard to quantify and must be done on a case by case basis.

Consolidation of tests- Another innovative means to save on costs, schedule and scope is to actually consolidate the tests. Dynamicists at SpaceX are actually able to combine multiple tests together. Doing this not only saves on test costs and complexity, but because one test encompasses two or more, there is a significant savings in schedule.

3 tests in 1

Test	Paragraph	Quantity Tested (5)		
		Cable X=3	Coupler X=3	Antenna X=3
Acceptance Tests	Table 4.16.1	X	X	X
Antenna Pattern	4.16.6	X	X	X
Performance Verification	4.10.4			
VSWR	4.16.2	X	X	X
Insertion Loss (1),(2),(3)	4.16.3	X	X	-
Isolation (1)	4.16.4	-	X	X
Abbreviated Antenna Pattern	4.16.7	-	-	X
Abbreviated Performance Verification	4.10.5			
VSWR(1),(2),(3)	4.16.5	-	-	X
Non-Operating Environment Tests	4.13.1			
Storage Temperature	4.13.2	X	X	X
Transportation Shock	4.13.4	X	X	X
Bench Handling Shock	4.13.5	X	X	X
Transportation Vibration	4.13.6	X	X	X
Fungus Resistance	4.13.7	1	1	1
Fine Sand	4.13.8	1	1	1
Operating Environment Tests(4)	4.14.1			
Thermal Cycling	4.14.2	X	X	X
Thermal Vacuum	4.14.3	X	-	X
Humidity	4.14.4	X	X	X
Salt Fog	4.14.5	X	X	X
Temperature/Humidity/Altitude	4.14.6	X	X	X
Acceleration	4.14.7	X	X	X
Shock	4.14.8	X	X	X
Acoustic	4.14.9	X	X	X
Sinusoidal Vibration	4.14.10	X	X	X
Random Vibration	4.14.11	X	X	X
Tensile Load	4.13.9	X	X-	X-
Internal Inspection	4.11.7	-	X	X

Figure 26: Consolidated Tests (Range Safety Group, 2010)

Figure 26 shows an example of Qualification by similarity. Random vibration tests vary its frequencies between 0 Hz and 2000 Hz over 3-6 minutes, depending on the component. (Range Safety Group, 2010). As a result, one can prove that Transport vibration which is a low vibration test at 10Hz is encompassed by the higher energy random vibration tests. Similarly, our dynamicists are able to prove that acoustic testing environments are fully encompassed in random vibration testing as well. This essentially consolidates 3 tests into 1 test, thereby cutting both schedule and cost for these tests by two thirds.

Multiple component testing- The Director of Avionics Testing and Manufacturing points out that to address the constant backfilling of the testing queue, he and his team have taken strides in innovating new ways to conduct tests for multiple components at once. He has been successful in doing this by modifying or purchasing test equipment with enough versatility for multiple components. Utilizing the thermal chamber example, His group now utilizes the thermal chambers in such a way that 2 or more different types of components can be tested at once. He accomplishes this by analyzing their operating temperatures and expected temperatures. He then couples those components together. For example, components which utilize a temperature mapping as seen in Figure 25 (-24C - +61C) for 8 cycles could now be placed together. They will also utilize a common test setup interface to monitor the component and run functional tests during the thermal cycling as needed. Traditionally, each component has been given its own test setup, but SpaceX has consolidated both the hardware and software setups for component testing, to allow quick changes from component to component. This innovation has paved the way for multiple component testing. Additionally, batch testing is something which is not traditionally done in industry. More than one flight's worth of hardware of the same component can be tested at the same time.

Taking into account the original example from the cost benefit analysis of the thermal chamber setup, if we were to place two different components instead of just one component in each thermal chamber, there would be no queue for the thermal chambers.

(Engineering labor/ hr) * 16 (since chambers are run overnight with no supervision) + (Electricity/hr *48hrs * 4 chambers(2 components in each))

= ($50 *16) + ($20*48* 4) =$4,640

This would amount to half the cost of to run the same tests as before, and cost less than 25% percent of running it at a test center. Additionally, the payback period for the hardware would be:

(inv cost/savings from in house) = ($120K/17k). This is roughly 7 X 4 day long thermal tests which can be recouped in less than one month!

An example of the savings via multiple component or "system" testing is realized when you can combine multiple components together. In this example we have two components, the Linear Shaped Charges and the Flexible Confined Detonating Cords. The two components were combined for testing, which consolidated two tests into one. This was allowable for many of the environment tests including pyrotechnic shock, random vibration, drop tests, and thermal cycling. The total estimated time for the combined tests was 10 weeks, a significant markdown from what would have easily been 20 or more weeks for all the components.

Overarching environments- SpaceX's dynamicists also take into account that the performance of every flight may vary. Sometimes there may be unaccounted for changes in performance of the propulsion system, which may drastically change the environments the FTS components experience. As a result, the dynamicists account for this by putting margin on top of margin by accounting for:

- Root sum squared of variability and uncertainties
- Flight to flight variability = 4.9dB
- Spatial variability = 0 dB
- Model uncertainty = 3dB (Jensen, 2008)

With this conservatism, there is a lot less delta qualification flight after flight, resulting in a lot less retest and possibility of test failures, which would result in a redesign.

Test Automation-The Director Avionics Testing and Manufacturing mentioned that test automation is a new innovation in testing SpaceX is currently implementing. Through the use of programmable test equipment, testing can be run by the apparatuses, with the software constantly monitoring the health of the FTS components. All parameters are accurately monitored by the Labview software, and in the event of a failure, an email is sent to the responsible engineer. Testing is then halted until the engineer is made known of the anomaly. By having automated testing, engineering resources can be freed up and used for other functions such as R&D work or other tests.

All FTS components must go through extensive testing. As shown, testing is neither cheap nor simple. It requires a lot of resources from engineers, program managers, and technicians. Going out of house for testing requires even more effort, since changes can no longer be made as easily, and the technicians at the testing houses do not always have the competencies in house team members have. Testing can also not be done at any time, including at night and over the weekend, unless it is a passive test, requiring no input from a technician or engineer. As a result, the innovative strides in testing which he and his team have made are a natural progression in meeting the growing demand of SpaceX to test its hundreds of components as efficiently as possible. As our thermal chamber example showed, thousands of dollars can be saved from only a few days of efficient testing. Imagine how much cost and schedule can be saved by multiplying these innovations across all components which need to be tested? According to him, millions have already been saved and that number is expected to grow even further.

Innovation at the Launch site

While much of the innovation at SpaceX occurs at the main headquarters in Hawthorne, where the majority of research and development, test, design, and decisions are made, it is at the launch site where the vehicle is assembled and integrated and system level tests are run. The FTS system is also installed at the launch site. Traditional launch vehicle companies take several months to complete vehicle integration and system level tests prior to running a static fire test on the vehicle to ensure all its systems run nominally. However, at SpaceX, all testing and integration are expected to be complete within a month of the vehicle's arrival at the launch site.

In order to meet this aggressive scheduling, several launch site innovations needed to take place. This included processes for efficient vehicle integration, streamlining systems testing prior to launch day and during launch countdown, and finally, software and hardware innovations including a streamlined user interface used by the engineers for console work and 3D model viewing for installations. These three areas and the innovation in each are discussed in the following sections.

Innovation in Integration

Traditionally, launch site integration occurs within a vertical integration building (VIB), where the vehicle and its processes are integrated vertically. This has been the preferred method for vehicle integration and many of the most successful launch vehicles, including the Shuttle, Titan, and Atlas vehicles have used this method. While this can work well for integration generally, it poses a challenge for testing FTS. Much of FTS system testing requires constant vehicle reconfiguration, such as signal strength sensitivity tests, where each opposing UHF antenna is tested, while the opposing side antenna is covered with an antenna hat. While this is possible in a vertical setup, the swaps can be made within minutes in a horizontal setup.

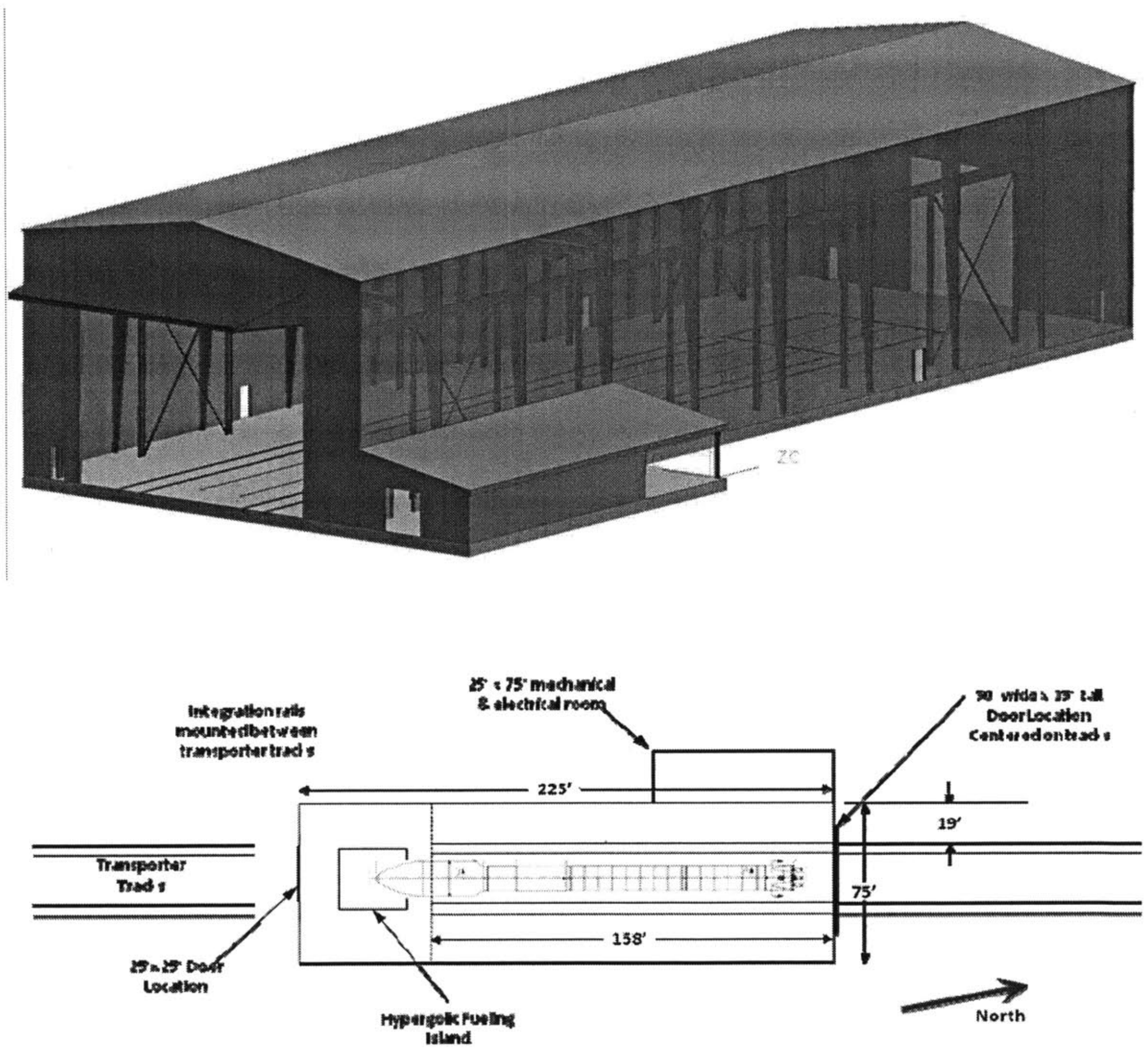

Figure 27: Horizontal Integration Building (SpaceX, 2009)

At SpaceX, to save significant time and resources, launch site activities were conducted as concurrently as possible. In order to meet this objective, engineers must have had access to the vehicle at all times. For components that are difficult to reach, the vehicle is simply rolled in place for reorientation to allow for easy access. For example, the FTS system utilizes Flexible Confined Detonating Cords which are long lines of detonating cord as seen in Figure 28

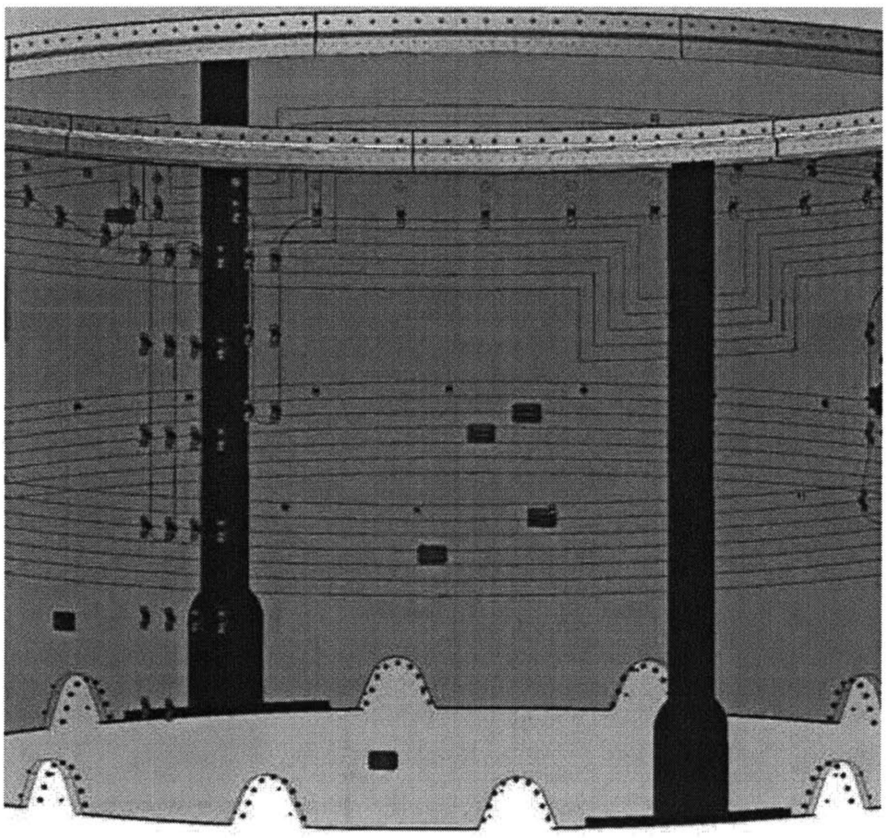

Figure 28: FCDC Detonation Cord (Hadden, 2010)

The vehicle utilizes over several hundred feet of cord which spans across the entire vehicle from the bottom of the first stage to just under the Dragon spacecraft. Such an installation in a vertical orientation poses extreme challenges, and often takes in excess of 3 weeks due to the requirements of fasteners and p-clamps every 12-14 inches, per Range requirements. For the first launch of the Falcon 9, this installation took 7 days in the horizontal orientation. The second launch installation was accomplished in a few days. This is a fraction of the time spent by SpaceX's competitors, and it is only possible due to the horizontal orientation of the vehicle.

As various systems are integrated onto the launch vehicle, fitment issues may occur resulting in rework. This is why easy access is absolutely necessary to complete this rework as quickly and accurately as possible. The Avionics section can be implemented much easier using the horizontal orientation. In the event something simple as an avionics component swap or a new key insert is needed, this change can be made on the fly and within minutes. Considering every component on the launch vehicle that can be similarly serviced with greater speed, safety, and convenience, the savings from the horizontal approach is immense.

Consolidated System Level Testing

Prior to launch, the FTS system must meet a multitude of launch site system level testing. These tests include:

- FTS Avionics Install Checkouts – Verify each component is installed properly and is functioning nominally
- Lanyard Pull Tests – Verify that the lanyard system used for the autodestruct system is installed properly and requires the proper pull force to actuate
- Radio Frequency (RF) Install and Checkouts – Verify the functionality of the RF System once it has been installed. This includes signal strength sensitivity and bandwidth tests

- Battery Tests – Verify the health of the battery
- System Level Testing – This includes simulations to Arm and Destruct the vehicle

The above tests are challenging and time consuming, but many have overlapping requirements. To increase efficiency in light of these overlaps, SpaceX tailored the governing documents to consolidate many of these tests, saving a significant number of days on the launch pad. The tests can be modified as such:

- **FTS Avionics Install Checkouts** – This test does not have much room for modification. All units need to be properly installed on the vehicle, and simple checkouts such as grounding concerns, voltage readings and proper torqueing are all taken into account. This process takes 1-2 days, but because of the horizontal orientation of the vehicle, other teams can work on different sections of the vehicle concurrently, allowing for shared resources.
- **Lanyard Pull Tests** – To verify the proper functionality of the autodestruct test, a total of 8 pulls (4 on each hemisphere), must be conducted and the pull loads must be verified by the Range. An initial challenge laid in the fact that since the vehicle is flown vertically, the pull test should be conducted in a vertical orientation as well. However, a vertical pull test is extremely time consuming since for every pull done, the vehicle must be lowered, data is verified, old shear pins are discarded, new ones are installed, lanyard cables are reoriented, and the vehicle must be re-raised. The horizontal pull test was much more streamlined and could be done in a fraction of the time. Once the tool for horizontal pull testing was proven accurate, SpaceX was allowed to do tests in both orientations.

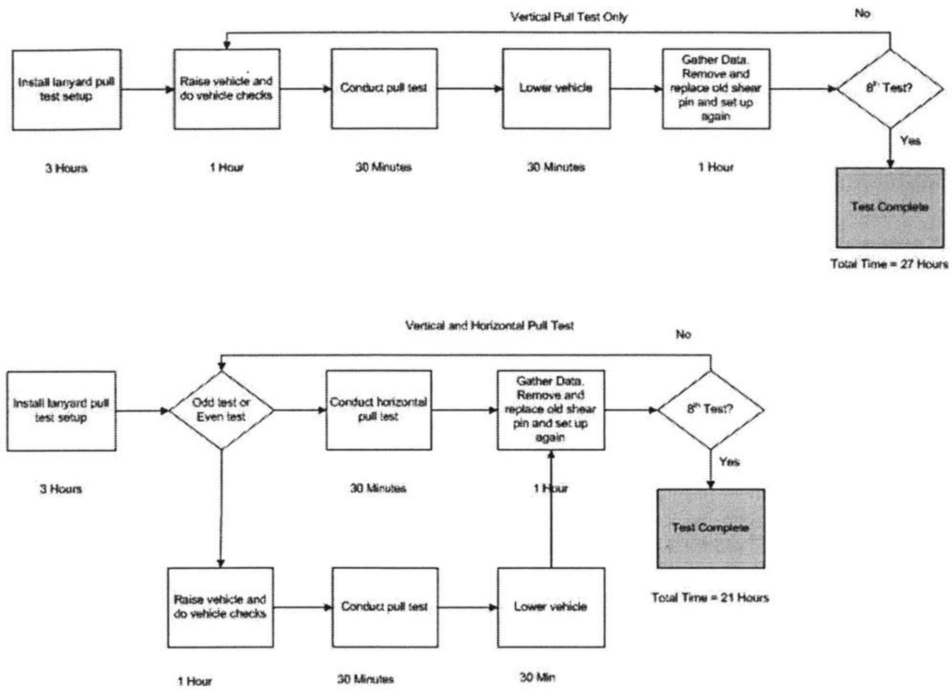

Figure 29: Vertical Pull Test versus Horizontal/Vertical Combination

Note: These times are notional and are not real data.

Figure 29 shows the sequences followed when conducting a vertical only pull test versus a combination of vertical and horizontal. Because it takes additional time to raise and lower the vehicle and do additional checks, an additional 1.5 hours is spent per test. The total time needed for vertical only testing was 27 hours while the total testing for a combination of 4 vertical and 4 horizontal pulls was 21 hours. While this is a difference of 6 hours, the actual savings to total integration time is greater because FAA and Range mandates prohibit more than 12 hours of consecutive work with ordnance. As a result, the true difference between the two test configurations is 3 days versus 2 days, and 1 day on the launch pad can be represent a significant cost. Furthermore, very little non-FTS work can be done during this time because ordnance requires a "clear zone" where personnel not running the pull tests are not allowed near the vehicle.

In addition to the time savings of horizontal integration, SpaceX created their own LPI simulator using the manufacturer's exact same shear pins. By proving the system to be identical to the flight system, eventually only 4 pull tests in the horizontal position were required, and none in the vertical position, thus, requiring a total of only 9 hours to complete! This is a significant savings from the original 27 hours.

- **RF Install and Checkouts** – Because of the horizontal orientation of the vehicle, installation of RF components was much simpler, due to easier accessibility. In addition, the checkouts required each antenna to be isolated, requiring antenna hats. This process of installing and uninstalling each hat required significant time.
- **Battery Tests** – Battery charging and discharging needed to be verified once the batteries were ready to be installed on the vehicle. However, to save time in this process, SpaceX elected to add an extra-long charge retention test during the Acceptance and Qualification testing. (Kwak,2007) This retention test allowed the batteries to go undisturbed at the launch site for over a month, thereby eliminating the extra battery test which would require approximately 16 hours to complete.
- **System Level Testing** – The day before launch, a System level test is conducted to verify that the entire FTS system works properly on internal power. Tones are sent from the MFCO to verify proper functionality of the FTS system. Ordnance simulators are installed on the vehicle to ensure that the proper amp pulse is sent from the FTS system to the ordnance train, thereby initiating the train. Normally, certain Arm commands are sent and evaluated during the countdown on launch day. However, to streamline the process for launch day, these tests were rolled into the System level test which occurs the day before launch. Arm commands are exhaustively checked out during this test. As a result, on actual launch day

when the FTS system is being checked out, it is an abbreviated version of what was checked out the day before. This can save up to 15 minutes during countdown which is critical in the event other anomalies are encountered. With the first launch, a multipathing anomaly was encountered due to a transporter erector obstruction. The 15 minutes saved in FTS checks allowed the problem to be quickly diagnosed with a proposed solution. As a result of this time savings, there was no delay in flight

Innovation Through Use of Software and New Technologies

To streamline processes at the launch site, innovative use of software and new technologies by SpaceX saved hundreds of hours and permitted the allocation of resources elsewhere. Specifically, there were two uses of software which helped streamline launch operations. They are in the form of the Console being built with National Instrument's Labview software and all models being built and viewed in Unigraphics. Additionally, the use of capacitive-based hardware has allowed for quicker testing.

Labview – Labview is very portable software which can be used on any Windows or Mac-based machine. No special equipment is required to run Labview software. SpaceX consoles all utilize the Labview software. It is extremely modular and the programming is all done in a graphical user environment. This allows for easy modifications and is easily understood even by non-programmers. One of the requirements for the FTS system is to have a fully certified working Graphical User Interface (GUI). To receive certification, the Range must verify the criteria of each component's functional limits, and have it accurately and clearly show up in the GUI. Because of the universal nature of Labview, it is not necessary to have the Range come to the launch site to review the GUI. Agreements can be made via teleconference with slight tweaks made on the fly. The changes are instantaneous and can be appreciated by all parties.

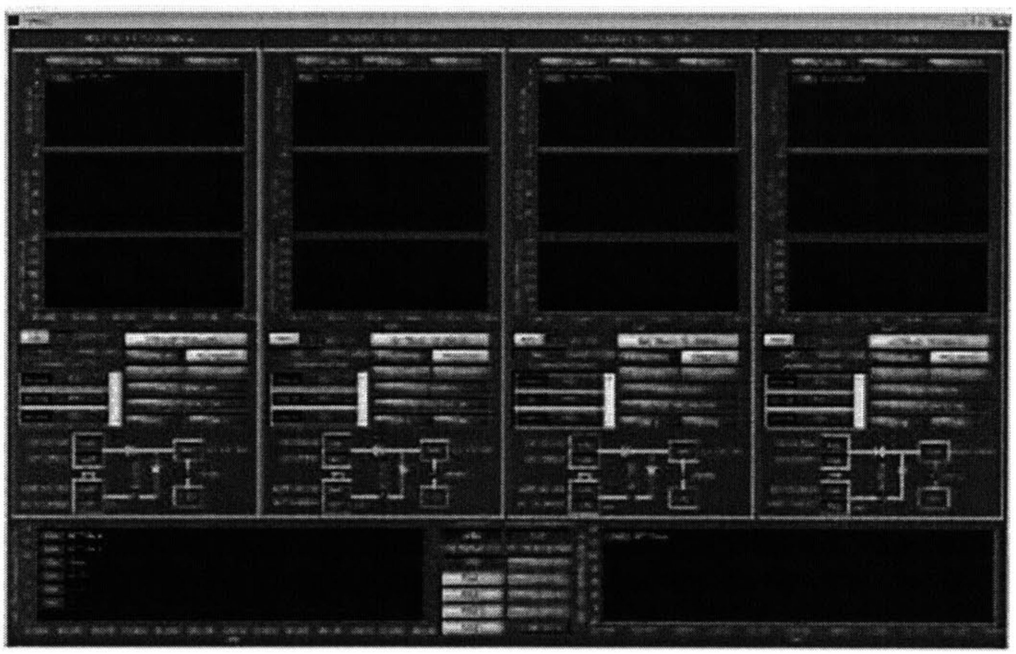

Figure 30: FTS Graphical User Interface (GUI)

As a result, an FTS GUI can be reviewed within a couple of hours either in person or via telephone or email, and any proposed changes are easily implemented. The certification process was usually accomplished within a few hours, saving considerable back and forth time in person. In addition, because of the power of Labview, many additional features could be added to help the Console Engineer. For example, various warnings and indications could be sent to the user if any component was reaching a minimum or maximum limit. Additionally, Labview could be programmed to send emails when a task was completed. While it is not recommended to do this during a launch countdown, these benefits could be realized in other tests, such as with the FTS battery which may be undergoing charge and discharge tasks. Because of the easy to use yet powerful tool in Labview, parameters can be changed instantaneously as well. If the Range and the FTS engineer decide at the last minute to change some of the parameter values, they are simply input into an excel sheet, and that parameter is immediately loaded. There is no additional process required.

Use of Models

SpaceX currently uses Unigraphics for all its CAD and CAM work. This is a very powerful modeling tool which through the use of Teamcenter, allows for all the subsystems of the vehicle to come together. For the purposes of installation, SpaceX started as most companies do utilizing drafts from their models. The drawing is a 2 dimensional version of the proposed orientation of the part, the dimensions, and not much else. An example of such a draft is shown in Figure 31.

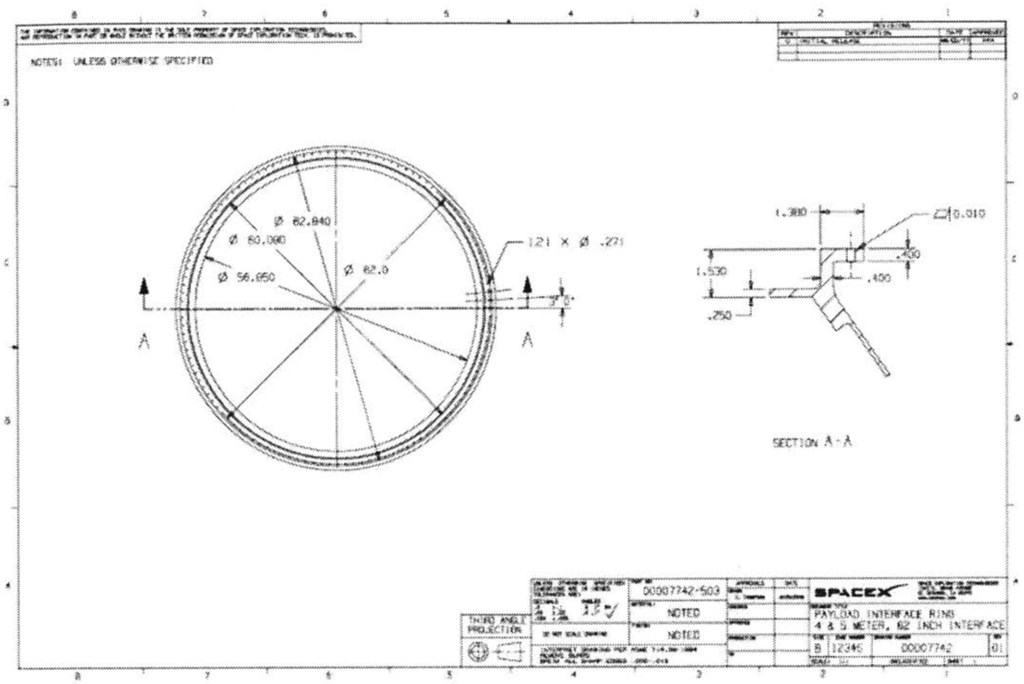

Figure 31: 2D Draft of the Orientation of the Payload Interface Ring (SpaceX, 2009)

To remove ambiguity of the 2D models and to provide real-time support in installing components on the launch vehicle, SpaceX elected to move all installation processes to 3D CAD based models. They were innovative in taking this approach, as all other launch companies and other engineering firms elected to stay with 2D based drafts. While you need powerful hardware to run 3D models for installation purposes, they provide real time feedback with exact locations, examples, and supporting parts which are used, such as bolts and washers with their prescribed torque values.

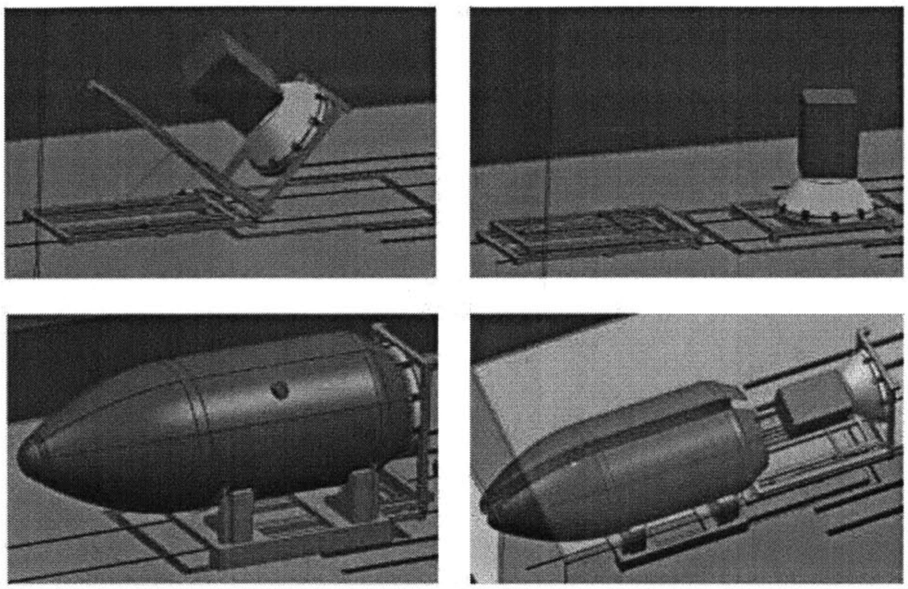

Figure 32:3D Modeling of the Payload Installation (SpaceX, 2009)

Figure 32 shows an example of the Falcon 9 payload encapsulation in the 3D model. It clearly shows the location of the payload and its orientation with respect to the vehicle. For more granularity, the 3D model allows the user to zoom in on any component in any orientation, and identify the proper part number, supplemental parts, and torque and connection values as needed. It also identifies if any special needs are required, such as the use of thermal grease, a grounding strap, or other supporting hardware or special requirements.

My initial experiences using traditional 2D based drafts left a lot to be desired. I often found myself having to open up the actual Unigraphics model to understand what the drawing was trying to represent. The need for a more accurate and clearly understandable model was not just for the FTS engineers, but all the technicians and other engineers needing to perform any install on the vehicle.

By implementing this innovative technique for installation, all of the guesswork of installing components properly had been removed.

Advanced Complementary Hardware

Similar to the installation process, SpaceX believes that cutting edge hardware will help realize the goal of quick installs and launch site processes. As a result, in addition to all installation drawings moving to 3D models, all installation procedures moved to the electronic space as well. While the upfront cost of the hardware may be more than simply printing out a procedure, the benefits are tremendous. Some of the benefits are touched upon below:

- **One document for all** – Because the document is an electronic document, it can be used by all parties when shared through the intranet. Engineer A, who is working the day shift, can put it in a repository for Engineer B to quickly access. This can be shared with managers and anyone else with an internet connection, allowing them to update schedules based on the status of the installation/test.
- **Installation Pictures** – With every installation, installation pictures are required. By using advanced hardware in the form of tablets, the engineer can simply take a picture on the fly with the tablet, and insert it into the document to show that the steps have been completed. This is significantly faster than having to grab a camera, take a picture, and upload the pictures. This is especially true when multiple steps require multiple pictures.
- **Voice Memos** – The promise of voice memos is especially attractive. If the engineer from the day shift had difficulty with a particular part of the installation or test, he can share this

information clearly with the night engineer, clearly outlining the steps he took to overcome the obstacle.

SpaceX has taken multiple innovative steps at the launch site to save resources and time. Combining all these innovations has allowed the company to be agile at the launch site and make changes quickly. As SpaceX expands to multiple launch sites, this value will be realized even further as the sharing of information will be instantaneous.

Further Innovation

SpaceX's pricing structure per launch vehicle is seen as a disruptive value proposition by many in the industry. SpaceX's CEO, Elon Musk has indicated that the Falcon 9 vehicle will remain between 50-60 million dollars per launch. This is compared to the several hundred millions per launch offered by its competitors. This price was only possible is through the use of several innovations as mentioned in the earlier sections. Further innovations must occur to drive costs lower going forward.

SpaceX has conducted 5 Falcon 1 launches, and 4 successful Falcon 9 missions. The technology behind the FTS system is now well established, and while further product innovations will still come down the pipeline, the focus must now shift to process innovation. As the Abernathy-Utterback Model in Figure 33 shows, the FTS system is now in a state where process innovations must be realized. Many innovations in the previous chapters touch upon both product and process innovation, but further and more expansive process innovations need to be realized in order to continue driving down the cost of the Falcon 9 vehicle. These innovations include the use of more efficient software and hardware, streamlining the FTS system to shed components which may potentially be omitted through requirements tailoring, as well as utilizing potential synergies with other entities. These are all discussed in the following sections.

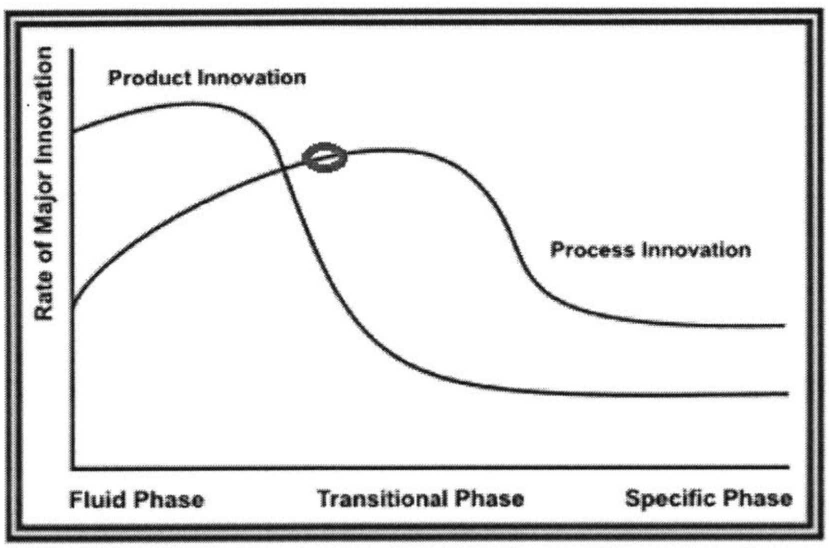

Figure 33-Abernathy-Utterback Model (Utterback, 1996)

NVIDIA Maximus and GPU Computing

In processing large quantities of data, the workload is typically handed off to the CPU, which serially crunches data and returns a result. However, with data becoming extremely complex, the CPU has not been able to keep up with the needs of users with large datasets. This is especially apparent with FTS data, which is often recorded at 10 Khz for several minutes or even hours. This results in data files which are over 1 gigabyte. Traditional computing time for such a process would require at least 10-12 hours utilizing a server farm. This leads to considerable downtime for the engineer looking for quick results to verify proper functionality of his component.

SpaceX has adopted GPU computing technology, which allows for accelerated calculations in engineering applications such as MATLAB, Simulink, and Nastran. Rather than just relying on the CPU cores for calculations, the GPU, which has thousands of additional cores, does the calculations in a fraction of the time. Combining both CPU and GPU allows for faster post-processing of data, allowing the engineer to enhance his workflow.

When looking at the relative speed up of simulations, we can look at both the single precision as well as the double precision performance when utilizing GPU-based computing. As Figure 34 shows, single precision sees a benefit of nearly 5x (100 Gigaflops for the CPU versus 500 Gigaflops for the GPU), and over 3x for double precision applications (50 Gigaflops for the CPU versus 160 Gigaflops for the GPU)

```
speedupDouble = results.gflopsDoubleGPU./results.gflopsDoubleCPU;
speedupSingle = results.gflopsSingleGPU./results.gflopsSingleCPU;
fig = figure;
ax = axes('parent', fig);
plot(ax, results.sizeSingle, speedupSingle, '-v', ...
     results.sizeDouble, speedupDouble, '-*')
legend('Single-precision', 'Double-precision', 'Location', 'NorthWest');
title(ax, 'Speedup of computations on GPU compared to CPU');
ylabel(ax, 'Speedup');
xlabel(ax, 'Matrix size');
drawnow;
```

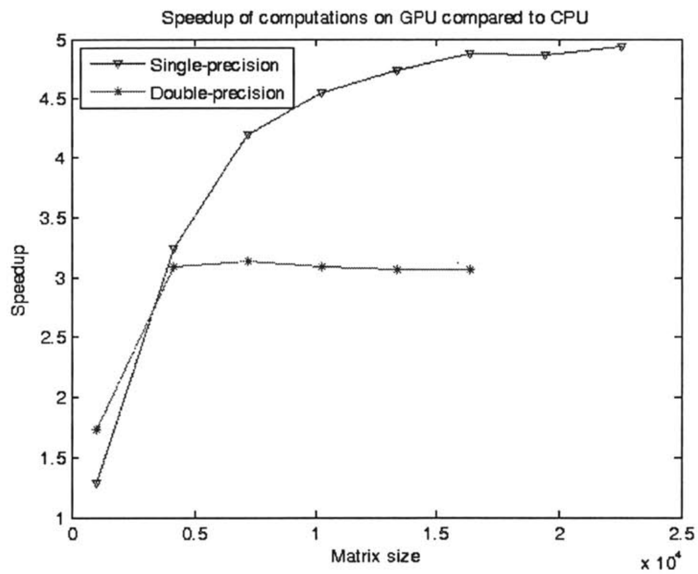

Figure 34: Relative Speedup of Using GPU Technology (Mathworks.com, 2012)

SpaceX, which utilizes a multitude of simulation and design software suites, will see faster compilation of datasets, which in turn allows for quicker decisions on how to proceed. The FTS specifically utilizes a substantial amount CAD software, whose data is processed in Matlab. This processing is done during testing, and based on the results, it is determined whether the unit meets its specifications. Sometimes waiting for the data to compile can take hours, especially if a server farm must be used to compute. However, with the use of GPU computing, a standard workstation with a Tesla C2075 can now compute in 10 minutes processes which normally take 1-2 hours.

Considering that each component will run through multiple tests with post-processing data, this is a significant savings in time and resources.

This need is even greater at the launch site where time is extremely critical. If an anomaly with FTS is experienced during System level testing or even during countdown, the fastest means to post process the data needs to be used. GPU computing's speed has allowed the FTS team to make decisions on the fly.

NVIDIA Maximus takes GPU computing a step further. Many FTS engineers at SpaceX are hybrid engineers, who do both computational and design work. They will take designed components and run simulations to ensure the FTS component is built properly to handle the operating environments. Maximus allows for simultaneous design and compute work as seen in Figure 35.

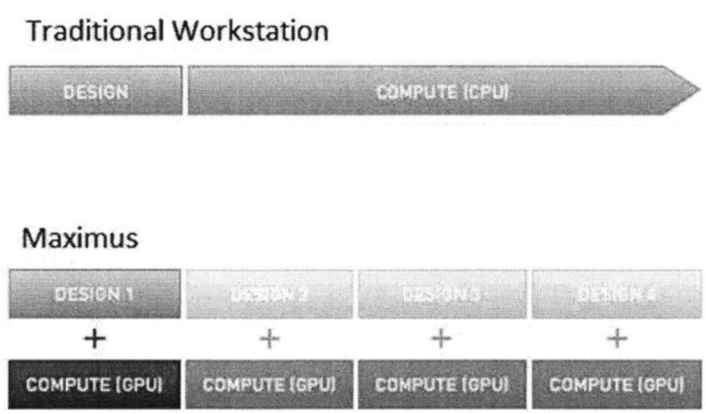

Figure 35: Change of Workflow (Nvidia, 2012)

Where traditionally an FTS engineer would design or make revisions to a component in Unigraphics, then run simulations in a FEMA program, the process remained serial. Because of the time constraints associated with having FTS components ready to be delivered to the launch site, revisions could only be made after each launch, out of fear of running out of time. However, with Maximus, revision work and simulations can be run concurrently. This allows for better refinement of the FTS component while doing all the due diligence in the simulation work. This new technology has been widely acclaimed at SpaceX and is currently being piloted by the engineers.

Synergies with NASA and Others

SpaceX would not have seen its current success without the help of many partnering organizations, especially NASA. . NASA has over 5 decades of experience, including with FTS, and SpaceX FTS engineers have begun to realize that synergies with NASA will enable them to enhance their FTS system further.

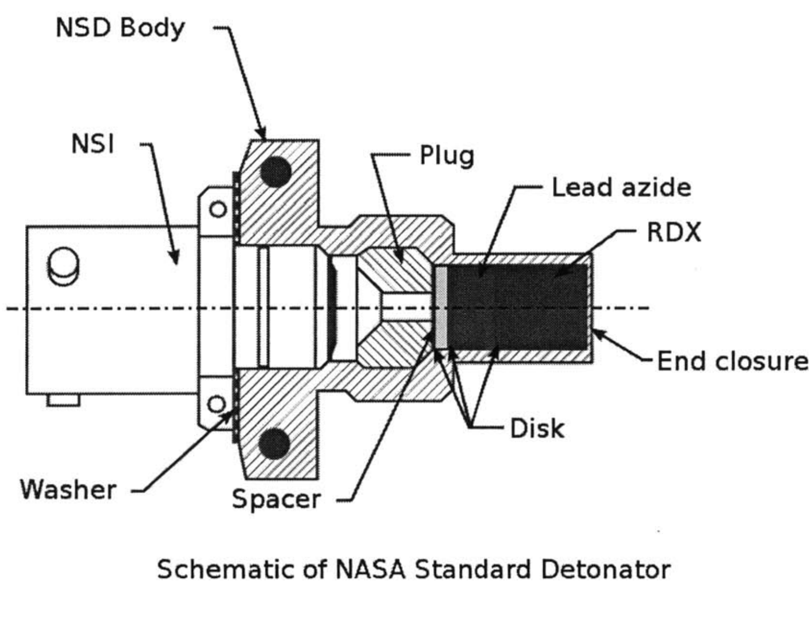

Figure 36: NASA Standard Detonator Assembly (Wikipedia, 2012)

The NASA Standard Detonator (NSD), which consists of an aluminum housing and a NASA Standard Initiator (NSI), have been used on almost all of the Shuttle missions with no failures. This is a highly reliable part which NASA uses as part of their FTS, in addition to other systems requiring an initiator or some form of ordnance. To keep in line with SpaceX's philosophy of innovation in-house, SpaceX has looked into developing some of the components which require ordnance in-house. While SpaceX does not yet have the core competencies to develop the explosives, they can develop the supporting hardware. In working with NASA's engineers, SpaceX was able to realize some synergies in developing an ordnance box. Because they are a partner, NASA is able to provide NSDs for testing at low cost. SpaceX in turn has taken these units and are now looking to build ordnance units in-house. A quick cost analysis:

Current Ordnance Component

(Unit Cost) + (Testing Per Unit) + (Non recurring engineering per unit)

(\$10,000) + (5,500+ (800)) = \$16,300

SpaceX + NASA

(NSD) + (Ordnance Body) + (Testing)

(\$400) + (\$500) + (\$1000)= \$1900

There would be a clear cost savings when working with NASA in this case. In addition, because the NSD has heritage and data which supports its reliability, SpaceX is afforded the right to forego many of the requirements and testing which are usually associated with FTS components.

If SpaceX continues to leverage its relationships with NASA and other entities, the synergies realized will not only help with FTS component design and manufacturing, but additional process innovations can be realized. Many of the lessons learned by these outside groups can be applied to SpaceX to prevent similar mistakes.

Thrust Termination Only

In an effort to streamline the FTS system, SpaceX has investigated the idea of implementing a thrust termination system only. This would mean the omission of all ordnance on the vehicle. This has not been done before at Cape Canaveral or Vandenberg. Because this is still very early in the process, little data is available. Tailoring has begun which opens the possibility of achieving a thrust termination only based FTS system. All the ordnance components including the FCDC Cord, Linear Shaped Charges, LPIs, Safe & Arms, and Ordnance Interrupters can be discarded. The approximate savings can be calculated below.

(15 X FCDC Cord) + (8 X LSC) + (2 X LPI) + (2 X S&A) + (2 X OI) + (Inert Manifolds)

= (15 * $2000) + (8 * $10,000) + (2* $5,000) + (2 * $15,000) + (2 * 8,000) + (4 * $500 + 2 * $1,000)

=$30,000 + $80,000 +$10,000 + $30,000 + $16,000 + $4,000 = $170,000 savings per flight

This would be based on the components, testing, program management and NRE only. Furthermore, there would be the additional space availability on the launch vehicle for other components or payload in addition to the weight savings which can be calculated to be approximately:

(15 * FCDC Cord+ Fasteners and P-Clamps) + (8 * LSC+ Fasteners) + (2 * LPI+ Fasteners and cabling) + (2 * S&A+ Fasteners) + (2 * OI+ Fasteners) + (Inert Manifolds + Fasteners)

(15 * 15.00lbs+ 20 lbs) + (8 *3.51lbs + 2 lbs) + (2*0.80lbs + .5lbs+ 10lbs) + (2 * 4.00lbs +2lbs) + (2 * 4.00lbs + 2 lbs) + ((4*.22lbs) + 2*.88lbs) + 2lbs) = 245 +30.08+ 12.1+10+10+4.64

=311.82 lbs. (Hadden, 2010)

With components spanning both the first stage and the second stage, assume the weight savings to be even on both stages.

1st stage = ~$5,555/kg of weight saved

2nd stage = ~$50,000/kg to LEO

(311.82/2)lbs = 155.91lbs per stage = 70.72 Kg

1st stage = ($5,555/kg * 70.72) = 392,849.60

2nd stage = $3.54M

Total cost savings from weight savings = ~$3.93M (Based on industry data per KG)

The savings calculated will vary based on what data is used per Kg, but the savings will be significant nonetheless.

Conclusion

As shown throughout this thesis, the FTS system must take into account not only the technical aspects of a system, but also societal and political factors, due to the fact that multiple stakeholders are involved with a primary focus on human safety. Cost is a tertiary concern to the Range and therefore not emphasized in the requirements of the governing documents. It is up to the Range user to seek innovation in architecting, designing, testing, and implementing an FTS system.

SpaceX has realized many innovations in the design of the FTS system, including the use of commercial parts, innovation in tailoring, launch site operations, and various forms of testing. In addition, SpaceX has leveraged many relationships with vendors, government entities, as well as NASA. SpaceX continues to look for new ways to innovate, whether through the streamlining of the FTS architecture, new technologies available to revolutionize their workflow, or even developing core competencies it previously did not have.

In-house development is vital to the success of SpaceX. With a large portion of its budget allocated to research and development, SpaceX looks for interdepartmental synergies, thereby eliminating the need for redundant processes for each department. As the FTS battery example showed, the FTS and Avionics groups both had a need for a new battery, and the innovation for cost reduction as well as the features offered within the battery were greatly improved due to the collaboration between multiple groups. This same philosophy must continue to be used for all other parts of the system as well.

Process innovation will also be an important contributing factor to the success of SpaceX. Following the Falcon 9 launch vehicle, other vehicles within the Falcon family are on the near horizon. These include Falcon Heavy, which will be the most powerful vehicle since the Saturn V, as well as new modifications to current vehicles to allow for flyback of each individual stage. Only with continued innovation within all departments, including FTS, will such ambitious ventures be realized.

SpaceX has grown from approximately 100 people in 2006 to over 2000 in 2012. The FTS team remains relatively small with approximately 5 engineers and 5 technicians to support all the functions of the FTS system. Notwithstanding the size of the group, because of the innovations the FTS team was able to realize as well as the key relationships they were able to establish with various stakeholders, the FTS team should be able to handle all future challenges by utilizing the same approaches which have brought them success so far.

References

SpaceX. (2009). Falcon 9 Launch Vehicle Payload Users Guide

Jensen, J. (2008), Falcon 9 FTS Environments Derivation

Committee on Space Launch Range Safety, Aeronautics and Space Engineering Board. (2000), Streamliming Space Launch Range Safety

Hadden, J. (2010), AV8001 Falcon 9 Flight Termination System Report (FTSR)

Kwak, E. (2009), Falcon 9 Lead Acid Flight Termination Battery Specification

Range Safety Office. (1997), Eastern Western Range Requirements (EWR) 127-1

Kwak, E. (2009), F9 FTS Progress Update (PPT)

Schmitz, T. (2009), F9 S2 Avionics Trays

Hillyer, T. (1999). Atlas Space Launch Vehicles—System Cost

Kwak, E.(2007), AV1118 Battery Screening Procedure

Wikipedia. (2012), http://en.wikipedia.org/wiki/Project_management

Wikipedia. (2012), http://en.wikipedia.org/wiki/NASA_standard_detonator

Utterback, J. (1996), Mastering the Dynamics of Innovation

Gifft, A. (2012), FTS Battery Acceptance Test Report

Von Hippel, E. (2012), Lead User

Nvidia. (2012) http://www.nvidia.com/object/maximus.html

The Mathworks. (2012)http://www.mathworks.com/products/parallel-computing/examples.html?file=/products/demos/shipping/distcomp/paralleldemo_gpu_backslash.html

Range Safety Group, (2010) Document 319-10

Appendix

Interview

Interview with the Senior FTS Manager

Eugene: Please give us a little background of your time and position here at SpaceX.

FTS Manager: I am the Senior FTS Manager here at SpaceX. I have been with the company for over three years now.

Eugene: How would you say your experience in tailoring has been?

FTS Manager: What started out as a painful process has evolved into something more pleasant. I guess the best way to describe it would be is a learning process which we have been able to improve through innovative relationship strategies with the various stakeholders.

Eugene: What has changed?

FTS Manager: Where we used to tailor specific to each Range which we fly out of, we now can have a more universal set of requirements which will satisfy the requirements for all Ranges, whether it is the Cape, Vandenberg, Kwajalein or other. We also have a lot more credibility than we used to due to our recent successes.

Eugene: What were some of the biggest obstacles?

FTS Manager: Because each Range is located in different regions with different geographical challenges, it was hard to come up with a universal set of guidelines for everyone to follow. It is still not perfect, and we are still working the process through, but huge strides have been made where requirements which were tailored for the Eastern Range, may mostly be used in the Western Range as well. This also includes the use of most of the same FTS on Falcon 9 and Falcon 9 heavy.

Eugene: Can you give us an example of when this conflicting interest between Ranges caused problems for SpaceX?

FTS Manager: Sure, we had originally built an FTS battery to fly out of Kwajalein, where the geography and population densities are significantly different than those at the Cape. While it passed Qualification testing and Acceptance testing, we did some Qualification by Similarity Analysis. We also tailored certain requirements, as we came to an agreement that they weren't necessary. Range documents have more general requirements, and they need to be honed into our specific system. So while it was Qualified to fly out of Kwajalein, the Eastern Range had different personnel and had modified requirements from Kwajalein. As a result, a lot of the requirements which we satisfied one way or other were no longer satisfied. A lot of time was wasted either requalifying or coming up with justification (analysis) as to why we should be able to fly.

Eugene: So it was both resources as well as time which were wasted on your part.

FTS Manager: Absolutely. Our engineers had to run additional Qualification tests, do additional analysis and due diligence to prove the part was acceptable for flight and in some cases make hardware design changes. It may have been easier to just build the battery backup from total scratch. The general culture at SpaceX is to keep things moving and not waste any time. This was directly in contrast to the company culture.

Eugene: How did you work your way around this problem?

FTS Manager: We continued to push through with our design and tailored as possible. We also were sure to keep other Ranges in the loop, since this is a process we never wanted to repeat again. Essentially we streamlined the process of working with each Range and the FAA.

Eugene: So your innovation in the tailoring process was to take multiple stakeholders and work with them concurrently in addition to actually challenging the status quo per requirement. Clearly, establishing a strong working relationship with them was important as well. Traditionally, you are only supposed to work with one Range at a time and follow the same process with every Range you launch with, correct?

FTS Manager: That is correct. Our innovation was in streamlining the red tape associated with dealing with the multiple Ranges and the FAA and establishing relationships. Each Range requires multiple buyoffs at the engineering, manager, and senior manager level. This process can take several months for each component. This is just not in line with the philosophy of SpaceX, where we are looking to revolutionize space travel. Imagine having to go through this process with 2 dozen components?

Eugene: How much time and resources have you been able to save as a result?

FTS Manager: It's hard to quantify. However, when you take into account each component, the engineering hours, the tailoring hours and the number of stakeholders, that number is easily in the millions.

Eugene: Wow, that is amazing. What future innovations are you taking within tailoring to help speed the process up?

FTS Manager: Well now that we have had a chance to establish a reliable FTS system, we want to continue building our relationships with the various Ranges and stakeholders to assure that we are always on the same page if a revision needs to be done to any component or subsystem. Also, we will continue to fine tune our tailoring to meet the specific needs of SpaceX. By innovating in the tailoring process, we can assure that we have components that have maximum reliability without any extraneous functions or use of expensive materials or tests. This is the biggest mistake our competitors make. Keeping requirements too general which leaves problems open ended. We streamline the process and keep everyone in the loop.

Eugene: While tailoring seems to be a necessary process, it seems like it has turned from one of the biggest bottlenecks to just any other process now through innovations in maintaining concurrent relations with all the Ranges, the FAA, and other stakeholders

FTS Manager: It will never be easy, but based on the innovations we have made with meeting technical requirements, we have overcome a huge hurdle. If we ever want to change the system moving forward, it will take a lot less time than when we had originally started building an FTS system. We now have the reliability, credibility, and process in place to ensure our stakeholders are in agreement with any plans which we set forth with the FTS. And we were able to do this with approximately 1/5 members in the FTS team than other launch groups which shows the efficiency and multitasking associated with each member.

Eugene: Great thank you .

Interview with the Senior Director of Avionics Test and Manufacturing (T&M)

Eugene: Please give us a little background of your time and position here at SpaceX.

Avionics T&M Director: Sure. I have been with SpaceX for over 7 years as the Director of Avionics Test and Manufacturing (T&M).

Eugene: How has testing changed?

Avionics T&M Director: You were here for over 5 years. When you first started, we only had a few different apparatuses for testing, including 1 thermal chamber, and one small shaker capable of less than 20 GRMS. We had to go out of house for most of our testing to Wyle, NTS, or other testing houses which charged upwards of tens of thousands of dollars per day. We now do over 90% of the testing in house with our nearly dozen thermal chambers, 3 vibration tables capable of over 100GRMS, shock setup, vacuum testing setup, plus many other setups.

Eugene: Agreed. We definitely did almost all our testing in house towards the end of my tenure at SpaceX. What led to this growth?

Avionics T&M Director: Well Elon (CEO), really wanted us to be innovative in the way we tested our products. So we took many different approaches to this. Our primary objective was to bring in as much testing in house as possible. Therefore, we did have to increase the overall quantity of test apparatuses we have in house. However, we did not stop there. We researched, developed and implemented batch testing capability of multiple components in Thermal, Vibration and Burn-In requirement, which is not very normal in much of industry. We've equally pushed the advancement of test automation which allows us to execute at a nearly 24/7 operation with minimal overhead.

Eugene: By multiple components, you mean if we had to test for example a battery and a Thrust Termination Box, we would look for ways to test both at the same time?

Avionics T&M Director: That is correct. Also other forms of batching would be to test multiple flights worth of the same hardware, so in essence we can test 2 flights worth of batteries at the same time, allowing for a higher level of efficiency and schedule reduction.

Eugene: How is this accomplished?

Avionics T&M Director: Well this couldn't be done for all components and all tests due to form factor, mass considerations and test levels. However, in a lot of tests such as thermal cycling. Many units could be tested together as they shared common thermal profiles. Per the Range requirements for example, you have to induce 8 cycles at -24C - +61C and for Qualification testing 24 cycles at -34C - +71C. If they have the same profiles, why not just test them together?

Eugene: And what did that accomplish?

Avionics T&M Director: By testing multiple components, the test equipment resources became free quicker, allowing us to test other components in the queue. This saved a lot of time and resources.

Eugene: How much would you guess?

Avionics T&M Director: Millions without a doubt. There's the waiting time of engineers. If a component fails late in the process and there is a queue, they may end up being the long pole in the mission. We also built all our own test fixtures. This usually takes weeks even months if you order out of house, where you have to send them drawings, have them manufacture it and mail it to us.

Eugene: You mean the fixtures where the components being tested are mounted?

Avionics T&M Director: Correct. We do this all in house, so changes can be made on the fly.

Eugene: Correct. And by doing so, you're saving a lot of wait time. This way tests are always moving and there's no down time.

Avionics T&M Director: That's correct. And with a place like SpaceX, you know how fast we are developing new products. We try to have components designed, prototyped and tested in under a month.

Eugene: What other innovations have you taken in testing?

Avionics T&M Director: Well in addition to the speed of tests we're able to do, we also have taken an innovative approach to the levels we test to.

Eugene: What do you mean?

Avionics T&M Director: Because every flight has the possibility of anomalies, we do not want to have to delta qualify after every launch. This would waste a lot of time and resources, and may lead to costly redesigns. We don't have the time and resources to be doing that. We would prefer to get it right the first time. So we test with margin on top of margin. While 4.9dB must be added for qualification testing, we usually add a few more dB to account for anomalies. So our components are very robust the first time around. The second thing we often look into with our more sensitive components is to isolate them. Whether through elastomeric or wire rope isolators, we can have our components handle a harsher environment than what would otherwise be allowed.

Eugene: I see. So by doing this, your components may initially be failing more during initial design, but then as it becomes more robust or through the use of isolators, they are able to handle a higher load, which makes it more viable to use on other launch vehicles in the SpaceX family with minimal changes.

Avionics T&M Director: That is right. Our components are built with margin from the beginning. Coupled with the innovative process we follow in testing, we're able to get components through very quickly. The queue is always full though, as you know, because we are constantly building for our newer vehicles on the horizon. So while the same component isn't being tested, additional components which may be needed are. We're always busy here. With our processes in place, we can do in 2 weeks what our bigger competitors do in 3-4 months out of house.

Eugene: Correct: and by my quick math, if they spend 3 months testing, assuming 5 days a week X 12 weeks at 5k a day, we are in the realm of 300k for the test.

Avionics T&M Director: That's right. That's the cost of one thermal chamber there.

Eugene: How much do you think it would cost for the same component in house?

Avionics T&M Director: Well we can probably do it in 2 weeks. There are no constraints in terms of time or day. As you are very well aware, we do testing at odd hours and on weekends. With all materials available, apparatus built in house, and fixtures, the only real cost we have is engineering hours and materials.

Eugene: So assuming 14 days, fixed material costs of 1k, and labor of let's say 1k per day, we are talking

14 X 1K + 1K= 15k. Only 15k!

Avionics T&M Director: That sounds about right. Also take into account that we concurrently test multiple components so there is some savings in there.

Eugene: That's right. Impressive. So what other innovations are you looking to do?

Avionics T&M Director: Well, there's always the possibility of renting our equipment out to offset costs incurred here, but that won't happen any time soon. We will continue to streamline our testing process, and ensure that we can fully meet all capacity for testing. That should continue to keep our costs low.

Eugene: Agreed. Thank you.