# AC 2007-1917: ENGINEERING EDUCATION LESSONS FROM A SOUNDING ROCKET CAPSTONE DESIGN COURSE

**Ralph Sandfry, US Air Force Academy**

Lieutenant Colonel Sandfry is Assistant Professor of Astronautics and Systems Division Chief, Department of Astronautics, United States Air Force Academy. He also serves as Program Director of the FalconLaunch Sounding Rocket Program. As Systems Division Chief, he leads 10 faculty members in developing and teaching 7 college-level courses in Astronautical Engineering. In directing the FalconLaunch program, he leads 5 faculty, 3 NCOs and 5 contractors in providing senior-level cadets an opportunity to design, build, test, and fly a sounding rocket to the edge of space. With sponsorship from the Air Force Research Laboratory, he led the cadets in flying the Academy's first successful supersonic rocket. He also teaches engineering courses in astrodynamics, attitude dynamics & control, rocket propulsion, linear systems analysis and controls. Lieutenant Colonel Sandfry is originally from Columbia, Missouri. He earned his commission from ROTC and the University of Kansas in 1989, graduating with a major in Aerospace Engineering. His Air Force career includes engineering and program management assignments with the Global Positioning System Joint Program Office in Los Angeles AFB, California and the Maverick Missile Program Office at Hill AFB, Utah. In 1995 he was selected as an Instructor of Astronautics at the US Air Force Academy. In addition to teaching, he served as Director of Research and Executive Officer. In 1998, the Air Force Academy selected him for the AFIT Civilian Institution program, and he chose to attend Virginia Tech to pursue a doctorate degree in Aerospace Engineering. Upon graduation in 2001 Lieutenant Colonel Sandfry was assigned to Detachment 4, Air Force Operational Test & Evaluation Center, Peterson AFB as Test Director for Wideband Communications. After managing three multi-service test programs for the Global Positioning System, Global Broadcast Service, and Wideband Gapfiller System, Major Sandfry was selected in 2002 to serve as Det 4 Director of Operations. Lieutenant Colonel Sandfry is a Distinguished Graduate of AFIT as well as Squadron Officer School. His PhD Dissertation was selected as the Outstanding Dissertation for all of Virginia Tech in 2001. He has published papers on satellite dynamics in several engineering journals.

**Michael Bettner, US Air Force Academy**

Lieutenant Colonel Michael P. Bettner is the Director of Labs, Department of Astronautical Engineering, United States Air Force Academy. In this position he supervises a $2 million state-of-the-art Engineering Division Laboratory supporting 7 academic departments, 13 academic courses, and over 2,000 cadets annually. He directs facility and technician support for the Space System Research Center's $4 million satellite and sounding rocket program. The Department of Astronautics helps produce the finest Air Force officers in the world who live our core values and understand space.

Lt Col Bettner attended the United States Air Force (USAF) Academy and graduated as a Distinguished Graduate with a Bachelor of Science degree in Astronautical Engineering in 1987. He earned a Master of Engineering Degree in Aerospace Engineering from the University of Colorado in 1995 as the Top Graduate. Lt Col Bettner has completed of Squadron Officers School, Air Command and Staff College in residence, and the Air War College.

Lt Col Bettner was commissioned as a second lieutenant in May 1987 and is a command pilot with over 4.000 hours in the T-37B, T-38A, T-3A, C-130E/H, RQ-01A (Predator) and C-17A.

After graduating from USAF Academy, Lt Col Bettner attended Undergraduate Pilot Training at Williams AFB and remained as a T-37 Instructor Pilot. His next assignment was to Yokota AB, Japan as an Aircraft Commander in the C-130E/H. Following this tour, he was selected for the Air Force Institute of Technology Civilian Institution program and attended the University of Colorado with a follow on assignment to the USAF Academy. During this assignment, he became an Assistant Professor in Astronautical Engineering and flew as a T-3A Instructor Pilot. During his time at USAF Academy, Lt Col Bettner distinguished himself by earning the Outstanding Academy Educator, Outstanding 1st Year Instructor, and the Wittry Award for outstanding instructor in engineering design; the only winner of all three awards in departmental history. His next assignment was to Nellis AFB as a pilot in the Predator Unmanned Aerial Vehicle. Following this tour, he attended Air Command and Staff College in Montgomery, Alabama. After school, he was assigned to Charleston AFB, SC and qualified as a C-17A Instructor Pilot. Lt Col Bettner flew missions in Operation Enduring Freedom and Operation Iraqi Freedom. During this time, he has served as an Assistant Operations Officer, Chief of Command Post, and the 437th Operations Group Director of Special Airlift. Lt Col Bettner is now assigned to the USAF Academy as the Lab Director and Assistant Professor in the Department of Astronautics.

**Tim Lawrence, US Air Force Academy**

Lt Col Lawrence is the Director of the Space Systems Research Center and assistant professor for the Department of Astronautics at the United States Air Force Academy. He directs one of eleven AFOSR funded USAFA research centers, conducting space technology research to design and build innovative low cost spacecraft and sounding rockets with 15 faculty from 5 academic departments, 56 cadets, 6 contractors, and 3 reservists under an annual $1M budget. Lawrence is also the small satellite program director, setting goals for performance, schedule and cost to meet DoD mission objectives for 3 microsatellites. He directs and teaches senior level capstone courses in spacecraft design determining content, leads sessions, and evaluates performance. Lt Col Lawrence is originally from Waterloo, Iowa. He was a 1988 graduate of the United States Air majoring in Mathematical Sciences. Lt Col Lawrence attended MIT where he won a Department of Energy Fellowship and received a Master of Science in Nuclear Engineering in 1993. Lt Col Lawrence received a Doctorate of Philosophy in Electrical Engineering, specializing in Satellite Engineering from the University of Surrey (UK) in 1998. His PhD research led him to receive the Thomas Hawksly Gold Medal from the Institute of Mechanical Engineering in 1999. Lt Col Lawrence’s professional experience includes advanced propulsion research in nuclear thermal and solar thermal propulsion at Edwards AFB. At the Air Force Office of Scientific Research’s London office, Lawrence was a program manager for space technology. His collaborative research with the Russians led to a text book in electric propulsion and development of the world’s first low power Hall Effect electric thruster. He has served as an instructor, research director, division chief, and systems engineering chairman in the Department of Astronautics at the Air Force Academy. Lt Col Lawrence is a co-chairman for the International Astronautics Federation’s advanced propulsion technical committee. Lt Col Lawrence is an open water swimmer, and has swum the English Channel, around the islands of Jersey (UK – 41 miles), Manhattan, and Key West, from Vis to Split Croatia (37 miles), Lake Zurich (26 km), the Solent Channel (UK), and the Tamp Bay marathon swim. He has also run the Boston Marathon and finished Ironman Florida twice.

**Michael Sobers, US Air Force Academy**

Captain Sobers is an Instructor of Astronautics in the Department of Faculty at the United States Air Force Academy. He is the Course Director for Space Systems Engineering and he also teaches core Astronautics. Captain Sobers attended Georgia Institute of Technology in Atlanta Georgia. He earned a Bachelor of Aerospace Engineering degree in 1998. He attended the Air Force Institute of Technology (AFIT) in the Aeronautical and Astronautical Engineering department. In 2002 he earned a Master of Science degree in Astronautics and graduated as a Distinguished Graduate. In 2004 he attended Squadron Officer School and finished as a Top Third Graduate. In 1998, Captain Sobers was commissioned through the ROTC program at Georgia Tech. His first assignment was at the Training Systems Product Group, Aeronautical Systems Center, Wright Patterson AFB, OH. During this assignment, Captain Sobers was a developmental engineer for the acquisition of several major flight simulators, including C-130 H2, JSTARS, and AWACS. While at Wright Patterson AFB, Captain Sobers was selected to attend AFIT. He earned a of Master of Science degree in Astronautics in 2002, with course sequences in Structural Analysis and Advanced Astrodynamics. After graduation from AFIT, he was assigned to the Air Force Advanced Composites Office, a field office of the Air Force Research Laboratory Materials Directorate. As a composites engineer, Captain Sobers was involved in the analysis and design of repairs for composite aircraft structures. He was also the lead engineer for Aircraft Battle Damage Repair of the F-117 Nighthawk. In 2005, Captain Sobers was assigned to the United States Air Force Academy as an Instructor in the Department of Astronautics. He is a member of the Tau Beta Pi and Sigma Gamma Tau engineering honor societies and holds Acquisition Professional Development Program Level II certification in Systems Planning, Research, Development and Engineering and Level I certification in Test and Evaluation.

# Engineering Education Lessons
# From a Sounding Rocket Capstone Design Course

## Abstract

The FalconLAUNCH program is a two-semester capstone engineering design experience for the Astronautical Engineering major at the United States Air Force Academy. The program's long term technical goal is to develop a reproducible sounding rocket capable of carrying small scientific payloads to an altitude of 100 km. In 2006-2007, the program's fifth year, the student team designed FalconLAUNCH-V, a single-stage solid-propellant sounding rocket capable of achieving 60 km altitude. The course closely approximates the DoD systems engineering process used to develop new aerospace systems. The student team begins with specific system requirements and progresses, within a single academic year, through a complete development cycle by designing, building, testing, and operating a supersonic sounding rocket. Through the process, students learn many practical lessons in this multidisciplinary program. The program benefits from a close association with the Air Force Research Laboratory, NASA Wallops Flight Facility, and the solid-rocket commercial industry. Along with their engineering mentorship, these partners provide an extremely valuable "real world" aspect to the course.

## I. Introduction

The Space Systems Research Center at the Air Force Academy began the FalconLAUNCH sounding rocket program in the academic year, 2002-2003. This Department of Astronautics two-semester capstone design course provides a realistic design experience for senior students majoring in Astronautical Engineering, Systems Engineering and Systems Engineering Management. The program focuses on "learning space by doing space." Each year, students apply systems engineering processes to design, build, test, and fly a solid-propellant sounding rocket. Through participation in the FalconLAUNCH program, students get a hands-on opportunity to apply many of the tools and skills developed in their engineering classrooms to a real problem. The experience is an excellent preparation for the challenges they may encounter in aerospace systems development following graduation. This paper discusses the overall program and specifically examines the integration of systems engineering processes, the multidisciplinary engineering & management opportunities, and the benefits of academic, government, and industry partnerships in engineering education.

## II. Program Overview and History

The FalconLAUNCH program has designed, built, and flown four sounding rockets; one each year since 2003. This year's rocket, FalconLAUNCH-V (FL-V), is designed to be the most advanced system to date. It's capable of reaching over Mach-5 speeds on its way to an altitude of over 60 km (200,000 ft). The program strives to provide a "hands-on" educational experience for students while applying a high level of practical engineering to solve real-world problems. The program emphasizes developing a basic capability to fly small scientific and engineering payloads on a yearly basis. Technical goals are focused on developing a reproducible design, built largely by students, capable of flying a 5 kg payload to over 100 km (330,000 ft). This altitude, commonly accepted as the edge of space, was also the objective for the recent Ansari X-prize, captured by SpaceShipOne on October 4, 2004.

The FalconLAUNCH program began in 2002-2003, named FalconLAUNCH I. The 14-student team designed, built, tested, and flew a single-stage sounding rocket with solid propellant. Launched from the Army range at Fort Carson, Colorado, the 90 lb rocket was aerodynamically stabilized and reached an altitude of 30,000 ft. On descent, an airbag-actuated parachute deployed at 2000 ft and the rocket was successfully recovered. This first subsonic rocket proved the technical feasibility of the program and paved the way for future classes to build a more powerful rocket design.

In 2003-2004, the 18-student team designed FalconLAUNCH II. This new design incorporated many new features necessary for attaining the programs ultimate altitude and payload goals, including a graphite composite case to reduce structural weight, a silica-phenolic nozzle liner, new avionics hardware & software, and a new recovery system. The team static fired the rocket motor in April 2004 and flight tested a supersonic, reduced-performance version at the Pinon Canyon Maneuver Area range in southern Colorado. The static firing was successful except for a nozzle failure attributed to manufacturing problems which were subsequently resolved. The flight test achieved supersonic flight, but soon after achieving Mach 1, at approximately 17,000 ft, the rocket experienced a problem and ultimately tumbled. Almost all technical goals were achieved, but the flight dynamics anomaly created new opportunities for the next class.

In program’s third year, FalconLAUNCH III focused the 21-student team on analysis of the anomalous flight. Their goal was to redesign and successfully fly supersonically at the Pinon Canyon Range. The student-led research and analysis uncovered two contributing factors to the flight stability problem. First, they discovered uneven erosion of the silica-phenolic nozzle liner at the nozzle throat, leading to slight thrust misalignment. Students used sophisticated 6-degree-of-freedom flight simulation software developed by the Sandia National Laboratory to show that even small thrust misalignment could significantly destabilize the rocket in flight. This problem was ultimately solved with a new, more robust, carbon-phenolic nozzle material. Through several tests, this new material proved much more capable of withstanding the high temperatures and has proven very successful during all subsequent static and flight tests.

Next, they discovered the likely onset of fin-flutter as the rocket became supersonic. With the help of engineers at the Air Force Research Laboratories Propulsion Directorate, students researched and applied methods to predict fin flutter and design fins much more resistant to the effect. The resulting design was static fired in January 2005 and produced over 3000 lbs of thrust. A full-size rocket was built and launched in April 2005 from the Pinon Range. FalconLAUNCH III successfully flew to over 18,000 ft and achieved the program’s first stable supersonic flight--over Mach 1.4. Only 30% of the rocket’s propellant capability was used to ensure the flight would remain within the range’s boundaries. The system transmitted position, velocity, and combustion chamber pressure data via the on-board telemetry and GPS systems to student ground stations. With almost all technical goals achieved, the program was ready to take the next step and attempt a full-power supersonic flight.

FalconLAUNCH IV built on the success of the previous three years and pushed the design goals higher and faster than ever. The 17-student team addressed design challenges to almost every major subsystem in an attempt to improve performance and add new capabilities. The propulsion team developed and tested a new grain design. They static fired the motor on February 14, 2006 at Jack's Valley on the Air Force Academy and produced over 4000 lbs of thrust. Student-designed and -built structures included the aluminum and carbon-phenolic nozzle, composite nosecone, and carbon composite fins. The avionics section contained a telemetry system that recorded on-board accelerations, motor chamber pressure, position, and velocity via the on-board accelerometers and GPS. The data was transmitted to two redundant ground stations that were designed to receive and store the data. A new real-time video camera payload was developed and integrated to transmit video from the rocket to a separate ground station. The student-designed composite motor case was built by ATK in Brigham City, Utah, while the rocket motor was cast and cured by Vulcan Systems of Penrose, Colorado.

The fully-loaded solid propellant rocket had much more range than available in Colorado, so the launch was planned for the Navy's Missile Range near San Nicholas Island, California. Computer simulations of the flight predicted a range of over 25 miles and a max altitude of 134,000 ft. Students began test planning with the US Navy's range personnel many months before the operation. The student operations team worked diligently to obtain approval of all their procedures, planned frequencies, and test plans using the same processes as other DoD test programs. The range safety approval required detailed modeling and simulation of the rocket aerodynamic properties and flight dynamics to predict the flight hazard pattern.

All the planning turned to action as the team deployed to San Nicholas Island on April 3, 2006 for system checkouts, dress rehearsals, and launch of FalconLAUNCH IV. After some wet weather and range use issues, the team received the green light to proceed with the countdown on Thursday afternoon, April 6. Students directed all rocket and ground station procedures and at 1640 PDT the test director pushed the button and launched the rocket. The rocket lifted off smoothly and quickly accelerated. Unfortunately, a structural failure occurred in the forward section after approximately 3 seconds while traveling at just over Mach 2. Subsequent analysis of the video and telemetry data, along with the recovered motor case, suggested a structural failure in the avionics/payload case. Although the rocket was not designed to spin intentionally, slight fin misalignment produced a 1-2 Hz roll rate which resulted in slight coning. This motion dramatically increased the bending loads on the structure and likely caused the structural failure.

As a result of the FL-4 experience, the FL-V team decided to tackle the challenge of a spin-stabilized rocket. With the help of several key partners, the team addressed the new flight dynamics, structural design, manufacturing, and other issues required for a spin-stabilized, Mach 5+ sounding rocket.

## III. System Development Processes

The two-semester course is structured with the class in the role of a contractor, and the faculty team as the government customer. The FalconLAUNCH team is made up of mostly astronautical engineering majors, but a small number of Systems Engineering (SE) and Systems Engineering Management (SEM) majors are also included. An SEM major is competitively selected beforehand to serve as the Program Manager. Interviews are held to select the other key management positions within the class: Chief Engineer, and team leads for the Propulsion, Mechanical, and Avionics subsystems. In the FL-V class, responsibility for payload integration is assigned to the Avionics team. With the team in place, the class begins the process of developing a system to meet customer needs.

Each year, the faculty defines a set of mission requirements for the class. These technical targets evolve each year as the design matures based on lessons learned from previous flight tests. Incrementally, each class moves closer to the long-term technical goals for altitude and payload. Some features of the design which perform well are retained from the previous year and are presented as design constraints to the current class. The motor case and nozzle design are examples of elements which have been maintained for several years.

With these simple requirements, the class begins requirements analysis to fully develop the hierarchy of requirements and constraints. This is the first step in the iterative Systems Engineering (SE) process to develop the sounding rocket design. The DoD mandates a tailored acquisition sequence for all its programs that closely follows the IEEE *Standard for Application and Management of the Systems Engineering Process*[1]. With 100% student turnover every year, a standardized SE approach is essential for FalconLAUNCH program success. Using an SE program that closely follows the DoD model, the FalconLAUNCH SE processes provide an excellent learning opportunity while remaining flexible enough to adapt to specific program goals and constraints each year.

As seen in Fig. 1, the SE process contains several processes and iterative loops. Requirements analysis translates user needs and desired capabilities into requirements. Subsystem requirements flow down from system-level ones, and are not specified initially but determined by the class. Functional analysis identifies all functions and sub-functions necessary to accomplish the mission. The class produces functional relationships and interfaces, resulting in a functional architecture. With the requirement and functional analysis complete, the design synthesis phase then translates those inputs into a physical design solution. The resulting physical system is organized in a hierarchy of subsystems, assemblies and components, often called the Work Breakdown Structure. Many program management activities also use this physical breakdown of the system to organize resources and work.

The iterative nature of the SE process is driven by the requirements, design, and verification loops. The requirements loop ensures all requirements are met by at least one function, and also determines if there are any missing requirements. The design loop assesses whether the design is providing the necessary functions. Finally, the verification loop examines how well the designed system performs in providing the required capabilities. For FalconLAUNCH, the verification loop is done with simulation and a great deal of component, subsystem, and system-level testing.

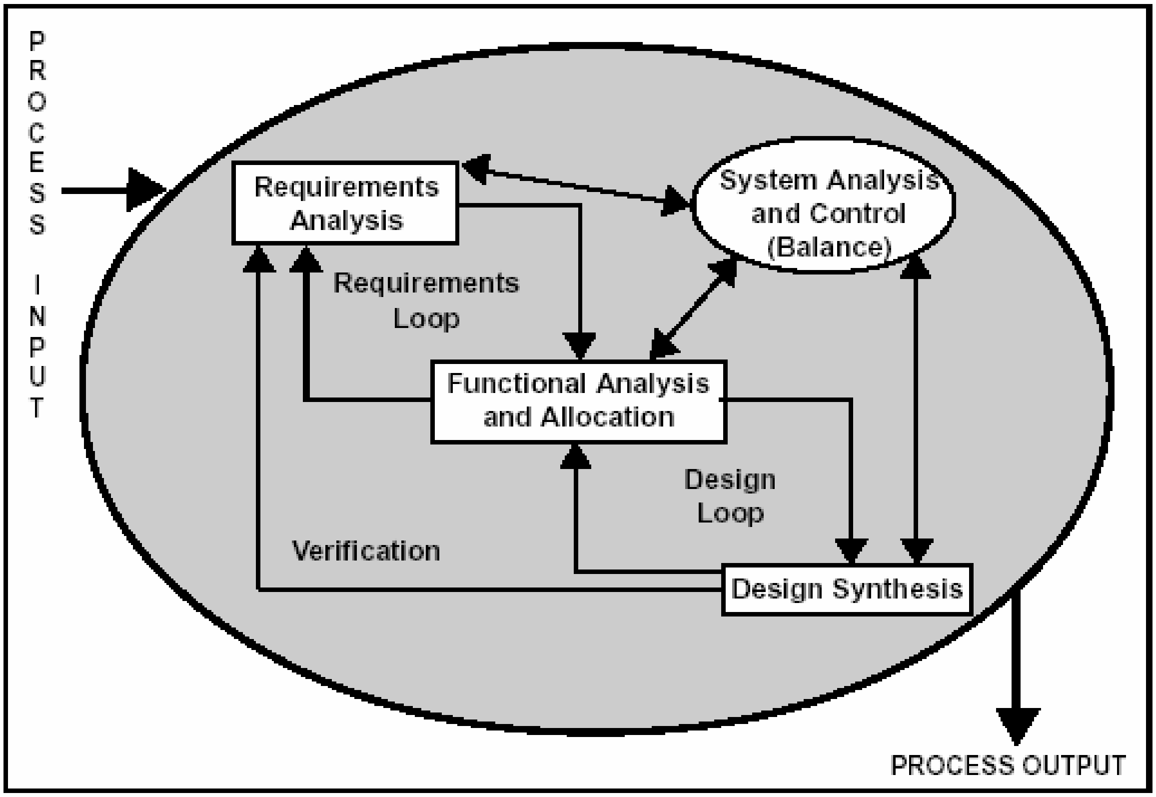

**Figure 1: Systems Engineering Process**

A vital SE element is System Analysis and Control of the other processes. This is done primarily through milestone reviews at key points in the process. A System Requirements Review assesses progress in defining system and subsystem requirements. The Preliminary Design Review is done following functional analysis and ensures the system is ready to proceed to detailed design. Finally, the first semester culminates with the Critical Design Review. This technical review, attended by invited reviewers from industry and government, determines whether the system can meet performance requirements within cost, schedule, risk and other constraints. Documentation must be sufficiently detailed and complete before the system is ready to proceed into fabrication and test.

With an approved baseline design, the second semester is focused on fabrication, integration, and test. Component-level environmental tests are conducted as appropriate for risk reduction, often because of new or sensitive components. Assemblies and sub-systems are fabricated and functionally tested. Several major subsystem-level tests are conducted each year, including a static-fire test of the rocket motor. Of course, much of the learning takes place in solving the many, unpredictable problems associated with integrating the system. Many practical lessons are learned each year regarding the importance of interfaces, documentation, scheduling, communication, and other overarching interdependency of all aspects of the system. A disciplined configuration control process is used, complete with Engineering Change Proposals, to approve and document any changes to the baseline design and its documentation.

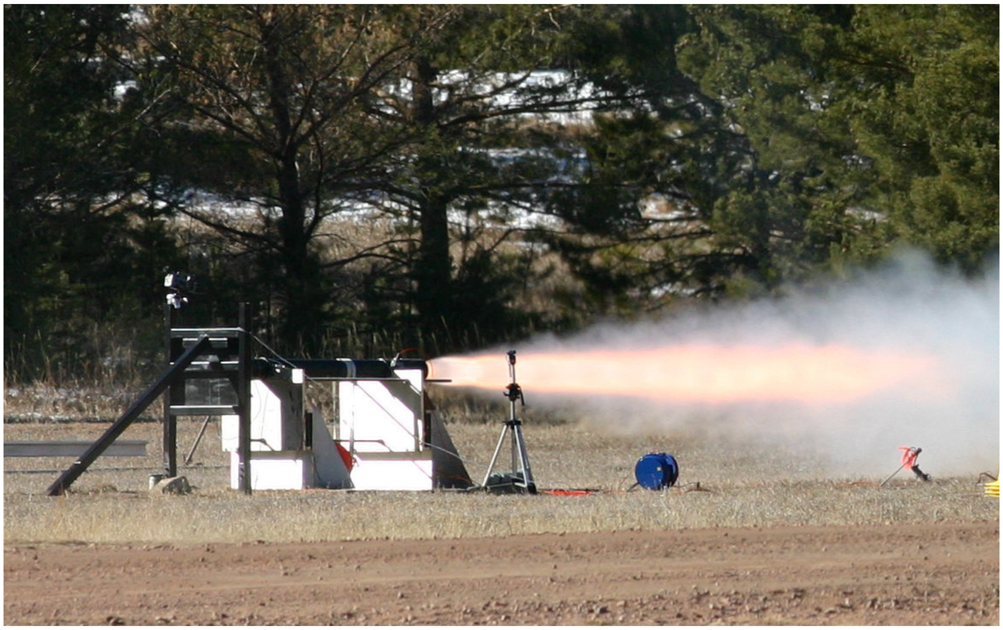

**Figure 2: Rocket Motor Static-Fire Test**

Finally, each year ends with the flight test of the FalconLAUNCH rocket. Each procedure for test and launch is developed using Operational Risk Management to identify and control risks to personnel, property, and equipment[2]. Extensive procedures and checklists for all aspects of the rocket buildup and launch are developed by students and approved by the administration and local safety personnel. Flight safety approvals are earned through detailed modeling and simulation of the rocket flight. Dispersion factors are included in a monte-carlo flight simulation to generate a statistical impact pattern. This data is used to determine how much range space to clear as well as safe locations for ground stations. Through these processes, students apply their undergraduate education to solve real problems, while also learning many valuable lessons in real-world operations of aerospace systems.

By its nature, any design class is open ended and difficult to program lesson-by-lesson compared to a traditional lecture-based course. However, by requiring students to follow prescribed, industry-standard systems-engineering processes, some formal structure can be imposed on each semester and the design reviews, program status reviews, readiness reviews, test plans and reports serve as major deliverables for grading purposes.

**Figure 3: FalconLAUNCH-IV Liftoff!**

## IV. FalconLAUNCH V Design

In 2006-2007, the latest edition of the FalconLAUNCH program set out to build on previous efforts and literally take the design to new heights. The first of several challenges was to learn from the FL-IV flight test results and to better address the complexities of supersonic flight dynamics and the corresponding structural design. In addition, the avionics systems were to be upgraded to fly two exciting new payloads. A final new development arose just as the semester began: a new partnership with NASA Wallops and the Sounding Rocket Program Office to provide mentorship as well as an established test range.

At the start of the Fall semester, the class is presented with system-level requirements to design, build, test and launch a solid-propellant rocket with the following capabilities:

- 45 km (threshold) to 75 km (objective) altitude
- 2.3 kg (threshold) to 5 kg (objective) payload
- Real-time telemetry to at least 1 ground station, including
  - 3-axis accelerations
  - Position & velocity
  - Payload data
  - Diagnostic data

Two payload options were presented to the team, and they eventually chose to fly both on FL-V. The first payload is an improved real-time video camera which transmits color video to each ground station. The second is a micro-electro-mechanical systems (MEMS) technology, inertial measurement unit (IMU), developed by the Air Force. The developers provided an engineering model, used in environmental testing, that was still functional. This is the first-ever externally-developed payload for the FalconLAUNCH program, and presents several new integration and communication challenges.

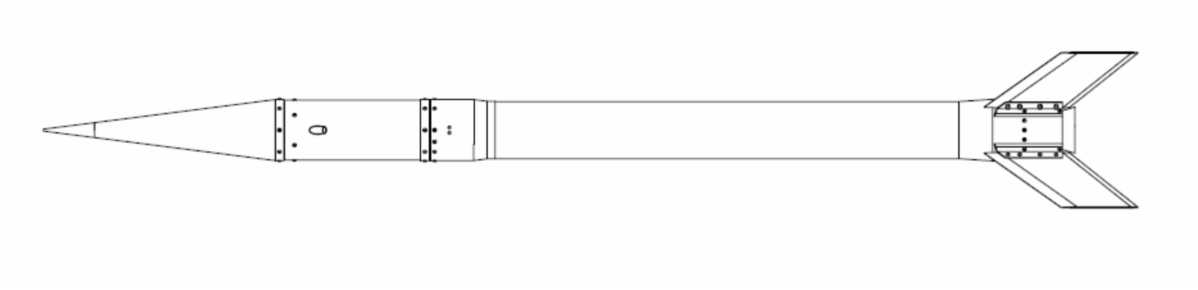

**Figure 4: FalconLAUNCH-V Design**

With these requirements, the team proceeded through the SE processes to determine subsystem-level requirements, functions, and ultimately designs. Prior to the system-level CDR, each of the major subsystem teams, Propulsion, Avionics, and Mechanical, conducted subsystem-level critical design review to assess the technical solutions of their detailed designs.

## Propulsion Subsystem

The responsibilities of the Propulsion Team include providing the required thrust to meet altitude goals and ensuring the accelerations sustained by the rocket are not excessive for the payload and structure. This year's team has two distinct propellant formulations available: 1) 2% aluminum propellant used on previous FL flights, and 2) a higher performance yet slower burning 16% aluminum propellant. The team analyzed the propellant options and grain geometries in order to meet several competing requirements. The team had to ensure all parts of the propulsion system would be capable of withstanding the harsh chamber pressures and temperatures during the thrusting phase.

**Derived Propulsion Requirements:** Given the system level requirements, the propulsion team derived requirements specific to their sub-system and task. The team worked with Vulcan Systems Inc. (the propellant sub-contractor) to get propellant characteristics and performance parameters. An additional limiting factor was the requirement to use a carbon, filament-wound case manufactured by ATK. This case, originally designed by students with ATK, was used in the FL II through FL IV programs. With these items to consider, the team derived a minimum start-up chamber pressure (450 psi) and maximum allowable chamber pressure (1400 psi). For flight stability a minimum initial thrust equal to five times the rocket's initial weight would be required. Lastly, the thrust profile must keep the vehicle acceleration below structural and payload limitations. Since one of the payloads saturates above 25 g's, every effort was made to stay below 25 g's or minimize the time above 25 g's while meeting all other requirements.

**Propulsion Subsystem Design:** The propulsion subsystem consists of four major parts: case, ignition system, propellant, and nozzle. The case was student-designed from the FL-II campaign, and is produced by ATK. It is constructed from M30S Carbon Graphite epoxy, and has a Kevlar filled EPDM mixture to provide insulation. The igniter is a small rocket motor which directs hot exhaust gasses to the surface of the propellant grain. The majority of the team's effort this year involved the nozzle and propellant designs.

*Nozzle:* The nozzle for FLV is made of 6061-T6 aluminum. The aluminum is insulated with a layer of carbon phenolic that has a variable thickness. At the throat the carbon phenolic is 0.762 cm (0.3 in) thick because the highest temperatures are expected to occur at this location. Except for the phenolic, the nozzle is manufactured from one solid piece of aluminum that is bored out to the required dimensions. After the aluminum section is fabricated, the phenolic is pressed into place on the inside.

The throat diameter and exit diameter were chosen through an iterative process. Nozzle parameters were selected, thrust simulated, results analyzed, then nozzle parameters adjusted until an optimum performance was achieved that still met requirements. The diameter of the throat was chosen to create the longest burn duration (to minimize g loading and increase altitude) while still meeting the initial start-up pressure. The exit diameter was chosen to give the expansion ratio which maximized Isp over the expected atmospheric pressure in flight. See Figure XX below for a visual depiction of the nozzle design, with phenolic material shown by the color black.

**FIGURE 5: Nozzle Drawing**

*Propellant:* The propellant used in the FL program was provided by Vulcan Rocket Systems and contained aluminum (Al), ammonium perchlorate (AP), and hydroxy-terminated polybutadiene (HTPB or rubber). The FL-V design consists of 16% Al as opposed to 2% Al used in previous designs. The advantage of the 16% Al propellant was the higher Isp. The 2% Al produces about 220 sec of Isp while the 16% Al was expected to produce approximately 245 sec of Isp. The higher Isp was necessary to meet the threshold altitude requirement according to the 6 DOF simulations performed by the students. However, this propellant delivered the increased specific impulse (Isp) mostly though higher chamber temperature. Thus the team was required to analyze the effect of the higher temperature on the other propulsion system components, particularly the nozzle.

*Grain Design:* The grain design was a major design emphasis during FL V. The grain design needed to maximize altitude while minimizing the g-loading. The 45g threshold and 25g objective requirements along with the chamber pressure requirements mentioned earlier limited the propulsion team's design space. Fortunately, the start-up pressure requirement for the designs considered always ensured an initial thrust sufficient to meet the thrust-to-weight > 5 requirement. Thus, the initial thrust level requirement was not a limiting factor.

The designs considered by the team had to keep the g-loading down, achieve the required altitude, and be suitable for the existing motor case produced by ATK Thiokol. The "double taper" design was selected by the team as the grain configuration that could meet requirements with the least perceived risk. This design resembles a center-perforation design except the aft-end of the grain is opened up to allow more burn area initially. This concept also decreases the max g-load since there is less maximum burn area through the duration of the burn, resulting in a lower peak thrust. The higher initial burn area also increases the start-up pressure. The double-taper design best satisfies all requirements and was the design chosen for this mission. A schematic of the grain design and grain specifications are shown in Fig. 5 and Table 1.

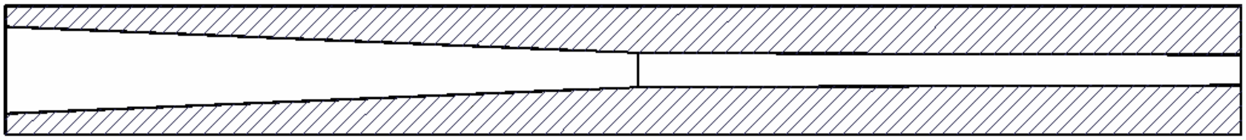

**FIGURE 6: Grain Design**

**TABLE 1: Grain Specifications**

| | |
|---|---|
| Grain Length | 156.21 cm (61.50 in) |
| Aft Length | 80.01 cm (31.50 in) |
| Forward Length | 76.2 cm (30.0 in) |
| Effective Grain Diameter | 15.9512 cm (6.280 in) |
| Propellant Mass | 45.958 kg (101.32 lbm) |
| Aft Port Diameter | 10.16 cm (4.0 in) |
| Middle Port Diameter | 4.318 cm (1.70 in) |
| Forward Port Diameter | 3.81 cm (1.50 in) |

The designed FLV propulsion system met all threshold requirements. The 25 g objective limit was expected to be met for all but 2 seconds of the flight. The predicted performance parameters of FLV propulsion design are listed in Table 2.

**TABLE 2: Predicted Performance**

| | |
|---|---|
| Altitude | 61 km |
| Max g's | 27.4 |
| Time over 25g | 1.8 sec |
| Initial T/W | 7.8 |
| Initial Pressure | 452 psi |
| Max Pressure | 1100 psi |

The simulated thrust profiles shown in Fig. 7 clearly illustrate the differences between the optimum solution for each year's requirements.

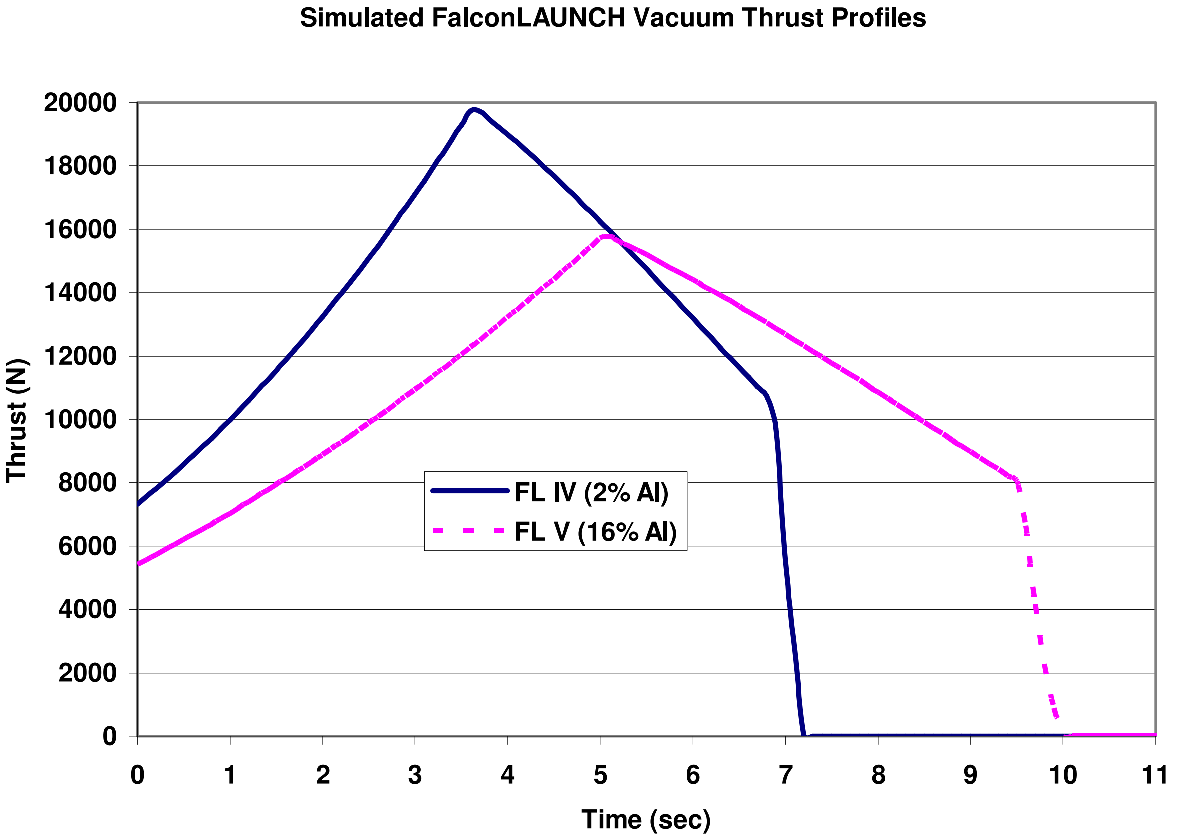

**FIGURE 7: Thrust Profile for 16% and 2% Al Grain Designs**

## Mechanical Subsystem:

The Mechanical team is responsible for the design and construction of all aspects of the rocket. Aside from the motor case, all of the primary and secondary structures are manufactured in-house. The students build composite parts, including the fiberglass nosecone and graphite fins, in the laboratory. Most of the metal parts, including the launch lugs, fin mounts, and avionics case, are built in the machine shop by (University) machinists, although students have the option of learning to use any of the equipment and actually building their own parts.

The nosecone is a simple conical design constructed from fiberglass and epoxy using a wet-layup technique. The students based the initial design on structural requirements to sustain aerodynamic and inertial loads produced during flight. To verify that the design was sufficient, a prototype of the nosecone was tested by students in the Engineering Mechanics department as part of a separate course. This partnership between the Engineering Mechanics department and the Astronautics department provided a critical capability to get actual test data that validated the structural design of the nosecone.

While the prototype nosecone withstood expected flight loads, initial thermal analysis indicated that the temperatures experienced during the Mach 5+ flight would cause the fiberglass strength to degrade resulting in failure. Students on the mechanical team applied the 1-D heat transfer equation to model temperature through the nosecone skin thickness and determined that a thicker skin wall would be needed to maintain structural integrity. In addition, a steel tip was added to withstand the extremely high temperatures (over 2000 degrees F) at the stagnation point behind the initial shock at the nose tip. To help validate the thermal model and test the design changes, the students contacted the (insert appropriate group name) at Arnold AFB in Tennessee to arrange a test in their re-entry vehicle test facility. A mockup of the nosecone tip was constructed and thermocouples were installed to measure temperature at various locations inside the nosecone. The test was successfully completed in December, and the results were used to validate and refine the thermal modeling. This opportunity to utilize DoD test facilities greatly improved our final nosecone design, ensuring that the nosecone will withstand the harsh environment.

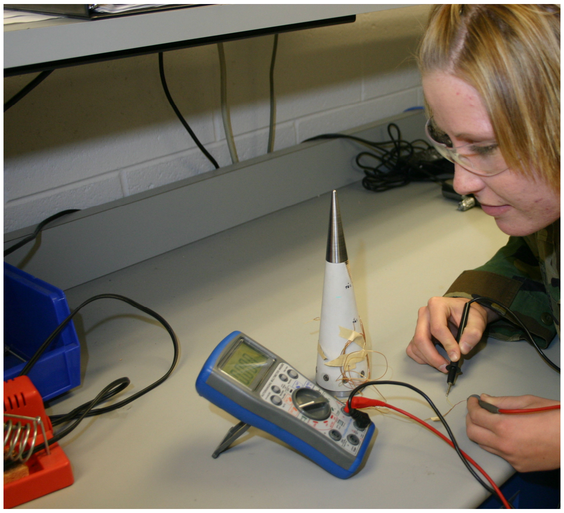

**Figure 8: Student tests thermocouple leads of nosecone test article**

The fins were designed through an iterative process using 6-DOF simulation software. Various planform shapes, span lengths, and airfoil cross-sections were considered while trying to optimize drag, weight, fin flutter, and aerodynamic stability. One of the primary driving requirements was the decision to use graphite/epoxy composite materials for the fin construction. Students flew simulations with various materials, but the lighter composite fins shifted the rocket center of gravity forward, allowing reduced fin size while maintaining acceptable static margins. The lower weight and reduced drag of the smaller fin design resulted in increased altitude.

One drawback to the composite design, however, was increased difficulty in manufacturing. The fins are constructed using graphite/epoxy panels donated by the Air Force Advanced Composites Office (ACO) located at Hill AFB, UT. The panels are manufactured by the ACO for use in training technicians to repair F-16 tail skins. The panels measure 12” by 18”, and are 0.08” thick. Students on the FL-V team bond several panels together to achieve the desired thickness, then cut out the final shape. The result is a fin that has the same stiffness as aluminum, but weighs about 40% less. Unfortunately, due to manufacturing limitations the composite design is limited to a flat airfoil instead of a wedge or diamond cross-section that is more common for supersonic airfoils. However, the weight savings and reduced planform area and fin span result in improved performance for the composite design in spite of its less desirable airfoil shape.

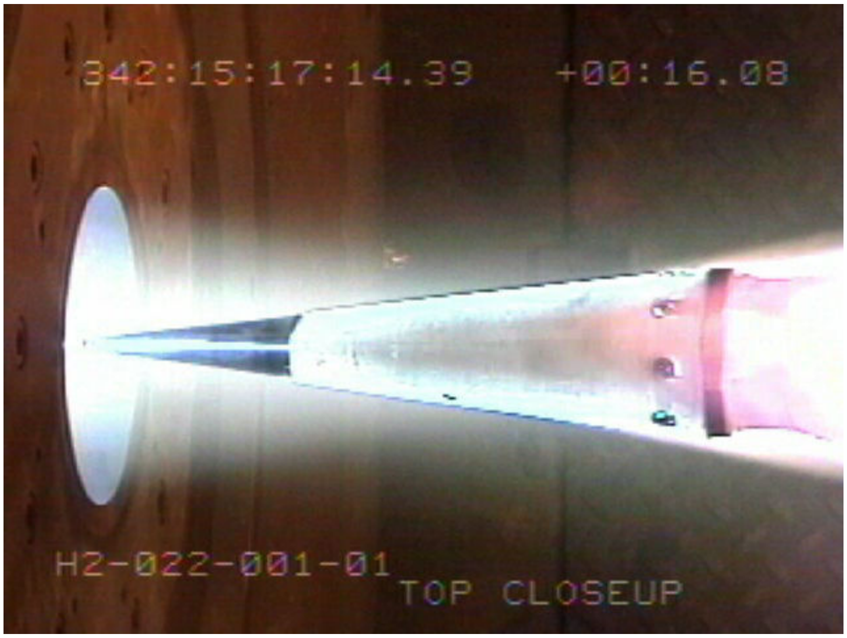

**Figure 9: Nosecone heat-flux test**

## VI. Lessons Learned for Engineering Education

Like many capstone engineering course, FalconLAUNCH provides many excellent opportunities for students to apply the knowledge gained through their undergraduate education. Synthesis of knowledge from various disciplines, applied to solve real-world problems, is a valuable part of an engineering education. However, the experiences of five years of this program have highlighted several factors which are important for program success.

Structured, systems engineering processes are important learning objectives for capstone design courses. A comprehensive, structured approach is a great benefit to the development of complex systems, both for large aerospace contractors and student projects. Systems engineering disciplines help provide the order necessary to the design and production processes. Common to the aerospace industry, systems engineering processes are often discussed in engineering curriculum, but opportunities to participate in these processes are rare. Capstone engineering courses, such as the FalconLAUNCH courses, are perhaps the best way to provide a meaningful experience in these important disciplines.

One of the important systems engineering disciplines is configuration control and managing changes during the design and manufacturing processes. An example of this is the engineering change proposal (ECP) processes. At the end of the detailed design phase, the Critical Design Review establishes the approved, product baseline. This baseline includes the detailed drawings, specifications, and supporting analysis that document all aspects of the design. As the team progresses into building and integrating the subsystems, there are always issues discovered that require changes to the design. An important learning lesson is to teach students to resist the strong desire to quickly make a change. This is especially tough when schedule pressure is high, as is almost always the case. Instead, students are taught to follow a very structured process of documenting and presenting the need for the change, performing or repeating any necessary technical analysis, and updating the technical data package. Updating drawings and specifications are all required before the faculty approve the engineering change. This process requires some time, but has proven extremely valuable in helping teach students to manage a very dynamic, complex process. These experiences are designed to mirror the methods and processes used by aerospace industry, and therefore also provide very practical lessons for future engineers.

Where possible, partnerships with industry and government experts provide tremendous learning experiences for students. These relationships can also provide access to unique resources, such as test facilities, that are not readily available to most universities. Perhaps even more valuable than facilities, or test ranges, or even money are the vast mentorship relationships possible between practicing engineers and the next-generation engineers. Working directly with these professionals, often as peers, absolutely inspires and motivates students toward their future careers.

Documentation requirements proved to be a huge lesson learned. With 100% student turnover from year to year, trying to document how and why each component was designed as flown proved challenging but necessary. The structure of the course is such that each class must capitalize off of previous year’s successes while readdressing failures. Without good documentation, this becomes extremely difficult.

The importance of a well thought-out schedule was another major lesson. The students discovered that going through the design process from initial requirements to delivered product in two semesters was very challenging. Their schedule naturally became very tight and success oriented. Unfortunately, the real world does not always work according to planned schedules. Funding and contract delivery delays as well as test failures (requiring redesign) are areas that the team must be prepared for. One approach used in the FalconLAUNCH program was to "leapfrog" in areas where redesign was not possible. For example, each year the program gets two motor cases, one to static test fire and one for flight. In order to mitigate the risk of a failure during the static test, the overall rocket was designed to accommodate the updated design as well as the previous year's motor. The students then had the flexibility to design toward objective requirements and fly that motor if successful. If their design did not perform as expected, they could then revert to a proven design and still get a launch.

Finally, capstone courses are uniquely capable of providing outstanding opportunities for multidisciplinary education, both within engineering disciplines and with management departments. Although many of the technical challenges can be addressed with foundational engineering disciplines, there are many aspects of a sounding rocket program that would benefit from the expertise of specific engineering disciplines. The avionics, communications, and payload systems offer excellent electrical engineering challenges. Aeronautical engineers would relish the flight dynamics design and simulation tasks. Of course, mechanical engineering roles are everywhere, including heat transfer, finite-element modeling, and structural design. But the intra-departmental prospects are not confined to engineering division. Of all the student projects available to our Systems Engineering Management majors, FalconLAUNCH is consistently cited as one of the best experiences possible by the management students. No other project allows actual application of almost any program management tool and technique taught within the SEM curriculum. Students learn best by doing, and there is no more realistic environment than the FalconLAUNCH program.

## VII. Conclusion

Year to year, progress is consistently made in meeting the long-term FalconLAUNCH technical goals. But without a doubt, the program overwhelmingly succeeds in achieving its primary educational goals—to teach future engineers to apply rigorous systems engineering practices, to understand the fundamentals of aerospace systems design techniques, and to work effectively as part of a design team. Students learned tremendous lessons in systems engineering, program management, modeling & simulation, manufacturing, test, and launch operations. Perhaps more important, they learned much more about development of complex systems than any textbook could possibly communicate. In some ways, the students benefit more from this experience by experiencing and overcoming problems than if the rocket flew precisely as predicted. As seen recently in industry, the initial development of a new rocket is filled with uncertainty and problems are common—this is not a simple or easy task. But the lessons of this program--the technical rigor, discipline, professionalism, and attention to detail--have an irreplaceable impact on these young engineers as they begin their careers.

## VIII. References

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