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Student Design, Development, and Operation of Sounding Rockets at the United States Air Force Academy

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Abstract

The FalconLAUNCH program is a unique, dynamic rocket launch vehicle research program that serves as a capstone course for Astronautical Engineering majors at the United States Air Force Academy. The goal of the program is to give students the opportunity to "Learn Space by Doing Space." The program results in a rocket launched into the upper atmosphere every year. It is conducted in the same manner required of a civilian company or Air Force organization delivering a new aerospace vehicle for use by the USAF or NASA. In addition to the design and construction of the rockets, students must meet all of the typical Department of Defense (DoD) milestones, including preparing and briefing the Alternative Systems Review (ASR), Preliminary Design Review (PDR), Critical Design Review (CDR), and (most recently) a report of failure analysis and cause determination. These reviews are given to and evaluated by members of the civilian aerospace community and scientists and engineers from U.S. Air Force space and propulsion organizations outside of the Academy. Each student is required to become familiar with the overall vehicle and become an expert in their particular subsystem. They develop skills in researching available technology, evaluating design and fabrication options, and then building or contracting out flight hardware. This paper discusses the current status of the FalconLAUNCH program, the challenges of an almost complete turnover of personnel every year, and the dynamics of managing the design, construction, and flying of a supersonic rocket every year by a completely student team. Since this program is conducted in the same manner as a typical Air Force science and engineering program, students from other academic departments also participate in the program. The program has been augmented by the participation of electrical engineering, and management students. The addition of this multidisciplinary real-world atmosphere adds an extra dimension of realism to the program. This paper discusses the various solutions the Academy has devised to address the many challenges of conducting a successful program in a highly constrained undergraduate environment.

I. Introduction

The FalconLAUNCH program at the United States Air Force Academy (USAFA) gives undergraduate students a chance to "Learn Space by Doing Space" through a two-semester capstone course taught by the Astronautics Department. This program allows cadets to gain real-world experience with rocket system design, assembly, integration, testing, and operations within the context of a two-semester engineering course. Another goal of the program is to provide a useful platform for University or Department of Defense (DoD) upper atmospheric experiments. Through FalconLAUNCH participation, cadets are given a hands-on opportunity to apply the tools developed in the classroom to a real program, ideally preparing them for the situations they may encounter as officers and as engineers after graduation.

Because rocket design is multi-disciplinary, select students from the Management and Electrical Engineering Departments participate with Astronautical Engineering majors in the program. This program uses an evolutionary design approach in which cadets employ or refine cutting-edge technologies and procedures developed by their predecessors. Lessons learned are then captured and help USAFA build a catalog of technical procedures for future vehicles. Because there is almost a 100% turnover every year, documentation is crucial to the success of the program [1]. The evolutionary approach would be very useful for many schools. The turnover factor is a great incentive to students for good communication skill development

This paper briefly discusses the history of rocket activity at USAFA and how it led to an on-going educational and engineering development program. Then the discussion will turn to the approach used to conduct a successful program, using only mentored undergraduate students to design, develop and operate sounding rockets.

II. Background

The USAF Academy has a long history of cadet built rockets. Between 1964 and 1994 many Astronautical Engineering majors took a one semester course in which they designed and build a 4-in diameter polycarbonate plastic rocket powered by a commercially available solid rocket motor. In 1991 this small rocket course achieved great success when several collaborating cadets built and launched a hybrid rocket using gaseous oxidizer and solid fuel. The following year a two stage rocket was build using a solid first stage and hybrid upper stage. None of these rockets flew more than 6000 feet above the Academy's Field Training area where they were launched and recovered via radio deployed parachutes. The interest in relatively safe hybrid rocket technology spawned a faculty led project to develop a large hybrid rocket capable of launching to over 20,000 ft. The 14 feet tall aluminum case vehicle was named Chiron and flew to an altitude of about 21,000 ft. After a three year hiatus of rocket activity another hybrid rocket was developed and launched in 1998. The "Dominator" was smaller but lighter than Chiron and employed a cardboard case. The rocket took a very low trajectory after launch and failed to reach high altitudes but further proved that rocket technology was a safe and effective way to bring the curriculum full circle from theory to practice. Both of these projects gave the students immediate, hands-on experience and gave the Astronautics Department the confidence to move on to more risky but higher performance solid propellant rockets.

III. A More Standardized Program

While hybrid rocket projects were taking place at USAFA the Dept of Astronautics was focusing the bulk of its efforts on creating an on-going satellite development program called FalconSAT which succeeded in building satellites that were launched into orbit in 1997 and 2000. In 2002 it was decided to apply the FalconSAT course model to a rocket experience and turn it into in a regularly scheduled course. FalconLAUNCH was designed as a two semester course in which cadets would carry out all phases of an engineering development program culminating with an actual launch at the end of the academic year. The lessons learned from FalconSAT motivated a significant structural change to previous rocket research, with the intention of building a *program* first and a *rocket* second. Thus, the new approach was to focus on building up infrastructure, including design and development tools that can serve as a firm foundation to allow the vehicle design to evolve steadily over the course of several academic years. FalconLAUNCH now runs in parallel with USAFA's FalconSAT program which has now developed 4 satellites and launched 2 (the next one is scheduled to launch in the summer of 2005). FalconLAUNCH 1 (FL-1) ran from August of 2002 to April of 2003 and resulted in the successful launch of "The Humble Rumble" rocket named after the late Dr. Ron Humble a key founder and contributor to USAFA rocket research. FL-1 was a solid propellant rocket that flew to 30,000 ft and was recovered under parachute. Following this success, cadets and faculty defined a new objective for the program – to fly a 5 lb payload to 100 km.

Figure 1. FalconLAUNCH-2

DATE	ROCKET	TYPE	PEAK THRUST / ALTITUDE
1965-1994	Numerous Small Rockets		2,000m
Apr 1994	CHIRON	Hybrid	4,000 N / 7,000 m
Apr 1998	DOMINATOR	Hybrid	1,800 N / Launch Problems
Apr 2003	FalconLAUNCH-1	Solid	3,500 N / 10,000 m
Apr 2004	FalconLAUNCH-2	Solid	5,000 N / 5,000 m Wend unstable at Mach 1.5
Proj Apr 05	FalconLAUNCH-3	Solid	Projected 6,500 N / 15,000 m
Proj Apr 06	FalconLAUNCH-4	Solid	Projected 13,000 N / 100,000 m

Table 1. Summary of FalconLAUNCH Program Milestones.[2]

FL-2 saw a significant jump in capability when ATK Thiokol agreed to produce two composite rocket motor cases for use in the program. This increased the allowable chamber pressure of the rocket without increasing weight significantly allowing for much better performance and a smaller vehicle. This advancement puts the goal of reaching 100 km theoretically within reach, provided cadets can overcome the challenges of supersonic flight. In November of 2003 cadets performed a static firing of a full-scale 100 km motor using the first composite case provided by ATK. This static firing successfully validated predicted performance for several seconds before severe ablation of silica phenolic nozzle material led to burning of exposed aluminium and a serious reduction of thrust (as well as several small fires in the surrounding field). Following this static firing cadets conducted a small rocket launch to test the avionics and parachute recover systems. Both systems worked well and a 3-D GPS model of the flight trajectory was available within minutes of the launch. After changing the compression moulding process for the silica-phenolic nozzle lining and integrating the avionics and recovery sections to the propulsion section, FL-2 was ready for launch.

In April 2004 the 10 ft FL-2 rocket took to the skies over southern Colorado at Pinion Canyon Tank & Artillery Range. Range size would not permit a safe launch to 100 km (330,000 ft) so the motor was poured with only enough propellant to reach 60,000 ft. Even so, the vehicle was projected to reach mach 3 before exhausting its propellant. Launch of FL-2 was spectacular to watch and a sonic boom was audible shortly after lift-off. Visually, the launch looked successful but Telemetry showed the flight was to only about 15,000 feet, with a flight duration of 6 seconds. Several minutes after launch the parachute was spotted descending without the rocket attached. Telemetry from the vehicle provided GPS speed and location and showed a top speed of only mach 1.5. Post-flight analysis of onboard accelerometer data indicated a coning motion of the rocket immediately followed by vehicle tumbling. The rocket body was recovered surprisingly in-tact and analyzed for clues to determine what caused the vehicle's stability problems.

Analysis of the spring 2004 accident was a major thrust of student activity in the FL-3 class which began in fall 2004. Cadets presented a "tiger team" report of their accident investigation which included numerous fly-out simulations using six degree of freedom simulation software from Los Alamos National Lab. Computer simulation coupled with testing of material strength and measurements of nozzle erosion led the investigating team to eliminate many candidate causes. Cadets presented their findings in October 2004, concluding that fin flutter, asymmetric thrust, or nosecone disintegration caused FL-2 to go unstable. The newly formed FL-3 design team then took those findings and made numerous changes to the design in the hopes of eliminating all three possible causes.

Composite (vs. aluminium) fins were designed and state-of-the-art, high-temperature resins are now being researched. Pre-impregnated Cloth Carbon Phenolic nozzle lining was selected instead of Silica Phenolic which required redesign of the aluminium nozzle structure and modification of the compression molding (and subsequent milling) process to handle this harder material. Lastly, a new composite nosecone was designed to replace the thin fiberglass one flown on FS-2. Finally a decision was made to spin the rocket to provide added stability while passing through the transonic regime. Test-firing of three small compression molded Carbon Phenolic nozzles using 100 lbf rocket motors with 1.5% aluminized propellant (same propellant as FL-2) confirmed that Carbon Phenolic is much more erosion resistant than Silica Phenolic. In January 2005, cadets manufactured a full-sized carbon phenolic nozzle and static test fired it in a motor that generated over 3500 lbf for 8 seconds. The test was successful validating several aspects of the solid motor as well as the nozzle. Another 3500 lbf motor with a shorter burn time will power FL-3 in April 2005 to over mach 3 before shutting down to ensure range safety restrictions are met. If cadets demonstrate the ability to fly stable at supersonic speeds the stage will be set for cadets in the class of 2006 to modify the design for flight to 100 km. If this is successful then the Academy can move on to other challenges such as active guidance and launching scientific payloads for the DoD and other organizations.

With this real-world focus, real-world funding and real-world visibility, it has become ever more important to run the program using real-world tools. Chief among these are rigorous systems engineering processes including technical reviews. 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]. This process begins with requirements analysis and culminates in system deployment. Along the way, major milestones in the form of formal technical reviews are conducted. In addition to multiple status reviews, these include:

- Preliminary Design Review (PDR)
- Critical Design Review (CDR)
- Final Readiness Review (FRR)

It should be emphasized that the cadets do all of the briefing in the many informal and semi-formal status reviews conducted continually throughout the program. The Preliminary Design Review (PDR) is a formal briefing with the objective of gaining permission to proceed with the detailed design, locating suppliers, as well as testing of materials and production methods. The cadets are not allowed to acquire materials or begin construction until all action items are closed from the PDR. This review forces the cadets to have a coordinated concept of the vehicle's design before committing funds and effort to fabrication and testing of subsystems. The importance of cost and ease of manufacturing are key lessons to the student who is used to academic versus practical solutions to engineering challenges. This practicality is a maturing process for many young engineers and introduces them to the importance of watching the schedule and maintaining communications with management, machinists, suppliers, and contractors. Students also learn how complex this relatively simple program (by Air Force standards) is and the responsibilities and pressures on a program manager. In this way, students come to appreciate the challenge of keeping a successful program under budget and on time. This is particularly important for USAFA graduates as many of them will be put in the position of program manager as young Air Force officers.

The Critical Design Review (CDR) is a formal, briefing lasting about 4 hours and targeted to reviewing experts from outside of the Air Force Academy (typically engineers from Air Force Research Lab who funds the program). The objective of the CDR is to spot problems with the design and gain permission to proceed with the construction, testing, and ultimately integration of actual flight hardware. Cadets conduct the entire briefing which amounts to an oral examination of their project. The Chief Engineer and Program Manager give an overview of the program and vehicle design and then each subsystem team describes their section of the design. FalconLAUNCH has 4 teams: Propulsion (5 students), Avionics (5 students), Mechanical Systems (6 students), and Operations (5 students). The Propulsion and Mechanical Teams are the busiest prior to the CDR while Avionics and Operations tend to get busy as the launch approaches. Cadets are subjected to questions throughout the CDR by USAFA faculty and outside experts. This presentation stimulates increased understanding of the program by students -- hopefully before the briefing, but always afterwards. The result of CDR is a list of action items that must be addressed before the Faculty Lead Mentor will give his/her blessing to the design and allow further progress in areas affected by the action item. Following CDR acceptance, the design is frozen and can only be modified through a formal process called a design change review in which all subsystem team leaders, the Chief Engineer, and the faculty safety and program advisor must first approve the change. This ensures all subsystems are aware of proposed design changes and can evaluate the impact on the vehicle and their subsystem.

The Test Readiness Review (TRR) and Flight Readiness Review (FRR) are equivalent to the Prototype Acceptance Demonstration (PAD) in the DoD procurement program. The TRR and FRR are formal reviews given to the Head of the Department of Astronautics that emphasize test and flight objectives and procedures and ensure safety procedures are adequate. For the Flight Readiness Review, FalconLAUNCH avionics results are presented to include range testing and shake-testing to ensure survival of sensitive electronics during launch. Results of a static firing (normally done in January or February) of a full scale motor are presented at the FRR and the impacts of those results on the design are considered. Scale model wind tunnel testing results and computer fly-out simulation results are presented to support stability predictions and ensure range restrictions will be met. Finally, condition of the motor (poured by a local contractor for safety reasons) is evaluated and all subsystems are physically assembled into a complete vehicle to ensure compatibility. The satisfactory completion of this review and completion of any follow-up items constitutes Dept Head approval for launch. By its nature, any real-world design class is open ended and difficult to structure lesson-by-lesson as a traditional lecture-based course is. By requiring students to follow prescribed, industry-standard systems-engineering processes with briefing milestones, structure is imposed on the course and the design reviews serve as major deliverables for grading purposes [3].

A good example from FL-3 of how the PDR-CDR-FRR process works is the development of a new nozzle compression molding process. At PDR in September 2004, the desire to use Carbon Phenolic lining material was presented as a solution to the problem of erosion that contributed to asymmetric thrust (and possibly failure) in FL-2. Following adoption of Carbon Phenolic at PDR, testing began on ways to compression mold the material while design of a nozzle was conducted in tandem. After 1 failed attempt at compression molding carbon phenolic the process was modified and a successful method demonstrated. Drawing upon this experience, a rocket nozzle design and manufacturing process was developed and presented at CDR in November 2004. Following CDR the first attempt to construct a nozzle was only partly successful and the process was further refined. In this case more heater cartridges were added to the end of the aluminum mold where Carbon Phenolic had failed to reach sufficient temperatures to flow under pressure and reach proper uniform density. Following a field trip to ATK Thiokol in Utah, cadets were inspired by the experience to research methods of analyzing the nozzle for defects using ultrasound. After determining that this was not feasible they elected to destructively analyze a nozzle to validate the success of their manufacturing process. Due to the failed first attempt at building a nozzle and schedule constraints, it was necessary to use the first successfully made nozzle in a January 2005 static firing without first analyzing the nozzle for defects. This proved a valuable lesson to members of the propulsion team (5 cadets) who were understandably nervous that the nozzle would fail during the January static test and jeopardize the April launch of FL-3 (and their grade) for themselves and the other 16 students in the class. Cadets learned the value of budgeting time for setbacks in all steps of the fabrication phase (a lesson learned time and again in the FalconLAUNCH program). Such experience is usually gained through much more costly (to the Air Force) schedule problems in real USAF programs. By giving cadets a systems engineering capstone program to run they enter the engineering and acquisition force with knowledge tempered with judgment and experience that we feel will foster success.

Learning objectives for the course vary from year to year, team to team, and even student to student. No two cadets have the same experience or learn the same lessons but frequent status updates ensure that important lessons are shared among the group. This also gives all students a chance to present their work to the program and refine their presentation and question fielding skills – a main objective of the course. The onus is on the team mentors (Mechanical systems, Propulsion, Operations, Avionics, Management) to identify learning opportunities and develop learning objectives and graded deliverables for their team and for individuals within the team. As an example following a static test in Jan, 2005 the propulsion team mentor required his students to revise their test report to serve as a complete documentation of not only the results of the test but as a detailed discussion of the analysis of that test and a roadmap for improving upon the system in the future. This entailed several areas of analysis such as erosive burning in the port, ways to increase Isp, ways to ensure ignition with an increased proportion of inert propellant, and many more. Each area was assigned to individuals who wrote the section of the report relating to the area. In this way, individual performance was assessed and individual understanding was evaluated by the team mentor. It was also emphasized that the report would be sent to ATK Thiokol in Utah to accompany the fired case which was sent back to ATK for post-fire analysis. This gave the cadets motivation (beyond their grade) to write a good report. Their report was representing their school to professional engineers supporting the program, many of whom they met during their field trip to ATK. The same report was sent to Vulcan Systems who poured the propellant grain for the program.

The FalconLAUNCH program received high marks when it was reviewed by the Accreditation Board for Engineering and Technology (ABET). In addition to meeting other ABET criterion, the program totally encompasses the section of ABET's "Criterion 4. Professional Component" which states, "Students must be prepared for engineering practice through the curriculum culminating in a major design experience based on the knowledge and skills acquired in earlier coursework and incorporating engineering standards and realistic constraints that include most of the following considerations: economic; environmental; sustainability; manufacturability; ethical; health and safety; social; and political." The FalconLAUNCH program addresses all of these issues [4].

IV. Course Grading and Cadet Reaction to the Program

Assigning individual grades to a multidisciplinary group project of this size is a challenge. The grading system developed includes the input of peer evaluations by the members of each subdivision team and evaluations by the faculty mentors of these teams. The final grades are assigned by the senior faculty members in charge of the course. Faculty members look at individual contributions, initiative, and time spent working outside of class, and quality of the student's documentation of their efforts. Time working on the program is tracked by students themselves by logging the number of hours on a spreadsheet. Cadets are on their honor to input accurate numbers but almost without exception the level of contribution to the program mirrors level of effort from the time-logs. Students who were underperforming in other Astronautics courses often gain a sense of accomplishment in the Astronautics program and confidence in their ability to perform as an engineer! This renewed confidence is important for students who were at the top of their class in high school but struggle with the rigors of USAFA Astronautics.

The overall reaction of the cadets to the program is very positive. Many cadets come into their own in this type of course. Comments from Spring 2004 student critiques include the following [2]:

- "Best academic experience I've had at the Academy."
- "It definitely had parts that are awesome: rocket design, getting to see all the issues you have to deal with, iterating designs, seeing results."
- "The course was one of the best I've taken at the Academy."
- "Fun, very rewarding, learned a lot, great experience."

Student response was high in all 21 categories of questions on the critiques. Here are some of the quantitatively scored questions and results:

- "Intellectual challenge and encouragement of independent thought were:" scored in the top 2 % of all the courses taught at the Air Force Academy
- "The amount you learned in the course was:" - scored in the top 2% of all courses at the Academy!
- "Relevance and usefulness of course content was:" – scored in the top 2% of all courses in the Engineering Division.
- "Encouragement given students to express themselves and participate." - scored in the top 2% of all courses in the Engineering Division.
- "Value of questions and problems raised by instructor was:" - scored in the top 2% of all courses in the Engineering Division.

V. Customer Reaction to the Program

One of the satisfying aspects of this program is the fact that USAFA sounding rockets will eventually perform real research and testing missions and are not just a textbook exercise. The program is continually reviewed by outside experts and evaluated against the work of the real space community, not just academia. The comments by outside space experts and some of the supporters of the program who were the reviewing officials at a recent Critical Design Review (CDR) of FalconLAUNCH-3 were very positive: "Very comprehensive in terms of subsystem technical analysis done." "Team was well prepared, organized, and used the right level of complexity to address technical issues." "Cadets were very professional and up-to-speed on their subsystems and most had a good handle on the overall design." "Those cadets who go on to work as engineers have a real leg up having gone through a CDR, they know what it's like to have their feet held to the fire."

VI. Conclusions

Of course, all programs are judged on their results. The physical result of the FalconLAUNCH program is significant. A unique solid propellant grain design has been developed that will reduce the G-loading below that of existing sounding rockets. This will ultimately allow more fragile and sensitive payloads to be flown. The cadets do what some nations and no other undergraduate university can do! The real product of the FalconLAUNCH program, however, is the professional Air Force officers who have had the "Learning Space by Doing Space" experience while at the Air Force Academy. The exposure to solving ill defined problems in the FalconLAUNCH program prepares them for the challenges of a professional military career. The lessons learned and pride of ownership in the program are the finishing touches on officers joining the cadre of space professionals who make the United States Air Force the world's preeminent air and space power. That being said, there is no reason why a similar program at a civilian university couldn't provide the same systems engineering capstone experience to their undergraduate or graduate programs so valuable to young engineers embarking on their careers.

VII. Acknowledgements

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Bibliography

1. Siegenthaler, K. E. Jerry J. Sellers, David J. Richie, and Timothy J. Lawrence "Student Design, Development and Operations of Small Satellites at the United States Air Force Academy" *Proceedings*

*of the 2004 American Society for Engineering Education Annual Conference & Expositio*n," Salt Lake City, UT, June 2004.
2. Siegenthaler, K. E., J. J. Sellers, D. A. Miller, T. J. Lawrence, D. J. Richie, and D. J. Barnhart "The Undergraduate Satellite and Rocket Design, Fabrication and Launch Program at the US Air Force Academy" presented at the 2004 International Symposium IGIP / IEEE / ASEE, Fribourg, Switzerland September 27-30, 2004.
3. Sellers, Jerry J., and Doug Bayley, "Spacecraft Design, Development and Operations in Just Five Hours per Week: Experience from the USAF Academy FalconSAT Program," *Proceedings of the 2001 American Society of Engineering Educators Annual Conference & Expositio*n, 2001.
4. Engineering Commission of The Accreditation Board of Engineering and Technology, *ABET ENGINEERING CRITERIA 2000*, Third Edition, Accreditation Board for Engineering and Technology, Inc., December, 1997.

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