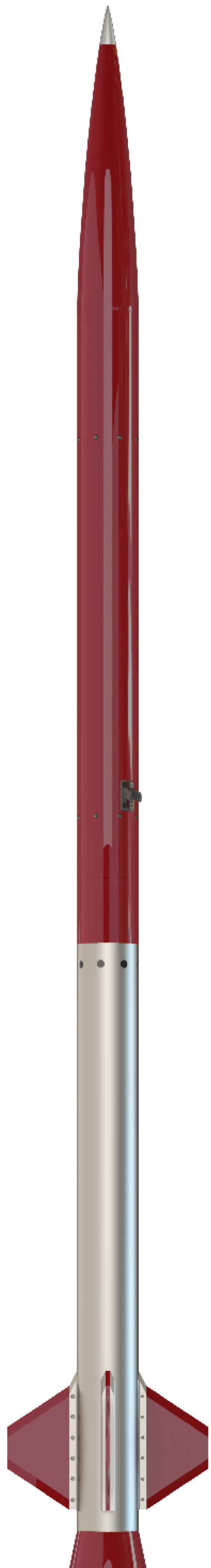
THE OLVT MEMBER'S GUIDE TO ROCKET SCIENCE



Everything you need to know to begin your journey as a rocket scientist.

The OLVT Member's Guide to Rocket Science

FIRST EDITION

This book is dedicated to:
Dr. Pat Artis
Dr. Kevin Shinpaugh
Mr. Robert DeHate

Welcome to the Orbital Launch Vehicle Team Member's Guide! If you are reading this you are most likely a new member or an individual excited by rocket design. In this book you will find everything you need to design a high power rocket on OLVT. The goal is to simplify and explain the fundamentals incorporated with solid rocket design and further inspire others to get involved. As you continue to read and learn, remember that safety should be your number one priority and having fun should be a close second. Enjoy and keep looking up!

Orbital Launch Vehicle Team at Virginia Tech

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Part One: The Round Table

1. Introduction to the Team

Orbital Launch Vehicle Team at Virginia Tech (OLVT) is a multidisciplinary team focused on developing an orbital launch vehicle for use with academic and research payloads. As opportunists and sensible adventurers, the team hopes to join multiple departments and colleges across Virginia Tech in achieving this goal. This is a university wide effort. Members must also recognize the long term nature of developing such a rocket. OLVT uses a stepping stone approach in which each increasingly advanced build develops and qualifies technology for use in later vehicles. This process culminates in Hokie 1.

1.1 Team History

OLVT was founded in the fall of 2016 with the goal of developing a launch vehicle capable of reaching orbit. Utilizing a student run organization, engaged faculty, and supportive industry personnel, OLVT hopes to reduce the cost of academic payloads while developing competent and experienced problem solvers among its members. OLVT currently has nearly one hundred members, a diverse set of advisors, and multiple close relationships within the aerospace industry.

The team started designing Level 1 and 2 Tripoli equivalent rockets dubbed "Okie" and "Dokie." Both of these rockets were propelled by either I or J motors and featured dual deployment recovery. They reached an altitude of around 5,000 ft and barely crossed Mach 1. Soon thereafter, OLVT built Hokie 0.5, our first two-stage rocket. Initially planned for launch at BALLS 26 in the Black Rock Desert, a technical issue with booster separation and sustainer ignition electronics meant a sustainer-only launch. The two-stage version of Hokie 0.5 successfully launched out of the Rocket Pasture in Argonia, Kansas. Hokie 0.5 reached an altitude of 17,000 ft and Mach 1.2 flying an M staged to an L. OLVT then constructed Hokie 0.6. This two stage Q to Q rocket was intended to become the first built by college students to reach 100 km. Unfortunately, the team experienced a misfire of the sustainer motor at BALLS 27. Thankfully, no one was seriously injured during the event.

OLVT has since created a subteam for launch operations focused on launch tower, pad integration, launch operations, and safety. In addition OLVT has created a business subteam with focus on funding, outreach, and social media. The team has efficiently split up roles and responsibilities so students have enough time to reliably and effectively work on their design.

OLVT is currently working on Hokie 0.75, a two stage launch vehicle capable of crossing the Kármán Line. If successfully launched, the vehicle will be the first two stage rocket built by a collegiate rocketry team to reach space, as well as set a new altitude record for both amateur and collegiate rocketry.

1.2 Team Structure

The team is divided into seven subteams, with their names and responsibilities listed below. Figure 1.1 depicts a graphical representation.

1. Avionics
    - Sensors, data transmission and storage
    - Power systems
    - Logic controllers
2. Business
    - Strategic communications with the public
    - Manage industry partner relations
    - Manage team finances and spending
3. Launch and Early Operations
    - Travel logistics
    - Lab and launch operations safety
    - Launch tower design
    - Launch procedures and checklists
4. Leadership
    - Oversee day to day operations
    - Lead direction of the team
    - Conduct meetings and manage team schedule
5. Structures
    - CAD models
    - Recovery subsystems
    - Staging subsystems
6. Propulsion
    - Propulsion subsystems and relevant safety
7. Trajectory and Analysis
    - Mission performance
    - Structural analysis and qualification
    - Aerodynamic analysis and qualification
    - Trajectory optimization

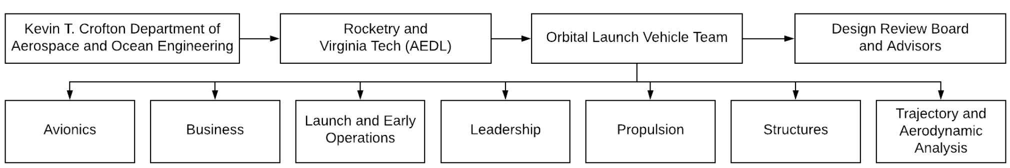


Figure 1.1: The hierarchical team structure.

1.3 Design Review Process

OLVT typically follows a one or two year design and build cycle, depending on the complexity of the project. Furthermore, a design review board consisting of industry personnel, academic advisors, mentors, and high power rocketry experts oversee the ongoing projects. A typical design cycle will consist of the following milestones and reviews:

1. Mission Concept Review (MCR)
    - Initial concept of the mission
    - High level requirements and basic design variables
    - Some preliminary design choices
    - "What do we want to do and why?"
2. Preliminary Design Review (PDR)
    - Fully defined mission requirements
    - Selected design from alternatives
    - Approximate dimensions
    - "How are we going to do this?"
3. Critical Design Review (CDR)
    - Detailed design, every nut and bolt, every wire, etc.
    - Changes since PDR
    - "Are we ready to begin construction?"
4. Flight Readiness Review (FRR)
    - Changes since CDR as a result of construction
    - Status of the build
    - Travel logistics
    - "Is the vehicle ready to fly?"

1.4 Lab Space

OLVT is currently part of the "Advanced Engineering Design Lab" at 501 Industrial Park Rd, Blacksburg, VA 24060. The facility is equipped with a basic machine shop and multiple cages for other design teams and projects. The machine shop boasts specialized equipment such as a filament winder, band saw, belt sander, and all types of hand tools. This along with multiple conference rooms and an outdoor painting area create a collaborative work space for the students to work. We share the building with Southern Printing Company. The lab is on the left side of the building and accessible via Main Street South and Corporate Research Center buses, both departing from Squires. Parking is also available. For those aged twenty one and older who are responsible drivers, Eastern Divide Brewing Company is within walking distance.

To participate in lab activities (and therefore help construct the rocket) a member must obtain their AEDL badge. You will have to join the AEDL Canvas page for specific links and instructions, but the process involves reading the lab policy manual successfully completing the lab policy manual canvas quiz, taking the required safety training through EHS, and signing the OLVT lab contract. One should then email the Ware and AEDL Lab manager proof of completion of the above requirements. Once this is done you can obtain your badge and hang it on the wall of OLVT's cage, as seen in Figure 1.2. Keep the tags in alphabetical order by last name.

Figure 1.2: OLVT's Lab Space in AEDL (2020)

1.5 Software

The team uses the following software:

- AeroRocket Suite: various simulations and analyses
- GitHub: code storage and synchronization
- Google Drive: file storage, smaller documents and reports, meeting slides
- GrabCAD: CAD file storage and synchronization
- LaTeX with Overleaf: large reports
- LTSpice: PCB design and electrical analysis
- Matlab: a lot of stuff
- RASAero-II and ASTOS: trajectory simulation and design optimization
- Slack: team communication
- SolidWorks: 3D modelling and simulation
- STAR-CCM+: aerodynamic analysis

Hopefully by this point, you have been added to all the necessary drives, slack channels, and other various software. It is important that every member familiarize themselves with the team's shared Google Drive. There are seven folders at the highest level - one for each subteam (excluding leadership) and a "General" folder. Talk with your subteam leads to learn about your subteam's specific folder. In the general folder you will find files of universal value to the team. Below are a few of the more important and frequented folders in "General":

- Handy and Useful Files: examples, instructionals, templates, software downloading and registering, the roster, contact list, references, etc.
- Meeting Notes: notes from meetings with advisors, design reviews, sponsors, etc.
- Meeting Slides: weekly general assembly meeting slides
- OLVT Documents: the team's Constitution and Responsibility Acknowledgement form
- Photos/Videos: media from previous trips, launches, etc.
- Design Reviews: design review papers and presentations

1.6 Onboarding Process

Onboarding for OLVT is a new concept to the team and, as such, is a work in progress. The total process from interest meetings to operational member should be a semester long. Regardless of the timeline, your onboarding process will entail, in chronological order:

1. A collection of $50 dues, goes toward:
   - OLVT polo and team sticker
   - Certification kit
   - Proving you have some skin in the game
2. Delivering of the Rocketry 101 Course
   - The information contained in this document
   - Lecture format and given by subteam leads
3. Obtaining your Tripoli Level 1 HPR Certification
   - Register as a Tripoli member ($10)
   - Construct your provided kit
   - Successfully fly your rocket
4. Complete the Tripoli Level 2 HPR Certification safety test
   - Really easy if you spend an hour studying

The total cost of membership for OLVT is $60 for the first academic year, and $50 every academic year thereafter. If you cannot afford dues, please reach out to your subteam lead or directly to leadership to find accommodations. OLVT will not turn you away because you can't afford dues. We are more than willing to work with you!

2. The High Power Rocketry Community

The high power rocketry (HPR) community is a complex mix of multiple organizations, loose groups of hobbyists, and codes of law. OLVT, in general, breaks the HPR community into three overlapping entities: local hobbyists/hobby organizations, national rocketry associations, and vendors/manufacturers. OLVT has separate but heavily involved relationships with all three. Furthermore, the entire community is governed by National Fire Protection Association Code 1127 (NFPA 1127). The next few sections are a poor attempt at describing these entities at large and how OLVT interacts with them.

2.1 NFPA 1127

The law of the land. The "Constitution," if you will, of high power rocketry. NFPA 1127 was created out of the rubble of the 60's and 70's, as parents and their children graciously lost appendages in rocketry accidents while rallying behind NASA and the global space race. NFPA 1127 was written and is maintained by these hobbyists in conjunction with fire protection experts. They know a thing or two because they have seen a thing or two. A PDF copy of the most recent version with exact wording is available in the google drive, General > Handy Useful Files > References [1]. Redistribution of this document is punishable by law, so don't copy or move it anywhere (Sanzio's name is on it).

2.1.1 The National Fire Protection Association

Believe it or not, all National Fire Protection Association Code is, just that, a code. It is not enforceable by itself and is not binding law. The code, and therefore NFPA 1127, are recommendations **to be enforced** and punishable by the Authority Having Jurisdiction. Now, you may ask, who is the authority having jurisdiction?

2.1.2 Authority Having Jurisdiction

NFPA 1127 defines the Authority Having Jurisdiction as, "An organization, office, or individual responsible for enforcing the requirements of a code or standard, or for approving equipment, materials, an installation, or a procedure." So it really depends. In Virginia, we look to the

Statewide Fire Prevention Code (SFPC), which adopts NFPA 1127 through a regulatory process known as “incorporation by reference.” Enforcing of SFPC code is yet again up to the local government in which you reside. Montgomery County enforces the SFPC, therefore making NFPA 1127 legally enforceable. Wherever you conduct launch operations, it is safe to assume NFPA 1127 applies, as most if not all local governments and states operate similarly.

2.1.3 NFPA 1127 Application

If enforceable, NFPA 1127 applies to the following, in simplified terms:

1. High power rocket motors
2. Motor components produced commercially for sale or for use by a certified user
3. High power rockets propelled by the high power rocket motors specified above
4. Conduct of launch operations of high power rockets specified above

It further defines a high power rocket motor as:

1. A rocket motor that has no more than 40,960 Ns of total impulse
2. Does not otherwise meet all the requirements for a model rocket motor set forth in NFPA 1125

2.1.4 NFPA 1127 Exemptions

NFPA 1127 does not apply to the following:

1. National, state, or local government
2. An entity engaged as a licensed business involved with rocketry
3. College or University

The last clause in these exemptions has been a hot topic for the HPR community for a few years now, long before the OLVT misfire. As it stands, colleges and universities do not have to adhere to NFPA 1127. However, if a college or university is attending a Tripoli Rocketry Association or National Association of Rocketry sponsored launch, they must adhere to the rules of those associations.

2.2 National Rocketry Associations

As alluded to in the last section, there are two primary and nationally recognized rocketry associations: Tripoli Rocketry Association (TRA or just Tripoli) and the National Association of Rocketry (NAR). Both of these organizations serve similar roles in the rocketry community, and it is a matter of personal preference and geographical location to who you associate. Traditionally, NAR is more focused on model rockets and caters to educational pursuits and the younger generation. Tripoli has been more open to supporting large projects, caring less about scale models or education. Both organizations can certify their members in accordance with NFPA 1127 to launch certain impulse classes of motors. The following sections will revolve mainly around TRA since OLVT has the strongest relationship with them.

2.2.1 Governance

Organization specific safety codes for TRA and NAR rely heavily on NFPA 1127. Any differences are merely additional restrictions which the organizations deem necessary. Individuals or groups who do not adhere to NFPA 1127 or association specific safety codes are not only in violation of the law, but not welcome at sponsored events and launches. In this way, NFPA 1127 is enforced socially and often without legal ramification or sever penalty. Even as an exempt college or university, TRA and NAR enforce their rules to guarantee safety of their members. With its inevitable faults, high power rocketry is essentially a self governing community.

Tripoli specifically is governed by a board of directors. The current standing Tripoli President has a permanent position on OLVT's design review board. Tripoli Gerlach (the branch that runs the annual "BALLS" event) also has major influence over the organization, specifically regarding the Tripoli Safety Code.

2.2.2 Tripoli Certifications

There are three certification levels. Level 1 covers H and I class motors. Level 2 covers J, K, and L motors. Level 3 covers M and higher motors. The upper limit of the O impulse category is what NFPA 1127 defines as a high power motor. A member is allowed to individually launch rockets with the motor impulse respective to their certification level. This Tripoli page lists the specific requirements for each certification level, but in general:

1. L1: Register as a member of Tripoli, successfully launch and recover a rocket launched with an H or I class impulse motor
2. L2: Take and pass the Tripoli L2 safety test, successfully launch and recover a rocket launched with a J, K, or L impulse motor
3. L3: Successfully launch and recover a rocket with an M or larger impulse motor. Prior to flight, the flyer shall successfully fly an L2 ranged rocket with electronic deployment. The L3 flight must have electronic deployment

As a member of OLVT, you are required to obtain an L1 certification. With support from the AOE department, this certification is covered in your yearly dues. See Section C of the appendix.

2.3 Hobbyists and Hobby Organizations

Most rocket enthusiasts form local groups or organizations, such as our local New River Valley Rocketry (NRVR). These organizations then adopt NAR or TRA as their structure for certification and operation. NRVR is home to high power rocketry experts such as Bob Schoner, Carlos Zapata, and Thomas Weeks. OLVT relies on NRVR for mentorship, certifications, and local launch operation management. As a TRA club, OLVT members get certified through Tripoli. Many of these local rocketry groups hold monthly events where members can launch their latest builds.

It is important to remember that these are hobbyists. They will all have different opinions for how to tackle a certain problem. All may work, none may work. Find the individuals who you believe have your best interest at heart and listen to them. The thought holds true not just for NRVR, but for any rocketry group in the country. Remember that any rocket you design and build is yours. There are many ways to skin a cat, so long as you are safe and having fun. The only opinions that matter on launch day are your own and the RSO's.

2.3.1 NRVR and Kentland Farm

NRVR deserves a special section due to their close relationship with the various rocketry teams at Virginia Tech. They hold monthly launches at Kentland Farm where OLVT members are encouraged to attend, launch, and meet with other hobbyists. NRVR is allowed to use Kentland Farm so long as they support Virginia Tech student organizations and rocketry teams. One can find a launch schedule on their website. Students are also encouraged to become members of NRVR.

Kentland Farm is a big place. One can find the launch location by searching "Kentland experimental aviation systems laboratory" on your phone's GPS. Alternatively, you can use the map in Figure 2.2 which will get you to the exact launch location after entering the front gates of the farm.

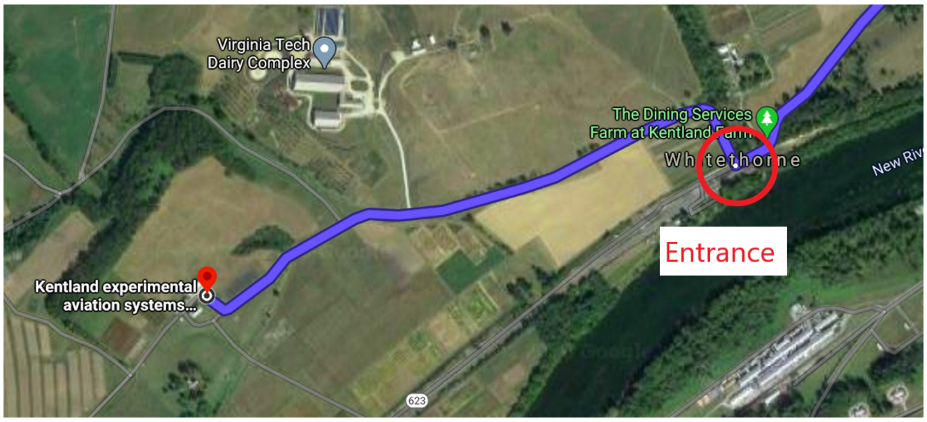


Figure 2.1: Kentland Farm

2.4 HPR Vendors and Manufacturers

Although small, a thriving industry surrounds the high power rocketry community. These manufacturers and vendors supply motors, motor casings, kits, recovery systems, avionics systems, etc. to hobbyists. The average hobbyist rarely has to visit out of industry suppliers for rocket parts. Below is a list of some of the primary manufacturers, notice there are only two major brands of motor systems:

- AeroTech: reloadable and single use motor systems
- Altus Metrum: avionics and telemetry systems
- Cesaroni Technology Incorporated (CTI): reloadable motor systems
- Estes: model rocket kits
- Fruity Chutes: recovery systems
- LOC Precision: kits, tubing, other various rocket parts
- Mach 1: kits and tubing
- MadCow Rocketry: kits, tubing, other various rocket parts
- Missile Works: avionics and telemetry systems

Although manufacturers sell their components directly online, most hobbyists find it easier to purchase parts through a vendor. Purchasing parts from a vendor allows for a single shipping fee, since few manufacturers make every part of a rocket. In addition, most vendors travel the country attending various rocket launches. This allows vendors to sell directly to the consumer. Below is a list of common vendors:

- Animal Motor Works
- Apogee Components
- Chris' Rocket Supplies
- Giant Leap Rocketry
- Performance Hobbies

It is worth noting that most manufacturers are also vendors, and most vendors are also manufacturers. The above lists cater to the primary operation of each organization.

2.4.1 Animal Motor Works

Animal Motor Works deserves a special section in this guide for a few reasons. First, they are our primary vendor. Robert and Gloria have worked tirelessly to give OLVT the best deals, shipping rates, and student discounts available. They have good relationships with most of the manufacturers which makes sourcing unique parts easy. Second, Robert has extensive knowledge of custom solid rocket motors. Having this close connection reduces the need for OLVT to develop our own propellant (an expensive and dangerous process). By outsourcing propellant casting, OLVT also outsources risk. If you are in the market for anything rocketry related, give Animal Motor Works a call and they will work with you individually. Last, but certainly not least, OLVT looks to Robert and Gloria as family. When things are looking bleak out on the firing line, you can count on them to lighten the mood. They genuinely care about our team and our projects.

Figure 2.2: Robert DeHate and Gloria Robinson, managers of Animal Motor Works.

2.5 OLVT's Place in the HPR Community

OLVT, and student rocket teams in general, are relatively new to the high power community. As such, we do not have an exact role to play. Student rocketry teams are currently viewed as largely beneficial to the hobby. National rocketry associations see their growth potential in student certifications. Vendors and manufacturers view students as a mutually beneficial business opportunity. Both value students as the future of the hobby. Hobbyists, however are hit or miss. Those with negative stances view students as hazardous groups who strain their local launches. Those with positive stances value mentorship and enjoy seeing their hobby persist to the younger generations in an educational light. The rise in popularity of student rocketry competitions such as IREC and NASA SLI guarantee students will remain a fundamental element of the high power rocketry community. These competitions rarely use altitude as the primary measure of success however, and as such usually remain under 50,000 ft or so.

So what about organizations like OLVT, Space Enterprise at Berkely, USC Rocket Propulsion Laboratory, or the Princeton Space Shot Team? These organizations are not directly competing against each other, but rather against themselves to push the boundaries of collegiate and amateur rocketry. With the poor track record of these organizations (the OLVT misfire, the USCRPL dead rocket launch, and countless other incidents), it appears that national rocketry associations are hesitant to be involved with such endeavours. OLVT has personally decided that this is where student rocketry and the high power rocketry community should separate. It becomes nearly impossible for an RSO to feel comfortable allowing a group of young and inexperienced students to launch such complex vehicles. Such projects should not be launched at national rocketry association sponsored events at all, let alone by students. OLVT has instead elected to form a Design Review Board for oversight, mentorship, and advice. Members from this design review board will then have authority at OLVT run launches. NFPA 1127 doesn't technically apply to Hokie 0.75 sized rockets launched by OLVT for a multitude of reasons. With that being said, it is important to realize the contributions of the high power rocketry community and the principles outlined in NFPA 1127. This is the foundation for where we are today. For this reason, OLVT continues to network with NRVR and Tripoli to gain members certifications and experience.

In a broader sense, OLVT hopes to fill the gap between amateur high power hobbyists and NASA sounding rockets. NASA skipped over Hokie 0.75 sized rockets and hobbyists lack the funding and man power to construct them. We are truly in a league of our own.

II

Part Two: Rocket Design

3. Systems Engineering Crash Course

This chapter serves to outline the principles and practices of systems engineering for team use. NASA defines system engineering as "A methodical, multi-disciplinary approach for the design, realization, technical management, operations, and retirement of a system." They further define a system as "The combination of elements that function together to produce the capability required to meet a need." [2]. In layman's terms, this is the iterative process that realizes an idea using various analysis, communication, and design management tools. This process is proven to provide practical and successful solutions. As engineering student's you have become experts at analyzing specific problems, however systems engineering allows you to abstract this analysis in a way that will contribute to a larger goal or system.

Aerospace senior design at Virginia Tech (AOE 4165 and 4166) forms the basis for this crash course and is the source of quotes and images contained in this section [3]. Adoption of systems engineering principles outlined here will give you a leg up when entering senior design. In a broader sense, systems engineering will allow you to operate as an exceptional engineer.

3.1 Akin's Laws of Spacecraft Design

Professor Akin worked in spacecraft design his entire life. This earns him something that we refer to as tribal knowledge or a deep rooted and practical understanding of a topic gained through years of experience. He teaches senior design at University of Maryland (and used to teach at MIT!). The list below contains a few of his laws that are well known in the rocket nerd community and strongly applicable to OLVT [4].

- Engineering is done with numbers. Analysis without numbers is only an opinion.
- Design is an iterative process. The necessary number of iterations is one more than the number you have currently done. This is true at any point in time.
- Your best design efforts will inevitably wind up being useless in the final design. Learn to live with the disappointment.
- Not having all the information you need is never a satisfactory excuse for not starting the analysis.
- When in doubt, estimate. In an emergency, guess. But be sure to go back and clean up the

mess when the real numbers come along.
- Sometimes, the fastest way to get to the end is to throw everything out and start over.
- Design is based on requirements. There's no justification for designing something one bit "better" than the requirements dictate.
- The previous people who did a similar analysis did not have a direct pipeline to the wisdom of the ages. There is therefore no reason to believe their analysis over yours.
- Past experience is excellent for providing a reality check. Too much reality can doom an otherwise worthwhile design, though.
- A bad design with a good presentation is doomed eventually. A good design with a bad presentation is doomed immediately.
- When in doubt, document.
- You can't get to the moon by climbing successively taller trees.
- A designer knows that they have achieved perfection not when there is nothing left to add, but when there is nothing left to take away.
- Any run-of-the-mill engineer can design something which is elegant. A good engineer designs systems to be efficient. A great engineer designs them to be effective.
- Capabilities drive requirements, regardless of what the systems engineering textbooks say.
- Space is a completely unforgiving environment. If you screw up the engineering, somebody dies (and there's no partial credit because most of the analysis was right...)

3.2 The Process

Systems engineering is an iterative process. With each successive iteration, the design gets closer to perfect. The design, however, will never and can never be perfect. As an engineer, you must determine what point is "good enough." This process is depicted in Figure 3.1 and as an activity matrix in Table 3.1.

Table 3.1: Systems Engineering as an Empty Activity Chart

Systems engineering process as depicted by an activity chart. The chart compares project phases with system engineering steps. Specific check marks in each box are unique to any given project [3].

Logic Steps →		1	2	3	4	5	6	7
Time Steps ↓		Problem Definition	Value System Design	System Synthesis	System Analysis	Optimize	Decision Making	Planning for Action
1	Program Planning							
2	Project Planning							
3	System Dev							
4	Production							
5	Distribute							
6	Operations							
7	Retirement							

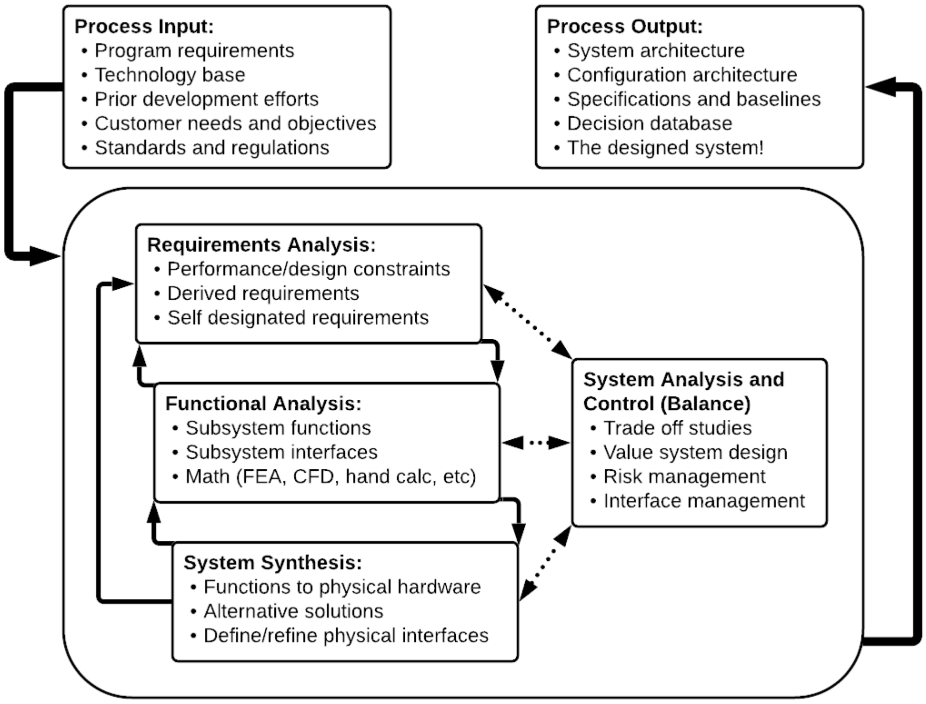


Figure 3.1: Systems Engineering Process

The iterative systems engineering process. Repetitions of elements in the ellipse will lead to a good design [3].

3.3 Problem Definition

The first step in solving the problem is to understand it. Restate the problem in your own words, infer what is really trying to be solved, and abstract the original or provided text. For example, someone on the team says "The vehicle needs dual deployment." You as an engineer should understand that the vehicle really needs to safely land near the launch site. Dual deployment may or may not be the best approach to accomplish this. One can organize such thoughts in the twelve products of problem definition:

1. A well-conceived title for the problem
2. A descriptive scenario, explaining the nature of the problem and how it came to be a problem, and presenting as much history and data as can be prepared with available resources
3. An understanding of what disciplines or professions are relevant to an attack on the problem
4. An assessment of the scope of the problem
5. A determination of the societal sectors involved
6. An identification of the actors to be involved in the problem-solving situation
7. An identification of needs
   - A condition requiring supply or relief
   - A lack of something required, desired, or useful
   - Ex: Decrease likelihood of loss of space-based assets
8. An identification of alterables
   - Things pertaining to the needs that can change

- Controllable to help achieve needs and objectives. Ex: orbit selection, attitude stabilization method
- Uncontrollable but subject to change. Ex: national policy

9. An identification of major constraints
    - Limiting boundaries of the system
    - Ex: Existing debris, existing satellites, international law
10. Some partitioning of the problem into relevant elements
11. Some isolation of the subjective elements of the problem
12. A description of interactions among relevant elements of the problem

Often the needs, alterables, and constraints are displayed together in a NAC Table.

3.3.1 Scoping and ConOps

Scoping is the process of defining every aspect of your project. The scope helps define the surrounding landscape. It's how you get your feet wet. Besides identifying the NACs, an engineer must become familiarized with the relevant stakeholders, there expectations and surrounding documentation. For OLVT, this includes understanding how the wants of Virginia Tech, directives set by our primary advisors, value added for our sponsors, and personal goals of the team relate to the current mission and vehicle design. "Scope is a definition of what is germane to your project."

Simply put, scoping is the who, what, when, where, and why of the engineering world. **Who** is involved. This is all of the stakeholders including you, your team, your investors, your superiors and your customers. **What** is the goal. This includes the needs, alterables and constraints associated with your project. **When** is the deadline. This should give the customers and investors a way to monitor your timely success throughout the project. **Where** is this taking place. Where is the launch location **Why** are you doing this. This should show why this project is either marketable or educationally beneficial.

AOE 4165 and 4166 define the concept of operations (ConOps) as "A description of how the system will be operated during the mission phases in order to meet stakeholder expectations." It provides a top down overview of the system and is the simplest form of describing the mission. Typically, figures and diagrams are the best way to portray a ConOps. Regardless of the presentation format a good ConOps often describes: major phases, operational scenarios, timelines, command and data architecture, relevant facilities, logistics and support, and critical events. An example ConOps is shown in Figure 3.2.

3.4 Value System Design

After defining the problem, fleshing out high level requirements, defining the scope, brainstorming some possible solutions, and creating a few concepts of operations, the team will engage in value system design. As the team progresses through the iterative design process they will need a method to weigh possible design alternatives and ensure the design improves with every iteration. Value system design (VSD) answers the question, "How do we know we have a good design?" On a deeper level, VSD relates the design to the mission requirements and measures how well the design meets those requirements. Objective hierarchies are used to organize and kick off the VSD. An example objective hierarchy is provided in Figure 3.3.

It is often hard to distinguish between requirements and objectives. For example, one may assume that maximizing payload would lead to a better design. In reality OLVT designs our

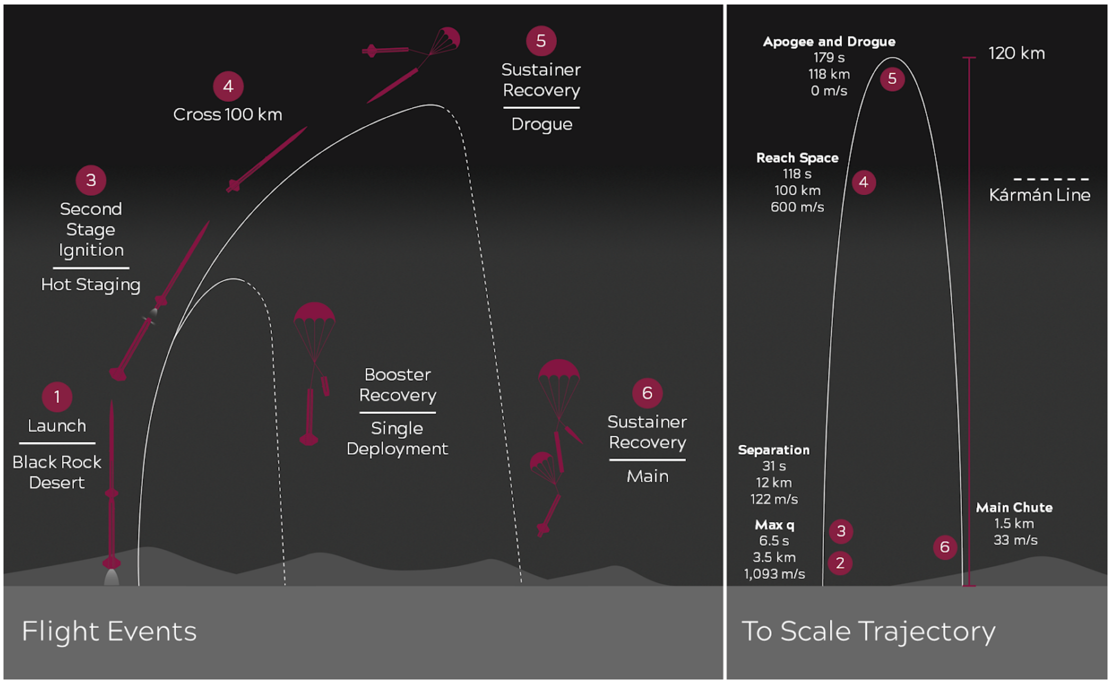


Figure 3.2: Example ConOps

OLVT's senior design team (AOE 4165) used this con-ops in their poster and final presentation in spring 2020.

rockets with specific payload capabilities in mind, making the metric a requirement. For most rockets flown by OLVT, the objectives should be to mitigate risk and minimize cost.

After creating an objective hierarchy, the team should use the analytical hierarchy process (AHP) to create quantifiable measures of "good design." The process uses pair wise comparisons of the objectives to create weights for each objective, ranking their importance. Quantitative information describing each alternative is then weighted with the objectives, determining which is the best solution.

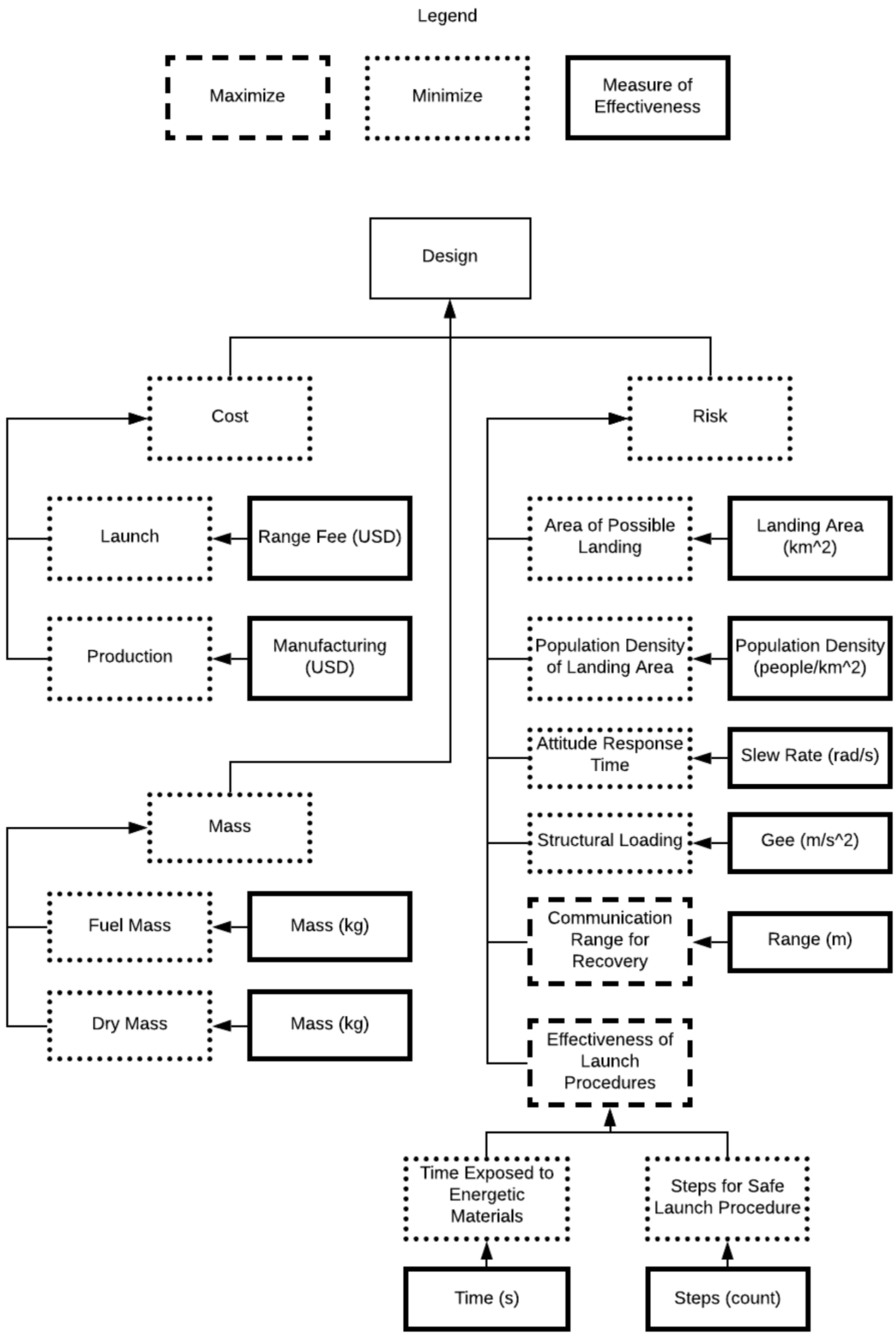


Figure 3.3: Hokie 0.75 Objective Hierarchy

An example objective hierarchy, used to value the design of Hokie 0.75.

3.5 System Synthesis

Synthesizing proposed designs allows an engineer to determine the feasibility and compatibility of the entire system. With this element of systems engineering, ask questions like “Can it be done in the time frame?” “Does it violate any constraints?” “Are the subsystems compatible?” “Does the design address the problem definition?” “What is required to achieve the ideal solution?” It is often beneficial to disassemble the problem, solve each component individually, and put the solutions together. System synthesis translates the system functional architecture into a physical architecture.

There are two ways to perform system synthesis. Objective-based alternative generation weighs proposed and complete mission concepts. For example, should we use one giant rocket with electric propulsion to land humans on Mars, should we use multiple chemical rockets launched individually, or should we utilize a single chemical rocket with orbital refueling? These are three completely different mission architectures with different technologies and timelines. After generating multiple mission architectures, the best alternatives are then carried to analysis. The second method, system-element or subsystem approach, considers specific subsystems to address each function of the mission. Alternatives which are incompatible, not feasible, or inferior are omitted. Alternatives are then generated by selecting one item from each list. For the Mars mission described earlier, an engineer would consider various forms of propulsion and launch plans, then combine the best compatible subsystems.

Given OLVT’s organizational structure, we generally find the subsystem approach more useful. For Hokie 0.75, we considered different methods of staging, different avionics components, different recovery systems, and different grain geometries independently. OLVT matches each subteam to the functions most commonly found in sounding rockets. Each subteam then aims to develop a subsystem to meet the needs of a specific function of the vehicle. Splitting subteams this way streamlines the system synthesis process.

3.6 System Analysis

System analysis is the development of models of the alternative solutions (system synthesis) with sufficient resolution to determine values for the measures of effectiveness (VSD). It is the act of valuing viable designs using the VSD. Models should be valid, manageable, able to differentiate alternatives, and complete with respect to the VSD. Analysis gives values to weigh in the AHP.

The analysis should first optimize each alternative to make it “as good as possible.” Quantitative values are then weighted in the AHP, determining the best solution. All designs are iterated to make them better and the process repeats.

On OLVT, we have an entire subteam dedicated to this specific systems engineering tool. Primary analyses include finite element, computational fluid dynamics, and trajectory analysis.

3.7 Requirements

Specific Mission Requirements (SMRs or simply requirements) are the most important and fundamental part of systems engineering. Requirements are hierarchical in nature, and should be necessary, verifiable, and attainable. Furthermore, requirements should form complete sentences of the form: **Some noun + “shall” + meet some requirement**. Most projects usually start with a set of basic requirements delivered by the customer. Since OLVT does not necessarily have a ‘customer’, we rely on ourselves to set program requirements and derivatives. Take, for example, the high level requirements set by OLVT for AOE 4166 Space Vehicle Design for the 2019-2020 academic year:

- SMR-1: The Hokie 0.75 launch vehicle shall reach an altitude of 100 km (+20 km).
- SMR-2: The Hokie 0.75 launch vehicle shall be capable of delivering a 5 kg payload to the desired altitude.
- SMR-3: The Hokie 0.75 launch vehicle shall prove technologies that will potentially be used on the Hokie 1 launch vehicle.
- SMR-4: The Hokie 0.75 launch vehicle shall have a structural design capable of enduring all flight conditions, utilizing a minimum factor of safety of 2.
- SMR-5: The Hokie 0.75 launch vehicle shall follow international regulations and adhere to all legal constraints.
- SMR-6: The Orbital Launch Vehicle Team shall employ risk reduction methods to ensure safety of the vehicle and all personnel.
- SMR-7: The sustainer and booster stages shall have a controlled descent and be recoverable.

Continuing with the senior design example and breaking SMR-6 down in a hierarchical manner yielded:

- SMR-6.1: The avionics system shall have audible warnings for arming of system.
- SMR-6.2: The avionics system shall employ simple but effective safety systems.
- SMR-6.3: The vehicle's machined components shall maintain a maximum tolerance of 0.005.

Breaking SMR-6.2 down yielded:

- SMR-6.2.1: The arming system shall use 1 level of electric shunts.
- SMR-6.2.2: Launch Operations personnel shall be stationed a safe distance from armed energetic material at all times.
- SMR-6.2.3: The recovery system shall use redundant deployment systems in sequence for each parachute deployed.

Notice how each requirement set becomes more specific and technical. Usually, top and some mid level requirements are depicted in a graphical requirements hierarchy, as depicted in Figure 3.4. It is also worth noting that these requirements are not static. Instead, they constantly shift and transform throughout the iterative design process as the design becomes more refined and new requirements are uncovered or old requirements revisited. Always remember that requirements drive the design. Constantly remind yourself to answer the question "Why are we designing it this way? What requirement or need does this fill?"

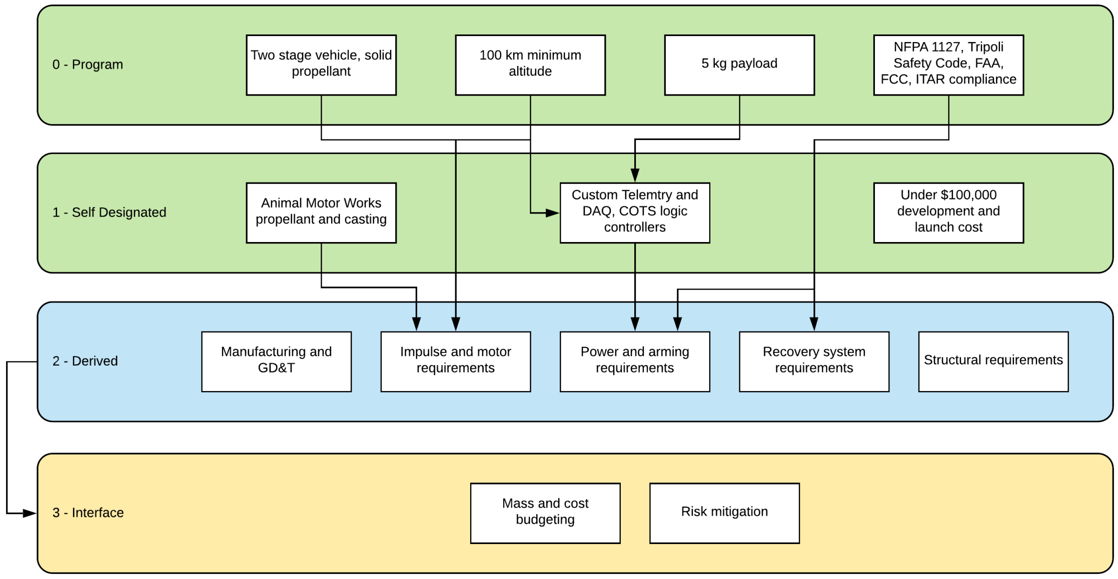


Figure 3.4: Example Requirements Hierarchy

Requirements and their derivatives for Hokie 0.75 organized by origin. "Program" or "Customer" requirements are given at the start of the project. "Self Designated" requirements are set by the team at the start of the project. "Derived" requirements are the result of systems engineering analysis of the system. The "Interface" is best represented by the objective hierarchy and is used to balance or weigh the requirements.

3.8 Risk Management

Risk Management could be considered the backbone of the design process. It encompasses all of the components that will lead to a mission success, or if misconducted, mission failure. The four major components to be discussed are cost, scheduling, technical and safety risks. It is important to begin brainstorming of possible risks before the design process begins. Once the design process has begun, check the list of risks weekly to add new risks and attempt to mitigate as many as possible.

- **Cost Risk:** Risks associated with funding and proper expenditure of funds. Cost estimates must be current, detailed, and accurate to mitigate this risk.
- **Scheduling Risk:** Risks associated with timeline and time management. This includes accommodations for manufacturer processing and shipping. Timelines must be current, detailed, and accurate to mitigate this risk.
- **Technical Risk:** Risks associated with how the design will change with time. This includes changes made to accommodate stakeholders, as well as risks in design, testing and production of the vehicle.
- **Safety Risk:** Risks classified as hazards. A hazard comes with a possibility to put a person or party in physical danger.

3.8.1 Risk Matrix

A risk matrix is a great tool to begin managing the potential risks at hand. Each risk will be ranked on a scale from 1 to 5 for two criteria, likelihood and consequence. The likelihood pertains to how probable it is that this risk will occur. The consequence refers to the severity of the outcomes of a risk if it is to occur. after the quantitative ranking is complete, colors can be assigned to each risk. The color designations consist of green, yellow, and red.

- Low Risk:
- Moderate Risk:
- High Risk:

Once all of the risks have been ranked and assigned a color, the risk matrix can be filled in. A template is shown in Figure 3.5

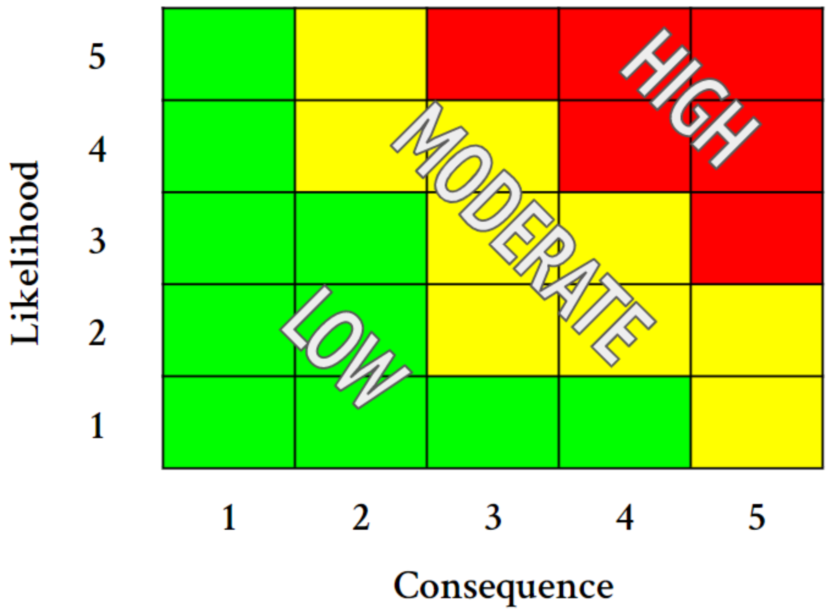


Figure 3.5: Risk Matrix template

Template outlining the basic structure of a Risk Matrix.

3.8.2 Failures Modes and Effects Analysis (FMEA)

After identifying risks and placing them into a risk matrix, the next step is to understand how those risks affect the design and develop a plan of action to mitigate them. A Failure Modes and Effects Analysis (FMEA) will aid in accomplishing this task. A typical FMEA will assess the identified risks from the risk matrix by assuming the risk comes to fruition in the form of a failure. Then it will analyze the impact of such a failure on the success of the mission, which will allow the user to brainstorm and form a mitigation strategy. The million dollar question here is "How will this failure affect the success of the mission?" In a broader sense, FMEA is the process of moving risks to lower positions on the risk matrix. The analysis can be conducted using tabulated risks and mitigation items, paragraph form responses to risks, or more complex and quantitative methods such as a Probabilistic Risk Assessment (PRA). Regardless of the FMEA format, the analysis can conclude when the technical case is made, meaning consequences are properly identified and risks effectively mitigated. For Hokie 0,75, the team simply used a tabulated version of the risk matrix and created a mitigation strategy for each item, as shown in Table 3.2. Lastly, it may be important to consider secondary failures as a result of the first. Will this failure cause any other possible failures? Such thoughts can be organized into a fault tree.

Table 3.2: Example Mitigation Techniques

Mitigation techniques for the motor of Hokie 0.75.

Component	**Failure Mode**	**Mitigations**
Motor	CATO	Make sure there are no bubbles, cracks, hard objects that could crack casing, casting motor with professional supervision, static fire to validate design/process
	Ignition Failure	Using redundant igniters and making sure the AIM XTRAs are connected properly to the igniters
	Improper Nozzle Alignment	Have all parts made within correct tolerance and fasten all bolts in diagonal order
	Accidental Ignition	Test all avionics and ensure electronics are powered for as little time as necessary

4. Structures and Configuration

4.1 Rocket Anatomy

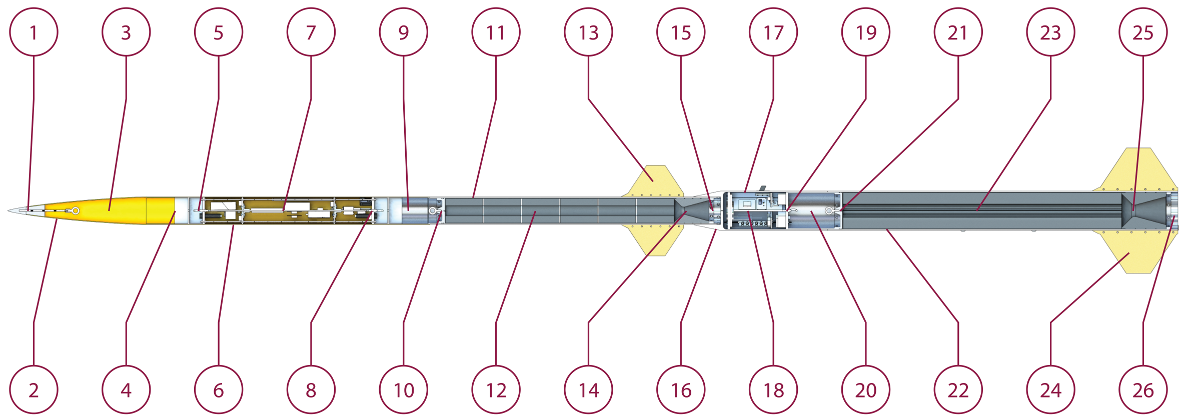


Figure 4.1: Labelled Hokie 0.75 Cutaway

Depicts the major components of a typical two stage solid rocket.

Before designing a launch vehicle, it is important to understand the basic anatomy of a rocket. A rocket is comprised of stages. These stages are numbered in the order that they will be ignited. For example, a three stage rocket will have a first stage, second stage and third stage. The first stage can be referred to as a booster as its primary function is to "boost" the vehicle towards a desired velocity and altitude. For two stage, suborbital rockets a sustainer will be used to achieve a desired altitude by "sustaining" the desired velocity. These stages will be comprised of many smaller components, each with varying degrees of complexity. For this reason, a team should use standardized terminology when referencing the locations of said components. As an example, we will define components from a two stage suborbital launch vehicle, Hokie 0.75, using the cutaway in Figure 4.1. The following directional terms will be useful when describing the location of components in reference to others:

- **Axial:** Referring to a central datum line running through the rocket's cylindrical axis

- **Radial:** Any direction perpendicular to axial
- **Forward:** Towards the nose cone (hopefully the direction of travel)
- **Aft:** Towards the rear of the rocket (hopefully opposite the direction of travel)

The following items pertain to the second stage, more commonly referred to as the sustainer. Sticking with with common convention, we start at the forward most portion of the rocket and work our way back. In this way, the zero reference point does not shift due to staging.

1. **Nose Cone Tip:** The most forward point on a rocket. Due to the component's complex and fine geometry, it is usually machined from a metal alloy.
2. **Nose Cone:** The nose cone geometry should minimize drag and aerodynamic heating, and is usually composed of fiberglass for RF transparency.
3. **Payload Bay:** A compartment designated to house and protect the payload throughout the duration of flight. Usually situated in or shortly aft of the nose cone.
4. **Sustainer Body:** Often referred to as a body tube, the body forms the geometric exterior of the vehicle and protects interior components.
5. **Main Parachute Bay:** A compartment that houses the main parachute, along with its tension lines and a shock cord. In the case of a black powder parachute deployment method a protective blanket will also need to fit in this portion.
6. **Main Parachute Ejection System:** Uses some form of stored energy to eject the main parachute. This can either be driven by ignition of an energetic material or by release of stored mechanical energy.
7. **Sustainer Avionics Bay:** Houses the sustainer avionics system which functions to record and transmit flight data as well as manage sustainer parachute ejection systems.
8. **Drogue Parachute Ejection System:** Serves a similar function as the main parachute ejection system, but deploys the drogue parachute.
9. **Drogue Parachute Bay:** Serves a similar function as the main parachute bay, but houses the drogue parachute and corresponding equipment.
10. **Sustainer Forward Closure:** A component used to cap and seal the forward end of the sustainer motor casing. This is usually comprised of a metal alloy due to the extreme temperatures and pressures within the motor core.
11. **Sustainer Motor Casing:** Contains the sustainer grains and nozzle. Additionally provides attachment points for the closure and nozzle hardware.
12. **Sustainer Grain(s):** Cast or molded propellant which burns to drive the sustainer. The interior geometry of the grain forms the core. Grains are often wrapped in a protective liner to insulate the casing.
13. **Sustainer Nozzle:** Converts thermal energy from the sustainer motor into kinetic energy to propel the sustainer. Often constructed of materials which can manage high heat flow such as carbon graphite.
14. **Sustainer Retaining Ring:** Anchors the sustainer nozzle to prevent it from being jettisoned out the aft end of the motor casing. A nozzle carrier is an alternative component to serve the same function.
15. **Sustainer Fins:** Stabilize the rocket during flight. Fins can be passive or active in their influence. Must be constructed to withstand aerodynamic loading and heating.

The following items comprise the first stage, more commonly referred to as the booster.

16. **Transition Piece:** A component which joins two stages, often of different diameters. Must be designed with stage separation mechanics in mind. In the case of Hokie 0.75, separation is driven by ignition of the sustainer.

17. **Booster Body:** Often referred to as a body tube, the body forms the geometric exterior of the vehicle and protects interior components.
18. **Booster Avionics Bay:** Houses the booster avionics system which functions to record and transmit flight data. Also manages the booster parachute ejection system and often handles sustainer motor ignition.
19. **Booster Parachute Ejection System:** Uses some form of stored energy to eject the booster parachute. This can either be driven by ignition of an energetic material or by release of stored mechanical energy.
20. **Booster Parachute Bay:** A compartment that houses the booster parachute, along with its tension lines and a shock cord. In the case of a black powder parachute deployment method a protective blanket will also need to fit in this portion.
21. **Booster Forward Closure:** A component used to cap and seal the forward end of the booster motor casing. This is usually comprised of a metal alloy due to the extreme temperatures and pressures within the motor core.
22. **Booster Motor Casing:** Contains the booster grains and nozzle. Additionally provides attachment points for the closure and nozzle hardware.
23. **Booster Grain(s):** Cast or molded propellant which burns to drive the vehicle. The interior geometry of the grain forms the core. Grains are often wrapped in a protective liner to insulate the casing.
24. **Booster Nozzle:** Converts thermal energy from the booster motor into kinetic energy to propel the vehicle. Often constructed of materials which can manage high heat flow such as carbon graphite.
25. **Booster Retaining Ring:** Anchors the booster nozzle to prevent it from being jettisoned out the aft end of the motor casing. A nozzle carrier is an alternative component to serve the same function.
26. **Booster Fins:** Stabilize the rocket during flight. Fins can be passive or active in their influence. Must be constructed to withstand aerodynamic loading and heating. Usually larger than the sustainer fins.

4.2 Recovery

Recovery can be viewed as the process of releasing and reefing a parachute to safely descend a vehicle at a desired velocity. Most conventional rockets utilize dual deployment, meaning both a drogue and main parachute will be used. The drogue parachute serves to stabilize the vehicle and begin the deceleration process while minimizing the total recovery area. At an altitude closer to the ground (1,000 ft or so) a main parachute is deployed and decelerates the vehicle to an acceptable impact velocity. If a single parachute is used, the recovery system is considered single deployment.

4.2.1 Parachute Design

A parachute consists of a flexible canopy that can be ejected from a vehicle with the intent of increasing the drag on a the body as it descends to a desired landing surface. Suspension lines are used to connect the parachute to the body. The flexibility of the materials used for a parachute allows the parachute to be folded and compacted to a minimal volume inside of the vehicle.

Once the parachute has opened to its maximum area, the weight of the vehicle is distributed amongst the suspension lines. This would cause the parachute to close in a static system. In a dynamic system where the body and parachute are falling, the parachute is kept open due to the internal pressure of air that is captured by the parachute. The equation for this internal dynamic pressure can be found in Equation 4.1. In this equation, P_i is the internal parachute pressure, ρ_{air} is the density of air at a desired altitude, and v is the velocity of the body approaching the ground.

$$P_i = \frac{1}{2} * \rho_{air} * v^2 \tag{4.1}$$

This internal parachute pressure can be considered as either a constant or a vector of constants when calculating the drag of the system. Equation 4.2 displays this correlation, where D is the drag acting on the system, C_D is the drag coefficient and A is the cross sectional area of the parachute. Figure 4.2 shows a physical representation of this layout.

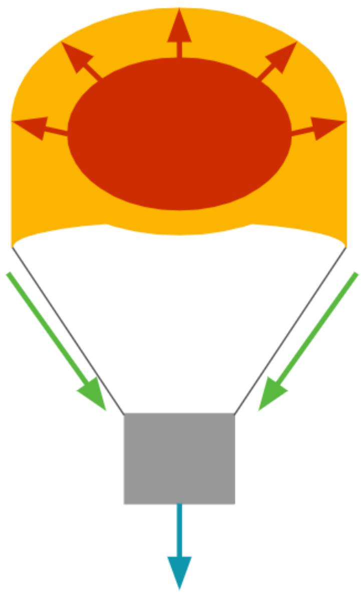


Figure 4.2: Parachute system forces

Visual Representation of the forces involved in recovery. The red circle and arrows show the internal parachute pressure applied to the area of the canopy. The green arrows show the weight of the body distributed amongst the suspension lines. The blue arrow shows the weight of the body.

$$D = P_i * C_D * A \tag{4.2}$$

Note that the drag coefficient varies with the shape of the parachute. Usually this unitless value for a C_D will range from 0.6 to 0.85. The area in this equation refers to the cross sectional area of the parachute when fully expanded. It is simple to say "more area equals more drag", however there is one more variable to consider, **drift**. Drift is the horizontal distance that the vehicle will travel before it reaches the ground. The goal is to minimize drift by optimizing the parachute area. This can be accomplished by utilizing every engineers favorite equation, $F = ma$. Equation 4.3

replaces the force in the equation with a 2D representation of drag versus weight.

$$a = \frac{mg - DRAG}{m} \tag{4.3}$$

In order to optimize a parachute the acceleration of the body should be close to zero. This means that the weight (mg) should be equal to the drag. This will work as long as the velocity in Equation 4.1 is set to the desired terminal velocity. Terminal velocity for drogue parachutes should be in the 50-200 ft/s range depending on the size of the vehicle, while main parachutes should be in the 15-50 ft/s range.

More important than terminal velocity is the vehicle's impact energy. This can be calculated simply by finding the kinetic energy of the vehicle with $\frac{1}{2}mv^2$. The NASA Student Launch Initiative (SLI) Rule Book sets a maximum impact energy of 100 J. Although this is unrealistic for larger vehicles, it is a good benchmark for comparison.

For the current purposes of OLVT constructing a parachute in house is an art that may never be learned, however this step in the design process will be utilized to aid in deciding what parachute will be purchased. Once a parachute design is optimized, a diameter, weight and compacted volume should be known. A safety factor of 10% can be used during the design process before selecting and purchasing a parachute. Most suppliers will provide data for their parachutes on the characteristics such as area and descent velocity versus payload mass to aid in final parachute selection.

4.2.2 Parachute Packing

You may have heard the expression "You pack your own chute" in the inspirational sense of controlling your own destiny. On OLVT we use this statement literally. After completing the design and construction of a rocket, you have put a seemingly countless amount of time and effort in this endeavor. For this reason, you should be hesitant to allow this creation to plummet to the ground with a thud that you will hear far later than the flight date. This apparently trivial step in the pre-flight process could be the difference between a mission success and a mission blunder, therefore should be taken seriously.

There are many ways to pack a parachute and anyone you talk to will have a favorite method. Figure 4.3 depicts the method most often used by OLVT. It is derived from "The Russian Parachute Packing Method."

1. Lay the parachute on a flat surface in a semicircle configuration.
2. Create four triangular pockets by pulling all tension lines to the center (at this point the parachute should look like a triangle with the tension lines coming out of the center of the base).
3. Fold the outermost points of the triangle to the center.
4. Repeat the previous step. this should result in a long and thin, triangular shape.
5. Ensure edges are clean and crease folds.
6. Fold the tension lines up the center of the parachute, until they are one third of the way up the height of the parachute.
7. Repeat previous step until all slack in tension lines are moved.
8. Fold the parachute from top to bottom, making a crease one third of the height from the bottom.
9. Fold the top third so that the peak of the parachute touches the crease made in the last step.

10. Roll the parachute from left to right until the cylindrical "burrito" shape is achieved.

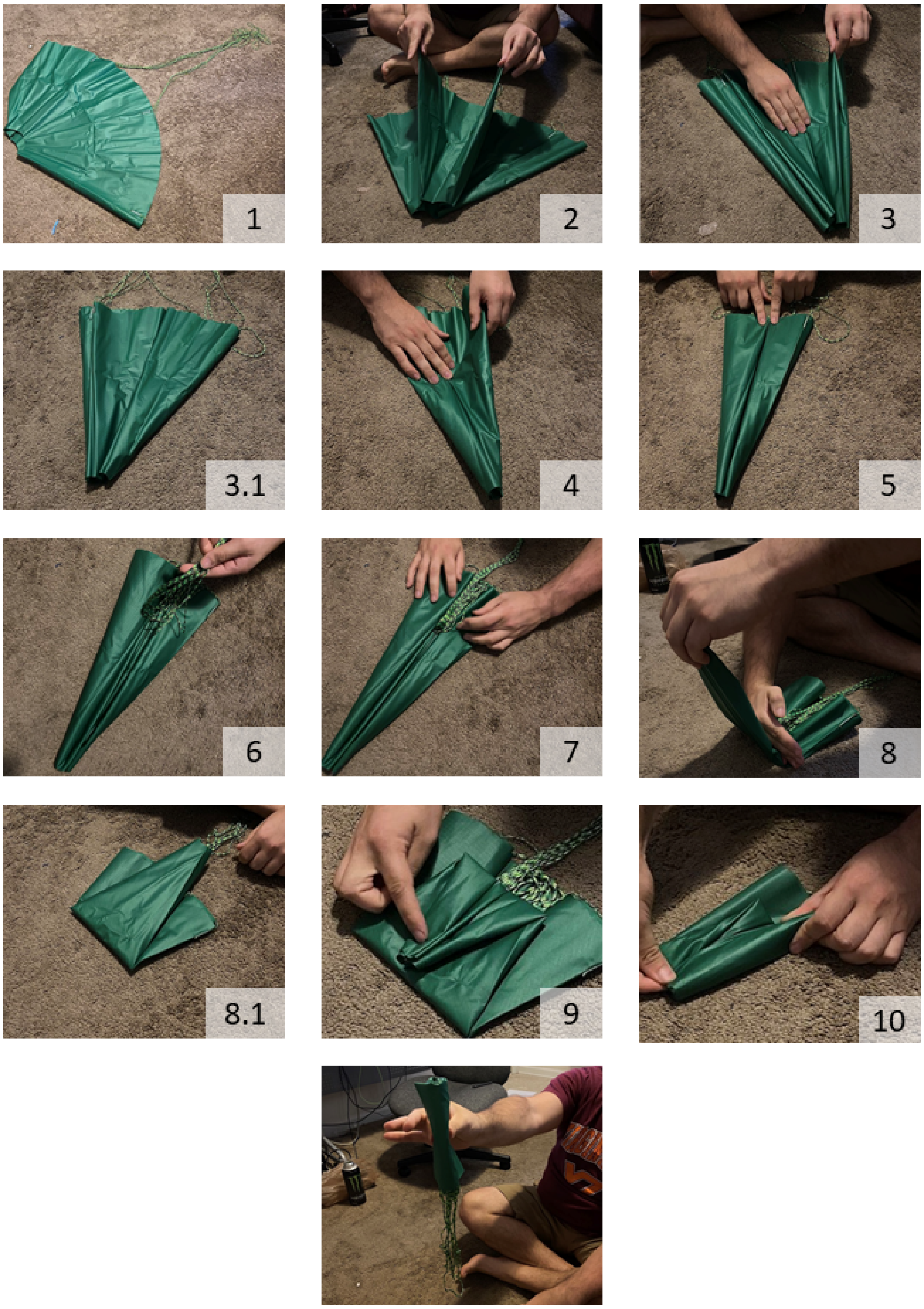


Figure 4.3: How to Pack a Parachute

4.2.3 Parachute Ejection

The HPR community has largely adopted the deployment setup as described in Figure 4.4. Shear pins are used to keep the parachute bays from opening during flight. Energetic material is used to create pressure in the parachute bay, breaking the shear pins and airframe in a piston like expansion.

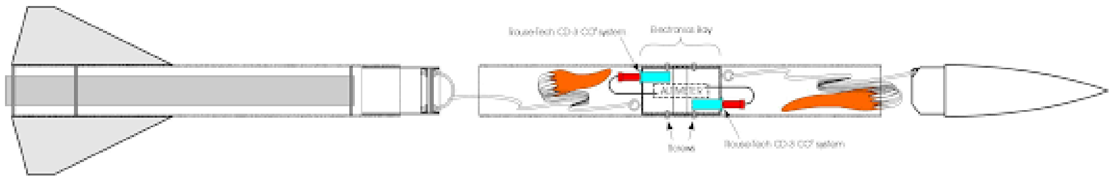


Figure 4.4: Parachute Deployment

The conventional deployment methodology for most high powered rockets. The parachutes are simply held in the airframe and attached to shock chord. Energetic material is used to separate the airframe and eject the parachute. The shock chord is attached to both of the now separated parts to keep the entire stack connected [5].

An engineer needs to consider a few key parameters when designing for this conventional and trusted parachute ejection setup: selection and amount of energetic material, the force difference between the two soon to be separated components, total parachute bay volume, and lastly the number and type of shear pins.

First, consider the energetic material. The HPR community commonly uses fine grain black powder or CO_2 to generate the pressure required for separation. Benefits of using black powder include reliability at low altitude and energy density, while cons include unreliability at high altitude and excess heat generation which could potentially damage the parachute. Benefits of using CO_2 include moderate reliability at all altitudes and zero heat generation, while cons include low energy density and overall complicated installation and use. Although black powder can burn without oxygen (it has its own oxidizer), low atmosphere environments tend to prohibit heat transfer between black powder particles and can reduce the overall percentage of combusted powder. CO_2 systems are more complicated and fail more often, however they work at any altitude. The general consensus is that flights below 10-20 km should use black powder while flights above aforementioned altitude should use CO_2. Designed and executed properly, either of these methods will work for any conventional rocket [1] [2].

Second, consider the forces acting on the two soon to be separated components. Employed shear pins must be sufficient to hold the two components together despite forces which could possibly pull the two components apart before the desired separation event. The following forces should be considered: drag difference (drag on the nosecone versus drag on the fins and a possible transition piece), ejection of the drogue parachute as a pulse on the rest of the vehicle, and lastly inertial forces due to the tumbling of the vehicle during drogue parachute descent. In general, four or eight relatively small nylon screws are used as shear pins. Most suppliers will provide the ultimate shear stress required to break the screw, and the total holding force of the combined screws must be greater than the maximum force difference between the two components. This is

[1] https://www.youtube.com/watch?v=7zQi6RGmbxw
[2] https://www.youtube.com/watch?v=eEFjobgoIyk

described by Equation 4.4:

$$\Delta F_{max} < \frac{n\tau_{max}}{A_p} \tag{4.4}$$

where ΔF_{max} is the maximum force difference between the two components, n is the number of shear pins used, τ_{max} is the critical shear stress of each shear pin, and A_p is the cross sectional area of each shear pin. Furthermore, a sufficient factor of safety should be used to ensure the the components do not separate prematurely.

Third, consider the total parachute bay volume. Whatever energetic material is chosen, sufficient pressure must be generated within the parachute bay to break the shear pins when the parachute should be deployed. This is described by Equation 4.5:

$$F_{breaking} > \frac{n\tau_{max}}{A_p} \tag{4.5}$$

where $F_{breaking}$ is the breaking force generated from pressure in the parachute bay and can be calculated with Equation 4.6:

$$F_{breaking} = P_{bay}A_{bay} \tag{4.6}$$

where P_{bay} is the pressure inside the parachute bay and A_{bay} is the cross sectional area of the parachute bay (or more specifically, the area of a bulkhead at the end of the parachute bay which the pressure acts against). Now, we need to determine what pressure will be generated in the parachute bay. Methods to determine this heavily depend on what energetic material is used to generate the pressure (black powder or CO_2). Although specific and technical equations are a bit out of scope for this book we will holistically examine these two pressure generation methods separately starting with black powder. The ONLY time you will hear no no words in rocketry is in the phrase "blow it up or blow it out." What this phrase means is that, a ruptured airframe or slightly singed parachute is safer than no parachute release.

Online calculators have been developed to determine the amount of black powder required to generate a specific pressure (given the parachute bay volume) [3]. Most of these calculators rely on the ideal gas law (as would a hand calculation).

No good calculators exist for CO_2, however most CO_2 ejection system manufacturers provide recommendations for what size canister to use with their system based on parachute bay volume.

4.3 Staging

Staging is the process of separating an expended portion of a rocket and igniting the next sequential stage. Although further discussion is appropriate in Chapter 5, staging can greatly improve a vehicle's performance by reducing the overall mass required to successfully complete a given mission. Since the two stages in question will often be of different diameter, hardware used to join the two stages is referred to as the transition piece. This discussion will cover different joints used to connect two stages as well as common separation techniques.

Sounding rockets and HPR commonly employ two different types of joints: coupling and radax. Couplers involve two telescoping tubes, joined roughly one body caliber, and generally

[3] http://www.rimworld.com/nassarocketry/tools/chargecalc/index.html

use shear pins to prevent the two stages from separating prematurely. When using couplers with stages of differing diameter, a weight penalty is incurred since two couplers are required (couple aft motor to the transition piece, couple transition piece to the forward motor). Bending loads are placed on the coupler itself or rather, structural capacity of the tubing, to prevent failure. The airframe itself carries axial forces from thrust and drag. Furthermore, couplers are easy to manufacture or otherwise acquire. For this reason, HPR almost exclusively uses couplers. Lastly, separation force from parachute ejection methods common to HPR place pure shear stress on the couplers shear pins.

Radial axial (radax) joints are described in Figure 4.5. These joints place bending stress on the bolts used to hold the joint together. Axial forces are distributed along the joint's touching faces. Although radax joints have considerable weight benefits when compared to couplers, they are expensive to manufacture and almost necessitate the use of pyrotechnic fasteners. For this reason, radax joints find their launch vehicle related use primarily in sounding rockets.

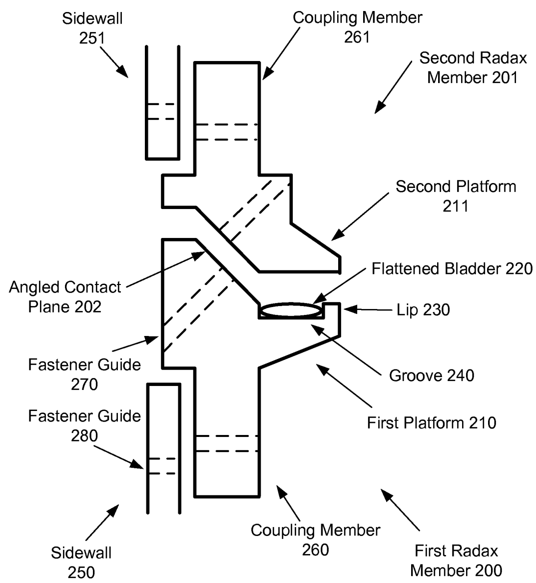


Figure 4.5: Radial Axial (Radax) Joint

[6].

Three common separation techniques exist in HPR and sounding rockets: mechanical separation, drag separation, and hot staging. Each of these techniques have their pros and cons, and are not all compatible

Mechanical separation often uses pyrotechnic fasteners to hold the two stages together. When separation is desired, the pyrotechnic fasteners are fired, the mechanical joint is broken, and the two stages are pushed apart via drag, retroactive motors in the spent motor, or ignition of the next motor. Drag separation is similar to mechanical separation, however the two stages are separated by a drag difference between the two components. Often times, drag plates are placed on the lower stage to ensure separation is completed successfully. Thrust from the lower stage and an unpinned coupler keep the stack connected during flight, and separation occurs when drag forces overcome residual thrust after motor burnout. The two stages should have an acceleration difference of at least 5 g. In hot staging, ignition of the next stage is used to mechanically separate the two stages.

Historically, OLVT has used hot staging in all of its multi stage vehicle designs.

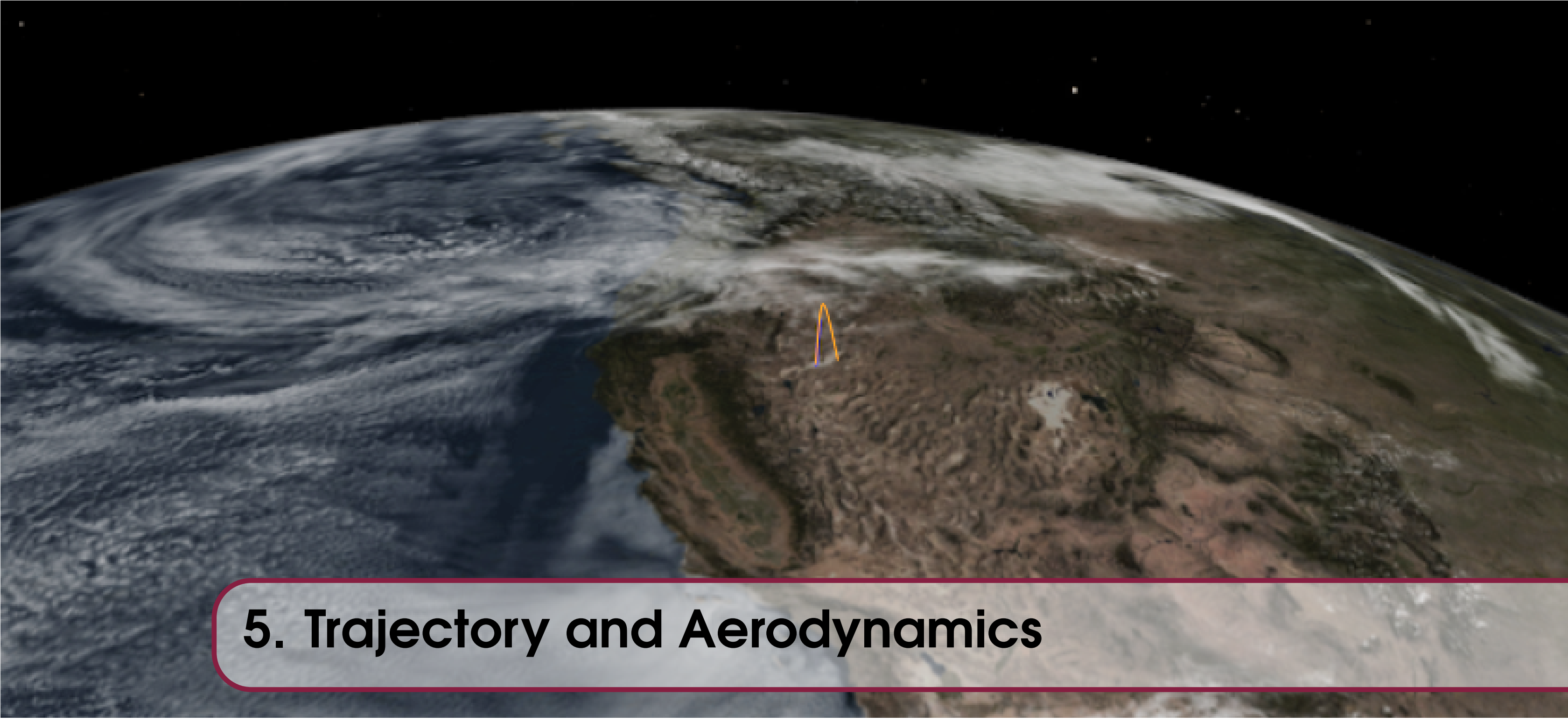
Three common methods of separation exist: mechanical, drag separation, and hot staging. Mechanical separation is the use of pyrotechnic fasteners, shear pins, or other latching mechanism. When separation is desired, the mechanical connection is broken and the stages separate via drag, retro rockets, or some other form of stored energy. Drag separation involves a soft coupling joint with no shear pins. Upon motor burn out, a drag force difference between the two stages pulls them apart. NASA Wallops recommends at least 5 g of acceleration difference between the two stages for a successful separation. Drag plates are often used on the spent stage to increase the drag difference. OLVT considers hot staging as the use of the ignition of the next sequential stage to both mechanically and physically separate the two stages. Table 4.1 weighs the pros and cons of each separation method, as well as outlines their compatibility with the referenced joints. One consideration is the ability of ignition of the next sequential stage.

Table 4.1: Summary of Separation Methods

Outlines the advantages and disadvantages of different separation methods.

Method	Advantages	Disadvantages	Compatibility Issues
Mechanical Separation	Low mass Reliable High performance	Expensive Team is unexperienced using	Difficult to pair with couplers
Drag Separation	Reliable Average performance Simple Low cost	High mass Hole in casing	Not compatible with radax joints
Hot Staging	Brutally simple Low cost	Poor performance	Not compatible with radax joins

As one final thought, consider the feasibility of ignition of the next sequential stage. If the stages separate before motor ignition, logic to handle the ignition must come from a controller in the stage itself. In such a configuration, ignition leads must either run along the exterior of the rocket and through the nozzle throat or directly through the forward closure. Either of these solutions impose risk. Hot staging allows the controller to be contained in the spent stage. In such a configuration, ignition wires can simply run through a bulkhead in the forward end of the spent stage's avionics bay and then through the nozzle throat. Although sounding rockets have solved this dilemma, OLVT has yet to design and test a reliable ignition system which involves compromising the integrity of the next sequential stage's forward closure.



5. Trajectory and Aerodynamics

This chapter serves to outline the basics of determining a desired trajectory. Trajectory is the displacement curve that an object in motion will follow while under the effects of given forces. For a typical rocket, the trajectory will begin on the ground, reach an apogee and then return to the ground. For an orbital vehicle the trajectory will become more complex as it will leave the ground, reach an apogee, and then work its way around the earth's circumference at a known altitude.

5.1 Preliminary Trajectory Analysis

The first step in designing for a desired trajectory is simple algebraic calculations. This level of analysis is sufficient to get general inferences on the design space. That is, the general size, acceleration, impulse class, and mass. This is by no means sufficiently accurate for final design, but is a good first step.

To initiate this process, these equations below will be used to assist in mapping out a preliminary trajectory model.

$$v = v_0 + at \tag{5.1}$$

$$\Delta x = \frac{t(v + v_0)}{2} \tag{5.2}$$

$$\Delta x = v_0 t + \frac{1}{2} a t^2 \tag{5.3}$$

$$v^2 = v_0^2 + 2a\Delta x \tag{5.4}$$

Equations 5.1 through 5.4 are the basic kinematic equations. In these equations v designates the velocity at a specific point in time, v_0 designates the initial velocity, a designates the vehicles acceleration, t designates the time since initiation, and Δx designates the change in displacement. It is important to set variables such as the maximum acceleration and goal altitude as independent variables.

Once the kinematic equations have been exhausted for results it is time to make more technical assumptions. Most importantly in this step is the rocket equation.

$$\Delta v = v_e ln \frac{m_o}{m_f} \tag{5.5}$$

$$v_e = I_{sp} g_e \tag{5.6}$$

In Equation 5.5, Δv designates the total change in velocity, v_e designates the exhaust velocity, m_o designates the total mass of the vehicle, and m_f designates the mass of the fuel in the vehicle that is pre-loaded into the vehicle. Equation 5.6 is used to find the exhaust velocity from I_{sp} and g_e, which are the specific impulse and earths gravity respectively.

One can estimate mass of propellant required using the propellants specific impulse, as shown in Equations 5.7 and 5.8.

$$I = \int F dt \tag{5.7}$$

$$I_{sp} = \frac{I}{m_p g_e} \tag{5.8}$$

Where I is the motors total impulse, F is the instantaneous thrust, and m_p is the mass of propellant.

Equations 5.1 through 5.8 are used to help determine the approximate mass of propellant required for the given mission. Furthermore, one can experiment with different propellants to give different flight characteristics. In general, two stage rockets perform best with a fast burning, high thrust booster and a low thrust, slower burning sustainer. The names are a bit self explanatory, but the booster "boosts" the vehicle to a high velocity which is then "sustained" by the sustainer.

Working through this preliminary math in an iterative process will allow you to conceptualize the design space for the mission. This means that the vehicle size, mass, and velocity profile can be estimated. This analysis will have to be revisited multiple times throughout the design process, making improvements and refinements as needed. It is impossible to set a timeline for this iterative process, however it is important to constantly question values that are set as constants and variables. It is not uncommon to find a constant or variable that will be challenged by the findings of other analyses. Do not be discouraged as each step will bring the design parameters closer to an optimal resolution. As discussed in Chapter 3, the design can never be perfect.

5.2 Trajectory Simulation

After establishing rough estimates for the vehicle's primary dimensions and mass values as described in Section 5.1, one should use trajectory simulation software to optimize the design. The team uses various simulation tools listed below:

- OpenRocket: Used for smaller high power rockets and most vehicles that fly under Mach 1
- RASAero-II: Used for higher velocity vehicles flying to the Kármán line or lower

- ASTOS: Used for high altitude and high velocity vehicles to the Kármán line and beyond
- Custom Simulations: Custom simulations built in Matlab used for a variety of applications

No single method exists to optimize the mass, g-loading, and velocity profile of a rocket. One must continuously simulate the build, determine where improvements can be made to the design, revisit their preliminary analysis, and resimulate a new design. Furthermore, each software listed above has its own advantages and disadvantages, ensuring that an engineer will heavily use two or three different softwares throughout the optimization process. Table 5.1 depicts a summary of each commercial software:

Table 5.1: Summary of Simulation Software

Outlines the advantages, disadvantages, and use cases of various commercially available trajectory simulation software.

Software	Advantages	Disadvantages	Use Case
OpenRocket	Component wise editing Avoid use of CAD Widely used in HPR community Small learning curve	Poor simulation for > Mach 1 Poor component mass estimates Long time to create the simulation	Use for smaller vehicles that fly under or slightly above Mach 1 and do not require the finer details of CAD or heavy involvement from multiple subteams
RASAero-II	Rapid build Rapid simulation Good simulation > Mach 1	Manually input mass No dispersion analysis	Use for larger vehicles flying above Mach 1 and sub-orbital. Good for rapidly editing and testing different builds.
ASTOS	Extremely accurate simulations Supports orbital trajectories Complex dynamic analysis Recovery dispersion analysis	Strong learning curve Slow simulations	Use for orbital missions, dispersion analysis, or other high altitude sub orbital flights where RASAero-II is not quite sufficient. This is basically professional Kerbal.

5.3 Stability

Stability is the tendency of a rocket to continuously correct to a desired trajectory. An engineer needs to consider two properties of an unguided rocket to determine its stability - the vehicle's center of pressure (cp) and the vehicle's center of gravity (cg). Center of mass, in a uniform gravitational field and for the purposes of our analysis, can be simply stated as the center of gravity. A vehicle in free motion will rotate about its center of mass (and therefore center of gravity). For larger vehicles with many complex components, software such as SolidWorks can be used to determine the vehicle's approximate center of mass. Upon completion of the vehicle's construction, the most accurate way to determine center of gravity is to balance the vehicle on a string or other similar object, as depicted in Figure 5.1.

Center of pressure is defined as the point where the total sum of a pressure field acts on a body. The location of a vehicle's center of pressure is a bit more difficult to determine. In a similar manner to how CAD software determines the center of mass, one may determine the overall vehicle's center of pressure using a weighted sum of each component's individual center of pressure. This is called the Barrowman method. A web search for "Barrowman equations" will

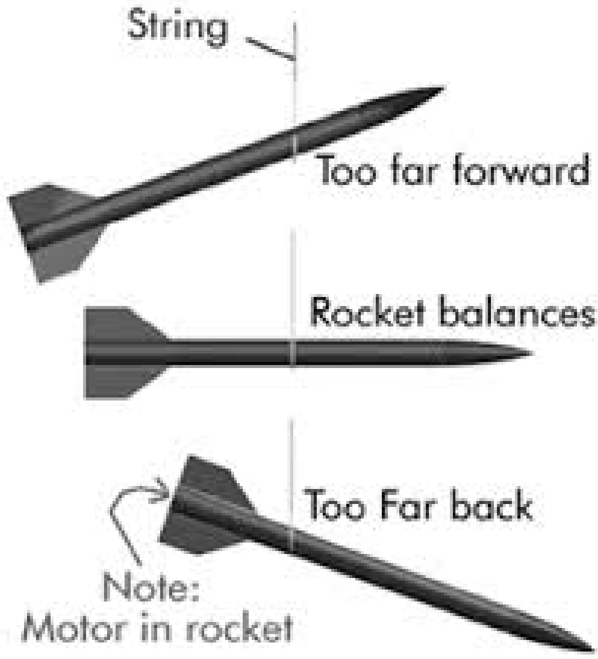


Figure 5.1: Determining the Center of Gravity

A crude but effective way to determine a constructed rocket's center of gravity. Although design can carry forward using CAD model estimates of the center of mass, this property's location should be double checked after vehicle construction [7].

yield equations for most geometric shapes commonly found on rockets. Although this method is practical, it can be cumbersome to calculate by hand and does not take into account Mach effects. Instead, we often turn to software like RASAero-II or more complex CFD simulations for more accurate calculations of the center of pressure.

To consider a vehicle stable, the center of gravity must be located forward of the center of pressure. Figure 5.2 depicts two scenarios, one were the center of gravity is forward the center of pressure (stable) and one where the center of gravity is aft the center of pressure (unstable). In a configuration with stable cp and cg locations, the moment created by the lift generated through the center of pressure helps restore the vehicle's orientation to the direction of travel. In a configuration with unstable cp and cg locations, the moment created by the lift generated through the center of pressure pulls the vehicle's orientation further away from the direction of travel.

Although a rocket would be considered mathematically stable if the center of gravity was just barely forward (say, a quarter of an inch) of the center of pressure, in practice this is not a good condition to fly. For a vehicle that is barely stable, a perturbation in orientation from the direction of flight may be too strong for the restoring moment to correct. Furthermore, many factors can change a vehicle's center of pressure and center of gravity during flight. For example, an uneven wind distribution across a particularly tall rocket may shift the center of pressure forwards enough so that rocket will become unstable. As the rocket burns propellant, mass on the aft of the vehicle is expelled, while mass in the forward portion remains constant. This shifts the overall center of

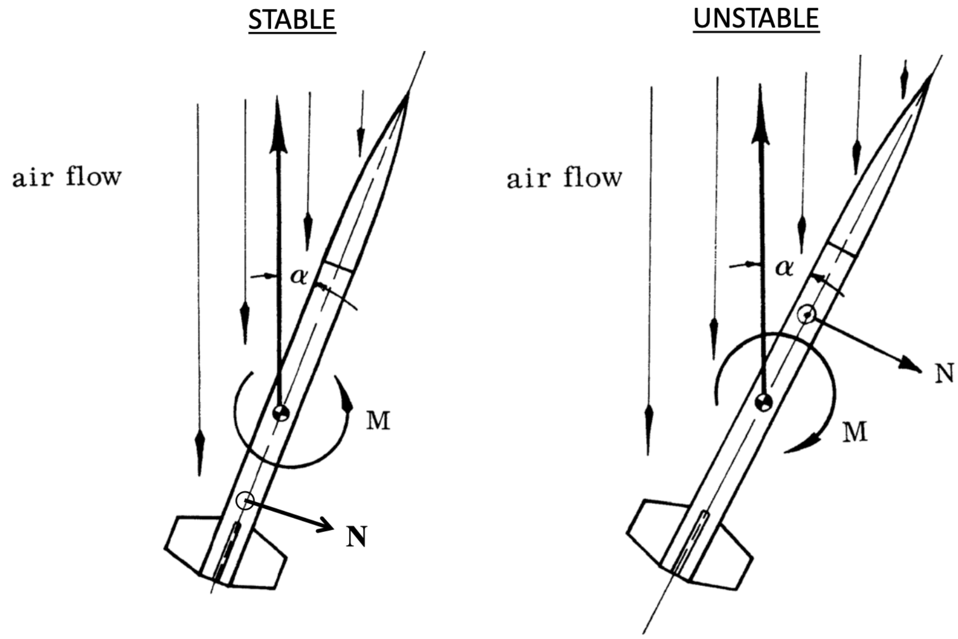


Figure 5.2: Stable and Unstable Scenarios

In the left drawing, a restoring moment created by the center of pressure returns the vehicle orientation to flight direction. In the right drawing, the moment created by the center of pressure pulls the vehicle's orientation further away from the flight direction [8].

gravity forward, increasing stability. How "stable" does a vehicle need to be to safely fly? The static margin helps answer this question. To find the static margin, start by taking the distance between the center of pressure and center of gravity. Then, normalize it by dividing this value by the caliber of the rocket, as shown in Equation 5.9 and further described in Figure 5.3. A caliber is defined as the rocket body's diameter. It is useful to always measure the location of the centers of gravity and pressure from the nose cone tip. Tripoli recommends maintaining a static margin of 1 caliber for subsonic flight, and 2 calibers for transitional or supersonic flight. Not adhering to these guidelines may result in an unstable flight. In general, OLVT designed vehicles will always maintain a static margin greater than 2.

$$\text{static margin} = \frac{\text{cp} - \text{cg}}{\text{caliber}} \tag{5.9}$$

Given this fundamental understanding of stability, ask yourself the question "Does a rocket need fins to be stable?" The short answer is no, a rocket does not necessarily need fins to be stable. As long as the center of gravity is forward the center of pressure by an acceptable static margin, the vehicle will remain stable. Consider a rocket with no fins or nose cone, a solid cylinder. Most rockets (especially solid fueled rockets) are designed with the motor (the densest part of a rocket) at the aft end of the stack. Such a configuration dictates an uneven mass distribution at the aft end. This will result in the center of gravity being aft the center of pressure. To offset the center of pressure, most unguided rockets employ fins to shift the center of pressure aft the center of gravity.

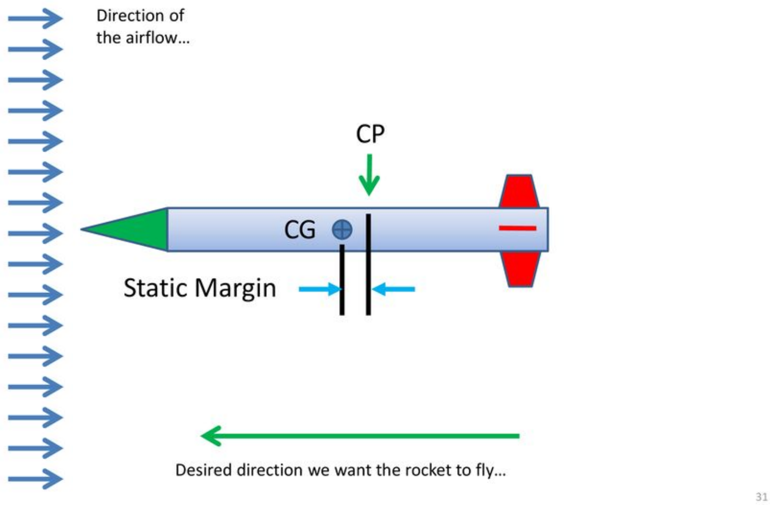


Figure 5.3: Static Margin

Static margin for rocketry is described as the distance between the center of gravity and the center of pressure. Often, this value is made dimensionless for the more generalized case by dividing by the caliber [9].

5.4 Fin Design

The fin design process begins with a qualitative understanding of fin planforms, cross sections, material construction, and anchor methods. A fin planform is best described as the fins overall shape as projected upon a horizontal plane. A cross section is best described as a thin cutaway of the wing shape at a specific radial location.

OLVT commonly uses the terminology defined by RASAero-II when describing the planform and cross section. Such terminology is best captured by the RASAero-II user manual and depicted in Figure 5.4. High performance solid rockets typically use the hexagonal or double wedge (diamond) airfoil cross sections, as illustrated in Figure 5.5. The RASAero-II users manual contains good figures of many others [10]. Typical planforms have quadrilateral faces orthogonal to the body with parallel root and tip chords. We use these shapes for the following reasons:

- Sharp edges reduce drag at speeds greater than Mach 1.
- Quadrilateral shapes with parallel root and tip chords also reduce drag at speeds greater than Mach 1
- Such shapes are easier to analyze for structural stability and heating
- Such shapes are easier to anchor to the rocket due to their simplified geometry
- Such shapes are easier to manufacture

Fins are often constructed out of aluminum, titanium, or fiberglass to withstand aerodynamic stresses and heating while keeping overall mass to a minimum. Although titanium has its place in the aerospace industry, this material is usually out of most amateur team's cost budget. The anchor method is usually dependant on the material selection. Aluminum motor casings often pair with aluminum fins, where the fins are either welded directly to the body or bolted into a channel, as shown in Figure 5.6 [11]. Fiberglass motor casings often pair with fiberglass fins, where the fins are glassed directly onto the body tube, as depicted in Figure 5.7 [12]. These are by no means the only way to construct or anchor fins, however they are the most common.

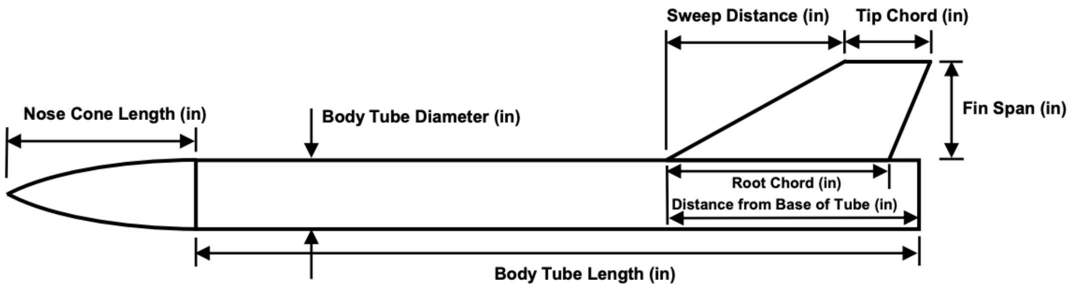


Figure 5.4: RASAero-II Fin Inputs

General fin terminology used by the team. Although this terminology is used by RASAero-II, it is also widely used in industry.

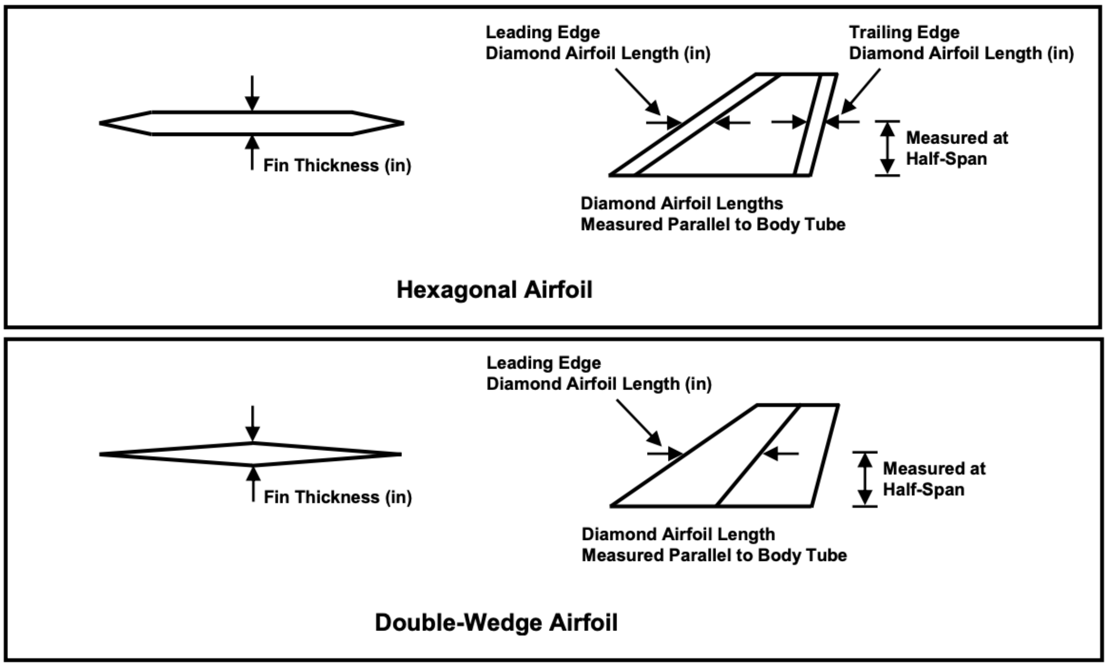


Figure 5.5: Two Typical Cross Sections

Typical cross sections. Compared to more traditional NACA airfoils, both of these provide good structural loading properties with reduced drag at high Mach numbers.

An engineer needs to consider two velocities, the flutter velocity and divergence velocity, to determine whether a given fin design is structurally capable of enduring the aerodynamic forces experienced during flight. Flutter velocity is best described by rolling down your car window while going down the highway and sticking your arm out the open window. Your hand will experience flutter as it wobbles back and forth. Likewise a fin will reach a critical flutter velocity where the fin will wobble, possibly without dampening, and eventually fail. The difference is that aluminum or fiberglass fins will experience flutter at high mach numbers instead of your local highway speed limit. Once a rocket pushes past flutter velocity, any small perturbation to the fin will cause an unsteady oscillation eventually resulting in failure of the fin.

Divergence velocity is simply the velocity at which aerodynamic forces exceed the structural

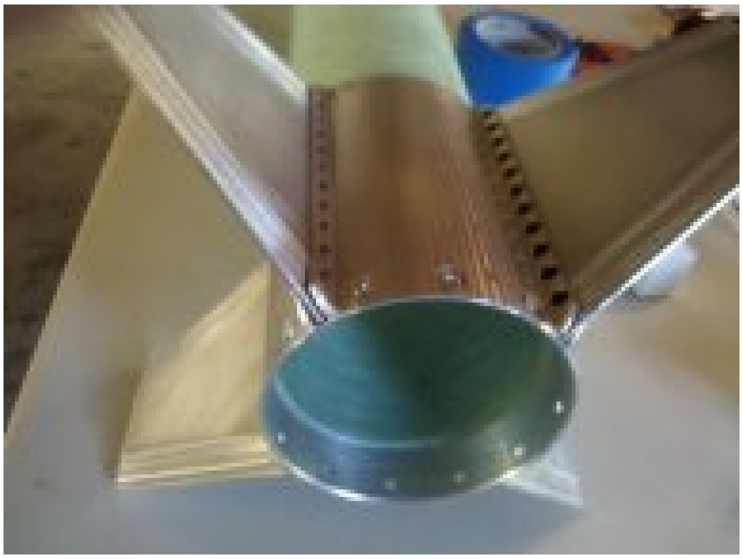


Figure 5.6: Aluminum Fin Can

A typical aluminum fin can. Notice how the fin anchors are attached to the body.

Figure 5.7: Fiberglass Fin Can

On minimum or subminimum diameter rockets, the fins are often glassed "tip to tip", meaning a single sheet of fiberglass is used on two faces of adjacent fins. This created the fin can as well as the fin itself.

integrity of the fin. Like flutter, this condition is also dependant on additional freestream conditions such as density and pressure.

Although one may calculate flutter and divergence velocities by hand for simple geometric fin shapes, the team uses software developed by John Cipolla/AeroRocket and WarpMetrics called AeroFinSim. The software comes preloaded with common fin shapes and allows varying basic geometric properties. In the iterative design process, RasAero-II is used in combination with AeroFinSim to optimize the fin design.

As a general place to start your analysis, use a diamond or hexagonal cross section with maximum thickness equal to 1/4 in, a radially symmetric planform with root chord equal to one body caliber, tip chord equal to half the root chord, and semi span equal to one caliber. Then, experiment with different spans, root and tip chord lengths, sweep distances, and thicknesses. The overall goal is to minimize drag while ensuring the vehicle remains stable and the fins do not fail.

5.5 Nose Cone Design

The nose cone is the component the leads the charge of a vehicle into battle against the forces of drag and gravity. For rockets moving at high velocities, it is common to use a metal tip to crown the nose cone. The purpose of this is to enforce the part of the nose cone that undergoes the most heat transfer and forces. Furthermore, metal alloys are easier to machine to fine geometric shapes, whereas fiberglass is difficult to manufacture a sharp tip. This tip is typically manufactured from aluminum or steel.

Two driving factors influence nose cone design. The maximum velocity the rocket will attain, and payload capability (more broadly, internal usable volume). For heavy launch vehicles such as Falcon 9, aerodynamic considerations are largely ignored in favor of usable payload volume. For high performance sounding rockets, however, drag is additionally considered. The figures and quantitative discussion in this section follow the work of Gary Crowell [13].

Many different nose cone geometries exist. The traditional list includes: ogive, conical, HAACK (and Von Karman), parabola series, and power series. In HPR and industry, the three most common are Von Karman (HAACK with C=0), ogive, and conical. Figure 5.8 explains the geometry of these three shapes. Furthermore, Figure 5.9 qualitatively describes the regimes on which various nose cone shapes are optimal.

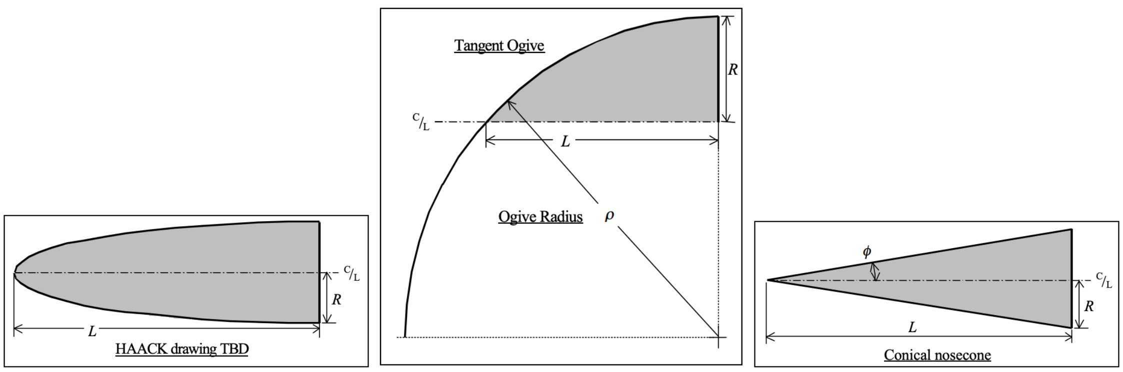
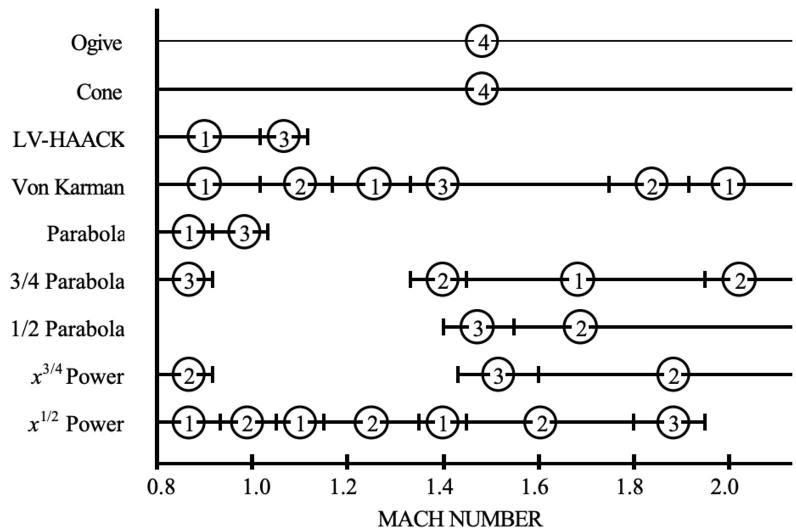


Figure 5.8: Mathematical Descriptions of Nose Cone Geometries

The Von Karman, conical, and tangent ogive shapes also have a few qualitative advantages. The HPR community primarily uses these shapes, meaning they are readily available to purchase from vendors at relatively low cost. Although the conical shape usually provides aerodynamic advantages at high Mach numbers over a Von Karman or tangent ogive, this shape is rather prohibitive when payload volume is considered. One more import note is the nosecone's fineness ratio. This ratio is simply the overall length of the nosecone divided by the base width. In general, longer fineness ratios will provide reduced drag. At some point, however, the benefits of increasing your nose cone length (and therefore fineness ratio) become marginal.



Comparison of drag characteristics of various nose shapes in the transonic-to-low Mach regions. Rankings are: superior (1), good (2), fair (3), inferior (4).

Figure 5.9: Optimal Nose Cone Regimes

6. Solid Rocket Motors

Solid rocket motors are a common propulsion systems for rockets, missiles and even fireworks as early as the 13th century. They have little to no moving parts and are not able to be throttled. Most solid rocket motors consist of grains, a forward closure, an aft closure, a nozzle, a liner, and a casing.

6.1 Motor Classification

Solid propellant motors are classified by their total impulse. Total impulse is simplified to the average thrust multiplied by the burn time. The lowest impulse motor is an A motor and the names for the motor classes follow an alphabetical sequence. Each letter in the sequence represents a doubling in total impulse from the previous motor class. For example, B motors have double the impulse of A motors and C motors have double the impulse of B motors.

Motors are then classified into three major categories, low, mid and high power. Low powered motors consist of A motors through D motors, Medium powered motors consist of E motors through G motors, and any motor classified as or greater than a H motor is classified as a High powered motor. A complete chart of motor classifications with examples can be found in Appendix D.

6.2 Grain Design

Grain design is essential when working with solid rocket motors. With no ability to throttle, the thrust can still be toggled proactively by adjusting grain geometry. Another important and non obvious note is that most solid rocket motors are ‘core burning,’ meaning a core running through the center of the entirety of the grain forms the burning surface. There are a few qualitative reasons for this. Most Ammonium Perchlorate Composite Propellants (APCP) burn relatively slowly, meaning a ‘front to end’ burner would not produce enough usable thrust and burn for too long. More importantly, propellant at the wall of the motor will insulate the casing from burning propellant.

A motor's output is represented in a graph called a thrust curve which displays Thrust vs Burn Time. Simple motors can follow one of three thrust curves, progressive, regressive and neutral. A progressive burn will increase in thrust as Burn Time increases. A regressive burn will show a decrease in thrust as Burn Time increases. A neutral burn will show neither an increase nor a decrease in thrust as Burn Time increases. Practically speaking, the general rule of thumb is that for the same grain core the surface area of the ID of the grain affects the peak thrust and the diameter of the core affects the burn time. However, adjusting the grain core geometry is what allows engineers to acquire a desired thrust curve.

The simplest example of core geometry is the circular core. This is a centered hole that connects the two faces of the cylindrical grain. When ignited, the propellant will burn from the ID to the OD until all of the propellant is used up. As the grain burns, the ID increases along with the surface area of the inner walls making the thrust increase. This means that with a circular core, a progressive thrust curve is generated. Figure 6.1 depicts various core geometries and their resulting thrust curves.

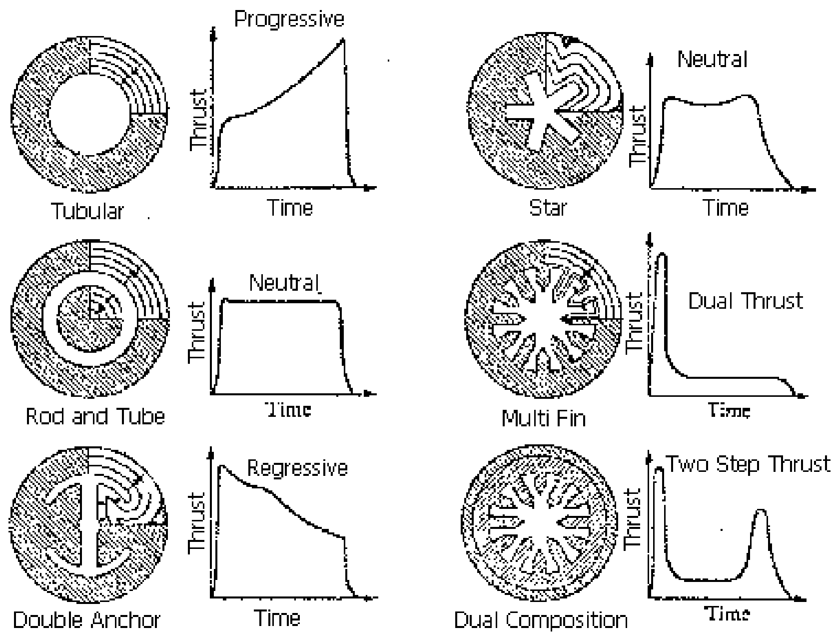


Figure 6.1: Core Geometry

Various core geometries and their resulting thrust curves.

OLVT typically uses "Bates" and "Fin-o-cyl" core geometries for their relatively neutral thrust profiles. When designing for a specific thrust curve the math becomes tedious. OLVT has followed a process to narrow the variability.

1. Have a goal for your thrust curve
2. Choose the visual core style that best estimates the desired curve
3. Adjust specific geometry in BurnSim software

Although the process is iterative it has been proven to get the job done.

6.3 Propellant Characterization

Propellant burning characteristics are described by Saint Robert's Law. This is written in Equation 6.1,

$$r_b = ap_c^n \tag{6.1}$$

where r_b is the burn rate measured as length per unit time, p_c is the chamber pressure, and a and n are constants specific to the propellant. These last two values are often referred to simply as, "the 'a' and 'n' values." If these two values as well as the propellant density and a few other properties are known, one can effectively design a grain and sufficiently predict the resulting thrust curve. We use BurnSim to speed up this process. OLVT has historically worked only with characterized propellant (meaning the 'a' and 'n' values are known).

There are multiple ways to determine these 'a' and 'n' values for a new propellant mixture, however the specific processes are not yet readily known by OLVT and should be the subject of future development.

6.4 Nozzle Design

The three commonly used nozzle types are the conical, bell and aerospike nozzles. The conical nozzle was often used in the early days of rocketry for its simplicity and ease of manufacturing. OLVT has utilized this design for these same reasons. The conical shape will result in small loss of efficiency when compared to the bell nozzle, but depending on the budget, the difference in efficiency will not be worth the cost. The bell nozzle is the most commonly found geometry in industry. It can be seen on the majority of NASA's vehicles since the beginning, as well as Spacex's Merlin and Raptor engines. The design has been popular because it offers lower weight and higher efficiency. The aerospike nozzle is the far from a traditional design and has the capability of disrupting the previous design in the future. Its major benefit comes from its ability to stay at peak efficiency throughout the entire flight. In a sense, it could be as efficient of the pad as it will be as it nears apogee. A cross section of these three nozzle types can be found in Figure 6.2.

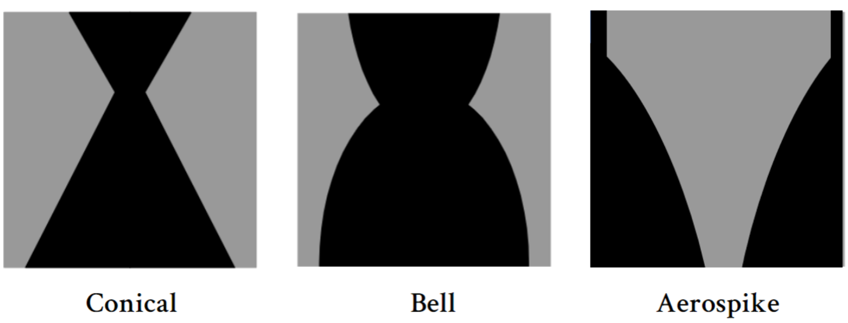


Figure 6.2: Types of Nozzles

Visual Representation of the Conical, Bell and Aerospike nozzle geometries.

The conical nose cone is most commonly used by OLVT because it will only show a 5% difference against a bell nozzle and is far more simple and inexpensive to design and manufacture.

The fist step in design is to acquire the Kn value from your chosen propellant. All Propellants will have a Kn value that they operate best at and can be found in the manual for a COTS motor, or during the characterization of an experimental motor. The Kn value is the ratio between the surface area of burning propellant to area of the throat (Equation 6.2). Naturally, the next step is to find the optimal throat area for your nozzle by rearranging this equation to resemble Equation 6.3.

$$Kn = \frac{A_b}{A_t} \tag{6.2}$$

$$A_t = \frac{A_b}{Kn} \tag{6.3}$$

At this point the chamber pressure can be found in BurnSim. This step does not have to be done here however you will need it later. Once the throat area has been found, you have the keystone to the rest of the nozzle design. From here there will be a 15°angle diverging from the throat to the exit and a 45°angle converging from the throat to the entrance. These angle will be capped by the entrance and exit holes that will be effective at diameters nearing one caliber of the rocket. Figure 6.3 Can be used as a reference for this. When manufacturing a Nozzle from graphite, there should be no sharp edges within this geometry. Sharp edges can cause a shock in the flow which can lead to cracking. If designed properly, the flow at the throat should have a velocity of Mach 1.

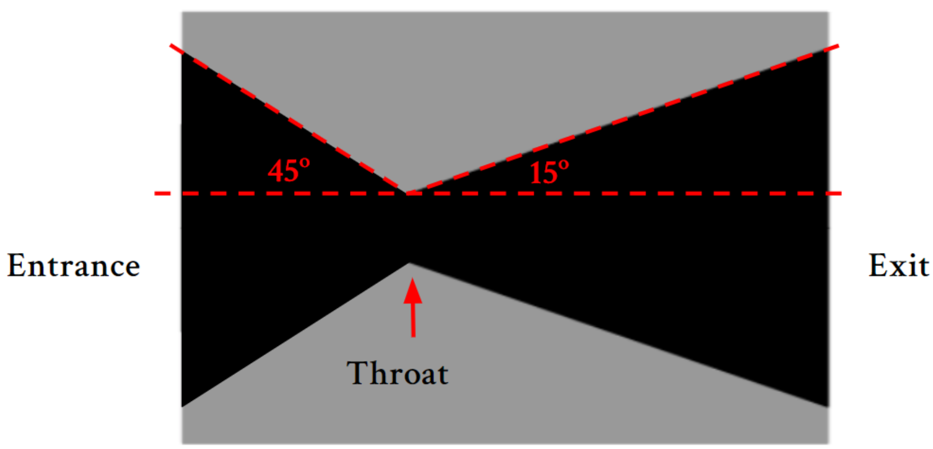


Figure 6.3: Reference for Conical Nozzle Geometry.

6.5 Motor Casing Design

A motor casing can be viewed as a pressure vessel. As such, two important factors should be considered - maximum chamber pressure and burn time. Chamber pressure drives major stresses while burn time affects the total heat transfer to the casing. The general construction involves a tube, forward closure, aft retaining ring, and nozzle. Furthermore, o-rings are often used to provide a sufficient seal between the previously listed components.

We will begin our analysis by examining the hoop stress on the casing due to the internal chamber pressure. We use the Young-Laplace hoop stress equation for a cylinder, shown in Equation 6.4.

$$\sigma_\theta = \frac{P_c r_{avg}}{t_c} \tag{6.4}$$

In this equation the hoop stress is denoted as σ_θ, the chamber pressure is P_c, the mean of the inner and outer diameter is r_{avg}, and the wall thickness of the chamber is t_c. The reason that a mean radius is used is because the chamber can be thought of as a thin walled vessel during this analysis. Figure 6.4 is a visual representation of the variables listed above.

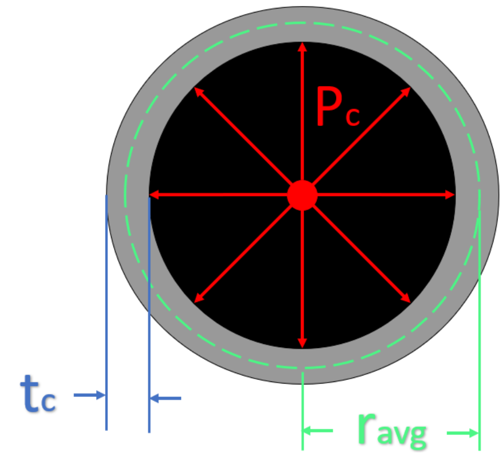


Figure 6.4: Reference for Hoop Stress Variables Geometry.

Most closure hardware setups involve radially oriented bolts sunk through the casing and fastened into the closure, as depicted in Figure 6.5. A tear or zipper will occur when the shear stress exerted by a bolt exceeds the maximum shear stress of the casing. To mitigate this source of failure, Equation 6.5 is used to determine the shear stress on the casing caused by a single bolt. Figure 6.6 is a visual representation of the variables listed above.

$$\tau_{plate} = \frac{F}{2ct_c} \tag{6.5}$$

Where F represents the force exerted on one bolt, c represents the distance from the center of the bolt hole to end of the motor casing, and t_c represents the thickness of the casing. To find the force exerted on each bolt, find the total force exerted on the closure by multiplying the internal area of the closure by the chamber pressure (A_cP_c) and dividing by the number of bolts used to secure the closure.

Motors operate at high temperatures. To prevent hot gases from burning through the casing or temperature exceeding the solidus point of the casing material, a liner is used to wrap the grains and shield the inner wall of the casing from the heat generated by the combustion chamber. This liner is often made from rubber, phenolic, or other flexible, insulative, and ablative materials. The team has been designing with EPDM rubber, a common rubber used in roofing and also in the high power rocketry community. A 1/8 in thick EPDM liner is the rule of thumb standard for large experimental motors.

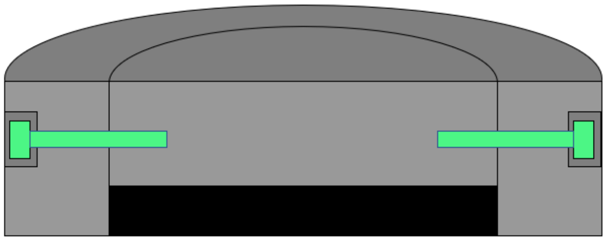


Figure 6.5: Typical Closure Hardware Configuration

Typical closure hardware with radially mounted bolts securing the forward closure. Similar bolts can be used on the nozzle's retaining ring.

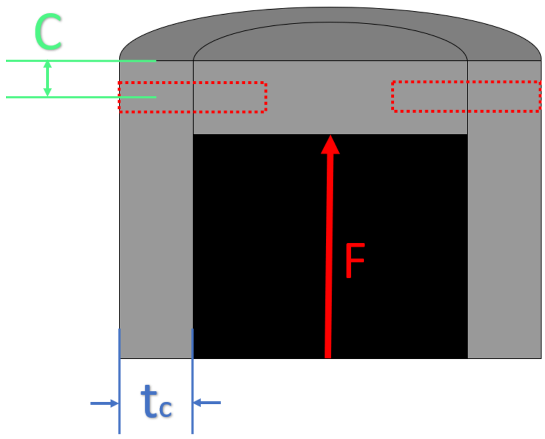


Figure 6.6: Reference for Plate Stress Variables Geometry.

Additionally, an unsteady heat transfer analysis may be conducted to ensure the liner is sufficient to shield the casing. Generally, grains should be designed to limit the amount of casing directly exposed to burning propellant. Although, when conducting heat transfer analysis, always assume direct exposure to burning propellant for the duration of the burn.

Casings are often constructed of aluminum or some form of composite. Historically, OLVT has designed exclusively aluminum casings, but advances in fiberglass have made this an attractive option. Aluminum offers ease of manufacturing while fiberglass can potentially result in significant weight savings. When picking casing material, consider the discussed stresses, overall mass contribution to the vehicle, fin attachment method, and other system synthesis oriented qualities. Utilize systems engineering principles to weigh the pros and cons of choice materials. Additionally, most casings designed by OLVT also doubled as the rocket's body. Rockets designed this way are referred to as "sub minimum diameter" in the HPR community. Outside of L1 certifications or other traditional HPR builds, it is not ideal to use motor mount tubes. Instead, consider how the fins will be anchored directly to the casing by way of fin can or other similar method.

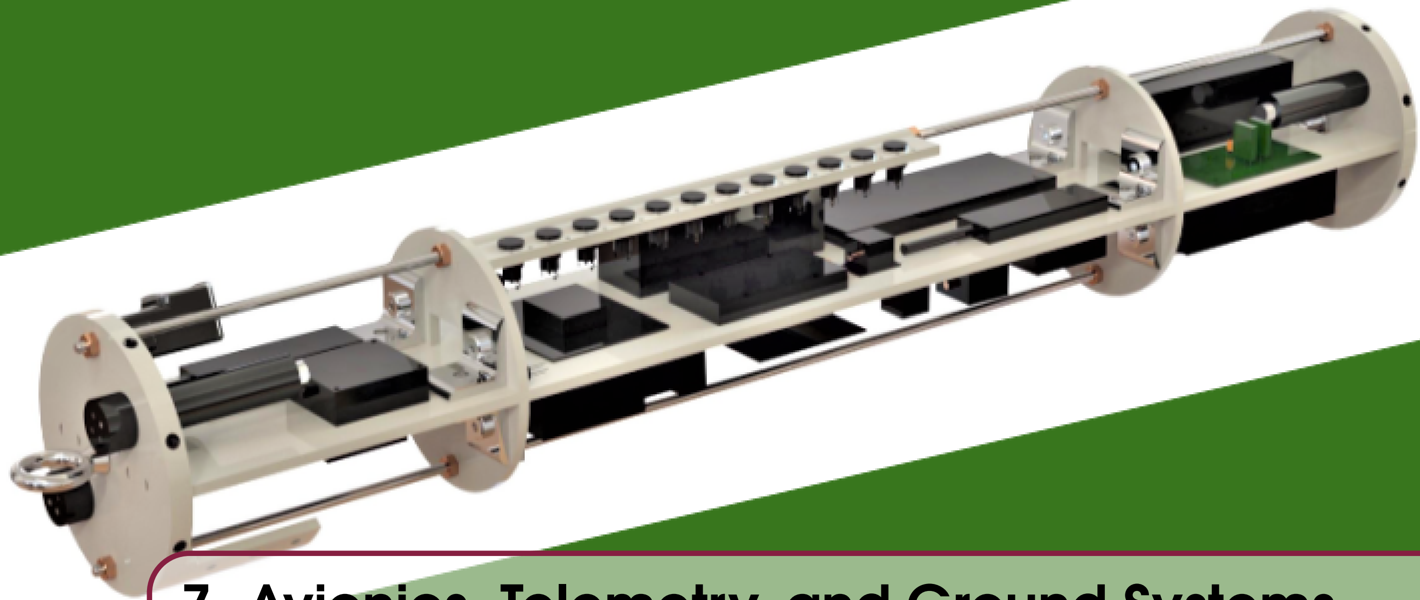
6.6 Igniters

Igniters are the devices used to light the motor and allow the burn to begin. They are typically made up of an electrical resistor coated in pyrogen, a material made from a fuel and oxidizer.

The resistor is more specifically a bridge resistor that is heated to ignite the pyrogen and then the pyrogen will heat and ignite the propellant. This works well for smaller motors because with smaller surface areas, less energy is needed. For larger motors another method has proven effective. The igniter is uses to ignite a small commercial grain hanging in the core of the large grain. This heats and ignites the grain of the large motor.

6.7 Commercial HPR Motors

Unless there is a specific need to design one from scratch, any motor requirement under an O impulse is best served by the commercial HPR industry. Aerotech and Cesaroni Technologies Inc. (CTI) develop reloadable motor systems through the O impulse range. These motor systems allow the user to fly multiple times on the same casing, reloading grains for each burn. Furthermore, both of these manufacturers have developed a wide range of propellants. An engineer should be able to find a reload/casing combination to fulfill nearly any requirement in these impulse classes. OLVT primarily purchases CTI casings and reloads because we get good deals through Animal Motor Works. Hardware is generally not compatible between the two brands. See Part 1 of this book for information on flyer certification required to use these motors.



7. Avionics, Telemetry, and Ground Systems

The term “Avionics” refers to the sensors, data acquisition and processing, logic controllers on board the rocket. “Ground Systems” refer to hardware used to capture and process data being transmitted from the rocket. “Telemetry System” refers to hardware used to transmit data from the avionics system to the ground system. Together, these subsystems are generally referred to simply as avionics. Avionics form the brains of the rocket, and OLVT has an entire subteam dedicated to this discipline.

7.1 Electronics Basics

In electronics there are two designations of electric signals; alternating current (AC) and direct current (DC). AC can be referred to as “wall power” and the direction of electrical flow is constantly changing or “alternating”. DC can be referred to as “battery power” and is much easier to utilize for mobile applications. For this reason, OLVT uses DC batteries to power the avionics of their rockets. When measuring the power of of a battery there are two important characteristics to look for, voltage and current. Voltage is measured in Volts and current is measured in Amps. For a typical AA battery, the voltage would be 1.5 V and the current would be 50 mA. These values are important to know because all electronics will a specific range of voltages and currents that they can operate at. Equation 7.1 To calculate the electrical power from a power source.

$$P = IV \tag{7.1}$$

A circuit can either be open or closed. A closed circuit is one that is complete and can transfer electricity from the power source to the ground point. An open circuit is one that is incomplete and will not allow electricity to flow from the power source to the ground point. This can be thought of as a race track loop. If the racetrack is a circle, the car can continuously travel around the track as a closed system. If a giant hole is created in the track at any point the car can no longer travel through the circuit. The hole is the open system. In general, a closed circuit is used to transfer power to a desired component, while an open system is used to deny power to a component. Switches can be used to open or close the system. These circuit types are shown in Figure 7.1

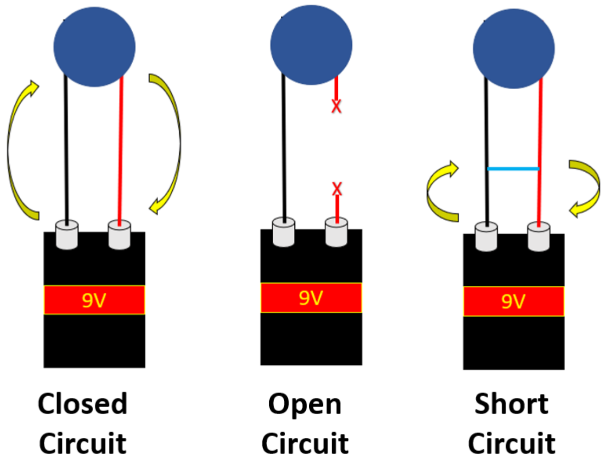


Figure 7.1: Visual of three types of circuits

Once a closed circuit is achieved, it is imperative that something is using the power from the battery. If the power is not being used, a short circuit is formed. Short circuits will cause the system to heat up and possible melt or catch fire. The use of this power can be achieved in the form of resistance. In the case of powering an avionics system, the board is the resistance or point that draws the load. Electricity will always flow the path of least resistance. Make sure that there are no other routes for the the electricity to travel other than what is desired. If give the choice between powering a system and following wire to ground, the wire to ground will be chosen.

7.2 Commercial Systems

The HPR community has developed a multitude of commercial off the shelf (COTS) avionics systems. These systems cover a wide range of sensor suites, price ranges, and capabilities. If used properly, these commercial systems can fulfill the requirements of most high power rockets. Furthermore, their proven reliability make them attractive options for OLVT's current projects. Although an orbital launch vehicle will require the development of custom avionics and logic, these commercial systems provide good insight into over arching design principles.

Selection of the appropriate commercial system is heavily dependant on vehicle requirements, expected trajectory, allotted avionics bay volume, and budget. Product documentation will explain the system in detail and discuss power requirements, acceleration and temperature limits, and recommended usage. The Entacore AIM XTRA, PICO AA2, Missile Works RRC3, and Multitronix Kate 2.0 are all fantastic systems which should work for most applications. These systems will come with software to allow the user to configure the avionics for the specific mission. Table 7.1 covers the sensors common to these systems. Depending on the COTS system, most will have some combination of these sensors to determine events such as launch, apogee, staging, parachute deployment, and landing.

Common limits or downfalls of COTS systems (and really on the sensors themselves) include:

- Barometric sensors only work in atmosphere or to the limit of the referenced atmospheric model

Table 7.1: Sensors Common to Commercial Avionics Systems

Depicts common sensors, what data they measure, and how this data is used. When combined, these sensors can adequately determine all relevant trajectory data. Furthermore, they will allow the team to find the rocket after landing.

Sensor	Measurement	Use
Accelerometer	Acceleration	Launch Detection Integrate for velocity and altitude
Barometer	Ambient Pressure	When compared to a predefined atmospheric model, can determine altitude. This is primarily used for main parachute deployment
Gyroscope	Orientation	Go-no-go staging logic Also used in combination with accelerometer to get more accurate altitude. References orientation to its initial state.
Magnetometer	Orientation	Go-no-go staging logic Also used in combination with accelerometer to get more accurate altitude. References orientation to earth's magnetic field.
GPS	Location and Velocity	Although GPS can be used to determine most trajectory data, it can be relatively inaccurate. COCOM limits prohibit use in high speed and high altitude vehicles. Mostly used to locate a rocket after flight.
Thermometer	Temperature	Although inaccurate, can be used to determine altitude with a reference atmospheric model. More often used to check internal avionics bay temperature to prevent over heating or freezing.
Timer	Time	Used to reference elapsed time from previous events.

- Thermometers typically have low sample rate (1-2 Hz)
- Gyroscopes become less accurate throughout the flight
- Accelerometers are only accurate within their listed operating range
- GPS systems are relatively inaccurate and lock out at predetermined velocity and altitude ranges (referred to as COCOM limits) to prevent people from building ballistic missiles or other weapons
- All sensors have vibration, acceleration, and temperature limits before failure

7.3 Shunts and Switches

Mechanical shunts and switches are perhaps the single most important design orientated safety measure. They allow launch operations personnel to arm or disarm avionics as necessary and prevent power from reaching energetic material at undesired times. The OLVT misfire in 2018 was caused by a failure to implement these kinds of safety measures. This discussion will cover a qualitative description of these components and recommended implementation, starting with switches.

A mechanical switch is just that - a switch. One common theme among COTS avionics components is their arming/disarming logic. Simply put, if the system is powered, the system is also armed and ready to detect launch. As such, switches should be used to power (and therefore turn on and arm) these systems once the vehicle is ready for launch. A notable exception is the

AIM XTRA, which uses a tilt lock out to arm itself once raised to vertical.

A shunt is a simple electrical connection which effectively shorts an energetic component (such as an igniter or electronic match). By shorting the igniter or e-match, power is prevented from actually setting off the component. Shunts can be as simple as two leads from an igniter tied together or as a switch which must be disconnected before flight. In all scenarios, shunts should be simple enough to allow trouble free connection or disconnection and sturdy enough to remain in the desired configuration throughout the flight. As depicted by Figure 7.2, a single switch can be used to simultaneously de-shunt and arm an igniter (or vice versa). Regardless of the shunting/arming mechanisms used, igniters and e-matches should remain shunted until the vehicle is vertical and ready for launch.

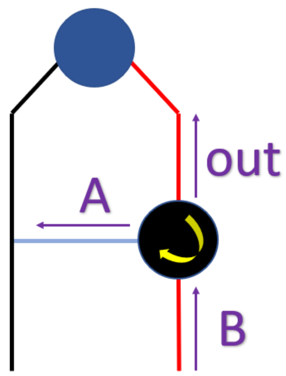
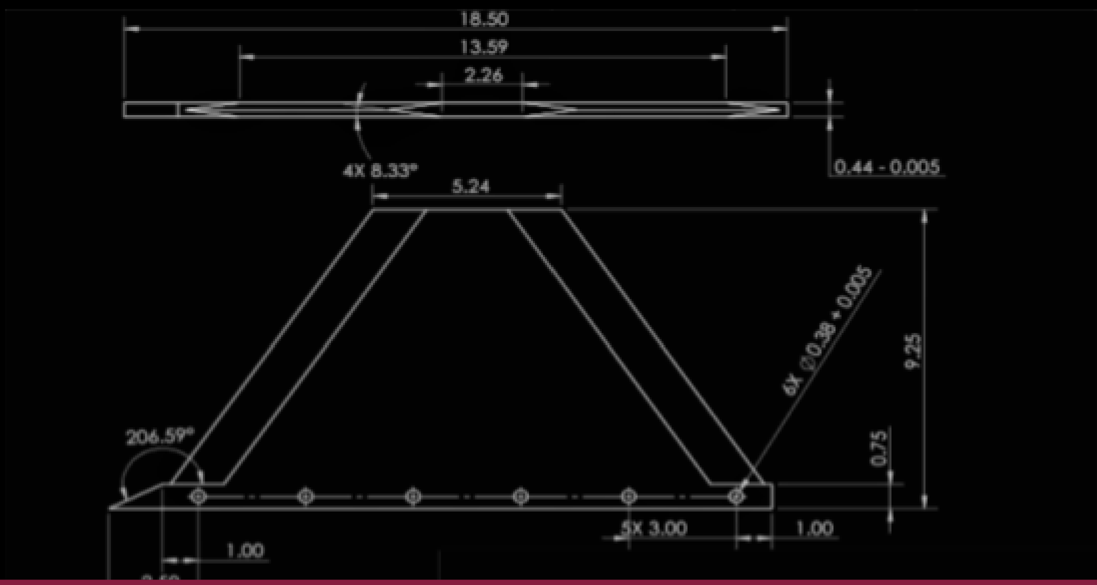


Figure 7.2: Recommended Circuitry for Igniters

In this set up, the igniter is either shunted or connected to avionics. In no scenario should the igniter be unshunted in an open circuit.

UNTIL THE VEHICLE IS UPRIGHT ON THE PAD AND READY FOR LAUNCH:

1. Energetic components should always be shunted
2. Avionics systems should never be powered (unless the commercial system documentation explicitly states otherwise)



8. Drafting

Drafting is the technical word for the transfer of a 3D model to a dimensioned 2D drawing. These drawings are used to give a manufacturer the data they need to fabricate a given part. For this reason, it is important for these drawings to be clear, neat and informational. As a rule of thumb, if you can not make the model by looking at the drawing, it is missing details and therefore missing data.

8.1 Rules to Generate Effective Manufacturing Drawings

The list below serves as a checklist for the drafter to use in order to ensure that their drawings are effective and neat.

1. Do not label the same dimension more than once
2. Always place a center mark on holes within plane
3. Always place a center line on holes bisected by the plane
4. Do not leave dimensions inside of the part on the drawing
5. Do not intersect dimension leader lines
6. Do not over- dimension drawings in general

For rule number 1, it seems simple but is common. Usually this mistake is made when looking at two different views in the same drawing. If a dimension is labeled in one view it does not need to be labeled in the other views on the same page. An example of this can be found in Figure 8.3

For rule number 2, it is important to always use center marks in order to properly locate each hole in your part. Put yourself into the point of view of the manufacturer. on their end they have a bit that has a diameter D, and they will plunge that bit into your part at location X,Y. If the drafter has properly labeled the center marks, diameter of the hole and the location of the center marks, the manufacturer is able to perfectly machine the hole.

There are two ways to fully dimension a hole center location. the first option is to provide a X,Y coordinate in reference to a known point on the drawing. the second option is to provide a dimension of a direct line between the center mark and a known point as well as the angle between that line and a known reference.

For rule number 3, treat is similarly to rule number 2 except the difference is in the orientation.

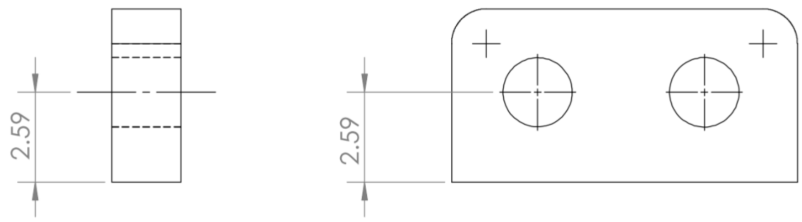


Figure 8.1: Violation of Rule #1

The error in this image is that the same dimension has been placed in both views (side and front).

Rule number 3 is for holes that are bisecting the plane to have a center line put through them. This is useful for something like a motor casing with a radial hole pattern. The center lines will allow you to label the angular location of the holes from a known datum.

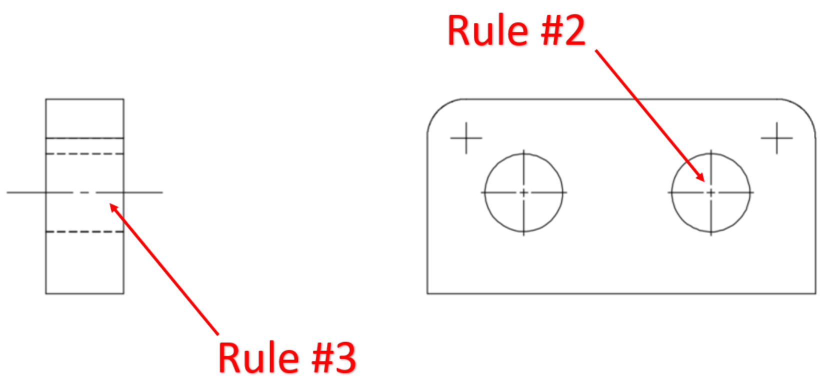


Figure 8.2: Visualization of Rule #2 and Rule #3

For rule number 4, it is important to check that none of the dimensions that you have added are inside of the part. This is more of a housekeeping rule that is in place to keep your drawings clean and legible. If a drawing contains dimensions inside of the part, the dimensions could block important part features or other dimensions.

For rule number 5, it is important to not intersect leader lines whenever possible due to the complexity it can bring to the manufacturer while trying to understand and digest the data. Sometimes if drawing have enough intersections, it can even appear that there are extra surfaces on the part which makes it even more difficult to decipher the parts geometry.

For rule number 6. Think of this as the most important rule. This rule follows the rule of thumb that if a dimension can be found out using labeled dimensions and some algebra, do not label it. The only exception to the rule of thumb is if the dimension has a specific tolerance it must be labeled. A properly dimensioned part is shown below in Figure 8.4

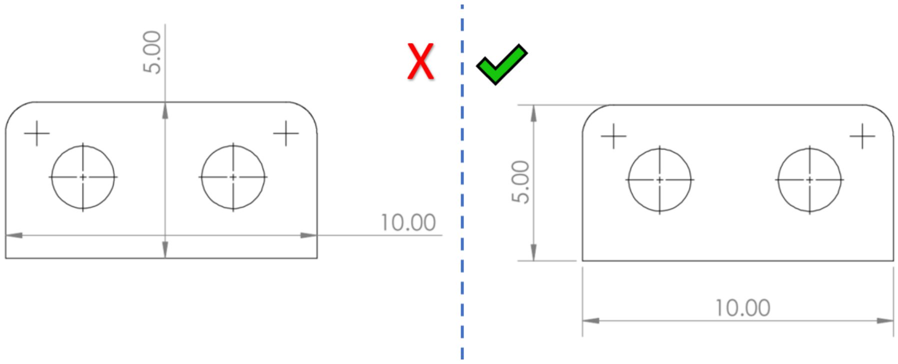


Figure 8.3: Violation of Rule #4 and Rule #5

The error in this image is that .

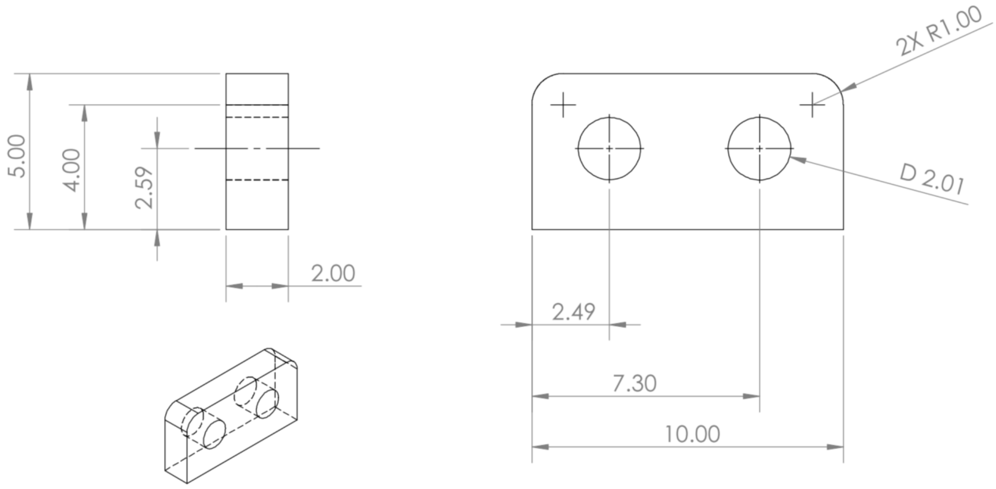


Figure 8.4: Properly dimensioned part

8.2 Dimensioning in Parallel vs Series

There are two exclusive types of linear dimensioning methods. These are referred to as dimensioning in parallel and dimensioning in series. Dimensioning in parallel is to dimension features of a part from a common origin (shown in Figure 8.5). Dimensioning in series is to dimension features of a part in reference to other features (shown in Figure 8.6). Upon first glance, it would seem that there is no difference of output from using either method, but they do have different uses. in general, The pros for one method are the cons for the other.

Parallel dimensioning allows for an established common datum to be measured from. This is necessary for situations where the part must fit in a specified area. For visualization purposes, Imagine a football field. This is dimensioned in parallel. Each line is measured from the common datum of the end zone to let the players, officials and fans know how far away from a touchdown they are.

Series dimensioning is used in situations where relative dimensions are important. This is most commonly used when another part must fit into a designated area of your current part. Note that the con of using this method is an increased potential for stack up errors. If the first dimension in the chain is incorrect, the rest will increasingly vary from their desired locations. For visualization purposes, imagine a road with lanes for cars and bikes. The car lanes must be the appropriate width for a car and the bike lanes must be the appropriate width for a bike, making them the critical dimensions. The width from the edge of the road is not important in this scenario you you would not need to dimension it in parallel.

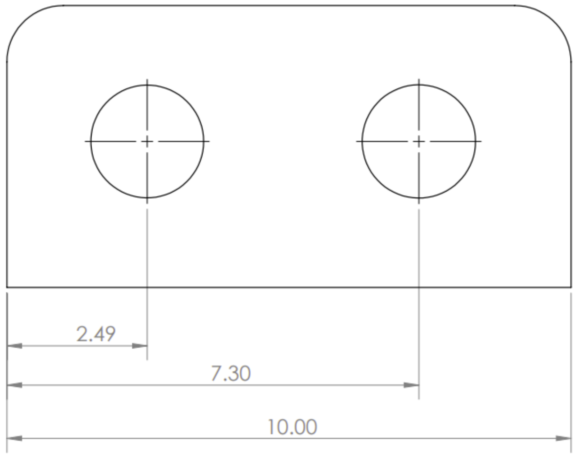


Figure 8.5: Example Part Dimensioned in Parallel

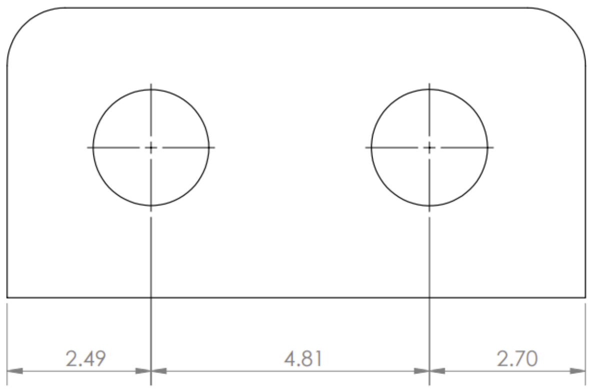


Figure 8.6: Example Part Dimensioned in Series

8.3 Geometric Dimensioning and Tolerancing (GD&T)

Standard dimensioning of a part serves to ensure that the part will be manufactured as intended. Geometric dimensioning and tolerancing (GD&T) serves to make sure that the manufactured part will operate in an assembly as intended. GD&T is an industry standard that is managed by the American Society of Mechanical Engineers (ASME). This means that all members of the design and manufacturing groups should have a basic understanding of the system.

The first step in setting up a part for GD&T is understanding datums. a datum is a set point or plane that you will be taking all measurements in the drawing from. Typically a drawing will have a primary, secondary and tertiary datum. You can imaging that these datums would each restrict the degrees of freedom in a given direction. Three datums means that your part is covered from all three possible linear degrees of freedom (X, Y, and Z). These datums are denoted by a flag with a capital letter inside of them. This can be seen in Figure 8.7.

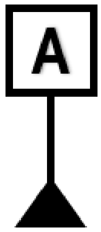


Figure 8.7: Image of a datum

The next portion of GD&T is the control frame. The control frame is a box-separated list that tells the viewer how a characteristic is constrained. This can be seen in Figure 8.8. The first box in the control frame is the geometric characteristic. This box tells the viewer how the feature is being measured. The next box to the right is referred to as the tolerance zone. This shows the tolerance of the feature as well as what type of feature is depicted and what the tolerance of this feature is. Finally there is the datum zone. This serves to show how the part should be set up for inspection. These must be in order of primary, secondary and then tertiary datum.

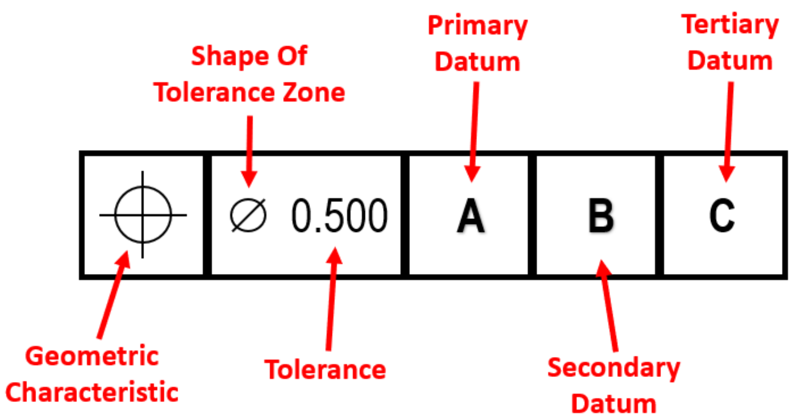


Figure 8.8: Labeled Engineering Drawing Control Frame

Part Three: Launch and Assessment

9. Pre Launch Considerations

Designing a rocket is half the battle. While executing the iterative design process, an engineer should also think about launching the vehicle and surrounding logistics.

9.1 Launch Location and Facilities

When selecting a launch location, and engineer should consider: maximum altitude, expected recovery area, required facilities and infrastructure, and travel logistics. Unfortunately the general trend is that as flight ceiling increases, so does required travel distance from Blacksburg. Most launch locations on the east coast are limited to under 20,000 ft due to heavily populated urban centers. Even in rural areas (Blacksburg, for example) the recovery area of higher altitude flights is so large that obtaining permission to launch above 10,000 ft is impossible. Space shots necessitate travel west of the Mississippi river, where vast deserts of uninhabited land provide lower risk flights. The one exception is Wallops Flight Facility.

Be weary of the logistics surrounding the launch. How will OLVT transport members and the rocket itself? Is there lodging? Are launch rails or a launch tower provided? How will you feed everyone? Generally, the team should determine and fund only launch essential personnel, meaning those required to ensure a successful launch. Table 9.1 summarizes common launch locations, the principle manager, its geographical location, the flight ceiling or recommended vehicles, and the steps necessary to launch there.

Kentland Farm, Higgs Farm, and the Rocket Pasture are all managed by local rocketry organizations. Black Rock Desert is home to an event called BALLS, which is the premier high power rocketry event with a space capable flight ceiling. It is hosted once per year in late September. Individuals can also launch in the Black Rock Desert outside of BALLS so long as they obtain appropriate FAA and BLM waivers independently. Spaceport America, FAR, and Wallops are bureaucratically disconnected from national rocketry associations but certainly within the realm of possible launch locations. Many more launch sites

Table 9.1: Launch Location Land Management

Shows common launch locations and the steps necessary to obtain permission to launch.

Site Name	Manager	Location	Rec. Vehicles	Steps to Launch
Kentland Farm	VT and NRVR	Blacksburg, VA	Under 10,000 ft	Attend NRVR launch or contact representative
Higgs Farm	MDRA	Church Hill, MD	Under 17,000 ft	Attend MDRA launch or contact representative
Rocket Pasture	KLOUDBusters	Argonia, KS	Under 50,000 ft	Attend Kloudbusters event or contact representative
Black Rock Desert	BLM/Tripoli Gerlach	Gerlach, NV	Above 50,000 ft	Attend BALLS event OR FAA and BLM Waiver
Spaceport America	NM Spaceport Auth	Truth, NM	Above 50,000 ft	Contact to RFQ
FAR Site	FAR	Randsburg, CA	Above 50,000 ft	Contact and FAA Waiver
Wallops Flight Facility	NASA	Wallops Island, VA	Orbital/related	Contact to RFQ

9.2 Waivers

Three federal level waivers are of importance:

- The Federal Aviation Administration's Certificate of Authorization (FAA COA)
- The Bureau of Land Management's Special Recreation Permit (BLM SRP)
- The Federal Communications Commission Waiver (FCC Waiver)

The team may need to fill out none, some, or all of these waivers depending on launch location and the vehicle's telemetry system. Each of these waivers will be discussed individually.

In a broader sense, OLVT should have complete and unambiguous permission to conduct safe and proper launch operations. All launch locations will have different management organizations and personnel at play. Communication is of the utmost importance - when in doubt, simply reach out to local authoritative figures (whether it be federal agencies or rocketry groups) and clarify the goals of the team and expectations for launch day. Verbal or written communication with relevant parties will tremendously help obtain the required paperwork.

9.2.1 FAA COA

The Federal Aviation Administration's (FAA) Certificate of Authorization (COA), otherwise known as the FAA COA or simply FAA waiver, serves to safely allow a vehicle to fly to an agreed upon altitude during an agreed upon time window. At its core, the waiver intends to prevent collision with aircraft and to ensure recovery operations are conducted in a safe manner. The FAA COA also helps ensure the vehicle remains on the expected trajectory (stability margin, impulse, etc.) and will fly as expected.

Regardless of launch location, an FAA COA must be obtained or standing in place to fly. Now, most launch events sponsored by national rocketry organizations will have the FAA COA obtained for the entire event, meaning OLVT does not have to obtain one on our own. Our local Kentland Farm has a standing FAA COA every weekend, for example. Reference the event's or local rocketry organization's website for information regarding details about their FAA COA.

If the team desire's to launch on our own or exceed the flight ceiling of the standing waiver, we will need to obtain an FAA COA independently. This is obtained by filling out FAA Form 7711, and supplying the information required by 14 CFR 101.29. Form 7711 must be submitted at least 45 days before the launch date. This will allow the FAA time to process and approve the form. An FAA waiver should be submitted 100 days in advance of a launch, however, to ensure that an edited re-submission can occur in the case of a waiver rejection. Lastly, one should submit these forms to the launch site's nearest FAA office.

As with all FAA COA waivers, constant communication with the FAA is required at predefined time intervals leading up to a launch. If the FAA COA is obtained by a local rocketry organization, personnel from the rocketry organization will handle this communication for you.

9.2.2 BLM SRP

The Bureau of Land Management (BLM) administers land owned by the federal government. Most of this land is barren desert or mountains, which make it suitable for high altitude rockets. A Special Recreation Permit (BLM SRP) is required to gain access to this federal land and conduct launch operations and recovery. Both BALLS and FAR Site operate on land managed by the BLM and are prime examples.

Similar to the FAA COA, events or permanent facilities hosted by established rocketry groups will have already obtained a BLM SRP, requiring no action on OLVT's part should we attend. If OLVT wishes to launch on their own and BLM manages the land, then the team must fill out Form 2930-1, submit the application, and obtain a permit. Permits should be filled 180 days in advance as per BLM guidelines. Contact the prospective launch site's local BLM office for specifics on any additional forms which may be required.

9.2.3 FCC Waiver

The Federal Communications Commission has blocked off certain frequencies for dedicated uses. Custom telemetry systems, should they utilize a frequency outside of its intended use, should file for a waiver through the FCC for dedicated use on the rocket. This section deserves further discussion, however the team has not had to file one of these yet. COTS systems can assume compliance with the FCC such that no waiver is required, unless manufacturer specifications specifically say otherwise.

9.3 Flight Readiness Review

After a designed vehicle is constructed, launch arrangements are in place, and final trajectory analysis has been conducted on the now complete vehicle, the team should hold a Flight Readiness Review (FRR) with the advisory board to asses team readiness for launch. FRRs usually consist of noted changes since the Critical Design Review (CDR), final notes regarding expected trajectory of the now designed vehicle, and field measurements taken directly from the physically constructed hardware. In addition, travel logistics, launch location, and launch operation checklists and procedures should be discussed. An FRR answers the question, "Are we ready to launch?" Shoot for a 30-50 page paper and a 30-50 slide presentation. FRRs should be conducted for larger, more complex vehicles such as Hokie 0.75. Smaller rockets such as Test Turkey 0.75 do not necessarily require an FRR, given constant communication with primary advisors during design and construction.

10. Launch Operations and Post Launch Assessment

As a result of the Hokie 0.6 misfire, OLVT created a dedicated Launch Operations subteam to manage vehicle assembly, launch tower integration, and launch. In combination with shunts, switches, and remote arming mechanisms developed by Avionics subteam, the team strives to prevent future misfires or other dangerous events. Launch Operations subteam requires close and frequent communication with other subteams to ensure the vehicle is safe and the launch can conduct according to plan.

10.1 Launch Tower

Launch towers provide guidance for the vehicle during booster ignition and the first short duration of flight. Until a rocket is moving with sufficient velocity, the fins are more or less ineffective in providing stability. As such, the launch rail must be sufficiently tall to keep the rocket flying straight until the rocket has enough velocity built up to be independently stable. Lastly, launch towers provide an easy way to move the rocket from a horizontal assembly position to a vertical launching position.

There are a seemingly infinite number of ways to design and construct a launch tower. This discussion will consist of some key factors to keep in mind, as well as provide examples of existing mechanisms and towers. An engineer should consider:

- Does the launch location have towers or rails available for us?
- How heavy is the rocket, can the tower be erected by hand?
- Does the tower need to make fine adjustments to the vehicle's initial launch angle?
- If the tower erects under its own power, a safety mechanism should prevent the tower from retracting should the primary power source fail
- How long does the rail need to be for the vehicle to generate enough speed to be stable?

A launch tower requires some form of channel or rod (more commonly referred to as a rail) that the vehicle can integrate with and slide along. The rocketry community most commonly uses two different types of rails: metal rods for smaller rockets and 8020 for larger high power rockets. Figure 10.1 depicts pictures of these rails and the primary form of integration with the vehicle.

Figure 10.2 provides a few examples of launch rails and towers. One noteable example is the

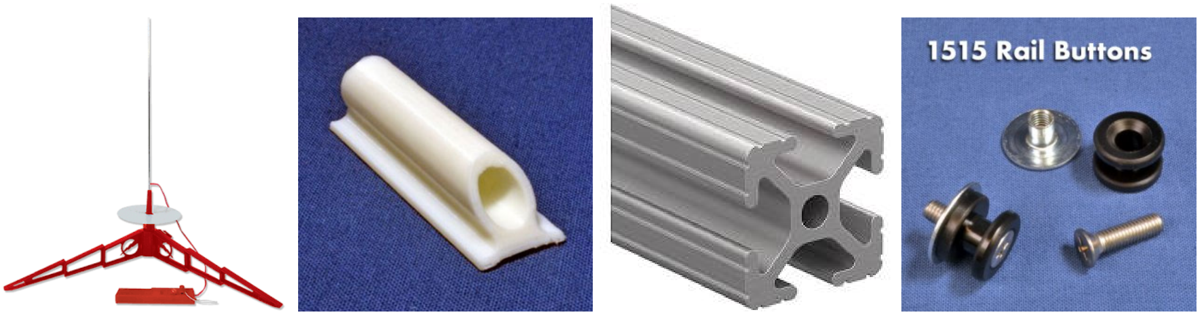


Figure 10.1: Two Most Common Launch Rails in HPR

Launch rod and conformal launch lugs (left). 8020 aluminum extruded rail and rail buttons (right) [14].

Qu8ke rocket by Derek Deville (pictured far left). This launch tower utilized four sides of support instead of a rail to guide the rocket.

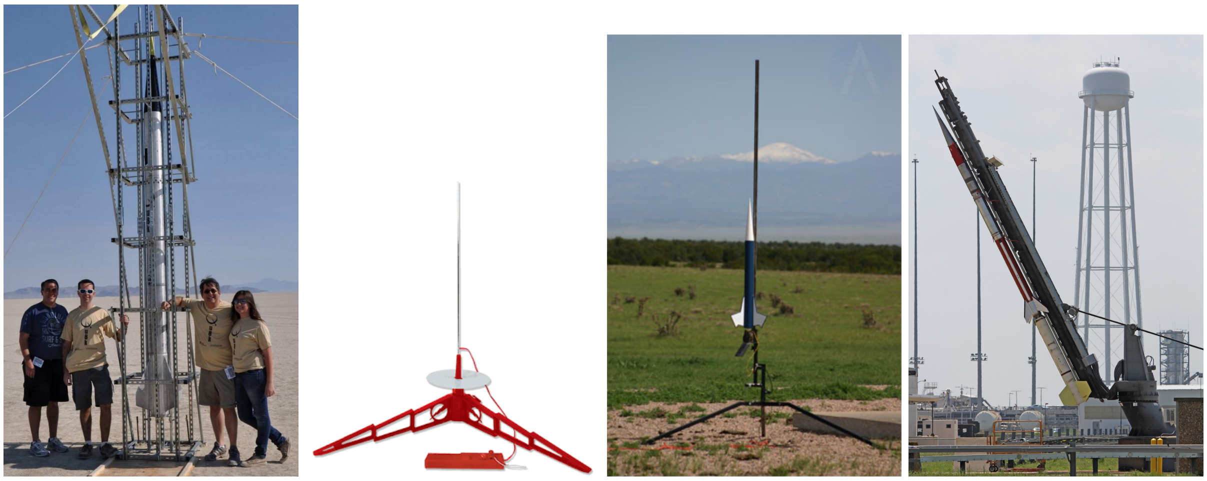


Figure 10.2: Common Launch Towers

(From left to right) Qu8ke rocket launch tower. Smaller, model rocket launch rod. Standard launch tower for high power rockets. Launch tower at Wallops Flight Facility. [14–16].

10.2 RSOs and Launch Coordinator

Every OLVT launch should include three key personnel:

- Senior Range Safety Officer (RSO): A representative from TRA or other trusted and experienced advisor or mentor
- Student RSO: A student who serves the same role as the Senior RSO, but as a member of the team knows much more information regarding the rocket itself
- Student Launch Coordinator: A student who directs assembly and launch procedures

While undergoing launch operations, a strict hierarchy must be observed. The Senior RSO (and student RSO) have ultimate authority to cease any ongoing launch operations should they deem a certain operation hazardous. These representatives have final say - meaning no current standing OLVT President or other member can overrule them. This is to ensure a completely unbiased decision, one made without the cloud of rocket fever. Second in command is the

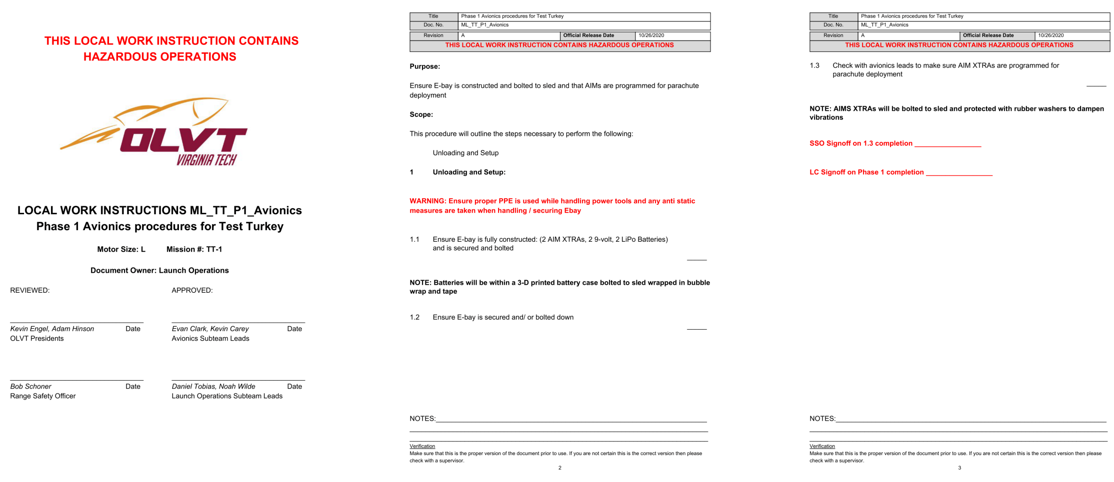
Launch Coordinator. The launch coordinator manages and directs assembly of the vehicle. They administer procedures and checklists, and oversee the general assembly process. Other than these three personnel, each vehicle will require a mix of subteam leads or other knowledgeable members to physically construct and launch the rocket. The exact members at play are unique to each rocket, but should be specific, deliberate, and consistent with required checklists and procedures.

Regardless of the launch, the team should take care to limit the number of personnel involved in launch operations. The fewer people required, the easier it will be to coordinate and manage. Remember, the team works with highly energetic, extremely dangerous components. Simple yet effective launch operations with minimal communicative complexity provide the most reliability.

10.3 Checklists and Procedures

The use of checksheets (a document that contains procedures in a checklist format) greatly reduces risk of human error while conducting dangerous activities, and ensures that tasks are completed properly. Checksheets provide structured, ordered ways to conduct operations in a safe and well thought out manner. As such, checksheets should be well maintained, easy to read, and use plain and candid English. Since launching contributes to most of OLVT's dangerous operations, the Launch and Early Operations subteam is responsible for creation, distribution, and revisions of OLVT's checksheets.

To determine if a given operation should utilize a checksheet, a Procedures Necessity Assessment (PNA) is conducted. Once the PNA determines sufficient risk, a new checksheet is created and appended to the team's Procedures Document Management system. OLVT has templates available for procedure creation, and procedures can be broken down into multiple different phases, sub phases, and documents. Figure 10.3 outlines an example procedure from Test Turkey, a precursor and test vehicle for Hokie 0.75.


THIS LOCAL WORK INSTRUCTION CONTAINS HAZARDOUS OPERATIONS

OLVT VIRGINIA TECH

LOCAL WORK INSTRUCTIONS ML_TT_P1_Avionics
Phase 1 Avionics procedures for Test Turkey

Motor Size: L   Mission #: TT-1

Document Owner: Launch Operations

REVIEWED: APPROVED:

Kevin Engel, Adam Hinson Date — OLVT Presidents
Evan Clark, Kevin Carey Date — Avionics Subteam Leads
Bob Schoner Date — Range Safety Officer
Daniel Tobias, Noah Wilde Date — Launch Operations Subteam Leads

Title	Phase 1 Avionics procedures for Test Turkey		
Doc. No.	ML_TT_P1_Avionics		
Revision	A	Official Release Date	10/26/2020

THIS LOCAL WORK INSTRUCTION CONTAINS HAZARDOUS OPERATIONS

Purpose:

Ensure E-bay is constructed and bolted to sled and that AIMs are programmed for parachute deployment

Scope:

This procedure will outline the steps necessary to perform the following:

Unloading and Setup

1 Unloading and Setup:

WARNING: Ensure proper PPE is used while handling power tools and any anti static measures are taken when handling / securing Ebay

1.1 Ensure E-bay is fully constructed: (2 AIM XTRAs, 2 9-volt, 2 LiPo Batteries) and is secured and bolted ____

NOTE: Batteries will be within a 3-D printed battery case bolted to sled wrapped in bubble wrap and tape

1.2 Ensure E-bay is secured and/ or bolted down ____

NOTES:____

Verification
Make sure that this is the proper version of the document prior to use. If you are not certain this is the correct version then please check with a supervisor.
2

Title	Phase 1 Avionics procedures for Test Turkey		
Doc. No.	ML_TT_P1_Avionics		
Revision	A	Official Release Date	10/26/2020

THIS LOCAL WORK INSTRUCTION CONTAINS HAZARDOUS OPERATIONS

1.3 Check with avionics leads to make sure AIM XTRAs are programmed for parachute deployment ____

NOTE: AIMS XTRAs will be bolted to sled and protected with rubber washers to dampen vibrations

SSO Signoff on 1.3 completion ______________

LC Signoff on Phase 1 completion ______________

NOTES:____

Verification
Make sure that this is the proper version of the document prior to use. If you are not certain this is the correct version then please check with a supervisor.
3

Figure 10.3: An Avionics Checksheet for Test Turkey

Notice the signatures for approval on the title page, the project scope, clearly written procedures, stop points, and completion signoffs.

10.4 Post Launch Assessment Review

Post launch, the team should conduct a Post Launch Assessment Review (PLAR) to discuss a summary of the launch. This review should include successes, failures, and steps for future improvement. Most PLARs will most likely manifest themselves as part of OLVT's undergraduate research curriculum.

10.5 Root Cause Analysis

Should the rocket fail in a severe way (i.e. Hokie 0.6 misfire) or otherwise fail to meet a program requirement, the team should conduct a Root Cause Analysis (RCA). This analysis will hopefully uncover the technical cause of the error and provide recommended changes to a future design. Additionally, the RCA should analyze the team itself. What in our design process was faulty to where we did not catch this critical error before construction and launch? How can the team operate more effectively to prevent similar design errors from happening in the future?

Take the Hokie 0.6 misfire as an example. OLVT not only analyzed avionics data to determine the technical cause, but completely changed its attitude towards rockets, the organization, and how we operate. We formed a design review board (DRB) with stepping stone like design reviews and an entirely new Launch Operations subteam.

There are often deeper problems with a team's organization, ways of thinking, and design process that manifest themselves in the form of a critical failure. The technical issue itself is almost irrelevant, aside from a quick learning experience. Don't just ask "What mistake was made?", instead ask "Why did we make this mistake?" The Boeing 737 MAX is another prime example. What is Boeing doing wrong, from an operational and teamwork point of view?

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IV

Appendices

A. Terminology and Definitions

The following is a list of common terminology used throughout the team. Refrain from using alternate phrases both in your writing and spoken exchange.

Aft - Towards the rear of the rocket (hopefully opposite the direction of travel)
Altimeter - A device with one or more sensors that obtains vehicle altitude
Avionics Bay - Houses the avionics system.
Avionics System - Contains the sensors, data acquisition and processing, and logic controllers
Axial - Referring to a central datum line running through the rocket's cylindrical axis
Body - Often referred to as a body tube, the body forms the geometric exterior of the vehicle and protects interior components.
Booster - The first stage of a two stage vehicle
Bulkhead - A circular, flat plate separating two areas of the vehicle
Caliber - A dynamic unit equal to the width of the stage or vehicle in question
Center of Gravity - A point where the total sum of gravity field acts on a body, is the same location as the center of mass
Center of Pressure - A point where the total sum of a pressure field acts on a body
Coupler - A joint between two telescoping tubes, where one tub's outer diameter is very near the other tube's inner diameter
Drogue Parachute - A parachute deployed at apogee, goal is to avoid ballistic decent but maintain a relatively high decent rate to avoid wind drift
Dual Deployment - Utilizing two separate parachutes for recovery, a drogue chute and a main chute
Electronics Bay - An area of the vehicle where all electronics are stored
Electronics Bay Shell - The body tube surrounding the Electronics Bay and the resulting wires and mechanical integration of the Electronics Bay with the vehicle
Electronics Bay Sled - A flat rectangular plate aligned axially with the vehicle, used to mount electric and avionics hardware
Fin Can - A complete assembly or single piece which includes the fins and secures them to the vehicle

Fins - Stabilize the rocket during flight. Fins can be passive or active in their influence. Must be constructed to withstand aerodynamic loading and heating.
Forward - Towards the nose cone (hopefully the direction of travel)
Forward Closure - A component used to cap and seal the forward end of the motor casing. This is usually comprised of a metal alloy due to the extreme temperatures and pressures within the motor core.
Grain(s) - Cast or molded propellant which burns to drive the rocket. The interior geometry of the grain forms the core. Grains are often wrapped in a protective liner to insulate the casing.
Ground System - A system most often used to receive trajectory data from the on board Telemetry System
Impact Energy - The kinetic energy of the vehicle at touchdown
Kit - A package containing parts to assemble a previously designed rocket
Launch Vehicle - A rocket designed to transport a payload
Main Parachute - A parachute deployed closer to the ground, goal is to slow the vehicle to a safe impact energy
Minimum Diameter - When a rocket's motor mount tube doubles as the body tube
Motor Casing - Contains the propellant grains and nozzle while maintaining motor chamber pressure. Additionally provides attachment points for the closure and nozzle hardware.
Nose Cone - The nose cone geometry should minimize drag and aerodynamic heating, and is usually composed of fiberglass for RF transparency.
Nose Cone Tip - The most forward point on a rocket. Due to the component's complex and fine geometry, it is usually machined from a metal alloy.
Nozzle - Converts thermal energy from the motor into kinetic energy to propel the rocket. Often constructed of materials which can manage high heat flow such as carbon graphite.
Parachute Bay - A compartment that houses the parachute, along with its tension lines and a shock cord. In the case of a black powder parachute deployment method a protective blanket will also need to fit in this portion.
Parachute Ejection System - Uses some form of stored energy to eject a parachute. This can either be driven by ignition of an energetic material or by release of stored mechanical energy.
Payload - A system which is transported by the vehicle but often designed separately. The launch vehicle is designed with generalized payload capabilities.
Payload Bay - A compartment designated to house and protect the payload throughout the duration of flight. Usually situated in or shortly aft of the nose cone.
Radial - Any direction perpendicular to axial
Recovery System - Includes the parachutes, deployment systems, and recovery harnesses
Retaining Ring - Anchors the nozzle to prevent it from being jettisoned out the aft end of the motor casing. A nozzle carrier is an alternative component to serve the same function.
Rocket - A projectile which expels mass to create thrust and propel itself
Shear Pin - A pin designed to hold two components together until a predetermined event, at which point the pin is broken or "sheared", releasing the two components. Often used in staging or parachute ejection.
Staging - The process of separating an expended portion of a rocket and igniting the next sequential stage
Sub Minimum Diameter - When a rocket's motor casing doubles as the body tube
Sustainer - The second stage of a two stage vehicle
Telemetry System - A system which transmits data between the Avionics and Ground Systems

Transition Piece - A component which joins two stages, often of different diameters. Must be designed with stage separation mechanics in mind. In the case of Hokie 0.75, separation is driven by ignition of the sustainer.

B. Preferred Writing

For consistency, all members shall adopt the preferred writing style outlined below when working on team related projects. Items are listed in lexical order.

B.1 Acronyms

AGL - Above Ground Level
AHP - Analytical Hierarchy Process
Al 6061-T6 - Aluminum Alloy 6061-T6
AMW - Animal Motor Works
AoA - Angle of Attack
AOE - Department of Aerospace and Ocean Engineering at Virginia Tech
APCP - Ammonium Perchlorate Composite Propellant
ASTM - American Society for Testing and Materials
AWGN - Additive White Gaussian Noise
BER - Bit Error Rate
BLM - Bureau of Land Management
CATO - Catastrophic Failure
CDR - Critical Design Review
CFD - Computational Fluid Dynamics
CG - Center of Gravity
CNC - Computer Numerical Control
CO_2 - Carbon Dioxide
COTS - Commercial Off The Shelf
CP - Center of Pressure
CPU - Central Processing Unit
CTI - Cesaroni Technology Incorporated
DAC - Digital to Analog Converter
ECE - Department of Electrical and Computer Engineering at Virginia Tech
EIRP - Effective Isotropic Radiated Power

EPDM - Ethylene Propylene Diene Monomer
FAA - Federal Aviation Administration
FAR - Friends of Amateur Rocketry
FCC - Federal Communications Commission
FEA - Finite Element Analysis
FM - Frequency Modulation
FMEA - Failure Modes and Effects Analysis
FOD - Foreign Object Debris
FPGA - Field Programmable Gate Array
FRR - Flight Readiness Review
FSK - Frequency-Shift keying
ID - Inner Diameter
IF - Intermediate Frequency
ITAR - International Traffic in Arms Regulations
MCR - Mission Concept Review
MMT - Motor Mount Tube
NAC - Needs, Alterables and Constraints
NCO - Numerically Controlled Oscillator
NFPA - National Fire Protection Agency
OD - Outer Diameter
ODE - Ordinary Differential Equation
OLVT - Orbital Launch Vehicle Team at Virginia Tech
PCB - Printed Circuit Board
PCM - Pulse-Code Modulation
PDR - Preliminary Design Review
PPE - Personal Protective Equipment
PR - Public Relations
PRA - Probabilistic Risk Assessment
PVC - Polyvinyl Chloride
RF - Radio Frequency
RFP - Request For Proposal
RSO - Range Safety Officer
SNR - Signal-to-Noise Ratio
SMR - Specific Mission Requirements
UART - Universal Asynchronous Receiver/Transmitter
VSD - Value System Design
WSC - Western Service Center Area
XPS - Extruded Polystyrene

B.2 Symbols

α - nozzle exit angle
c - distance from the center of bolt to end of casing
ΔV - change in velocity
F - force
I_{sp} - specific impulse

λ - exhaust velocity correction error
m - mass
m_f - final mass
m_o - initial mass
P - load
p - momentum
P_c - chamber pressure
r - radius
r_{avg} - average radius
σ_θ - hoop stress
t - time
t_c - casing thickness
τ_{plate} - plate shear stress
v - velocity
v_e - exhaust velocity
$ - US dollars

B.3 Units

A - ampere
°C - degrees Celsius
°F - degrees Fahrenheit
G - acceleration as a factor of Earth's gravity
Hz - hertz
K - Kelvin
M - Mach number
MB - megabytes
Mbps - megabits per second
MPa - megapascal
MSPS - million samples per second
N - newton
Wh - Watt hour
cal - caliber
dB - decibel
°- degrees (angle)
fl oz - fluid oz
fps - feet per second
ft - feet
g - gram
hr - hour
in - inch
kg - kilogram
km - kilometer
kN - kilonewton
kPa - kilopascals
ksi - kilopounds per square inch

lb - pound
m - meter
min - minute
mm - millimeter
oz - ounce (weight)
psi - pounds per square inch
rad - radian
s - second

B.4 Grammar and Style

Below are a few good practice rules to follow when writing. Any member is expected to adhere to them.

B.4.1 Units and Numbers

When writing units, always put a space between the unit and the number. For example, 100 km. Never write a period after the unit unless at the end of a sentence. If the number is followed by a standard unit, write it out numerically (for example, 27 mi or 8 mm). Never write out the full unit, instead use the abbreviated versions listed in Appendix B.3. If the number is a quantity or otherwise does not have units, write it out alphabetically (for example, eight students or two parachutes). Always use commas when writing large numbers numerically (for example, 400,000 ft or 2,000 K). Always insert a zero before decimal points (for example, 0.25 in). Never put an 's' to make a unit plural (write 3 lb, not 3 lbs). Never use quotations or apostrophes to denote inches or feet. Wherever possible, list both imperial and metric units.

B.4.2 Avoid the Passive Voice

This common stylistic rule aids the clarity and conciseness of your writing. The following formula describes passive voice quite well:

form of "to be" + past participle = passive voice

For example:

The launch tower has been scorched by the motor.
OLVT is guided by our Constitution.

Should read:

The motor scorched the launch tower.
The Constitution guides OLVT.

The verb "to be" does not always have to be passive, for example:

The motor casing is 48 in long.

B.4.3 Itemized and Enumerated Lists

Try to avoid enumerated and itemized lists wherever possible. Only use a list if the situation directly calls for one (for example, a checklist or procedure, or list of parts). If you are having trouble writing thoughts or design parameters in paragraph form, go to sleep and write full sentences and paragraphs like a normal person in the morning.

B.4.4 Decimals

In general, only use the amount of decimals required to transmit the design intent. Design review papers often require higher levels of precision than a presentation. In a presentation, the audience does not care that the trajectory simulation generated a 411,275.32 ft apogee. Instead, saying “The vehicle was designed to hit 400,000 ft, and our trajectory predictions put the vehicle at 410,000 ft” will convey more information and insight into the design process without burdening the reader or audience.

B.4.5 Tables and Figures

Tables and figures should be clean, concise, and informational. They should not distract the reader. All tables and figures should be referenced in text. Always refer to the figure directly. For example, write “... as shown in Figure #.” Never use phrases such as “in the following figure” or “in the table below.” The words “Figure” and “Table” should always be capitalized when referencing. Include both technical and graphical renderings of parts. All figures should have a transparent background for any use with OLVT.

B.4.6 Other Grammar Notes

A parenthetical statement at the end of a sentence is punctuated outside of the closing parenthesis (like this). The same goes for references and citations. “However, the period goes inside quotation marks.”

Never write in first person. Instead, write “The team determined that...” or “The analysis results were inconclusive.”

C. Level 1 Certification Guide

As you are aware, every member on OLVT must be level 1 HPR certified. Minus the $10 Tripoli registration fee, the team will cover the cost of this certification. Certifying the team helps build our general rocketry experience and understanding. Holding a level 1 certification allows members to launch rockets with motors up to 640 Ns of installed impulse. Besides registration, the only real requirement is that the individual must successfully build, fly, and recover a rocket launched on an H or I motor. The member must build the entireity of the vehicle with minimal help from friends, family, or other team members. Asking someone to help you hold something while glue dries, for example, is permitted. Below is a summarized list of the requirements, which can be found on the Tripoli Website:

- The rocket must have a marked center of pressure and center of gravity
- The rocket must be of conventional design (no flying pyramids, saucers, or spools)
- Standard parachute recovery is required
- The rocket must fly on a single H or I impulse motor. Staged or clustered rockets are not allowed
- Electronics are not required for the certification
- The certifying member (Prefect, TRA Director, or TAP Member) must be present and witness the flight
- The vehicle must ascend without tumbling and descend in a stable manner controlled by the recovery system
- Upon recovery, the vehicle must be in a condition where, if the member were immediately handed another motor, the vehicle could safely be reflown. Damage due to excessive wind dragging the vehicle after touchdown will not void a certification
- The vehicle can be inspected in place should it not be recoverable (ie powerlines, trees, etc.)

The team purchases kits in bulk which satisfy the above requirements. To help you construct your level 1 kit, we have assembled a set of instructions. Bear in mind, there are multiple ways to build and assemble a rocket. Consider the following manual as a reference should you get stuck. You can, and are encouraged, to modify the design in a way that makes it unique to you (for example, using different fin geometry or painting your rocket). It is highly recommended that you read the entire set of instructions before building. This build can easily be completed in a single day, allowing room for a trip to the local hardware store and food/bathroom breaks. The kit shown in the pictures was assembled in under five hours.

Disclaimer

Following these instructions does not guarantee you a successful certification flight. This is a guide, not a lego assembly manual. Rocketry is hard and nothing is ever certain. It is up to you to ensure your rocket is safe and operational.

C.1 General Construction Advice

Below are a few general recommendations for building any project:

1. Always have paper towel on hand, especially when working with epoxy. Tear off a few sheets and rip them into halves or quarters and use as necessary. Paper towels are cheap, your time is valuable. Don't be afraid to waste it
2. Have a trash bag handy
3. Popsicle sticks are great for applying epoxy. Wipe them off with paper towel before the epoxy sets and you can reuse them unlimited times
4. Always test fit parts before you assemble something. Go through the motions of assembly before applying epoxy. Plan, don't just start slapping things together
5. 220 grit sandpaper can remove a lot of material and also leaves a smooth finish
6. Don't mix an excessive amount of epoxy for a small application
7. Craftsmanship is important, not just for the success of the vehicle but also for your own character. Take pride in your build or project and it will turn out great. Spend a lot of time making your fillets perfect, avoid paint drips, don't use excessive amounts of epoxy, etc.
8. When cutting with a razor, always use multiple passes for a single cut
9. As you are building, consider the flight and operation of the vehicle. Why am I building this specific component this way? Should I be doing something else that will result in a lower risk flight?
10. I've said it before and I'll say it again, you can't test assemble things enough before applying epoxy
11. Sand components before applying epoxy. Most stock tubes have wax or some other slick coating on the outside. Epoxy doesn't stick to that very well. Roughing up the surface helps the epoxy adhere between the two components
12. Sand paper creases and tears in very straight lines. A small square lasts a long time
13. Remember that epoxy doesn't dry, it sets. As soon as you start mixing, you're on the clock

C.2 OpenRocket

OpenRocket is a rocketry simulation tool originally developed by Sampo Niskanen in 2009 as part of his master thesis at the Helsinki University of Technology. The software is free to download and will help you immensely during your build. Simply download the software from the developer's website. The software allows you to completely design your rocket from the ground up, determine its stability margin, and provide trajectory simulations with different motors. User guides and other documentation are available from the developers website. The Google Drive contains an OpenRocket file of an example build.

C.3 Required Parts, Supplies, and Tools

To build this rocket, you will require the following parts. They are shown in Figure C.1:

1. The Kit
   (a) Qty 1 - 11 in x 1.625 in MMT
   (b) Qty 1 - 34 in x 4 in body tube
   (c) Qty 1 - Centering ring and hardware bag
      i. Qty 1 - 1/4-20 eye hook
      ii. Qty 1 - 1/4-20 bolt
      iii. Qty 2 - Centering ring with 1/4 in hardware hole
      iv. Qty 1 - Machine screw
      v. Qty 1 - Solid centering ring
      vi. Qty 1 - T-nut
      vii. Qty 2 - Washers
   (d) Qty 4 - Fins
   (e) Qty 1 - Nose cone
2. Supplies
   (a) Qty 1 - 8-1/2 in x 11 in printer paper
   (b) Qty 1 - JB Weld clear weld 5 min 0.85 oz epoxy
   (c) Qty 1 - Role of paper towel
3. Tools
   (a) Qty 1 - Box cutter or razor
   (b) Qty 1 - Hammer
   (c) Qty 1 - Pencil and eraser
   (d) Qty 1 - Ruler (imperial)
   (e) Qty 1 - Door frame

C.4 Test Fitting Parts and Sanding

Test fit the centering rings, nose cone, and motor mount tube. Sand as necessary. The nose cone should slide out with minimal effort but not jiggle around in the body tube. You will have to sand the plastic fitting rings down a lot. The centering rings should require minimal sanding, just enough to remove the laser burns. Sand the fins smooth to remove any splinters. Sand the slick finish off the motor mount tube to prepare for epoxy. Consider how important tolerances are for parts to fit together properly. What kind of fit do you want? Figure C.2 depicts sanding a few components.

C.5 Epoxy Forward Centering Ring

Test fit a centering ring with a hardware hole to the forward end of the motor mount tube. Using the provided mixing stick and tray, mix a small amount of epoxy and apply a fillet around the centering ring as shown in Figure C.3. Let set for 15 min.

C.6 Epoxy Middle Centering Ring

Slide the solid centering ring on the motor mount tube and situate in the middle of the mount. Then, place the remaining centering ring with hardware hole on the aft end of the motor mount

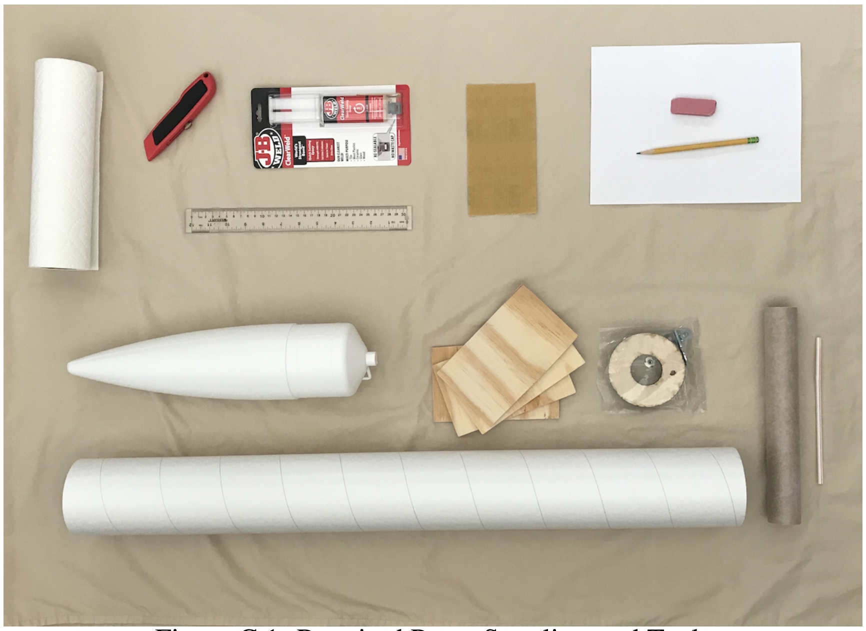


Figure C.1: Required Parts, Supplies, and Tools

All of the required parts, supplies, and tools. Everything is shown except for the hammer.

Figure C.2: Test Fitting Parts and Sanding

Fold and tear off a piece of sand paper. Sand the centering rings, nose cone, motor mount tube, and fins.

tube. Flip the assembly over, so that the centering ring you epoxied in Section C.3 is on top of the assembly. While keeping the aft most centering ring flush with the floor, grab two fins and adjust the middle centering ring to sandwich the fins. Remove the fins and aft centering ring and, without moving the middle centering ring, epoxy it in place. The process is shown in Figure C.4. Allow 15 min for epoxy to set.

C.7 Cutting Fin Slots

While epoxy is setting during the previous two steps, begin cutting the fin slots by perfectly folding a sheet of paper in half. Fold it perfectly in half the other way, making a perfect cross in

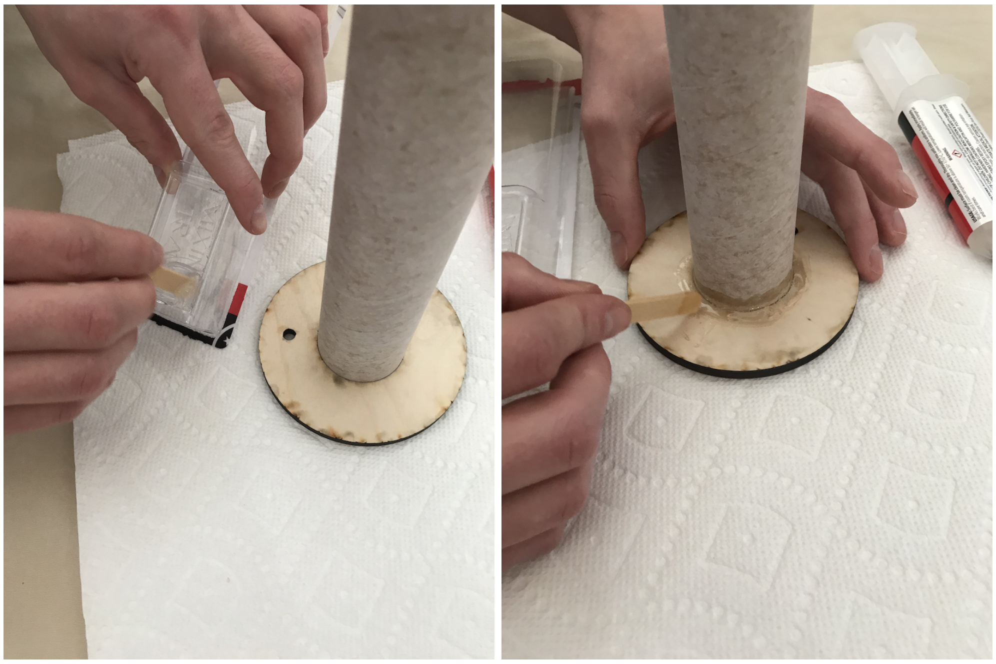


Figure C.3: Epoxy Forward Centering Ring

Apply a fillet of epoxy to the aft side of the forward centering ring. Ensure centering fits before applying epoxy. Align centering flush with the end of the motor mount tube.

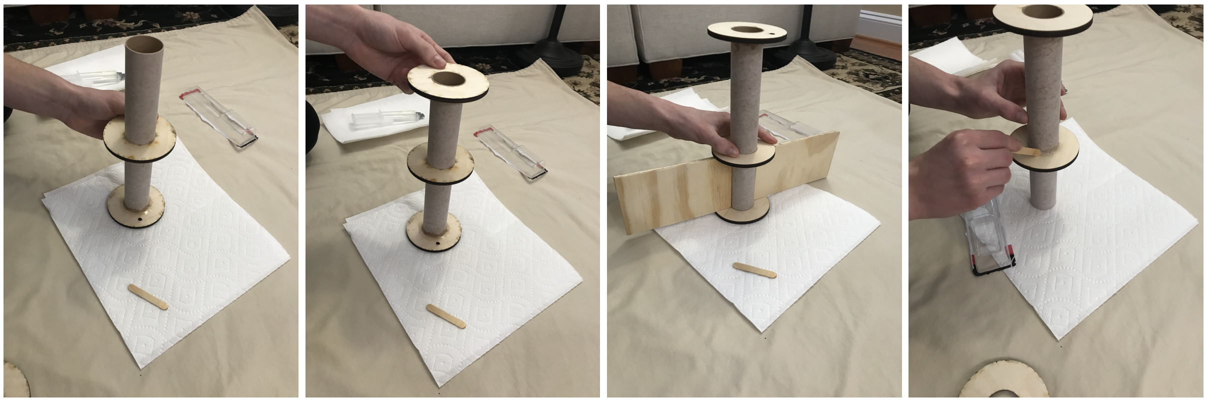


Figure C.4: Epoxy Middle Centering Ring

Slide on the middle centering ring (no hardware hole), slide on the aft centering ring (with hardware hole), flip the assembly, adjust middle centering ring to sandwich two fins. Without moving middle centering ring, epoxy it in place.

the center of the paper. Using a ruler, mark 2 in off each axis of the cross. Center the body tube on the cross, making sure each 2 in mark is half visible. On the body tube, mark where each fold touches the base of the tube. You should now have four marks on the body tube, each perfectly 90 deg apart. Using a door frame, trace each mark to make four lines at least 5 in long. Draw arrows pointing in the same radial direction on each line. Label each fin 1 through 4, and label each line on the body tube 1 through four. Matching each fin to its respective fin slot, mark the width of the fin in the radial direction described earlier. Go back to the door frame and trace each mark to make four more lines at least 5 in long. Using a ruler, mark 4.25 in up the length of each fin slot to define the forward limit of the slot. Using the box cutter trace the outline of each fin slot until they cut. Test fit each fin and sand the slots as necessary. The fins should snugly fit in their respective slot without wiggling around and without bending the body tube. This process is described in Figures C.5-C.8.

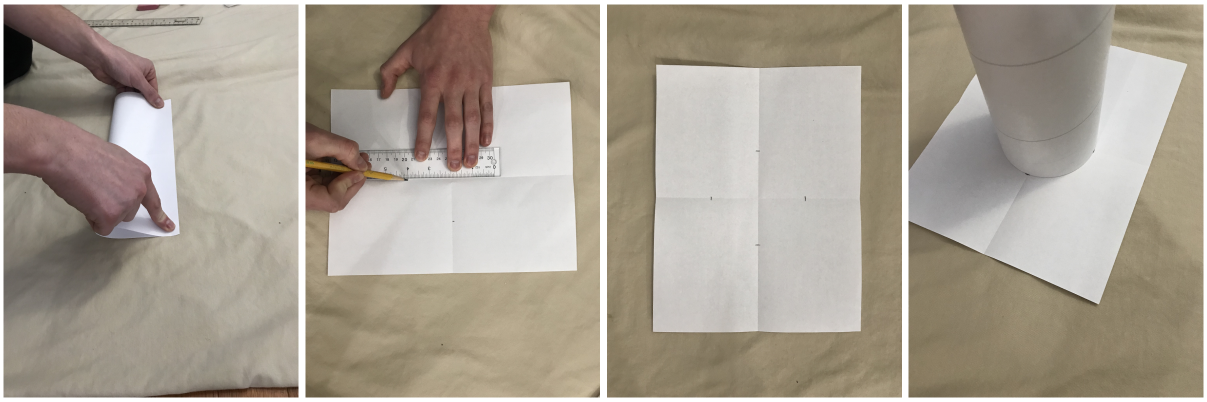


Figure C.5: Marking 90 Deg Fin Slots

Folding the paper creates perfectly perpendicular lines. Marking the paper with a ruler establishes a reference for the center of the body tube. Use the creases to mark the body tube.

Figure C.6: Marking an Axially Straight Line on a Tube

Although a door frame works quite well, any extended right angle can make these kinds of lines. Mark one side of each fin slot at least 5 in. A standard eraser will erase the pencil marks of your kitchen wall. Use the right hand rule to mark arrows on each line.

C.8 Recovery and Motor Retention Hardware

To assemble the recovery anchor at the forward end of the motor mount and fin can assembly, gather the 1/4-20 eye hook, the two washers, and the 1/4-20 nut. Sandwich the bulkhead between the two washers, coaxial with the hardware hole. Insert the eye hook. Apply a very small amount of epoxy to the threads of the eye hook. Hand tighten the bolt on. Apply a very small amount of epoxy to the base of the hook itself, attaching it to the washer. Ensure the assembly is firmly

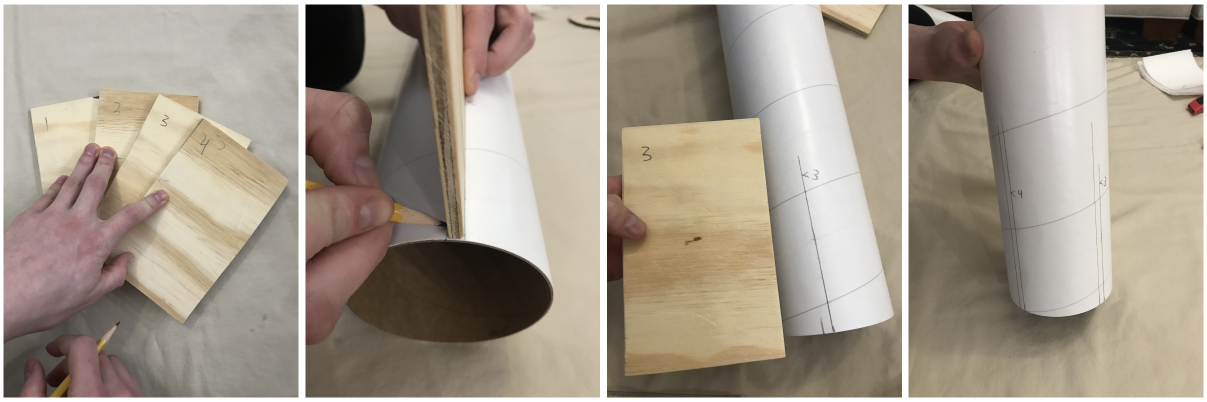


Figure C.7: Marking The Fin Width

Mark each fin and fin slot with a number. Match each fin to its slot and mark off the fin width in the direction of the arrows drawn previously. Continue the line using a door frame to fully define the fin width. Use a ruler and mark 4.25 in up the length of each fin slot to define the forward limit of the slot.

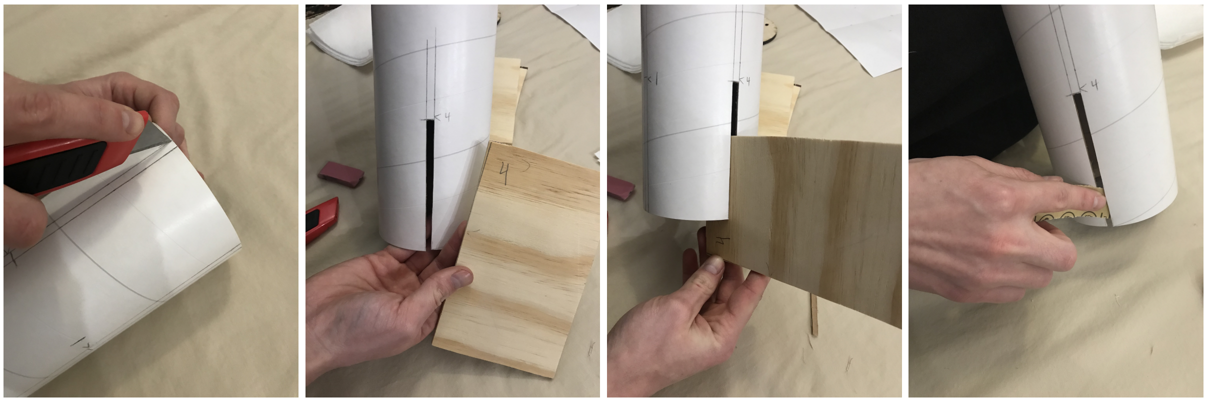


Figure C.8: Cutting the Fin Slot

Using the box cutter or razor blade, cut out each fin slot using multiple passes. I would recommend cutting directly on the line. Do not try and cut through the body tube in one pass, you will cut yourself. This is already dangerous enough.

tightened. Rotate the eye hook so it is "looking" perpendicular to the motor mount tube. See Figure C.9.

To assemble the motor retainer, find the T-nut and the remaining centering ring. Apply a small amount of epoxy to the spiked side of the T-nut. DO NOT get any epoxy in the threads of the T-nut. Hammer the T-nut into the bulkhead through the hardware hole. Ensure no epoxy is in the T-nut threads. See Figure C.10.

C.9 Test Assemble the Fin Can and Motor Mount (NO EPOXY)

DO NOT use any epoxy in this step. Slide the motor mount tube with the two epoxied centering rings into the body tube. Align the recovery hardware with the fin marked 1. Align the middle centering ring with the forward end of the fin slots. Slide in the four fins and place the remaining centering ring. Align the motor retention with fin numbered 3. Why do we have the hardware spaced radially even around the vehicle and not all on one side? Flip the assembly over, reach into

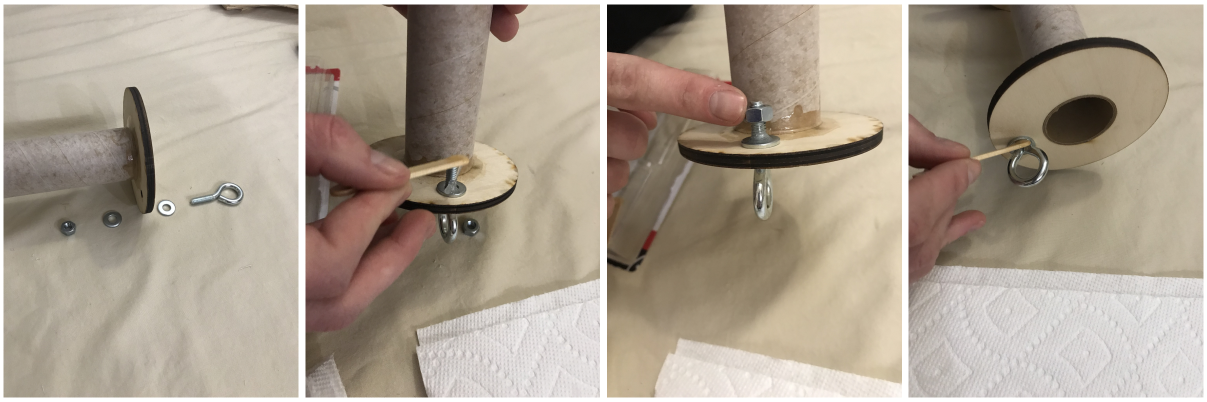


Figure C.9: Recovery Hardware

Assemble the recovery hardware as stacked in the first picture. Epoxy and hand tighten. Orient the eye hook so it is facing away from the motor mount tube. Why would we want to do this?

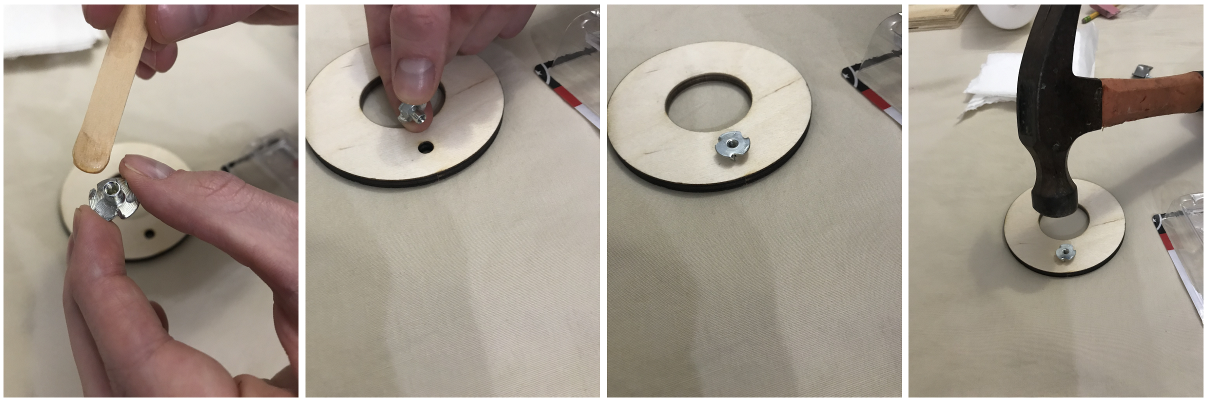


Figure C.10: Motor Retention

Apply epoxy to the spiked side of the T-nut. Hammer into hardware hold on remaining centering ring. Why do we not want to get epoxy in the threads of the T-nut?

the body tube, and push the motor mount tube into the ground, making the aft end of the motor mount tube and aft centering ring flush with the floor. Flip the assembly back over and adjust each fin so they sit 90 deg apart and square. Your goal is to get the assembly to sit flush and square without having to hold anything in place. Sand the fin slots as necessary. Once satisfied, take the assembly apart and practice assemble once more. Be thinking about where you are going to put epoxy to hold the entire unit together. See Figure C.11.

C.10 Epoxy the Motor Mount and Fin Can

Slide the motor mount tube with the two epoxied centering rings into the body tube. Align the recovery hardware with the fin marked 1. Apply a small amount of epoxy to the root of the fins. Leave one inch on either side of the root to account for drip. Place the fins in their respective slots and place the aft centering ring. DO NOT epoxy the aft centering ring into place, this is just to hold the fins in place while the epoxy sets. Flip the assembly over and make the motor mount tube flush with the floor. Flip the assembly back over. By hand, adjust the fins so they are firmly touching the motor mount tube and at 90 deg angles to each other. Let the epoxy set for 15 min.

Figure C.11: Test Assemble Fin Can and Motor Mount

Slide the motor mount assembly into the body tube, aligning the recovery hardware with fin 1. Slide in the fins, place the remaining centering ring, and make flush with the floor. Align the fins by hand, sand fin slots as necessary.

You need to be able to remove the aft centering ring for the next step so don't go crazy with the epoxy. See Figure C.12.

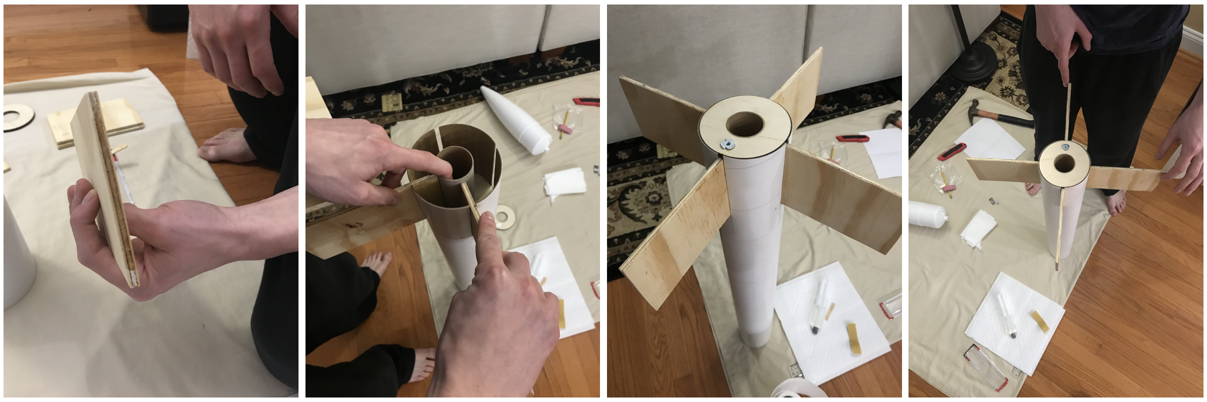


Figure C.12: Permanently Align Fins

Apply epoxy to root of the fins, leaving an inch on either end of the root. Place fins in their respective slots. Place aft retaining ring. Make motor mount tube flush with the floor. Hand align and place fins.

Remove the aft centering ring. If you are having trouble getting it out, twist the machine screw into the T-nut and use it as a small handle. Use 90% of the remaining epoxy on every joint in the fin can. This should look like an epoxy mess. Spread epoxy on the aft side of the fin anchors and the interior 1/4 in of the body tube and place the aft centering ring. Ensure the T-nut is aligned with the fin marked 3. Also, ensure the T-nut is inside the body. We have this wrong in the pictures. By placing the T-nut on the forward side of the aft centering ring, ejection forces from the motor will pull the T-nut further into the bulkhead. The way we have it in Figure C.13 is not recommended as motor ejection could rip the T-nut out of the aft bulkhead. Simply flip the aftmost centering ring over to seat it properly.

Figure C.13: Fully Assemble Fin Can Motor Mount Assembly

Apply epoxy to every joint in the motor mount fin can. Ensure epoxy runs down the entire length of every joint. Apply epoxy to the aft end of each fin anchor and place the aft centering ring. Don't go light on the epoxy.

C.11 Verification and Quick Tests

You have now completed the build! Wait 24 hr to let epoxy fully set before continuing. You can run some pretty crude tests to verify the durability of your rocket. Grab a fin and hold the rocket horizontal to the ground, only supporting the rocket by the single fin. Reach into the body tube and pull on the recovery hardware with 15 to 20 lb of force. If your rocket can withstand these crude tests as depicted in Figure C.14, you should be good to fly. Consider how to verify a design such as Hokie 0.75.

Figure C.14: Crude Verifications

Test the durability of the fins and parachute retention.

C.12 Considerations

A friendly reminder that the team's level 1 certification requirement will boost our overall experience and knowledge base. It may seem like busy work, but at the end of the day you will receive a fast tracked, low cost Level 1 HPR certification and invaluable construction experience. Here are a few things to consider to help you apply the lessons learned in this build to OLVT's larger rockets.

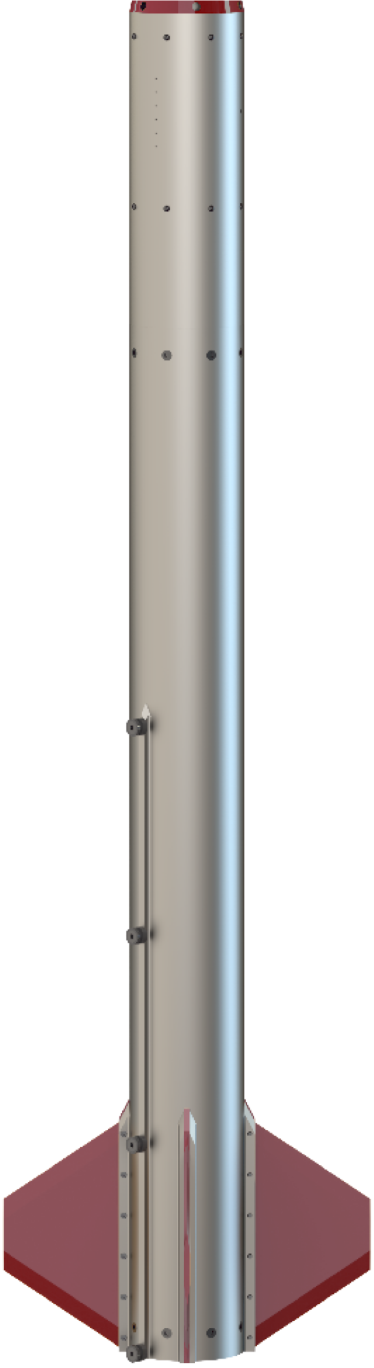
Figure C.15: Finished Build

- Will this method of fin attachment work for minimum or sub minimum diameter rockets?
- How about the recovery system and recovery harness?
- Should we use epoxy for larger builds?
- What effects would painting the rocket have in terms of performance? (paint weighs a lot!)
- If you could do this build again, what would you do differently?
- Did you deviate from the provided instructions? If so, why? We encourage you to explore alternative methods of construction!
- Could the assembly process have been better?
- How would you align the fins on a rocket with only three fins?
- How would the construction process have been different if you had access to more tools? Maybe you did have access to more tools, how did it turn out?
- Does the stability criteria (1 caliber, cg in front of cp) apply to larger rockets? How about at speeds around Mach 1 or greater than Mach 1?
- Play around with the OpenRocket file provided in the Google Drive. How does adjusting the fins change the stability margin of the rocket?
- If you used your own fins, how did you achieve stability?
- Does OpenRocket seem like a good software to simulate larger and more complex rockets? Does RASAero-II seem like a good software to simulate the certification rocket? Weigh the pros and cons of each.
- The motor has a set time delay before ejecting the parachute. Why may this method not be the best design choice for larger rockets?
- This rocket was constructed out of cardboard and wood. Consider the implications of making a rocket out of aluminum.

D. Solid Rocket Motor Classification

The universally recognized classification of solid rocket motors based on impulse. A Space Shuttle SRB is classified as an AD motor. An S motor is the largest launched by amateurs and collegiate rocketry. A Hokie 1 booster would be somewhere in the V range.

<table>
<tr><th>Designation</th><th>Impulse (Ns)</th><th>Examples</th><th>Classification</th><th>Category</th><th>Reqs</th></tr>
<tr><td>Micro</td><td>0-0.3125</td><td></td><td rowspan="10">Model Rocket</td><td>Micro</td><td rowspan="10">None</td></tr>
<tr><td>1/4A</td><td>0.3125-0.625</td><td></td><td rowspan="6">Low Power</td></tr>
<tr><td>1/2A</td><td>0.625-1.25</td><td></td></tr>
<tr><td>A</td><td>1.25-2.5</td><td>Intro to Aero gliders</td></tr>
<tr><td>B</td><td>2.5-5</td><td></td></tr>
<tr><td>C</td><td>5-10</td><td></td></tr>
<tr><td>D</td><td>10-20</td><td></td></tr>
<tr><td>E</td><td>20-40</td><td></td><td rowspan="3">Mid Power</td></tr>
<tr><td>F</td><td>40-80</td><td></td></tr>
<tr><td>G</td><td>80-160</td><td></td></tr>
<tr><td>H</td><td>160-320</td><td></td><td rowspan="8">High Power</td><td rowspan="2">Level 1</td><td rowspan="2">L1 Cert</td></tr>
<tr><td>I</td><td>320-640</td><td>Hokie 0.25 1st launch</td></tr>
<tr><td>J</td><td>640-1,280</td><td>Hokie 0.25 2nd launch</td><td rowspan="3">Level 2</td><td rowspan="3">L2 Cert</td></tr>
<tr><td>K</td><td>1,280-2,560</td><td></td></tr>
<tr><td>L</td><td>2,560-5,120</td><td>Hokie 0.5 sustainer</td></tr>
<tr><td>M</td><td>5,120-10,240</td><td>Hokie 0.5 booster</td><td rowspan="3">Level 3</td><td rowspan="3">L3 Cert</td></tr>
<tr><td>N</td><td>10,240-20,480</td><td></td></tr>
<tr><td>O</td><td>20,480-40,960</td><td></td></tr>
<tr><td>P</td><td>40,960-81,920</td><td>Hokie 0.75 sustainer</td><td rowspan="4">None</td><td rowspan="4">None</td><td rowspan="4">FAA Permit</td></tr>
<tr><td>Q</td><td>81,920-163,840</td><td>Hokie 0.75 booster</td></tr>
<tr><td>R</td><td>163,840-327,680</td><td></td></tr>
<tr><td>S</td><td>327,680-655,360</td><td>CSXT GoFast</td></tr>
</table>



Welcome,

and congratulations on joining OLVT

In an effort to rapidly educate our members in all things rocketry, the team has assembled this member's guide. Space is hard. Rockets are complicated and nothing is ever certain. We embark on these endeavors because we believe in the pursuit of adventure, in pushing the boundaries of human achievement. With confidence in your displayed character and ingenuity, we look forward to seeing what you accomplish while a member of this team.