Advanced Rocketry Workshop
NASA Student Launch Projects 2012

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What is a Rocket?

A rocket is a type of engine that pushes itself forward or upward by producing thrust. Unlike a jet engine, which draws oxygen from the outside air, a rocket engine uses only the substances carried within it. As a result, a rocket can operate in space, where there is almost no air. A rocket can produce more power for its size than any other kind of engine. For example, the Space Shuttle Main Engine weighs only a fraction as much as a train engine, but it would take 39 train engines to produce the same amount of power. The word rocket can also mean a vehicle or object driven by a rocket engine.

Rockets come in a variety of sizes. Some rockets shoot fireworks into the sky and measure less than 2 feet (60 centimeters) long. Rockets 50 to 100 feet long (15 to 30 meters) serve as long-range missiles that can be used to bomb distant targets during wartime. Larger and more powerful rockets lift spacecraft, artificial satellites, and scientific probes into space. For example, the Saturn V rocket that carried astronauts to the moon stood about 363 feet (111 meters) tall.

Rocket engines generate thrust by expelling gas. Most rockets produce thrust by burning a mixture of fuel and an oxidizer, a substance that enables the fuel to burn without drawing in outside air. This kind of rocket is called a chemical rocket because burning fuel is a chemical reaction. The fuel and oxidizer are called the propellants. A chemical rocket can produce great power because it burns propellants rapidly. As a result, it needs a large amount of propellants to work for even a short time. The Saturn V rocket burned more than 560,000 gallons (2,120,000 liters) of propellants during the first 2 3/4 minutes of flight. Chemical rocket engines become extremely hot as the propellants burn. The temperature in some engines reaches 6000°F (3300°C), much higher than the temperature at which steel melts.

Military forces have used rockets in war for hundreds of years. In the 1200's, Chinese soldiers fired rockets against attacking armies. British troops used rockets to attack Fort McHenry in Maryland during
the War of 1812 (1812-1815). After watching the battle, the American lawyer Francis Scott Key described "the rocket's red glare" in the song "The Star-Spangled Banner." During World War I (1914-1918), the French used rockets to shoot down enemy observation balloons. Germany attacked London with V-2 rockets during World War II (1939-1945). In the Persian Gulf War of 1991 and the Iraq War, which began in 2003, United States troops launched rocket-powered Patriot missiles to intercept and destroy Iraqi missiles.

Rockets are the only vehicles powerful enough to carry people and equipment into space. Since 1957, rockets have lifted hundreds of artificial satellites into orbit around Earth. These satellites take pictures of Earth's weather, gather information for scientific study, and transmit communications around the world. Rockets also carry scientific instruments far into space to explore and study other planets. Since 1961, rockets have launched spacecraft carrying astronauts and cosmonauts into orbit around Earth. In 1969, rockets carried astronauts to the first landing on the moon. In 1981, rockets lifted the first space shuttle into Earth orbit.

What is a Sounding Rocket?

A sounding rocket is an instrument carrying suborbital rocket designed to take measurements and perform scientific experiments during its flight. The rockets are commonly used to take readings or carry instruments from 50 to 200 km above the surface, the region above the maximum altitude for balloons and below the minimum for satellites. The term 'sounding' is taken from the maritime expression. Certain sounding rockets, such as the Black Brant X and XII, have an apogee between 1,000 and 1,500 km, well above Low Earth Orbit.

A common sounding rocket consists of a solid-fuel rocket motor and a payload. The flight is a simple parabolic trajectory and the average flight time is less than forty minutes. The rocket consumes its fuel on the rising part of the flight then separates and falls away, leaving the payload to complete the arc and return to the ground via a parachute.

Why Use Sounding Rockets?

**Unique Opportunities for Scientific Research:** Sounding rockets carry scientific payloads along parabolic trajectories providing near vertical traversals along their ascent and descent, while appearing to 'hover' near their apogee location. Furthermore, there are some important regions of space that are too low to be sampled by satellites (i.e., the lower ionosphere/thermosphere and mesosphere below 120 km altitude) and thus sounding rockets provide the only platforms that can carry out direct *in-situ* measurements of these regions. Astronomy, solar, and planetary science missions include sophisticated telescopes with optional joy-stick operated, sub-arc-second pointing for >5 minute continuous
observations of astronomical objects, including those too close to the sun for Hubble or EUVE observations. Microgravity missions are carried out on high altitude, free-fall parabolic trajectories which provide ideal microgravity environments without the vibrations frequently encountered on human-tendered platforms.

Low-cost Access to Space: Because the science payload does not go into orbit, sounding rocket missions do not need expensive boosters or extended telemetry and tracking coverage because NASA uses old and existing repurposed military missile motors and systems. As a result, mission costs are substantially less than those required for orbiter missions. Furthermore, because the program is managed and the payloads are built in one central location (e.g., the NASA/Wallops Flight Facility), significant savings are realized through efficient, cost-savings operations that procures parts and rocket motors in large quantities and utilizes past designs of sub-systems for follow-on missions. In other words, the sounding rocket program takes advantage of a high degree of commonality and heritage of rockets, payloads, and sub-systems flown repeatedly. In many cases, only the experiment -- provided by the scientist -- is changed. Costs are also very low because of the acceptance of a higher degree of risk in the mission (compared to orbital missions), although safety is never compromised. In some cases (such as almost all astronomy, planetary, solar, and microgravity missions), the payloads are recovered which means the costs of the experiment and sub-systems are spread out over many missions.

Rapid, quick-turn-around: Not only are sounding rocket missions carried out at very low cost, but also the payload can be developed in a very short time frame -- sometimes as quickly as 3 months! This rapid response enables scientists to react quickly to new phenomena (such as observing the Shoemaker-Levy comet impact to Jupiter) and to incorporate the latest, most up-to-date technology in their experiments.

Validating New Instruments and Developing New Technology: The sounding rocket program continues to serve as a low-cost test-bed for new scientific techniques, scientific instrumentation, and spacecraft technology, eventually flown on numerous satellite missions. The Solar Ultraviolet Magnetograph Investigation (SUMI) telescope demonstrates improved forecasts of solar flares. Technology tested here may be used onboard orbital satellite to improve the scientific data collected in space. This and other missions have enabled technology and technique development in the suborbital program.

Education: In addition to science and technology, sounding rockets also provide invaluable tools for education and training. NASA Student launch projects just concluded the pilot year for USLI Level 2 in which three university teams successfully completed a high fidelity sounding rocket mission project launching their own student built rockets at NASA Wallops and recovered them in the coastal waters of Virginia.

Summary: One of the most robust, versatile, and cost-effective flight programs at NASA for over forty years, the Sounding Rocket Program, has provided critical scientific, technical, and educational contributions to the nation's space program.
Structures Systems

Materials:
- Parts & Subassemblies
- Nose Cones
- Airframes & Couplers
- Motor Tube
- Motor Retainers
- Centering Rings & Bulk Plates
- Fins
- Rail Buttons

Construction Techniques
Design Considerations
Stability
Center of Gravity
Center of Pressure

Hands On:
Rocket Build
Synopsis

The structure of a rocket is the skeleton that everything is integrated into. It is an aerodynamically optimized shape that carries the load of all the components of the rocket and protects them from external forces throughout the flight. This section will break down all of the major structural components that make up a high powered rocket. You will learn about the materials used to build rocket parts. You will learn how to design a stable rocket using equations to determine the Center of Pressure (CP) and the Center of Gravity (CG). You will also gain hands-on experience by building and flying a rocket in the workshop.

Parts & Subassemblies

All high powered rockets have the same basic parts. From the outside of a rocket, only a few are visible. You can distinguish the nose cone, the airframe, and the fins quite easily. On the inside, there are couplers, motor tubes, centering rings, and bulk plates. Other small parts that are not initially obvious are rail buttons/launch lugs, and motor retainers.

Many of these basic parts come together to form subassemblies. A subassembly is an assembled unit designed to be incorporated with other units into a finished product. The nose cone can be considered a subassembly. Many nose cones require a bulk plate and a u-bolt or eye-bolt. An avionics bay is another example of a subassembly. Avionics bays can be built from couplers and bulk plates. A booster subassembly is an assembly built from a section of airframe, a motor tube, centering rings, bulk plates, fins, motor retainers, and sometimes couplers.
Nose Cones

The term nose cone is used to refer to the forward most section of a rocket, missile, or aircraft. The cone, a solid of revolution, is shaped to offer minimum aerodynamic resistance. On rocket vehicles, the nose cone may consist of a chamber or chambers in which a payload maybe carried. The nose cone maybe be the payload itself or used to shield the payload until ready to deploy.

The shape of the nose cone must be chosen for minimum drag. An important problem is the determination of the nose cone geometrical shape for optimum performance. Such a task requires the definition of a solid of revolution shape that experiences minimal resistance to rapid motion through a fluid medium.
General Dimensions

In all of the following nose cone shapes, \( L \) is the overall length of the nose cone and \( R \) is the radius of the base of the nose cone. \( y \) is the radius at any point \( x \), as \( x \) varies from 0, at the tip of the nose cone, to \( L \). The equations define the 2-dimensional profile of the nose shape. The full body of revolution of the nose cone is formed by rotating the profile around the centerline (C/L). Note that the equations describe the 'perfect' shape; practical nose cones are often blunted for manufacturing or aerodynamic reasons.

Conical Nose Cones

A very common nose cone shape is a simple cone. This shape is often chosen for its ease of manufacture and for its drag characteristics.

\[
y = \frac{xR}{L} = x\tan(\varphi) \quad \varphi = \arctan\left(\frac{R}{L}\right)
\]

Ogive Nose Cones

Next to the conical, the Tangent Ogive shape is the most familiar in hobby rocketry. The profile is formed by the segment of a circle such that the rocket airframe is tangent to the curve of the nose cone. The popularity of this shape is largely due to the ease of constructing its profile.

\[
\rho = \frac{R^2 + L^2}{2R}
\]

\[
y = \sqrt{\rho^2 + (L-x)^2} + R - \rho
\]

Elliptical

The profile of this shape is one-half of an ellipse, with the major axis being the centerline and the minor axis being the base. This shape is popular in subsonic flight (such as model rocketry) due to the blunt nose and tangent base. This is not normally found in professional rocketry.

\[
y = R \sqrt{1 - \frac{x^2}{L^2}}
\]
High powered rocketry (HPR) nose cones are generally constructed from fiberglass, carbon fiber, urethane, or composites of other non-metallic materials. The nose cone shoulder should be no less than one body diameter in length.

**Nosecone Drag Characteristics**

For rockets travelling under Mach 0.8, the nose cone pressure drag is essentially zero for all shapes. The major significant factor is friction drag. Friction drag is largely dependent upon the wetted area, the surface smoothness of that area, and the presence of discontinuities in the shape. For rocket flying in the subsonic region (below Mach 0.8) a short, blunt, smooth elliptical is best. In the transonic region and beyond (above Mach 0.8), where the pressure drag increases dramatically, the effect of the nose cone shape becomes highly significant. The factors influencing the pressure drag are the general shape of the nose cone, the fineness ratio, and its bluffness ratio.

The *Fineness Ratio* is the ratio of the length of the nose cone compared to its base diameter. At supersonic speeds, the fineness ratio has a significant effect on nose cone wave drag, particularly at low ratios; but there is very little additional gain for ratios increasing beyond 5:1. As the fineness ratio increases, the wetted area, and thus the skin friction component of drag, is also going to increase. Therefore the minimum drag fineness ratio is ultimately going to be a tradeoff between the decreasing wave drag, increasing friction drag, and the resulting mass of the nose cone.

The *Bluffness Ratio* describes a blunted tip, and is equal to the tip diameter divided by the base diameter. There is little or no drag increase for slight blunting of a sharp nose shape. In fact, for constant overall lengths, there is a decrease in drag for bluffness ratios of up to 0.2, with an optimum of 0.15. Most commercially made *Tangent Ogive* hobby nose cones are blunted to a bluffness ratio of about 0.1.

**Airframes & Couplers**

Rocket airframes are generally smooth thin walled cylinders with a high length to diameter ratio and encompass the rocket’s propulsion system, recovery system, electronics, and payload. On large launch vehicles, the airframe is the outer surface of large pressurized fuel and oxidizer tanks.

Generally, rockets have a nose cone fitted to the forward end of the airframe and a set of fins are mounted towards the aft end. On a *Minimum Diameter* rocket, the airframe also serves as the motor tube. This design eliminates the need for centering rings and a motor tube, but presents new challenges due to the fact that the fins must be surface mounted.

Figure 9 United Launch Alliance
High powered rocket airframes are typically made of non-metallic, high strength to weight ratio composite materials like carbon fiber, fiberglass, phenolic and PVC (NAR rules). Paper and cardboard will not handle the loads of high powered rocket motors unless they are sufficiently reinforced with composite materials.

Composite airframes can be manufactured in many different ways. Long lengths of epoxy infused fiberglass or carbon fiber cloth can be rolled around a mandrel until the layers or “plys” accumulate into a tube of desired thickness – typically 2 plys or more.

The rocket that you are building in the workshop is an example of a filament-wound fiberglass airframe. A long spool of epoxy infused fiberglass string or “tow” is wound around a mandrel in an overlapping pattern until a cylindrical tube of desired thickness is formed.

Depending on the design, your Student Launch Project may require slots through the airframe for fins. Many manufacturers will slot airframes to your specification or you can do them yourself. Generally, fin slots in airframes come one of two ways - End Slotted and Tang Slotted. For end slotted airframes, the fin slot is cut all the way to the end and the airframe can be slipped over a booster subassembly. For tang slotted airframes, the fin slot is stopped before the end of the airframe and the fins have to be epoxied on after the motor tube subassembly is installed. The rocket you will build in the workshop is tang slotted.

Custom fin slots can be made with the use of common power tools and a jig. A jig is any device used to maintain, mechanically, the correct position relationship between a piece of work and the tool.
A drill template is another type of tool you may use on your student launch project. A drill template is a printout of all airframe penetrations that can be wrapped around the airframe tube to locate and drill holes for mounting hardware such as rail buttons, centering rings, bulk plates, and fin brackets. It is a common practice in industry to use a template of sorts to keep a record of all penetrations and processes to be performed on a structure. A drill template for a high powered rocket airframe would specify both Cartesian and cylindrical coordinates of all penetrations plus callouts for drill bits, taps, and fasteners to be used. An example of a drill template is below.

On this drill template, the series of penetrations at the bottom of the airframe are designed to accept a unique surface mounted fin bracket concept that allows the fins and fin brackets to be modular and greatly improved versatility of rocket by allowing for parts to be replaceable and upgradable. This is an example of designing a multi-mission capability into a rocket.
The drill template was wrapped around and taped to the airframe tube. With the assistance of a manual mill machine and an indexing chuck, the penetrations were precisely transferred onto the airframe.

Multiple segments of airframe can be joined by using a coupler. A coupler is a tube that’s Outer Diameter (OD) is equal to the Inner Diameter (ID) of the airframe as to snugly fit inside. Generally, rocket builders follow the convention that when joining airframes with a coupler, the coupler should extend at least one airframe diameter into each joined segment. So, if you were to join two 4 inch diameter airframes, you would need a coupler at least 8 inches long.

Couplers, because of their required lengths to join airframe sections, make a good place to store electronics such as altimeters, batteries, switches, and so on. Most rocket builders use the coupler as an avionics bay. The avionics bay in the photo to the right is built from a 12 inch long coupler with a 4 inch collar in the center. The collar is a segment of airframe that is epoxied to the middle of the coupler and allows direct access to the switches that power on the altimeters. This coupler joins two airframe segments that contain the recovery system by clicking into place with quick connect snap buttons.
Motor Tubes

A motor tube is any tube inside of a rocket that is intended to fit a rocket motor. Motor tube diameters are typically called out in millimeters and refer to the size motor that they are designed to hold. A typical high powered rocket may have a 38mm, 54mm, 75mm, or 98mm motor tube.

Recall that on a Minimum Diameter rocket, the airframe is the motor tube. Generally on smaller rockets, the motor tube encompasses the entire rocket motor case. Larger rockets motor tubes may only encompass half of the motor tube with the rest freely suspended inside the rocket airframe. That is because a full length motor tube can get heavy. Some rocket designs do not use motor tubes at all. They simply axially restrain the motor front and back. This technique can increase a rocket’s mass fraction by eliminating the weight of the motor tube completely.

Motor Retainers

A motor retainer is a device that positively retains the rocket motor case inside of the rocket prohibiting it from falling out during flight. There are many commercial motor retainers available for every size motor. It is also very common for rocket builders to fashion their own motor retainer from common screws and washers from a hardware store. In this workshop, you will be provided an Aero Pack 38mm motor retainer. The Aero Pack motor retainer base epoxies to the bottom end of a motor tube. The threaded cap screws on to the base after the motor has been installed into the motor tube.
You may choose to manufacture your own method of motor retention. Commercial snap rings are a viable and cheap option to explore and can be integrated into the structures of your rocket project.
Centering Rings & Bulk Plates

*Centering rings* are used to concentrically align small tubes, like motor tubes, inside of an airframe. Centering rings can be made of many different materials and take many shapes depending on the number of inside tubes that are to be aligned. *Bulk plates* are circular disks that fit inside of tubes to separate volumes. Typically centering rings and bulk plates are either made out of plywood like birch, or from composite materials like fiberglass and serve as the mounting structure for other systems’ components like recovery hard mounts, payloads, and electronics. Typically, rocket builders use one centering ring above the fins and one below. Centering rings act as the primary load path for the motors thrust to the airframe.

Centering rings are available from almost all rocket component providers in a variety of sizes. Suppliers often have the capability to build-to-order any design you need. If not, there are some tools available at almost every hardware store that can. A properly sized hole saw and arbor from Lowes or Home Depot can make centering rings and bulk plates for your smaller projects. There are internet companies that can build to design almost any size hole saw you need. A Saber saw and a steady hand can do almost as good a job as the professionals.
Fins are flat fixed stabilizing structures extending from the body of a rocket that give stability in flight. The effectiveness of fins depends mainly on the size, shape, and surface finish. Fins can be many different shapes. Four common shapes are tapered, simple delta, cropped, and elliptic. Each fin has several features used to parametrically characterize its design. Tip chord ($c_t$), root chord ($c_r$), span ($b$), leading edge (LE), trailing edge (TE), aspect ratio (AR), and tang. Most fins are tapered or delta type due to ease of manufacturing. Also, most rocket fins are designed with low aspect ratios (AR < 4) and taper ratio ($c_t/c_r$) between 0.2 and 0.4 is ideal for minimum induced drag (δ). The tang is the part of the fin that extends inside of the airframe.

Typically fins are attached to a rocket using one of two methods – surface mounted (minimum diameter rockets) and through-the-wall. Some rockets employ removable fins. Removable fins are difficult to successfully design but you would gain multi-mission capability or just the simple ability to replace a damaged component. Typically fins are constructed of G10 fiberglass, carbon fiber, plastics, and/or plywood sheets cut to size. More complex fins are composites of two or more of these materials. The fins on the rocket in the image to the right have an Aluminum insert epoxied inside of an ABS plastic shell.
**Rail Buttons**

Most high powered rockets are launched from a rail rather than a rod and require a rail button. A rail button is a ‘H’ shaped component usually made of a hard smooth plastic, that mounts to the airframe of a rocket and slides freely inside of a channel along an extruded aluminum launch rail. This system constrains the rocket’s movement until sufficient velocity is achieved that the fins become effective for flight stability.

Rail buttons should not be an afterthought of the design process. Their location should be documented as part of the vehicles design requirement. The rocket should have one rail button near the bottom of the booster, and another near the center of gravity.
Construction Techniques

These are many construction techniques used in the construction of high-powered rockets. This section will touch on a few that you need to know about.

Through-The-Wall (TTW)

Widely used fin mounting technique where the fin tang passes through a slot in the airframe and epoxies flush against the motor tube. Epoxy fillets are applied on every side of each joint.

TTW fins are double supported cantilevers. This method shares the load distribution between shear, tension, and compression as the fin is flexed during flight. There are obvious areas of stress concentrations against the airframe and the motor tube. This is the reason you might want to consider reinforcing these areas by adding large fillets at the interface of the fin and airframe, and/or adding fiberglass reinforcements at the fin and motor tube interface.

3M Epoxy Guns

Epoxies are two-part adhesive systems that chemically react to cure and adhere materials together. Mixing the two parts together can prove to be messy. Many quick curing epoxies, like the one used in this workshop are time critical tasks that require some technique and planning to maximize use. The 3M Corp. developed the mixing epoxy applicator gun we are using in this workshop. The gun and long lengths mixing nozzle allows you to reach otherwise hard to reach areas easily and control the location and amount of epoxy applied to your rocket.
Zipper-less Design

This is a common booster design concept, where a coupler segment with a bulk plate and u-bolt is epoxied into an airframe section. The concept is that the shock cord, connecting the rocket sections to the recovery system, is allowed the most possible clearance from contacting the rocket to prevent an airframe tearing failure known as a “zipper”.

Rocket builders may use this technique on hand to replace parts like booster or avionics bays. Then if a tube does zipper, it is isolated to an easy to replace airframe segment.

Slotted Centering Rings

Slotted centering rings are an easy way to align fins and ensure a secure fit that firmly grips the entire fin tang. This centering ring below was built with a common table saw, a dado set, and a custom jig. Two perpendicular grooves were routed into a plywood centering ring. The width and depth of the groove matched the fin tang thickness. The photos below show a finished centering ring before installation and how a set of two slotted centering rings grip the four fins securely.
**Rail Button Jig**

A simple tool to accurately and quickly repeat rail button alignment can be made from a length of angled aluminum with drill bit alignment guides. The angled aluminum will align itself when laid flush on the airframe. Tape the jig in place with some masking tape. Drill the forward and aft rail button screw holes with the desired size drill bit. Small rail buttons usually use a #8 size machine screw.

**Hole Saws for bulkheads and Centering Rings**

Holesaws are great tools for making round disks of holes. There are many sizes available at hardware stores that can be used to make rocket centering rings and bulk plates. However, there are not a lot of holesaws that can make the large centering rings and bulk plates you want. There are online vendors that can custom build holesaws for you like the one in the photo to the right. The holesaw requires a drill press. Like all other power tools, use eye protection and do not wear loose-fitting clothing that can be caught by the tool.

**Cutting Airframes and Couplers**

There are several ways to cut an airframe to the required lengths. The easiest is to request them precut by the manufacturer. You may wish to purchase the full uncut length of airframe and cut it yourself. Airframes can be cut using a mitre saw or tile saw. Most mitre saws have a fence the airframe can be held against. For larger airframes the saw blade might not reach all the way through the tube. If this is the case, once the saw blade is about half way through the tube, the tube and be easily rotated slowly and safely until the entire tube is cut. Use eye protection and do not wear loose-fitting clothing that can get caught in the saw.
Stability

An object is directionally stable if it tends to return to its original direction in relation to the oncoming medium (water, air, etc.) when disturbed away from that direction. Directional stability is also called “weather vaning” because a directionally stable vehicle free to rotate about its center of mass is similar to a weather vane rotating about its pivot. Without stability, a rocket would tumble end over end, spin, or orient itself at a high angle of attack. At high angles of attack, drag forces may become excessive and the rocket may experience structural failure. Generally, a rocket is considered stable if its Center of Gravity (CG) is at least one body diameter in front of its Center of Pressure (CP). A practical approach to efficient rocket design is to allow the structural design to mature to the point where the CG location is stable (does not vary much with tweaks to the configuration) and then tailored for the desired stability margin by selecting where you want your CP to be.

Center of Gravity (CG)

The Center of Gravity of a rigid body is the mean location of all the masses in a system. The position of the CG is fixed in relation to the body and does not generally coincide with the geometric center. The CG can be determined analytically or empirically. The analytical method requires accounting for all of the individual point masses that compose the system and their location in the system as measured from a common datum plane, typically the tip of a rocket’s nose cone. The average of their positions weighted by their masses is the location of the center of gravity. The basic assumptions used in calculation of the theoretical center of gravity for this rocket are uniform gravitational field ($g = \text{constant}$) and that the components have uniform density ($\rho = \text{constant}$).

One would first tabulate the known weight and station data in a table like this one. Each component’s weight ($W_i$), for simplicity, is treated as a point mass or single force acting through the centroid of the component. In physics, the word centroid means the geometric center of the objects shape. Each component’s centroid is recorded by Station ($\bar{X}_i$) or position of the component’s centroid as measured from the tip of the rockets’ nose cone. Secondly, the tabulated data would be used to calculate the center of gravity using the center of masses equation found below.

\begin{align*}
(1) \quad \bar{X}_{CG}W_{CG} &= \sum_{i=1}^{n} W_i \bar{X}_i = W_1 \bar{X}_1 + W_2 \bar{X}_2 + W_3 \bar{X}_3 + \cdots \\
(2) \quad W_{CG} &= \sum_{i=1}^{n} W_i = W_1 + W_2 + W_3 + \cdots \\
(3) \quad \bar{X}_{CG} &= \frac{\bar{X}_{CG}W_{CG}}{W_{CG}}
\end{align*}

The empirical approach relies on observation and experience. An example of determining the CG empirically would be a simple balance method. Find the point on the rocket where it balances and you have found the Center of Gravity. It is very accurate, however, this method is not practical on very large and heavy rockets and is not useful during the design phase of your student launch project. It can be an easy check just to verify your analytical model once your rocket is complete.
The Analytical Model is the most difficult, but it is very useful during the design phase of your student launch project. Computer programs like Excel can be a powerful tool to manage point mass data and make calculating an accurate CG easy once set up. Other computer software programs, like RockSim, are available that can perform CG and stability calculations as well as flight performance simulations.

Center of Pressure (CP)

As a rocket flies through the air, aerodynamic forces act on all parts of the rocket. In the same way that the weight of all the rocket components acts through the center of gravity cg, the aerodynamic forces act through a single point called the Center of Pressure (CP). You can calculate the CP, but this is a complicated procedure requiring the use of calculus. The aerodynamic forces are the result of pressure variations around the surface of the rocket. In general, you must determine the integral of the pressure times the unit normal, times the area, times the distance from a reference line. Then divide by the integral of the pressure times the unit normal, times the area. Lots of work!

A much simpler analytical method will find the Center of Pressure (CP or \( \bar{X}_{CP} \)) by regional influence using algebraic forms of the Barrowman equations. Each primary component has a Normal Force \( (C_{n\alpha}) \) corresponding to its contribution. Each Normal Force is recorded by Station (\( X_{i} \)) or position of the component’s Normal Force as measured from the tip of the nose cone. The basic assumptions used in calculation the theoretical center of pressure for this rocket are:

- The angle of attack (\( \alpha \)) of the rocket is near zero (less than 10°)
- The speed of the rocket is much less than the speed of sound
- The air flow over the rocket is smooth and does not change rapidly
- The rocket is thin compared to its length (L >> D)
- The nose of the rocket comes smoothly to a point
- The rocket is an axially symmetrical rigid body
- The fins are thin flat plates
With these assumptions, the regional influences of the nose cone, airframe, and fins can more easily be calculated using the algebraic forms on the Barrowman Equations:

**Nose cone:**

In general, the Normal Force ($C_{Na}$) on the nose cone is identical for all shapes and always has the value 2. The Station ($\bar{X}_n$) varies with each different shape. The algebraic form equations for calculating the normal force and center of pressure for a conical nose cone are:

\[
(C_{Na})_n = 2 \quad \bar{X}_n = \frac{2}{3} L_n
\]

**Airframe:**

The Airframe provides no response for low angles of attack.

\[
(C_{Na})_a = 0 \quad \bar{X}_a = L_n + \frac{1}{2} L_a
\]

**Fins:**

The rocket’s fins contribute the bulk of the aerodynamic forces. The forces ($C_{Na}$) and Station $X_f$ for these fins are calculated using the following equations:

\[
(C_{Na})_f = \frac{4N(\frac{S^2}{B})}{1 + \left(\frac{2B}{A+B}\right)^2} \quad \bar{X}_f = X_f + \Delta X_f
\]

\[
\Delta X_f = \frac{M(A + 2B)}{3(A+B)} + \frac{1}{6} \left(\frac{A + B - \frac{AB}{A+B}}{A + B}\right)
\]

Where:
- $N$ represents the number of fins on the rocket.
- $S$ represents the span of each fin measured from the airframe to the tip.
- $D$ represents the diameter of the rocket airframe.
- $A$ represents the length of the fins root cord.
- $B$ represents the length of the fins tip cord.
- $L$ represents the length of the fin’s half cord.
Once the regional \((C_{na})\) and \((\bar{X}_n)\) values are calculated, one would place the values into a matrix like the one below. Notice that the fins have a significantly larger normal force than the nose cone.

<table>
<thead>
<tr>
<th>Component</th>
<th>Shape</th>
<th>C(_{na})</th>
<th>(\bar{X}) (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nose cone</td>
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<td>Fins (Set of 4)</td>
<td>Clipped Delta</td>
<td>6.4</td>
<td>48.9”</td>
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</table>

The total normal force is the sum of the regional forces:

\[ C_{na} = (C_{na})_n + (C_{na})_a + (C_{na})_{fb} \]

The Center of Pressure (CP) of the entire rocket is found by taking the moment balance about the nose cone tip and solving for the total center of pressure location

\[ \bar{X} = \frac{(C_{na})_n \bar{X}_n + (C_{na})_a \bar{X}_a + (C_{na})_{fb} \bar{X}_f}{C_{na}} \]

A simple empirical method is the cardboard cutout method. This method assumes that the center of pressure coincides with the centroid, or geometric center, of the rocket. Make a cardboard cutout of the rocket silhouette and find the balance point. This is an easy approximation of the area where the CP might be located. This method could be useful early on in the preliminary design of your student launch projects, but is not recommended as your primary method for determining your rockets CP.

**Static Margin**

*Static Margin* or *Margin of Stability* describes the directional stability of a rocket. Recall that an object is directionally stable if tends to return to its original direction in relation to the oncoming medium (water, air, etc.) when disturbed away from that direction and that a rocket is considered stable if its *Center of Gravity (CG)* is at least one body diameter in front of its *Center of Pressure (CP)*.

\[ S.M. = \frac{\bar{X}_{CP} - \bar{X}_{CG}}{\text{Body Diameter}} \geq 1.0 \]

Generally, it is desirable to have a static margin of 1.5 to 2.0. A rocket is considered over stable if it has a static margin of 3.0 or greater. An over stable rocket will lean or “weather vane” further into the wind and not travel as high. It is important to note that a rocket’s CG will change as the motor exhausts combusted fuel. Generally, the CG will move forward as a solid rocket motor burns, causing the rocket to become more stable. Typically, with hybrid rockets motors, the oxidizer tank is forward of the CG. As oxidizer is consumed, the rocket’s CG moves aft and there is a danger the rocket could become unstable. Also, it is important to note that as the angle of attach increases, or the rocket approaches Mach 1, the CP can change. Recall the Barrowman equation’s for rocket stability requires the angle of attack \((\alpha)\) of the rocket is near zero (less than 10°) and its speed be much less than the speed of sound.
Aerodynamic Drag

Drag refers to forces that oppose the relative motion of an object through a fluid. Types of drag are usually divided into three categories: Parasitic Drag consisting of form drag, skin friction, and interference drag, Lift-Induced drag, and Wave Drag. For high velocities, or more precisely, at high Reynolds numbers, the overall drag of a rocket is characterized by its Drag Coefficient. And is calculated using the drag equation.

\[ D = \frac{1}{2} \rho V^2 SC_d \quad (\text{Drag equation}) \]

Reynolds numbers is the ratio of inertial forces to viscous forces. More simply, it tell if the fluid flow around a rocket is Laminar (smooth) or Turbulent (rough). Laminar flow, low Reynolds numbers, is dominated by viscous forces. Flow is said to be turbulent for Reynolds numbers greater than 500,000. Turbulent flow is dominated by inertial forces which produce eddies, vortices, and flow instabilities.

\[ Re = \frac{\rho VL}{\mu} = \frac{VL}{\nu} \quad (\text{Reynolds number}) \]

(\(\mu\) = dynamic viscosity, \(\nu\) = kinematic viscosity, \(\rho\) = fluid density, \(V\) = mean fluid velocity, \(L\) = a characteristic linear dimension).
Forces on a Rocket

In flight, a rocket is subjected to four forces; weight, thrust, and the aerodynamic forces, lift and drag. The magnitude of the weight depends on the mass of all of the parts of the rocket. The weight force is always directed towards the center of the earth and acts through the center of gravity, the yellow dot on the figure. The magnitude of the thrust depends on the mass flow rate through the engine and the velocity and pressure at the exit of the nozzle. The thrust force normally acts along the longitudinal axis of the rocket and therefore acts through the center of gravity. The magnitude of the aerodynamic forces depends on the shape, size, and velocity of the rocket and on properties of the atmosphere. The aerodynamic forces act through the center of pressure, the black and yellow dot on the figure. Aerodynamic forces are very important for model rockets, but may not be as important for full scale rockets, depending on the mission of the rocket. Full scale boosters usually spend only a short amount of time in the atmosphere and have controllable nozzles (thrust vectoring).

In flight the magnitude, and sometimes the direction, of the four forces is constantly changing. The response of the rocket depends on the relative magnitude and direction of the forces, much like the motion of the rope in a "tug-of-war" contest. If we add up the forces, being careful to account for the direction, we obtain a net external force on the rocket. The resulting motion of the rocket is described by Newton's laws of motion. Although the same four forces act on a rocket as on an airplane, there are some important differences in the application of the forces:

- On an airplane, the lift force (the aerodynamic force perpendicular to the flight direction) is used to overcome the weight. On a rocket, thrust is used in opposition to weight. On many rockets, lift is used to stabilize and control the direction of flight.
- On an airplane, most of the aerodynamic forces are generated by the wings and the tail surfaces. For a rocket, the aerodynamic forces are generated by the fins, nose cone, and body tube. For both airplane and rocket, the aerodynamic forces act through the center of pressure (the yellow dot with the black center on the figure) while the weight acts through the center of gravity (the yellow dot on the figure).
- While most airplanes have a high lift to drag ratio, the drag of a rocket is usually much greater than the lift.
- While the magnitude and direction of the forces remain fairly constant for an airplane, the magnitude and direction of the forces acting on a rocket change dramatically during a typical flight.
Structures Exercise 1: Center of Pressure Calculation

This exercise will teach you to analyze your rocket’s Center of Pressure \( \overline{CP} \) or \( \bar{X}_{CP} \) by regional influence using algebraic forms of the Barrowman equations. Each primary component has a Normal Force \( (C_{n\alpha}) \) corresponding to its contribution. Each Normal Force is recorded by Station \( (\bar{X}_i) \) or position of the component’s Normal Force as measured from the tip of the nose cone. The basic assumptions used in calculation of the theoretical center of pressure for this rocket are:

- The angle of attack \( (\alpha) \) of the rocket is near zero (less than 10°)
- The speed of the rocket is much less than the speed of sound (not more than 500 mph)
- The air flow over the rocket is smooth and does not change rapidly
- The rocket is thin compared to its length \( (L >> D) \)
- The nose of the rocket comes smoothly to a point
- The rocket is an axially symmetrical rigid body
- The fins are thin flat plates

Nose cone:

In general, the Normal Force \( (C_{Na}) \) on the nose cone is identical for all shapes and always has the value 2. The Station \( (\bar{X}_n) \) varies with each different shape. The algebraic form equations for calculating the normal force and center of pressure for a conical nose cone are:

\[
(C_{Na})_n = 2 \quad \bar{X}_n = \frac{2}{3}L_n
\]

\( L_n \) is the length of the nose cone. Solve for \( (\bar{X}_n) \) and enter the values into the solution matrix.

Airframe:

The Airframe provides no response for low angles of attack.

\[
(C_{Na})_a = 0 \quad \bar{X}_a = L_n + \frac{1}{2}L_a
\]

\( L_a \) is the length of the airframe. Solve for Station \( (\bar{X}_a) \) and enter the values into the solution matrix.

Fins:

The rocket’s four fins contribute the bulk of the aerodynamic forces. The forces \( (C_{Na})_f \) and Station\( \bar{X}_f \) for these four fins are calculated using the following equations:
The rocket’s fin dimensions are shown below. Solve for \( (C_{Na})_f \) and \( \bar{X}_f \).

Solution:
Calculating for the normal force of the fins \( (C_{Na})_f \):

\( N \) represents the number of fins on the rocket. The rocket you are analyzing has 4 fins (\( N=4 \)).

\( S \) represents the span of each fin measured from the airframe to the tip. (\( S = 2.6” \))

\( D \) represents the diameter of the rocket airframe. (\( D = 2.6” \))

\( A \) represents the length of the fins root cord. (\( A = 6” \))

\( B \) represents the length of the fins tip cord (\( B = 2.6” \))

\( L \) represents the length of the fins half cord (\( L = 4” \) measured empirically)

An interference factor must be used to correct for the presence of the airframe. The algebraic form equation to correct for this airframe interference is:

\[
K_{fb} = 1 + \frac{r}{s+r} \quad (C_{Na})_{fb} = K_{fb} (C_{Na})_f
\]

\( R \) is the radius of the airframe and \( S \) is the span of the fin.
Solution:

Calculating the center of pressure of the fin's $\bar{X}_f$:

$X_t$ represents the distance from the tip of the nose cone to the forward root of the fins.

$\Delta X_f$ represents the distance from the forward root of the fins to the fins center of pressure.

Enter the values for $(C_{n\alpha})_f$ and $\bar{X}_f$ into the matrix on sheet 3.

Center of Pressure Solution Matrix:

<table>
<thead>
<tr>
<th>Component</th>
<th>Shape</th>
<th>$C_{n\alpha}$</th>
<th>$\bar{X}$ (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nose cone</td>
<td>Ogive</td>
<td>2</td>
<td>5.7”</td>
</tr>
<tr>
<td>Airframe</td>
<td>Cylindrical</td>
<td>0</td>
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<tr>
<td>Fins (Set of 4)</td>
<td>Clipped Delta</td>
<td>6.4</td>
<td>48.9”</td>
</tr>
</tbody>
</table>

The total normal force is the sum of the regional forces:

$$C_{n\alpha} = (C_{n\alpha})_n + (C_{n\alpha})_a + (C_{n\alpha})_f$$

Solution:

The Center of Pressure (CP) of the entire rocket is found by taking the moment balance about the nose cone tip and solving for the total center of pressure location

$$\bar{X} = \frac{(C_{n\alpha})_n \bar{X}_n + (C_{n\alpha})_a \bar{X}_a + (C_{n\alpha})_f \bar{X}_f}{C_{n\alpha}}$$

Solution:
Structures Exercise 2: Center of Gravity Calculation

This exercise will teach you to analyze your rocket’s Center of Gravity \( (CG \ or \ \bar{X}_{CG}) \) using the Center of Masses equation.

\[
\bar{X}_{CG} W_{CG} = \sum_{i=1}^{n} W_i \bar{X}_i = W_1 \bar{X}_1 + W_2 \bar{X}_2 + W_3 \bar{X}_3 + \ldots
\]

\[
W_{CG} = \sum_{i=1}^{n} W_i = W_1 + W_2 + W_3 + \ldots
\]

\[
\bar{X}_{CG} = \frac{\bar{X}_{CG} W_{CG}}{W_{CG}}
\]

Each component’s weight \( (W_i) \), for simplicity, is treated as a point mass or single force acting through the centroid of the component. In physics, the word centroid means the geometric center of the objects shape. Each component’s centroid is recorded by Station \( (\bar{X}_i) \) or position of the component’s centroid as measured from the tip of the nose cone. The basic assumptions used in calculation the theoretical center of gravity for this rocket are:

- Uniform gravitational field \( (g = \text{constant}) \)
- Components have uniform density \( (\rho = \text{constant}) \)

Each component’s Weight \( (W_i) \) and Station \( (\bar{X}_i) \) is shown in table below. Solve for the rocket’s Center of Gravity using the data in table below and the Center of Masses equation.

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight ( (W_i) ) (oz.)</th>
<th>Station ( (\bar{X}_i) ) (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiberglass Nose cone</td>
<td>3.4</td>
<td>6.5</td>
</tr>
<tr>
<td>Nose cone Mass</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>G10 Nose cone Bulkplate</td>
<td>0.3</td>
<td>10.5</td>
</tr>
<tr>
<td>Nose cone Eye-Bolt</td>
<td>0.8</td>
<td>10.5</td>
</tr>
<tr>
<td>Pre-slotted Fiberglass Airframe</td>
<td>7.7</td>
<td>21</td>
</tr>
<tr>
<td>12' Shock Cord</td>
<td>2</td>
<td>18</td>
</tr>
<tr>
<td>30” Parachute</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>9x9 Chute Protector</td>
<td>0.5</td>
<td>18</td>
</tr>
<tr>
<td>Forward G10 Centering Ring</td>
<td>0.2</td>
<td>26</td>
</tr>
<tr>
<td>Forward Centering Ring Eye-Bolt</td>
<td>0.2</td>
<td>26</td>
</tr>
<tr>
<td>38mm Motor Tube</td>
<td>2.3</td>
<td>31</td>
</tr>
<tr>
<td>G10 Fins (4x)</td>
<td>1.9</td>
<td>31</td>
</tr>
<tr>
<td>Aft Centering Ring</td>
<td>0.2</td>
<td>34</td>
</tr>
<tr>
<td>Aero Pack 38mm Motor Retainer</td>
<td>0.8</td>
<td>34</td>
</tr>
<tr>
<td>CT1 Pro 38-2G Case</td>
<td>3.5</td>
<td>30</td>
</tr>
<tr>
<td>CTI H225 Motor Reload</td>
<td>6.8</td>
<td>30</td>
</tr>
</tbody>
</table>
Solution:
Structures Exercise 3: Stability Calculation

This exercise will teach you to calculate your rocket’s Static Margin. The Static Margin or Margin of Stability is a non-dimensional characteristic that describes the directional stability of a rocket.

\[ S.M. = \frac{X_{CP} - X_{CG}}{\text{Body Diameter}} \]

A rocket is generally considered stable if it has a margin of 1.0 or greater. The ideal Stability Margin is 1.5 to 2.0. Calculate the Static Margin of your rocket:

Solution:
Propulsion Systems

Materials:

Propulsion Theory
Solid Rocket Motors
Definition of HPR
Motor Classifications
Commercially Certified Motors
Thrust to Weight
Thrust Curves
Ballistics Coefficients
Trajectory Analysis
Propulsion Exercises
Demo: Static High Power Motor Test
Propulsion Theory

Traditional propulsion systems rely on thermodynamic expansion of a supersonic gas to produce thrust. Non-traditional propulsion systems still rely on Newton, but get creative in how they produce thrust.

Propulsion systems:

- Store propellants
- Move propellants into a combustion chamber
- Burn propellants to raise their energy and pressure
- Expand the combustion gases through a converging-diverging nozzle to achieve high exit velocities

Newton’s Laws

Rocket science is grounded in fundamental laws of physics & thermodynamics. Newton’s Laws (published in 1687) established the phenomena known as inertia, force, and action/reaction.

- 1st Law: Objects in motion/rest will remain in that state until acted on by an outside force.
- 2nd Law: Acceleration of an object is proportional to the sum of the external forces & inverse to mass.
- 3rd Law: Action/Reaction: Two bodies interact with equal and opposite force.

The 2nd Law provides the definition of the force used in the 1st and 3rd law. It becomes the backbone of the discussion of rocket propulsion.

\[ F = ma \quad (Newton’s \ 2nd \ Law) \]

Force equals mass times acceleration. By definition, acceleration is the derivative of velocity with respect to time. By application, the mass of the vehicle changes over time with the expulsion of propellant. So, what Newton is really saying is:

\[ F = m(t) \frac{du}{dt} \quad (Newton’s \ 2nd \ Law – rewritten) \]

Momentum equals mass times velocity, therefore force equals change in momentum with respect to time. Another way to say this is that thrust equals change in momentum of a vehicle.

\[ F = \frac{d}{dt} (mu) \quad (Momentum = mu) \]
Thrust

Thrust is a force produced by the expulsion of matter at high velocities. It is the force produced by a spacecraft’s propulsion system which changes that spacecraft’s momentum. Thrust comes from two main physical phenomena:

- Momentum exchange between exhaust & vehicle.

\[ T_{mom} = \dot{m}u_e \]

- Pressure imbalance at nozzle exit plane. \( P_2 \) is the pressure of the gases at the exit plane of the rocket motor’s nozzle. \( P_3 \) is the ambient atmospheric pressure.

\[ T_{press} = A_e(P_2 - P_3) \]

So the total thrust equation is:

\[ Thrust = \dot{m}u_e + A_e(P_2 - P_3) \]

All of these variables depend on the design of the nozzle.

Figure 18 Solid rocket engine diagram from Glenn Research Center

Total Impulse

Impulse is the work done by the propellant and is typically measured in units of Newton-seconds. The impulse parameter is used to categorize different classes of rocket motors in hobby rocketry. Impulse can be calculated for both variable and constant thrust rocket motors.
\[ I = \int_0^t T \, dt = T_{\text{avg}} t_{\text{burn}} = \int m V_{\text{eq}} \, dt = m V_{\text{eq}} \]  
(Total Impulse Equation)

The Thrust \(T\) and Total Impulse \(I\) equations above work for both liquid and solid rocket motors.

**Specific Impulse (Isp)**

*Specific impulse (Isp)* is an efficiency parameter like miles per gallon. It is a measure of the work per unit mass of propellant. The units of specific impulse are the same whether we use English units or metric units.

\[
\frac{\text{Work we want to do}}{\text{Propellant we use to do it}} = \frac{\text{Impulse}}{\text{Propellant Mass}} = \text{miles/gallon}
\]

\[ I_{\text{sp}} = \frac{I}{mg_0} = \frac{V_{\text{eq}}}{g_0} = \frac{V_e + \frac{(P_e - P_0) A_e}{m}}{g_0} \]  
(Specific Impulse)

Why are we interested in specific impulse? It shows the tie between engine parameters and propulsion thermodynamic parameters like exit velocity. The result of our thermodynamic analysis is a certain value of specific impulse. The rocket weight will define the required value of thrust. Dividing the thrust required by the specific impulse will tell us how much weight flow of propellants our engine must produce. This information determines the physical size of the engine. It is an indication of engine efficiency. Two different rocket engines have different values of specific impulse. The engine with the higher value of specific impulse is more efficient because it produces more thrust for the same amount of propellant. **HPR solid rocket motors generally have an Isp between 170 sec and 220 sec.** It gives us an easy way to "size" an engine during preliminary analysis.

**Rocket Equation (Tsiolkovsky’s Equation)**

The *Rocket Equation (Tsiolkovsky’s Equation)* is essentially a reordering of Newton’s 2\textsuperscript{nd} Law that relates the maximum change of speed of a rocket (assuming no other external forces) to the effective exhaust velocity \(v_e\) of the combustion gases and the initial and final mass of a rocket.

\[ \Delta V = v_e \ln \left( \frac{m_i}{m_f} \right) = I_{\text{sp}} g_0 \ln \left( \frac{m_i}{m_f} \right) \]

Rocket trajectory programs use Tsiolkovsky’s idea rocket equation with additional parameters to take into account gravity and drag penalties:

\[ \Delta V_{\text{modified}} = I_{\text{sp}} g_0 \ln \left( \frac{m_i}{m_f} \right) - \text{gravity penalty} - \text{drag penalty} \]

The Ideal rocket equation can be re ordered to solve for the amount of propellant needed to provide a required \(\Delta V\).
$m_{prop} = m_i \left(1 - \exp\left(\frac{-\Delta V}{g_0 l_{sp}}\right)\right) = m_f \left(\exp\left(\frac{\Delta V}{g_0 l_{sp}}\right) - 1\right)$

**Solid Rocket Motors (SRMs):**

The earliest solid rockets were used by the Chinese, Mongols, and Arabs in warfare as early as the 13th century. SRMs are widely used in military applications because they can remain in storage for long periods and they reliably launched on short notice. Typical space exploration applications of SRMs include the launch vehicle booster, kick stages for geosynchronous and interplanetary spacecraft, and braking motors for interplanetary spacecraft. SRMs are simpler in design than liquid or hybrid motors. Every solid rocket motor has a nozzle, a combustion chamber, solid propellant, and an igniter. The fuel itself acts as part of the combustion chamber. More complicated SRMs have a thrust vector control (TVC) system that steers the rocket. **SRMs are extensively used where total impulse requirement is known accurately in advance and where no restart is required.**

SRMs use solid propellants to provide the combustion that drives thrust. Oxidizer and fuel are stored in a combustion chamber in solid form. Solid propellant carries mechanical loads in addition to providing thrust. When propellants are ignited, they burn in place.

There are two types of SRMs in sport rocketry - black powder and composite propellant. Black powder motors are typically used for low power applications and are end burners (the propellant burns from one end to the other.) Composite motors are typically used for HPR motors. **Composite propellants are heterogeneous grains with crystalline oxidizer and powder fuel tied together with a chemical binder.**
Composite propellant ingredients are:

- **Inorganic Oxidizers**
  - Most common is Ammonium Perchlorate (AP)
  - Toxic chlorine gas in exhaust
- **Fuels**
  - Most common is Powdered Aluminum
  - Causes exhaust smoke
- **Binders**
  - Serves dual purpose as fuel and binder
  - Common binders are HTPB, PBAN
- **Contain small amounts of chemical additives to improve physical properties**
  - Burn rate, smooth burning, casting characteristics, structural properties, absorb moisture during storage

Some additives can make the motor burn different colors. Motors like the CTI Skidmark add titanium flakes that burn brightly and create lots of noise and a shower of sparks.

**Definition of a High Powered Rocket**

Rockets use a propulsive device called a rocket motor that generates thrust by exhausting hot gases at high velocities. The momentum of the hot exhaust gases produces a net force in the opposite direction causing the rocket to move upwards. This happens because the rocket obeys *Newton’s 3rd Law of Motion*, which states that for every action there is an equal and opposite reaction.

A rocket exceeds the definition of a model rocket under NFPA 1122 and becomes a high powered rocket under NFPA 1127 if it:

- Uses a motor with more than 160 Newton-seconds of total impulse (and ‘H’ motor or larger) or motors that all together exceed 320 Newton-seconds
- Uses a motor with more than 80 Newtons average thrust (see rocket motor coding)
- Exceeds 62.5 grams of propellant
- Weighs more than 1,500 grams including motor(s)
- Includes any airframe parts of ductile metal
Rocket Motor Classifications:

HPR motors approved for sale in the United States are stamped with a two-part code that gives some basic information about the motor’s power and behavior: A letter specifying the total impulse ("H"), and a number specifying the average thrust ("225"). *Average thrust* is a measure of how slowly or quickly the motor delivers its total energy, and is measured in Newtons. *Total impulse* is a measure of the overall total energy contained in a motor, and is measured in Newton-seconds.

<table>
<thead>
<tr>
<th>Impulse Class</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>H 160.01Ns to 320.01Ns</td>
<td>Level 1</td>
</tr>
<tr>
<td>I 320.01Ns to 640.00Ns</td>
<td>Level 1</td>
</tr>
<tr>
<td>J 640.01Ns to 1280.00Ns</td>
<td>Level 2</td>
</tr>
<tr>
<td>K 1280.01Ns to 2560.00Ns</td>
<td>Level 2</td>
</tr>
<tr>
<td>L 2560.01Ns to 5120.00Ns</td>
<td>Level 2</td>
</tr>
<tr>
<td>M 5120.01Ns to 10240.00Ns</td>
<td>Level 3</td>
</tr>
<tr>
<td>N 10240.01Ns to 20480.00Ns</td>
<td>Level 3</td>
</tr>
<tr>
<td>O 20480.00Ns to 40960.00Ns</td>
<td>Level 3</td>
</tr>
</tbody>
</table>

HPR motors cannot be purchased over the counter. Members must be certified by either the National Association or Rocketry (NAR) or the Tripoli Rocketry Association (TRA) to the appropriate level to purchase motors from vendors. As part of this workshop, you will be certified NAR Level 1 pending a successful flight. You can then purchase ‘H’ and ‘I’ motors, and one ‘J, K, or L’ on the day you intend to certify Level 2. To certify Level 2, you must pass a written test as well as conduct a successful flight.

Commercially Certified Motors

You are required to use a certified commercially manufactured motor for your NASA Student Launch Project. The certifying agencies are the National Association or Rocketry (NAR), Tripoli Rocketry association (TRA), and Canadian Association of Rocketry (CAR). Some of the more popular solid rocket motor manufacturers are Cesaroni Technology Inc. (CTI) and Aerotech (AT). Each manufacturer produces a wide variety of commercially certified rocket motors in all different impulse and thrust ranges.

Reloadable solid rocket motor systems are composed of a reusable motor case and a reload kit. All HPR motor cases come standard in 38mm, 54mm, 75mm, and 98mm diameters. Most cases have three standard parts: the case, a forward closure, and an aft closure. Some cases have a forward closure build in and have a removable aft closure where the reload is loaded from. The closures are usually interchangeable between cases of same diameter but in different lengths.

Solid rocket motor reload kits include the assembly instructions, the propellant, the nozzle, and all other one-time use hardware for the flight. A typical reload kit will include a phenolic or paper liner that acts as thermal protection for the motor case, a series of O-rings that will seal the reload inside of the motor case, a set of phenolic disks that act as thermal protection for the aft and forward closures.

Figure 19 Aerotech Motor Assembly
a delay grain for the motor ejection charge or a tracking smoke element if the motor does not use an ejection charge, and an igniter. You will also need o-ring grease for the assembly of the reload. It is very important not to deviate from the manufacturer’s direction for motor assembly.

Thrust to Weight:

In order for a rocket motor to lift a rocket, it must produce enough thrust to overcome the force of gravity. This means a rocket motor, at a minimum, must produce enough mechanical energy to achieve a **Thrust to Weight Ratio** of just over 1.0. The Space Shuttle has a thrust to weight ratio of 1.5 as it leaves the launch pad. But nearly 90% of the Space Shuttle is propellant and that ratio quickly rises as fuel is consumed. NASA Student Launch Projects will require that your rocket have a thrust to weight of no less than 5:1. That means the rocket motor must produce 5 times the force of the weight of your rocket. So if your rocket weighs 20 lbs, then the motor needs to produce at least 100 lbs. of thrust.
Thrust Curves:

Thrust curves are obtained experimentally for solid rocket motors by placing the motor on a test stand, igniting the propellant, and recording the thrust as a function of time. This allows you to know how the motor will perform when placed in your rocket. Total impulse is most accurately determined by calculating the area under the curve. Average thrust is calculated as the total impulse divided by the burn time. Burn time is generally considered the time when thrust drops below 5% of the maximum thrust.

\[ F = \frac{\int F \, dt}{t_b} \quad \text{(Average Impulse)} \]

\[ I = \int F \, dt \quad \text{(Total Impulse)} \]

A thrust curve can also show whether a motor has a regressive, progressive, or neutral burn profile. Thrust varies directly with the surface area of propellant being combusted. As surface area increases, thrust increases and the motor is said to be progressive. As surface area decreases, thrust decreases and the motor is said to be regressive. If a motor’s thrust varies 10% or less from the average, then the motor is said to have a neutral burn. The thrust curve to the top right shows a regressive motor burn. The thrust slowly tapers off until burn out. The thrust curve to the bottom right shows an aggressive motor for the first half of the burn, and then regressive for the rest of the burn. What type of burn profile does the thrust curve at the top of the page have?
Ballistics Coefficient

Three parameters that characterize a rocket’s performance can be reduced to a single parameter called the Ballistics Coefficient ($\beta$). The ballistics coefficient of a body is a measure of its ability to overcome air resistance in flight. It is inversely proportional to the deceleration—a high number indicates a low deceleration. BC is a function of mass, diameter, and drag coefficient. Considering the expected vehicle physical parameters, a range of $\beta$ values can bracket the influences of the physical parameters of the rocket.

$$\text{Ballistics Coefficient: } \beta = \frac{W_f}{Sc_{D}}$$

Using the ballistics coefficient associative parameter, three rocket parameters can be traded simultaneously. It is a convenient way to objectively consider what size your rocket should be. For example, assume you rocket needs a ballistics coefficient of between 2.5 and 3.0 in order to have enough energy to reach an altitude of one mile. Assume that your rocket will have an average drag coefficient of 0.5. If you look at the red band in the plot below, you can make an association between the diameter and the weight of your rocket. A 5” diameter rocket could weigh between 24lbs and 30 lbs. A 6” diameter rocket could weigh between 35lbs and 42lbs.
Trajectory Analysis

You are required to perform a trajectory analysis for your student launch project. There are many commercial software packages (some free) available to help you, but you can also write your own code if you like. Below is an example of a completed trajectory analysis. The analysis displays important events in the flight like maximum altitude, velocity, and acceleration. It may also display the rockets recovery events and descent rate.

![A2 Mission Flight Data - Feb 13, 2011](image)

Propulsion requirements

The first step in performing analysis should be to review and identify all of the project requirements that apply. For example, the target altitude of one mile above ground level would be one. Another would be the restrictions on class of motors you can use. Also, there may be other requirements you might want to impose on yourself. Once you draw the box around the problem, it is easier to continue with the analysis.

<table>
<thead>
<tr>
<th>Requirement #</th>
<th>Description of Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>One mile AGL target altitude</td>
</tr>
<tr>
<td>16(SLI), 17(USLI)</td>
<td>Commercially certified motors</td>
</tr>
<tr>
<td>17(SLI)</td>
<td>SLI-restricted to K-class and lower motors</td>
</tr>
<tr>
<td>18 (USLI)</td>
<td>USLI-restricted to L-class and lower motors</td>
</tr>
<tr>
<td>Custom #1</td>
<td>Minimum thrust/weight of 5:1</td>
</tr>
</tbody>
</table>

There may be many more requirements in the NASA Student Launch Project’s Statement of Work (SOW), so review the book carefully. There may be requirements you impose on yourself that are specific to the experiment you want to fly (G-loads, target velocities, etc).
Commercial Software Packages

The easiest way to perform a trajectory analysis is to purchase a commercially produced trajectory analysis program like RockSim, or RASAero. There are also free software packages available like OpenRocket. These programs have simple CAD programs that allow a user to build a model of the rocket in the program. The programs can help calculate many rocket parameters like weight, length, and stability in addition to performing a three degrees of freedom (3DOF) flight analysis.

These commercial programs offer the user a lot of control over the simulation environment also. The user can manipulate the winds, the launch angle, temperature, and many other parameters to match the simulation environment to the real world.

Links to Commercial Software Packages:

- RockSim:  http://www.apogeteckets.com/rocksim.asp
- RASAero:  http://rasaero.com/
- OpenRocket:  http://openrocket.sourceforge.net/
Custom Software Programs

It is entirely possible to write a trajectory program using the material covered in this workshop. The pieces are all there, and with a good understanding of how to write some visual basic code, anyone could write an excel VBA macro to perform the analysis. It takes a lot of work and troubleshooting to get it right, but this approach hammers home the equations and theories behind rocket propulsion and aerodynamics.

Much of the analysis begins with reducing all variable depended inputs to parametric equations that can be written to the macro. An example of this is a motor thrust curve. The easiest way to write the analysis software is a looping analysis where time is incremented forward; usually in one second intervals. Every variable is again calculated using the variable values from the previous iteration. With regard to the motor thrust curve, the curve was reduced to fitted trend line; usually a high order polynomial equation.

![CTI N3400 Propellant Performance Data](image)

Now, the thrust and mass of the motor is known at every second through the burn. Other parametric variables are:

- Drag coefficient as a function of mach number
- Air Pressure and Density and a function of altitude and temperature
- Wind speed and direction
- Speed of sound

These equations get used in an iterative loop that steps forward in one second intervals.
Sample Trajectory Code:

* Initialize Loop

For SS = SZ To SL

* Calculate Motor Thrust, Mass, and Rocket C.G. and Moment of Inertia

If Worksheets("System Data").Range("B24").Value = "M3400" Then

If SS < Worksheets("System Data").Range("B26").Value Then

TT = (-173.55 * SS ^ 6) + (1305.3 * SS ^ 5) - (3582.3 * SS ^ 4) + (4326.7 * SS ^ 3) - (2212.6 * SS ^ 2) + (449.04 * SS) + 753.76

WP = (0.2094 * SS ^ 3) - (0.7857 * SS ^ 2) - (3.1239 * SS) + 10.501

CG = (0.0263 * SS ^ 3) - (0.244 * SS ^ 2) - (0.5175 * SS) + 58.655

II = Worksheets("System Data").Range("B27") + (59.847 * SS ^ 4) - (253.73 * SS ^ 3) + (159.26 * SS ^ 2) - (1755.3 * SS) + 5681.8

Else

TT = 0

WP = 0

II = Worksheets("System Data").Range("B27")

End If

* Calculate Weight of Rocket

WR = Worksheets("System Data").Range("B23") + WP

* Calculate Delta Velocity Vacuum

AX = VX + (GR * TT / WR) * Cos(LA)

AY = VY + (GR * TT / WR) * Sin(LA)

VV = Sqr(AX ^ 2 + AY ^ 2)

* Calculate Mach Number

MA = (VV / AA)

* Calculate Drag Coefficient (Jared Greens CDR phase CD vs Mach Analysis)

If MA < 0.9 Then
The code will output all calculated data into a large spreadsheet, which can be used to create plots that display useful information about the rocket design performance. The performance can be reviewed and checked against the initial propulsion and vehicle design requirements. Design changes can be made until all requirements are met.
**Propulsion Exercise 1: Thrust Curve**

This exercise will teach you to read a thrust curve plot and identify the motor you will be flying on. A thrust curve is obtained experimentally for solid rocket motors by placing the motor on a test stand, igniting the propellant, and recording the thrust as a function of time. This allows you to know how the motor will perform when placed in your rocket. The chart below is a thrust curve plot for the motor that you will be flying in your workshop rocket.

Total impulse is most accurately determined by calculating the area under the curve. Average thrust is calculated at the total impulse divided by the burn time. Burn time is generally considered the time when thrust drops below 5% of the maximum thrust.

Using the thrust curve plot, determine the following:

1. **Burn Time (s):**
2. **Maximum Thrust (N):**
3. **Average Thrust (N):**

Using the determined values, calculate the following:

1. **Total Impulse (N-s):**
2. **Impulse Class (Alpha):**
3. **Motor Designation:**

<table>
<thead>
<tr>
<th>Impulse Class</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>160.01Ns to 320.01Ns</td>
</tr>
<tr>
<td>I</td>
<td>320.01Ns to 640.00Ns</td>
</tr>
<tr>
<td>J</td>
<td>640.01Ns to 1280.00Ns</td>
</tr>
<tr>
<td>K</td>
<td>1280.01Ns to 2560.00Ns</td>
</tr>
<tr>
<td>L</td>
<td>2560.01Ns to 5120.00Ns</td>
</tr>
<tr>
<td>M</td>
<td>5120.01Ns to 10240.00Ns</td>
</tr>
</tbody>
</table>
If your rocket weights 2.6 lbs, calculate the thrust to weight ratio: (4.45 N = 1 lbf)
Propulsion Exercise 2: Delta-V Calculation

This exercise will help you practice calculating the ΔV of a rocket using data about the rocket you are building and the motor you will certify on. The basic assumptions used in the ideal rocket equation calculation are:

1. The rocket is operating in space (no drag or gravity penalties).
2. The gravitational constant ($g_0$) is constant throughout the universe.
3. The motor is instantly on and off (no throttling up or tailing off).

Given the following parameters:

$$I_{sp} = 216.6 \text{ s} \quad g_0 = 32.2 \text{ ft/s}^2 \quad m_i = 2.6 \text{ lbm}$$

$$m_p = 0.28 \text{ lbm} \quad m_f = m_i - m_p \quad \Delta V = \sqrt{2} \ln \left( \frac{m_1}{m_f} \right) = I_{sp} g_0 \ln \left( \frac{m_i}{m_f} \right)$$

Calculate the following:

1. $\Delta V$
2. $v_e$

Solution:
Propulsion Exercise 3: Ballistics Coefficient Calculation

This exercise will help you practice determining the ballistics coefficient of a rocket.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>2.6 lbs</td>
</tr>
<tr>
<td>Drag Coefficient</td>
<td>0.5</td>
</tr>
<tr>
<td>Diameter</td>
<td>2.6 in</td>
</tr>
</tbody>
</table>

Determine $\beta$:

$\text{Ballistics Coefficient: } \beta = \frac{W_f}{SC_D} = \frac{W_f}{\frac{\pi}{4}D^2C_D}$

Solution:
Recovery Systems

- Parachutes
- Parachute Protectors
- Shock Cords
- Quick Links

Single Event Recovery Systems
Dual Event Recovery Systems

Perfectflite MAWD
Batteries
Switches
Ejection Charges
E-Matches
Shear Pins

Parachute Selection
Parachute Folding Instruction
Parachute Care

Recovery Exercises

Demo:
Ejection Charge Test

Hands On:
Parachute Folding
High-powered rockets are required to have a recovery system. This section will help teach you how to design a recovery system for your Student Launch Projects. You will learn about the hardware needed to build a recovery system, how to apply Newton’s 2nd Law of Motion to calculate the size parachute needed to safely recover your rocket and how to use the Ideal Gas Law to appropriately size black powder ejection charges to deploy your recovery systems. This section will also cover the electronics you will use to control the recovery system, and how to test that system safely on the ground.

Recovery Hardware

There are four primary hardware components common to most traditional rocket recovery systems:

1. Parachutes
2. Parachute Protectors
3. Recovery Harness
4. Quick Links

This section details each component. You will learn the purpose of each component, general material selections, and construction. Later in this section, you will learn how to appropriately select hardware for your rocket project.

Parachutes

Parachutes are the most commonly used recovery device in high powered rocketry. A parachute is a high drag device that retards the high speed descent of the rocket by producing a force that opposes the weight of the rocket. The effectiveness of a parachute depends on velocity, air density, surface or “reference” area, and a drag coefficient. A drag coefficient is a dimensionless quantity that is used to quantify the drag of resistance of an object in a fluid environment such as air. For non-streamline objects like parachutes, the drag coefficient can be greater than 1.

High-powered rocketry parachutes typically have three major features.

1. Canopy
2. Support lines
3. Steel connector link

Figure 14 Model Patriot with drogue and main chute deployed
The canopy is made of several rip-stop nylon cloth panels, or gores, sewn together to form a round, cruciform, annular, or other shape. The support lines are attached to the outer edge of the canopy. The steel connector link gathers all the support lines together and can be connected to the rocket’s recovery harness. Most of these connectors also have a swivel built in to aid in stability. Some parachute have an apex vent; a small hole in the top of the canopy that allows small amounts of air to spill out from the top of the canopy adding to its stability. Otherwise the parachute will rock from side to side to dump air out from the bottom sides of the canopy which would cause the rocket to swing like a pendulum.

Parachute Protectors

Nylon cloth is susceptible to melting and charring. It is necessary to protect your recovery system from the hot gases and any burning debris that are generated by the ejection charge. A flameproof Aramid cloth or Kevlar cloth will protect the parachute from these hot gases and burning debris. Other options include deployment free bags (D-bags). D-bags provide parachute and support line protection and can insure a reliable and orderly deployment. Great care should be taken to not tightly wrap the parachute with both techniques.

Recovery Harness

A “recovery harness” is a generally long length of static cord that attaches structural components that separate as part of the recovery system. Typical materials for a recovery harness are Aramid/Kevlar, Kevlar/Fiberglass, and nylon. Each end is typically secured by quick-link to a u-bolt or eye-bolt that is rigidly mounted to a bulkplate on an avionics bay, nose cone, or booster. The main parachute is generally attached to a loop in the shock cord tied just below the nose cone by a quick-link. The length of recovery harness required will be the subject or empirical testing and evaluation. Your workshop rocket has 12 feet of shock cord. An L3 type rocket may require more than 100 feet of shock cord.
The recovery harness can be bundled into groupings using rubber bands or masking tape. This technique helps to dissipate the momentum of the separating components when they are ejected. In the photo above, the shock cord was bundled into four 10 feet long lengths that were folded in 8” - 10” lengths and wrapped a couple of times with masking tape. During deployment, energy is used up to tear the tape to release more cord. This technique performed very well in flight dissipating momentum of the two 25 lbm rocket sections that were ejected at 200 lbf before the shock cord became taught. Recall that nylon is susceptible to melting and charring. Take measures to protect nylon cords and inspect all shock cords before flights.

**Quick-links:**

Quick-links make connecting and rigging a recovery system very easy. There are many different types of quick links available commercially. Always use quick-links with a locking gate. Also, the by-products of black powder ejection charges are acidic. While zinc-plated steel quick-links are safe for many flights, inspect the levels of corrosion and clean all metallic hardware between flights. Take care in choosing a quick-link that will safely carry the maximum expected load that will be experienced. Too small of a quick-link may yield under heavy loading when the main parachute opens.

The quick links attach the recovery system to the rocket’s structures. There are several hard points on the rocket’s bulkplates and/or centering rings. These hard points are generally made using eye-bolts or U-bolts. U-bolts are preferred on large rockets. Eye-bolts should be closed and/or welded closed.
Recovery Systems Overview

High-powered rockets typically have one of two types of recovery systems - Single Event Recovery or Dual Event Recovery. This section outlines the general systems and their purposes.

Single Event Recovery System (SERS)

A typical *Single Event Recovery System* ejects a parachute at apogee. This can most commonly be achieved by using a motor ejection charge. Most low to mid power rocket motors have this capability. At motor ignition, the propellant and a delay grain begin to burn. The delay grain burns slowly. Once it burns through, the ejection charge is set off and the parachute is deployed. If the timing is good, this happens near apogee. SERS is the simplest recovery system and is good for low altitude flights on small launch fields and high altitude flights on large launch fields. If you do not mind walking that is. You may want to use a tracker in that case.

The plot below shows the trajectory of a rocket with a single event recovery system. The rocket reaches apogee and deploys a parachute using the motor ejection charge. The rocket then descends slowly at 20 fps. With an apogee of 3000 feet, it takes two and a half minutes for the rocket to touch down.
Dual Event Recovery System (DERS)

Student Launch Project rockets are required to use a Dual Event Recovery System. A typical DERS has one event at apogee and the second at a much lower altitude, typically 700 feet or more Above Ground Level (AGL), and requires electronics do to so. This recovery technique significantly reduces the recovery area by allowing the rocket to fall much faster from apogee and deploying a main parachute much closer to the ground. The 1st event recovery system is typically a long length of shock cord and perhaps a drogue parachute. The 2nd event recovery system is the main parachute which slows the rocket down considerably for a safe touchdown.

Dual Deploy Plot

The plot above shows the trajectory of a rocket using a dual event recovery system. The rocket reached an apogee of 4800 feet. It then deployed a drogue that slowed the descent to 90 fps. At 1100 feet, the main parachute deployed further slowing the decent rate to 18 fps. It takes only one and a half minutes for the rocket to touch down.
A rocket equipped with a typical dual event recovery system has this general layout. The main parachute is generally forward of the electronics bay. This adds advantage to the rocket’s center of gravity and hence the rocket’s stability margin by having the larger and heavier of the recovery devices far forward. The electronics bay is generally between the two parachutes. This adds advantage to the locations of the recovery ejection charges. The charges are generally placed in cups on the electronics bay’s end closures or bulkplates.

The system level diagram below details the dual event recovery system’s configuration. This system is a fully redundant recovery system. There are two altimeters which each have a dedicated battery and switch. Each altimeter has its own set of recovery charges to fire. There are four in total in the rocket. Your rocket will need to have a recovery system that uses this system’s diagram.
The diagram below shows three different ways the dual event recovery system’s hardware may be configured. Each has benefits and risks. Your rocket will adopt one of these configurations:

**Configuration #1:**
Main Parachute Attached to the end of the shock cord along with the Nosecone for quick extraction.

**Configuration #2:**
Main Parachute 1/3rd the way from the end of the shock cord to keep the nosecone from contacting the rest of the rocket.

**Configuration #3:**
Main Parachute Attached to the end of the shock cord and the nosecone in the middle.
The Avionics Bay

Avionics refers to any electronic systems flown on a rocket, whether they are flight computers, guidance and control systems, telemetry systems or payloads. These systems are typically built into an Electronics Bay. An ‘E-Bay’, is a subsystem of a high powered rocket that typically contains altimeters, batteries, and switches. The Recovery Systems Section details the discrete components. This section covers how the components become systems. A typical E-Bay is comprised of three structural components: the housing, a forward and aft end-cap and an avionics sled.

E-Bay Housing

The E-Bay housings is typically built from a coupler tube and can have a collar made from a segment of airframe that is epoxied to the middle of the coupler and allows direct access to the switches that power on the altimeters. The collar also supports static pressure ports that equalize the housings interior pressure with the exterior atmosphere. Generally, rocket builders follow the convention that when joining airframes with a coupler, the coupler should extend at least one airframe diameter into each joined segment.

End Caps

The E-Bay end-caps close out the housing, separating the rocket’s volumes, and support the recovery harness hard mounts, charge cups, and all-threads. Typically, end-caps are made from G-10 fiberglass bulk plates, or plywood. The all-threads act as a two-force member that connect both end-caps and carry the recovery harness load through the E-Bay. End-caps should create a good seal around the end of the housing to prevent hot gas seepage from the ejection charges.
Avionics Sled

Typically, the avionics sled is a G-10 fiberglass board or boards that mount in the avionics by sliding onto the all threads that connect the end plates; like a sled. The avionics electronics, batteries, and switches are mounted to the sled and wired together to form systems. The avionics sled in the photo to the right is slid onto ¼” diameter all-threads using ¼” I.D. G-10 fiberglass tubes that are epoxied to the corners on the G-10 boards. This simple sled supports only altimeters, batteries, and switches. The sled was designed to slide into the avionics bays of several different rockets.
Recovery Electronics

Beyond the hardware of the recovery system, this section will detail out some of the electronics you will need to be familiar with such as the Perfectflite MAWD rocket altimeter, batteries, and switches.

Perfectflite MAWD

Dual Event Recovery Systems require the use of electronic devices called Altimeters that can determine altitude and initiate events at desired altitudes. It is common to outfit your rocket use at least one Perfectflite MAWD or ALT15 altimeter. The perfectflite altimeters are powerful robust commercial altimeters. They support deployment event programmable settings for the main ejection charge from 300 feet to 1,700 feet AGL. The default setting for the drogue is apogee.

The pressure sensor of the Perfectflite MAWD works to 25,000 feet MSL and its stores over 5 minutes of flight data at 20 Hz (Hertz - samples per second). All of the data is stored in a nonvolatile memory and is preserved even if power is lost. The Perfectflite’s robust power supply is not affected by up to two seconds loss of power in flight and will fire 10 parallel-rendant e-matches even after 24 hours of operation on a standard 9V battery. The default low battery alarm (continuous tone) is set at 8.4 V. The perfectflite MAWD produces a firing current of 27 A (Amps) peak, and performs a continuity check at 8.9μA/V.

Altimeters, usually mounted in the rocket’s avionics bay, need to sample the outside air pressure. Your rocket will need a static pressure port along the outside to allow the inside pressure to equalize to the outside pressure.
Other Avionics Devices

RRC2 Mini Altimeter

G-WIZ Avionics Bay

ARTS2 Flight Computer

AED Electronics R-DAS Tiny

Apogee Altimeter One

Perfectflite MAWD
**Batteries**

Typically rocket builders prefer each altimeter have a dedicated battery. The NASA Student Launch Projects official handbook requires your rocket have a minimum pad stay time of one hour. This means your electronics should be able to remain switched on and reliably operate if the rocket remains on the pad for up to one hour on the pad before launch.

There are two main types of batteries used in high-powered rocketry, primary and secondary. Primary batteries such as a 9V alkaline battery are designed for a one-time use and then discarded when they are exhausted. Even if never taken out of the original package, primary batteries can lose 8% - 20% of their original charge every year when stored at room temperature. This “self discharge” rate is known to occur due to a non-current producing side chemical reaction which occurs within the cell even if no load is applied.

Secondary batteries, like Nickel Cadmium (NiCad) or Lithium Polymer (Li-Po) batteries are designed to be rechargeable and used multiple times. Secondary batteries weigh less than primary batteries and manufacturers can shape them however they please, but they are more expensive than primary batteries and some require sophisticated chargers to safely recharge them. **Improper use or charging of some secondary batteries can result in fire or explosion.**

Secondary batteries self discharge more rapidly than primary batteries. A freshly charged NiCad battery can lose 10% of its initial charge in 24 hours, and discharges at a rate of about 10% every month thereafter. Most Li-Po batteries have reduced self discharge rates to a relatively low level but are still poorer than primary batteries. Even though secondary batteries have their energy content restored by charging, some deterioration occurs on each charge/discharge cycle. Secondary batteries like Li-Po batteries are gaining favor in the work of high powered rocketry where the advantages of both lower weight and greatly increased run times can be sufficient justification for the price.

**Switches**

Typically rocket builders prefer to power up their electronics from the outside of the rocket once it is placed on the launch pad. This method maximizes battery life. The switches can either be surface mounted to the airframe of the rocket or mounted inside the rocket with an access hole or panel. The two categories of switches used on high powered rockets are the *Single Pole Single Throw (SPST)* and the *Dual Pole Single Throw (DPST).* The *Single Pole Single Throw (SPST)* is a simple on-off switch where the two terminals are either connected together or disconnected from each other. The *Dual Pole Single Throw (DPST)* is equivalent to two SPST switches controlled by a single mechanism. In these two categories, there are toggle switches, push button switches, and selector switches.
Ejection Charge Sizing

A black powder charge is the most common and reliable method of ejecting a parachute from your rocket. In your rocket, the motor’s ejection charge will ignite and generate hot gases that pressurize the rocket’s airframe and exert a net force on the bulkplate of the nose cone. This net force will eject the nose cone, shock cord, and parachute out of the rocket airframe. This all happens because the rocket is obeying the Ideal Gas Law.

The Ideal Gas Law is the equation of state for a hypothetical incompressible or “ideal” gas. The state of an amount of gas is determined by its pressure, volume, and temperature.

The modern form of this equation is $PV = NRT$ where $P$ is the absolute pressure of the gas, $V$ is the volume occupied by the gas, $N$ is the amount of substance (in this case the substance is black powder), $R$ is the gas constant, and $T$ is the absolute temperature. The equation can be reordered to solve for $N$ directly and known values substituted. The design pressure is determined by the desired net force on a surface divided by the area of that surface. Typical net force values for a 4 inch diameter rocket range from 100 lbf - 200 lbf. This translates to a typical pressure range of 8psi – 16psi. Also, black powder charge amounts are typically reported in the unit grams. Recall there are 454 grams in 1 pound.

Pressure: $P = \frac{F}{A} = \frac{200 \text{ lbf}}{\pi (2\text{ in})^2} = 16 \text{ psi}$

Volume: $V = \pi R^2 L = 12.5\text{ in}^2 L$

Black Powder: $N = \frac{PV}{RT} = \frac{16\text{ psi} \cdot 12.5\text{ in}^2 L}{266 \text{ in lbf} / \text{lbm} \cdot 3307^\circ R} \left(\frac{454 \text{ grams}}{\text{1 lbf}}\right) = 0.1 L$

The reduced equation for this case, states that 0.1 grams of black powder is needed for every 1 inch of airframe containing the recovery system. Therefore, if $L = 20\text{ in}$, then 2.0 grams of black powder is needed to eject the recovery system with 200 lbs of force. This theoretical value should now be tested.

Typically, rocket builders use a charge cup or well to contain the measured amount of black powder for the ejection charges. Everything from PVC end caps, brass pipe fittings, to a rolled length of blue masking tape can be used. Some fixed volume charge cups will require a filler of some type to occupy the empty volume in the cup once the black powder and e-match have been installed. Rocket builders typically use soft foam ear plugs or shredded housing insulation material more commonly called “dog barf”. Cannon plug
covers, electrical tape, masking tape, and duct tape can be used to seal the charge cups.

E-Matches

Electric matches, commonly called “E-Matches”, are a universal initiator of many rocketry pyrotechnics and motors. A typical e-match is made from a thin nichrome (nickel-chromium) wire laminated to a small non conductive flake of fiberglass. Each end is soldered to one wire of a two conductor solid core copper shooter wire. The nichrome bridge is dipped into a pyrogen formula that dries hard and looks like a match, hence the name. E-matches are typically high current or low current. Kits for making your own e-matches can be purchased on the internet, or you can purchase them from most vendors on launch day. E-matches can be augmented to serve as motor igniters also.

Shear Pins

Shear pins are generally used on mid to high powered rockets to prevent dynamic separation or premature/incomplete deployment of the recovery system. Dynamic separation occurs when a rocket separates in the coasting phase because the different sections are decelerating at different speeds. An example would be when a rocket’s booster section separates from the forward airframe or nose cone because the fin drag or the base drag effects creates a significant enough force to overcome the frictional force keeping the sections together.

Rocket builders generally use small nylon machine screws as shear pins. A #2-56 nylon machine screw has an average shear strength of 25 lbs. A #4-40 nylon machine screw has an average shear strength of 40lbs. Typically, rocket builders will use two #2 nylon shear pins for each separating section (cumulative shear strength of 50 lbs).
Parachute Selection

The NASA Student Launch Projects handbook requires you safely recover your rocket and that it be able to fly again. Selecting the right size parachute is a large part of that. There are two good methods to help determine the appropriate size of parachute – Kinetic Energy Equation and Newton’s 2\textsuperscript{nd} Law of Motion.

Kinetic Energy

Kinetic Energy (KE) is the energy of motion. There are many forms of KE, but for simplicity, this section will focus on translational motion – the energy of motion linearly from point A to point B. KE is a scalar quantity typically shown in units of foot-pounds force (ft-lbf) [English], and Joules (J = Nm) [SI]. The KE of an object is dependent upon two variables: the object’s mass (m) and the speed (V).

\[
KE = \frac{1}{2} m V^2
\]

The reason this is important in the context of rocket recovery is two rockets of the same final descent rate and different masses will have different KEs. The same is true with two rockets that have the same mass but different descent rates.

Case 1:

Consider two rockets. One weighs 30 lbs and the other 60 lbs. They both descent under a main parachute at 20 ft/s.

\[
KE_1 = \frac{1}{2} (30 \text{ lbs}) (20 \text{ ft/s})^2 \left( \frac{1 \text{ lbf s}^2}{32.2 \text{ lbm ft}} \right) = 186.3 \text{ ft lbf}
\]

\[
KE_2 = \frac{1}{2} (60 \text{ lbs})(20 \text{ ft/s})^2 \left( \frac{1 \text{ lbf s}^2}{32.2 \text{ lbm ft}} \right) = 372.7 \text{ ft lbf}
\]

The 60 lb rocket has twice the KE of the 30 lb rocket, therefore it impacts the ground twice as hard. In order for the two rockets to have the same KE at touchdown, the 60 lb rocket would need to have a descent rate of 14 ft/s.
Case 2:

Consider two rockets that both weight 30 lbs that descend under a main parachute at 15 ft/s and 20 ft/s respectively.

\[
KE_3 = \frac{1}{2} (30 \text{ lbs})(17 \text{ ft/s})^2 \left( \frac{1 \text{ lbf s}^2}{32.2 \text{ lbm ft}} \right) = 134.6 \text{ ft lbf}
\]

\[
KE_4 = \frac{1}{2} (30 \text{ lbs})(22 \frac{\text{ft}}{s})^2 \left( \frac{1 \text{ lbf s}^2}{32.2 \text{ lbm ft}} \right) = 225.5 \text{ ft lbf}
\]

The second rocket’s KE value is nearly twice that of the first. This case demonstrates a small change in descent velocity has a more pronounced effect on KE than changes in mass of the rocket. An 18 lb rocket descending at 22 ft/s would have the same KE as the 30 lb rocket descending at 17 ft/s.

This plot below compares different KE slopes and relates a rocket’s final mass to a touchdown velocity. These plots demonstrate that setting a design constraint on a target Kinetic Energy, rather than a target descent rate range, offers more control over the design of the recovery system my limiting the energy at which the rocket impacts the ground thus improve safety and survivability. At good target KE range might be 75 ft-lbf (102 Joules).
Newton’s 2\textsuperscript{nd} Law of Motion

The rocket and parachute obey Newton’s 2\textsuperscript{nd} Law of Motion. Newton’s 2\textsuperscript{nd} Law states the relationship between an object’s mass $m$, its acceleration $a$, and the applied force $F = ma$. The basic assumptions used in calculating the descent rate of a rocket are:

1. The rocket descends at a constant speed (steady state)
2. The rocket’s mass is a constant
3. The rocket moves simply downward (constrained to $z$-axis)
4. The atmosphere is a continuum. (constant air density)

$$\Sigma F_z = ma = 0$$

If you make these assumptions, there are only two forces acting on the rocket – Weight and Drag.

$$\Sigma F_z = D - W = ma = 0 \text{ (steady state)}$$

Drag is determined by Velocity, air density, reference area, and a drag coefficient ($c_d$). The equation for Drag is:

$$D = \frac{1}{2} \rho V^2 S c_d$$

Substituting the drag equation, Newton’s 2\textsuperscript{nd} Law becomes:

$$W = D = \frac{1}{2} \rho V^2 S c_d$$

The equation is reordered to solve for the reference area ($S$):

$$S = \frac{2W}{\rho V^2 c_d}$$

Recall the drag coefficient is a dimensionless quantity that is used to quantify the drag of resistance of an object in a fluid environment such as air. For non-streamline objects like parachutes, the drag coefficient can be greater than 1. This value is determine empirically and can usually be found on a manufacturer’s website.

Consider a descent rate range of between 18 ft/s and 22 ft/s. If you make an initial guess and set your drag coefficient to 2.0, you can determine a range to begin shopping for parachutes. Estimate that your rocket will weigh 20 lbm. Substituting these estimated values, you can determine the range in size parachutes needed. Once you find some parachutes in this range, you can perform the calculations again using the specific parachutes reference area and the manufacturer’s calculated drag coefficient.
Upper Bound (Descent Velocity = 18 ft/s):

\[
S = \frac{2W}{\rho V^2 C_d} = \frac{2 \times 20\text{lbm}}{0.075 \text{lbf/ft}^3 \times 18 \text{ft/s} \times 2.0} \left(\frac{32.2 \text{ lbm}}{\text{lb} \cdot \text{s}^2/\text{ft}}\right) = 26.5 \text{ft}^2
\]

Lower Bound (Descent Velocity = 22 ft/s):

\[
S = \frac{2W}{\rho V^2 C_d} = \frac{2 \times 20\text{lbm}}{0.075 \text{lbf/ft}^3 \times 22 \text{ft/s} \times 2.0} \left(\frac{32.2 \text{ lbm}}{\text{lb} \cdot \text{s}^2/\text{ft}}\right) = 17.7 \text{ft}^2
\]

For this case, the rocket will require a parachute that has a reference area between 18 ft$^2$ and 26 ft$^2$. Throughout the design of your Student Launch Projects, your design will continue to mature and you will need to re-evaluate your parachute selection as you get better estimates for your rocket’s weight. Below are some examples of typical rocket parachute characteristics from Sky Angle:

<table>
<thead>
<tr>
<th>Classic/Classic II Specs</th>
<th>36</th>
<th>44</th>
<th>52</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tested* Load Capacity</td>
<td>2.7 - 5.7</td>
<td>4.4 - 9.5</td>
<td>6.8 - 14.8</td>
<td>10.2 - 22.1</td>
</tr>
<tr>
<td>Surface Area (sq. ft.)</td>
<td>14.2</td>
<td>21.1</td>
<td>29.5</td>
<td>39.3</td>
</tr>
<tr>
<td>Suspension Line Length (inches)</td>
<td>36&quot;</td>
<td>44&quot;</td>
<td>52&quot;</td>
<td>60&quot;</td>
</tr>
<tr>
<td>Tested Cd</td>
<td>1.34</td>
<td>1.87</td>
<td>1.46</td>
<td>1.89</td>
</tr>
<tr>
<td>Classic Net Weight (oz.)</td>
<td>5.0</td>
<td>7.0</td>
<td>9.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Classic II New Weight (oz.)</td>
<td>8.4</td>
<td>10.5</td>
<td>13.3</td>
<td>18.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CERT-3 Size</th>
<th>Large</th>
<th>X-Large</th>
<th>XX-Large</th>
<th>Drogue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tested* Load Capacity</td>
<td>16.2 - 35.0</td>
<td>32.6 - 70.6</td>
<td>60.0 - 129.8</td>
<td>1.0 - 2.2</td>
</tr>
<tr>
<td>Surface Area (sq. ft)</td>
<td>57.0</td>
<td>89.0</td>
<td>129.0</td>
<td>6.3</td>
</tr>
<tr>
<td>Tested Cd</td>
<td>1.26</td>
<td>2.59</td>
<td>2.92</td>
<td>1.16</td>
</tr>
<tr>
<td>Suspension Line Length (inches)</td>
<td>80</td>
<td>100</td>
<td>120</td>
<td>24</td>
</tr>
<tr>
<td>Net Weight (oz.)</td>
<td>34.0</td>
<td>45.0</td>
<td>64.0</td>
<td>6.0</td>
</tr>
</tbody>
</table>
Parachute Folding Instructions

These instructions demonstrate the procedures for folding a Sky Angle Classic II 36” parachute. These procedures can be applied to almost every parachute, but may vary slightly depending on parachute size, type, rocket diameter, and if you choose to use a deployment bag (D-bag). Practice folding your parachute many times to gain experience.

Step 1:
Lay the parachute on the ground. Gather the support lines in both hands at the bottom of the canopy and the bottom of the shroud lines. Remove any twists in the lines. Stretch the lines out so they are taut. On larger parachutes with long support lines, use a weight to hold the steel connector link while you work with the support lines from the canopy end.

Step 2:
Arrange the canopy so it lays flat on the floor. Neatly tuck-in the nylon fabric from the multiple parachute panels (the material between the support lines) in towards the center line of the canopy.

Step 3:
Fold the top of the parachute down to the bottom of the parachute where the shroud lines attach.
Step 4:
Fold the parachute in thirds by folding the top corners in towards the center of the parachute as shown.

Step 5:
Using one hand to hold the parachute down, fold the top half of the parachute down over the bottom half of the parachute.

Step 6:
Flip the parachute over and roll it up into a cylinder type arrangement.

Step 7:
Wrap the support lines around the rolled parachute. A tight wrap with more turns will lead to a smaller pack job with a slower opening. A loose wrap will lead to a larger pack job with a faster opening. The amount and tightness of the wraps should be determined...
based on the desired fit in the rocket and opening speed.

**Recovery System Testing**

Before you fly your high powered rocket, it will be necessary for you to perform ground tests of components or entire systems before risking the entire project.

**Vacuum Chamber Test**

A vacuum chamber test will prove a pressure based rocket altimeter functional. The test can be as simple as a single altimeter in a mason jar using a marinade syringe to pull the air out, or as complex as a full systems test of the entire rocket recovery system. A simple visual indicator of an altimeter’s health can be a Christmas tree light wired in to the ejection charge terminal blocks. The photo to the right shows one such test. This test is performed just before the recovery charges are installed.

**Ejection Charge Test**

You will want to conduct several ejection charge tests before flight. This full-up test is the best way to assess if the ejection charges are of sufficient size, and to assess the configuration and effectiveness of the recovery systems setup.

The photo to the right was taken just after a successful ground test of the rocket’s dual event recovery system. The successful criteria where:

- Both main and drogue systems deployed as expected
- The parachutes are extracted from the airframe
- The parachutes and shock cords are suitably protected from the ejection charge

The tests proved the design ready for flight.
Parachute Care

Get the most life out of your parachutes and recovery hardware by taking care of them. These are some suggestions that will extend their use:

- Protect your parachutes from damaging hot ejection charge gases by using a kevlar parachute protector, piston system, recovery wadding, dog barf (i.e. spray insulation material) or a deployment bag.
- Keep your parachutes indoors, dry and unfolded, when in storage. Take them out of your rockets and wipe them off with a damp and lightly soaped rag.
- Fold your large parachutes on a large blanket or tarp when in the field (not on the ground). This will reduce the odds of damage from FOD (foreign object debris) and keep them cleaner.
- Use stainless steel hardware in your recovery system. It is a bit more expensive, but will resist the effects of corrosion longer. Residue from black powder ejection charges will corrode other metals quicker and you will find yourself replacing hardware more often.
Recovery Exercise 1: Ejection Charge Calculation

A black powder charge is the most common and reliable method of ejecting a parachute from your rocket. This exercise will teach you how to determine the ideal amount needed for your rocket by using the Ideal Gas Law.

\[ PV = NRT \quad \text{(Ideal Gas Law)} \]

\[ P = \frac{F}{A} \quad \text{(Pressure)} \]

The constants for 4F black powder are:

\[ R = 266 \frac{\text{in} \cdot \text{lbf}}{\text{lbf} \cdot \text{in}} \quad \text{(Gas Constant)} \]

\[ T = 3307^\circ R \quad \text{(Temperature)} \]

The variables for your rocket are:

\[ F = 75 \text{ lbf} \quad \text{(Ejection Force)} \]

\[ A = 5 \text{ in}^2 \quad \text{(Area)} \]

\[ V = 100 \text{ in}^3 \quad \text{(Volume)} \]

Use the Ideal Gas Law and Pressure formula to determine the required amount of black powder to eject a parachute from your rocket. Note: There are 454 grams in 1 lb.

Note: All CTI Pro 38 High Powered Reloads come standard with a 1.3 grams black powder charge installed. Well more than is actually required for this particular kit.
Recovery Exercise 2: Descent Rate Calculation

This exercise will teach you to calculate your rocket’s descent rate under a 30” parachute. The parachute is a high drag device that retards the high speed descent of the rocket by producing a force that opposes the weight of the rocket. You will use Newton’s 2nd Law of Motion to determine the descent rate of your rocket. The basic assumptions used in calculation the descent rate of a rocket are:

4. The rocket is descending at a constant speed (steady state)
5. The rocket moves simply downward (constrained to z-axis)

If you make these assumptions, there are only two forces acting on the rocket – Weight and Drag. Given

\[ \sum F_z = D + W = ma = 0 \text{ (steady state)} \]

\[ D = \frac{1}{2} \rho V^2 S C_d \quad W = mg \]

\[ D = W = \frac{1}{2} \rho V^2 S C_d = mg \]

Given the following parameters, determine your rocket’s descent rate using the Descent Velocity Equation:

Weight (W) = 41.6oz. = 2.6lbf

Drag Coefficient (C_d) = 0.87 (theoretical)

Air Density at 70°F (\(\rho\)) = 0.075 lbf/ft³

Surface Area (S) = \(\pi r d^2 / 4\) = 4.9 ft²

Descent Velocity = \(V = \sqrt{\frac{2 W}{\rho S C_d}} \left(\frac{32.2 \text{ lbf}}{lb \cdot s^2/ft}\right)\)

Solution:
Recovery Exercise 3: Kinetic Energy Calculation

This exercise will teach you to calculate your rocket’s Kinetic Energy (KE) at touchdown. The basic assumptions used in this calculation the rocket’s KE are:

1. The rocket is a point mass (no tethered parts).
2. KE refers to translational KE only (simple movement in one direction).

Given the following parameters, determine your rocket’s KE using the equations below:

\[ Weight \ (W) = 41.6 \text{oz.} = 2.6 \text{lbm} \]

\[ Descent \ Rate \ (V) = 22 \text{fps} \]

\[ KE = \frac{1}{2} (W)(V)^2 \left( \frac{1 \text{ lbf s}^2}{32.2 \text{ lbm ft}} \right) \]

Solution:
Avionics Systems

Materials:

Basic Electronic Circuits

Microprocessors
Basic Electronic Circuits

Basic electrical circuits operate on a few fairly simple ideas – voltage, current and power. Voltage is a measure of the electrical potential difference between two points.

Voltage (V)

A good analogy for voltage is dropping a ball from a cliff – the higher the cliff, the more energy associated with a single ball. Voltage is a direct measurement of the amount of energy contained in a group of electrons.

The two major voltage types are direct current and alternating current. Direct current (DC) is a straight and level voltage which does not change over time. These are often seen in batteries, computer power supplies, memory modules, cell phone backlights, and in absolutely anything which has a keypad or screen. Alternating current (AC) is just what it sounds like – voltage swings from high to low, then back to high. This process occurs rapidly, (60 times per second for household electricity). AC current is effective for transmitting power over long distances.

Most payload applications will not use AC for anything, as sensors and other electronics operate on DC voltages. Technically, signals sent by microprocessors and other talking electronics are alternating currents. AC of this type is critically important. How these systems work is covered in the Microprocessors section.

Current (C)

Current is a measure of the number of electrons per second with pass through a point. Keeping the cliff analogy in mind, current would be how fast the balls are dropping off the cliff. Literally, it is a measure of how fast electrical current is moving from one side to the other. An Amp [Ampere] is a measure of how many coulombs of charge pass through a point per second. Most electronics used for payloads will be measured in milliamps, with is .001 amps. So, 250 milliamps is .25 amps. A lot of small components each drawing a few milliamps add up pretty quickly. A power budget is an absolute must to determine what type of battery is needed, and how long it will be able to keep the payload powered.

Power (P)

Power is used to determine how much heat will be generated by the electronics. On large scale super complicated payloads this has to be watched very carefully, but for smaller microcontroller based things it is not a huge concern. Payloads that operate under about 5 Watts usually will not generate enough heat to melt anything. The largest heat concern on payloads would be a short circuit, which absolutely dumps power. Short circuits occur constantly with small custom made components, simply because it is easy to cross wires and wire things backward. They may not always be fatal to the power supply, but tiny little components cook themselves easily. This especially happens in preparing critical component right before launch. The general rule is that the more expensive and critical a component is the easier it fries.
Laws of Basic Circuitry

Three rules dominate basic circuits. These are Ohm’s law, Kirchhoff’s voltage law (KVL), and Kirchhoff’s current law (KCL). Ohm’s law states that the amount of current flowing through an object depends on the voltage applied and the resistance of the object. This is usually used for figuring out what is going on in a single simple component, or to determine what kind of resistor is needed. Some components like thermistors (resistors that change with temperature) or photoresistors (resistors that change based on lighting conditions) can turn out useful data just using Ohm’s Law. This law is also highly useful if it is necessary to change DC voltages from a high to low voltage.

\[
\text{(Ohm's Law)} \quad \text{Voltage} = \text{Current} \times \text{Resistance}
\]

How this works in practical application is fairly simple. Imagine a battery, wire, and resistor - the world’s most boring circuit. Wires are designed with sufficiently low resistance, so any resistance from the wire can be ignored. To determine how much current is going through the resistor simply apply a little algebra, and come up with:

\[
\text{Current} = \frac{\text{Voltage}}{\text{Resistance}}
\]

Assume a 9 volt battery and 1,000 Ohm resistor [1K Ohm]. The current would be:

\[
\text{Current} = \frac{\text{Voltage}}{\text{Resistance}} = \frac{9 \text{ Volts}}{1000 \text{ Ohms}} = .009 \text{ Amps} = 9 \text{ milliamps}
\]

Being able to determine the voltage across an object should be and what it actually is proves highly useful when determining why a component is not working. Also, when the circuit is drawing excess current the culprit may be identified by a low resistance reading. Alternatively, if a component is not working, the voltage drop across it indicates if it is connected correctly.
Kirchhoff’s voltage law and Kirchhoff’s current law are both used for pretty complicated circuits. Put bluntly, his voltage law says for every voltage rise there is a voltage drop. The current law states that the amount of current going into a point is the same as the amount of current leaving the point. Using these two laws enables having multiple batteries wired up to multiple resistors and be able to determine what current is going where. These two can get pretty complicated. The best method of determining what is happening in a circuit is to use a Multi-meter or Oscilloscope after more than a few components are in use.

Here is an example of a fairly typical KCL/KVL circuit as it would be analyzed in an entry level circuit class. Several batteries and resistors are wired up in a giant mess. In practice it is rare to see anything like this, but if you did these are the two laws needed to determine what is going on.

![Circuit Diagram]

Particularly useful applications of Kirchhoff’s laws are shown below. Wiring two batteries in series increases the voltage readable across the resistor. Wiring two batteries in parallel keeps the voltage the same as just one battery, but allows powering the circuit for twice as long. These two methods are seen constantly in all types of batteries. Cutting open a battery exposes a litany of cells (mini-batteries) which are joined in series to raise the voltage.

![Series Batteries and Parallel Batteries Diagrams]

Payloads typically resemble the one below from a basic circuitry perspective. Several pieces are wired to a single battery. Each of the resistors shown below could be a memory, sensor, or bunch of other resistors, or anything needing power. The easiest way to determine the amount of current drawn is to calculate (or read from the Datasheet) the amount of current each component takes and add them all together. However, it is unusual for it to be so simple. Usually it takes a little testing to determine just how much current the circuit is drawing. The most accurate method of determining how much current is being drawn is to take a direct measurement. The Multi-Meter description will show how to do that.
Symbols

Battery  Resistor  Diode  Wire

Calculations

The level of difficulty in calculating the output of a circuit can range from easy to considerably complicated. The objective is to keep it as simple as possible. It may be a neat trick to be able to calculate what is happening with 50 components, but when a measurement will do just use that. There is no reason to run the risk of an oversight or miscalculation when it is unnecessary.

Datasheets

Datasheets are one of the most important tools ever when dealing with electrical devices. Manufacturers literally tell just what their component was designed for, how to use it, and sometimes how not to use it. Most important information is listed including the amount of current expected to be drawn, to the typical operating voltages, to exactly how to communicate with it. Spend a lot of time going over component data sheets. It may take anywhere from 30 minutes to several hours to evaluate a component based on the datasheet, but it takes a lot more time trying to determine how to re-wire a board because of reading the operating voltages or pin description wrong. If the goal is to push the limit on how fast a memory will operate, the datasheet will have everything needed to know about it. Some data sheets are much better than others. It is very obvious when a manufacturer describes just how a component is designed to work and just how to get it to work, as opposed to a manufacturer who provides only general information about 10 similar parts all in the same document. Careful reading of data sheets are step number one in using a new chip. It cannot be stressed enough just how critical studying a component until it becomes 150% completely clear how the device works. When in doubt, (and it is not unreasonable to be in doubt even if it appears you are doing everything correctly), call the distributor or manufacturer. A couple of hours on the phone can save several weeks of regret if you spec the wrong component. It is not uncommon that several additional documents on a chip will exist which may not be as easily found, so search the manufacturer’s website. Sometimes the datasheet will have been revised or lead to other documents. This is one of, if not the most, time consuming parts of designing electrical equipment.

Here is an example of a typical Datasheet. This is a tiny accelerometer that can be used in various devices from model rockets to game controllers.


Notice on the cover page how much information is listed. The manufacturer lists 1) the operating voltages, 2) the communication protocol to use, 3) the types of measurements the chip makes, 4) additional capabilities the chip can
be programmed to do besides make basic measurements, and 5) possible applications for the chip. Page Eight (8) lists which pin on the chip does which function. Notice that some pins have more than one function; this is common and can be a major stumbling block. Most of the pins listed on this page are for communication, and we will go over that in another section. The important part is being able to determine which pin lines up to what function using this table and the diagram on page 7. What pin number does the wire frame arrow point to, and what does the pin do?

The pin number is 11, and it is listed as INT 1- Inertial Interrupt 1. It can get confusing when both a top and bottom view is listed. There is absolutely no shame in making a little drawing with pin numbers on it with their functions listed beside them, and even flipping it over to try and see through the card if the data sheet drawing is confusing. The more time spent in the planning and understanding section the less time needed later on. Designing a circuit board gets fairly complicated sometimes, so spend as much time as possible going over the data sheets. Misunderstanding a pin function does not always sink a board, but it can go a long way toward it.

Pages nine and ten list the accuracy and ranges of the sensor, which is a must if performing an uncertainty analysis. Pages eleven and twelve describe how to communicate with the device. These two pages describe two different methods of communicating with the chip. The important thing to understand on seeing a timing diagram for the first time is that this describes when certain events happen. There are several common methods for getting data from one place to another, and the manufacturer decided to make this chip so that it could use two of them. That is rare, and a nice feature. Looking at the first entry in both charts on pages eleven and twelve we see clock information. One says 10 Megahertz (ten million cycles per second) and the other says 400 Kilohertz (four hundred thousand cycles per second). These numbers are directly related to how fast data can be retrieved from the device. For making as many measurements as fast as possible a quick clock cycle is a good thing.

Page sixteen of the sheet lists an ‘application hint’ which more or less means ‘this is how to wire it up.’ The diagrams in these sections aren’t always the only way to wire up a chip, but they are a good start. It is a very good idea in most cases to just stick with what they have listed. Manufacturers spend a lot of man-hours designing, building, and testing components so the first step in implementing anything is to go with what they have given.

The chip-specific things the chip does goes from page twenty three on. This is a pretty complicated section. This chip has a lot of registers used to control it. In order to understand exactly how to operate the chip should take a couple hours and a good deal of testing. Step one is to wire up the chip like it was shown in the application hint section. In a nutshell: Send a signal to turn it on [even though it is already wired up], set some configuration options, tell it what to measure, then tell it to return the measurement. The way to communicate with the chip is dealt with in the I²C and SPI sections. It involves sending out numbers over one of the electrical lines. (There will be more on chip communication in the microprocessors section.) Glance through the control registers on page 24 on to see useful information.

Control registers are where the magic happens. These are just what they sound like- some number in a big list that controls the chip. The chip sits there and watches its control registers nonstop and everything it does is based on those. Take a look at page 24, the control register labeled CTRL_REG1. The
20h in parenthesis is a number to send it in order to change that control register. The h on the end means hex. If programming a device to talk to the accelerometer simply tell the computer or microcontroller to send the number 20 in hex, and then send the value desired for the control register to be. This register is written in binary. This means each of the 8 little blocks can be either a 1 or a 0. They are fairly straightforward to read. It may be easiest to think of each box as a check mark or an on-off switch when changing them around. Take a minute to look through the register. The registers can change whether or not the chip is on, how fast the chip makes a measurement, and which axes are on or off.

### CTRL_REG1 (20h)

<table>
<thead>
<tr>
<th>PM2</th>
<th>PM1</th>
<th>PM0</th>
<th>DR1</th>
<th>DR0</th>
<th>Zen</th>
<th>Yen</th>
<th>Xen</th>
</tr>
</thead>
</table>

#### Table 16. CTRL_REG1 register

- **PM2 - PM0**: Power mode selection. Default value: 000 (000: Power-down; Others: refer to Table 18)
- **DR1, DR0**: Data rate selection. Default value: 00 (00:50 Hz; Others: refer to Table 19)
- **Zen**: Z axis enable. Default value: 1 (0: Z axis disabled; 1: Z axis enabled)
- **Yen**: Y axis enable. Default value: 1 (0: Y axis disabled; 1: Y axis enabled)
- **Xen**: X axis enable. Default value: 1 (0: X axis disabled; 1: X axis enabled)

Changing a register is just as simple as telling the chip what to do. Here is an example of what number to send to the chip to turn it on. The first three bits deal with the power. We know that because the manufacturer was nice enough to label everything clearly in the datasheet. They tell us to look at the chart in Table 18, where they have listed which switch does what.
From this chart we see there is one configuration to turn it off, three low power modes, and one on mode. Obviously we want the on mode, so we put those numbers down. We are actually building up to the number we want the control register to be. These are the only three numbers we know out of the eight for now.

<table>
<thead>
<tr>
<th>PM2</th>
<th>PM1</th>
<th>PM0</th>
<th>Power mode selection</th>
<th>Output data rate [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Power-down</td>
<td>--</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>Normal mode</td>
<td>ODR</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>Low-power</td>
<td>0.5</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>Low-power</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>Low-power</td>
<td>2</td>
</tr>
</tbody>
</table>

The next two bits involve the data rate. This is how fast the chip will make a measurement. We will just leave those alone, since 50 measurements per second is a good rate. (If desired, use table 19 to crank the speed up.) The last three involve which of the three axes the chip will measure over. We want all three, so we put all ones in there to turn them on.

This is the binary number the control register should be: 00100111. To change this over to a hex or decimal value open up the calculator on Microsoft Windows. Click View, go down to scientific. On the upper left side click the button next to BIN. This means Binary. Type in the value of the control register (in the binary mode you can only click on ones or zeros). Next, click the button next to HEX. The result should be 27. This is sometimes written as 0x27, or 27h. Calculator converts things between Hex, Binary, Decimal, and Octal. (Octal is rarely used.) This number is what to tell the microcontroller to send out to flip switches in the chip it is talking to.
Most chips operate kind of similarly; each type has its own little things to get used to. It takes some work and some frustration to get comfortable flipping switches and changing around control registers, but after a little experimenting you can get fancy with it. Far and away the best method of getting acclimated to reading data sheets is just trying to do it over and over. This section was an exercise in reading data sheets. If you have a general idea what is going on and are able to keep up with the fact that data sheets have significant information on chip operation then are doing fine. Each chip has a lot of information that goes with it. Different manufacturers approach the same problems differently.

As you can imagine, memory chips have a lot of information about how to program information, how long to wait after programming information, how the information is arranged, and similar particulars. Here is an example of a data sheet for memory:


The gist of what the chip is about is on page one. Glancing through we see another timing diagram, a list of neat things it can do (like sector protection), and how to use it. Page seven shows a list of Opcodes. Opcodes are what they sound like also, operation codes. In order to perform operations send it the appropriate number in the chart. Sometimes the Opcode is followed with more information; sometimes it is just the number they give. This data sheet does a good job at explaining just how to program and read the chip. Keep in mind that the manufacturer usually does a good job at describing how to use the component. Their objective is to get people to use their chips, and there is absolutely no other way whatsoever to know how to use the chip.

From the data sheet reading portion it should be clear that each chip is a mini-project. It may take more than a couple of days to get through a data sheet to determine just how to implement a chip. To get a chip like the accelerometer working is a bit of an undertaking. Getting through the data sheet the first time from scratch should take several hours, maybe even a couple of days. Working out a general idea how to code for a chip should be done from the data sheet first. Make a list of what code does what and your understanding of how the chip works. Then, try to implement that code. 95% of the time it does not work the first time. Keep going over the data sheet for something missed, or some little thing that initially did not seem important. This is why the test phase is important. It is impossible to be 100% sure it is done right until the device is actually working. If you run into a wall with the chip try to contact the manufacturer’s technical support. It may take time to get a response, but they can offer insight that is not in the datasheet. After analyzing, contacting the manufacturer, and tried everything you can think of: switch out components. No sense in breaking yourself over one chip.
Multimeters

A multimeter is a tool that allows measuring electrical properties around a circuit. Typically multimeters are used to check DC or AC voltage, the amount of electrical resistance between two points, and whether or not two wires are connected called a continuity check. Multimeters are pretty basic in the sort of information they give. Usually it is only in the form of a DC voltage or DC current. This is a critical piece of hardware for testing and troubleshooting also. Using a multimeter involves placing the probes on two points in the circuit to measure the number of interest. An easy way to remember how to make a measurement properly is that voltage is measured across something and current is measured through something. Trying to measure the current across something can fry a cheap multimeter.

In making a voltage measurement remember that the voltage test feature causes the multimeter to have an extremely high resistance so that the circuit is not disturbed. When making a current measurement it causes the multimeter to go into a very low resistance state so that when measuring the current though the circuit it does not disturb the circuit much. A high end multimeter has some built in features to keep the meter from being burnt if placed in a circuit improperly. Usually the probes must be removed and connected in a different fashion if it is needed to change from making a voltage measurement to making a current measurement. It is a good idea to check to see what configuration the multimeter is in before starting to measure just in case it is sensitive to being connected improperly.
**Oscilloscopes**

Oscilloscopes are used to determine waveform characteristics. This means whether or not waves that look like squares actually are square shaped, and sometimes even checking to see if the serial communications are saying what you think they should. Oscilloscopes are used for checking the frequency of a signal and the signal strength at various places. They require that at least two points be checked at the same time. There are some fairly advanced features on most oscilloscopes to allow checking several different locations on the same screen as shown in the picture. The most important things to set properly are the test locations and the trigger voltage. The trigger voltage tells the oscilloscope exactly when to graph the circuit voltage. The scope takes a snapshot of the circuit over a brief period and displays it on the screen. The screen is refreshed whenever the trigger voltage is crossed, either when the voltage goes from below to above or above to below the trigger. You can set some offset on most oscilloscopes when checking multiple channels. The two main controls other than the trigger set are the sweep time and volts per division. Changing the sweep time changes the amount of time each square on the graph is worth in the X direction. Raising the sweep time has the effect of squishing the waveform together on the screen. Raising the volts per division has the effect of squishing the waveform together in the Y direction. Very precise measurements of just what is happening in the circuit can be made with an oscilloscope, and it is an absolutely mandatory piece of hardware for testing and troubleshooting. Even an older oscilloscope, as shown above, will do just fine for most applications.
**Microcontrollers**

A microcontroller (uC or μC) is a small but complete computer on a single IC. A microcontroller contains a processor core, memory for program execution and program storage, and peripherals for I/O. It can be used to construct a complete system; sometimes such arrangements are called a “system on a chip”. Microcontrollers are used in embedded applications, where this small digital system is dedicated to a specific task, and is usually a component in a larger system.

Microcontrollers typically have much less computing power than a microprocessor found in a typical desktop computer. Clock speeds are in the tens of MHz, and system RAM and program storage areas are in the tens of k-bytes. There is usually no operating system; when an OS is present, it is typically a very small real-time operating system (RTOS) designed for embedded applications.

Memory for program execution (what is thought of as “RAM” in a desktop computer) is usually SRAM (static RAM). SRAM is slower than other memory architectures, but requires no management to maintain its contents, so the overall system is simpler. To keep external component requirements low, a microcontroller also uses non-volatile memory to store the program onboard as well. Modern microcontrollers usually use either FLASH or EEPROM memory for program storage. In addition, some include additional non-volatile memory for storage of non-volatile user data. For example, the Atmega8 has 1 kbyte of SRAM, 16kbytes of FLASH for program storage, and 512 bytes of EEPROM for non-volatile user data.

Modern microcontrollers may contain a variety of IO interfaces. Digital IOs, where each pin is either a digital logic input or output (or, more usually configurable as either), is standard. Many microcontrollers include more complex digital interfaces such as UARTs (universal asynchronous receiver-transmitter, also known as a “serial port” or “RS232 port”). An analog to digital converter (ADC) is often supplied as well, since many microcontroller applications involve interfacing to analog systems.

**Analog to Digital Converter**

The ADC is an important part of many embedded systems. A signal we wish to measure is usually continuous over a particular range of interest, and a simple on-or-off digital input cannot tell us what we want to know about the signal. Because a microcontroller is a digital system, we use an ADC to convert this continuous signal into a digital representation that can be used by the microcontroller.
A typical ADC operates by successive approximation. In this method, a sample and hold circuit captures the analog value. The ADC uses successive approximation register (SAR) and a digital to analog converter (DAC) to convert a digital value to analog. This analog value is compared to the sampled value; if they are not the same, the control logic generates another digital value and the process is repeated until the correct digital representation of the value is found.

![Successive approximation analog to digital converter](image)

A microcontroller may have multiple analog inputs, but usually has only one ADC and an analog multiplexer (mux) to switch between the different inputs. While allowing cheaper construction of the microcontroller, this means that only one analog signal can be sampled at a time.

**Peripherals**

A microcontroller is frequently interfaced to external devices. For instance, a rocket altimeter may use a pressure sensor to convert barometric pressure into an electrical signal. The PerfectFlite altimeter converts pressure into an analog voltage using a Freescale analog pressure sensor. This sensor output is connected to a microcontroller's ADC input so that it can be converted to a digital signal.

Not only do the types of sensors available vary widely, but so does the level of analog and digital components that are added to the sensor. For instance, a simple strain gauge is nothing more than a resistor that varies with the force applied to it; in order to use this signal in a microcontroller other resistors, an amplifier, and an ADC must be used. In the example of the Freescale pressure sensor, the device not only contains a strain gauge fabricated into a housing so that it measures barometric pressure, it also contains the bridge, amplifier and other hardware needed so that a simple 0V to 5V signal is present in the sensor's output. Even more complex sensors may contain an ADC, so that the microcontroller simply reads a digital value from the sensor.
There are other peripherals available for use with microcontrollers. For example, ICs with large amounts of FLASH storage are useful to store data so that it can be retrieved at a later date. A system may not use telemetry, or may gather so much data the telemetry has insufficient bandwidth to convey the data at the desired resolution or sampling rate. Examples of other peripherals are: external UARTs, if interfacing to many RS232 devices such as GPS units or data radios; external ADCs, for increased resolution, or an increased number of analog channels; and digital IO expansion devices.

**Interfacing**

There are many ways to interface digital peripherals. Some manufacturers design their own custom interface and protocol. This can result in many hours spent with the vendor’s datasheet learning to interface the device. Some device interfaces are serial (meaning bits are sent down a single wire, one after the other), or parallel (several digital signals travel down different wires at the same time).

Fortunately there are some interface standards which simplify both the electrical and the software interface to the peripherals. Two common interfaces are the Serial Peripheral Interface (SPI) and Inter-Integrated Circuit (I²C). SPI is a 4 wire interface that uses a shared serial bus among one or more devices. It is full duplex, and some vendors support clock rates 66MHz or higher. I²C is a two wire interface, and the standard speeds are 100 kHz and 400 kHz.

ICs are usually not designed to have long wires connecting peripherals to microcontrollers. If it is necessary to run wires long distances (feet instead of inches), make sure your interface is designed for it.

Another interface standard is the RS232 serial interface. This was originally designed to transfer data serially over longer distances (up to 1500 feet) between computers and peripherals such as terminals, modems, and printers. It is commonly used in GPS units and data radios (such as the Maxstream Xtend). RS232 is not only designed for longer distances, but interface ICs frequently have added features such as electrostatic discharge (ESD) protection built it.

RS232 is a common pitfall for microcontroller users. Microcontrollers that have UARTs provide logic-level voltages and signals. This means logic 1 on the microcontroller is represented as 5V, and logic 0 is 0V. On RS232, the logic 1 (known as “mark”) is typically represented by a voltage of -12V; a logic 0 (or “space”) is +12V. Note that not only are the voltages quite different, but the logic is “inverted”. Connecting an RS232 level device to a TTL device can result in permanent damage to the TTL device.

**IC Packages**

The physical packaging of ICs has changed dramatically. At one time through-hole (or plated through hole, PTH, referring to the PCB construction) device packages such as DIP (dual-inline package), SIP (single-inline package), TO-series (commonly used for transistors), and common leaded resistors and capacitors dominated. As fabrication techniques have provided smaller and smaller devices, the packaging for those devices has decreased accordingly. Surface mount technology (SMT, also known as surface mount devices, SMD) dominates new IC designs. These devices are designed not to mount through holes in the printed circuit board (PCB), but to be soldered directly onto exposed pads on the board. The devices are small enough that the solder joint has sufficient mechanical strength to hold the
device. Some devices have no pins; these are known as “lead-less”. Their electrical connection is provided at exposed pads on the bottom of the device.

These SMT devices can be challenging, since a PCB must frequently be designed and fabricated in order to experiment or prototype. Fortunately PCB fabrication services are available for prototype quantities at reasonable prices and turnaround times. Some vendors provide “breakout boards”. A very small PCB for a single surface mount IC, perhaps with some required resistors and capacitors, is used to “break out” those SMT leads to a through-hole connection that can be used to mount a header or wires that are used to access the device. Some breakout boards are simple adapters to convert an SMT package to a DIP or other through-hole package. Breakout boards allow the development of complex payloads using SMT devices without requiring the soldering of SMT components.

Microcontrollers are also frequently provided on a PCB with some minimal interface hardware. These are known as development boards. A good microcontroller development board for a beginner is the Arduino. It is an open source project based on a board containing an Atmel ATmega microcontroller with the minimum of external devices required for a complete system. There is a free, easy to use software development environment, many daughterboards (known as “shields” in the Arduino community) with peripherals and connectors mounted, and a large user community.

**Software Development**

Software is a critical component of a microcontroller system. Modern microcontroller development environments usually provide a compiler for C or some other high level language, so the microcontroller developer is no longer forced to code in assembly language. They also include an interactive development environment (IDE) with a user-friendly interface for editing, compiling, and downloading programs to the microcontroller.

Just like structures, propulsion systems, and recover systems should be planned carefully, software should also be designed. The software system should be laid out in advance of any coding. Complex areas of the algorithm should be developed in more detail until they can be easily coded.

Programming on a microcontroller should be carried out with special care, since there is no operating system to monitor and report on the program. Programming errors can be very difficult to troubleshoot. Software should be designed and implemented carefully to avoid time-consuming and frustrating debugging efforts later.
A flow chart is a common tool for developing a program. Below is a flow chart for a basic altimeter system.
Telemetry

Telemetry is defined as measurement at a distance. In rocketry, telemetry can be used to provide in-flight reporting of launch vehicle status or payload experiment results. In some cases the launch vehicle or payload are designed with the assumption that the system will not be recovered.

RF Communication

Radio frequency (RF) communications are used for wireless telemetry systems. RF communications take place by modulating (or encoding) information onto an RF signal known as the carrier. An RF signal is usually identified by the carrier's frequency. The base unit of measure for frequency is the Hertz (Hz), which represents one cycle per second. Most frequency values are so large that SI prefixes are used, so our favorite FM radio station's frequency is measured in MHz and Wi-Fi radiates in the 2.5 GHz range. In addition to a frequency, a system may be identified by the band that it operates in. A band is a contiguous range of frequencies that are similar in nature. VHF and UHF are two such band designations. One of the most common amateur radio bands is the 2 meter band, which includes the frequencies from 144MHz to 148MHz in the US. Channel is another frequency designation. The channel identifier is a logical or tactical designation specific to a particular implementation and is used to simplify things for the operator. We don't have to remember 536.31MHz when tuning to Huntsville's local public television station; we tune the TV to channel 25.

Licensing

Licensing is an important issue in RF communications. RF signal propagation is a physical phenomenon that does not respect arbitrary boundaries such as political borders. The use of RF frequencies is coordinated by the International Telecommunication Union (ITU). There are three ITU regions; the United States is in region 2. All RF use is governed by the Federal Communications Commission (FCC) in the US. For example, an amateur radio operator holding a technician's class license is allowed to use, among others, frequencies between 144MHz and 148MHz with power levels up to 1.5kW as required by the application. Within that range, amateur radio operators have self governance, and a plan known as “the 2m band plan” identifies the technical and logical use of these frequencies.

Not all RF equipment requires the operator to hold a license. In some cases a service provider will hold the license and make provisions for hardware that makes use of the assigned spectrum. The license holder is responsible for the behavior of the RF devices. The license holder may then allow others to use those devices. This is how the cellular telephone network frequencies are managed.

A set of frequencies in different bands are set aside by the FCC (and governing bodies of other nations) for “industrial, scientific, and medical” use. These frequencies are referred to as the ISM band. Even though they are referred to as a band, they are in fact narrow frequency ranges in several bands. ISM frequencies are used by garage door openers, Wi-Fi, Bluetooth devices, and ZigBee modules. While there is some overlap, ISM frequencies vary between countries and ITU regions.
Modulation

RF communications takes place by modulating information onto an RF carrier. Two common modulation techniques are Amplitude Modulation (AM), where information is represented by changing the amplitude of the carrier signal, and Frequency Modulation (FM), where the frequency of the carrier is changed to encode the information. Other common modulation techniques are on-off keying (OOK) and various forms of phase shift keying (PSK).

Bandwidth

An important property of an RF signal is its bandwidth. The bandwidth of an RF signal is the difference between the upper and lower frequencies occupied by the signal. An amateur radio 2m FM voice signal occupies 25 kHz, an FM broadcast signal 200 kHz, and a UHF TV channel occupies 6MHz. The amount of information that can be transmitted directly correlates to the bandwidth of the RF signal. Note that RF bandwidth is not the same as data bandwidth, which is the rate a system can transfer digital data, measured in bits per second or bytes per second.

Even though a signal occupies a particular bandwidth, it is referred to as a single frequency. This is usually the frequency in the middle of the range (where the signal is strongest). This is referred to as the center frequency.

Another important signal characteristic is the baud rate, which is the number of symbols or transitions per unit time. This is distinct from the bit rate because some modulation techniques are not binary in nature. Quadrature phase shift keying (QPSK) encodes two bits per symbol, so that data rate is double the baud rate.

Antennas

A critical part of an RF system is the antenna. An antenna is the part of the system that converts an RF signal to an AC (alternating current) electrical signal, and vice versa. An antenna usually consists of one or more elements made from electrically conductive material. When receiving, the antenna converts some of the electromagnetic signal present at the elements into electrical energy, which is then passed to the receiver via the transmission line. When transmitting, the antenna converts electrical energy from the transmitter to electromagnetic waves.

In addition to referring to an RF signal by its frequency, it is useful to know the wavelength of the signal. The wavelength of a signal in a vacuum is \( c/f \), where \( f \) is the frequency in Hz and \( c \) is the speed of light. The signal will propagate more slowly in a physical medium. The difference between this speed and \( c \) is known as the velocity factor and is expressed as a percentage or fraction of \( c \).

Wavelength is especially important in antenna design, since the physical size of the elements will be a function of the wavelength of the signal in the material making up the antenna element. \( \frac{1}{4} \) and \( \frac{1}{2} \) wavelength antenna elements are common because they correspond well to the electrical characteristics of the signal. The propagation of a radio signal depends largely on the frequency of the signal and the environment. In free space a signal propagates uniformly; in reality a signal is affected by atmospheric conditions, terrain, manmade structures, and other factors. The effect depends on the
frequency of the signal as well. Some frequencies are reflected by the atmosphere, depending on the time of day.

Telemetry systems used on rockets will usually use VHF or higher frequencies. These frequencies are known as “line of sight” since they are not typically reflected by the atmosphere, and a direct line between the receiver and transmitter must be available. Buildings, utility towers, trees, hills, the horizon, and other natural and manmade objects attenuate or reflect the signal.

Antenna performance is usually compared to a theoretical antenna known as an isotropic point source, a point at which the signal would radiate outwards in a three dimensional spherical pattern (assuming the antenna was located in free space). The difference between an antenna's performance and the theoretical point source is called gain, and is measured in decibels (dB). The decibel is on a logarithmic scale. A 3dB change is a factor of 2; 10dB is a factor of 10.

There are two ways to increase the amount of RF signal available to a receiver. One is to increase the amount of power at the transmitter, so that there is simply more energy available to the receiving antenna. The other way is to increase the gain or sensitivity of the receiving antenna. We change the gain of an antenna by changing the radiation pattern, increasing the efficiency in some directions by sacrificing a corresponding decrease in efficiency in others.

Our theoretical isotropic point source has a perfectly spherical radiation pattern, equally efficient in all directions. Half or more of the energy from such an antenna would be wasted in many terrestrial applications, since the antenna would be near the ground, where the earth itself would block half the signal. A very common antenna design is the half-wave dipole, which produces a toroidal radiation pattern so that it is more sensitive perpendicular to the axis of the dipole elements, but less sensitive in the direction that the elements point. If we orient the dipole vertically, we will have an area that is less sensitive above and below the antenna, but more sensitive toward the horizon. Because the dipole is uniformly sensitive about its axis, it is known as an omnidirectional antenna.
It is possible to concentrate sensitivity even more in a particular direction. A Yagi antenna is more sensitive along the axis of the beam where the elements are mounted. The design consists of a reflector, a driven element to which the transmission line is attached, and one or more directors. The driven element is usually a half wave dipole. The reflector is slightly longer, and the director elements are shorter than the driven element and decrease in length the farther they are from the driven element. More directors will result in increased gain and a corresponding reduction in the volume of sensitivity.
When choosing an antenna for flight hardware, keep in mind that the rocket's orientation will change constantly; not only will the position change in all 3 dimensions, but the yaw, pitch, and roll will change as well. An antenna that is truly omnidirectional in all directions, such as a simple 1/2 wave dipole, is usually the best candidate for the flight antenna.

The ground station antenna depends on the power output of the transmitter. If the transmitter is weak, a directional antenna with appropriate gain is needed. This gain antenna must be pointed at the rocket or communications can be lost; the higher the gain, the more precise this pointing must be. If the transmitter is capable of higher RF power output (which may be constrained by mass, power, heat, or monetary budgets, or by licensing), then a simpler ground station antenna may be used.

The signal from a typical terrestrial RF system is polarized. The waves have a particular orientation as a result of the antenna geometry. A dipole antenna with the elements oriented vertically results in a signal that is vertically polarized. If the transmit and receive antennas do not have the same polarization, up to 3dB (half) of the signal is lost. If the rocket's antenna is along the axis of the rocket's main structure it will be vertically polarized. Upon landing, it will usually be horizontal (tree landings and core samples being two obvious exceptions).
A variety of commercial off the shelf (COTS) radio modules are available. Complexity of use can range from simple plug-in pairs that act as a wireless RS232 cable to modules that require the operator to provide handshaking, error detection and correction, and all other communications functionality. A few devices have complete enclosures, but most are PCB modules that require external support for regulated power and interfacing. Antennas may be built in or external. Output power is usually low, as most of these devices utilize ISM frequencies. Most are 2.5GHz or 900MHz ISM devices. Some example types are the various ZigBee family devices, the Digi/Maxstream Xtend, or the Nordic nRF2401A. The flight hardware component of a typical telemetry system would include one of these modules, an antenna, power source, one or more sensors, and a microcontroller.
ARCAS Rocket Assembly Instructions

Parts List:

1. Secant-Ogive fiberglass nose cone
2. G10 coupler bulk plate
3. Pre-slotted fiberglass booster airframe
4. G10 centering rings
5. 38mm motor tube
6. G10 fins
7. Eyebolt, nut, washer set
8. Nylon shock cord
9. ¼” launch lugs
10. Cut letter vinyl decal
11. 9”x9” flameproof parachute protector
12. 30” nylon parachute
13. Aero Pack 38mm motor retainer

Specifications:

Length: 52.5”
Diameter: 2.6”
Weight: 32 oz
Recovery: 30” nylon parachute
Motor Mount: 38mm
Fins: 4 -1/16” G10
Motor Mount Assembly

The motor mount assembly consists of the forward centering ring with eyebolt, aft centering ring, and motor retainer body. Surfaces should be cleaned with an alcohol wipe to remove dust and mold release, sanded where epoxy is to be applied, and cleaned again with an alcohol wipe. This preparation is important to ensure the epoxy bonds the components properly.

**NOTE:** Sand, dry fit and clean all components before applying epoxy.

The centering ring with the 1/4” hole for an eyebolt will be the forward ring. Mount the eyebolt using two nuts as shown in the forward ring hole. Test fit the forward ring over the motor mount tube and sand if necessary. Also test fit the forward ring in the body tube and sand if necessary. Sand the surface of the motor tube to increase adhesion strength. Mark the motor tube 1/2” from the end and slide the forward ring until it aligns with the mark.
The remaining centering ring will be the aft ring. Test fit the aft ring over the motor mount tube and sand if necessary. Also test fit the aft ring in the body tube and sand if necessary. Sand the surface of the motor tube to increase adhesion strength. Slide the aft ring on to and up the motor tube approximately 2” (DO NOT EPOXY).

Remove the nut from the motor retainer and set aside. Dry fit the motor retainer onto the motor mount tube, sanding as needed.

Once all components have been sanded to fit properly and the components have been cleaned, the assembly is ready for epoxy. Slide the aft centering ring onto the motor tube approximately 2”; do not apply epoxy to this part yet. Apply a thin even layer of epoxy on the aft 3/8” of the motor mount tube, and install the motor retainer. Slide the aft ring down and against the motor retainer. Apply a bead of epoxy on the forward edge of the aft ring where it meets the motor mount tube.
Slide the forward centering ring (with eyebolt and 2 nuts already installed) approximately ¼” from the forward end of the motor mount tube. Ensure the eyebolt and nuts are oriented so that they will not interfere with either the body tube or the motor once installed.

Apply a bead of epoxy to the forward end of the motor mount tube at the mark made previously. Slide the forward centering ring to the mark. Apply a bead of epoxy to the forward edge of the forward centering ring where it meets the motor mount tube. Apply epoxy to both nuts to secure the eyebolt. This eyebolt is the anchor for the recovery harness.

**IMPORTANT:** Make sure there is no epoxy on the outside of motor tube that would interfere with the fin tangs later on. Make sure there is no epoxy on the inside of the motor tube that would interfere with the motor case later on.
Set aside the motor mount assembly and allow the epoxy to cure at least 1 hour before handling.
Coupler Bulkplate Assembly

Mount the remaining eyebolt to the bulkplate using ¼” nuts and washers. Install components onto the eyebolt in the following order:

- Nut
- Small washer
- Bulkplate
- Fender washer (large washer)
- Lock nut (nylon insert locknut)

Thread the eyebolt into the locknut until at least one full thread is above the nut. Tighten the lower nut against the bulkplate.
Test fit the bulk plate in the coupler and sand if necessary. Epoxy the bulk plate about a 1/4" into the coupler. Next, apply a fillet of epoxy around the bulk plate and coupler joint.

Lay the coupler horizontally with the eyebolt resting on the 1-3/16" support block provided. Allow the epoxy to cure for at least one hour before handling.
Motor Mount Installation

Test fit the motor tube assembly into the body tube to ensure a snug fit. Sand the centering rings if necessary. Remember to clean any sanded surfaces before applying epoxy to ensure a strong joint.

When satisfied with the fit, install the shock cord by tying it to the eyebolt in the forward centering ring. Fold the shock chord into a small bundle and place it inside the motor tube so that it does not protrude from either end.

Lay the motor mount assembly beside the aft end of the aft body tube so that the aft centering ring is approximately \( \frac{3}{4} \)” forward of the end of the body tube. Note where the forward centering is located; mark the body tube if needed.
Apply epoxy on the inside of the body tube just aft of the final location of the forward centering ring. Slide the forward centering ring of the motor assembly into the body tube. Make sure the motor assembly is facing the right way!

With the motor mount assembly about halfway inserted, apply a bead of epoxy to the inside edge of the body tube before sliding the rear centering ring into the body tube.

Continue sliding the assembly inside the body tube until the aft ring of the motor tube is 1/8” to 1/4” inside the aft end of the body tube. Apply another bead of epoxy to the aft centering ring where it meets the body tube.

Set the assembly aside and allow the epoxy to cure for at least one hour.
Payload Airframe, Coupler and Nosecone Assembly

Test fit the coupler into the forward airframe tube. Mark the coupler at the midpoint and slide the open end of the coupler into the airframe until it reaches this point.

Apply masking tape to the junction of the coupler and airframe to hold it while drilling. Mark the airframe 1-1/2” from the end of the airframe on opposite sides. Use the provided cradle to hold the airframe assembly while drilling. Drill one hole and install a rivet into the hole, securing the coupler. Drill a second hole on the opposite side of the airframe and install a second rivet.

Install the nosecone in the forward end of the payload airframe in the same manner.
Fin Installation and Alignment

Test fit each of the fins into the pre-cut fin slots. The fin tang should seat firmly against the motor tube and the fin shoulder should seat against the airframe - sand each fin if necessary. Mark fins and slots, so that the fin is installed in the slot to which it is fitted. Sand the airframe around each slot so epoxy will bond securely. Clean all surfaces.

When satisfied with the fit, apply some epoxy to the end of the fin tang that will contact the motor tube. Also, spread a thin layer of epoxy on each side of the fin tang.

Slide the fin into place and check the alignment. Insert the airframe and fin into the fin alignment jig provided. Use masking tape to secure the fin while the epoxy cures, being careful not to allow the tape to block adjacent fin slots. Repeat this process for the remaining fins.

Next, apply epoxy fillets to both sides of each fin by applying a thin bead of epoxy at the fin-body tube joining. Carefully smooth the epoxy before the epoxy sets.

Allow the assembly to cure for at least one hour before handling.
Rail Buttons

After the fins have cured, use the rail button jig provided to drill the holes for the rail buttons. The angled aluminum will align itself when laid flush on the airframe. Align the end of the jig with the aft end of the airframe and tape the jig in place with masking tape. Ensure the forward rail button will not interfere with the coupler when installed. Drill the forward and aft rail button screw holes with the designated size drill bit and remove the jig.

Apply a small amount of epoxy on the hole and screw in the rail button. Once the rail button is fully seated, use an alcohol wipe to clean off any excess epoxy before it hardens. An optional nut is provided to reinforce and smooth the forward rail
button screw.

**Connect the Recovery System**

Tie an over hand knot or double-figure-8 knot at the end of the shock cord.

Collect all the support lines of the parachute so that they are even. Tie the collection of support lines in a knot leaving a large enough loop at the end for the quick link.

Using the supplied quick link, link together items in this order:

- the payload eye bolt
- the knot at the end of the shock chord
- The parachute protector
- The knot tied at the end of the parachute support lines
Assemble the Motor

Remove the motor reload from the packaging and inspect. Verify that the paper disk covering the ejection charge does not look tampered and that the nozzle looks clean and unobstructed. Place the yellow cover onto the nozzle of the motor reload. Insert the reload into the case and securely screw together. Present to the certifying official to verify complete assembly before proceeding at this time. Remove the motor retainer cap, insert the motor, and securely reinstall the motor retainer cap. Hold on to the igniter.
Prepare the Recovery System

First, place a hand full of “dog barf” into the rocket. Dog barf is cellulose insulation that will protect the recovery system from the ejection charge. Begin placing the shock cord into the rocket. Fold several lengths as shown in the photo and lay them inside the rocket on top of the “dog barf”.

Loosely wrap the folded parachute into the parachute protector. The parachute folding directions are in the recovery section of this workbook. Place the parachute inside of the rocket with the stitched loop facing the top.
Flying Your Rocket

Attach the end of the shock cord and the parachute to the payload section’s eyebolt. The chute protector must be attached so that it cannot slide up the shroud lines, reefing the chute – this will decrease the chute’s drag and may result in an unsafe descent rate. When packing the chute, wrap the chute protector around the chute with the opening in the chute protector facing forward. Always make sure the chute is well protected as the hot ejection charge gasses will melt the nylon chute.

**IMPORTANT:** Always use positive motor retention to secure the motor in the motor tube. Failure to use motor retention may allow the motor to be ejected during the ejection charge instead of the parachute, making for a dangerous ballistic reentry.

**IMPORTANT:** Always remember to check the balance point and ensure the CG is forward of the recommended CG point.

**IMPORTANT:** Always follow the NAR safety code and remember that rockets are not toys and can be dangerous if not prepared and used properly. If you are a beginner, it is a good idea to fly with a club or other groups of experienced rocketeers until you have gained some experience.
Checklists

Pre-Launch Checklist
Launch Pad Checklist
Pre-Launch Checklist:

Complete this checklist prior to launch attempt and under the supervision of an appropriately certified NAR member. This checklist is to be completed by the certifying individual.

Structures: Inspect each component for security and flight worthiness.

1. [ ] Nosecone
2. [ ] Airframe
3. [ ] Fins
4. [ ] Rail Buttons
5. [ ] Motor Retainer

Recovery: Inspect each component for security and flight worthiness.

6. [ ] Shock Cord – Secured between nosecone and forward ring eye-bolts.
7. [ ] Chute Protector
8. [ ] Parachute – Fold and install parachute according to the parachute folding direction.

Propulsion: Inspect each component for security and flight worthiness.

9. [ ] Motor Case -Inspect for cleanliness.
10. [ ] Motor Reload – Install into motor case per manufacturer’s instructions.
12. [ ] Igniter – Locate and retain igniter until needed. ***DO NOT INSERT IGNITER***.

Documentation:

13. [ ] NAR Certification Form – Fill in appropriate fields and retain copy for endorsement by an appropriately certified NAR member.
14. [ ] Complete this checklist below and inform a workshop staff member for review.

Checklist is completed by: [name] ________________________________[date]______________

Checklist is reviewed by: [name] ________________________________[date]______________

Proceed to Range Safety Officer (RSO) for final inspection and further instruction. Fill in appropriate fields on a Flight Card. Declare to the RSO that your flight is a Level 1 Certification Flight.
Launch Pad Checklist:

Complete this checklist at the launch pad under the supervision of a Launch Safety Officer (LSO) or appropriately certified NAR member. This checklist is to be completed by the certifying individual.

Launch Pad:

1. [     ] Launch Rail – Inspect launch rail for excessive corrosion or snags that would risk the rocket jamming on the rail.
2. [     ] Rocket – slide the rocket down onto the rail until it is against the rest.

Propulsion: - The Launch Control System (LCS) pad bank must be switched OFF.

3. [     ] Insert igniter fully into the rocket motor thru the nozzle and install the nozzle cover.
4. [     ] Strip 1" - 2" of the wire’s sheath to expose both wire cores.
5. [     ] Short LCS circuit by tapping both alligator clips together.
6. [     ] Connect one wire core to each alligator clip wrapping the excess wire around the clip.

NOTE: The LSO may ask you to do any number of these steps in a different order. Be prepared to deviate from this checklist. If you feel you are being asked to do anything unsafe, respectfully ask for clarification on the reason for the change.

NOTE: You may also change the launch angle on the launch pad up to 20 degrees off of vertical depending on the winds.

7. [     ] Before returning to the RSO tent, switch the LCS pad bank **ON** if you are the last person leaving the area.

Documentation:

8. [     ] Complete this checklist below and inform a workshop staff member for review.

   Checklist is completed by: [name] ____________________________ [date]________________

   Checklist is reviewed by: [name] ________________________________ [date]________________

Return to the RSO tent with your Flight Card pad number filled in. After flight, remain behind RSO line until the field is reopened.
Exercise Solutions

Structures Exercises

Propulsion Exercises

Recovery Exercises
Structures Exercise 1: Center of Pressure Calculation

This exercise will teach analysis of the rocket’s Center of Pressure \((CP \text{ or } \overline{X}_{CP})\) by regional influence using algebraic forms of the Barrowman equations. Each primary component has a Normal Force \((C_{na})\) corresponding to its contribution. Each Normal Force is recorded by Station \((\overline{X}_i)\) or position of the component’s Normal Force as measured from the tip of the nose cone. The basic assumptions used in calculation the theoretical center of pressure for this rocket are:

- The angle of attack \((\alpha)\) of the rocket is near zero (less than 10\(^\circ\))
- The speed of the rocket is much less than the speed of sound (not more than 500 mph)
- The air flow over the rocket is smooth and does not change rapidly
- The rocket is thin compared to its length \((L >> D)\)
- The nose of the rocket comes smoothly to a point
- The rocket is an axially symmetrical rigid body
- The fins are thin flat plates

Nose cone:

In general, the Normal Force \((C_{Na})\) on the nose cone is identical for all shapes and always has the value 2. The Station \((\overline{X}_n)\) varies with each different shape. The algebraic form equations for calculating the normal force and center of pressure for a conical nose cone are:

\[
(C_{Na})_n = 2 \quad \overline{X}_n = \frac{2}{3}L_n
\]

\(L_n\) is the length of the nose cone. Solve for \((\overline{X}_n)\) and enter the values into the solution matrix.

Airframe:

The Airframe provides no response for low angles of attack.

\[
(C_{Na})_a = 0 \quad \overline{X}_a = L_n + \frac{1}{2}L_a
\]

\(L_a\) is the length of the airframe. Solve for Station \((\overline{X}_a)\) and enter the values into the solution matrix.

Fins:

The rocket’s four fins contribute the bulk of the aerodynamic forces. The forces \((C_{Na})_f\) and Station\(\overline{X}_f\) for these four fins are calculated using the following equations:
The rocket's fin dimensions are shown below. Solve for \((C_{Na})_f\) and \(\bar{X}_f\).

**Solution:**

Calculating for the normal force of the fins \((C_{Na})_f\):

- \(N\) represents the number of fins on the rocket. The rocket we are analyzing has 4 fins (N=4).
- \(S\) represents the span of each fin measured from the airframe to the tip. (\(S = 2.5''\))
- \(D\) represents the diameter of the rocket airframe. (\(d = 2.6''\))
- \(A\) represents the length of the fins root cord. (\(A = 6''\))
- \(B\) represents the length of the fins tip cord (\(b = 2.6''\))
- \(L\) represents the length of the fin’s half cord (\(L = 3.1''\) measured empirically)

\[
(C_{Na})_f = \frac{4N(S/2)^2}{1 + \sqrt{1 + \left(\frac{2L}{A+B}\right)^2}}
\]

\[
\bar{X}_f = X_f + \Delta X_f
\]

\[
\Delta X_f = \frac{M(A + 2B)}{3(A + B)} + \frac{1}{6} \left(A + B - \frac{AB}{A + B}\right)
\]
An interference factor must be used to correct for the presence of the airframe. The algebraic form equation to correct for this airframe interference is:

\[ \text{(C}_{Na}\text{)}_f = \frac{4(4)(2.55)^2}{1 + \sqrt{1 + \left(\frac{2(3.1)}{6 + 2}\right)^2}} = 5.4 \]

\[ K_{fb} = 1 + \frac{r}{s + r} \quad \text{(C}_{Na}\text{)}_{fb} = K_{fb} \text{(C}_{Na}\text{)}_f \]

R is the radius of the airframe and S is the span of the fin.

\[ K_{fb} = 1 + \frac{1.3^*}{2.6^*+1.3^*} = 1.4 \quad \text{(C}_{Na}\text{)}_{fb} = 1.4(5.4) = 7.56 \]

**Solution:**

Calculating the center of pressure of the fin’s \( \bar{X}_f \):

\( X_f \) represents the distance from the tip of the nose cone to the forward root of the fins.

\( \Delta X_f \) represents the distance from the forward root of the fins to the fin’s center of pressure.

\[ \bar{X}_f = 29'' + \frac{2.75''(4.75'' + 2(2''))}{3(4.75'' + 2'')} + \frac{1}{6} \left( 4.75'' + 2'' - \frac{4.75'' + 2''}{4.75'' + 2''} \right) = 48.9'' \]

Enter the values for \( \text{(C}_{Na}\text{)}_{fb} \) and \( \bar{X}_f \) into the matrix on sheet 3.

**Center of Pressure Solution Matrix:**

<table>
<thead>
<tr>
<th>Component</th>
<th>Shape</th>
<th>( \text{C}_{n\alpha} )</th>
<th>( \bar{X} ) (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nose cone</td>
<td>Ogive</td>
<td>2</td>
<td>5.7&quot;</td>
</tr>
<tr>
<td>Airframe</td>
<td>Cylindrical</td>
<td>0</td>
<td>26.25&quot;</td>
</tr>
<tr>
<td>Fins (Set of 4)</td>
<td>Clipped Delta</td>
<td>7.6</td>
<td>48.9&quot;</td>
</tr>
</tbody>
</table>

The total normal force is the sum of the regional forces:

\[ \text{C}_{na} = (\text{C}_{n\alpha})_n + (\text{C}_{n\alpha})_a + (\text{C}_{n\alpha})_{fb} \]

**Solution:**

\[ \text{C}_{n\alpha} = 2 + 0 + 7.6 = 9.6 \]
The Center of Pressure (CP) of the entire rocket is found by taking the moment balance about the nose cone tip and solving for the total center of pressure location

\[ \overline{X} = \frac{(C_{nA})_n \overline{X_n} + (C_{nA})_a \overline{X_a} + (C_{nA})_f \overline{X_f}}{C_{nA}} \]

Solution:

\[ \overline{X} = \frac{2(5.7") + 0(26.25") + 7.6(48.9")}{9.6} = \frac{11.4" + 369.7"}{9.6} = 39.7" \]

The Center of Pressure for the rocket is located at 39.7 inches from the nose cone tip.
Structures Exercise 2: Center of Gravity Calculation

This exercise will teach analysis of the rocket’s Center of Gravity \((CG\ or\ \bar{x}_{CG})\) using the Center of Masses equation.

\[
\bar{x}_{CG} W_{CG} = \sum_{i=1}^{n} W_i \bar{x}_i = W_1 \bar{x}_1 + W_2 \bar{x}_2 + W_3 \bar{x}_3 + \ldots
\]

\[
W_{CG} = \sum_{i=1}^{n} W_i = W_1 + W_2 + W_3 + \ldots
\]

\[
\bar{x}_{CG} = \frac{\bar{x}_{CG} W_{CG}}{W_{CG}}
\]

Each component’s weight\((W_i)\), for simplicity, is treated as a point mass or single force acting through the centroid of the component. In physics, the word centroid means the geometric center of the object’s shape. Each component’s centroid is recorded by Station \((\bar{x}_i)\) or position of the component’s centroid as measured from the tip of the nose cone. The basic assumptions used in calculation the theoretical center of gravity for this rocket are:

- Uniform gravitational field \((g = \text{constant})\)
- Components have uniform density \((\rho = c\text{onstant})\)

Each component’s Weight \((W_i)\) and Station \((\bar{x}_i)\) is shown in table below. Solve for the rocket’s Center of Gravity using the data in table below and the Center of Masses equation.

<table>
<thead>
<tr>
<th>Component</th>
<th>Qntity</th>
<th>Length</th>
<th>Weight (oz)</th>
<th>Margin</th>
<th>Weight (oz)</th>
<th>Station (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiberglass nosecone</td>
<td>1</td>
<td>10.00 in</td>
<td>3.40 oz</td>
<td>0%</td>
<td>3.40 oz</td>
<td>6.5 in</td>
</tr>
<tr>
<td>Nosecone mass</td>
<td>1</td>
<td>N/A</td>
<td>2.00 oz</td>
<td>20%</td>
<td>2.40 oz</td>
<td>1.0 in</td>
</tr>
<tr>
<td>G10 Nosecone Bulkplate</td>
<td>1</td>
<td>0.06 in</td>
<td>0.30 oz</td>
<td>20%</td>
<td>0.36 oz</td>
<td>10.5 in</td>
</tr>
<tr>
<td>Payload Airframe Tube</td>
<td>1</td>
<td>16.00 in</td>
<td>4.80 oz</td>
<td>5%</td>
<td>5.04 oz</td>
<td>18.0 in</td>
</tr>
<tr>
<td>Payload Coupler Tube</td>
<td>1</td>
<td>6.00 in</td>
<td>1.80 oz</td>
<td>20%</td>
<td>2.16 oz</td>
<td>26.0 in</td>
</tr>
<tr>
<td>Payload Coupler Bulkplate</td>
<td>1</td>
<td>0.06 in</td>
<td>0.30 oz</td>
<td>20%</td>
<td>0.36 oz</td>
<td>29.0 in</td>
</tr>
<tr>
<td>Payload Bulkplate Eyebolt ASSY</td>
<td>1</td>
<td>1.00 in</td>
<td>0.80 oz</td>
<td>10%</td>
<td>0.88 oz</td>
<td>29.0 in</td>
</tr>
<tr>
<td>12 feet shock cord</td>
<td>1</td>
<td>6.00 in</td>
<td>2.00 oz</td>
<td>0%</td>
<td>2.00 oz</td>
<td>39.0 in</td>
</tr>
<tr>
<td>30 inch parachute</td>
<td>1</td>
<td>6.00 in</td>
<td>1.00 oz</td>
<td>0%</td>
<td>1.00 oz</td>
<td>39.0 in</td>
</tr>
<tr>
<td>9x9 Parachute Protector</td>
<td>1</td>
<td>6.00 in</td>
<td>0.50 oz</td>
<td>0%</td>
<td>0.50 oz</td>
<td>39.0 in</td>
</tr>
<tr>
<td>Booster Airframe (Slotted)</td>
<td>1</td>
<td>26.00 in</td>
<td>7.70 oz</td>
<td>5%</td>
<td>8.09 oz</td>
<td>39.0 in</td>
</tr>
<tr>
<td>38mm Motor Tube</td>
<td>1</td>
<td>8.00 in</td>
<td>2.30 oz</td>
<td>5%</td>
<td>2.42 oz</td>
<td>47.0 in</td>
</tr>
<tr>
<td>Forward Centering Ring</td>
<td>1</td>
<td>0.06 in</td>
<td>0.20 oz</td>
<td>20%</td>
<td>0.24 oz</td>
<td>45.0 in</td>
</tr>
<tr>
<td>FWD Centering Ring Eyebolt ASSY</td>
<td>1</td>
<td>1.00 in</td>
<td>0.80 oz</td>
<td>10%</td>
<td>0.88 oz</td>
<td>45.0 in</td>
</tr>
<tr>
<td>G10 Clipped Delta Fins</td>
<td>4</td>
<td>5.00 in</td>
<td>0.50 oz</td>
<td>20%</td>
<td>2.40 oz</td>
<td>49.0 in</td>
</tr>
<tr>
<td>Aft Centering Ring</td>
<td>1</td>
<td>0.06 in</td>
<td>0.20 oz</td>
<td>20%</td>
<td>0.24 oz</td>
<td>52.0 in</td>
</tr>
<tr>
<td>38mm Aero-Pack Motor Retainer</td>
<td>1</td>
<td>0.25 in</td>
<td>0.80 oz</td>
<td>0%</td>
<td>0.80 oz</td>
<td>52.0 in</td>
</tr>
<tr>
<td>CTI pro38 2G case</td>
<td>1</td>
<td>8.00 in</td>
<td>3.50 oz</td>
<td>0%</td>
<td>3.50 oz</td>
<td>49.0 in</td>
</tr>
<tr>
<td>CTI H225 Reload</td>
<td>1</td>
<td>8.00 in</td>
<td>6.80 oz</td>
<td>0%</td>
<td>6.80 oz</td>
<td>49.0 in</td>
</tr>
</tbody>
</table>
Solution:

\[ \bar{X}_{CG} \bar{W}_{CG} = 3.4\text{oz}(6.5\text{”}) + 2.4\text{oz}(1\text{”}) + 0.36\text{oz}(10.5\text{”}) + 5.4\text{oz}(18.0\text{”}) + 2.16\text{oz}(26\text{”}) \\
+ 0.36\text{oz}(29\text{”}) + 0.88\text{oz}(29\text{”}) + 2.0\text{oz}(39\text{”}) + 1.0\text{oz}(39\text{”}) + 0.5\text{oz}(39\text{”}) + 8.1\text{oz}(39\text{”}) \\
+ 2.42\text{oz}(47\text{”}) + 0.24\text{oz}(45\text{”}) + 0.8\text{oz}(52\text{”}) + 3.5\text{oz}(30\text{”}) + 6.8\text{oz}(30\text{”}) = 741\text{ oz.in.} \]

\[ W_{CG} = W_1 + W_2 + W_3 + W_4 + W_5 + W_6 + W_7 + W_8 + W_9 + W_{10} + W_{11} + W_{12} + W_{13} + W_{14} + W_{15} \]

\[ = 43.46\text{oz (2.72 lbs)} \]

\[ \bar{X}_{CG} = \frac{\bar{X}_{CG} \bar{W}_{CG}}{W_{CG}} = \frac{1503 \text{ oz.in.}}{43.46 \text{ oz.}} = 34.6 \text{ in.} \]

The Center of Gravity for the rocket is located at \textbf{34.6 inches} from the nose cone tip.
Structures Exercise 3: Stability Calculation

This exercise will teach calculation of the rocket’s Static Margin. The Static Margin or Margin of Stability is a non-dimensional characteristic that describes the directional stability of a rocket.

\[ S.M. = \frac{\bar{x}_{cp} - \bar{x}_{cg}}{\text{Body Diameter}} \]

A rocket is generally considered stable if it has a margin of 1.0 or greater. The ideal Stability Margin is 1.5 to 2.0. Calculate the Static Margin of the rocket:

Solution:

\[ S.M. = \frac{39.7" - 34.6"}{2.6"} = 1.9 \]

The rocket has a Static/Stability Margin of \textbf{1.9}
Propulsion Exercise 1: Thrust Curve

This exercise will teach reading a thrust curve plot and identifying the motor that will be used in flying. A thrust curve is obtained experimentally for solid rocket motors by placing the motor on a test stand, igniting the propellant, and recording the thrust as a function of time. This allows knowing how the motor will perform when placed in the rocket. The chart below is a thrust curve plot for the motor that you will be flying in the workshop rocket.

Total impulse is most accurately determined by calculating the area under the curve. Average thrust is calculated at the total impulse divided by the burn time. Burn time is generally considered the time when thrust drops below 5% of the maximum thrust.

Using the thrust curve plot, determine the following:

4. Burn Time (s): 2.15 s
5. Maximum Thrust (N): 152.6 N
6. Average Thrust (N): 125.1 N

Using the determined values, calculate the following:

4. Total Impulse (N-s):
5. Impulse Class (Alpha):
6. Motor Designation:

**Solution:**

Total Impulse = 125 N × 2.15 s = 268.8 Ns
Impulse Class = H Class
Motor Designation: H125

If the rocket weights 2.6 lbs, calculate the thrust to weight ratio: (4.45 N = 1 lbf)

**Solution:**

\[
\frac{T}{W} = \frac{125 \text{ N} \times (1 \text{lbf}/4.45\text{N})}{2.6\text{lbf}} = 10.8 : 1
\]
Propulsion Exercise 2: Delta-V Calculation

This exercise will provide practice calculating the ΔV of a rocket using data about the rocket you are building and the motor that you will certify on. The basic assumptions used in the ideal rocket equation calculation are:

6. The rocket is operating in space (no drag or gravity penalties)
7. The gravitational constant (g₀) is constant thought the universe.
8. The motor is instantly on and off (no throttling up or tailing off).

Given the following parameters:

\[ l_{sp} = 216.6 \, s \quad g_0 = 32.2 \, \frac{ft}{s^2} \quad m_i = 2.6 \, lbm \]

\[ m_p = 0.28 \, lbm \quad m_f = m_i - m_p \]

\[ \Delta V = v_e \ln \left( \frac{m_i}{m_f} \right) = l_{sp} g_0 \ln \left( \frac{m_i}{m_f} \right) \]

Calculate the following:

3. ΔV
4. \( v_e \)

Solution:

\[ \Delta V = 216.6 \, sec \times 32.2 \, \frac{ft}{s^2} \times \ln \left( \frac{2.6 \, lbm}{2.6 \, lbm - 0.28 \, lbm} \right) = 795 \, fps = 542 \, mph \]

\[ v_e = l_{sp} g_0 = 216.6 \, s \times 32.2 \, \frac{ft}{s^2} = 6,975 \, fps = 4,756 \, mph \]

The propulsion system of this rocket is capable of accelerating it to a speed of 542 mph. Note that this calculation assumes no aerodynamic drag or gravitational losses. A more in depth analysis must be done to determine the actual ΔV, but this is a good ball park.
Propulsion Exercise 3: Ballistics Coefficient Calculation

This exercise will provide practice determining the ballistics coefficient of a rocket.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>2.6 lbs</td>
</tr>
<tr>
<td>Drag Coefficient</td>
<td>0.5</td>
</tr>
<tr>
<td>Diameter</td>
<td>2.6 in</td>
</tr>
</tbody>
</table>

Determine $\beta$:

**Ballistics Coefficient:**

$$\beta = \frac{W_f}{SC_D} = \frac{W_f}{\frac{\pi}{4} D^2 C_D}$$

**Solution:**

$$\beta = \frac{W_f}{\frac{\pi}{4} D^2 C_D} = \frac{2.6 \text{ lbs}}{\frac{\pi}{4} (2.6)^2 (0.5)} = 3.9$$

The rocket has a ballistics coefficient of **3.9**.
Recovery Exercise 1: Ejection Charge Calculation

A black powder charge is the most common and reliable method of ejecting a parachute from the rocket. This exercise will teach determining the ideal amount needed for the rocket by using the Idea Gas Law.

\[ PV = NRT \text{ (Ideal Gas Law)} \quad P = \frac{F}{A} \text{ (Pressure)} \]

The constants for 4F black powder are:

\[ R = 266 \text{ in lbf/} \text{lbm} \text{ (Gas Constant)} \quad T = 3307^\circ R \text{ (Temperature)} \]

The variables for the rocket are:

\[ F = 75 \text{ lbf (Ejection Force)} \quad A = 5 \text{ in}^2 \text{ (Area)} \quad V = 100 \text{ in}^3 \text{ (Volume)} \]

Use the Ideal Gas Law and Pressure formula to determine the required amount of black powder to eject a parachute from the rocket. \textbf{Note: There are 454 grams in 1 lbm}

\[
\text{Pressure: } P = \frac{F}{A} = \frac{75 \text{ lbf}}{5 \text{ in}^2} = 15 \text{ psi}
\]

\[
\text{Black Powder: } N = \frac{PV}{RT} = \frac{15\text{ psi} \times 100\text{in}^3}{266 \text{ in lbf/} \text{lbm} \times 3307^\circ R} \left( \frac{454 \text{ grams}}{1 \text{ lbf}} \right) = 0.77 \text{ grams} \approx 0.8 \text{ grams}
\]

\text{Note: All CTI Pro 38 High Powered Reloads come standard with a 1.3 grams black powder charge installed. Well more than is actually required for this particular kit.}
Recovery Exercise 2: Descent Rate Calculation

This exercise will teach calculating the rocket’s descent rate under a 30” parachute. The parachute is a high drag device that retards the high speed descent of the rocket by producing a force that opposes the weight of the rocket. We will use Newton’s 2nd Law of Motion to determine the descent rate of the rocket. The basic assumptions used in calculation the descent rate of a rocket are:

1. The rocket is descending at a constant speed (steady state)
2. The rocket moves simply downward (constrained to z-axis)

Under these assumptions, there are only two forces acting on the rocket – Weight and Drag. Given

\[ \sum F_z = D + W = ma = 0 \] (steady state)

\[ D = \frac{1}{2} \rho V^2 S C_d \quad W = mg \]

\[ D = W = \frac{1}{2} \rho V^2 S C_d = mg \]

Given the following parameters, determine the rocket’s descent rate using the Descent Velocity Equation:

\[ Weight \ (W) = 41.6 \text{oz.} = 2.6 \text{lbm} \]

\[ Drag \ Coefficient \ (C_d) = 0.87 \text{ (theoretical)} \]

\[ Air \ Density \ at \ 70^\circ \text{F} \ (\rho) = 0.075 \text{ lb} \text{f} / \text{ft}^3 \]

\[ Surface \ Area \ (S) = \pi r^2 / 4 = 4.9 \text{ ft}^2 \]

\[ Descent \ Velocity = V = \sqrt{\frac{2 W}{\rho S C_d} \left( \frac{32.2 \text{ lbm}}{\text{lb} \cdot \text{s}^2 / \text{ft}} \right)} \]

**Solution:**

\[ V = \sqrt{\frac{2 \times 2.6 \text{ lbm}}{0.075 \text{ lb} \text{f} / \text{ft}^3 \times 4.9 \text{ ft}^2 \times 0.87 \times 32.2 \text{ lbm} / (\text{lb} \cdot \text{s}^2 / \text{ft})}} = 22 \text{ ft/s} \]

The rocket has a descent rate of **22 ft/s**
Recovery Exercise 3: Kinetic Energy Calculation

This exercise will teach calculating the rocket’s Kinetic Energy (KE) at touchdown. The basic assumptions used in this calculation the rocket’s KE are:

3. The rocket is a point mass (no tethered parts).
4. KE refers to translational KE only (simple movement in one direction).

Given the following parameters, determine the rocket’s KE using the equations below:

\[
\text{Weight } (W) = 41.6 \text{ oz.} = 2.6 \text{ lbm}
\]

\[
\text{Descent Rate } (V) = 22 \text{ fps}
\]

\[
KE = \frac{1}{2} (W)(V)^2 \left( \frac{1 \text{ lbf s}^2}{32.2 \text{ lbm ft}} \right)
\]

Solution:

\[
KE = \frac{1}{2} (2.6 \text{ lbm})(22 \text{ fps})^2 \left( \frac{1 \text{ lbf s}^2}{32.2 \text{ lbm ft}} \right) = 19.5 \text{ ft lbf}
\]

The rocket has a KE of: **19.5 ft lbf**.