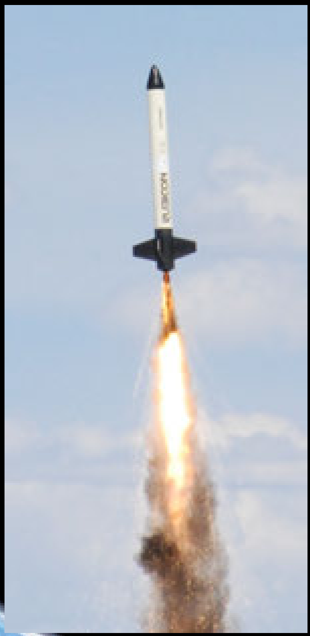
National Aeronautics and Space Administration

NASA High Powered Video Series
Counterpart Documents



Structures Systems

Materials:

Parts & Subassemblies

Nose Cones

Airframes & Couplers

Motor Tubes

Motor Retainers

Centering Rings & Bulk Plates

Fins

Rail Buttons

Construction Techniques

Design Considerations

Stability

Center of Gravity

Center of Pressure

NASA High Power Rocketry Video Series
Counterpart Documents

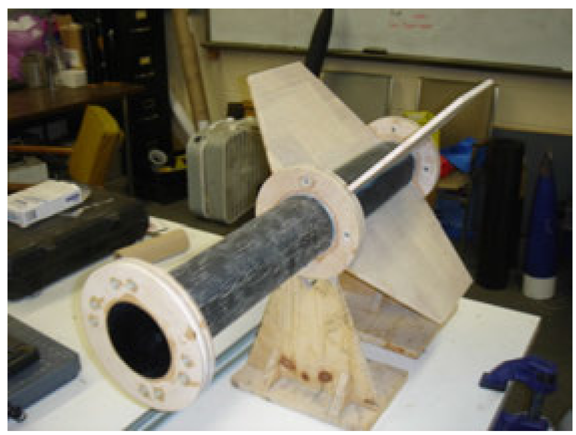
Written by Daniel Cavender

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 also learn how to design a stable rocket using equations to determine the Center of Pressure (CP) and the Center of Gravity (CG).

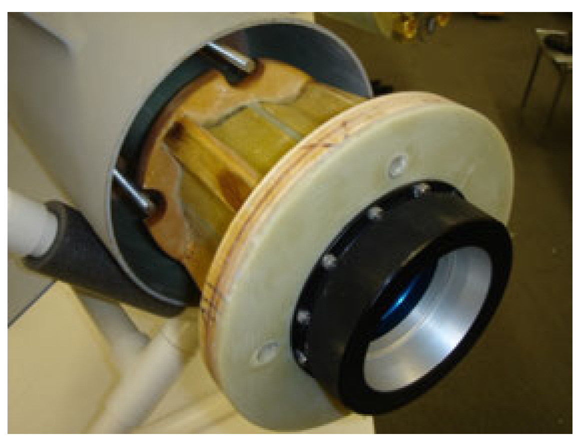
S.1. Parts & Subassemblies

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*, sometimes called a "*fin can*", is an assembly built from a section of airframe, a motor tube, centering rings, bulk plates, fins, motor retainers, and sometimes couplers.

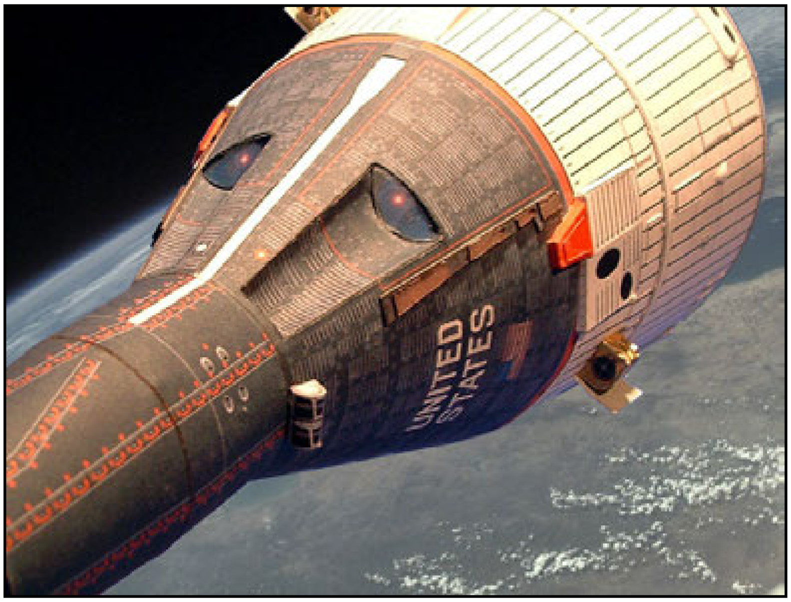


The photos to the right are examples of some subassemblies. The nose cone assembly at the top has a removable plate on the bottom for access to the interior volume where a payload can be carried. The fin can subassembly in the middle is ready for installation into a custom made carbon fiber airframe. The motor tube subassembly at the bottom is removable so the builder can inspect the fin tangs and centering rings between flights.



S.1.1. Nose Cones

The term nose cone is used to refer to the forward most section of a rocket, missile, or aircraft. The cone is shaped to offer minimum aerodynamic resistance. On rocket vehicles, the nose cone may consist of one or multiple 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.



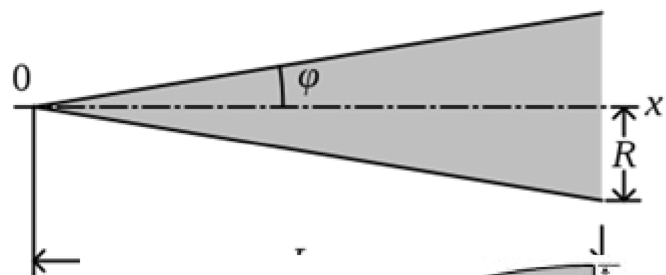
The shape of the nose cone will affect the drag on the rocket, and the proper shape should be chosen to reduce drag. An important problem is the determination of the nose cone geometrical shape for optimum performance. Such a task requires the definition of a solid of revolution shape that experiences minimal resistance to rapid motion through a fluid medium.

S.1.1.1. 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.

S.1.1.2. Conical Nose Cones

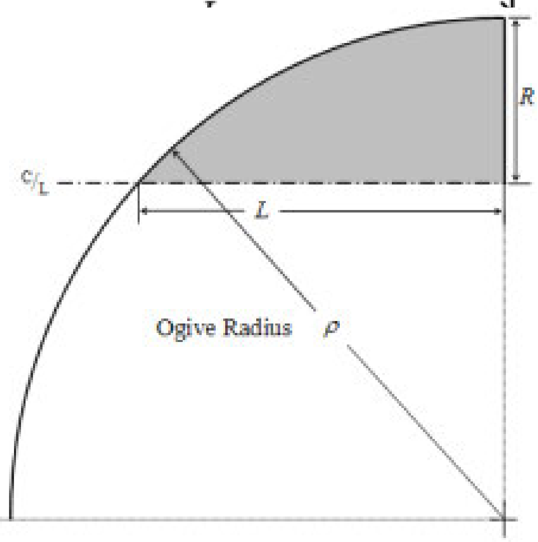
A very common nose cone shape is a simple cone. This shape is often chosen for its ease of manufacture and for its drag characteristics.



$$y = \frac{xR}{L} = x\tan(\varphi) \qquad \varphi = \arctan\left(\frac{R}{L}\right)$$

S.1.1.3. Ogive Nose Cones

Next to the conical, the *Tangent Ogive* shape is the most popular 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.

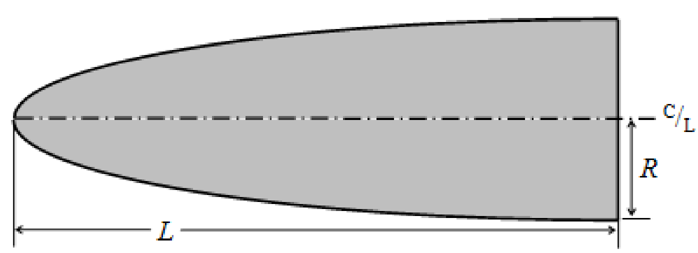


$$\rho = \frac{R^2 + L^2}{2R}$$

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

S.1.1.4. 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 cone 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.

S.1.1.5. Nosecone Drag Characteristics

For rockets travelling under Mach 0.8, the nose cone pressure drag is negligible 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 a rocket flying in the subsonic region (below Mach 0.8) a short, blunt, smooth elliptical cone 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*.

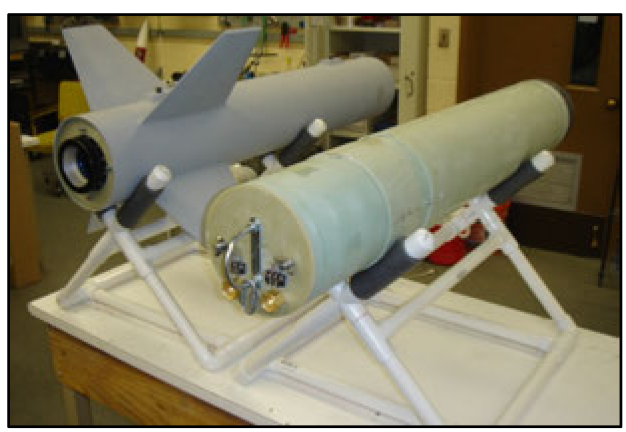
The *Fineness Ratio* is the ratio of the length of the nose cone compared to its base diameter. At supersonic speeds (above Mach 1.0), the fineness ratio has a significant effect on nose cone wave drag, particularly at low ratios; but there is very little additional gain for ratios increasing beyond 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.

S.1.2. 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.



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

Phenolic tubing is like cardboard, except it has been impregnated with an epoxy resin to increase its strength. While cheap and easy to work with, phenolic tubing is brittle, and may not handle the loads of some more aggressive rockets.

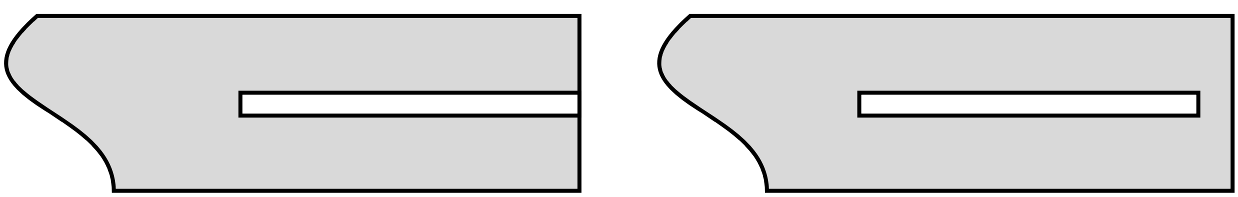
Fiberglass is much stronger and more robust than phenolic tubing. It is not brittle like phenolic, but fiberglass is more expensive. Fiberglass tubing is usually pre-manufactured, although some rocketeers prefer to manufacture their own tubing by winding fiberglass sheets around a mandrel and impregnating it with an epoxy resin. When working with fiberglass, be sure to wear the proper safety equipment as fiberglass produces a hazardous dust when sanded.

Carbon fiber tubing is the strongest and most rigid material used in high power rocketry. It is also very lightweight and aesthetically pleasing. The drawback, however, is that carbon fiber is the most expensive material to use. Like fiberglass, carbon fiber produces a hazardous dust when sanded and proper safety equipment should be worn while handling it.

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 20 plys or more.

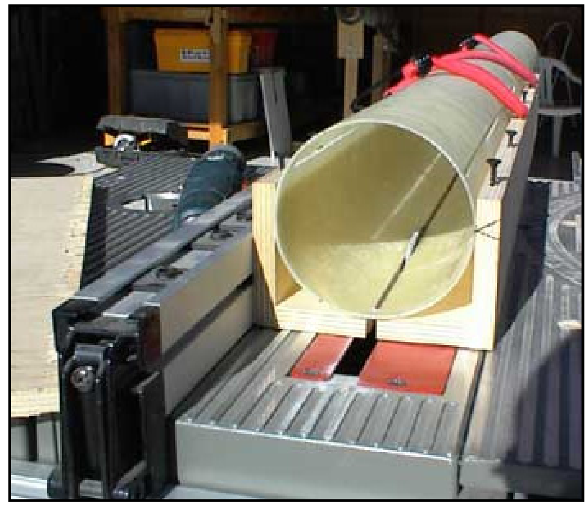
The airframe pictured on the previous page is an example of a filament-wound fiberglass airframe. A long spool of epoxy infused fiberglass string or *"tow"* is wound around a mandrel in an overlapping pattern until a cylindrical tube of desired thickness is formed.

Depending on the design, your rocket may require slots through the airframe for fins. Many manufacturers will slot airframes to your specification, or you can cut them yourself. Generally, fin slots in airframes come one of two designs - *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.

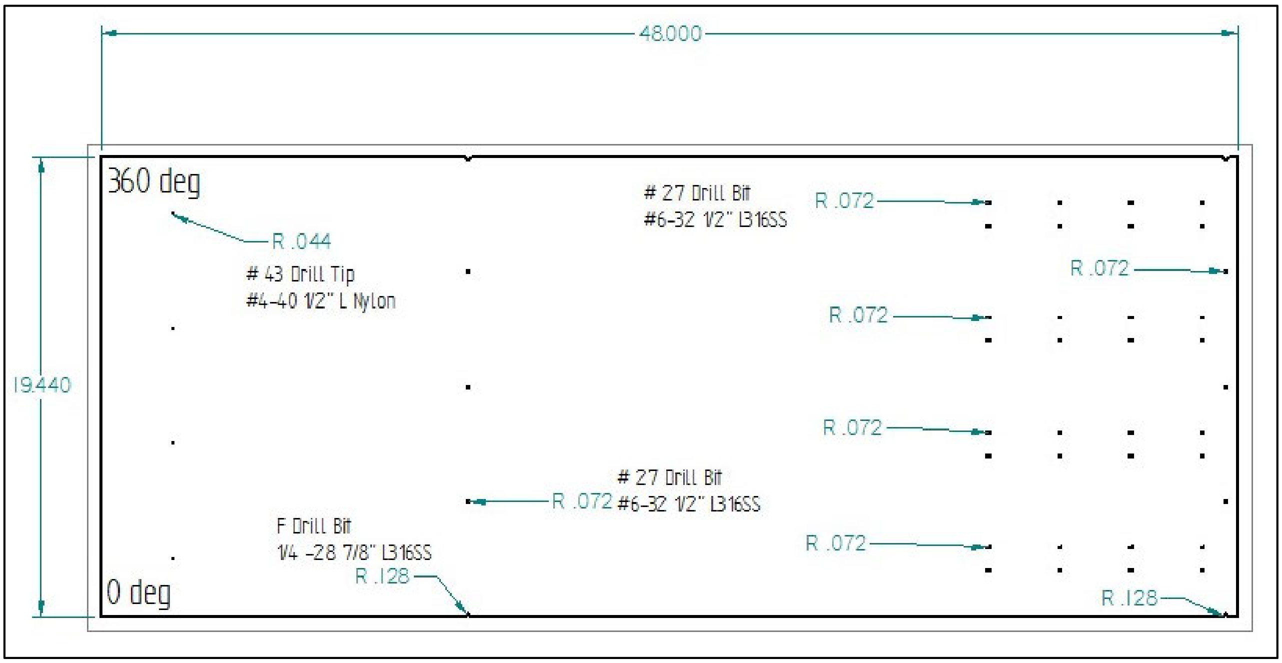


End Slotted Airframe **Tang Slotted Airframe**

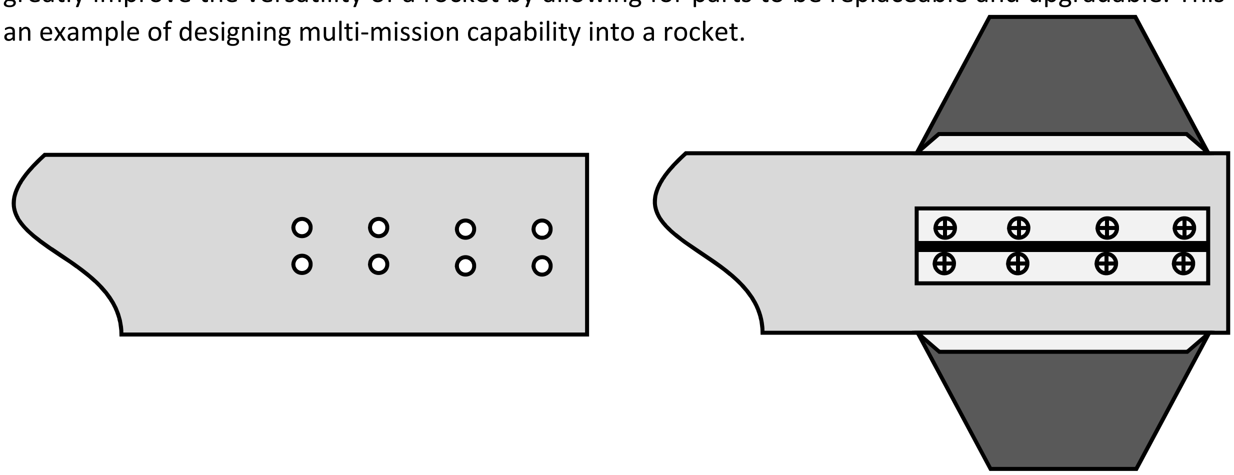
Custom fin slots can be made with the use of common power tools and a jig. A jig is any device used to mechanically maintain the correct positional relationship between a workpiece and the tool.

A drill template is another type of tool you may use on your rocket. 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 common practice in industry to use a template 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 indications for which drill bits, taps, and fasteners to be used. An example of a drill template is shown below.



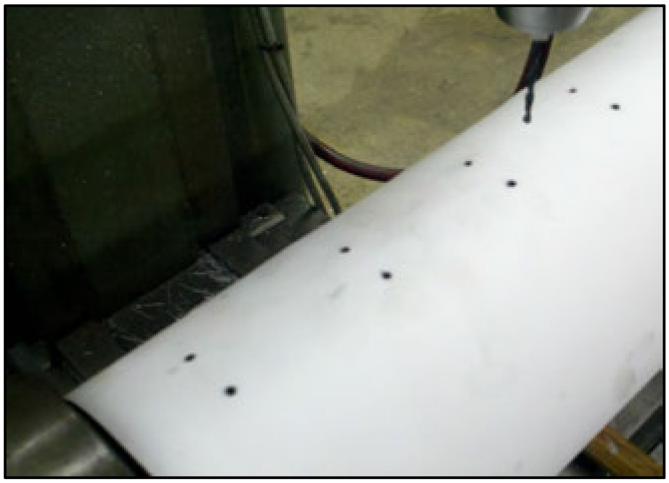
On this drill template, the series of penetrations at the bottom of the airframe are designed to accept a unique surface mounted fin bracket concept that allows the fins and fin brackets to be modular and greatly improve the versatility of a rocket by allowing for parts to be replaceable and upgradable. This is an example of designing multi-mission capability into a rocket.



Template Drilled Airframe

Drilled Airframe with Brackets

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 which has an *Outer Diameter (OD)* equal to the *Inner Diameter (ID)* of the airframe. ***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 other electronics. 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 1 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.

S.1.3. 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.

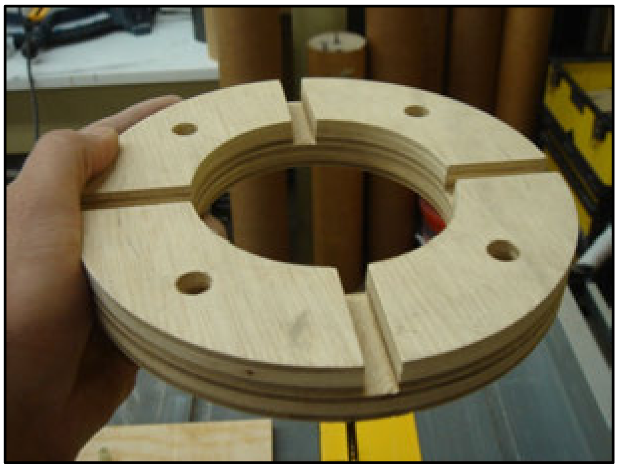
S.1.4. Motor Retainers

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 with common screws and washers from a hardware store. Pictured to the right is 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.

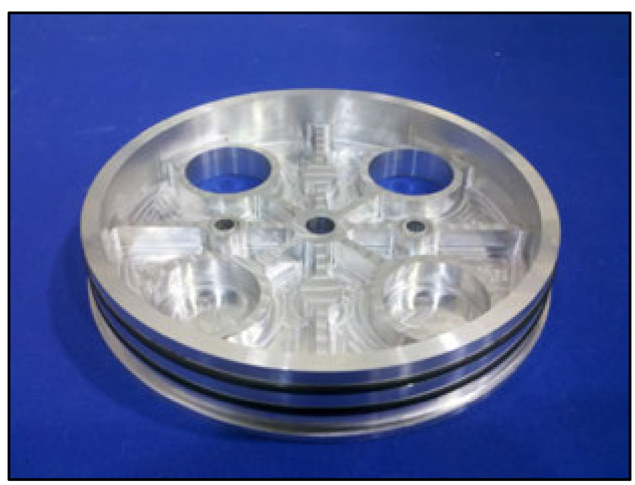
You may choose to design your own method of motor retention. Commercial snap rings are a viable and cheap option to explore and can be integrated into the structures of your rocket project.

S.1.5. Centering Rings & Bulk Plates

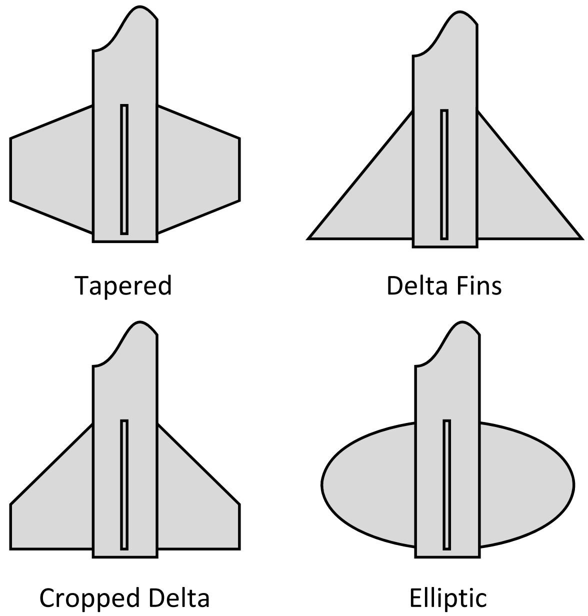
Centering rings are used to concentrically align small tubes, like motor tubes, inside of an airframe. Centering rings can be made of many different materials and take many shapes depending on the number of inside tubes that are to be aligned. *Bulk plates* are circular disks that fit inside of tubes to separate volumes. Typically, centering rings and bulk plates are either made out of plywood or from composite materials such as 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.



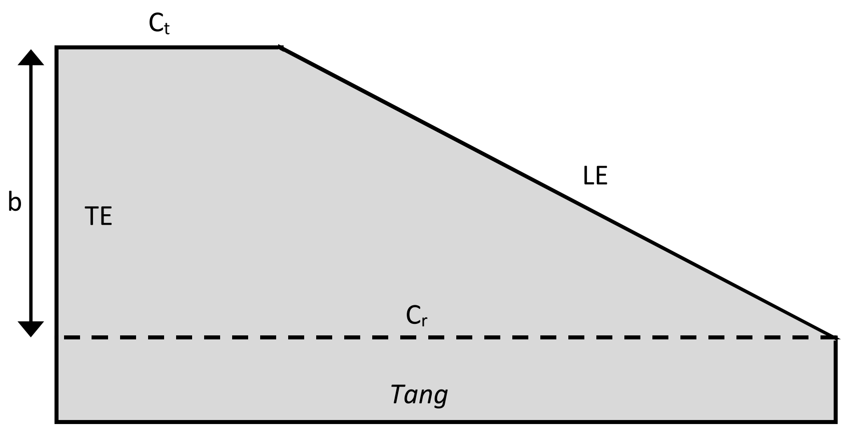
Centering rings are available from almost all rocket component providers in a variety of sizes. Suppliers often have the capability to build-to-order any design you need. If not, there are some tools available at almost every hardware store that can help. A properly sized hole saw and arbor from Lowes or Home Depot can make centering rings and bulk plates for your smaller projects. Additionally, there are internet companies that can build almost any size hole saw you need. A Saber saw and a steady hand can also do a very good job.



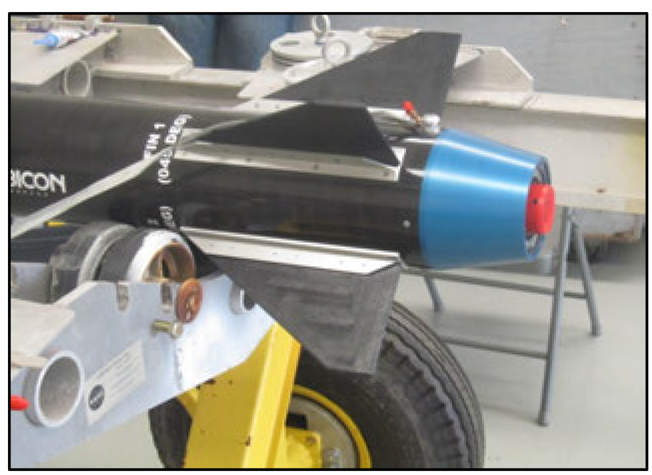
S.1.6. Fins



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 their 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). A 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 offer multi-mission capability or the ability to easily 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.



S.1.7. Rail Buttons

Most high powered rockets are launched from a rail rather than a rod and require a rail button. A rail button is an '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 vehicle design requirements. The rocket should have one rail button near the bottom of the booster and another near the center of gravity. Be sure to use only two rail buttons. Adding any more than two buttons increases the chance that the rocket will bind on the rail.

S.1.8. Ejection Piston

An ejection piston is a recovery systems configuration option that uses a section of coupler, a bulk plate, and a short recovery harness. The concept is that the ejection charge will push the piston forward and out of the airframe. The piston will push the recovery system out as well. The piston also protects the recovery system by physically separating them from the hot gases. Pistons are viable for rockets between 3 and 6 inches in diameter.

S.1.9. Baffles

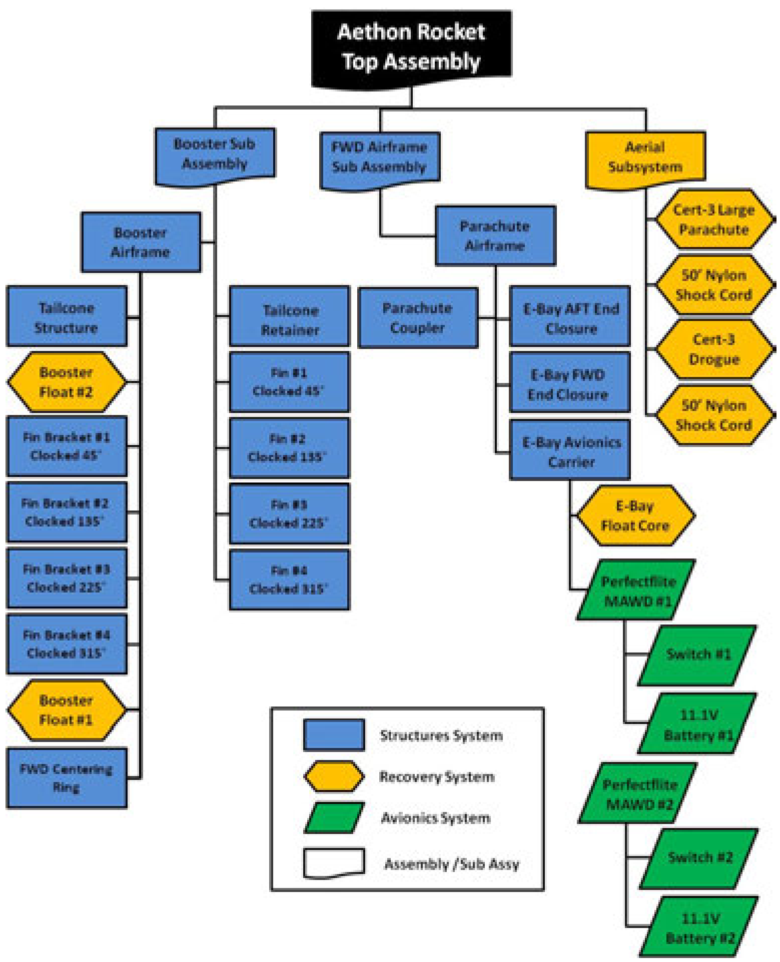
Baffles are another technique that protects the recovery system from hot ejection gases. The baffle uses a metal heat sink like steel wool to absorb the heat and capture any burning debris and allow the expanded gases to push the recovery system out of the rocket. Baffles are a good option on small rockets that use motor ejection.

S.2. Design Consideration

Many parts and subassemblies form the structure of a high powered rocket. Specific design considerations to *human factors* or *ergonomics* will greatly improve the design's effectiveness and reduce risk of failures. Detailed design layout drawings and exploded models are useful tools used by rocket builders to design rockets. These tools can be generated by computer or can be hand drawn. Hand drawn layout drawings are quick and easy ways to convey ideas and designs quickly when in the preliminary design phase. Computer design programs like AutoCAD, Solid Edge, and Pro-E are more difficult to use but can keep track of far more information and are widely used in mature designs.

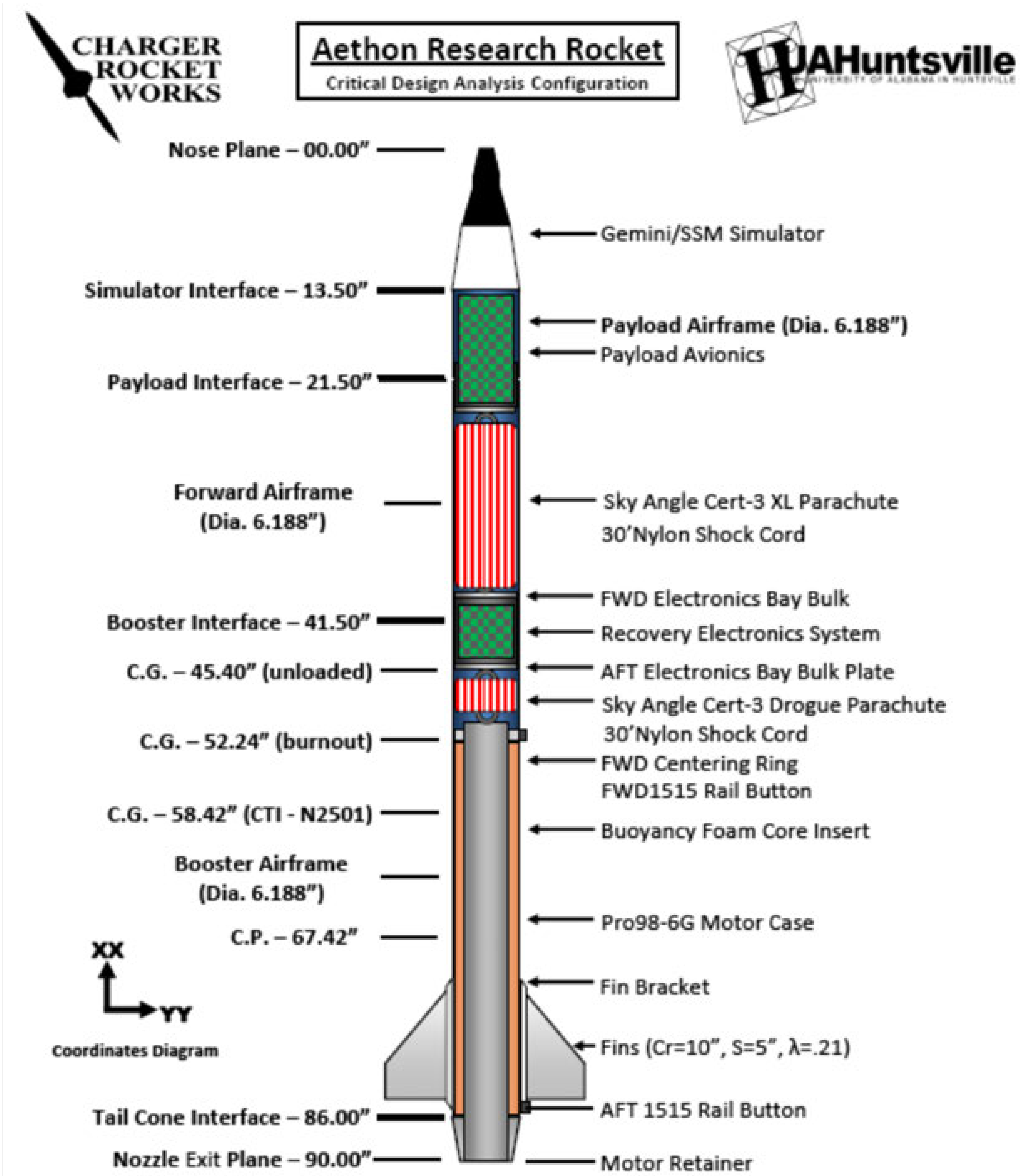
S.2.1. Components/Process Tree

A components tree is a visual tool design to aid in the layout and construction of your rocket. The tree lays out all major parts and systems in order of assembly from bottom to top and left to right. Lines link parts to the next higher assembly. In the example below, structures, recovery, and avionics components are designated by unique colors. Parts and assemblies are designated by unique shapes. Notice that the first process in the assembly of this rocket is the installation of the *FWD centering Ring* into the *Booster Airframe*. The Last is the *Aerial Subassembly* into the Rocket's *Top Assembly*.



S.2.2. Detailed Design Layouts

Detailed design layout drawings are very helpful in accounting for the location of all components in an engineered system and identifying interfaces between components, clearance issues, and assembly plans. As you can see in the example below, layout drawings can include dimensions, materials, detail callouts, reference datums, and assembly methods.



S.2.3. Mass Balance Statement

A Mass Balance Statement table is an account for all components in a high powered rocket. For each component, the table tracks quantity, *length*, *weight, margin*, and *flight station*. Simple math functions calculate each component's contribution to the vehicle's Center of Gravity. A mass Balance Statement is another powerful tool that can help budget the vehicle. This data can be used for propulsion and recovery system design.

ARCAS Mass Balance Statement						
Component	**Qantity**	**Length**	**Weight (oz)**	**Margin**	**Weight (oz)**	**Station (in)**
Fiberglass nosecone	1	***10.00 in***	3.40 oz	0%	3.40 oz	6.5 in
Nosecone mass	1	N/A	2.00 oz	20%	2.40 oz	1.0 in
G10 Nosecone Bulkplate	1	0.06 in	0.30 oz	20%	0.36 oz	10.5 in
Payload Airfame Tube	1	***16.00 in***	4.80 oz	5%	5.04 oz	18.0 in
Payload Coupler Tube	1	6.00 in	1.80 oz	20%	2.16 oz	26.0 in
Payload Coupler Bulkplate	1	0.06 in	0.30 oz	20%	0.36 oz	29.0 in
Payload Bulkplate Eyebolt ASSY	1	1.00 in	0.80 oz	10%	0.88 oz	29.0 in
12 feet shock cord	1	6.00 in	2.00 oz	0%	2.00 oz	39.0 in
30 inch parachute	1	6.00 in	1.00 oz	0%	1.00 oz	39.0 in
9x9 Parachute Protector	1	6.00 in	0.50 oz	0%	0.50 oz	39.0 in
Booster Airframe (Slotted)	1	***26.00 in***	7.70 oz	5%	8.09 oz	39.0 in
38mm Motor Tube	1	8.00 in	2.30 oz	5%	2.42 oz	47.0 in
Forward Centering Ring	1	0.06 in	0.20 oz	20%	0.24 oz	45.0 in
FWD Centering Ring Eyebolt ASSY	1	1.00 in	0.80 oz	10%	0.88 oz	45.0 in
G10 Clipped Delta Fins	4	5.00 in	0.50 oz	20%	2.40 oz	49.0 in
Aft Centering Ring	1	0.06 in	0.20 oz	20%	0.24 oz	52.0 in
38mm Aero-Pack Motor Retainer	1	***0.25 in***	0.80 oz	0%	0.80 oz	52.0 in
CTI pro38 2G case	1	8.00 in	3.50 oz	0%	3.50 oz	49.0 in
CTI H225 Reload	1	8.00 in	6.80 oz	0%	6.80 oz	49.0 in
Totals	**22 Parts**	**52.25 in**	**41.20 oz**	**2.26 oz**	**43.46 oz**	**N/A**
		4.35 ft	**2.58 lbm**	**0.14 lbm**	**2.72 lbm**	**N/A**

S.2.3.1. Length

It is important to maintain a record of the size and shape of all components in the rocket as a tool to mitigate integration problems later in the construction process. Note that only the lengths of external primary structural components are used to calculate the vehicles total length. Lengths of components on the rocket may also carry a margin.

S.2.3.2. Weight

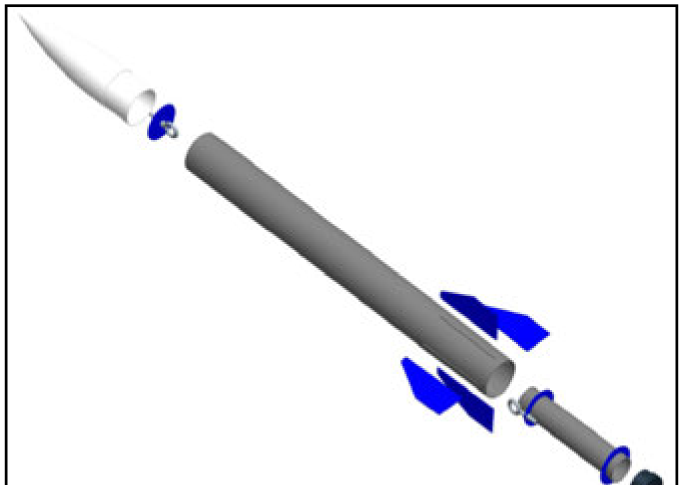
The *weight* or mass of every component is recorded in the mass balance statement. It may not be necessary to account for every piece-wise part in the rocket. Some smaller components such as nuts and washers are rounded up into the next higher assembly and their mass is accounted for there. An example of this would be the bulk plate and centering ring eyebolts which included two hex nuts and a washer.

S.2.3.3. Margin

Margin is a way to track growth in the vehicle through the design cycle. Commercial parts generally carry no margin because they already exist. Components that must be designed should carry a margin to account for the estimated mass increase in the system. In this table, most small components carry a 20% margin to account for the epoxy needed to assemble them to the next higher assembly. Some larger components carry a 5% margin to account for variations in optimal fabric to resin ratios and tolerances in the manufacturing process. The hardware that will most readily be available for your rocket is made for a hobby rocketry community where high tolerance aerospace materials are not viable options. There will be minor manufacturing variations in just about every piece of commercial hardware.

S.2.4. Exploded Models

The exploded view below helps to convey the location of all piece-wise parts in a rocket. This is an exploded model of the Arcas rocket. Parts have been color coded to indicate that they are made from the same raw material. The blue components are built from 1/16" thick G-10 fiberglass. Note that this exploded view shows the motor tube subassembly with hardware attached, the motor tube subassembly is shown assembled for clarity.



S.2.5. Drawing Versions and Iterations

During the developemnt process of rocket components, it will be necessary to revise designs in order to meet design requirements. It is a good idea to maintain a table that lists what drawings and models of parts make up the Top Assembly CAD model.

As a model is revised, the file version should be iterated. Revisions are usually designated by letters A-Z. An initial model would be designated by a dash " – ".

The status of drawings change as versions are revised. They are usually marked "In Work" or "Released" showing that a model is ready for fabrication.

Part Number	REV	COMPONENT	Status
MAE4931001	A	Booster Airframe	Released
MAE4931002	D	Forward Centering Ring	Released
MAE4931003	C	Tailcone	Released
MAE4931004	E	Fin Bracket	In Work
MAE4931005	D	Fin	In Work
MAE4932001	A	Forward Airframe	Released
MAE4932002	A	Forward Airframe Coupler	Released
MAE4932003	A	Recovery Avionics End Closures	In Work
MAE4932004	F	Recovery Avionics Rack	Released
MAE4932100	D	Non-Pyro Ejection Device	In Work
MAE4933001	A	Payload Airframe	Released
MAE4933002	A	Payload Airframe Coupler	Released
MAE4933003	B	Gemini Capsule	In Work
MAE4933004	C	Gemini Service Structure	In Work
MAE4933005	E	Space Science Module	In Work
MAE4933006	C	Payload Rack	In Work

S.2.6. Component Development Sheet

The Component Development Sheet (CDS) is a good tool to manage lots of design details at a piece-wise parts level. The CDS can be used to track details such as:

- Component designer
- Model version and revision (i.e. FWD Centering Ring Rev D)
- Detailed part dimensions & description
- Manufacturing processes
- Cost per unit
- Vendor information
- Risk/hazard analysis
- Parts list

Every major component in the rocket should have its own CDS. When used in conjunction with the Components/Process Tree tool, a comprehensive view ot the rocket is created. The CDS should be updated often. An example of a good CDS is shown below. The designer took time to document a good deal of information about the part.

Component Description Sheets

Component:

Forward Centering Ring

Designer:

Jarred Green / Dan Cavender

General Dimensions:
Outside Diameter 6.02" O-ring OD 4.125"
Inside Diameter 3.95" O-ring ID 4"

Material:

Aluminum 6061-T6

Manufacturing Process:

Horizontal Band Saw, CNC Lathe, and CNC Mill

Component Weight:

.40 pounds

Component Description:

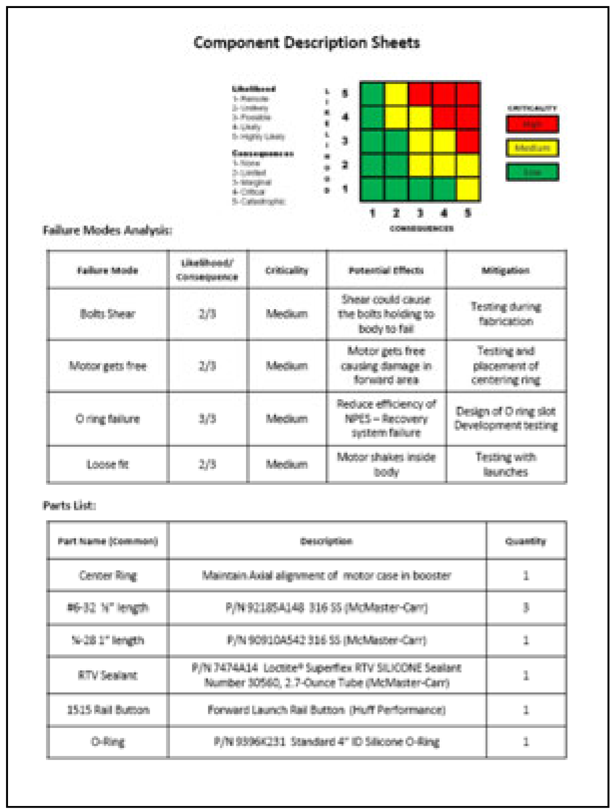
The centering ring will give the motor tube stability near the top end, and hold it in place to prevent any undesired movement. The centering ring will protect the parachutes from any hot gasses and high temperatures that the motor will produce during operation.
The centering ring will designed using Solid Edge and then manufactured by a CNC machine with Aluminum 6061-T6. The centering ring will have an outside diameter of 6.02" and an inside diameter of 4", there will be an O-Ring that will be included as well, with an outer diameter of 4.125" and an inside diameter of 3.875". The end aluminum part must weigh in around .5 lbs in order for the aluminum to stay competitive to the ply wood.
There will be challenges during design and eventually manufacturing, one of these challenges is material selection. Aluminum weighs a lot even when there is a small amount of it. Other challenges include weight reduction, and testing that needs to be done to ensure that it will withstand the stress due to lateral loads and pressures that it will encounter during operation. Some failures that could be expected include set screws shearing, anodizing finish compromised allowing corrosion to begin, resulting in loss of motor tube stability, O-ring failure resulting in decreased efficiency of recovery ejection system.

Prospective Vendor:

McMaster Carr, Huff Performance, UAHuntsville MAE Machine Shop

Cost/Unit:

$40



Component Description Sheets

Failure Modes Analysis:

Failure Mode	Likelihood/ Consequence	Criticality	Potential Effects	Mitigation
Bolts Shear	2/3	Medium	Shear could cause the bolts holding to body to fail	Testing during fabrication
Motor gets free	2/3	Medium	Motor gets free causing damage in forward area	Testing and placement of centering ring
O ring failure	3/3	Medium	Reduce efficiency of NPES – Recovery system failure	Design of O ring slot Development testing
Loose fit	2/3	Medium	Motor shakes inside body	Testing with launches

Parts List:

Part Name (Common)	Description	Quantity
Center Ring	Maintain Axial alignment of motor case in booster	1
#6-32 ½" length	P/N 92185A148 316 SS (McMaster-Carr)	3
¼-28 1" length	P/N 90910A542 316 SS (McMaster-Carr)	1
RTV Sealant	P/N 7474A14 Loctite® Superflex RTV SILICONE Sealant Number 30560, 2.7-Ounce Tube (McMaster-Carr)	1
1515 Rail Button	Forward Launch Rail Button (Huff Performance)	1
O-Ring	P/N 9396K231 Standard 4" ID Silicone O-Ring	1

S.3. Construction Techniques

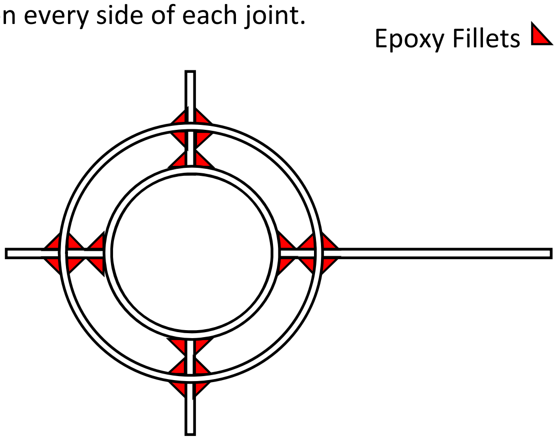
There are many construction techniques used in the construction of high-powered rockets. This section will touch on a few that you should know about.

S.3.1. Cutting Airframes and Couplers

There are several ways to cut an airframe to the required lengths. The easiest is to request them pre-cut from the manufacturer. You may wish to purchase the full uncut length of airframe and cut it yourself. Airframes can be cut using a miter saw. Most miter saws have a fence that 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.

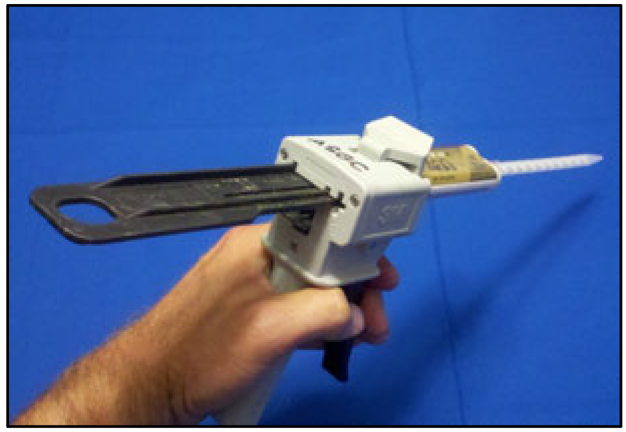
S.3.2. Through-The-Wall (TTW)

Through-The-Wall mounting is a 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.

S.3.3. **3M Epoxy Guns**

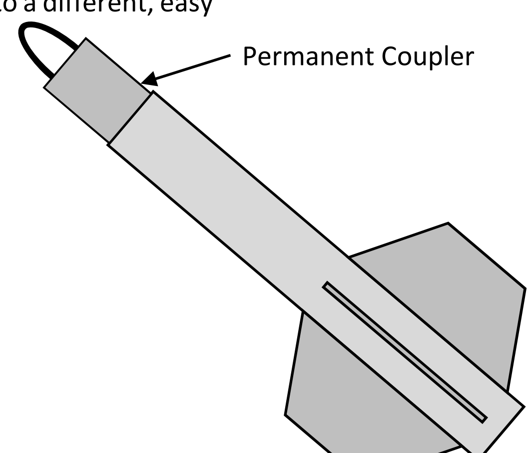


Epoxies are two-part adhesive systems that chemically react to cure and adhere materials together. Mixing the two parts together can prove to be messy. Many quick curing epoxies are time critical tasks that require some technique and planning to maximize use. The 3M Corp. developed the mixing epoxy applicator gun pictured to the right. The gun and long length mixing nozzle allow you to reach otherwise hard to reach areas easily and control the location and amount of epoxy applied to your rocket. Before applying epoxy, be sure to sand the bonding surface. This provides more surface area for the epoxy to bond and will provide a stronger bond. Epoxy is a hazardous material and should be treated as such. As epoxy cures, it releases irritating fumes and heats up to potentially injury-causing temperatures.

S.3.4. 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. With this design, the shock cord connecting the rocket sections to the recovery system is allowed the largest possible clearance from contact with the rocket in order to prevent the airframe from tearing. This failure is known as a “zipper”.

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

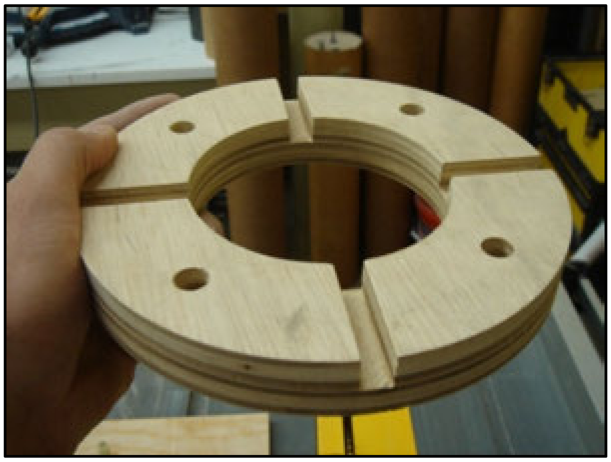


S.3.5. Tip-to-Tip Glassing

Another common fin stiffening technique is to layup fiberglass or carbon fiber from the tip of a fin across to the other tip of the same fin. It is not a difficult process to master, but it does require some special tools and strict timing. Generally, one would make a template from paper that can be transferred to the glass and to a sheet of peel-ply. The glass would be cut using the template and then laid across the rocket to dry (no epoxy yet). Some epoxy would be mixed and first drizzled or brushed on top of the glass sheet on the rocket. Once the epoxy saturates all of the glass, lay the peel-ply on top and use a small sponge roller to press the peel-ply down onto the glass and the airframe, eliminating all air pockets. Have a shop rag and some isopropyl alcohol (70% or higher) available to wipe up all excess resin. It is much easier to wipe it up than to sand it off later. Typically, you will have about 20-30 minutes of work time before the resin is no longer workable. After the epoxy has cured, peel off the peel-ply and clean up the area with some light sanding. Scissors and sand paper are helpful to remove hardened fiberglass. The process will need to be repeated until all sides are glassed tip to tip.

S.3.6. Slotted Centering Rings

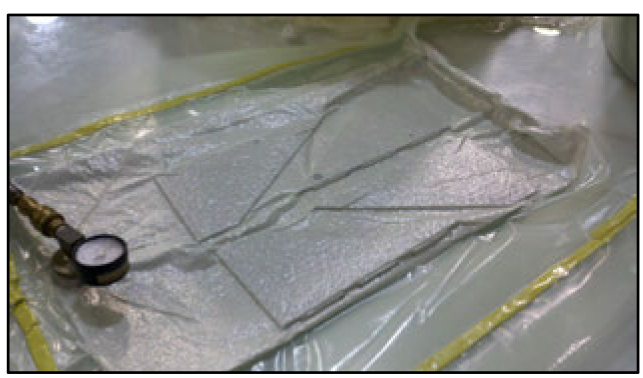
Slotted centering rings are an easy way to align fins and ensure a secure fit that firmly grips the entire fin tang. The centering ring below was built with a common table saw, a dado set, and a custom jig. Two perpendicular grooves were routed into a plywood centering ring. The width and depth of the grooves 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.



S.3.7. Vacuum Bagging

Vacuum bagging is a clamping method that uses atmospheric pressure to hold the adhesive or resin-coated components of a lamination in place until the adhesive cures. This is a common, but advanced technique used in HPR construction. Vacuum bagging may be applied to airframe or fin construction. Like all epoxy resin projects, the process follows a strict timeline of preparation, lay-up, work, and curing. A vacuum pump is required to provide the vacuum.

A simple approach to vacuum bagging requires sheets of a bagging film about the same thickness and toughness as a Ziploc freezer bag, sealant tape, a thin perforated plastic film known as peel-ply, and a breather material (typically a sheet of cotton or cotton like nylon material). A sheet of bagging plastic is cut in a rectangle and two proportionally smaller rectangles of breather material and peel ply are cut and centered on the rectangle. The peel ply should be on top. This is the inside of the bag.

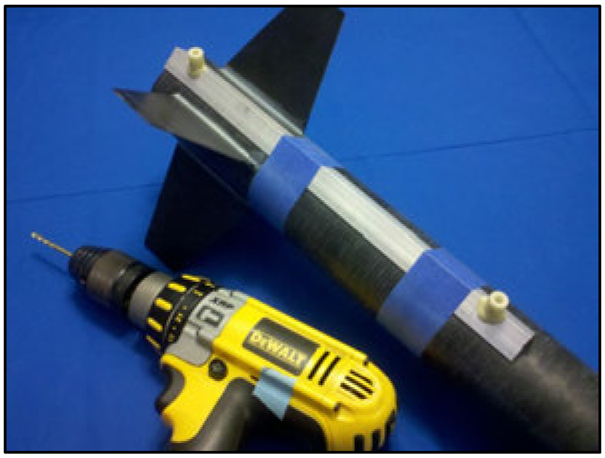


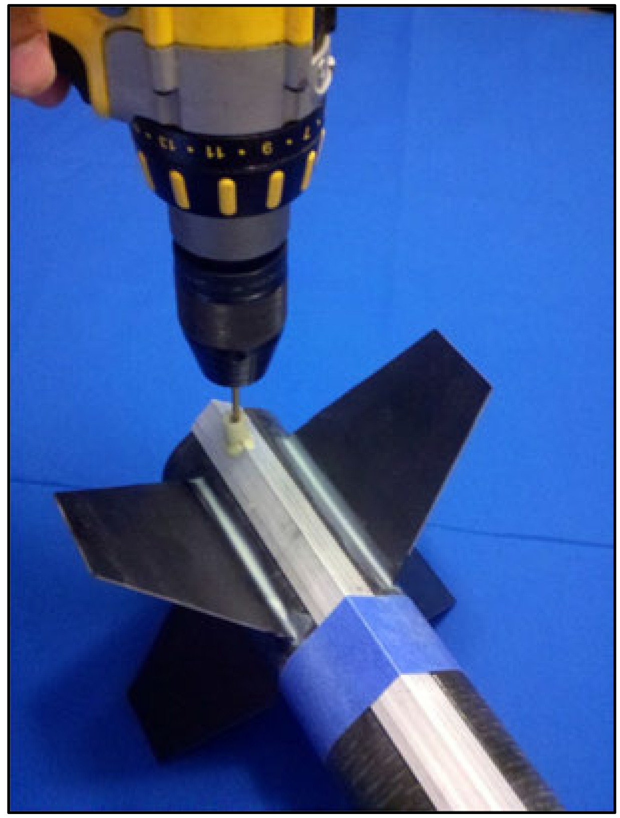
First, lay-up the parts on one half of the peel-ply. When the wet lay-up is done, lay a strip of sealant tape all the way around the bagging sheet, about an inch or so inside the border. Next, fold the other half of the peel-ply, breather material, and bag over and press the sealant tape together to seal the bag. Place the vacuum pump hose into the bag near the perimeter, laying the tip of the hose inside of the breather material.

Turn the pump on and then look and listen for leaks around the bag, sealing them with tape as you go. The vacuum guage should be reading a vacuum in the bag and you will see the entire bag begin to collapse onto the parts, applying pressure to them. After a few hours, switch off the pump and allow the parts to continue to cure.

S.3.8. Rail Button Jig

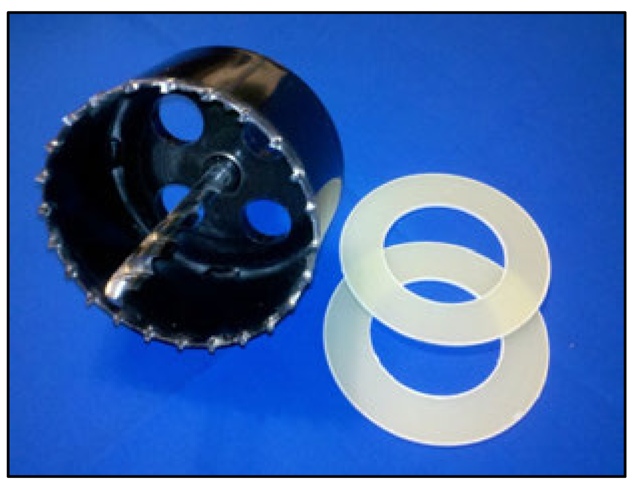
A simple tool to accurately and quickly repeat rail button alignment can be made from a length of angled aluminum with drill bit alignment guides. The angled aluminum will align itself when laid flush on the airframe. Tape the jig in place with some masking tape and drill the forward and aft rail button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





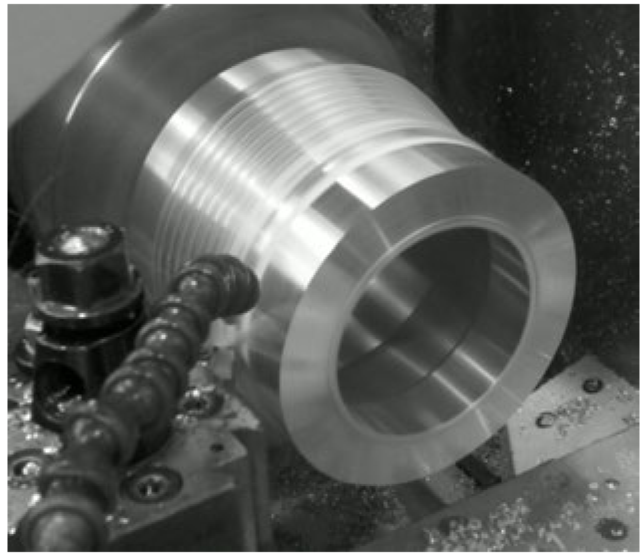
S.3.9. Hole Saws for bulkheads and Centering Rings

Holes saws are great tools for making round disks. Many sizes are available at hardware stores that can be used to make rocket centering rings and bulk plates. However, hole saws capable of making larger rings and plates are hard to find. There are serveral online venders that can build custom holesaws for you like the one in the photo to the right. These holesaws requires a drill press. Like all other power tools, use eye protection and do not wear loose-fitting clothing that could be caught in the tool.



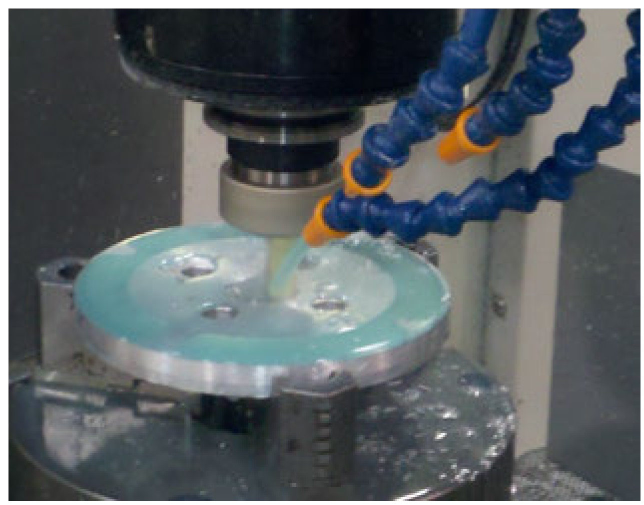
S.3.10. Lathe

A lathe is a power tool used to form cylindrical parts. There are two main catagories of lathes – those designed for wood and other soft materials, and those designed for metals and hard materials. The photo to the right shows a rockets tailcone being machined. The raw block of material, “the blank”, is turned at high speeds while a cutting tool is run up and down the side, removing small amounts of material with each pass. Many lathes have a computer numerical control (CNC). Computer models of parts can be turned into a sequence of manuvers to be performed by the lathe to produce the desired part. Lathes can be dangerous and even deadly. Use the utmost care and do not work alone.



S.3.11. Mills

Mills are powerful tools used to form many different types of parts. Generally, a block of material is secured on a deck which has X and Y directional drives. This cutting tool rotates at high speeds and moves up and down in the Z direction removing small amounts of material with each pass. Many mills have a computer numerical control (CNC). Computer models of parts can be turned into a sequence of manuvers to be performed by the mill to produce the part. Mills can be dangerous and even deadly. Use the utmost care and do not work alone.



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

NASA High Power Rocketry Video Series
Counterpart Documents

Written by Daniel Cavender

P.1. Propulsion Theory

Traditional propulsion systems rely on thermodynamic expansion of a supersonic gas to produce thrust. Non-traditional propulsion systems still rely on Newton's laws, 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

P.1.1. 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 and becomes the backbone of the discussion of rocket propulsion.

$$F = ma \qquad (Newton's\ 2nd\ Law)$$

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. We can use this knowledge to define Newton's 2nd law as:

$$F = m(t)\frac{du}{dt} \qquad (Newton's\ 2nd\ Law\ Rewritten)$$

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.

$$F = \frac{d}{dt}(mu) \qquad (Momentum = mu)$$

P.1.2. 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.

$$T_{mom} = \dot{m}u_e$$

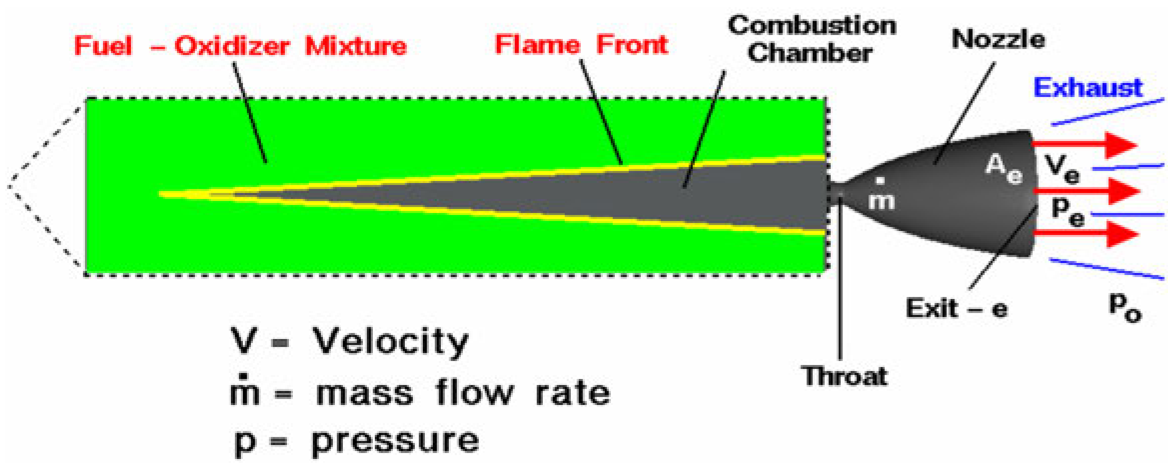
- Pressure imbalance at the nozzle exit plane. P_2 is the pressure of the gases at the exit plane of the rocket motor's nozzle. P_3 is the ambient atmospheric pressure.

$$T_{press} = A_e(P_2 - P_3)$$

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.



P.1.3. 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.

$$I = \int_0^t Tdt = T_{ave}t_{burn} = \int \dot{m}V_{eq}dt = mV_{eq} \quad (Total\ Impulse\ Equation)$$

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

P.1.4. 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.

$$\frac{Work\ we\ want\ to\ do}{Propellant\ we\ use\ to\ do\ it} = \frac{Impulse}{Propellant\ Mass} = \frac{miles}{gallon}$$

$$Isp = \frac{I}{mg_0} = \frac{V_{eq}}{g_0} = \frac{V_e + \frac{(P_e - P_0)A_e}{\dot{m}}}{g_0} \quad (Specific\ Impulse)$$

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.

P.1.1. Rocket Equation (Tsiolkovsky's Equation)

The *Rocket Equation (Tsiolkovsky's Equation)* is essentially a reordering of Newton's 2nd 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.

$$\boldsymbol{\Delta V = v_e ln\left(\frac{m_i}{m_f}\right) = I_{sp} g_0 ln\left(\frac{m_i}{m_f}\right)}$$

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

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

The Ideal rocket equation can be re-ordered to solve for the amount of propellant needed to provide a required ΔV.

$$\boldsymbol{m_{prop} = m_i\left(1 - exp\left(\frac{-\Delta V}{g_0 I_{sp}}\right)\right) = m_f\left(exp\left(\frac{\Delta V}{g_0 I_{sp}}\right) - 1\right)}$$

P.2. 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 of time and they can be reliably launched on short notice. Typical space exploration applications of SRMs include the launch vehicle booster, kick stages for geosynchronous and interplanetary spacecraft, and breaking 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 Cesaroni Technology Skidmark add titanium flakes that burn brightly and create lots of noise and a shower of sparks.

P.3. 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 (an 'H' motor or larger) or multiple motors that, when the thrust is summed, 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

P.4. 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.

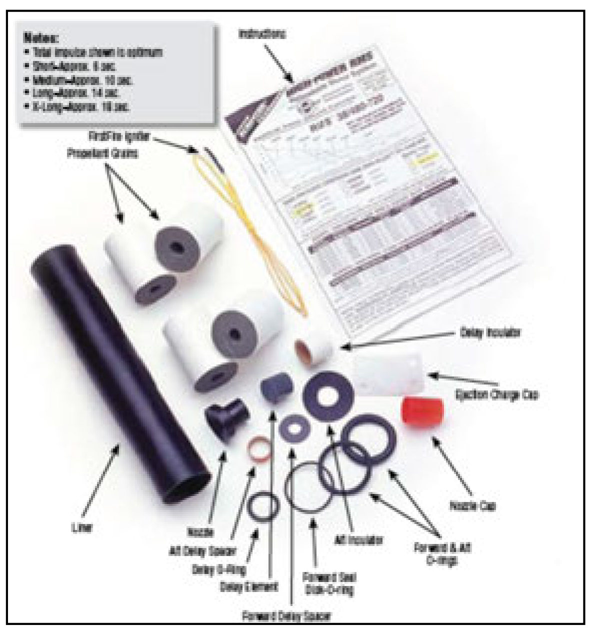
Impulse Class		Category
H	160.01Ns to 320.01Ns	Level 1
I	320.01Ns to 640.00Ns	
J	640.01Ns to 1280.00Ns	Level 2
K	1280.01Ns to 2560.00Ns	
L	2560.01Ns to 5120.00Ns	
M	5120.01Ns to 10240.00Ns	Level 3
N	10240.01Ns to 20480.00Ns	
O	20480.00Ns to 40960.00Ns	

High power rocket motors cannot be purchased over the counter. Members must be certified by either the National Association of Rocketry (NAR) or the Tripoli Rocketry Association (TRA) at the appropriate level to purchase motors from vendors. To become level 1 certified, you must first launch a rocket using an H or I class motor. You may purchase one H or I motor prior for your certification flight. Once level 1 certified, you may purchase H and I motors as well as one J, K, or L motor for your intended level 2 certification launch. After successfully passing a written test and launching a rocket on a J, K, or L motor, you will be level 2 certified.

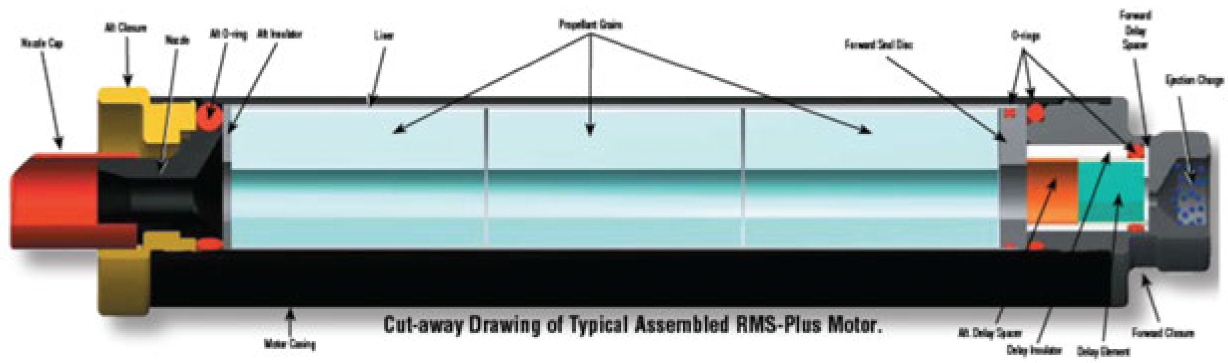
P.5. Commercially Certified Motors

Unless stated otherwise, you are required to use a certified commercially manufactured motor at high power rocket launches. The certifying agencies are the National Association of Rocketry (NAR), Tripoli Rocketry Association (TRA), and the 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 many different impulse and thrust ranges.

Reloadable solid rocket motor systems are composed of a reusable motor case and a reload kit. All high power rocket motor cases come in standard sizes of 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 built in and have a removable aft closure where the reload is loaded from. The closures are usually interchangeable between cases of the 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, 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 directions for motor assembly.



Cut-away Drawing of Typical Assembled RMS-Plus Motor.

P.6. Hybrid Motors:

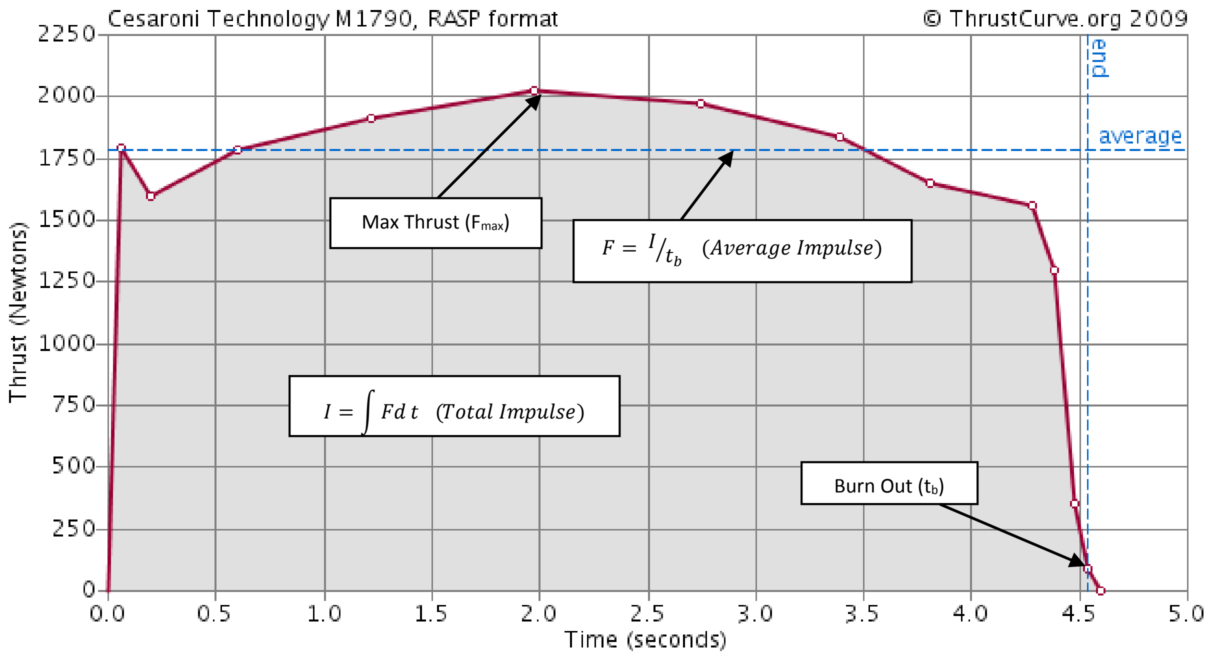
Hybrid motors are another type of high power rocket motor, although they are not commonly used. In a hybrid motor, a solid fuel grain and a liquid oxidizer are kept separate from each other until launch. Hybrid motors are typically cheaper than solid reloadable motors, but they do require some costly ground support equipment to launch. An external Oxygen tank is required in order to produce a medium in which a spark can ignite the motor.

P.7. Thrust to Weight:

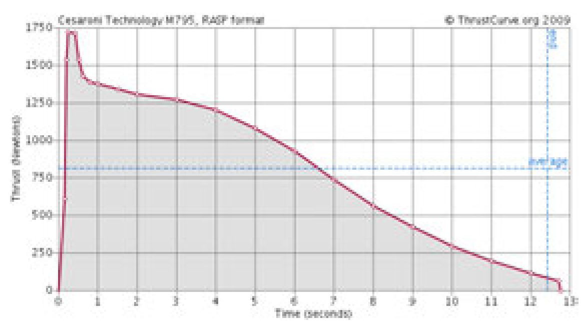
In order for a rocket motor to lift a rocket, it must produce enough thrust to overcome the force of gravity. This means a rocket motor, at a minimum, must produce enough mechanical energy to achieve a *Thrust to Weight Ratio* of just over 1.0. The Space Shuttle has a thrust to weight ratio of 1.5 as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

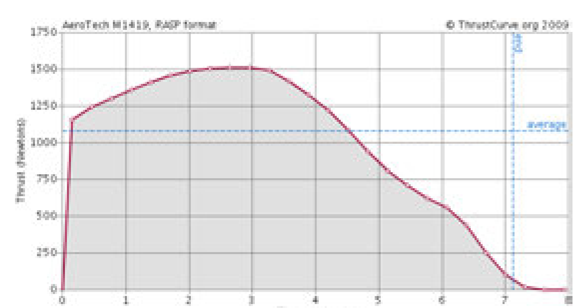
P.8. Thrust Curves:

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.



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 motors 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 a progressive thrust for the first half of the burn and then a regressive thrust for the rest of the burn. What type of burn profile does the thrust curve at the top of the page have?



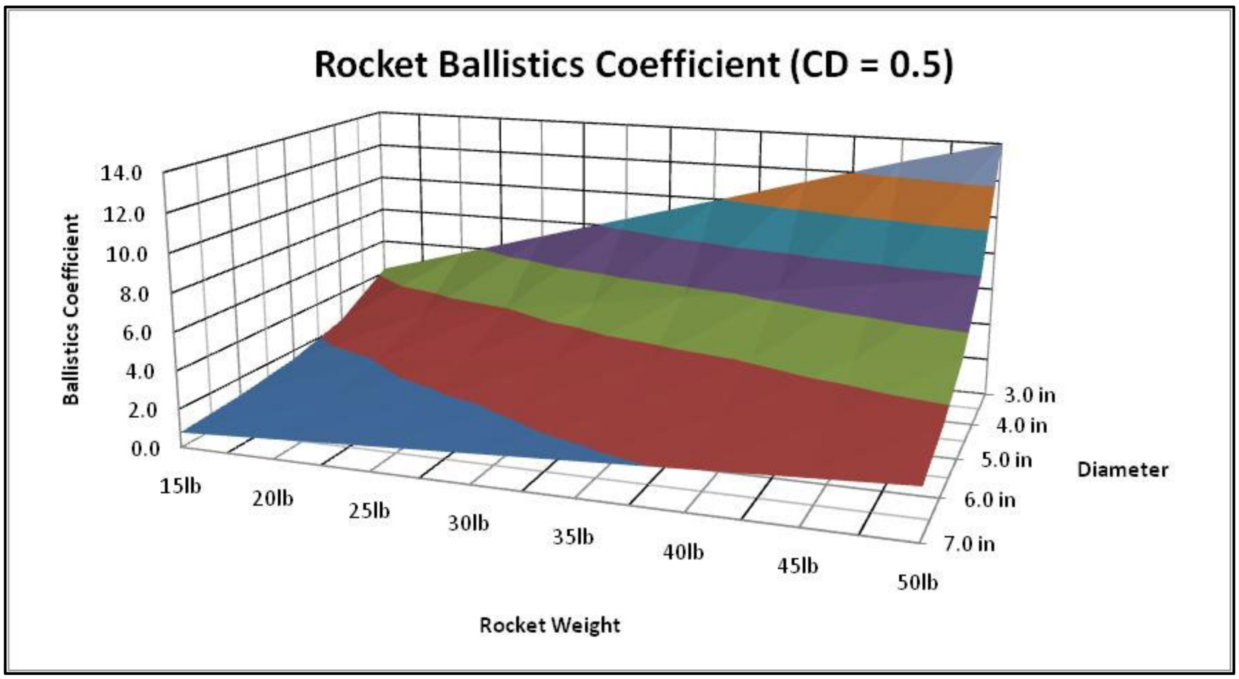


P.9. Ballistics Coefficient

Three parameters that characterize a rocket's performance can be reduced to a single parameter called the Ballistics Coefficient (β). 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.

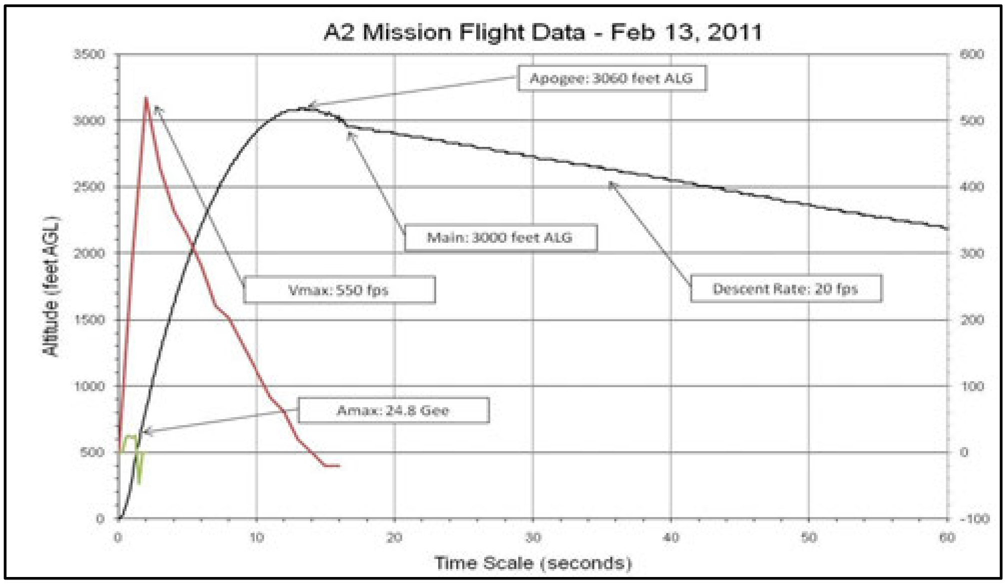
$$\textbf{Ballistics Coefficient:} \quad \beta = {}^{W_f}\!/_{SC_D}$$

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 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.



P.10. Trajectory Analysis

A trajectory analysis should be performed multiple time throughout your rocket's design phase. 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.

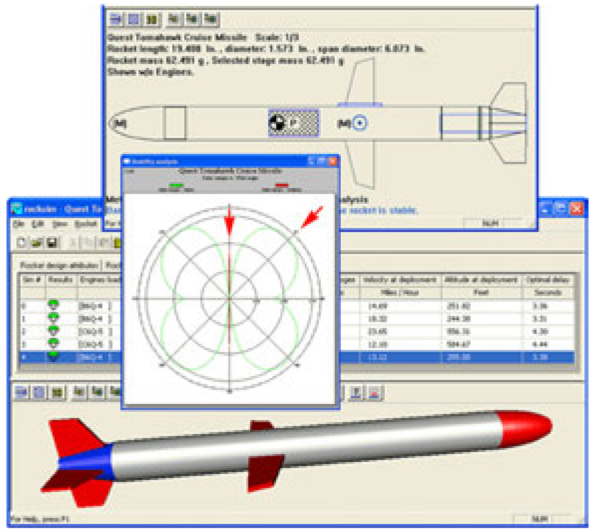


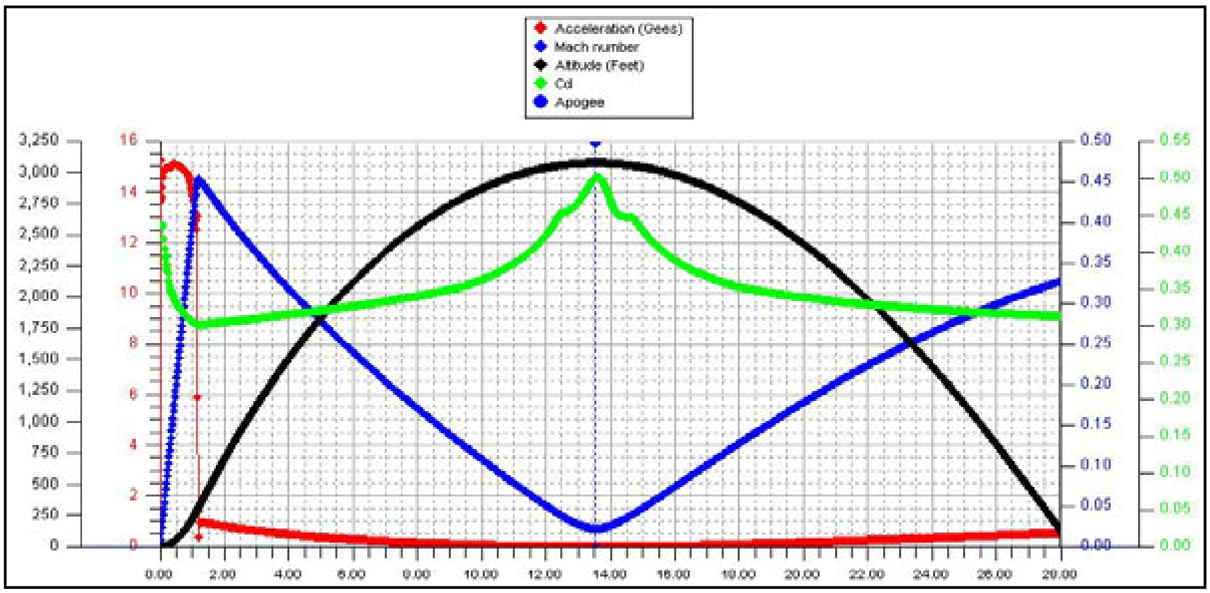
P.10.1. Propulsion requirements

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

P.10.2. 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 such as OpenRocket. These programs have simple CAD elements 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.

P.11. 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 directionaly 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.*

P.11.1. 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 requres 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 = constant) and that the components have uniform density (ρ= constant).

One would first tabulate the known weight and station data in a table like this one. Each components 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 rocket's nose cone. Secondly, the tabulated data would be used to calculate the center of gravity using the *center of masses* equation found below.

$$(1)\ \ \bar{X}_{CG}W_{CG} = \sum_{i=1}^{n} W_i\bar{X}_i = W_1\bar{X}_1 + W_2\bar{X}_2 + W_3\bar{X}_3 + \cdots$$

$$(2)\ \ W_{CG} = \sum_{i=1}^{n} W_i = W_1 + W_2 + W_3 + \cdots$$

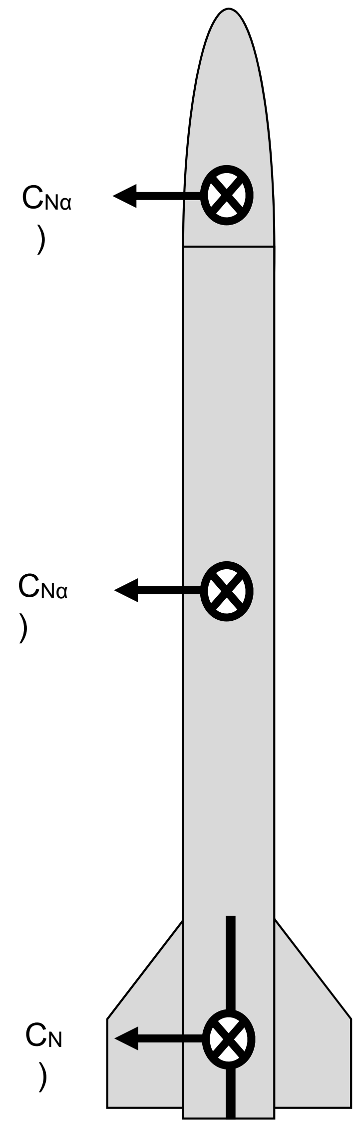
$$(3)\ \ \bar{X}_{CG} = \frac{\bar{X}_{CG}W_{CG}}{W_{CG}}$$

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. Although this method is accurate, it is not practical on very large and heavy rockets and is not useful during the design phase of your rocket. 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 rocket. Computer programs like *Excel* can be powerful tools to manage point mass data and make calculating an accurate CG easy once they are set up. Other computer software programs, like *RockSim*, are available that can perform CG and stability calculations as well as flight performance simulations.

P.11.2. 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 ($\bar{X}_i$) or position of the component's Normal Force as measured from the tip of the nose cone. The basic assumptions used in calculating the theoretical center of pressure for this rocket are:

- The angle of attack (α) 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 ($C_{N\alpha}$) 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:

$$(C_{N\alpha})_n = 2 \qquad\qquad \bar{X}_n = \frac{2}{3}L_n$$

Airframe:
The Airframe provides no response for low angles of attack.

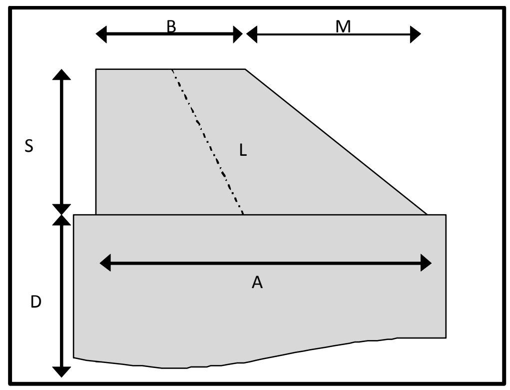
$$(C_{N\alpha})_a = 0 \qquad \bar{X}_a = L_n + \frac{1}{2}L_a$$

Fins:

The rocket's fins contribute the bulk of the aerodynamic forces. The forces $(C_{N\alpha})_f$ and Station $\bar{X}_f$ for these fins are calculated using the following equations:

$$(C_{N\alpha})_f = \frac{4N\left(\frac{S}{D}\right)^2}{1+\sqrt{1+\left(\frac{2L}{A+B}\right)^2}} \qquad \bar{X}_f = X_f + \Delta X_f$$

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



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 $(C_{N\alpha})$ 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.

Component	Shape	Cnα	$\bar{X}$ (inches)
Nose cone	Ogive	2	5.7"
Airframe	Cylindrical	0	26.25"
Fins (Set of 4)	Clipped Delta	6.4	48.9"

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

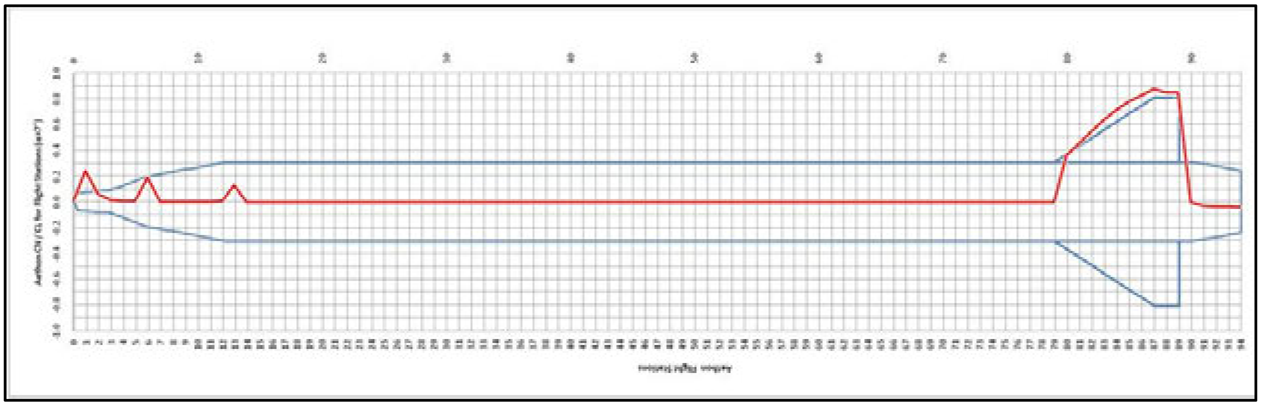
$$C_{n\alpha} = (C_{n\alpha})_n + (C_{n\alpha})_a + (C_{n\alpha})_{fb}$$

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

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

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 rocket, but is not recommended as your primary method for determining your rockets CP.

A very detailed CN/CL analysis can be performed using excel and a good understanding of how to apply both the contribution of cross sectional geometries for the nosecone and airframe Thin Airfoil Theory (TAT) to determine a fin size needed to achieve an ideal CG & CP relation. The model can also be used to determine structural loads at various angles of attack and speeds. When done correctly, this CN/CL analysis can be a powerful tool.



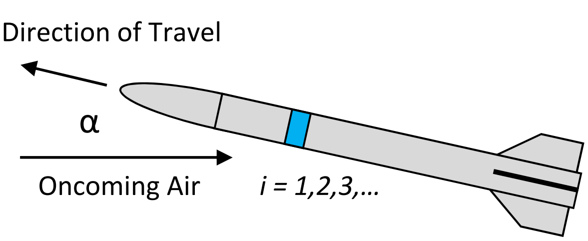
In the same way that excel was used to make a mass balance statement, a table that captures the OML (Outer Mold Line) or plan points of the rockets geometry, as a function of flight stations, can be manipulated to calculate normal force coefficients (CN's) at every point along the rocket's nosecone and airframe. The analysis must be performed for every flight station (*i*) starting at the nosecone and moving aft; generally in increments of one (1) inch.

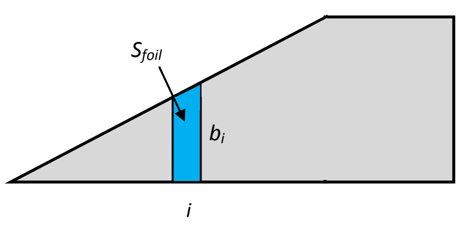
$$(1)\quad CN_i = 2sin(\alpha)\left[1-\left(\frac{D_i}{D_{i-1}}\right)^2\right] \qquad \text{(CN}_\text{i}\text{ Equation where)}$$

$$(2)\quad N_i = \frac{1}{2}\rho V^2 S_{body,i} CN_i \qquad \text{(Normal Force Equation)}$$

$$(3)\quad CL_i = 4\pi\alpha\left(\frac{AR_i}{AR_i+2}\right) \qquad \text{(Equations based on T.A.T.)}$$

$$(4)\quad AR_i = \frac{b^2}{S_{foil,i}} \qquad \text{(Aspect Ratio Equation)}$$





Variables D (diameter), S_{body} (Body Reference Area), b (fin half span), and S_{foil} (Foil Reference Area), and CN have the subscript '*i*' to designate a unique flight station. Each operation at a flight station must be discretely analyzed by the unique variables at that flight station. A modification of the *center of masses* equation can be applied to determine the CP location for any fin design.

P.11.3. Static Margin

Static Margin or *Margin of Stability* describes the directional stability of a rocket. Recall that 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 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)*.

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

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 attack increases or the rocket approaches Mach 1, the CP can change. Recall the Barrowman equations for rocket stability requires the angle of attack (α) of the rocket is near zero (less than 10^0) and its speed be much less than the speed of sound.

P.12. Aerodynamic Drag

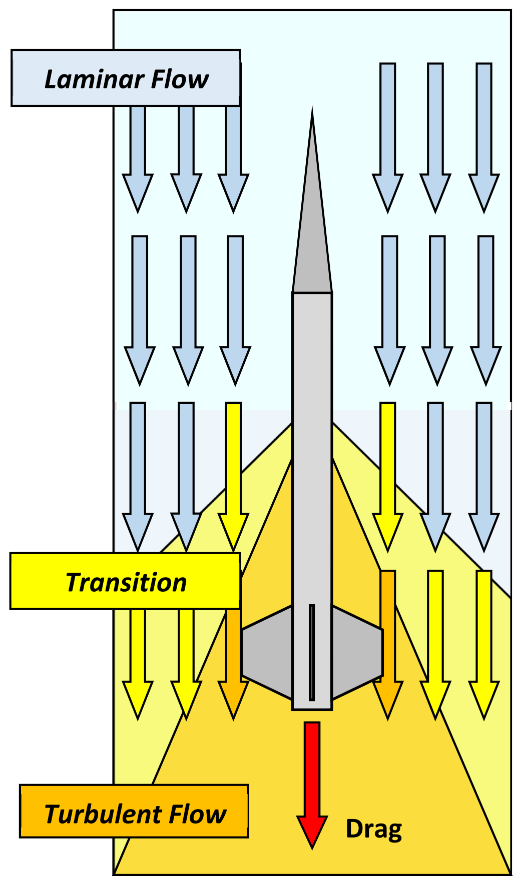
Drag refers to forces that oppose the relative motion of an object through a fluid. Types of drag are usually divided into three catagories: *Parasitic Drag* consisting of form drag, skin friction, and interference drag; *Lift-Induced drag*; and *Wave Drag*. For high velocities, or more precisely, at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

$$D = {}^{1}\!/_{2}\, \rho V^2 S C_d \quad (Drag\ equation)$$

The Reynolds number is the ratio of inertial forces to viscous forces. More simply, it tells us 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.

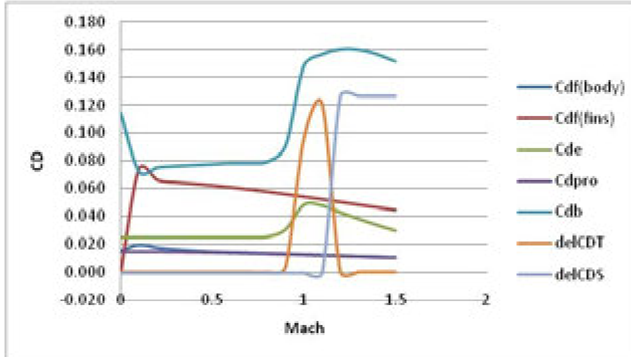
$$Re = \frac{\rho V L}{\mu} = \frac{VL}{v} \quad (Reynolds\ number)$$

(μ = dynamic viscosity, v = kinematic viscosity, ρ = fluid density, V = mean fluid velocity, L = a characteristic linear dimension).



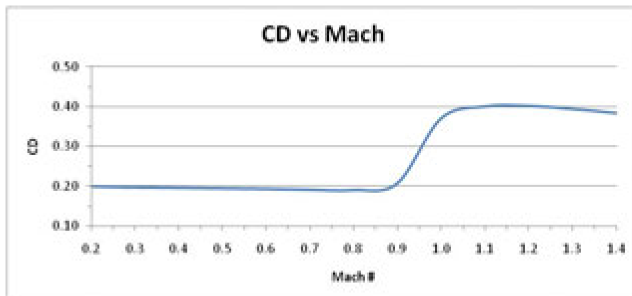
P.12.1. CD vs. Mach Analysis

A more difficult to develop but useful tool in analyzing your rocket's performance is the CD vs. Mach plot. As a rocket's speed increases, different types of drag become prominent. The two graphs at the right are CD vs. Mach plots for a rocket developed at UAHuntsville. As the rocket reaches the transonic region (around mach 0.9), wake drag increases significantly. This translates to a significant increase in the amount of energy or thrust needed to maintain or accelerate beyond this point.



$$C_D = \left[Cd_f(body) + K_F Cd_f(fins) + K_F Cd_{pro} + Cd_e\right] + Cd_b + \Delta Cd_T + \Delta Cd_S$$

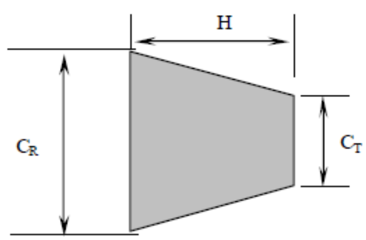
C_D is the total drag coefficient, $C_{d_{f(body)}}$ is the body drag due to friction, K_f is an interference factor, $C_{d_{f(fins)}}$ is the fin drag due to the friction, $C_{d_{pro}}$ is drag based on protrusions (rail buttons), C_{d_e} represents the drag based on excrescences (scratches, joints), C_{d_b} is the base drag, ΔC_{d_T} and ΔC_{d_S} are transonic and supersonic wave drag. Each term in this equation has their own set of equations in order to calculate the different values.



P.12.2. Fin Flutter Analysis

Unsteady fin flutter occurs when the frequency of vibration associated with flapping and twisting is small relative to linear flight speed. An excessive amount of fin flutter can result in a failure of the fin, i.e. shear, deformation, dislocation, etc. Supersonic flight amplifies these effects. Fin size and composition is crucial to reducing the effects of fin flutter. Fins are the main control surfaces of the rocket. Their failure can result in the loss of the vehicle.

Theodorsen methodology is one way of calculating the speed at which fin flutter will begin to emerge. That is at the point when the vibrations become undamped.



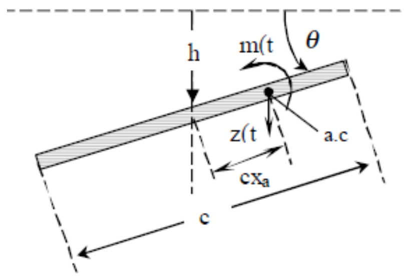
Where,

H = exposed fin half span
C_R = exposed fin root chord
C_T = exposed fin tip chord

Then:

$$\lambda = C_T / C_R = \text{Taper Ratio}$$

$$A = \frac{4H}{(1+\lambda)C_R} = \text{Aspect Ratio}$$



h = plunging degree-of-freedom

θ = rotational degree-of-freedom

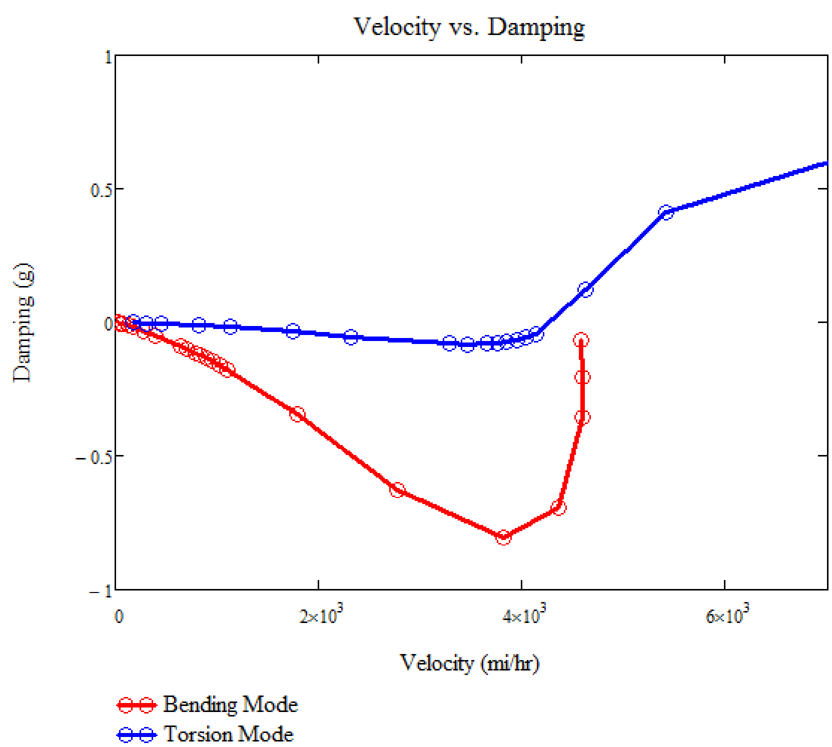
c = section chord length

x_a = distance of the aerodynamic center ahead of the midchord as a fraction of the chord length.

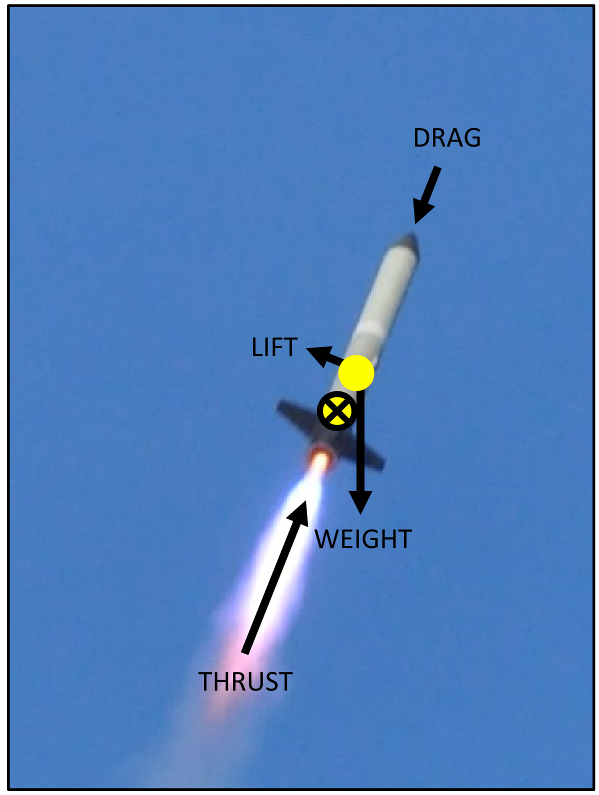
z(t) = aerodynamic normal force

m(t) = aerodynamic moment

Theodorsen solution gives us the ability to predict the flutter speed for unsteady flutter. With this we can see how much damping will occur and plot it versus flight velocity. Theodorsen uses multiple values of reduced frequency to calculate velocity and damping. Theodorsen assumes that the fins are a solid homogeneous material. The calculations require an input value for a Modulus of Rigidity (G). Below is an example of the finished analysis plot. The fin being analyzed becomes undamped when the damping value rises above zero.



P.13. Forces on a Rocket



In flight, a rocket is subjected to four forces: *weight*, *thrust*, and the aerodynamic forces of *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 magnitudes and sometimes the directions of the four forces are constantly changing. The response of the rocket depends on the relative magnitudes and directions of the forces, much like the motion of the rope in a "tug-of-war" contest. If we sum 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 act 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 an airplane and a 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.

P.13.1. "Design To" Loads Analysis

Throughout a rocket's flight, there are several specific cases that are of interest because they bracket the rocket's "design-to" loads sets. This section will examine two of them – maximum acceleration and maximum velocity. The analysis of these cases will consider aerodynamic data and the data established in the rocket's mass budget statement. Another Excel spreadsheet can be developed to manage this analysis.

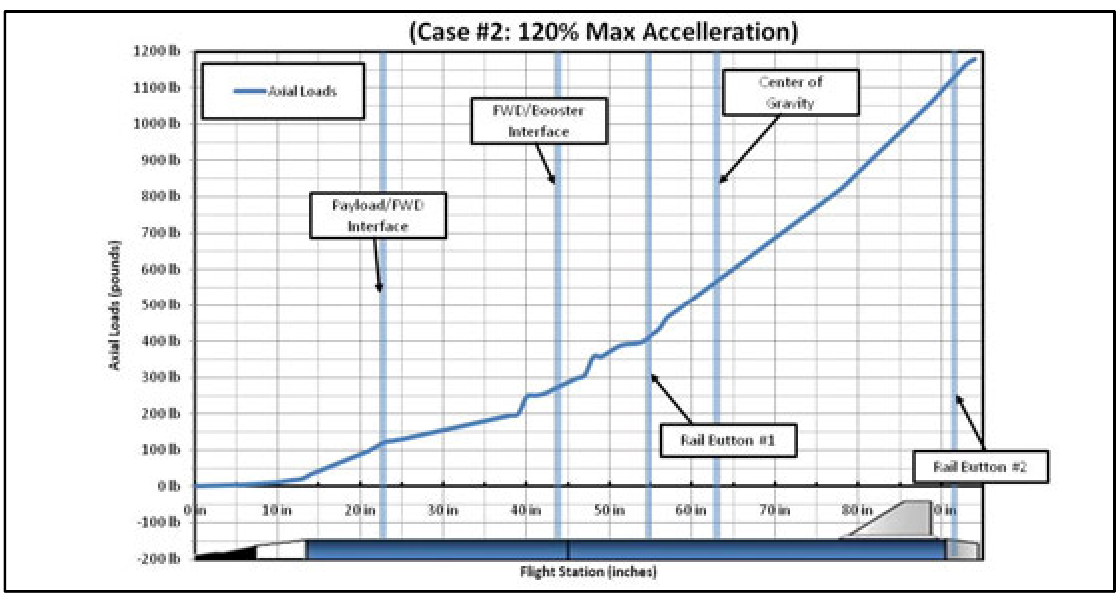
There are three types of loads that are commonly calculated – axial, shear, and bending moment. Axial loads are those loads that act along the major axis or centerline of the rocket. Shear loads are those loads that work orthogonally to the rockets centerline. Bending moment loads (torques) are those that cause the rocket to bend. Moments and torques are measured as a force multiplied by a distance so they have units of inch pounds force (in-lb) or Newton-meters (Nm). We will constrain the analysis to two dimensions so that we are only working with one shear and one moment load.

P.13.1.1. Maximum Acceleration Analysis

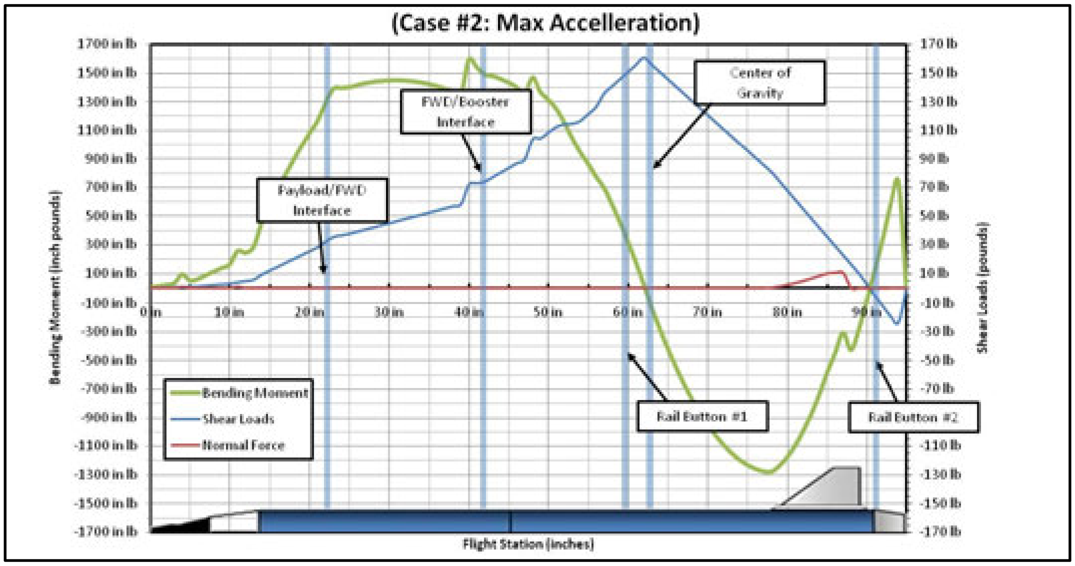
The rocket may experience the maximum axial compression and/or maximum shear and bending moment when it reaches maximum acceleration. Some positive margin can be built into the loads analysis by performing the analysis at 120% of the maximum T/W. That will yield a more conservative answer and the analysis doesn't have to be as high fidelity. For every flight station of the rocket, take a summation of the contributions of the elements at that flight station. That task alone is not easy but is fundamental to the analysis process.

$$M_i = \sum m_{1i} + m_{2i} + m_{3i} + \cdots + m_{ni} \qquad \textit{(For all flight stations)}$$

Below is an example of the axial loads analysis at the point of maximum acceleration. This information reveals that trend in increasing axial loads moving from the nose aft. Vehicle interfaces are labeled for easy reference to show loads at specific points on the rocket.

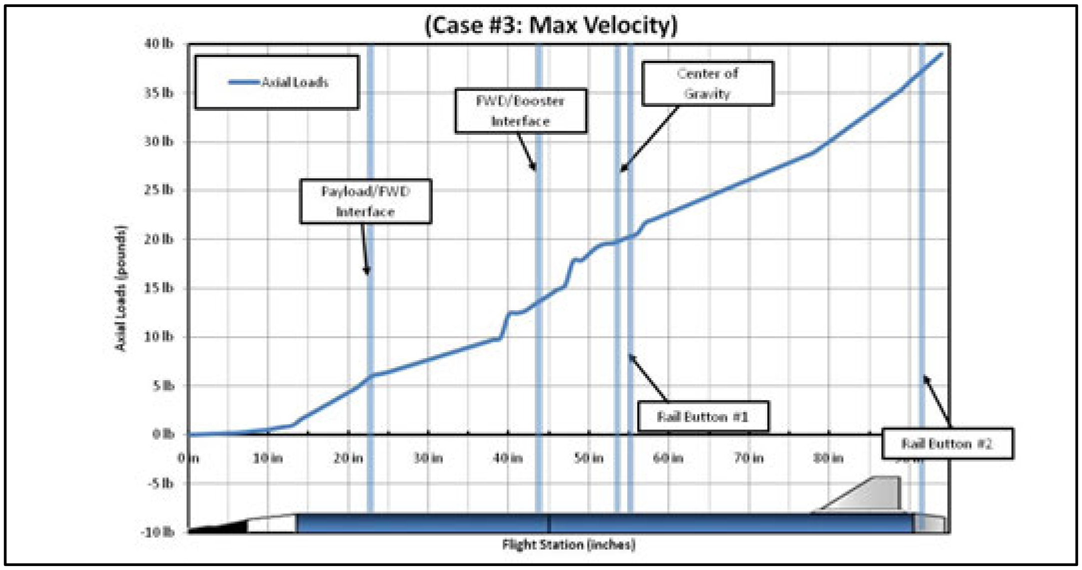


Using the same seed data, the shear and moment plot below was developed. The plot reveals some unique trends. The shear and bending moments where calculated using the CG as the reference point since the vehicle will be rotating about this point during flight. The shear load peak and the bending moments approach zero at the CG. Notice the bending moment loads are high at the two airframe interfaces. This is an important piece of information to have when designing the interface. Also notice that the Normal Force (Aero loads) are much less significant than shear and bending loads because the vehicle is still moving very slowly at this point.

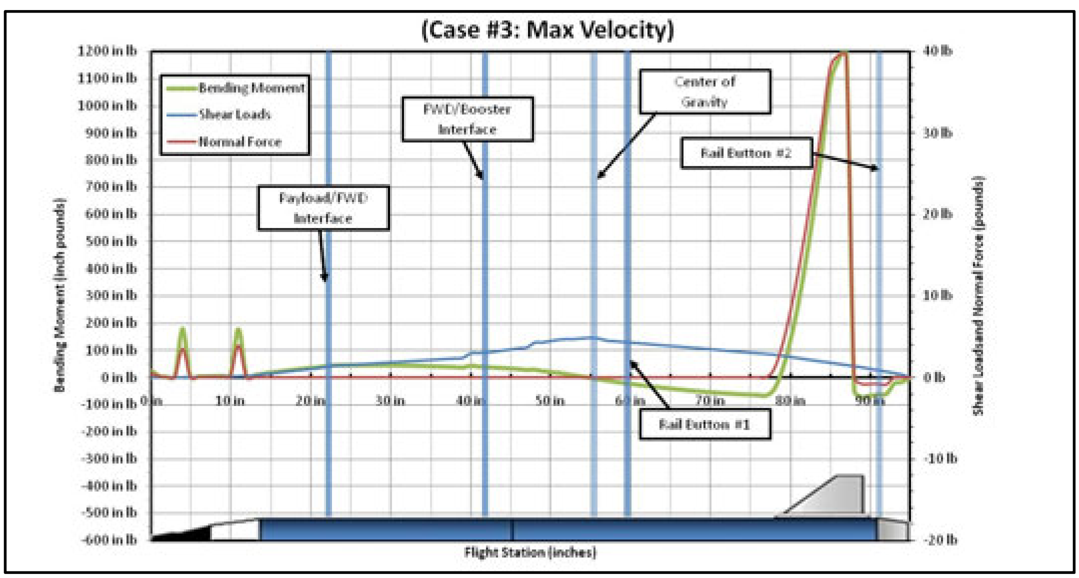


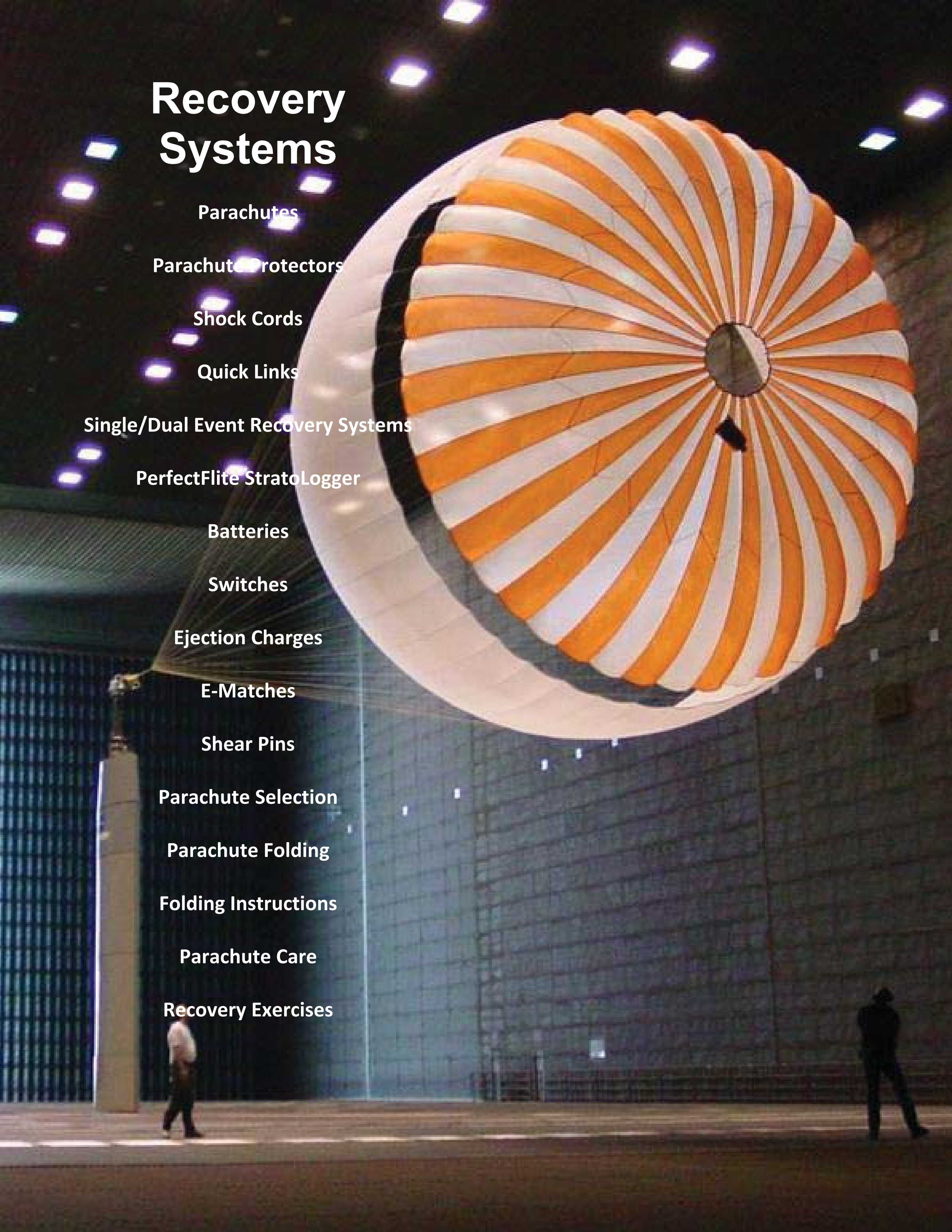
P.13.1.2. Maximum Velocity Analysis

The rocket may experience the maximum axial compression and/or maximum shear and bending moment when it reaches maximum velocity. The same analysis was performed for max velocity considering the velocity, flight angle, and altitude at the moment of max velocity. For this rocket, max velocity is also the moment of max-Q or maximum dynamic pressure, the analysis confirms this. Notice that the maximum bending moments occur at the rocket's fins. The nosecone's geometry has a pronounced effect at this point as well, but the highest loads recorded in this analysis are lower than those recorded at maximum acceleration.



What has been shown is that the maximum acceleration loads set brackets the "design to" requirements for the rockets airframe and the max velocity loads set brackets the "design to" requirements for the rocket's fins.





Recovery Systems

Parachutes

Parachute Protectors

Shock Cords

Quick Links

Single/Dual Event Recovery Systems

PerfectFlite StratoLogger

Batteries

Switches

Ejection Charges

E-Matches

Shear Pins

Parachute Selection

Parachute Folding

Folding Instructions

Parachute Care

Recovery Exercises

NASA High Power Rocketry Video Series
Counterpart Documents

Written by Daniel Cavender

High-powered rockets are required to have a recovery system. This section will help teach you how to design a recovery system for your rocket. You will learn about the hardware needed to build a recovery system, how to apply Newton's 2nd Law of Motion to calculate the parachute size 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 decelerates 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.

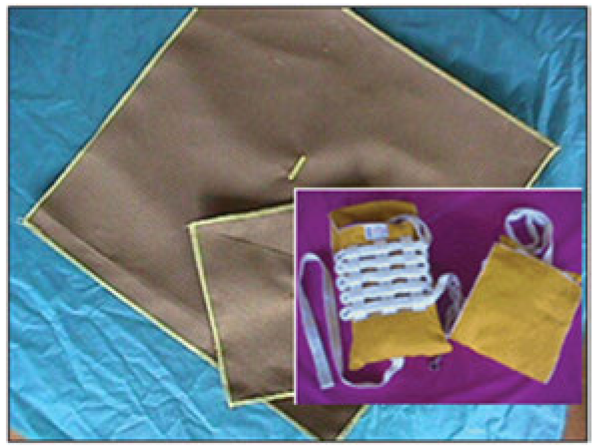
High-powered rocketry parachutes typically have three major features.

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

Rocket 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 shaped canopy. 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 with both techniques, do not wrap the parachute too tightly.

Recovery Harness

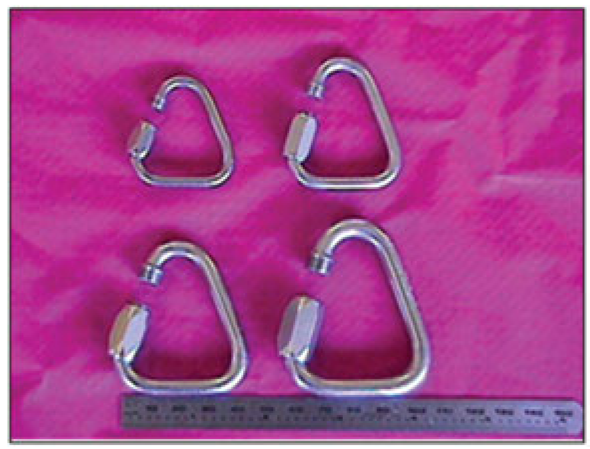
A "recovery harness" is generally a long length of static cord that attaches structural components that separate as part of the recovery system. Typical materials for a recovery harness are Aramid/Kevlar, Kevlar/Fiberglass, and nylon. Each end is typically secured by quick-link to a u-bolt or eye-bolt that is rigidly mounted to a bulk plate on an avionics bay, nose cone, or booster. The main parachute is generally attached to a loop in the shock cord which is tied just below the nose cone by a quick-link. The length of recovery harness required will be the subject of empirical testing and evaluation. Some shock cords are as short 12 ft. and others can get as long as 100 ft.!

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 to the right, 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 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 taut. Recall that nylon is susceptible to melting and charring. Take measures to protect nylon cords and inspect all shock cords before flights.

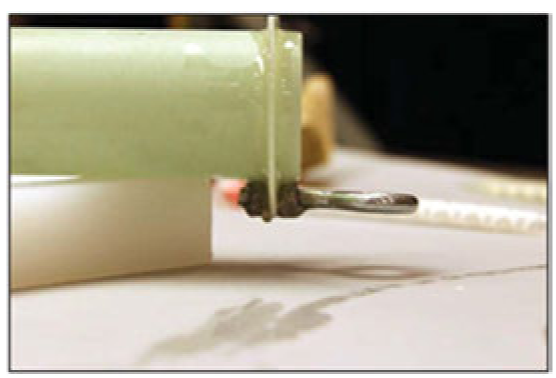
Shock cord bundle courtesy of the Rocketry Forums.

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 to help prevent the harness from slipping free. Also, the bi-products of black powder ejection charges are acidic and will cause corrosion. 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 such as when the main parachute opens.



The quick links attach the recovery system to the rocket’s structures. There are several hard points available on the rocket’s bulk plates and/or centering rings. These hard points generally consist of eye-bolts or U- bolts; U-bolts are preferred on large rockets. Eye-bolts should be closed and/or welded closed to prevent the recovery harness from slipping free.



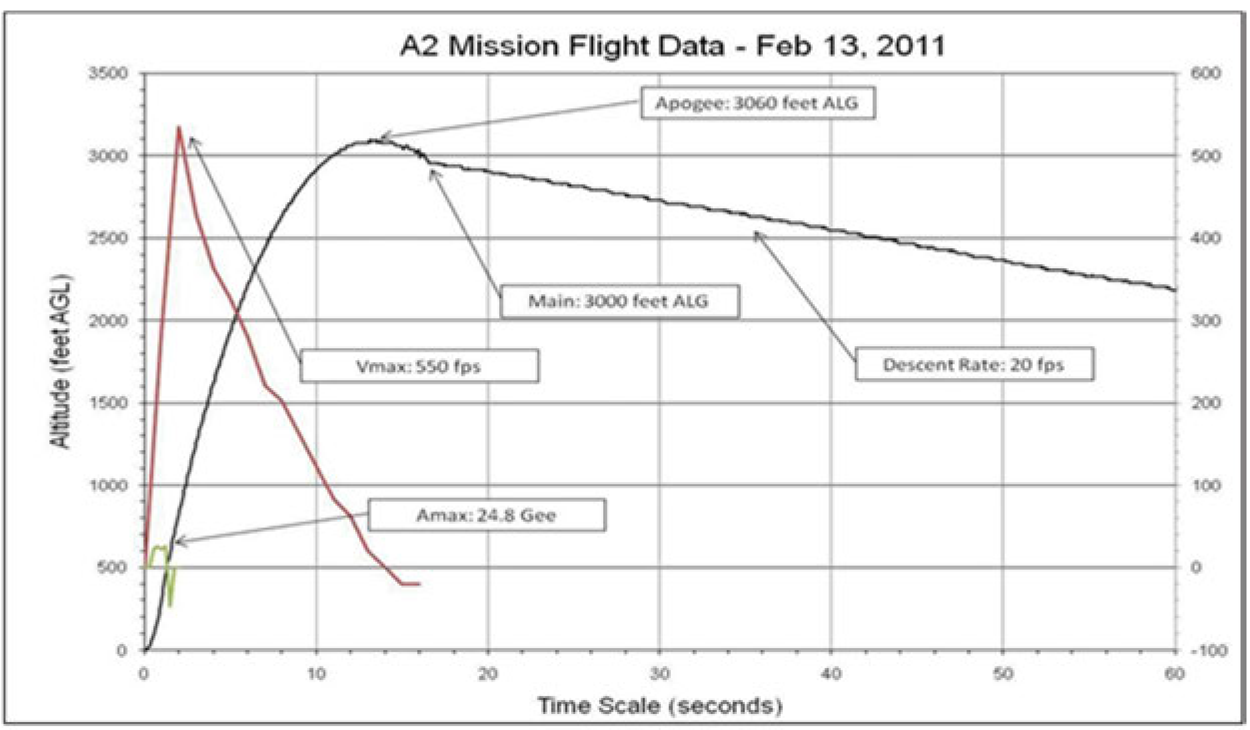
Recovery Systems Overview

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 ignited and the parachute is deployed. If the timing is correct, this happens near apogee. SERS is the simplest recovery system and is good for low altitude flights on small launch fields.

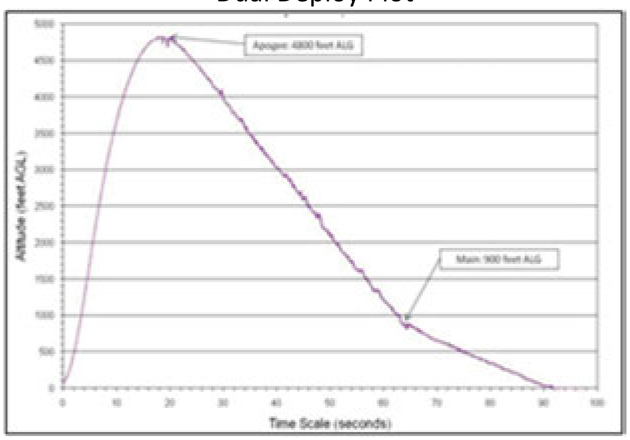
The plot below shows the trajectory of a rocket with a single event recovery system. The rocket reaches apogee and deploys a parachute using the motor ejection charge. The rocket then descends slowly at 20 fps. With an apogee of 3000 feet, it takes two and a half minutes for the rocket to touch down.



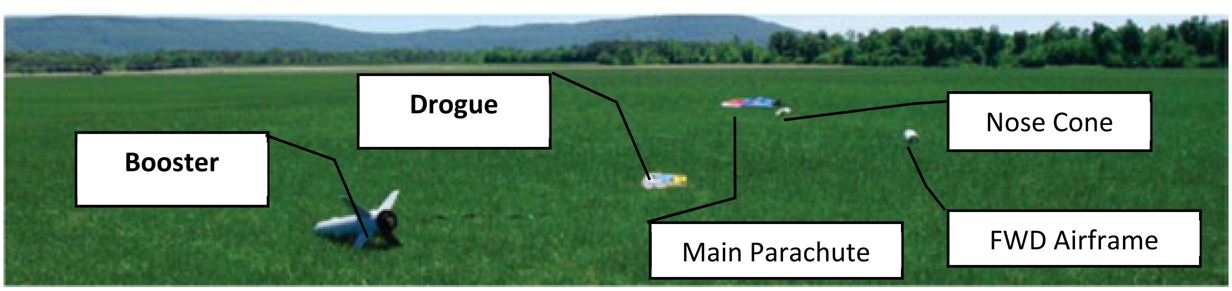
Dual Event Recovery System (DERS)

Larger rockets with higher apogees should 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.

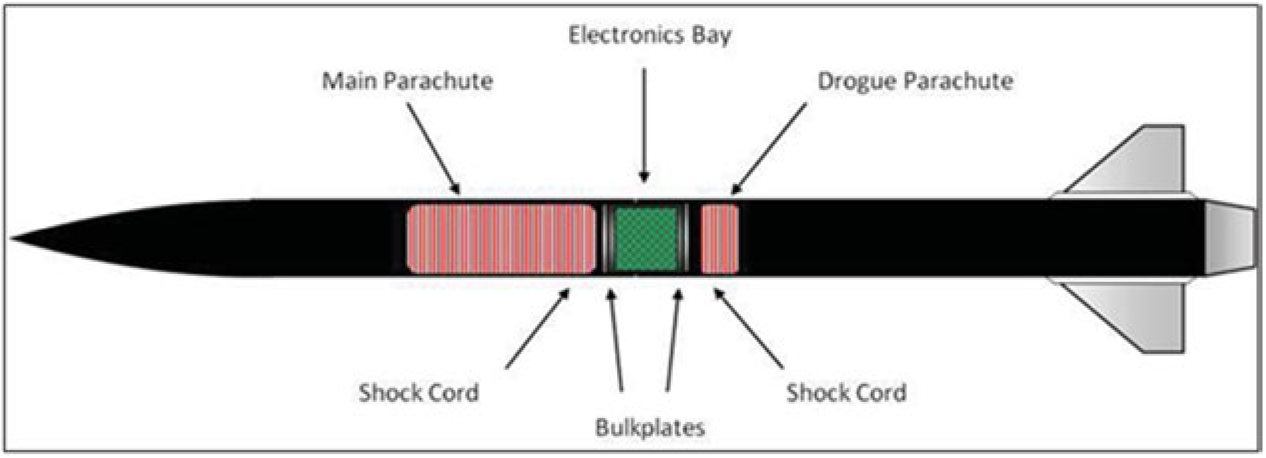
Dual Deploy Plot



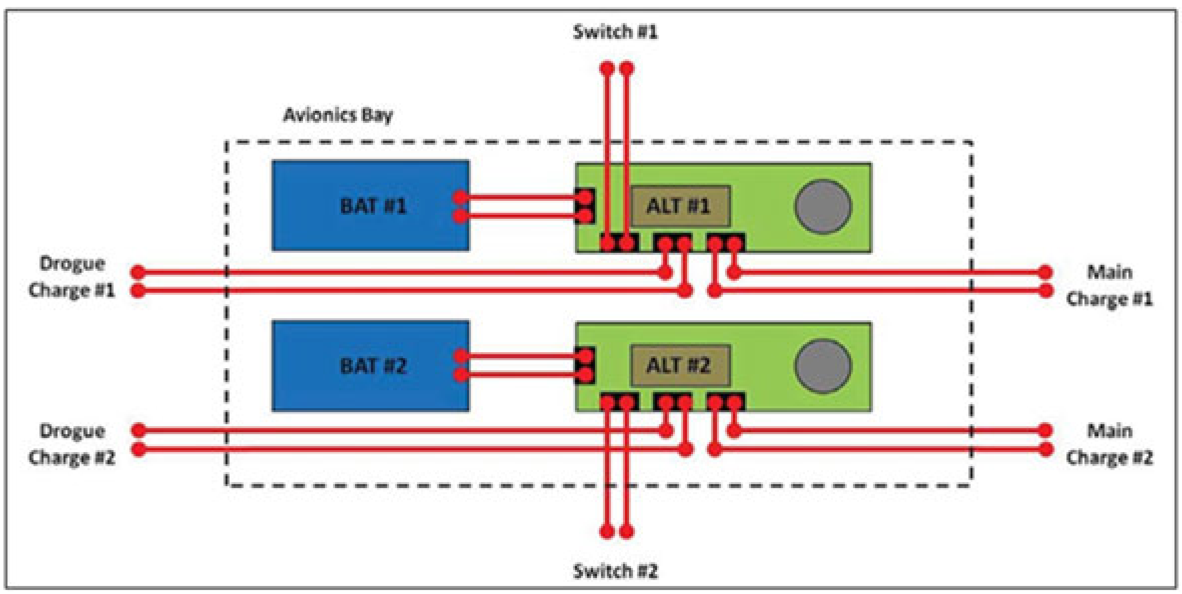
The plot above shows the trajectory of a rocket using a dual event recovery system. The rocket reached an apogee of 4800 feet. It then deployed a drogue that slowed the descent to 90 fps. At 1100 feet, the main parachute deployed, further slowing the decent rate to 18 fps. It took only one and a half minutes for the rocket to touch down.



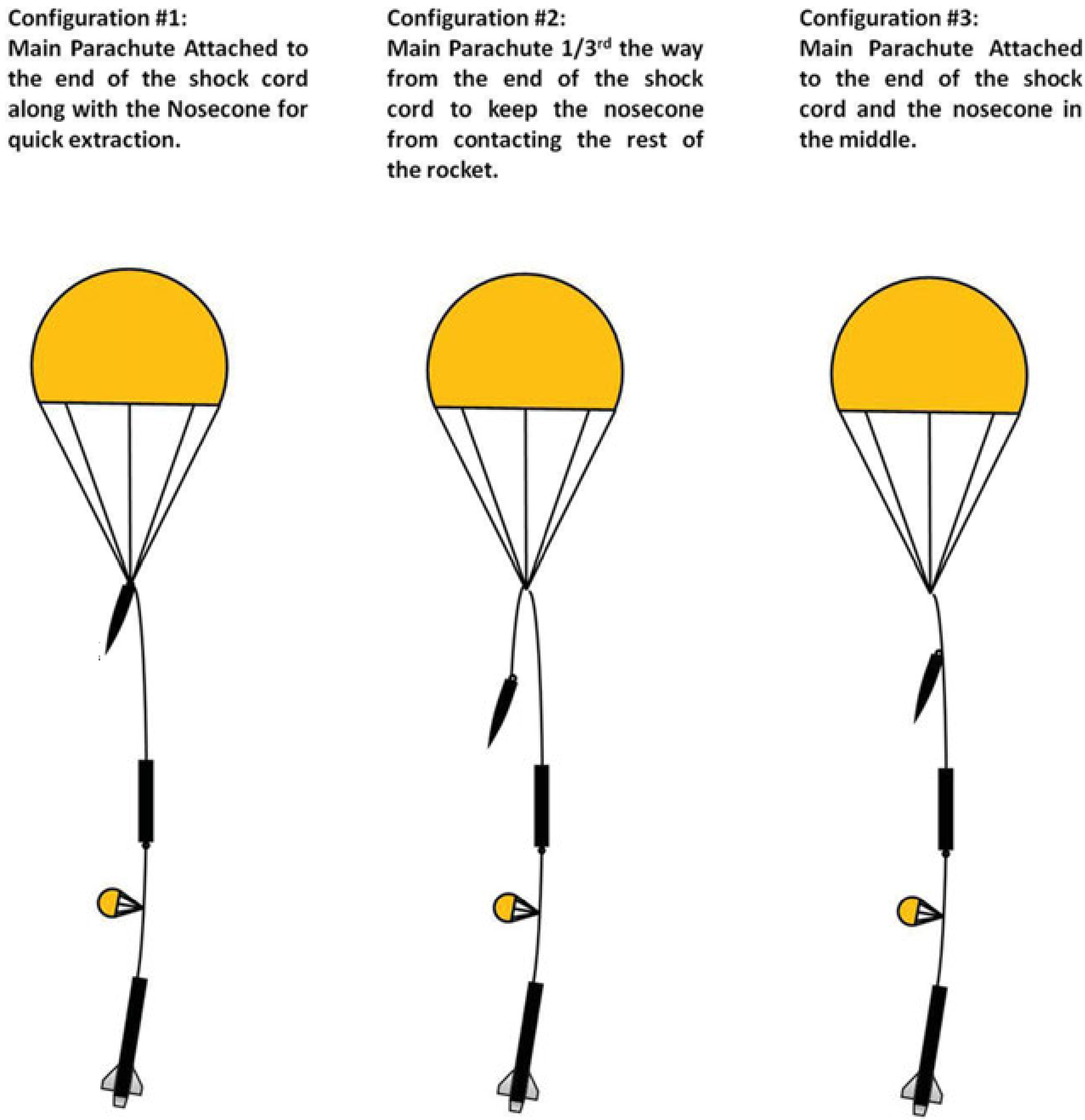
A rocket equipped with a typical dual event recovery system has this general layout. The main parachute is generally forward of the electronics bay. This adds advantage to the rocket's center of gravity and hence the rocket's stability margin by having the larger and heavier of the recovery devices far 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 bulk plates.



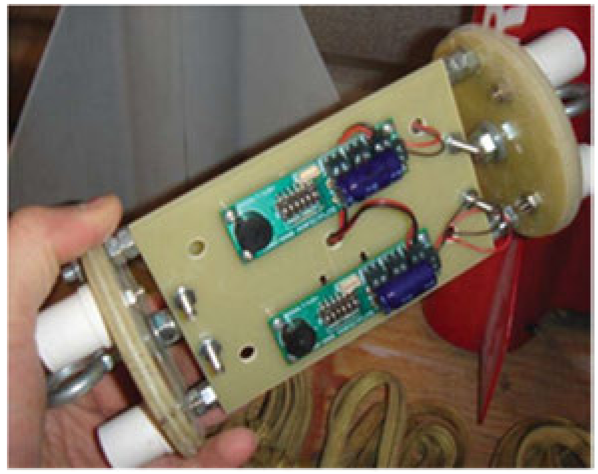
The system level diagram below details the dual event recovery system's configuration. This system is a fully redundant recovery system. There are two altimeters which each have a dedicated battery and switch. Each altimeter has its own set of recovery charges to fire. There are four charges in total in the rocket.



The diagram below shows three different ways the dual event recovery system's hardware may be configured. Each has benefits and risks:

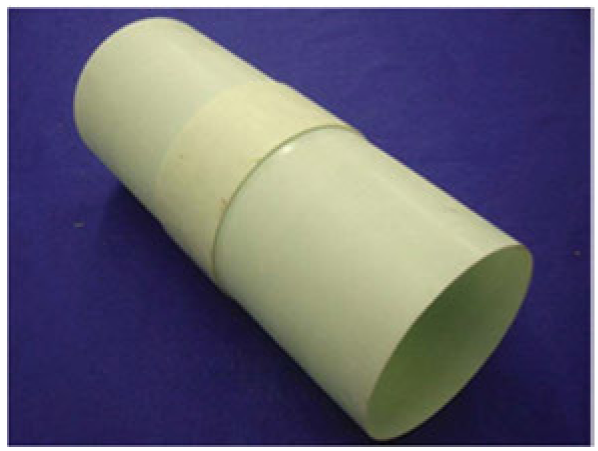


The Avionics Bay



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 seal the housing from hot ejection gases, separate 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. 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. 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 mounted onto ¼" diameter all- threads using ¼" I.D. G-10 fiberglass tubes that are epoxied to the corners of the G-10 boards. This simple sled supports only altimeters, batteries, and switches. This sled was designed to slide into the avionics bays of several different rockets, allowing the same electronics to be utilized by several different rockets.

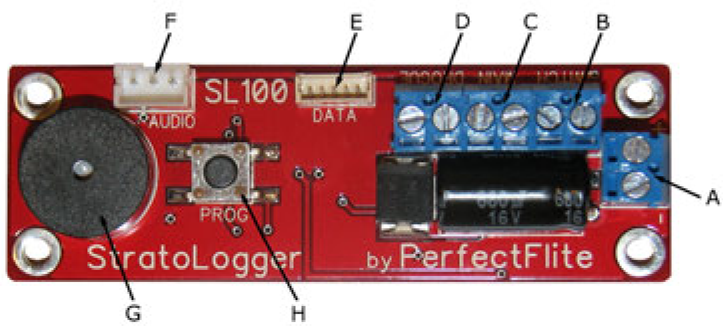
Recovery Electronics

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

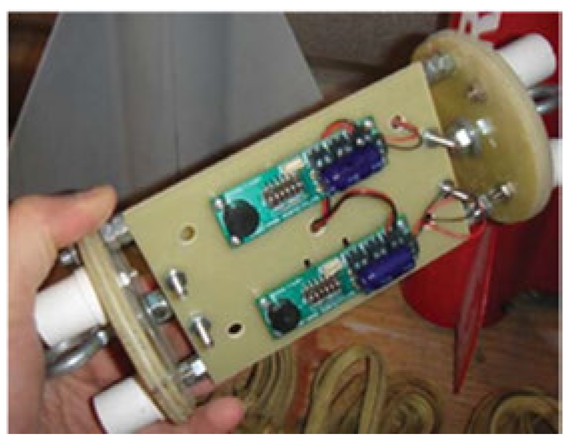
PerfectFlite StratoLogger

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 with at least one PerfectFlite StratoLogger or other altimeter. The PerfectFlite altimeters are powerful robust commercial altimeters. They support deployment event programmable settings for the main ejection charge from 100 feet to 9,999 feet AGL. The default setting for the drogue is apogee.

StratoLogger Features:
A: Battery Terminal
B: Power Switch Terminal
C: Main Ejection Charge Terminal
D: Drogue Ejection Charge Terminal
E: Data I/O Connector
F: External Audio Connector
G: Beeper
H: Preset Program Button

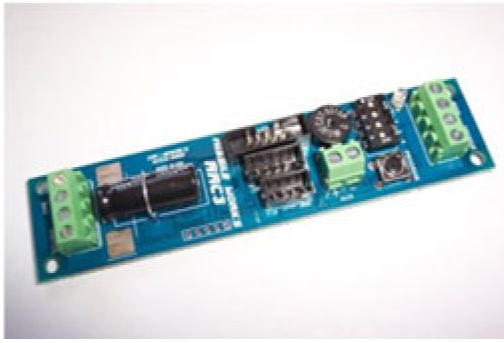


The pressure sensor of the PerfectFlite StratoLogger works to 100,000 feet MSL and its stores over 9 minutes of flight data at 20 Hz (Hertz - samples per second). All of the data is stored in a nonvolatile memory and is preserved even if power is lost. The PerfectFlite's robust power supply is not affected by up to two seconds loss of power in flight and will fire 10 parallel-redundant 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 StratoLogger produces a firing current of 10 A (Amps) peak.

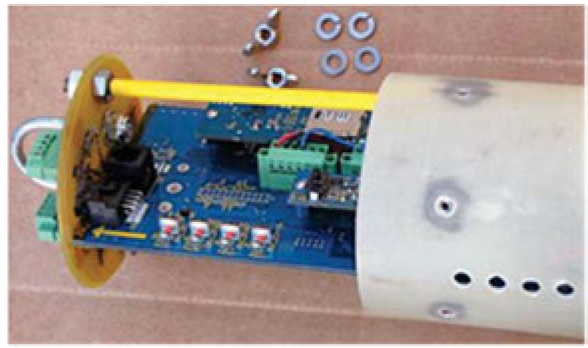


Altimeters, usually mounted in the rocket's avionics bay, need to sample the outside air pressure. Your rocket will need a static pressure port along the outside to allow the inside pressure to equalize to the outside pressure. Be sure to check the manufacturer's guide to determine the proper number of holes and how they are sized.

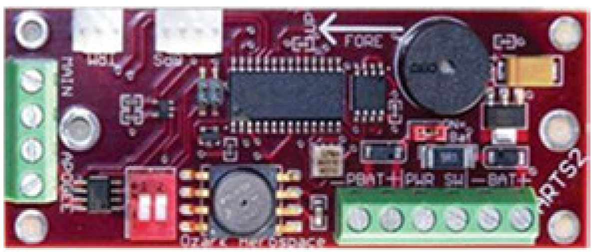
Other Avionics Devices



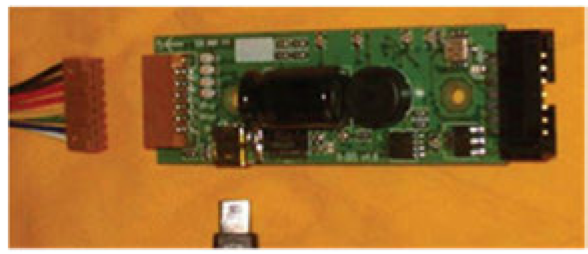
RRC3 Altimeter



G-WIZ Avionics Bay

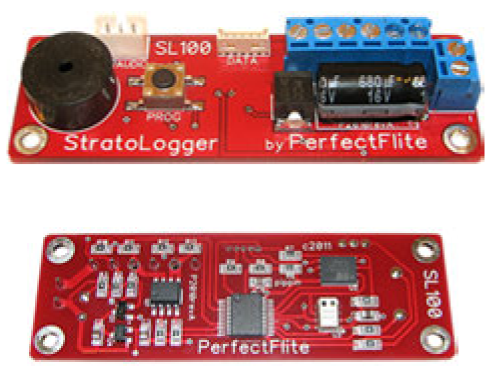


ARTS2 Flight Computer



AED Electronics R-DAS Tiny

Apogee Altimeter One



PerfectFlite StratoLogger

Batteries

Typically, rocket builders prefer each altimeter have a dedicated battery and switch. There are two main types of batteries used in high-powered rocketry: primary and secondary. Primary batteries, such as a 9V alkaline battery, should be used once and then discarded. 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 world 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 turn on their electronics from the outside of the rocket once it is placed on the launch pad. This method maximizes battery life and is safer than activating the electronics, which are capable of initiating the black powder charges, while the rocket is still being handled or transported. 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 bulk plate of the nose cone. This net force will eject the nose cone, shock cord, and parachute out of the rocket airframe. This happens because the rocket is obeying the Ideal Gas Law.

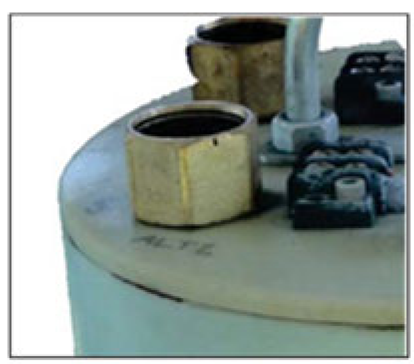
The Ideal Gas Law is the equation of state for a hypothetical incompressible or "ideal" gas. The state of an amount of gas is determined by its pressure, volume, and temperature.

The modern form of the Ideal Gas Law 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 8 to 16 psi. Also, black powder charge amounts are typically reported in grams.

$$Pressure: P = \frac{F}{A} = \frac{200lbf}{\pi(2in^2)} = 16\,psi \qquad Volume: V = \pi R^2 L = 12.5in^2 L$$

$$Black\ Powder: n = \frac{PV}{RT} = 16psi * \frac{12.5in^2 L}{266\,\frac{in\ lbf}{lbm} * 3307^o R}\left(\frac{454\ grams}{1\ lbf}\right) = 0.1L$$

The reduced equation for this case states that 0.1 grams of black powder is required for every 1 inch of airframe containing the recovery system. Therefore, if L=20 in., then 2.0 grams of black powder is required 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 nonconductive 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 manufactured E-matches from most vendors on launch day. E-matches can also be augmented to serve as motor igniters.

Shear Pins

Shear pins are generally used on mid and 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 effect 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

Every rocketeer wants to safely recover their rocket so they can fly it again. Selecting the right size parachute is the first step to a successful recovery. There are two good methods to help determine the appropriate size of your parachute – the Kinetic Energy Equation and Newton's 2nd 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 velocity (V).

$$KE = \frac{1}{2} mV^2$$

Two rockets of the same final descent rate and different masses will have different KEs. The same is true of 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 descend under a main parachute at 20 ft/s.

$$KE_1 = \frac{1}{2}(30\ lbs)\left(20\frac{ft}{s}\right)^2\left(\frac{1\ lbf\ s^2}{32.2\ lbm\ ft}\right) = 186.3\ lbf$$
$$KE_2 = \frac{1}{2}(60\ lbs)\left(20\frac{ft}{s}\right)^2\left(\frac{1\ lbf\ s^2}{32.2\ lbm\ ft}\right) = 372.7\ lbf$$

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.

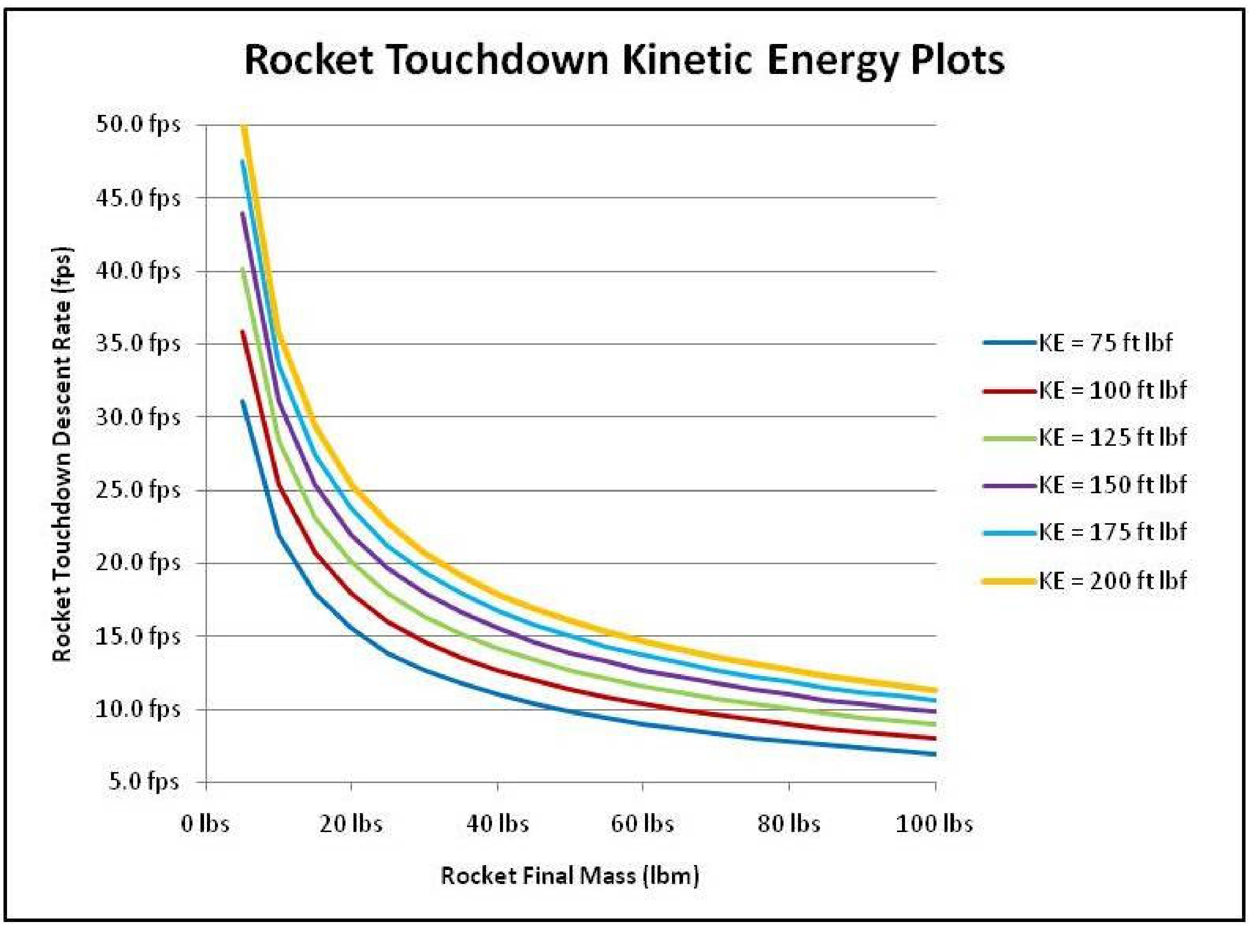
Case 2:

Consider two rockets that both weight 30 lbs that descend under a main parachute at 17 ft/s and 22 ft/s respectively.

$$KE_3 = \frac{1}{2}(30\ lbs)\left(17\frac{ft}{s}\right)^2\left(\frac{1\ lbf\ s^2}{32.2\ lbm\ ft}\right) = 134.6\ lbf$$
$$KE_4 = \frac{1}{2}(30\ lbs)\left(22\frac{ft}{s}\right)^2\left(\frac{1\ lbf\ s^2}{32.2\ lbm\ ft}\right) = 225.5\ lbf$$

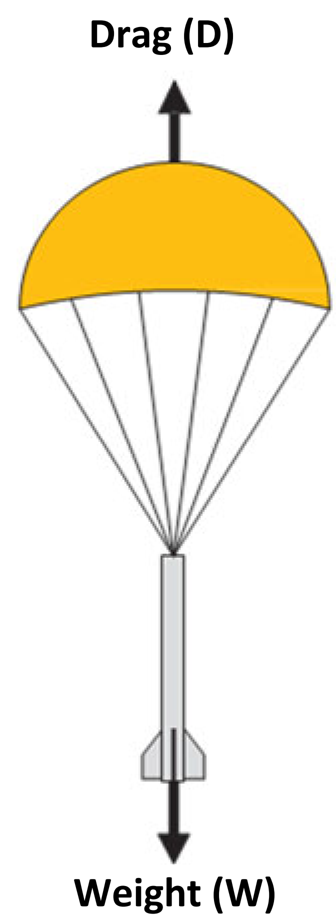
The second rocket's KE value is nearly twice that of the first. This case demonstrates a small change in descent velocity has a more pronounced effect on KE than changes in mass of the rocket. An 18 lb rocket descending at 22 ft/s would have the same KE as the 30 lb rocket descending at 17 ft/s.

The 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 by limiting the energy at which the rocket impacts the ground thus improving safety and survivability. A good target KE range might be 75 ft-lbf (102 Joules) or less.



Newton's 2nd Law of Motion

The rocket and parachute obey Newton's 2nd Law of Motion. Newton's 2nd Law (F=ma) states the relationship between an object's mass (m) and its acceleration (a). 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 constant
3. The rocket moves simply downward (constrained to z-axis)
4. The atmosphere is a continuum (constant air density)

$$\sum F_Z = ma = 0$$

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

$$\sum F_Z = D - W = ma = 0 \; (steady\ state)$$

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

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

Substituting the drag equation, Newton's 2nd 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 or 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 determined empirically and can usually be found on a manufacturer's website.

Consider a descent rate range 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. For example, if you estimate that your rocket will weigh 20 lbm and substitute these estimated descent rates, 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 parachute's reference area and the manufacturer's calculated drag coefficient.

Upper Bound (Descent Velocity = 18 ft/s):

$$S = \frac{2W}{\rho V^2 C_d} = \frac{2 * 20\ lbm}{0.075 \frac{lbf}{ft^3} * 18 \frac{ft}{s} * 2.0} \left(\frac{32.2\ lbm}{lbf * s^2 / ft} \right) = 26.5\ ft^2$$

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

$$S = \frac{2W}{\rho V^2 C_d} = \frac{2 * 20\ lbm}{0.075 \frac{lbf}{ft^3} * 22 \frac{ft}{s} * 2.0} \left(\frac{32.2\ lbm}{lbf * s^2 / ft} \right) = 17.7\ ft^2$$

For this case, the rocket will require a parachute that has a reference area between 18 ft^2 and 26 ft^2. Your design will continue to mature throughout the design process 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:

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

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

Parachute Folding Instructions

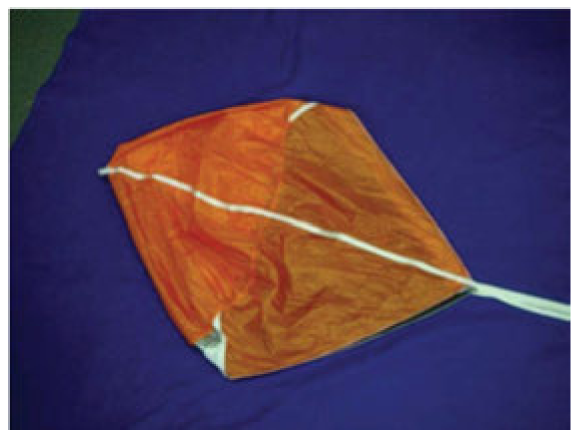
These instructions demonstrate the procedures for folding a Sky Angle Classic II 36” parachute. These procedures can be applied to almost every parachute, but may vary slightly depending on parachute size, type, rocket diameter, and if you choose to use a deployment bag (D-bag). Practice folding your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

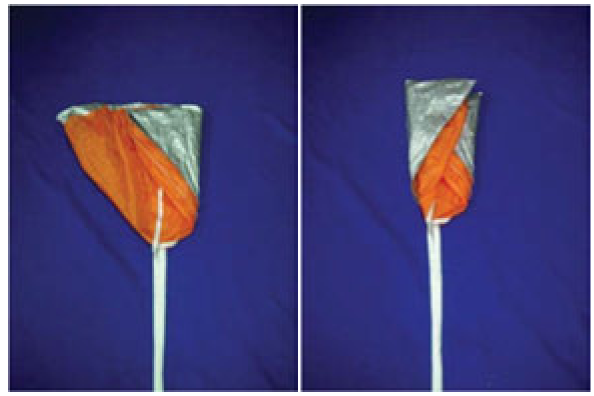


Step 3:

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.

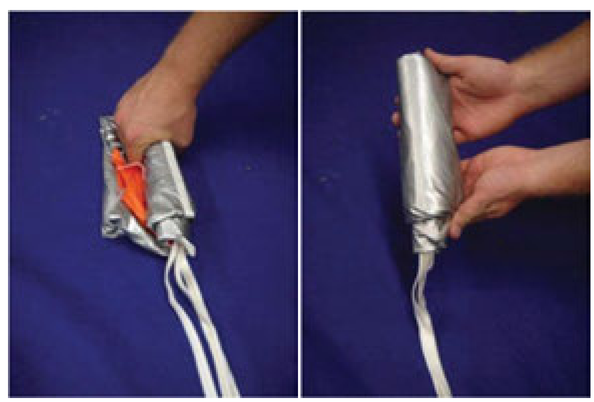


Step 5:

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.



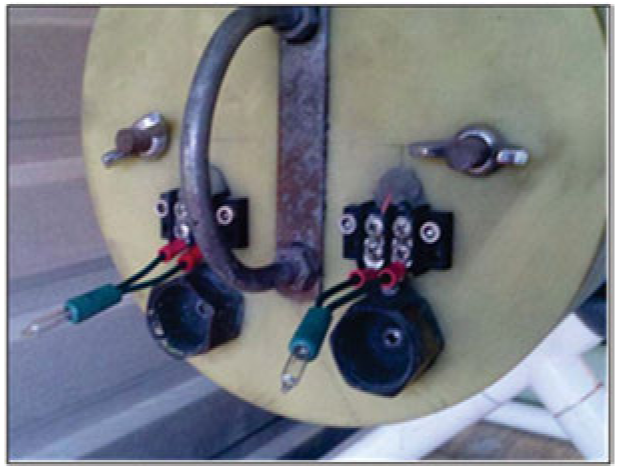
Step 7:

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 that a pressure based rocket altimeter is functional. The test can be as simple as a single altimeter in a mason jar, using a marinade syringe to pull 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 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 system setup.

UAH SL 2011

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

- Both main and drogue systems deployed as expected
- The parachutes were extracted from the airframe
- The parachutes and shock cords were 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:

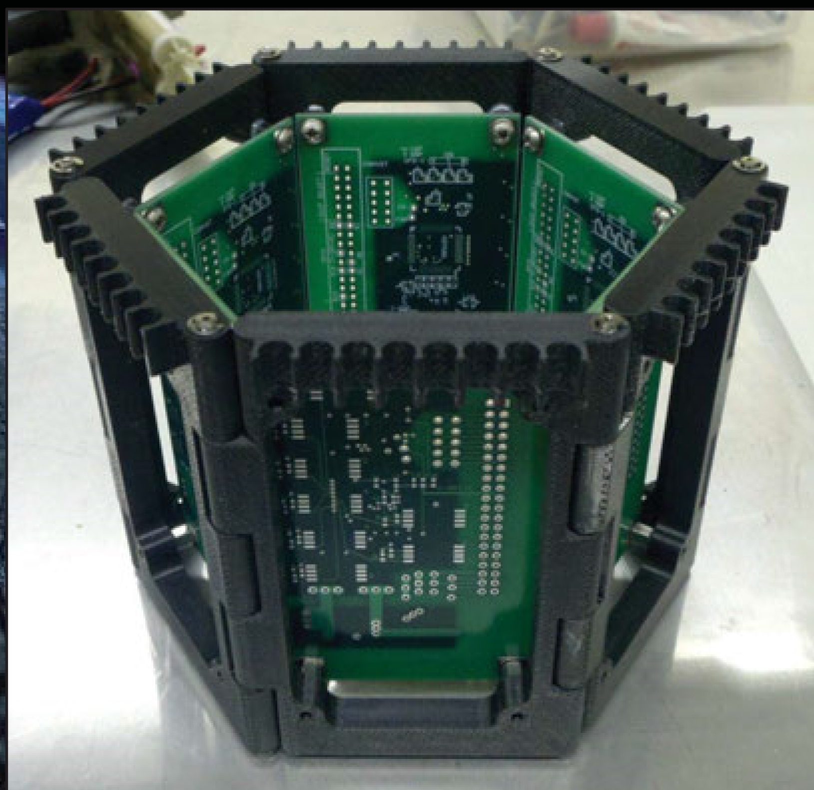
- Protect your parachutes from damaging hot ejection charge gases by using a Kevlar parachute protector, piston system, recovery wadding, dog barf (i.e. spray insulation material) or a deployment bag.
- Keep your parachutes indoors, dry and unfolded, when in storage. Take them out of your rockets and 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.

Avionics Systems

Materials:

Basic Electronic Circuits

Microprocessors



NASA High Power Rocketry Video Series
Counterpart Documents

Written by Daniel Cavender and Jason Winningham

Basic Electronic Circuits

Basic electrical circuits operate on three variables – voltage, current and power. Voltage is a measure of the electrical potential difference between two points. Current is the flow of electrons between two points, and is equal to the time rate of flow of an electric charge. Power is the rate at which electrical energy is transferred by an electric circuit.

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 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. 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 (I)

Current is a measure of the number of electrons per second which pass through a point. Keeping the cliff analogy in mind, current would be how fast the balls are dropping off the cliff. 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, which 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 necessity in determining 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, complicated payloads this has to be watched very carefully, but for smaller microcontroller based electronics 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 continually 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 is an especially big concern when preparing critical component right before launch. A common rule-of-thumb when working with circuits is that the more expensive and critical a component is, the easier it will be destroyed.

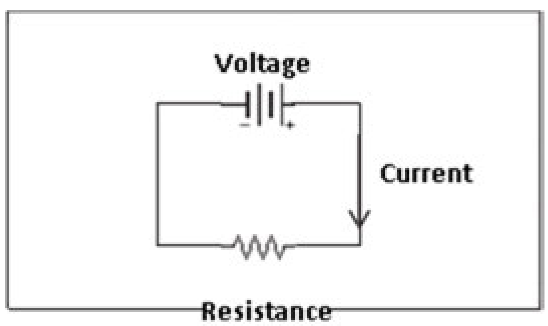
Laws of Basic Circuitry

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 resistor is needed. Some components like thermistors (resistors that change with temperature) or photoresistors (resistors that change based on lighting conditions) can provide useful data using Ohm's Law. This law is also highly useful when it is necessary to change DC voltages from a high to low value.

$$(Ohm's\ Law) \qquad Voltage\ (V) = Current(I) * Resistance(R)$$

How this works in practical applications is fairly simple. Imagine a battery, wire, and a resistor. 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:

$$Current(I) = \frac{Voltage(V)}{Resistance(R)}$$



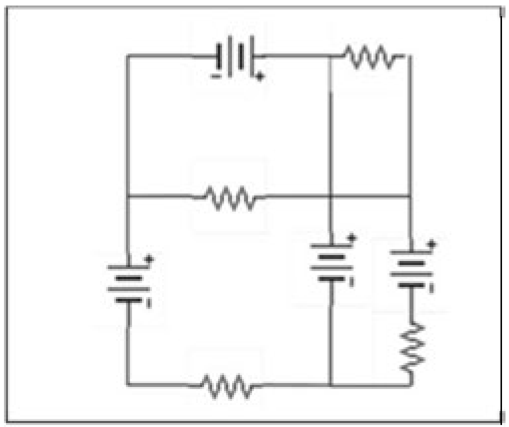
Assuming a 9 volt battery and 1,000 Ohm resistor [1K Ohm], the current would be:

$$Current(I) = \frac{Voltage(V)}{Resistance(R)} = \frac{9\ Volts}{1000\ Ohms} = .009\ Amps = 9\ milliamps$$

Being able to determine what 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 whether it is connected correctly.

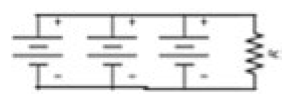
Kirchhoff's voltage law and Kirchhoff's current law are both used for complicated circuits. His voltage law states that for every voltage rise there is a voltage drop. The current law states that the amount of current going into a point is the same as the amount of current leaving the point. Using these two laws enables us to connect multiple batteries to multiple resistors and predict what current is travelling where. Working with these two laws can get pretty complicated. The best method of determining what is occurring in a circuit, when more than a few components are in use, is to use a multi-meter or oscilloscope.

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 less than ideal fashion. In practice, it is rare to see anything like this, but if you did, these two laws will help you to analyze what is going on.



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

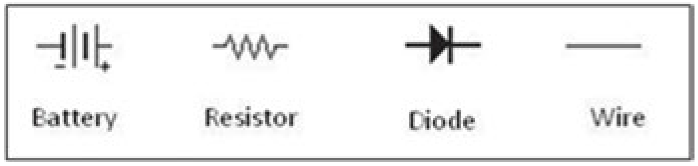
Series Batteries



Parallel Batteries

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 the calculation 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 section will show you how to do that.

Symbols



Calculations

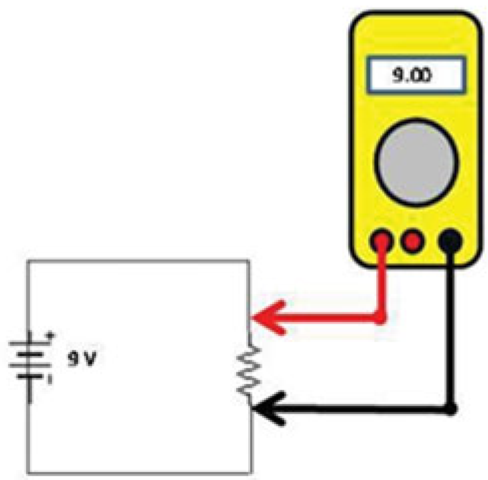
The level of difficulty in calculating the output of a circuit can range from easy to considerably complicated. The objective is to keep it as simple as possible. It may be a neat trick to be able to calculate what is happening with 50 components, but when a measurement will provide the same data, there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

Multimeters

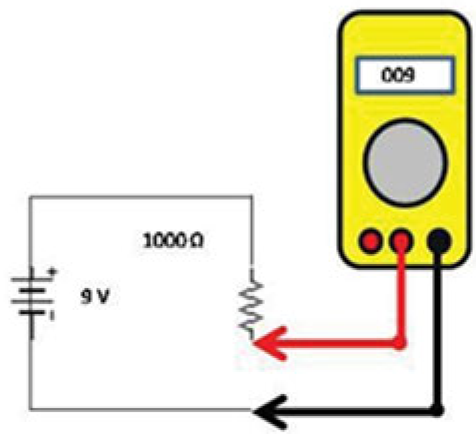
Multi-meter image courtesy of Mastech Electronics.

A multi-meter is a tool that allows measuring electrical properties around a circuit. Typically, multi-meters 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). Multi-meters provide very basic information, usually in the form of a DC voltage or DC current. This is a critical piece of hardware for testing and troubleshooting. Using a multi-meter involves placing the probes on two points in the circuit to measure the value 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 destroy an inexpensive multi-meter.

In making voltage measurements remember that the voltage test feature causes the multi-meter to have an extremely high resistance so that the circuit is not disturbed. When making a current measurement, the multi-meter goes into a very low resistance state to prevent disturbance of the circuit. A high end multi-meter has some built in features to keep the instrument from being damaged if placed in a circuit improperly. When it is needed to change from taking a voltage measurement to taking a current measurement, the probes must be removed and connected in a different fashion. It is a good idea to check to see what configuration the multi-meter is in before starting to measure in order to prevent permanent damage to your instrument.



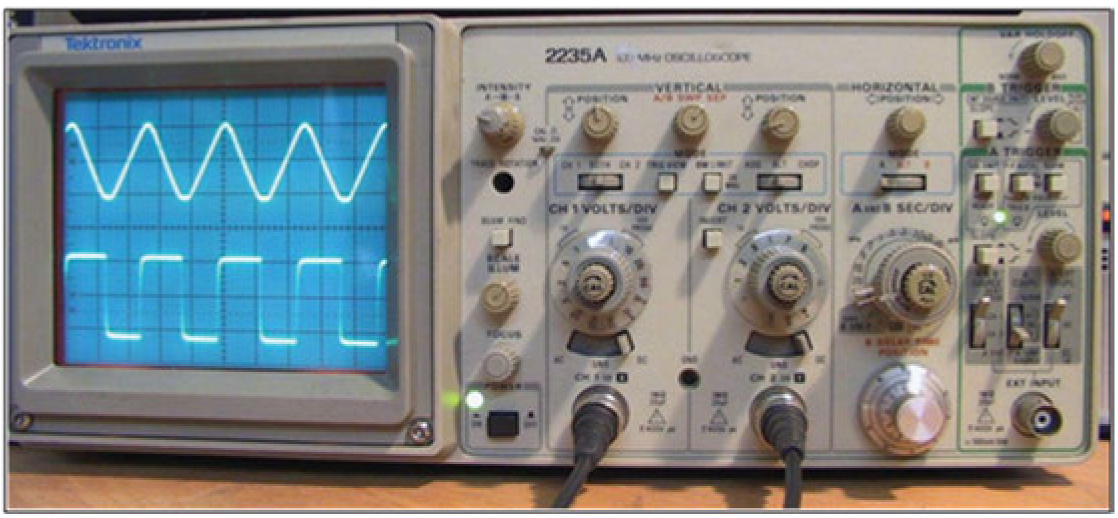
Checking voltage drop *across* a resistor

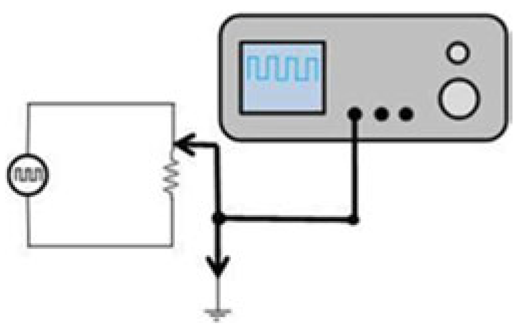


Checking current *through* the circuit

Oscilloscopes

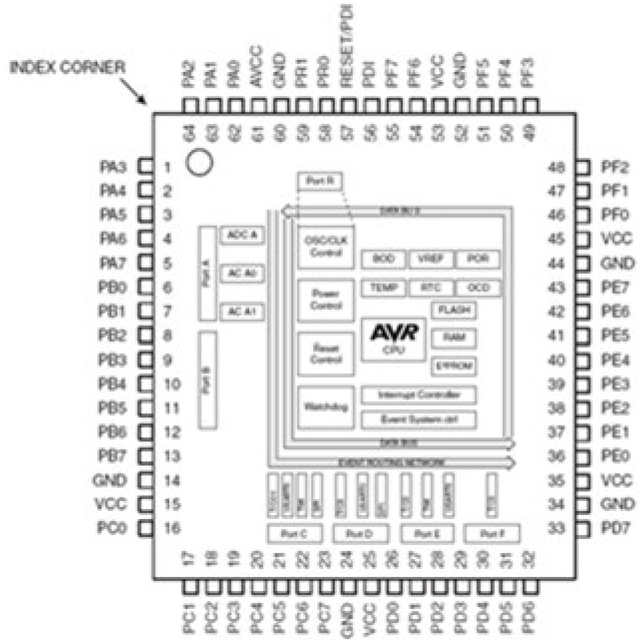
Oscilloscopes are used to determine waveform characteristics. This means whether or not waves that look like squares are actually square shaped. These instruments are also helpful when checking to see if the serial communications are acting as you think they should. Oscilloscopes are used for checking 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 settings 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 a small amount of offset on most oscilloscopes when checking multiple channels. The two main controls, other than the trigger set, are the sweep time and the 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. Because using an oscilloscope allows very precise measurements of what is occurring in the circuit can be made, it is a priceless piece of hardware for testing and troubleshooting. Even an older oscilloscope, as shown below, will do just fine for most applications.





Microcontrollers

A microcontroller (uC or µC) is a small but complete computer on a single integrated circuit (IC). A microcontroller contains a processor core, memory for program execution and program storage, and peripherals for input/output (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 kilobytes. There is usually no operating system (OS); when an OS is present, it is typically a very small real-time operating system (RTOS) designed for embedded applications.

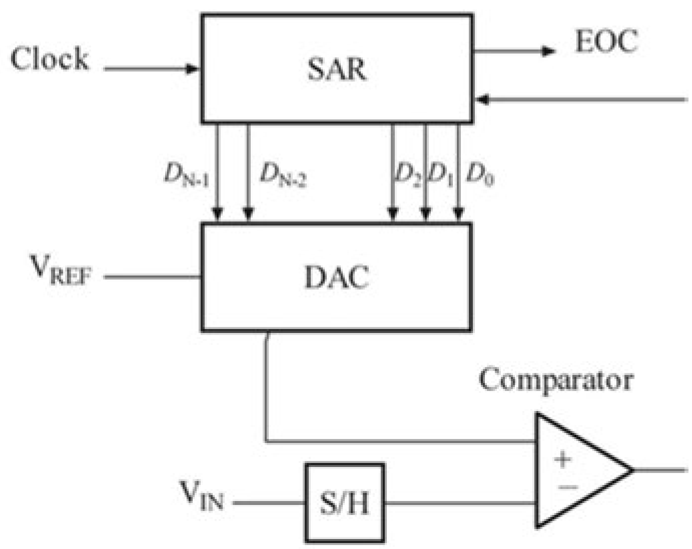
Memory for program execution (what is thought of as “RAM” in a desktop computer) is usually SRAM (static RAM). SRAM is slower than other memory architectures, but requires no management to maintain its contents, so the overall system is simpler. To keep external component requirements low, a microcontroller 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 kilobyte of SRAM, 16kilobytes of FLASH for program storage, and 512 bytes of EEPROM for non-volatile user data.

Modern microcontrollers may contain a variety of I/O interfaces. Digital I/O’s, where each pin is either a digital logic input or output (often 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. The signals we wish to measure are 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

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. More complex sensors may contain an ADC so that the microcontroller can simply read a digital value from the sensor.

There are many 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 that 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 I/O 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 of 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 through a serial connection 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 in.

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 over recent years. 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 industry. 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 beginners is the Arduino. It is an open source project based on a board containing an Atmel ATmega microcontroller with a minimum number 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

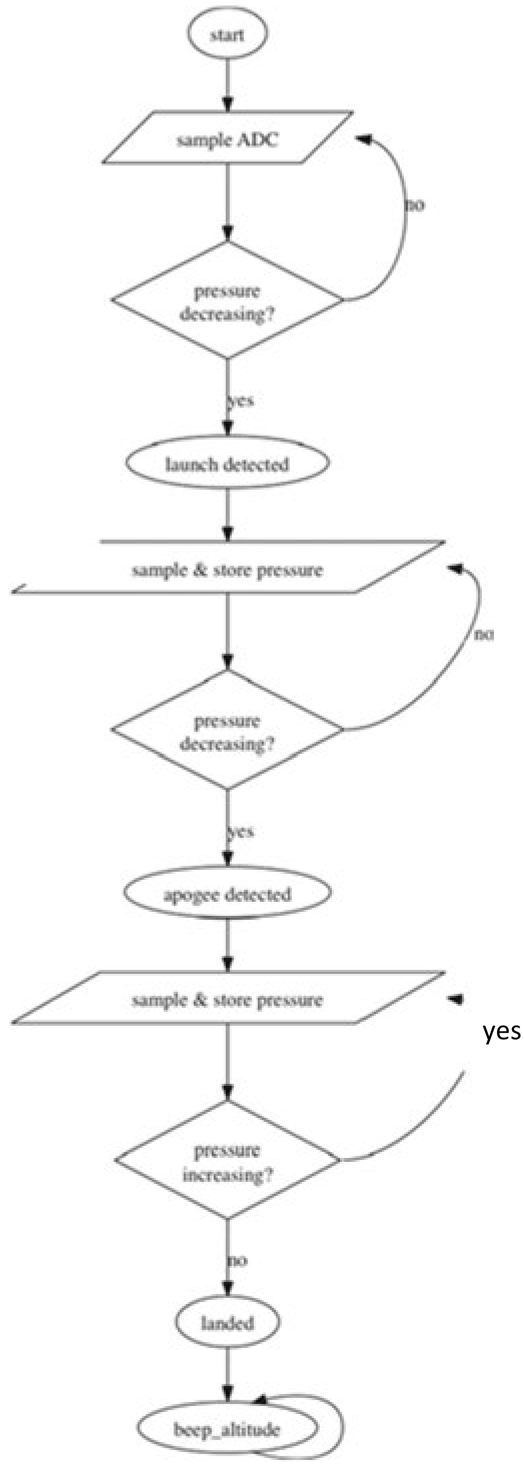
Software is a critical component of a microcontroller system. Modern microcontroller development environments usually provide a compiler for C or some other high level language, so the microcontroller developer is no longer forced to code in assembly language. They also include an interactive development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

Just like structures, propulsion systems, and recovery systems should be planned carefully, software should be carefully 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 takes 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 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 frequency stepping for the operator.

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 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 2 meter 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 $\frac{c}{f}$, 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. ¼ and ½ 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 during certain times 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.

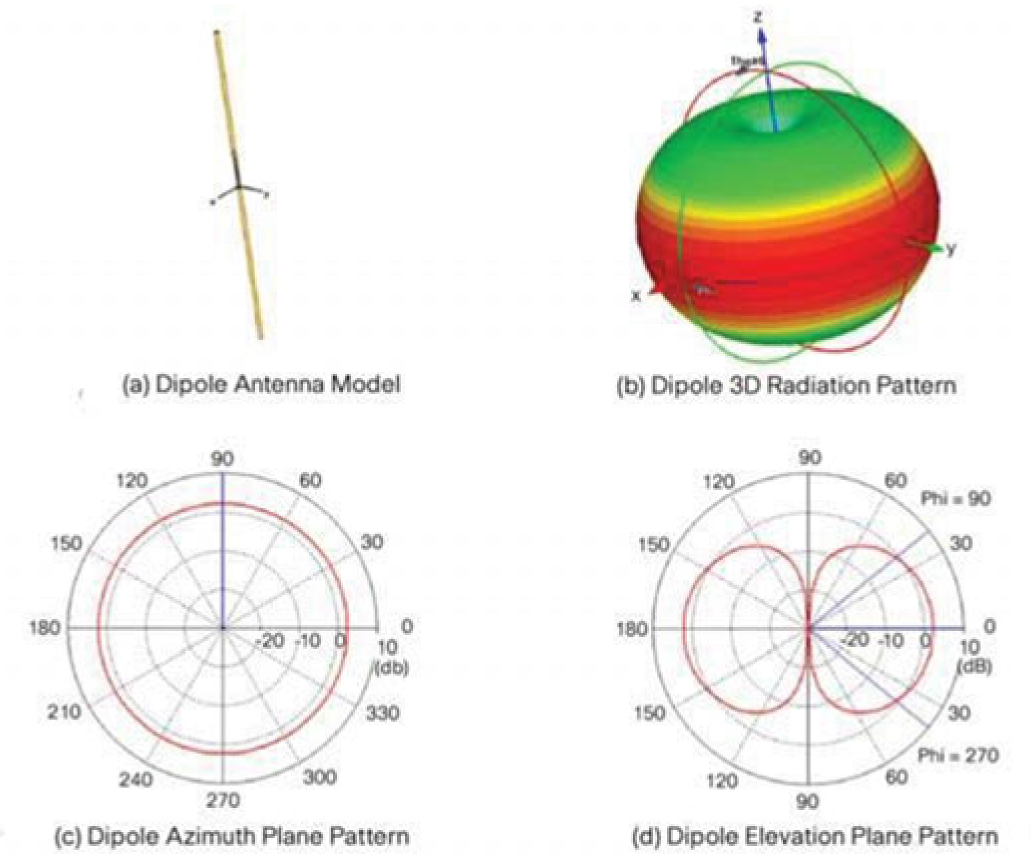
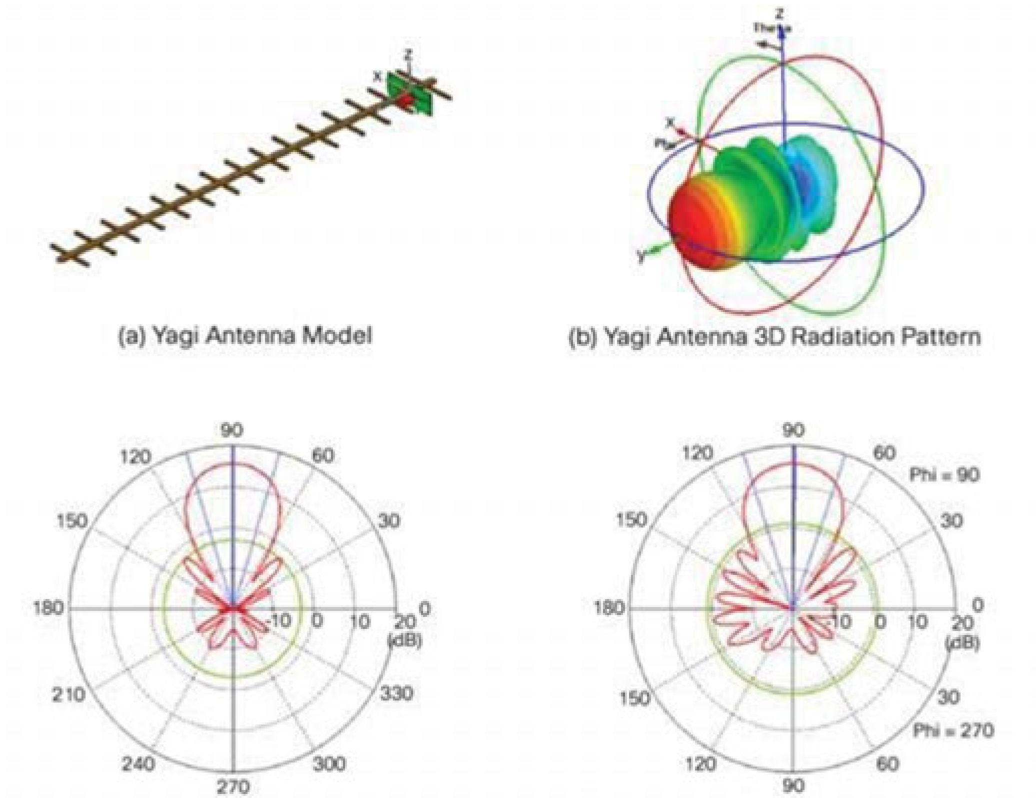


Image courtesy of Cisco

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.



(a) Yagi Antenna Model (b) Yagi Antenna 3D Radiation Pattern

(c) Yagi Antenna Azimuth Plane Pattern (d) Yagi Antenna Elevation Plane Pattern

Image courtesy of Cisco

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.

Safety

Materials:

Material Safety

Material Safety Data Sheets (MSDS)

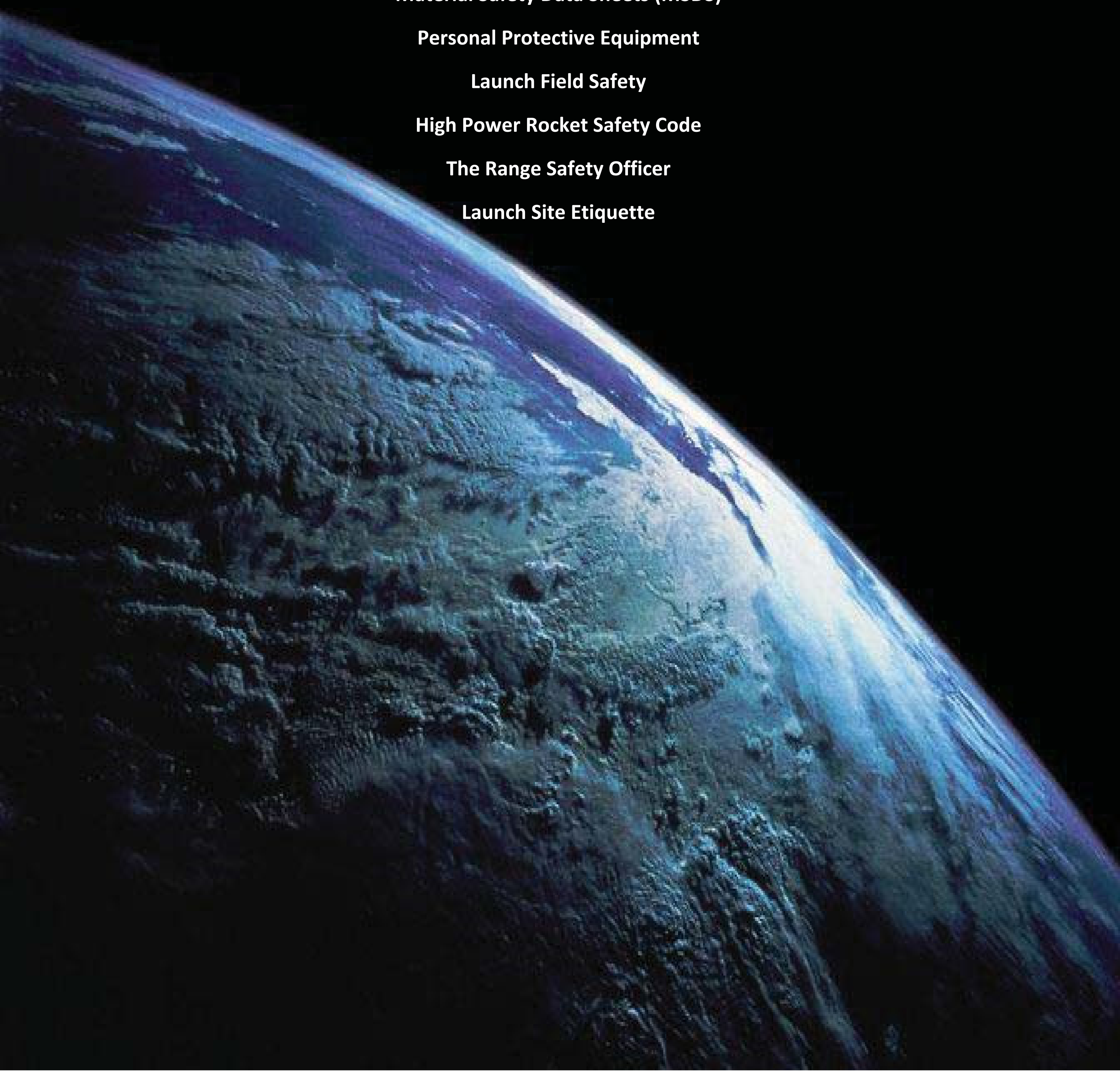
Personal Protective Equipment

Launch Field Safety

High Power Rocket Safety Code

The Range Safety Officer

Launch Site Etiquette



NASA High Power Rocketry Video Series

Counterpart Documents

Section Written by Ian Bryant and Zachary Koch

Section Edited by Daniel Cavender

Safety is always the highest priority when building and constructing rockets. A whole launch event could be ruined by a single accident. This section will help teach you about the various risks of working with high power rockets, and provide solutions to help mitigate those risks. **NOTE: This section does not serve as an instructional document for all safety in rocketry. An experienced mentor/rocketeer should be consulted prior to construction and launching.**

Material Safety

There are a number of materials commonly used in the construction and flight of rockets. Listed are a few common examples:

1. Fiber based rocket components
2. Black powder
3. Epoxy
4. Motors

This section will discuss how to handle each material safely. You will learn about material safety data sheets, handling procedures, storage instructions, and more.

Material Safety Data Sheets (MSDS)

A MSDS is an important document that provides many handling details for the material you are working with. A MSDS should be carefully read prior to working with any material. These sheets are easily be obtained online, or upon a request to the manufacturer.

A typical MSDS will have 16 sections detailing every safety aspect of the material.

Product and Company Identification	• Product name • Manufacturer • Manufacturer Contacts • Emergency Contacts
Hazard Identification	• Emergency Overview – what the material can cause • Potential Health Effects – What different types of contact can cause
Composition/Information on Hazardous Ingredients	Outlines the ingredients used in manufacturing
First Aid Measures	Treatment measures for hazardous contact
Fire Fighting Measures	List the flash point of the material, and the proper extinguishing media to use in the event of a fire.
Accidental Release Measures	Details what to do in the event of a spill, leak, or other form of accidental release
Handling and Storage	Describes handling temperature and location. May include special precautions to consider prior to handling.
Exposure Controls/Personal Protection	Informs you about the different forms of personal protective equipment that should be used while handling.

Physical and Chemical Properties	Lists what the material looks/smells like and other chemical properties.
Stability and Reactivity	Describes what media the material is safe in, and how it reacts with other materials
Toxicological Information	Describes any toxins that may be present in the material (I.e. mutagens, carcinogens, etc.)
Ecological Information	Lists possible environmental hazards
Disposal Considerations	Details proper disposal techniques and locations
Transportation Information	Describes the rules and regulations for transporting the material.
Regulatory Information	Describes which organizations regulate the material.
Other Information	Any other information that the manufacturer deems important.

Fiber Based Components

In rocketry, there are two fiber based materials commonly used in construction; these fibers are fiberglass and carbon fiber. Each of these materials are briefly discussed in the structures section of this document, but both share very similar risks, and handling procedures.

When working with fiber based products, it is common for small fiber particles to cloud the surrounding area. Coming into contact with these particles can cause severe irritation to the eyes, skin, and respiratory system. Cutting these materials may also leave sharp edges capable of lacerating the skin. To avoid these injuries, it is advised that workers should wear eye and hand protection, a face mask, and long sleeves to reduce skin contact. It is also a good idea to rinse the components with a damp cloth to remove residual particles from the component.

Black Powder

Considered a low explosive, black powder (BP) is one of the most dangerous materials to handle in Rocketry. Black powder handling is a top safety concern in rocketry, and the handling requirements on the MSDS should be closely followed. Mishandling of BP can lead to severe burns to the body, loss of limbs, and if used in ejection, impalement from the rocket.

Black powder has a very low flash point, and even a small spark could be enough to cause ignition. For this reason, BP should be stored in a cool, dry place, away from any heat sources. Additionally, BP should not be stored in the same location as an igniter or e-match.

When working with black powder, eye and hand protection are a must. Staying away from sources of electricity, water, heat, etc. is also recommended to prevent contaminating the BP or accidentally igniting it. If you are a minor, adult supervision is mandatory.

If you are unsure about proper BP handling procedures, consult a trained rocketeer. He/She will be able to instruct you in the safe operation and handling of BP activities.

Epoxy

Epoxy is a useful bonding agent when constructing rockets. It comes in two parts, a resin and a hardener. Even by themselves the resin and hardener can be hazardous. Neither should be ingested, and they can both irritate the skin. When mixed together to form epoxy, additional hazards are introduced.

All epoxies heat up when the two components are mixed together. An exothermic reaction occurs, and the heat is noticeable even on weaker epoxies. Different epoxies have different temperatures when mixing, and some can reach temperatures that can cause burns to the skin. Depending on the epoxy, the mixing process can cause noxious fumes that should not be inhaled.

When handling epoxy, be sure to wear hand and eye protection, along with a respirator. A normal face mask does not prevent the inhalation of noxious fumes. Sometimes epoxies use filler material to change its consistency. If working with a filler, all of the above safety equipment should be used.

Each part of an epoxy comes in its own container. Be sure to keep the two components away from each other to prevent accidental mixing.

Motors

Motors are a fun part of rocketry. There are many different styles of motors that can make each launch exciting. However, motors are a leading cause of launch site accidents and injury. Mishandling a motor could cause a rocket to travel along a dangerous trajectory, will cause serious burns if someone is exposed to the exhaust flame, and can cause hearing damage if someone is standing too close as it is ignited.

The motor itself is a stable object. They will not ignite in typical working environment. However, storage procedures are strictly regulated to ensure the safety of nearby personnel. First, a motor should never be removed from the static proof bag it is sold in until it is ready to be launched. Static electricity can inadvertently ignite a motor if the charge is sufficiently large. When not being launched, the motor should be stored in a fire and weather proof box. This box is typically made of wood with a steel liner. The box should be lockable, painted red, and contain the work “EXPLOSIVES” in large letters to inform others of its contents. More detail about motor storage can be found in the Code of Federal Regulations chapter 27, section 55.209 (17 CFR 55.209).

Only certified rocketeers should handle a motor, and only one that is at or below their certification level. The only exception is when the rocketeer is handling a motor for their certification flight. If you are unsure of how to operate with a certain brand of motor, consult the instruction provided by the manufacturer. Do not tamper with the motor in any way.

In this section we described some of the hazardous materials common in rocketry. **Please note that this is not an instructional section. The information provided here is meant to introduce you to the different hazards possible, and encourage you to think about possible hazards. Consult the proper documentation or a mentor prior to working with any hazardous material.**

Personal Protective Equipment

Personal Protective Equipment (PPE) refers to protective clothing, helmets, goggles, or other garments or equipment designed to protect the wearer's body from injury. The hazards addressed by protective equipment include physical, electrical, heat, chemicals, biohazards, and airborne particulate matter.

Which PPE and when to wear them is commonly specified in the MSDS for the material being used, on the instructions/label for the tool or equipment, in shop or laboratory handbooks, and on the specific piece of equipment.

Common examples of PPE include:

Safety Glasses, Goggles, or Face Shields	These items cover all or part of the face and eyes to prevent materials, sharp objects, chemicals, and dust/particulates from contacting the face and eyes. Sunglasses and prescription eyeglasses are NOT adequate eye protection. Most eye protection is made to accommodate prescription eyeglass use while also wearing the PPE.
Respirators/Dust Masks	These items cover all or part of the mouth and nose. They are designed to prevent inhalation of dusts, gasses, and particulate matter.
Safety Gloves	Safety Gloves include latex, nitrile, cotton, and leather hand wear that prevent direct skin contact with chemical, cutting edge, or sharp/abrasive materials.
Ear Protection	Ear protection includes ear muffs and ear plugs. They reduce exposure of the sensitive parts of the ear to loud, high decibel noise. Ear plugs and muffs can be used in conjunction for greater noise cancelling effect.
Hard Hats/Safety Helmets	Hard hats and safety helmets cover part or all of the head. They are designed to prevent impact to the head. Some helmets include chin straps. They are commonly sized and adjustable for a tight fit.
Boots, Protective Footwear	Boots, work shoes, and foot/ankle covers prevent impact or contact with materials, chemicals, and sharp edges. Boots include leather work boots, and steel toed construction or industrial use footwear.

In order for PPE to be effective, it must be worn at the appropriate times and in the manner described by the manufacturer. Additionally, some PPE is only effective for only a single use and must be replaced for subsequent uses. Follow manufacturer recommendations for use of PPE.

Launch Field Safety

Rocket Launches are exciting events. Watching other rocketeers launch their projects can be fun and educational for all attendees. However, the event can quickly be ruined by a lack of launch field safety. This section is meant to inform you of safe launch field operations in order to avoid launch site accidents, and ensure a safe and enjoyable event.

High Power Rocketry Safety Code

The National Association of Rocketry (NAR) and Tripoli Rocketry Association both publish a code that all of their members must follow. Each code is slightly different in wording, but the rules remain the same. The codes discuss what motors and materials each rocketeer can use, weight limits, launching and recovery systems, etc. Both codes also provide a launch site dimension table, and a minimum launch distance table. Both tables are shown below.

Installed Total Impulse (N-sec)	Equivalent Motor Type	Minimum Site Distance (feet)	Equivalent Distance (miles)
160.01 – 320.00	H	1,500	.28
320.01 – 640.00	I	2,500	.50
640.01 – 1280.00	J	5,280	1.00
1280.01 – 2560.00	K	5,280	1.00
2560.01 – 5120.00	L	10,560	2.00
5120.01 – 10240.00	M	15,480	3.00
10240.01 – 20480.00	N	21,120	4.00
20480.01 – 40960.00	O	26,400	5.00

Minimum Launch Site Dimension Table

Installed Total Impulse (N-sec)	Equivalent Motor Type	Minimum Safe Distance (feet)	Complex Minimum Safe Distance (feet)
160.01 – 320.00	H	50	100
320.01 – 640.00	I	100	200
640.01 – 1280.00	J	100	200
1280.01 – 2560.00	K	200	300
2560.01 – 5120.00	L	300	500
5120.01 – 10240.00	M	500	1,000
10240.01 – 20480.00	N	1,000	1,500
20480.01 – 40960.00	O	1,500	2,000

Minimum Safe Launch Distance Table

The first table describes the minimum launch field dimensions for each motor classification. The values listed can either be the diameter of the field, or the shortest dimension. The second table lists the distances from the crowd line that each motor classification must be launched.

The Range Safety Officer

The Range Safety Officer (RSO) is the leading authority of the launch field. He/She is a certified rocketeer with years of experience, and has the authority to deny launch pad access to other rocketeers. It is the RSO's responsibility to maintain the safety of all personnel attending the launch, and ensuring that the launch field is not damaged. Some RSO responsibilities include:

- Performing hardware checks on rockets.
- Working with the launch control officer (LCO) to organize when each rocket will launch
- Checking to see that weather is clear, and the cloud ceiling is high enough
- Checking downrange to ensure that there are no personnel and other wildlife in the area while launching.
- Checking the skies for planes and other objects that impede rocket launches

Prior to launching, the RSO will perform a hardware check on every rocket. He/She will check for structural integrity, stability information, and any damage that could lead to an unsafe launch.

Weather can make or break a launch. A low cloud ceiling will cause force a rocket out of site. Not knowing where a rocket is, is highly unsafe. By losing site of the rocket, the chance of the rocket landing on a spectator, building, lake, etc. greatly increases. If the cloud ceiling is too low, the RSO reserves the right to postpone or cancel the launch.

Checking the range and skies ensures that there is no wildlife or rocketeer is near the rocket as it launches. High power rocket motors generate high amounts of heat and thrust that can easily cause serious damage. If the launch club properly filed a waiver with the Federal Aviation Administration (FAA), than there should be no aircraft in the launch vicinity. However, sometimes a plane or two will wander into the area. The RSO must constantly check the sky for aircraft to prevent harm to the pilot and passengers.

Both NAR and TRA publish information regarding RSO responsibilities. The important thing to remember is that the RSO has authority over the entire launch field, and his/her directions should be closely followed.

Launch Site Etiquette

The RSO may be the leading safety personnel on the field, but everyone in attendance is responsible for safety. Proper launch site etiquette is easy to follow, and will help maintain safety. For one, all spectators should remain outside of a tent or other structure as a rocket is in the air. As mentioned above, losing site of a rocket is dangerous, and it is hard to see the rocket under a roof!

Absolutely no cell phones should be in the vicinity of a rocket. The frequencies transmitted by the phone can potentially energize black powder chargers or other pyrotechnics. It is best to leave your cell phones in your car. Plus you will miss all the fun of a launch if you are chatting on the phone!

When preparing your rocket, be mindful of the location of other rocketeers and spectators. It is common to perform ejection charge preparation and testing in the prep areas prior to launches and you do not want another team member, or bystander to be hurt or distracted by your prep work.

National Aeronautics and Space Administration

George C. Marshall Space Flight Center
Huntsville, AL 35812
www.nasa.gov/marshall

www.nasa.gov

NP-2015-09-84-MSFC
G-122203