BOONE COUNTY 4H AEROSPACE PROJECT

"ROCKETRY 201"

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Purpose

This is a guidance document for 4H kids and parents working at the intermediate and advanced levels in the Aerospace to begin to gain an understanding of some of the scientific and engineering principles which explain how a model rocket is designed. Additionally, some of the rules of thumb that they will need to get started in designing and building their own model rockets (i.e., not store-bought kits) are presented.

Table of Contents

References

1) Model Rocket Design and Construction (2nd edition) by Timothy Van Milligan (copyright 2000)
2) Handbook of Model Rocketry (7th edition) by G. Harry Stine (copyright 2004)
3) Centuri Model Rocket Design Manual (2nd edition) by Grant Boyd (copyright 1975)
4) http://www.info-central.org/design_rulesofthumb.shtml
5) http://www.thrustcurve.org/

GLOSSARY OF TERMS

Acceleration – the change in velocity of the rocket within a given period of time; usually measured in feet per second per second (ft/s^2) or meters per second per second (m/s^2)
Aerodynamics – the study of how air flows around an object in flight; usually when we say a rocket is more aerodynamic, we mean it has less drag, but rocket stability is also affected by aerodynamics
Apogee – the highest point a rocket reaches in its flight
Caliber – a length equal to one diameter of the body tube
Center of gravity – the point along the body tube of a rocket where all of the weight of the rocket is centered
Center of pressure – the point along the body of a rocket where all of the force from air pressure on the rocket body is centered
Chord edge – the outer edge of the fin; the edge of the fin that is parallel to the root edge (may also be called the tip edge)
Density – the weight of a given volume of fluid, often expressed in pounds per cubic foot (lb/ft^3), kilograms per cubic meter (kg/m^3), or grams per milliliter (g/ml)
Descent Mass – the mass of the rocket with a spent rocket motor; this is the mass which the streamer or parachute will be sized to recover
Drag – this is the friction force caused by the flow of air over the surface of a rocket; this frictional force acts against the thrust force of a rocket's motor to try to slow the rocket down
Drag Coefficient – a theoretical number used in scientific equations which helps us tell how much drag is present in our rocket design; the higher the drag coefficient, the higher the drag
Impulse – The thrust multiplied by the amount of time the thrust is applied; impulse is usually expressed in Newton-seconds (N-s)
Leading edge – The upper edge of the fin
Newton (N) – a unit of measure of force in the metric system
Propellant – the fuel in a rocket motor that provides thrust when ignited
Root edge – The edge of a fin that is glued to the body tube
Spill hole – a hole cut in the center of a parachute to reduce how much it will cause the rocket to drift before touching down
Stability – the tendency of a rocket to move in a straight upward flight path
Thrust – the force provided by the rocket's motor which must overcome the force of gravity and the drag force in order for the rocket to fly; this force is usually expressed in Newtons (N)
Trailing edge – the edge of the fin that is closest to the aft part of the rocket
Trajectory – the rocket's flight path
Velocity – the speed of the rocket; usually measured in feet per second (ft/s) or meters per second (m/s)

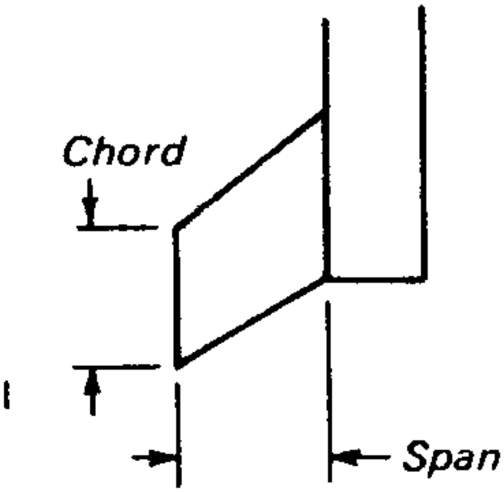
FINS

Fin Sizing

A good starting point for the size of the fins is:

1) The root edge (the edge that is glued to the body tube) should be about 2 calibers (or two body tube diameters) in length
2) The chord edge should be about 1 caliber in length
3) The width (or span) of the fin should be about 2 calibers

See the diagram below:



Fin Shapes

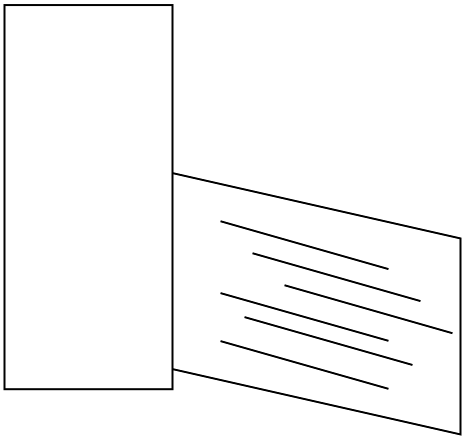
More about fin shape will be presented in the section on DRAG.

Number of Fins

Usually, three fins are adequate. Four fins might be used sometimes, to improve stability, but it usually does not improve stability very much. If any more than four fins are added then this starts increasing the drag while not improving the stability at all.

Fin Construction

If you are cutting your own balsa fins, ALWAYS cut them so that the grain of the wood is parallel to the leading edge. NEVER cut your fins so that the grain is parallel to the body tube. This will make the fins structurally weak, with the fins having a higher tendency to break along the grain.



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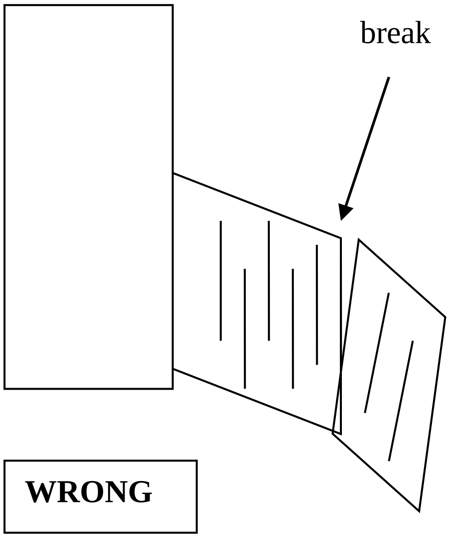


WRONG

STREAMERS AND PARACHUTES

Streamer or Parachute?

In general, streamers are used on model rockets that are lighter than 30 grams (1.05 oz.). However, if you wish to use streamers for larger models (up to 4 oz.) then a streamers may be used as long as the streamer is very wide (typically 4 inches).

Use streamers on rockets that are expected to fly to an extremely high altitude. Whether it is a streamer recovery rocket or a parachute recovery rocket, it will drift sideways due to the wind at the same time it is falling back to the earth. A parachute will cause a rocket to drift more than a streamer will. The higher the rocket flies, the more time there is for a rocket to drift sideways due to the wind. A rocket which flies to an extremely high altitude with a parachute recovery system may drift so far it is out of sight before it ever reaches the ground.

In a situation where you want to use a parachute instead of a streamer for a higher altitude rocket, another thing you can do is cut a hole (called a spill hole) in the center of your parachute to reduce the amount of drift. If you don’t want to cut a hole in your parachute, another technique you can use is called “reefing”. In reefing, you tape the shroud lines together close to the parachute so that it does not open as far.

Whether you use a streamer or parachute, try to make it out of something that is brightly colored, red or orange. Another good alternative is to use reflective silver plastic which is used for party banners or party balloons. You can usually find this material at your local Walmart or other convenience store.

Streamer Sizing

A good rule of thumb for the size of a streamer is that it should be ten times as long as it is wide. For example, a one inch wide streamer should be about 10 inches long.

The area (length multiplied by width) of the streamer depends on the descent mass of the rocket. A good rule of thumb here is that for every gram of rocket weight, the streamer should have 8.5 square centimeters of single surface side of a streamer.

Example:

My rocket weighs 16 grams. A spent motor casing will weigh about 4 grams. What is the length and width of the streamer that I should use?

1) First calculate the total weight of the rocket which will be recovered (the descent mass). This will be the weight of the rocket plus the spent motor casing.

16 g + 4 g = 20 g

2) Next calculate how much streamer surface area is needed. We will use our rule of thumb for surface area of streamer per mass of rocket.

(20 g) X (8.5 sq cm / 1 g) = 170 square centimeters

3) Now we need to determine the length and width of the streamer. We will have to use a little algebra here……..

Let W equal the width of the streamer.

We know from our other rule of thumb that the length should be ten times the width. Therefore the length will equal 10W.

We know that the streamer area is equal to length X width, so…..

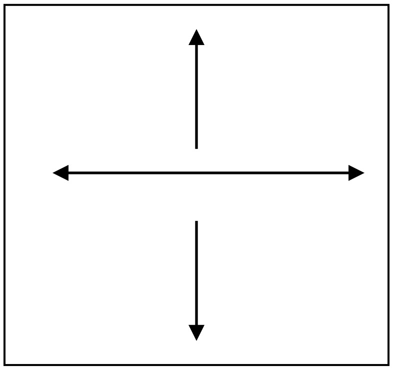
$W \times 10W = 10W^2 = 170\ \text{cm}^2 \rightarrow$ dividing each side by ten, $W^2 = 17.0\ \text{cm}^2$

$W = \underline{\underline{4.1\ \text{cm} = 1.6\ \text{inches}}}$

Since the length of the streamer is 10 times the width, the length is $\underline{\underline{\text{41 cm (16 inches).}}}$

Parachute Materials

For smaller models, plastic parachutes work well. You can buy plastic parachutes from hobby stores which carry model rocketry supplies or also from online model rocket suppliers. If you decide to use your own plastic material to create your parachute, make sure the plastic is tear-resistant in two directions. Some plastic will not tear easily in one direction, but will tear easily in the other direction (see the example below which shows a square parachute).



Make sure the parachute plastic will not tear easily in *both* directions.

If your rocket's descent mass is more than 300 g (10.5 oz.), then you should use a cloth material such as cotton, silk, polyester, or nylon.

Parachute Shroud Lines

The shroud line length should be about one to one and half times the parachute diameter.

Shock Cords

Do NOT tie additional knots in the middle of your shock cord! Knots in the middle of your shock cord serve no purpose and will weaken the strength of the shock cord.

The shock cord should generally be about two to three times the length of the body tube. It should be about two times the length of the body tube if you use a non-flame-resistant shock cord that must be attached inside the body tube near the nose cone. If you use a Kevlar shock cord (which is flame resistant) which you attach to the motor mount assembly, then the shock cord should be closer to three times the length of the body tube.

Parachute Sizing

What affects the size of the parachute needed?

1) the descent mass of the rocket
2) the shape of the parachute (which will affect how much drag the parachute has)
3) the surface area of the parachute

The math for determining a properly sized parachute is a bit more complex than that used to size a streamer, so instead of doing a calculation, just refer to the chart below for some general guidelines for sizing your parachute.

Rocket descent mass	**Round and octagonal parachute diameter**	**Square parachute width**	**Hexagonal parachute width**
20 grams	22 cm	25 cm	23 cm
40 grams	31 cm	35 cm	33 cm
80 grams	43 cm	49 cm	45 cm
100 grams	48 cm	54 cm	50 cm
150 grams	59 cm	67 cm	62 cm
200 grams	69 cm	78 cm	72 cm
300 grams	84 cm	95 cm	88 cm

Note : square and hexagonal parachute width is measured from one flat side across to another flat side (that is, not from corner to corner)

STABILITY

CG and CP

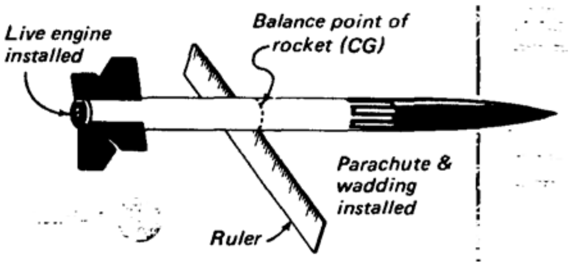
There are two very important design parameters for determining if your rocket will be stable during flight. One is called the center of gravity (CG) and the other is called the center of pressure (CP).

The center of gravity (CG) is the point on an object where all of the weight of the object seems to be acting. Here is one way to think about it. Suppose you have a yard stick (36 inches long). Now you stick your arm out straight from your body with your palm stretched flat upwards. Next you balance the yardstick in your upturned palm. Where on the yardstick did it balance in your palm? It will balance at the 18-inch mark, halfway down the yardstick. Now suppose you have a 36-inch long baseball bat and try to balance it the same way. You notice that the bat won't balance in your hand at the halfway point along the bat's length. Instead you find the bat balances about two-thirds of the length down the bat, with the balance point being closer to the barrel of the bat than the handle. This is because, unlike the yardstick, the bat is not a uniform width all the way down its length. Therefore, the balance point (the center of gravity) is closer to the wider end of the bat, where more of its mass is located.

While the rocket is flying, the air that flows over the rocket exerts a pressure on the body and fins of the rocket. The center of pressure (CP) is the point along the side of the rocket where the force from that air pressure seems to acting. A way to imagine this is to think of a weather vane mounted on a spinning rod. If the weather vane is mounted so the rod is at a place on the vane so that the wind blowing on the vane makes the vane face 90 degrees to the direction the wind is blowing, then the rod is at the CP of the weather vane. (Question: does it make sense to place the rod at the weather vane's CP?)

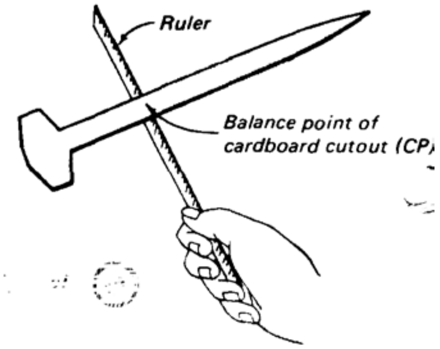
Determining CG for a Rocket

The way to determine the CG of a rocket is similar to what we did to determine the CG of the yardstick or baseball bat. Take your fully assembled rocket and find the point where you can balance it on the edge of your hand, or the edge of a ruler. Be sure that when you do this exercise, that you have an unused rocket motor installed, as well as the recovery system and ejection wadding. Unless you install these things, you will not be measuring the CG for the true weight of the rocket at liftoff.



Determining CP for a Rocket

To determine the CP for your rocket you can make a cardboard cutout profile of your rocket and then find the point where the cardboard cutout balances on a ruler.

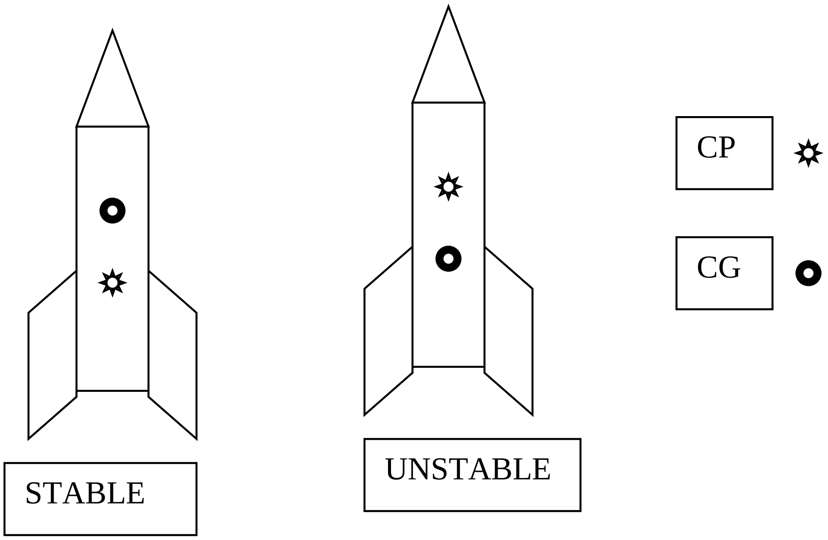


Using Computer Simulations to Determine CP & CG

The methods of determining CG and CP (especially CP) that we have just described are “rough estimate” methods and may lead one to a very conservative rocket design. One way to get better estimates of where the CG and CP are really located would be to use a computer simulation program, such as Rocksim. By getting more accurate representation of your rocket design using design software allows you more freedom to do what you would really like to do with your rocket design. This same software can also help you get a better handle on other topics discussed later in this document, such as drag, altitude, and trajectory. If you would like to obtain free demonstration software that can be used to help you make better rocket designs, then contact your Aerospace Project Leader.

How Does This Tell Me If My Rocket Is Stable?

In order to have good stability, the CG must be one to two calibers ahead of the CP. When we say the CG is ahead of the CP, we mean it is nearer to the nose cone.



If the CG & CP are at about the same location, then the rocket will tend not to fly in a very straight path, and unfortunately, not a very predictable flight path either. If the CP is very far ahead of the CG, the rocket will want to try to fly tail first, which will cause it to spin end-over-end as it comes off the launch pad. Both of these cases mean disastrous consequences for your rocket and maybe the people at the launch site as well.

How to Correct Instability

If you determine your rocket design is unstable, here are some things you can do.

To move the CP back
Add another fin
Increase the size of the fins
Move the fins further back on the body tube
Use swept back fins

To move the CG forward
Add some counterweight to the nose cone
Use a smaller motor
Increase the body tube length

DRAG

What is Drag?

Maybe an easy way for you to think of drag is to imagine a swimmer at a competitive swim meet. The swimmer wants to try to be as fast as he (or she) can be, but as he/she tries to glide through the water, the water itself is slowing him/her down. He/she has to work hard just to push himself/herself against the weight of the water in the pool. In order to help the swimmer go as fast as possible, he/she will do several things. The swimmer will wear a swim cap, and a swimsuit that has a very smooth and streamlined appearance. Some male swimmers even will go so far as to shave hair off their legs and arms. The reason for doing all these things is to overcome drag. Drag is the force of resistance to the swimmer’s motion which is caused by the pool water.

Maybe you have never thought about it this way before, but air is a fluid just like water is a fluid. That is, both gases and liquids are fluids. Just like the water causes drag on the swimmer, air causes drag on a rocket. As it flies through the air, the air causes drag on the rocket, which will slow it down and limit the peak altitude of the rocket.

The equation that scientists and engineers use to determine the drag force on a rocket is:

$D = 0.5\rho v^2 C_d A$

D = drag force
ρ = density of the fluid (air, water, etc.)
v = velocity, or speed, of the rocket
C_d = drag coefficient
A = frontal area of the rocket

In addition to the force of gravity from the earth, drag is another force that must be overcome for the rocket to fly.

The density of the fluid tells us how heavy the fluid is. Think about a bucket of water versus a bucket of air (that is, an empty bucket). Which bucket is heavier? It takes more force to lift a bucket of water, which has a higher density than air. In the same way, if the fluid has a higher density, it would cause more drag on an object trying to move through it.

The velocity is how fast the rocket is moving, or its speed.

The drag coefficient is a number that helps give us an idea how much drag we have in our rocket design. The higher the drag coefficient value, the higher the force from drag. Scientists and engineers determine drag coefficients for different rocket designs by doing wind tunnel tests where they can very accurately determine values for all the other variables in the drag equation. After the scientists/engineers do enough wind tunnel tests, they are also able to predict using computer models what the drag would be on similar shapes without doing more wind tunnel tests.

The frontal area is the cross-sectional area that is measured by looking straight down the nose cone of a rocket.

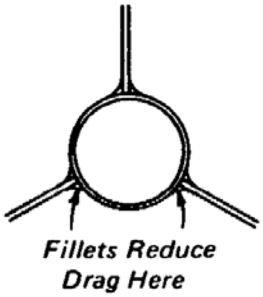
Now looking at this equation, you might say, when I move around, I have a much higher frontal area than my rocket, and the drag from air doesn’t slow me down very much. Why would it slow down my rocket? What you say about drag from air not slowing you down is true, but what you have to remember is that your rocket moves much faster than you can move. It has a much higher velocity. When we look back at the drag equation, we realize that as velocity becomes that big, it doesn’t matter whether the density of air is small. The drag force is still going to be significant.

Designing Rockets to Reduce Drag

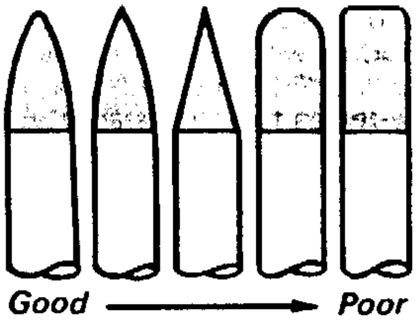
In general, we don’t like drag. It slows down our rocket, and won’t allow it to fly as high as we would like. We cannot get rid of drag altogether, but we can try to reduce it as much as possible. We do what we can to reduce drag by making a more aerodynamic rocket design. Drag can actually be broken down into more specific types of drag such as friction drag, pressure drag, interference drag, and induced drag. We will not go into detail about that here though. If you want to learn more about the different types of drag, read more in one of the books listed on Page 1. Then try to see if you can figure out which kind of drag each of these design guidelines is meant to eliminate.

The first and simplest way to reduce drag is to have a good paint finish on your rocket. Having a smooth paint finish without runs, and having decals which don’t stick up higher than the other surfaces of the rocket model help a lot. If you have balsa wood fins or nose cones, this means making sure that the grains of the balsa wood have all been filled in with primer and paint so that the wood is so smooth you can’t tell whether it is wood or plastic by looking at it.

Another way to reduce drag is to put glue fillets on your fins where the fins are attached to the body tube. A fillet is a bead of glue that has been laid down the edge of the fin and smoothed out, and then been allowed to dry. This eliminates sharp corners where the fin attaches to the body tube. You will also want to put fillets where the launch lug is attached.



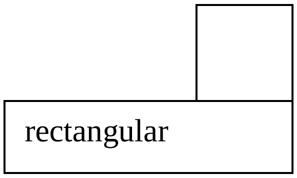
Another way to reduce drag is to use a nose cone shape which has a lower drag coefficient. See the diagram below which shows different nose cone shapes, and which ones cause less drag.

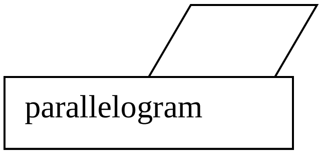


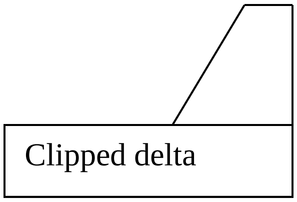
Reducing the number of fins on your model will reduce drag too. In order to have good stability, you need to have at least three fins. A model rocket with four fins will have more drag than a model with three fins though. You may remember in the section on STABILITY, we said adding an extra fin was a good way to increase stability by moving the CP back. That is true, and here is an example where you may have to make a trade-off in which is more important to you: a little less drag, or a little more stability. As you start to design your own rockets, you will find there all kinds of little trade-offs and compromises you have to make between one thing and another to get the design that will work best for you.

Another place where you may have to make some trade-offs in fin design is the size of your fins. By making your fins larger, it may increase stability, but it will also increase drag. A good rule of thumb for fin size which takes these two things into consideration has already been shown in the section on FINS.

Another thing that affects drag is the shape of the fin. Generally, the most aerodynamic shapes for a model rocket are going to be rectangular, or some type of parallelogram. In Harry Stine’s Handbook of Model Rocketry, he suggests that the clipped delta shape could be the best fin design.

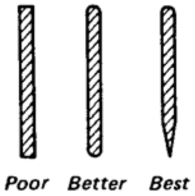






One other way that fin shape can affect aerodynamics is the shape of the edges of the fins. The chord edge should always be left square. However, how you shape the leading edge and trailing edge of a fin can be varied, with differing affects on drag. The easiest thing to do is just leave the leading and trailing edges square, because it won’t be as hard to sand. But that is also the design that has the most drag. The next best approach is to round the leading and trailing edges. This design has less drag, and is not that much more difficult to sand the fin edges. The best fin edge design though is to have the leading edge rounded and the trailing edge tapered. This is the most difficult design from a sanding and forming standpoint though.

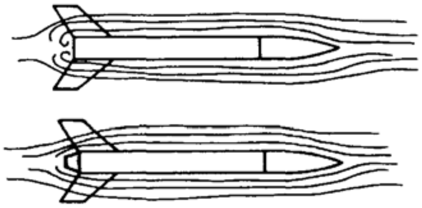
The diagram below shows cross sectional areas of the fin with the leading edge shown at the top and trailing edge shown at the bottom.



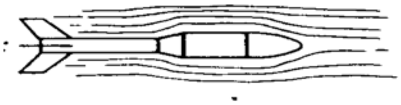
Another way to reduce drag is to use a “boat-tail” design for the end of the rocket.

BOAT TAIL

Curving the rear portion of the rocket inward will reduce base drag at this point. This is of course, only possible on rockets that have an inside body diameter larger than that of a model rocket engine.



And similar to the boat-tail effect, you can use transition pieces to reduce the diameter for part of your rocket. Maybe you have some reason to make the front larger (maybe you have a payload rocket), but you can still reduce drag by having a smaller diameter for the back part of the rocket. On the other hand, maybe you want to have the back part of the rocket be wider to accommodate a larger motor, but you can reduce the size of the front part of the rocket.



MOTORS

Motor Codes

When you buy a motor, it usually has a letter and two numbers. The letter tells you the total impulse. The first number tells you the average thrust, and the second number tells you the number of seconds after fuel burnout when the ejection charge blows. In this section, we are just going to touch briefly on what impulse and thrust mean.

Thrust

Thrust is the force that is caused by the motor fuel (or propellant) burning. The thrust force must overcome the force of gravity and also the drag force to make the rocket fly up in the air. The first number in the model rocket code tells us the average thrust. The thrust is expressed in average thrust because a rocket motor does not burn with the same amount of thrust all the time. When the fuel burns, most of the time it burns, the thrust force is constant. However at the beginning of the launch, the thrust provided is much higher. This is because the rocket needs some extra oomph at the beginning of the launch to get it off the pad and quickly flying at a fast velocity so that its flight path is stable.

Thrust is usually expressed in the standard metric unit for force, Newtons. The force of 4.45 Newtons is the same as the force of one pound.

Impulse

Impulse is the thrust of a rocket multiplied by the amount of time the propellant burns. It is usually expressed in units of Newton-seconds (N-s). Impulse is a way of telling us how long the rocket propellant will burn, and also gives us a better idea of how high the rocket will go with that motor versus another motor. The letter codes on a rocket motor (see table) tell us which impulse range the motor falls within.

Total Impulse (N-s)	**Engine Type**
1.26 - 2.50	A
2.51 - 5.00	B
5.01 - 10.00	C
10.01 - 20.00	D
20.01 - 40.00	E
40.01 - 80.00	F

Generally, the higher the impulse, the higher the rocket is going to fly. Impulse shows us that it is not just the thrust that is important to know but also the fuel burn time. Therefore a rocket which has an average thrust of 4 Newtons but burns for 2 seconds (impulse = 4 N X 2 s = 8 N-s) might fly just as high as a rocket that only has an average thrust of 2 Newtons that burns 4 seconds (impulse = 2 N X 4 s = 8 N-s).

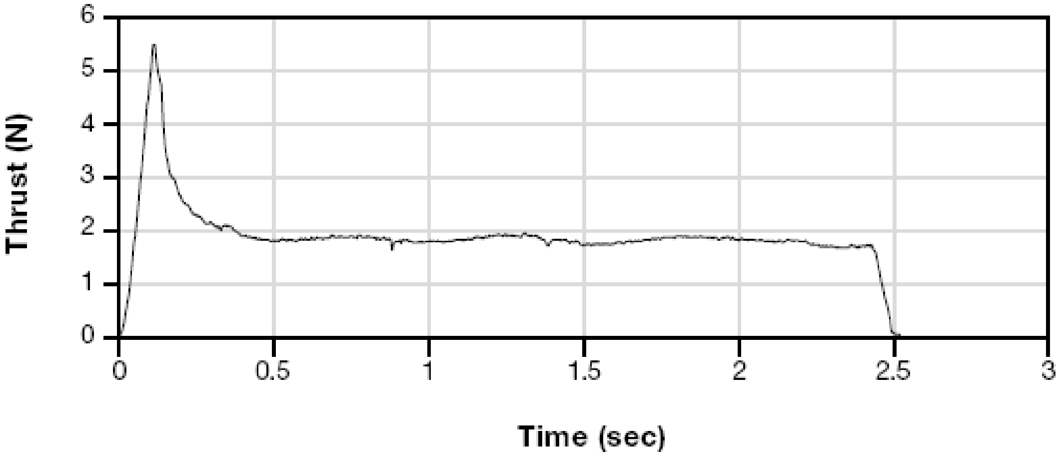
Delay Timer

The second number in a motor code tells you the number of seconds after fuel burnout when the ejection charge blows. In general, the delay time should be set so that the recovery system ejects as close to the peak trajectory (or apogee) as possible. Within the same motor class, a larger rocket will coast upwards after burnout for a shorter amount of time than a lighter rocket will. Therefore, you may want to use a B6-4 on a lighter rocket, but a B6-2 on a heavier rocket.

Thrust curve

What is shown below is a thrust curve. We can use it to determine average thrust and impulse. The vertical axis (y-axis) shows us thrust (in Newtons) and the horizontal axis (x-axis) shows us how long the rocket propellant burns (in seconds).

As we said before, at the very beginning of the launch, the thrust gets very high, and then it comes back down to a lower level which is mostly the same throughout the rest of the motor fuel's burn time. Because the burn time for the peak thrust is very short, the average thrust is going to be very close to the lower thrust that the motor burns at most of the time. So we can say the average thrust is going to be pretty close to 2 N. The impulse is going to be the average thrust multiplied by the total burn time. The total burn time is 2.5 seconds, so the impulse must be about 5 N-s. What is the class (what letter code?) for this motor?



How High Will My Rocket Fly?

You can estimate how fast your rocket will go and how high your rocket will fly if you know how much your rocket weighs, and also if you understand how thrust and impulse work. The mathematical equations needed to determine velocity and altitude involve use of formulas which follow the laws of physics. We are not going to explain that here, but if you want to know more about how to do this then read Harry Stine's Handbook of Model Rocketry.