The Tethered Electric Airplane
A Teacher's Guide (revised November 2014)

By Jason Brett, based on a project developed by Jason Brett and Todd Ablett

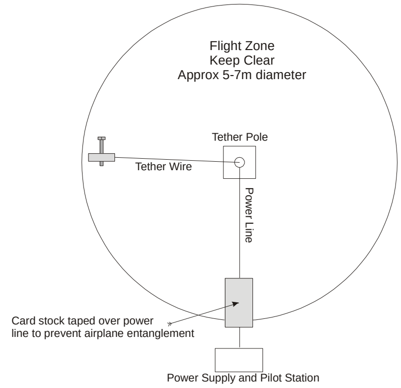
Introduction:
The tethered electric airplane project is an exciting, low-cost project that addresses a diverse range of technology education learning outcomes. The teacher can modify the project to make it fit well in an electronics class, by focussing on electric power, motor speed control circuits, and motor power curves, or in to a more general technology or engineering course by emphasizing aerodynamic elements and a design/build/test iterative cycle. The project has been successfully implemented with students from grades nine through twelve at a number of schools throughout British Columbia.

Typical Equipment and Materials Required:

Quantity	Item	Approximate Cost
Reusable Equipment:		
1	Tether Pole (described below)	$10 (made in shop)
2 – 4	High Current (3 to 5 Amp) Power Supply	see below for options
2 – 4	Hot Wire Cutter (described below)	$4 each (made in shop)
2 – 4	Propeller Testing Stand (described below)	$1 each (made in shop)
2 – 4	Digital Postage Scale (0 – 1 kg is fine)	$30-$40 each
4 – 8	Multimeters (if not built in to power supply)	$20 each
1 or more	band saw or scroll saw for wing templates	
1 or more	drill press	
1 or more	machine lathe or jig for drilling centre holes in dowels	
1	*large indoor space, approx 6-7m (20-23') in diameter, for flying airplanes*	
Many	scissors and xacto knives	
A Couple	Motor Boring Tools (described below)	
Several	hacksaws and pliers	
A Few	soldering irons	
Lots and Lots	of pennies, or other suitable weight for "heavy lift" flights	
Consumable Materials:		
1 per class	2'x4' sheet of ¼" thick hardboard for templates	$5
1 per class	can of spray adhesive (or several glue sticks)	$8
3 per class	3/8" dowel for propeller hubs	
3 per class	tubes of 5 minute epoxy adhesive for propellors	
1 per 2 students	Airplane, made of:	
	1/5th sheet (2'x8') of 1.5" thick pink styrafoam insulation	
	12" long piece of 1/16" dia. welding rod (or similar wire)	
	Electric motor (see below for details)	
	Plastic pop bottle for propeller blades	
	2"x8" piece of 3/32" thick balsa wood (for tail)	
	3 rubber bands (typically #63 or #73, about 3-4" long and ¼"-3/8" thick)	
	9 V battery clip	
	30" of 16-18ga stranded wire (preferably red and black)	

The Tether Pole

The tether pole serves to distribute electric power to the airplane as the plane flies in circles about the pole.



The tether pole has been constructed in many different configurations, including one that enabled the operator to control the elevator while the plane was in flight. While the configuration presented here is not the highest performance tether pole we have constructed (the power line to the airplane, in particular, is a bit heavy) it is the most reliable.

In the photo, at right, you can see the “business” end of the tether pole, using two ball bearings as commutators to transfer electricity to and from the wire leading to the plane. The wires from the power supply are press-fit to the inner race of the bearing, and the hose clamps hold the wire leading to the plane. The lexan plate serves as a strain relief for the wire, as tensile loads during flight can become rather significant.

The “business end” of the tether pole.

The Motors

The choice of motor is very important. Do not expect to be able to use “just any” DC motor. Most small DC motors are wound to use a 6V or 12V supply, however we will be running these motors at 24V-30V. The advantage of using a high voltage motor is that it can achieve high power output while at a reasonably low current... 3 to 5 amps. Once a motor is selected, the students can design their propeller to match the motor’s power characteristics... which is one of the main electronics-related learning outcomes of this project.

After some research, I have selected the “Motor 385” from Pitsco Education, not necessarily because it is the very best motor, but because it is a good motor that is available on-line from: http://www.pitsco.com/Motor_385 as part number W50076. (If you find a better motor, please let me know… Pitsco charges too much for shipping.)

Other similar “Speed 400” or “RS-385” motors are available at Lee’s Electronics, in Vancouver, or from http://www.banebots.com I suggest you buy one and try it before purchasing a class set.

The Power Supply

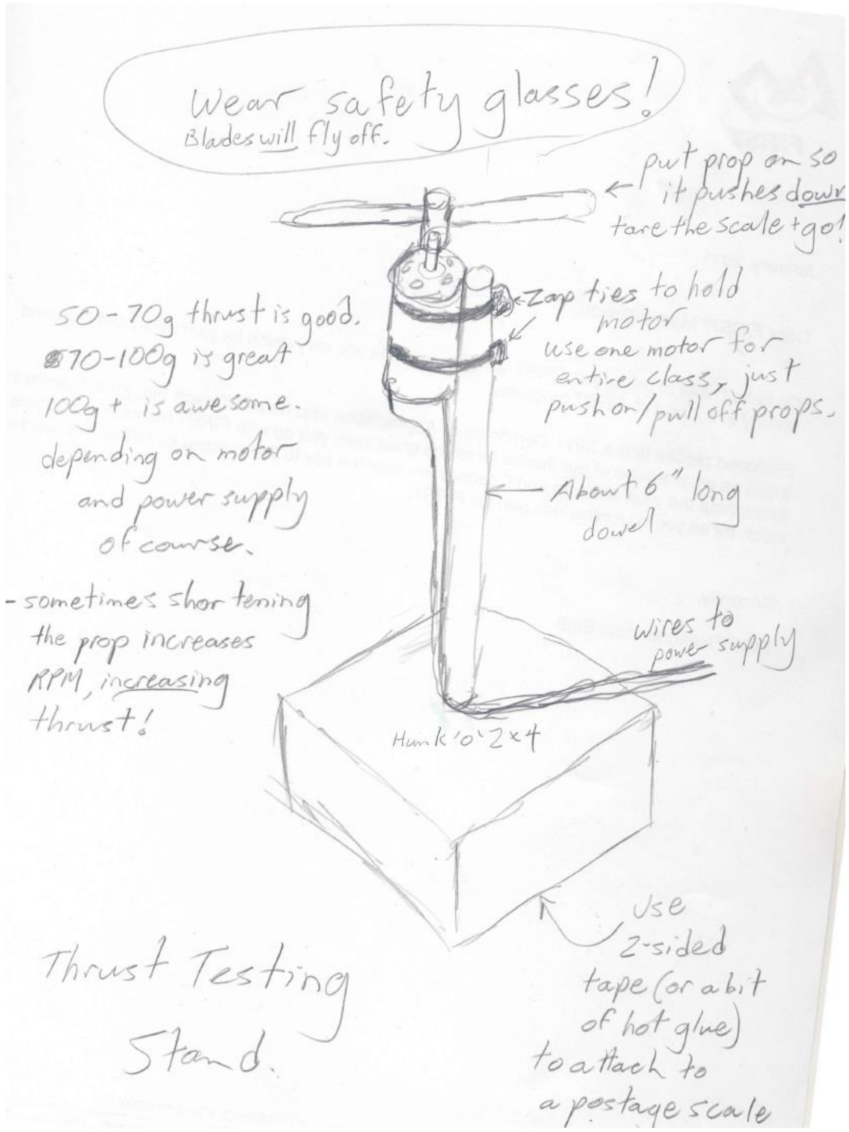
A good, variable power supply, capable of delivering 3-5 amps on a reasonably continuous basis is required to make this project work. It needs to be variable so that students can adjust their motor speed while

Variable Power Supply. 0-30 volts, 5 amps. #RXN305D from Leeselectronic.com for $135

in flight, and it needs to be able to deliver 3-5 amps in order to get sufficient power to the motors. It is an added bonus if it displays a readout of voltage and current as this eliminates the need for multimeters to measure voltage and current. Many schools already have power supplies that meet these requirements, however in the event you need to purchase one, the best price I have seen is from Lee's Electronics (see inset photo, previous page) located at Main Street and 29th Avenue, in Vancouver.

There are other alternatives. Using two 12 volt batteries, in series to give 24 volts, or even three in series for 36 volts will work. Make sure you have some kind of fuse or circuit breaker installed, as batteries can deliver a huge amount of current when shorted out and may damage your apparatus or start a fire. To regulate the motor speed you can use a PWM speed controller. If you don't immediately 'get' what I mean by this… just buy the power supply from Lee's and we'll speak no more of this option.

The Propeller Testing Stand



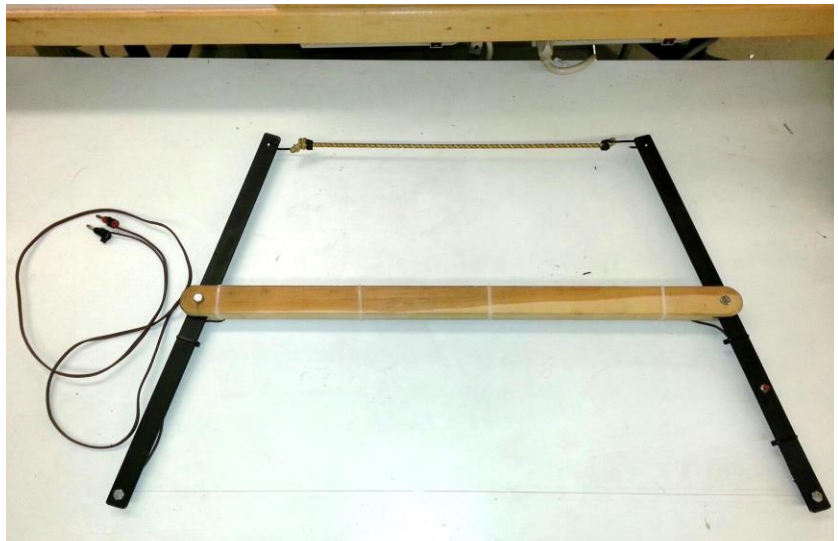
Okay… I'll say one more thing about this option… it does allow you to use a single 12 volt battery and lower voltage/higher current speed 400 style motors such as would be used in radio controlled cars and electric planes. But again, if you're not exactly sure what I'm talking about here… you will be much happier using a pre-made power supply. MUCH happier.

Propellor Testing Stand

The lovely sketch, above, shows a painstakingly illustrated, highly detailed representation of the propeller testing stand. The prop should be mounted 'backwards', so the air is blowing upwards. Students should be able to press their propellors on to the motor shaft and pull them off after testing.

Hot Wire Cutter

The Hot Wire Cutter: about 30" wide



The hot wire cutter is used for cutting the styrafoam wings to shape. The key component is NiChrome Wire, also known as resistance wire or heater wire. If you don't have any in your shop, you can likely get some from the science department, or from an online supplier such as http://jacobs-online.biz/nichrome_wire.htm Normally I use wire that is around 26-28 AWG, as 28 AWG wire (0.0126" diameter) gives a resistance of 4.25Ω/foot. That means a 2.5' long hot wire cutter will have a resistance of about 11Ω, and a power output of 44W at 22V and 2A. That is more than enough for cutting styrafoam and doing a simple power calculation worksheet.

Other people have reported having luck using stainless steel wire, or even guitar strings, but the high resistance of the nichrome wire keeps me coming back to it. It works very well with the power supplies that we use to drive the motors.

The hot wire cutter is shown. Note the small, momentary, pushbutton switch in the handle on the right side that automatically turns the cutter off as soon as the student lets go of it.

Designing a Propeller

A good propeller is crucial to the success of your airplane. Because propellers often break, it is important that you have three or four good propellers ‘ready to go’ on the day of your flight test. You will not have time to repair your favorite prop if it breaks… you’ll have to pop it off and put on a spare.

You can also design propellers to accomplish different tasks… you may have one for speed, one for heavy lift, and one for efficiency…. Or you may have one that does all three pretty well.

While computers can model larger propellers very well, the size of our props and the fact that they are hand made makes it very difficult to know what prop will work well with which motor. The best way is to make lots of propellers and test them to see what works best for you.

The Hub

The hub should be made of a short piece of hardwood dowel, between 15-20mm long. Normally I use ½” diameter dowel, but slightly larger, or slightly smaller sizes can be used if desired. Technically there is no reason that a square piece of wood couldn’t be used in place of a dowel.

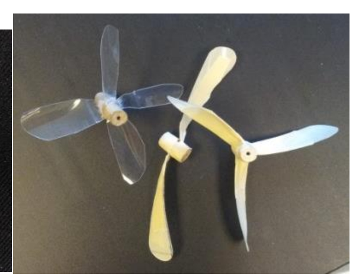
Drill a hole in the centre of the dowel. Getting it centered helps with performance, so I prefer to do this in the machine lathe and start the hole with a centre drill. The shaft of most 385 sized motors is 2.3mm, slightly undersized… use either a 2mm bit or a 5/64” bit.

Decide what pitch you want. The pitch of a propeller is much like the gear ratio on a car or bicycle. A steep pitch is like high gear… designed for going fast, while a shallow pitch is like low gear. A good starting point will be around 30°. Resist the urge to make the pitch too steep as a steep pitch will cause the blades to stall.

Alternative Designs

Depending on the time and resources available different propeller and hub designs may be encouraged. Some successful examples have involved lathe work, thermoforming, and 3D printing. As always, beware of the fact that the propeller WILL impact the ground, spinning at high speed, and may shatter.



Propeller Testing Worksheet

Name: ____________________________

Record the following details for each propeller you build and test. If you trim a blade, you record it as a new propeller… but mention that in the notes column. If you can choose from different motors, make sure you record which motor you used.

Prop #	Blade Shape (sketch)	Number of Blades	Blade Length (mm)	Pitch (see below)	Maximum Thrust (g)	Voltage at Max Thrust	Current at Max Thrust	Power Input at Max Thrust	Notes
1									
2									
3									
4									
5									

For pitch, sketch a line that shows the angle at which you mounted the blade in the propeller hub.

Vocabulary

Angle of Attack:

Lift:

Drag:

Thrust:

Lift to Drag Ratio:

Thrust to Weight Ratio:

Centre of Lift:

Centre of Gravity:

Camber:

Chord:

Span:

Aspect Ratio:

Reynolds Number:

Stall:

Laminar Airflow:

Turbulent Airflow:

Propeller Pitch:

Elevator:

Rudder:

Horizontal Stabilizer:

Vertical Stabilizer:

Aileron:

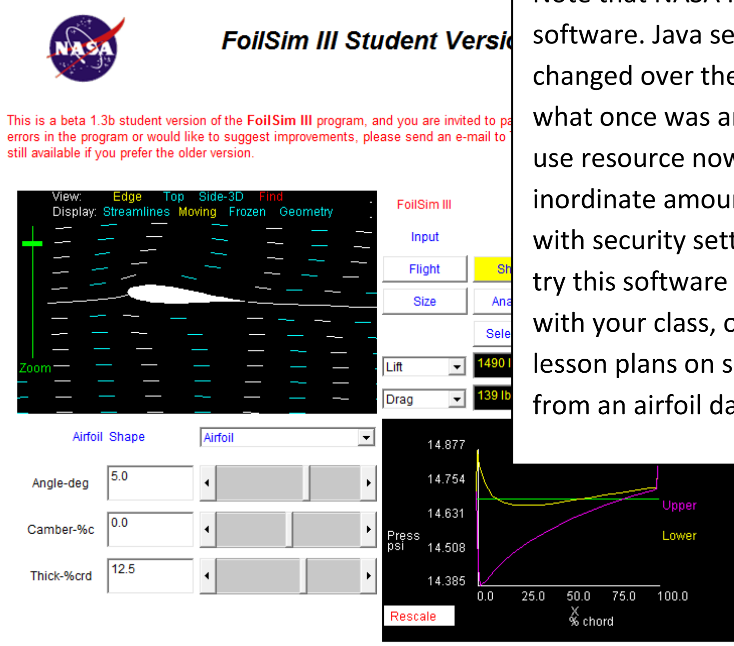
Flaps:

Designing An Airfoil Using NASA Foilsim

NASA has a free, on-line java airfoil simulator suitable for introductory use. It is available at:

http://www.grc.nasa.gov/WWW/K-12/airplane/foil3.html

Note that NASA Foilsim is Java based software. Java security settings have changed over the past few years and what once was an excellent, easy to use resource now requires an inordinate amount of messing about with security settings. Make sure you try this software before sharing it with your class, or switch to the new lesson plans on selecting an airfoil from an airfoil database.



Step 1) Click on the "units" and set them to metric.

Step 2) Click on the "size" box. Use the sliders or text boxes to set:

a) The chord length to your desired value (typically 0.10-0.15 metres)

b) The wing span to your desired value (typically 0.3 – 0.6 metres)

Note the wing area and aspect ratio change as you change these values

Step 3) Click on the "flight" box. Use the sliders or text boxes to set:

a) The speed to your estimated airplane speed in km/h (typically 20-40km/h)

Note the "lift" and "drag" boxes now have useful values in them

One Newton (1N) is roughly the equivalent of 100g of mass

If you have tested your motor & prop you know your max thrust

The predicted drag must be lower than measured thrust

Or else you won't be able to fly that fast!

The predicted lift must be greater than predicted mass

Airplanes are typically 100-200g (1-2N)

Unless you are going for "heavy lift", of course

The predicted lift and drag will change as you do step 4

Note that the Reynold's number changes as you change speed and chord length

You can leave the other values set to their defaults on this screen

Or you can set them to try flying on Mars, or at high elevation on Earth

If you will be testing your plane on Mars, please follow all field trip rules

Step 4) Click on the "shape" box. Use the sliders or text boxes to set:

a) Your angle of attack. This is the angle that the airfoil "cuts through" the airflow
   - Note that if you set the angle too high that your wing stalls (not good!)

b) Your camber

c) The thickness of the wing relative to the chord length of the wing.
   - Keep watching your lift and drag boxes.
     - Try for a maximum Lift to Drag (L/D) ratio
     - Keep Drag lower than your maximum measured thrust
     - Keep lift higher than your estimated airplane weight

Step 5) Click on the "select plot" box. Select lift vs. Angle. You may need to click on "rescale"

a) What does this plot tell you? Can you see what angle will cause a stall?

b) Try "Drag vs. Angle" Is there a large range of angles that have about the same drag?

c) Now go back to "shape", "flight" and "size" to optimize your airfoil.

Step 6) Click on the "geometry" box. A bunch of data will scroll past your lower right corner window

a) Look in the lower right corner window and see what is there
   - There should be some general flight test pararmeters
   - There should be "Upper Surface" followed by a list of numbers
     - These are the co-ordinates for the upper surface of your airfoil
       - We mainly want the X and Y, we don't need Pressure or Velocity
     - There should be "Lower Surface" followed by a list of numbers

b) You may want to copy and paste all of this data in to a text editor and save/print it.

c) If you know Excel or AutoCAD, you can use these numbers in those programs.
   - Multiply the "x" values by the chord length of your wing to get the "x" stations
   - Multiply the "y" values by the chord length of your wing to get the "y" positions
   - Plot the x and y values for each data point for the lower surface
   - Plot the x and y values for each data point for the upper surface
   - Join them with a smooth curve and print at a 1:1 scale.

Step 7) Complete the "Plotting an Airfoil" worksheet using the "geometry" data, but first, record:

Shape:	**Size:**	**Flight:**
Angle: _______ degrees	Chord: _______ meters	Speed: ______ km/h
Thickness: ______ % of chord	Span: ______ meters	Lift: ________ N
Length: ________ metres	Aspect Ratio: ________	Drag: ________ N
		Lift to Drag Ratio: ________

You may want to repeat this test several times to find idea airfoils for speed trials and heavy lift trials. Be sure to record this data if you do, so that you can re-create your airfoil when you need it.

Plotting An Airfoil
Using NASA Foilsim Co-ordinates

After you have designed an airfoil using NASA's Foilsim Software, this is how you can draw the airfoil life size. Once you have drawn the airfoil, you can use your drawing as guide to cut templates out of wood, and then use the wooden templates to cut the wing out of a piece of styrafoam.

This is an ideal task for a spreadsheet. If you know how to use a spreadsheet such as Excel or Open Office Calc, use copy and paste from Foilsim to transfer your data, do your calculations for Step 1 and Step 2 and print your results.

Step 1: After you have pressed "geometry" in foilsim, copy the data it shows to the "X" and "Y" columns boxes, below. Do this for both the Upper Surface and the Lower Surface.

	Upper Surface					Lower Surface			
Stn.	X	X*chord	Y	Y*chord		X	X*chord	Y	Y*chord
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									
16									
17									
18									
19									
20									

Step 2: What is your chord length? __________ Metres.
Multiply each X and Y value by the chord length and record that in the X*chord and Y*chord columns. Round your answers to three decimal places. (eg: -0.083m)
Want to save time? You can skip Stn (station) #4,6,8,10,12,14 and 16 completely.

Step 3: Jump ahead to the sheet for step 3 titled “Airfoil Cross Section” and sketch your airfoil. If you are familiar with AutoCAD, or a similar drafting program, you may choose to do step 3 in CAD, and connect the points using a smoothed polyline.

Step 4: You will use the sketch of the airfoil to generate four templates for cutting your wing.

Two will be “top templates” and will follow the upper surface of the airfoil.

Two will be “bottom templates” and will follow the bottom surface of the airfoil.

To make it so that the hot wire cutter can follow your templates you need to provide entry and exit points for the hot wire.

Mark a vertical line to indicate the leading edge of the template and foam about 1 cm to the left of the leading edge of your airfoil.

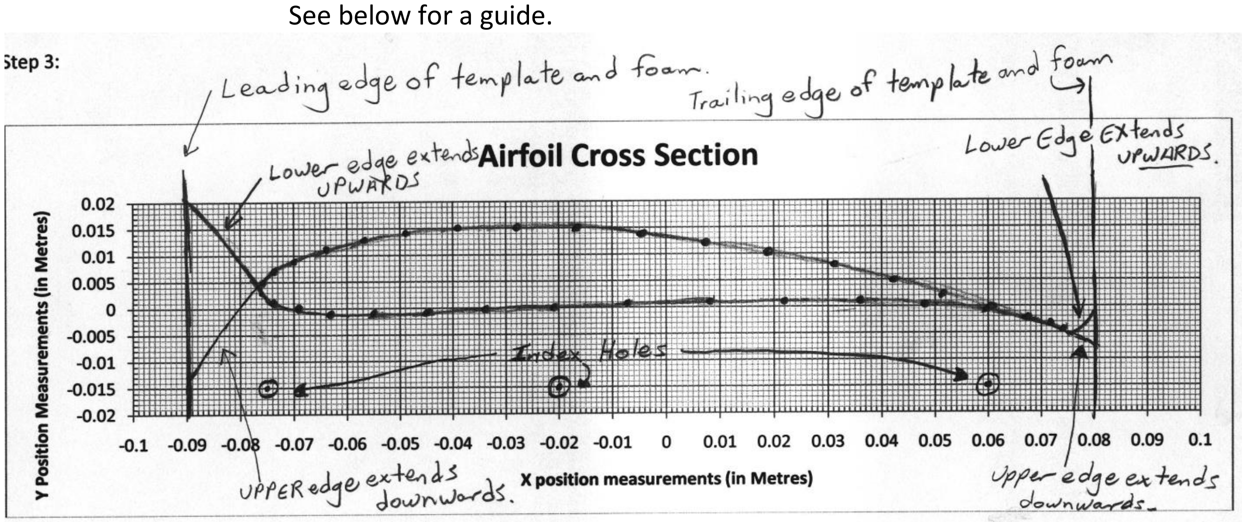
Mark a vertical line to indicate the trailing edge of the template and wing about 1 cm to the right of the trailing edge of the airfoil.

Smoothly extend the front lower edge (leading lower surface) of the airfoil upwards so that it exits near the leading edge of the template.

Smoothly extend the front upper edge of the airfoil downwards, so that it exits the leading edge of the template about 1 cm above the very bottom of the template.

Do similar steps for the trailing edges of the upper and lower airfoil surface. It is okay to have these lines emerge from the trailing edge of the template.

See below for a guide.



Step 5: Mark three “Index Holes” about 0.5cm above the bottom of the template.

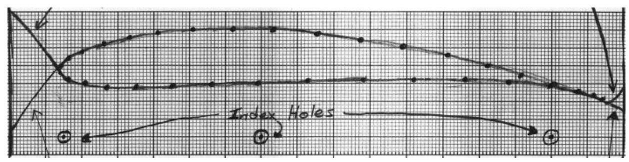
The index holes MUST be BELOW the bottom surface of the airfoil.

We will put pins through these holes later to hold the template to the foam

Step 6: Make two photocopies of your Airfoil Cross Section.

Do NOT lose or destroy the original sketch at any time during this project.

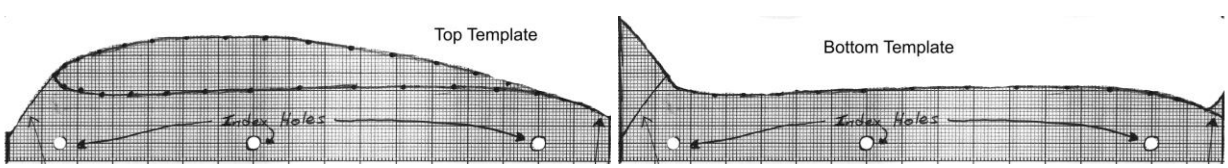
Step 7: Cut your photocopies along the top of the template and bottom of the graph.
Cut them along the leading edge of the template and foam and the trailing edge of the template and foam.
We call these your paper templates, and they should look something like this:



Step 8: Cut four pieces of ¼" thick hardboard (or other wood as provided) to the length and height of your paper template.
It is okay if they are a bit too tall, but they be the correct length and have square (90 degree) corners.
Take two pieces, align all four sides, and tape them together with double-sided tape.
These will become your "upper templates"
Take two pieces, align all four side, and tape them together with double-sided tape.
These will become your "bottom templates".
Use spray adhesive or glue stick to attach one paper template to the wood that will become the "upper template".
Make sure you align the leading (left) and bottom edge of the paper template with the wood.
Do the same, attaching the other paper template to the wood that will become the "bottom template".

Step 9: Take both pieces to the drill press and drill 5/32" (4mm) holes at the locations marked as "Index Holes" on your paper templates.

Step 10: This is where a lot of people make mistakes, so pay attention!
Use the bandsaw to cut along the top edge of the top template.
Use the bandsaw to cut along the top edge of the bottom template.
You should have two templates, as shown below.
When you put your bottom template over top of your top template the difference between them will be your airfoil!



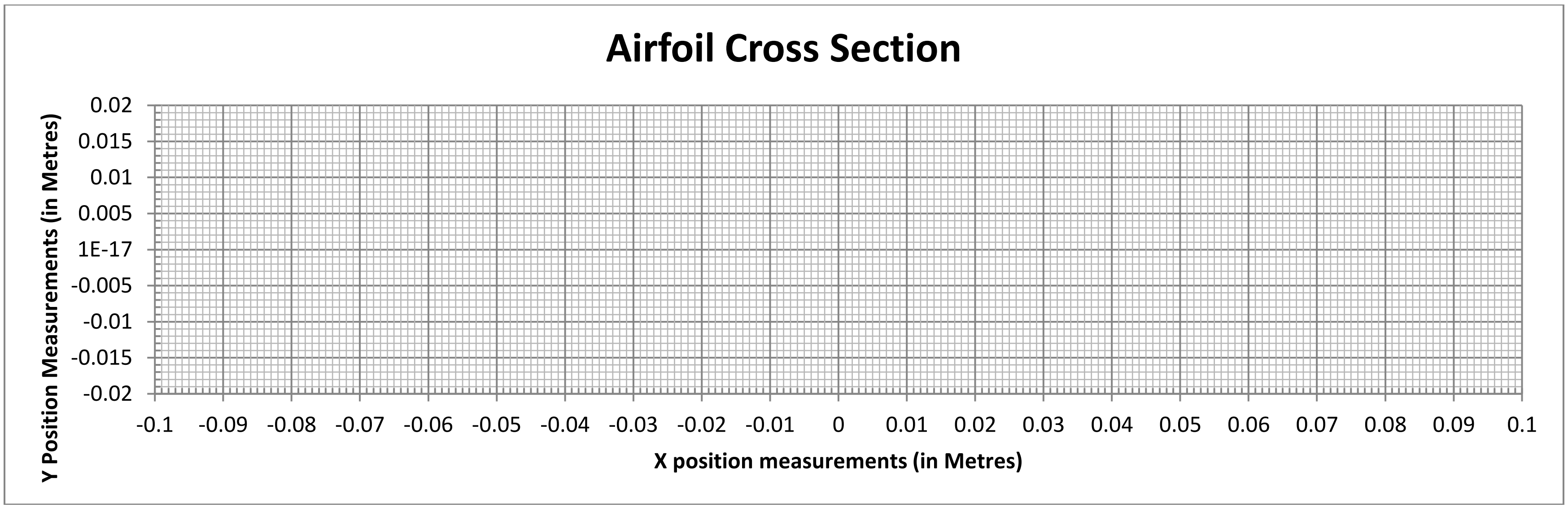
Step 11: Use a file and/or sandpaper to smooth your templates.
There must be no bumps or dents that will catch the hot wire.
Copy the location of each dark line (1cm spacing) on the paper template across to the wooden template that does not have paper on it.
You will need these marks to guide you and your partner as you cut the foam.
Seperate your templates... you are now ready to cut some foam!

Name: ______________________________________

Step 3:

Take the data that you calculated in Step 2. Find the x and y co-ordinates for each point, or station, on the graph, below. Place a small, but clear dot in pencil at each point.

Once you have plotted the upper and lower surface of the airfoil, use a pencil to lightly sketch out the shape of the airfoil by joining the dots together. If you have a set of "French curves" (drafting tools) they might help. Once you have sketched out the shape of the airfoil, go over it in a single, clean, dark line. You may use a fine tipped felt pen, or soft pencil for this.



Now return to "step 4" on the instruction sheet.