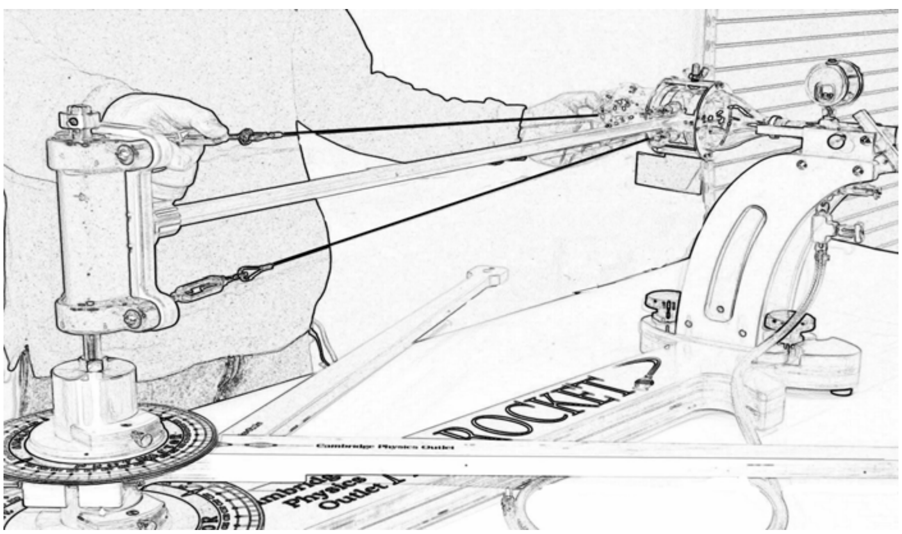
Air Rocket
Instruction Manual



THE CPO SCIENCE AIR ROCKET

Introduction

The Air Rocket will allow you and your students to explore many fascinating areas of science and technology. The rocket uses compressed air from a bicycle pump as its energy source. The air rushing out the open end of the bottle makes a spectacular sonic boom as the rocket jumps off the launch tower at accelerations exceeding 100 ‘g’s. The CPO Timer and Photogates allow students to make accurate measurements of speed and acceleration. It is easy to change the mass of the rocket and the launch pressure. Here are some of the things you can do:

- ✓ Measure speed, position, acceleration, and pressure to very high accuracy.
- ✓ Conduct exciting experiments that are accurate, reliable and repeatable.
- ✓ Explore Newton’s Second Law by changing the rocket mass while leaving the force (pressure) constant.
- ✓ Design and carry out experiments on inertia and Newton’s First and Third laws.
- ✓ Explore the concept of momentum since the rocket’s forward momentum comes from the backward momentum of the escaping jet of air.
- ✓ Learn about pressure, volume, temperature, and energy by investigating how the pressure of the air in the bottle affects the motion of the rocket.
- ✓ Generate real excitement in your science or mathematics class!

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AIR ROCKET ASSEMBLY

The Air Rocket comes with the following components and accessories:

The Air Rocket Components

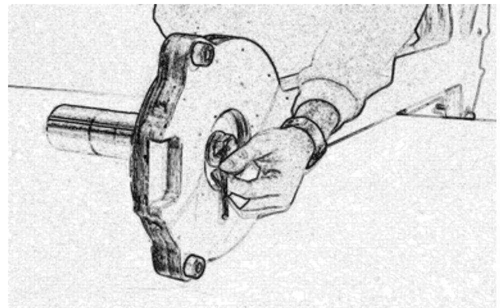
1. Curriculum Resource Guide for the Air Rocket
2. The Air Rocket base
3. An aluminum pedestal with a large bolt and washer
4. Upper and lower arms
5. Large and small protractors
6. The swing arm with one round, concave washer
7. The launch tower with two square washers and two large black knobs
8. The catcher with two screws for connecting to the Air Rocket base
9. The safety zone: six wooden dowels with rings and string

Tools and Accessories

1. A bicycle pump
2. Two photogate mounting posts
3. Two photogate cables
4. One allen wrench
5. One steel rod
6. One wrench

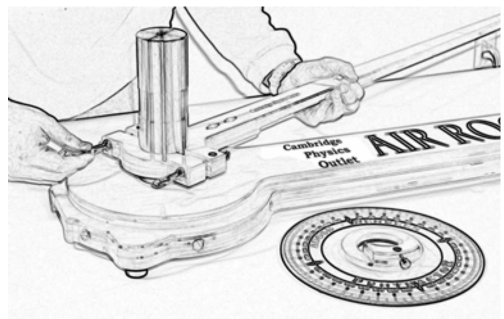
The *Supplemental Curriculum Resource Guide* also contains assembly instructions.

Step-by-Step Assembly Instructions



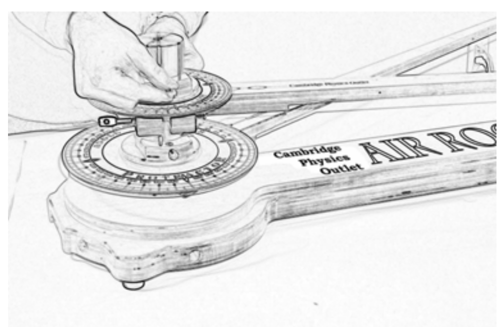
Step 1: Attach the Aluminum Pedestal to the Air Rocket Base.

Attach the pedestal to the Air Rocket base using the large bolt provided. The bolt has a drilled hole for inserting the steel rod for tightening. This bolt should be snugged up fairly tight.



Step 2: Attach the Lower Arm and Protractor to the Pedestal.

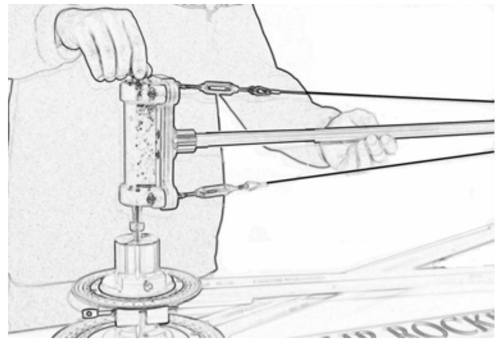
The lower arm fits in the lower of the two shallow grooves on the pedestal. There are two screws that set the tension in the arm. These screws must be tightened simultaneously to maintain proper alignment. Tighten the screws by hand, just enough so that you can rotate the arm but it stays put after it is moved. Attach the larger of the two protractors by dropping it over the pedestal. The brass thumbscrew on the protractor allows you to set the reference of zero degrees to the position of the lower arm.



Step 3: Attach the Upper Arm and Small Protractor.

The upper arm fits in the higher of the two shallow grooves on the pedestal. Just like the lower arm, tighten the two screws just enough that you can rotate the arm but it stays put after it is moved. Attach the small protractor by dropping it over the pedestal like you did with the large protractor.

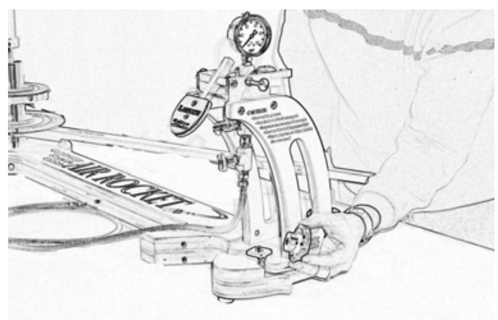
Step 4: Attach the Swing Arm to the Pedestal.



The swing arm attaches to the top of the aluminum pedestal. First, place the round washer, convex side up, over the hole on top of the pedestal. Spin the nut on to the threads of the swing arm until 1 inch of thread is showing below the nut. Thread the end of the shaft through the washer and into the pedestal using the metal knob at the top of the shaft. Tighten the nut against the washer to lock the shaft in place.

The swing arm should now swing freely around the Air Rocket base.

Step 5: Attach the Launch Tower to the Air Rocket Base.



Attach the launch tower using the two big black knobs and square washers. First, place the launch tower over the two studs on the Air Rocket base as shown. Place the square washers on the studs and fasten with the two black knobs.

Leave knobs fairly loose so adjustments can be made to the tower in the next step.

Step 6: Align the Rocket and Launch Tower.

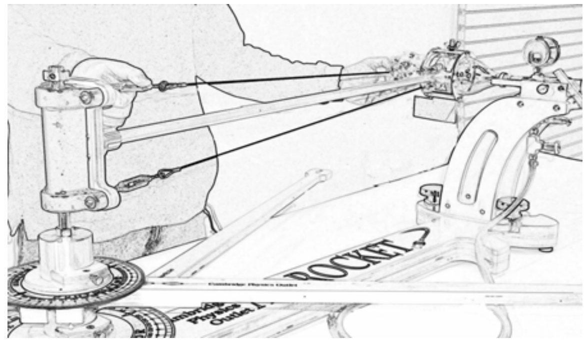
The rocket must be adjusted so the rubber stopper of the launch tower is aligned with the mouth of the bottle. There are two separate adjustments to make:

1. The cables on the arm can be adjusted to raise or lower the rocket. By turning the turnbuckles with your hand. **(6A)**

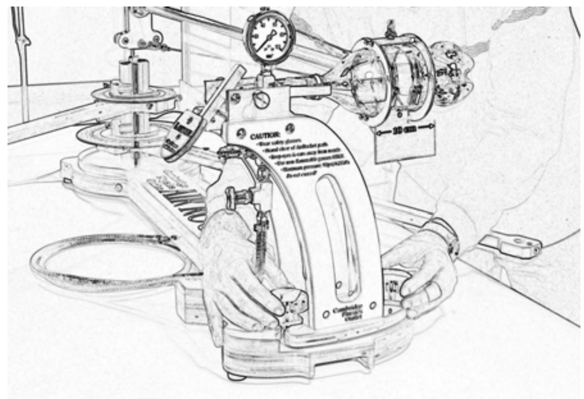
2. The horizontal and rotational position of the launcher can be adjusted by loosening the two black knobs. Retighten by hand when desired position has been achieved. **(6B)**

When you have completed these adjustments the rocket should swing back so the rubber stopper lines up with the center of the opening in the bottle. (**6C)**

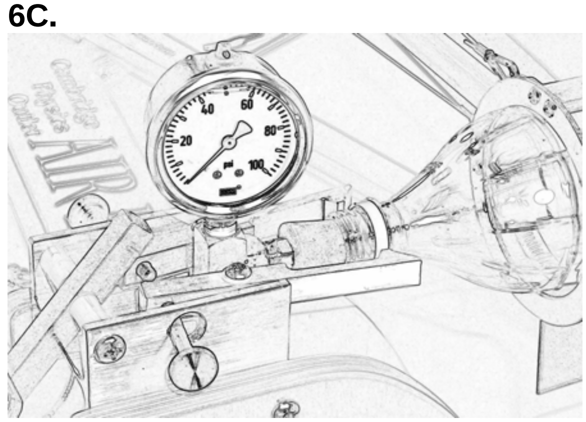
6A.



6B.

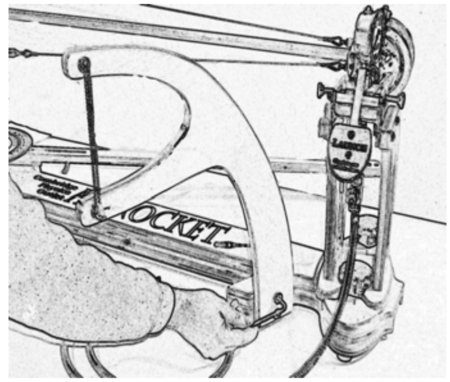


6C.



Step 7: Attach the Catcher to the Air Rocket Base.

The rope on the catcher stops the rocket after it has been fired. The catcher is attached to the Air Rocket base using the allen wrench and two allen screws that are provided as shown.



Step 8: Setting up the Safety Zone.

In order to keep observers out of the path of the rocket the safety zone <u>MUST</u> be set up before operation.

WARNING!

<u>UNDER NO CIRCUMSTANCES SHOULD THE ROCKET BE LAUNCHED WITH OUT THE SAFETY ZONE SET UP PROPERLY. SERIOUS INJURY COULD RESULT!</u>

There are six wooden dowels with rings that insert into the Air Rocket base to keep objects and people out of the path of the rocket's orbit.

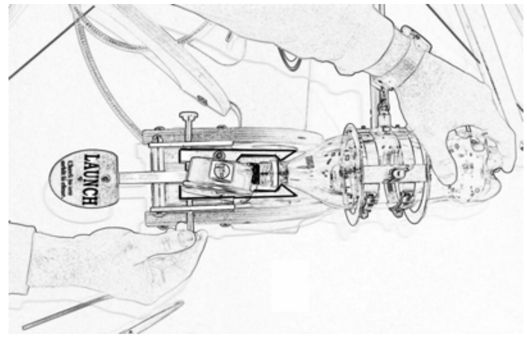
Insert all six long wooden dowels into the holes in the side of the Air Rocket base below the aluminum pedestal. Thread the rope through the rings on the dowels and attach the rope to the two eyes on either side of the base. The rope will form a semi-circle around the Air Rocket and should be tight enough that it keeps the dowels from being removed.

REMEMBER

1. <u>Always</u> be sure every observer is clear of the rocket's orbit and remain outside of the safety zone until travel has been completed!

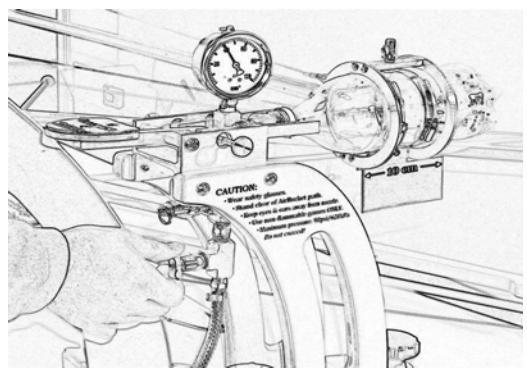
2. <u>Always</u> be sure <u>all</u> observers and those present during the operation of the Air Rocket are wearing Safety Glasses!

Step 9: Launch the Rocket



To Attach: Swing the rocket back to the launch tower and push it onto the rubber stopper. A very small amount of vacuum grease or petroleum jelly will help the stopper fit into the end of the bottle.

Set Release Arms: The release arms should grip the ridge at the end of the bottle as shown. There are two long adjustment screws that should be set so the arms have the right amount of ‘grip’ on the bottle. Raise the launch pad and tighten the two adjustment screws against either side of the launch pad shaft. As you do this the arms’ grip will increase on the top of the bottle. These screws should be equally finger-tight (See Diagram).



Pump to Pressure: There is a pump and a bleeder valve that control the air pressure in the rocket. The valve allows you to ‘bleed off’ a little air to get the desire launching pressure.

WARNING!

Make sure orbit of rocket is clear at <u>ALL</u> times when the rocket is pressurized!

Use the bleed valve to reduce the pressure until you reach the exact amount of air pressure desired. Counter clockwise will open the valve (See Diagram).

Launch: Make sure everyone is clear of the safety zone. Count ‘ready, three, two, one, launch!’ and push down firmly on the release lever. The rocket should make a loud noise as it takes off from the launch tower and spins around its orbit.

Congratulations! Your Air Rocket is now assembled.

SETTING UP EXPERIMENTS ON THE AIR ROCKET

These procedures will help you and your students to use the Air Rocket in experiments. The CPO Timer is assumed, although other timing equipment could be adapted to make similar measurements.

Attaching the Photogates and Setting the Proper Height

The Photogates attach to the upper and lower arms with the photogate mounting posts. The posts should be threaded into the bottom of the Photogate. Hand tightening should be sufficient as there is not much force acting on the post. **DO NOT OVERTIGHTEN** the post, the threaded end is aluminum and can be snapped off by using tools (such as vise-grips or pliers) to screw the post into the Photogate.

Setting the Angle of the Large and Small Protractors.

The upper and lower arms operate independently but it is useful to have them set to the same reference position. The speed and acceleration measurements are made using the angle of the arms as a measure of position. This angle can be read from the large and small protractors once you have set the proper angles.

We recommended the following technique to set the angle of the Large and Small Protractors:

1. Bring the rocket to the launch Tower and attach it as if preparing for a launch (Do Not Pressurize Yet).
2. Rotate the lower arm so the Photogate is about one centimeter in front of the flag on the rocket.
3. Loosen the setscrew on the large protractor and align zero degrees with the mark on the lower arm. Tighten the protractor set screw again. The arm may now move and the protractor will stay fixed.
4. Use one of the photogate mounting posts to align the upper arm with the lower arm. Adjust the small protractor so its zero degree mark is identical to the large protractor.
5. You may now move the upper and lower arms to the desired positions for each experiment. The protractors will allow you to measure the position of each arm.
6. After you have moved the arms to their desired positions, place the photogate mounting posts (with Photogates attached) into the holes on the arms. Adjust the height of the Photogates to the point where the flag on the bottom of the rocket just breaks the light beam as the rocket rotates. After you have adjusted the height, tighten the setscrews in the arms to hold the Photogate at the adjusted level.

INTERESTING INVESTIGATIONS WITH THE AIR ROCKET

Measuring Speed and Acceleration

There are two ways to measure the **speed** of the Rocket:

- ✓ Method 1) Use two Photogates and measure the distance between them. The speed is the distance between the Photogates divided by the time from A to B.
- ✓ Method 2) Use one Photogate and calculate the speed by dividing the length of the flag (10 cm) by the time it takes to pass through one Photogate.

Method 2 is easier for many students to understand but can be less accurate since it gives an average speed over the distance between the Photogates. Method 1 is preferred since each Photogate can make an independent speed measurement that is localized to the position of the Photogate.

There are also two ways to determine **acceleration**:

- ✓ Method 1) Take two single-Photogate speed measurements and a 'time-A-to-B' measurement. The acceleration is the change in speed ($v_B – v_A$) divided by the time from A to B (t_{AB}).

$a = \frac{v_B - v_A}{t_{AB}}$	The acceleration is the change in speed (v_B - v_A) divided by the time taken from A to B.
$v_B = v_A + at$	The speed at B is the speed at A plus the acceleration multiplied by the time from A to B.

- ✓ Method 2) Use the distance traveled and measured speed to estimate the acceleration (equation 3). The equations for uniformly accelerated motion in a line are given on the next page.

Equation 1

$$x = x_0 + v_0 t + \frac{1}{2} a t^2$$

Equation 2

$$v = v_0 + at$$

where:	*x*	is the position at time *t*
	x_0	is the initial position at time $t = 0$
	v	is the speed at time *t*
	v_0	is the initial speed at $t = 0$
	a	is the acceleration
	t	is the time

These may be combined to solve for the acceleration as a function of the distance. Essentially, the argument is: If the Rocket has reached speed *v* after moving distance *d*, then it's acceleration must have been at least *a*.

Equation 3

$$a = \frac{v^2}{d} - \frac{v_0^2}{2d}$$

Since the Rocket starts at rest, with $v_0 = 0$, the result is $a = v^2/d$. This method will yield some very impressive numbers. We have observed peak accelerations exceeding 1,000 m/sec^2!

Pressure, Volume, and Energy

The Air Rocket converts the energy stored in the pressure of the gas into **kinetic energy** of the rocket and of the escaping gas. The amount of energy depends on the pressure, volume, and temperature of the gas in the bottle.

If the units of pressure are worked out the result is Joules per cubic meter! Since Joules are a measure of energy, pressure is then a measure of energy density. A pressure of 100,000 Pa (100,000 N/m^2) is equivalent to an energy density of 100,000 Joule/m^3. The relationship becomes exact when the temperature and specific heat of the gas are included.

For the Air Rocket it is instructive to begin with the **Ideal Gas Law** (Equation 4).

Equation 4

$$PV = nRT$$

where:	P	is the pressure in Pa
	V	is the volume in cubic meters
	n	is the number of moles of the gas
	R	is the universal gas constant = 8.31 J/mole·°K
	T	is the absolute temperature in °K

To a reasonable approximation the volume of the bottle is constant. The pressure of the gas changes from a high pressure (before launch) to a lower pressure (one atmosphere). This difference in pressure is the source of the energy that propels the rocket forward.

Students may notice that the air cools substantially when the rocket is launched. To a lesser extent the drop in temperature is also a source of energy. The energy available from the change in temperature is less than from the change in pressure. Under the first approximation it is acceptable to estimate the energy available to the rocket as equal to the volume in the bottle times the change in pressure.

The pressure gauge on the rocket measures in pounds per square inch, or psi. The formula (equation 4) uses Newtons per square meter. The conversion factor is:

1 lb/in^2 (psi) = 6,944 N/m^2 (Pa)

The gauge measures pressure above one atmosphere, or ‘gauge pressure’. The actual pressure of gas in the bottle is the gauge pressure plus atmospheric pressure. Since the average atmospheric pressure is 14.7 psi, a measured pressure of 80 psi in the bottle corresponds to an ‘absolute pressure’ of 94.7 psi (80 + 14.7).

The energy available to the rocket comes from the difference between the starting pressure (gauge pressure plus atmospheric pressure) and the final pressure after all the air has expanded out of the bottle (atmospheric pressure). The atmospheric pressure cancels out and the pressure available to do work, i.e. accelerate the rocket, is the gauge pressure.

At a gauge pressure of 80 psi (555,521 Pa) and a volume of one liter (0.001 m^3) the energy available is approximately 555 Joules (555,521 $J/m^3 \times 0.001\ m^3$). This is a substantial amount of energy!

If we make an assumption that the rocket moves in a straight line while accelerating (which is nearly true) the kinetic energy is $^1/_2 mv^2$. This relation can be inverted to show that the speed of the rocket depends on the energy and mass (equation 5).

Equation 5

$$v = \sqrt{\frac{2E}{m}}$$

where:	*v*	is the speed of the rocket in m/sec
	E	is the energy in Joules
	m	is the mass of the rocket in kg.

In reality, some interesting things happen (like the sonic boom) that use up some of the energy so the rocket does not convert all the pressure energy to kinetic energy (speed). However, since the energy is proportional to the pressure, the speed of the rocket should increase as the square root of the pressure (equation 6). This prediction can be tested by experiment and is quite well demonstrated by the data.

Equation 6

$$v \propto \sqrt{P}$$

Momentum and Sonic Booms

The Air Rocket does some pretty impressive things that students can observe and measure. While detailed understanding will be beyond many students (and is the subject of an upcoming book) many good questions are generated that stimulate conceptual understanding of key concepts such as energy, power, pressure, momentum, and the gas laws.

The **Law of Conservation of Momentum** is one interesting application. This law leads directly to the rocket equation that is explanation for how the Apollo missions reached the Moon and why jet planes fly. At the start, when the rocket is at rest, the momentum of the system (rocket plus gas inside) is zero. At some later time the total momentum must still be zero. The rocket is moving forward and the gas is moving backward. We express the momentum equations as equation 7.

Equation 7

$$m_1 v_1 = m_2 v_2$$

where:	m_1, v_1	is the mass and speed of the system at the start.

	m_2, v_2	is the mass and speed of the system at a later time.

For the rocket, $v_1 = 0$ since the rocket starts and rest. At a later time the total momentum of the rocket plus the gas must be zero.

Equation 8

$$0 = m_R v_R - m_P v_P$$
$$\downarrow$$
$$v_R = \frac{m_P}{m_R} v_P$$

where:	m_R, v_R	is the mass and speed of the rocket.
	m_P, v_P	is the mass and speed of the propellant gas.

One may use the Ideal Gas Laws to calculate the mass of the gas in the bottle. At 80 psi and room temperature the result is about 6-7 grams. The rocket is much more massive (about 400 grams). Application of the law of momentum conservation allows us to calculate that the speed of the propellant gas is a factor of 60 or so higher than the speed of the rocket! If the rocket travels forward at 10 m/sec the propellant must travel backward at 600 m/sec for the momentum to balance. The speed of sound is around 340 m/sec, so we hear a sonic boom as the rocket exhaust breaks the sound barrier! The effect of the sonic shock wave that forms is to reduce the speed of the propellant gas to below the speed of sound, making the rocket less efficient. Turbulent flow in the nozzle and bottle further contribute to lowering the efficiency of the rocket.

Air Friction and the Wall

We expect that the rocket will accelerate as the pressurized air leaves the nozzle. Once the air is gone, the rocket should coast, losing energy slowly to friction. Students will notice that the rocket reaches top speed fairly soon after leaving the launch tower. A good question is “how quickly does the rocket use up its fuel?”

This question can be answered easily by measuring the speed of the rocket every few centimeters along the beginning of its orbit. The rocket does indeed accelerate rapidly but there is substantial air friction that limits its speed.

SUGGESTED INVESTIGATIONS

Level A Lessons

Level A lessons are suitable for grades 5-9 and use minimal math skills.

Introduction to the Air Rocket

Have the students launch the rocket, observe and record some data at different places and pressures, and propose reasons to explain why the speed and pressure act the way they do. They will observe that the rocket

Pressure and Air

Launch the rocket at different pressures and show how pressure can store energy that is converted to motion of the rocket.

Measuring the Speed of the Rocket

Measure the speed versus distance graph for the rocket.

When Does the Rocket Run Out of Fuel?

Deduce the end of the powered flight from a change in slope on the speed versus distance graph.

Space Travel With Rockets

This is a pencil and paper experiment. Have the students calculate how long it would take a rocket to reach different places, such as the Moon, Pluto, the nearest star, and another galaxy.

Level B/C Lessons

Momentum and Rocket Propulsion

Have the students calculate the propellant velocity from momentum conservation and speed measurements. They will observe that the exhaust speed does not increase with pressure past a certain point.

Pressure, Volume, and Temperature

Have the students propose a model for the speed of the rocket as a function of the launch pressure. The model assumes that the volume times the change in pressure yields energy which is converted into kinetic energy of the rocket and propellant. Experimental observations can confirm the model, or disprove it!

Acceleration, g-Forces, and Fighter Pilots

Have the students measure the maximum acceleration and power of the rocket. Ask whether humans could survive accelerations similar to those measured

Warranty

The CPO Science warranties this instrument against defects in materials and workmanship for a period of one year. Repair and/or replacement parts can be obtained from CPO Science by sending the damaged or defective parts to us. You must call prior to shipping to obtain a return authorization number.

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