2. Boyle's Law

How Does a Trapped Gas Behave?

Objective

Students investigate the effect of changes in the volume of a confined gas on pressure at constant temperature. Using the pressure sensor, students observe simple tables or graphs and compare the change of pressure with varying volume.

Students measure the change in pressure by varying the volume of trapped air in a syringe while:

- Understanding that substances have characteristic properties, such as density, a boiling point, and solubility, all of which are independent of the amount of the sample
- Realizing that energy is a property of many gases and is associated with heat and mechanical motion
- Observing the relationship between volume of a gas and the resulting pressure in a container
- Gaining skills and confidence in using a scientific measurement tool, the pressure sensor, as well as the spreadsheet and graphing capacity of a computer to represent and analyze data

Procedural Overview

Students gain experience conducting the following procedures:

- Setting up the equipment and work area to measure the change in pressure in a syringe as the volume is changed
- Measure the pressure in a syringe while decreasing and then increasing the volume in 2-mL increments
- Using math skills to obtain a linear relationship between pressure and volume by computing the inverse of pressure and plotting the resulting values versus volume

Time Requirement

■ Introductory discussion and lab activity, Part 1 – Making predictions	25 minutes
■ Part 2 – Decreasing the volume of trapped gas	15 minutes
■ Part 3 – Increasing the volume of trapped gas	15 minutes
■ Analysis	25 minutes

Materials and Equipment

For teacher demonstration:

- ☐ Absolute pressure sensor
- ☐ Quick-release connector[1]
- ☐ Syringe (20 ml or 20 cc)
- ☐ Plastic tubing[1]
- ☐ Plastic soda bottle, 1-L
- ☐ Eyedropper
- ☐ Tap water, 10 mL
- ☐ Glass or beaker, 100-mL or tall enough to hold the eyedropper ("diver")
- ☐ Clean toilet plunger

[1] Included with PASPORT Absolute Pressure Sensor

For each student or group:

- ☐ Data collection system
- ☐ Absolute pressure sensor
- ☐ Quick-release connector[1]
- ☐ Sensor extension cable
- ☐ Syringe, 20-ml or 20-cc
- ☐ Plastic tubing[1]
- ☐ Clean toilet plunger

[1] Included with PASPORT Absolute Pressure Sensor

Concepts Students Should Already Know

Students should be familiar with the following concepts:

- Forces exerted by air result in pressure
- Because air pressure is largely invisible to our senses, it can be more difficult to comprehend than temperature, light intensity, or other more tangible phenomena occurring around us
- How to calculate the slope of a line
- The meaning of the inverse of a value, in this case the inverse of pressure
- How to find the inverse of a value
- The general form of inverse variation is the equation $y = k/x$. The product of x and y is always k
- How to plot data on a set of coordinate axes using graph paper, ruler, and pencil

Related Labs in This Guide

Labs conceptually related to this one include:

- Conservation of Matter
- Yeast Growth

Using Your Data Collection System

Students use the following technical procedures in this activity. The instructions for them are in the appendix that corresponds to your PASCO data collection system (identified by the number following the symbol: "�"). Please make copies of these instructions available for your students.

- Starting a new experiment on the data collection system �(1.2)
- Connecting a sensor to the data collection system �(2.1)
- Putting the data collection system into manual sampling mode with manually entered data. �(5.2.1)
- Recording a run of data �(6.2)
- Starting a new manually sampled data set �(6.3.1)
- Recording a data point �(6.3.2)
- Stopping a manually sampled data set �(6.3.3)
- Displaying data in a graph �(7.1.1)
- Adjusting the scale of a graph �(7.1.2)
- Saving your experiment �(11.1)

Background

Boyle's Law states that for a given amount of a gas at a fixed temperature the pressure of the gas is inversely proportional to the volume. A pressure versus volume graph of a gas at a fixed temperature will yield a negatively sloping curve. It is often helpful for the students to plot a graph of "volume versus (1/pressure)" to obtain a linear relationship. By doing this, they can calculate the slope (change in *y*/change in *x*) of the line to show that pressure times volume is a constant value.

The effect of Boyle's law is demonstrated by deep sea divers who experience decompression sickness. Commonly known as the "bends," this condition is caused by bubbles of nitrogen gas forming in the blood and tissues of the body after breathing gas at a high pressure when at great depths and then rising too quickly to the lower pressure at the surface. Just as a balloon filled with air at the surface shrinks in size when it is taken under water, due to the compressibility of the air and the pressure of the water, the air in the lungs also compresses at greater depths.

When the same balloon is returned to the surface, the balloon expands to its original volume. If a diver goes underwater, where the pressure is greater, the diver's blood can hold more nitrogen than it did before. As the diver breathes from the tank, more nitrogen gets into the blood, which becomes saturated at high-pressure levels. If the diver returns to the surface too quickly, then the air pressure is lowered quickly, and the extra nitrogen expands and comes out of the blood as bubbles.

Pre-Lab Discussion and Activity

Engage students in the following discussion or activity.

Show the class the simple Cartesian diver (refer to the "Preparation and Tips" section). Have one student apply pressure to the sides of the bottle, hold it for a few seconds, and then release the pressure.

Ask students to work in groups to discuss what happened to the eyedropper. Allow each group to operate the diver. Have students examine closely the air trapped in the eyedropper. What happens to the amount of air in the eyedropper when they press the sides of the bottle? What happens to the amount of air in the eyedropper when they release the pressure? After a few minutes, ask the students to share their thoughts with the class.

> Students should observe that pressure on the sides of the bottle causes the "diver" to sink, while releasing the pressure allows the diver to rise again. The volume of air trapped inside the eyedropper decreases when pressure is applied to the bottle and increases when the pressure is released.

Share with the class that applying pressure to the sides of the bottle increases the pressure on the water, forcing it into the dropper and reducing the volume of air in the dropper. The eyedropper becomes heavier and sinks. Releasing the pressure allows the volume to increase, forcing out some of the water. Since the eyedropper weighs less it will once again float.

Ask students to describe the relationship between the volume of the air in the eyedropper and the pressure applied on the bottle.

> Students should say that as the pressure applied to the bottle increases, the volume of air in the eyedropper decreases. As the pressure decreases, the volume of air increases.

Direct students to “Thinking about the Question.” After a few minutes, ask the groups to share some of their ideas with the class.

Demonstrate the effect of pushing the air out of a plunger. Ask students to describe the relationship between the volume of the trapped air in the plunger and the pressure needed to release it from the floor.

> Students should say that the smaller the volume of trapped air, the greater the pressure needed to release the plunger from the floor.

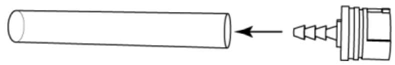
Share with the students that in science and mathematics we describe the relationship between two variables, like pressure and volume, as either “direct” or “inverse.” In a direct relationship, if one variable increases in value, the other variable also increases. In an inverse relationship, if one variable increases, the other variable decreases. Ask the students if both the Cartesian diver and the toilet plunger show a direct or inverse relationship.

Demonstrate how to prepare the absolute pressure sensor by pressing one end of the plastic tubing onto the syringe and twisting the other end of the tubing to connect to the quick-connect port of the pressure sensor (by twisting, this connection should snap into place). Direct the students to “Investigating the Question.”

Preparation and Tips

These are the materials and equipment to set up prior to the lab:

- Insert the quick-release connector into one end of the tubing for each lab group.



- Build a simple Cartesian diver with a liter plastic bottle and an eyedropper, as follows:

  a. Prepare the diver: Fill the glass or beaker with water and put the eyedropper in it. Fill the dropper so that it just barely floats – just the tip of the rubber bulb should be above water. This is the diver, which now has neutral buoyancy (it will not float up or sink down on its own). By testing for neutral buoyancy in the glass, you avoid having to retrieve the diver from the bottom of the plastic bottle if it should happen to sink.

  b. Now fill the plastic soda bottle all the way to the top with water. Avoid leaving any air between the water and the cap. Place the eyedropper into it and screw the cap on tightly. Test the Cartesian "diver" by squeezing the sides of the bottle with your hands. The diver should sink while you squeeze the bottle and float back up when you release the pressure.

  c. As you increase the pressure by squeezing the bottle, the air inside the eyedropper is compressed. This allows room for more water to enter the dropper, which you can observe as you squeeze the bottle. As more water enters, the dropper becomes heavier and sinks. Practice applying just the right amount of pressure so you can hold the diver steady in the middle of the bottle.

- Syringes often are marked in cubic centimeters (cc). These are equivalent to milliliters (mL).

Safety

Add this important safety precaution to your normal laboratory procedures:

- Wear protective goggles for this activity.

Driving Question

How does a change in volume of a confined gas affect its pressure?

Thinking about the Question

Observe a clean toilet plunger pressed against a smooth surface like the floor. It may be necessary to lightly wet the rim with a wet towel so that no more air can get under the rim once you press down on the plunger. Propose an explanation about why the plunger sticks to the floor when you gently pull it away.

Discuss with the members of your group whether the volume of the pocket of trapped air changes when you pull on the plunger. Record your thoughts below. Be prepared to share your thoughts with the class.

Air will be trapped inside the toilet plunger. As students push on the plunger, they decrease the volume of the space that the air can fill. Decreasing the volume will increase the pressure of the trapped air. It should be harder to remove the toilet plunger from the floor.

Sequencing Challenge

Note: This is an optional ancillary activity.

The steps below are part of the Procedure for this lab activity. They are not in the right order. Determine the proper order and write numbers in the circles that put the steps in the correct sequence.

5	1	3	4	2
Calculate the inverse pressure and graph inverse pressure versus volume. What is the relationship?	Make certain each lab group member is aware of safety rules and procedures for this lab.	Obtain absolute pressure data points as you decrease the volume, then begin again and increase volume.	Make a table of the pressure and volume data when decreasing the volume and when increasing the volume.	Set the initial volume of the syringe and then connect it to the pressure sensor (connected to the data collection system).

Investigating the Question

Part 1 – Making predictions

1. ☐ Predict the effect of decreasing the volume on the pressure in the syringe (as volumes go from 20 mL to 18 mL, 16 mL, 14 mL, 12 mL, 10 mL, 8 mL, and 6 mL) of the syringe. Describe and explain your prediction.

   Air will be trapped inside the syringe like the air trapped inside the toilet plunger. The pressure inside the syringe will increase as the volume decreases, because the number of air molecules will stay the same but will be squeezed more tightly together.

2. ☐ Predict the effect on pressure in the syringe of increasing the volume (from 6 mL to 8 mL, 10 mL, 12 mL, 14 mL, 16 mL, 18 mL, 20 mL) of the syringe. Describe and explain your prediction.

   Air will be trapped inside the syringe like the air trapped inside the toilet plunger. The pressure inside the syringe will decrease as the volume increases, because the number of air molecules will stay the same but the amount of space available to them will increase, and they will have to travel farther before having collisions with each other or with the walls of the syringe.

Part 2 – Decreasing the volume of trapped gas

3. ☐ Start a new experiment on the data collection system. �[1.2]

4. ☐ Put the data collection system into manual sampling mode with manually entered data. �[5.2.1]

   Note: Enter "Absolute pressure" with the units of "kPa" and "Distance" with the units of "cm", with two digits past the decimal point displayed.

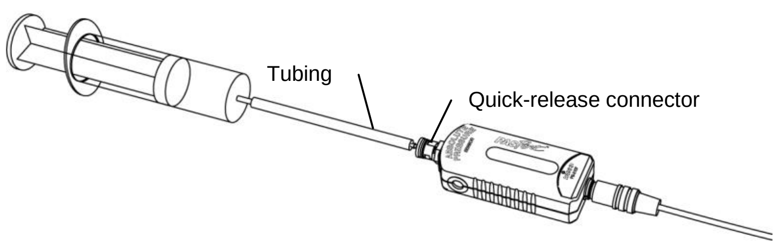
5. ☐ Use the sensor extension cable to connect an absolute pressure sensor to the data collection system. �(2.1)

   Note: The syringe should not yet be connected to the sensor.

6. ☐ Display Pressure on the y-axis of a graph with Volume on the x-axis. �(7.1.1)

7. ☐ Move the plunger of the syringe to the 20 mL mark.

8. ☐ Connect one end of the plastic tube to the syringe. Attach the other end of the tube (with the quick-release connector) to the pressure sensor by twisting until it clicks into place. Check with your teacher if you have any questions about how to connect this system properly.



9. ☐ Start a new manually sampled data set. �(6.3.1)

10. ☐ Move the plunger to the 18 mL mark. Record this data point. �(6.3.2)

11. ☐ Move the plunger to the 16 mL mark. Record this data point (both pressure and volume). �(6.3.2).

12. ☐ Move the plunger to the 14 mL mark. Record this data point �(6.3.2)

13. ☐ Move the plunger to the 12 mL mark. Record this data point �(6.3.2)

14. ☐ Continue recording data points as you decrease the volume in the syringe by 2 mL increments, until you reach a volume of 6 mL.

15. ☐ When you have recorded all of your data, stop the data set. �(6.3.3)

Part 3 – Increasing the volume of trapped gas

16. ☐ Disconnect the tube from the pressure sensor.

17. ☐ Move the plunger of the syringe to the 2 mL mark.

18. ☐ Display a new graph with Pressure on the y-axis and Time on the x-axis. �(7.1.1)

19. ☐ Reconnect the tube to the pressure sensor.

20. ☐ Start a new manually sampled data set. �(6.3.1)

21. ☐ With the plunger at 2 mL, record this data point �(6.3.2)

22. ☐ Move the plunger to the 4 mL mark. Record this data point �(6.3.2)

23. ☐ Move the plunger to the 6 mL mark. Record this data point �(6.3.2)

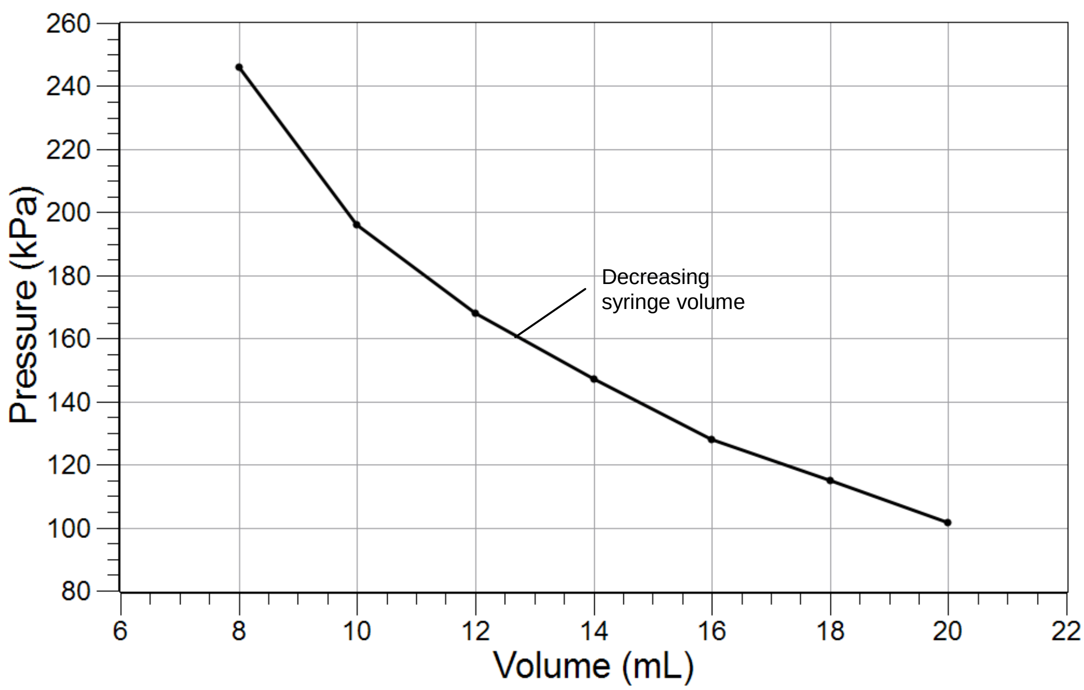
24. ☐ Move the plunger to the 8 mL mark. Record this data point �(6.3.2)

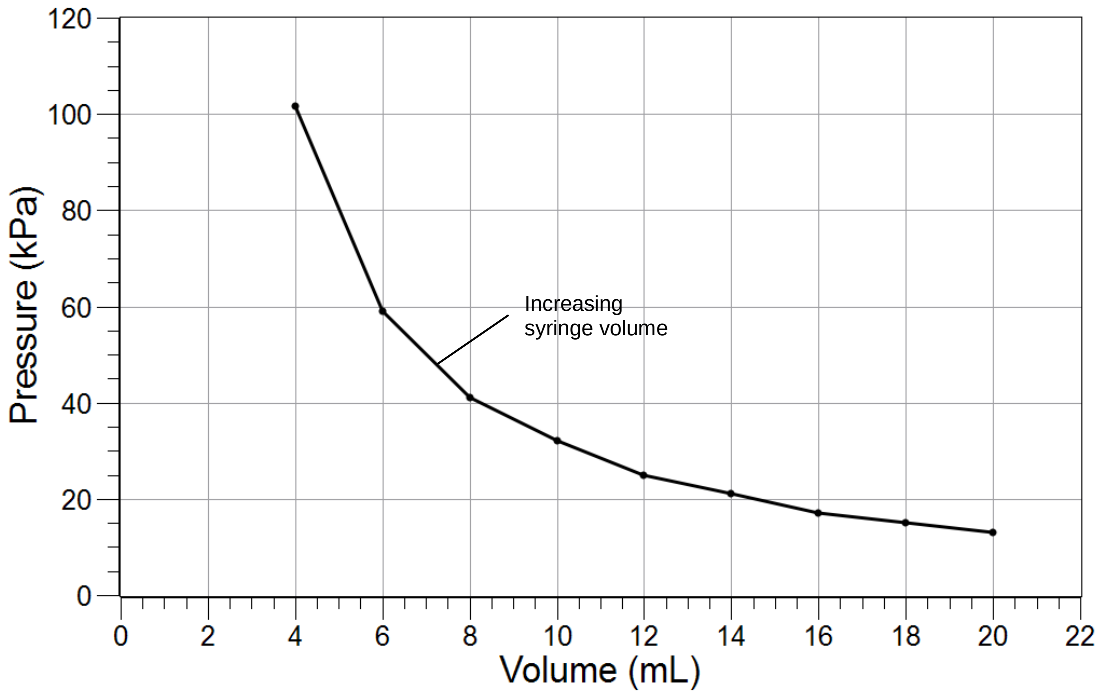
25. ☐ Continue recording data points as you increase the volume in the syringe by 2 mL increments, until you reach a volume of 20 mL.

26. ☐ Stop data recording. �(6.3.3)

27. ☐ Save your experiment �(11.1) and clean up according to your teacher's instructions.

Sample Data





Answering the Question

1. What type of relationship did you see when you decreased the volume of trapped air?

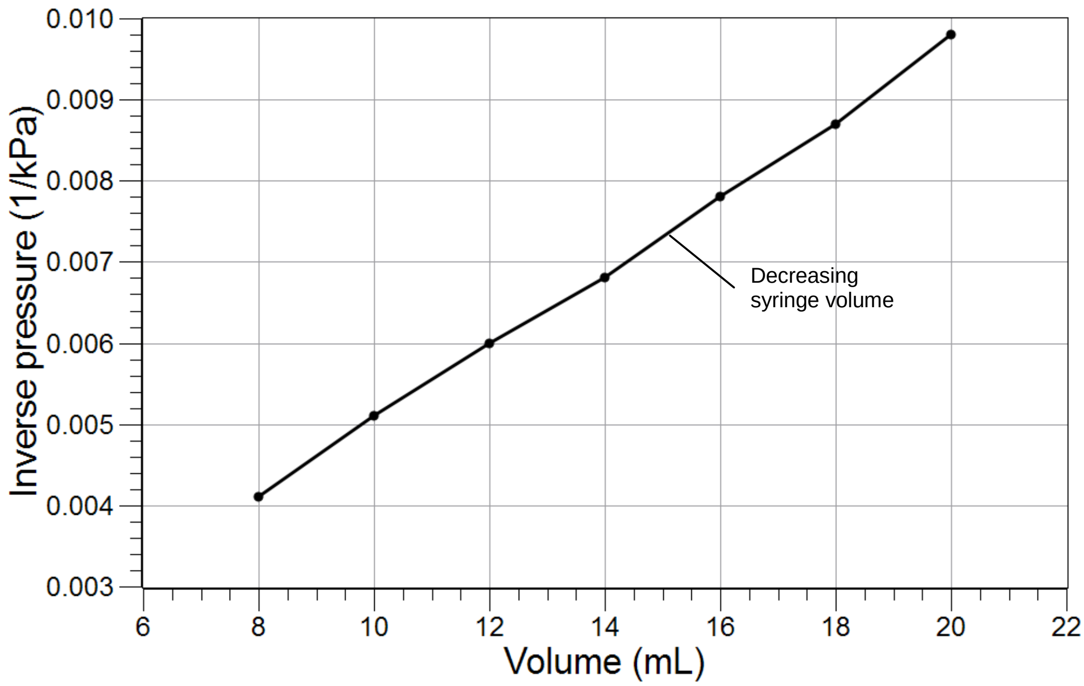
   As the volume decreased, the pressure increased. The graph of pressure versus volume is a curve sloping downward.

2. Using data from the first data run when decreasing the volume of trapped gas, complete Table 1. Calculate the value of 1/Pressure for each volume.

Table 1: Pressure with decreasing volume

Decreasing Volume (mL)	Pressure (kPa)	1/Pressure (kPa^{-1})
20	101.7	0.0098
18	115	0.0087
16	128	0.0078
14	147	0.0068
12	168	0.0060
10	196	0.0051
8	246	0.0041

3. Graph 1/Pressure versus Volume using the data in Table 1.



4. Does the graph show a direct or an inverse relationship? Explain your reasoning.

   The graph shows an inverse relationship, since the 1/Pressure versus Volume graph results in a straight line sloping upward.

5. What type of relationship did you see when you increased the volume of trapped air?

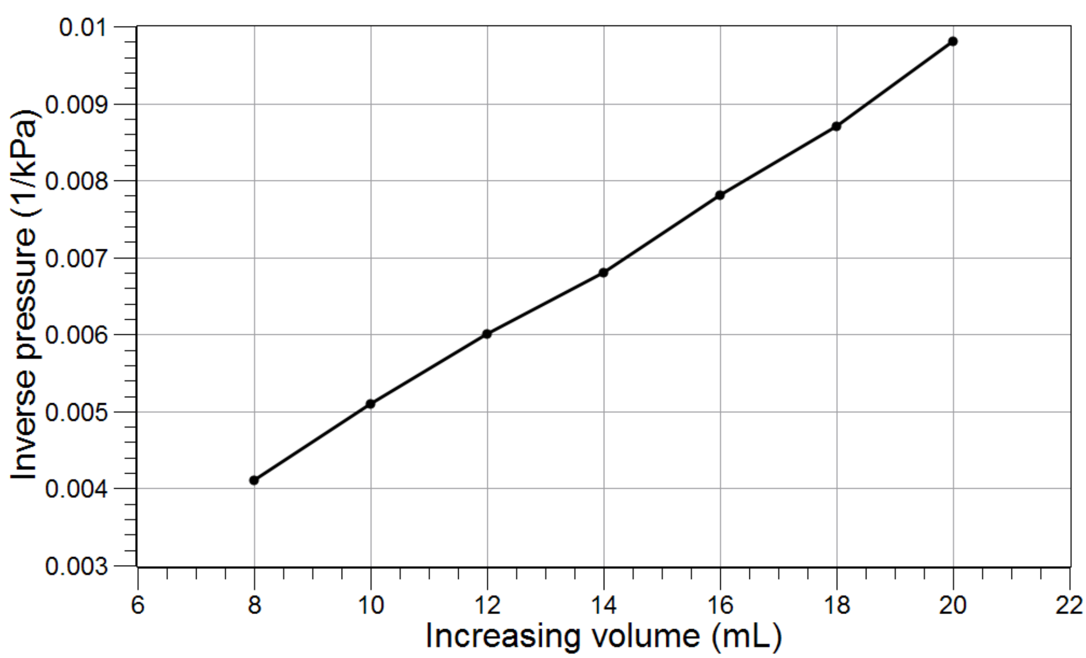
   As the volume increased the pressure decreased. The graph of pressure versus volume is a curve sloping downward.

6. Using data from your second graph, when increasing the syringe volume, complete Table 2. Calculate the value of 1/Pressure for each volume.

Table 2: Pressure with increasing volume

Increasing Volume (mL)	Pressure (kPa)	1/Pressure (kPa^{-1})
4	101.7	0.0098
6	59	0.017
8	41	0.024
10	32	0.031
12	25	0.040
14	21	0.048
16	17	0.059
18	15	0.067
20	13	0.077

7. Graph 1/Pressure versus Volume using the data in Table 2.



8. Did the graph show a direct or an inverse relationship? Explain your reasoning.

The relationship is inverse based on the 1/P versus V graph resulting in a straight line.

9. Describe the similarities and differences for both 1/Pressure versus Volume graphs.

   Both graphs show straight lines with a positive slope, indicating there is an inverse relationship between pressure and volume.

10. Explain how the graphs display Boyle's Law. Be prepared to share your thoughts with the class.

   Boyle's Law states that for a given amount of a gas at a fixed temperature the pressure of the gas is inversely proportional to the volume. By plotting a 1/Pressure versus Volume graph, a linear relationship results. The slope (the change of y compared to the change in x) of the line shows that Pressure times Volume is a constant value.

True or False

Enter a "T" if the statement is true or an "F" if it is false.

___T___ 1. Collisions between air molecules and the walls of their container create pressure.

___F___ 2. There is a direct relationship between the volume of a gas and its pressure, when the gas is held at a constant temperature.

___F___ 3. In the SI system, pressure is measured in units called newtons.

___F___ 4. The graph of increasing volume versus increasing pressure is a straight line.

___T___ 5. The inverse of a number is equal to one divided by the number.

Multiple Choice

Circle the best answer or completion to each of the questions or incomplete statements below.

1. Which is the best way to characterize an inverse relationship?

   A. As one quantity decreases, the other quantity decreases at the same rate.
   B. As one quantity increases, the other quantity decreases proportionally.
   C. As one quantity increases, the other quantity undergoes a random change.

2. Air molecules confined in a closed volume undergo more collisions when that volume:

   A. Decreases
   B. Increases
   C. Is chilled by at least 10 degrees Celsius

3. The inverse of 4.0 is equal to:

   A. 40.0
   B. 1.0
   C. 0.25

4. Suppose you are given a closed air-tight container that holds a particular gas at room temperature. You then squeeze the container and put a big dent in it. Which of the following is *not* true about the gas inside the dented container?

   A. There is less room for the gas molecules that are sealed inside the container.
   B. There are exactly as many gas molecules now as there were before you dented the container.
   C. The pressure of the gas has remained the same as it was before you dented the container.

5. The relationship between the volume of a gas and its pressure can be seen in which example?

   A. The adhesive used to glue labels onto containers
   B. A suction cup used to attach something to a wall
   C. An empty balloon waiting to be inflated with helium gas

Further Investigations

Does multiplying pressure times volume in the data collected result in a constant? What could be the cause of any variation?

Marshmallows are mostly sugar and water wrapped around a bunch of air bubbles. Place several miniature marshmallows inside a syringe. Predict the affect on the marshmallows as the volume of trapped gas in the syringe is changed. Test your prediction.

Often when you are given bags of chips and snacks on airplanes, the bags are fully inflated. Design and perform an investigation that will use the pressure sensor to show changes of volumes of trapped gases at different altitudes

Rubric

Rubric focuses on successfully performing the scientific process, collecting and displaying data, understanding the concepts, and communicating conclusions.