AP2 Thermal Physics

A canister of pressurized nitrogen gas at room temperature is cooled in a freezer. More nitrogen gas at room temperature is pumped into the canister until the canister returns to its initial pressure. The sealed canister is then returned to room temperature. A measurement of the pressure in the canister shows that the pressure in the canister is now twice its initial value.

Was more gas initially in the canister than was added?
(A) Yes
(B) No
(C) The amount of gas added to the canister is equal to the amount initially in the canister
(D) Not enough information is given

Answer: C

In order to answer this question, you only need to examine the initial and final conditions of the canister. Initially, the canister exhibited some pressure P. In its final condition, the gas has the same volume and temperature, but twice the pressure. If it has twice the pressure at the same volume and temperature, it must have twice the gas according to the ideal gas law PV=nRT, therefore the amount of gas in the canister was doubled, so the same amount of gas must have been added to the canister as was initially in the canister.

EK: 7.A.3 In an ideal gas, the macroscopic (average) pressure (P), temperature (T), and volume (V), are related by the equation PV = nRT.

SP: 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

LO: 7.A.3.2 The student is able to design a plan for collecting data to determine the relationships between pressure, volume, and temperature, and amount of an ideal gas, and to refine a scientific question concerning a proposed incorrect relationship between the variables.

AP2 Thermal Physics

A refrigerator is placed in a room which is completely sealed except for a working electrical outlet. The refrigerator is plugged in, and the door of the refrigerator is opened. Does the temperature in the room increase, decrease, or remain the same? Justify your answer.

Answer: The temperature in the room increases. From an energy perspective, energy is entering the room through the electrical outlet, but it is not exiting the room. This energy accumulation will result in an increase in the room's temperature.

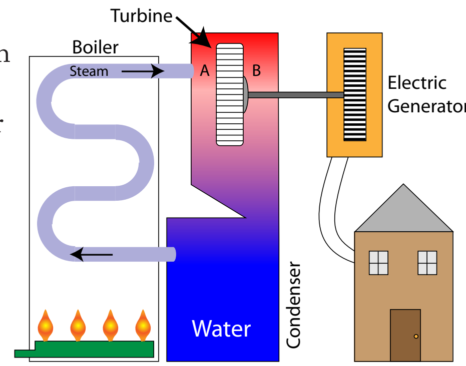
EK: 5.B.7 The first law of thermodynamics is a specific case of the law of conservation of energy involving the internal energy of a system and the possible transfer of energy through work and/or heat.

SP: 6.1 The student can justify claims with evidence. 7.1 The student can connect phenomena and models across spatial and temporal scales.

LO: 5.B.7.1 The student is able to predict qualitative changes in the internal energy of a thermodynamic system involving transfer of energy due to heat or work done and justify those predictions in terms of conservation of energy principles.

AP2 Thermal Physics

A power plant runs by means of a boiler used to vaporize water, turning a steam turbine which turns an electric generator, moving a coil of wire through a magnetic field to create electricity, as shown in the diagram.



(a) Is the water vapor at position A (prior to striking the turbine) warmer than, cooler than, or the same temperature as the water vapor after it has struck the turbine at position B? Justify your answer.

_____ Warmer Than _____ Same
_____ Cooler Than _____ More Information Needed

(b) Assume you want to examine the efficiency of your power plant as a total system. Draw a dashed line encompassing the system you would examine.

(c) Is the amount of electrical energy delivered to the house greater than, less than, or the same as the amount of thermal energy generated by burning the fuel in the boiler? Justify your answer.

_____ Greater Than _____ Same
_____ Less Than _____ More Information Needed

(d) Is the kinetic energy of the spinning turbine greater than, less than, or equal to the kinetic energy of the electric generator? Justify your answer.

_____ Greater Than _____ Same
_____ Less Than _____ More Information Needed

(e) Is the average velocity of the water vapor molecules prior to hitting the turbine greater than, less than, or the same as the average velocity of the water vapor molecules after hitting the turbine? Justify your answer.

_____ Greater Than _____ Same
_____ Less Than _____ More Information Needed

Answers:

(a) Warmer Than. As the water vapor molecules strike the turbine and transfer a portion of their momentum and energy to the turbine, they slow down, reducing their average temperature.
(b) Dashed line should encompass everything except the powerlines and house.
(c) Less Than. The system cannot be 100% efficient.
(d) More Information Needed. Even if you assume they rotate at the same speed (which may not be the case due to gearing assemblies), you do not know the rotational inertia of either the turbine or electric generator.
(e) Greater Than. The water vapor molecules slow down upon hitting the turbine, transfering a portion of their momentum and energy to the turbine.

EK: 7.A.2 The temperature of a system characterizes the average kinetic energy of its molecules. 4.C.3 Energy is transferred spontaneously from a higher temperature system to a lower temperature system. The process through which energy is transferred between systems at different temperatures is called heat. 5.B.5 Energy can be transferred by an external force exerted on an object or system that moves the object or system through a distance; this energy transfer is called work. Energy transfer in mechanical or electrical systems may occur at different rates. Power is defined as the rate of energy transfer into, out of, or within a system.

SP: 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 3.3 The student can evaluate scientific questions. 6.1 The student can justify claims with evidence. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

LO: 7.A.2.1 The student is able to qualitatively connect the average of all kinetic energies of molecules in a system to the temperature of the system. 4.C.3.1 The student is able to make predictions about the direction of energy transfer due to temperature differences based on interactions at the microscopic level. 5.B.5.4 The student is able to make claims about the interaction between a system and its environment in which the environment exerts a force on the system, thus doing work on the system and changing the energy of the system (kinetic energy plus potential energy).

AP2 Thermal Physics

An ice cube is placed in a cup of hot coffee. After a period of time, the ice cube melts. Which of the following best explains why the coffee becomes cooler? Select the two best answers.

(A) The ice absorbs energy from the coffee as heat travels from the warmer to cooler material.
(B) The cool molecules in the ice radiate energy which is absorbed by the warmer molecules of the coffee.
(C) As the ice melts in the water, the cooler water molecules diffuse through the warmer coffee, lowering the average kinetic energy of the drink.
(D) The hot molecules in the coffee slow down as they are absorbed by the ice cube, causing the ice cube to melt.

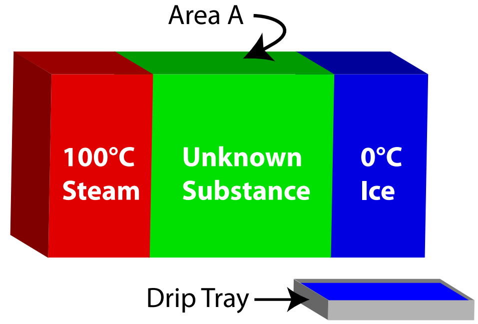
Answers: (A) and (C). The ice absorbs energy from the coffee as heat travels from the warmer to cooler material. As the ice melts in the water, the cooler water molecules diffuse through the warmer coffee, lowering the average kinetic energy of the drink.

EK: 4.C.3 Energy is transferred spontaneously from a higher temperature system to a lower temperature system. The process through which energy is transferred between systems at different temperatures is called heat. During average collisions between molecules, kinetic energy is transferred from faster molecules to slower molecules. 5.B.6 Energy can be transferred by thermal processes involving differences in temperature; the amount of energy transferred in this process of transfer is called heat.

SP: 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 6.5 The student can evaluate alternative scientific explanations.

LO: 4.C.3.1 The student is able to make predictions about the direction of energy transfer due to temperature differences based on interactions at the microscopic level. 5.B.6.1 The student is able to describe the models that represent processes by which energy can be transferred between a system and its environment because of differences in temperature: conduction, convection, and radiation.

AP2 Thermal Physics



Students design an experiment to determine the thermal conductivity (k) of an unknown substance. A cube of the material to be tested with side area A is clamped to a steam chamber on one side, which maintains a constant temperature of 100°C, and a block of ice on the other side, which maintains a constant temperature of 0°C, for a difference in temperature from one side to the other of ΔT=100°C. The heat transferred is determined by finding the mass of water melted from ice, M_w, in time t.

(a) Express the thermal conductivity of the substance as a function of the side area of the substance A, the latent heat of fusion of ice L_f, the mass of the melted water M_w, the time over which the water is collected t, and ΔT.

In ambient conditions, without the steam chamber attached, one gram of water is collected every 10 minutes. With the steam chamber attached, 5 grams of water are melted in 10 minutes. Ice has a latent heat of fusion (latent heat of melting) of L_f = 334 J/g. The unknown substance has a side length of 10 cm.

(b) Determine the thermal conductivity of the unknown substance.

Answers:

(a) $H = \frac{Q}{\Delta t} = \frac{kA\Delta T}{L} \xrightarrow[A=L^2 \rightarrow L=\sqrt{A}]{Q=M_w L_f} k = \frac{M_w L_f \sqrt{A}}{A \Delta t \Delta T} = \frac{M_w L_f}{\sqrt{A} \Delta t \Delta T}$

(b) $k = \frac{(4g)(334\,{}^{J}\!/\!_{g})}{(0.1m)(600s)(100K)} = 0.223\,{}^{J}\!/\!_{s \cdot m \cdot K}$

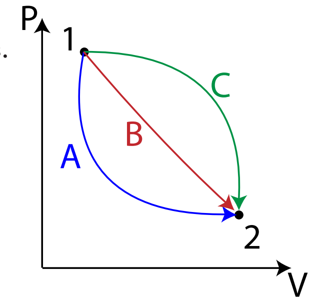
EK: 1.E.3 Matter has a property called thermal conductivity. 5.B.6 Energy can be transferred by thermal processes involving differences in temperature; the amount of energy transferred in this process of transfer is called heat.

SP: 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 4.4 The student can evaluate sources of data to answer a particular scientific question.

LO: 1.E.3.1 The student is able to design an experiment and analyze data from it to examine thermal conductivity. 5.B.6.1 The student is able to describe the models that represent processes by which energy can be transferred between a system and its environment because of differences in temperature: conduction, convection, and radiation.

AP2 Thermal Physics

An ideal gas can move from state 1 to state 2 on a PV diagram by a variety of different pathways. Which of the following are the same regardless of pathway? Select two answers.



(A) The work done on the gas.
(B) The heat added to the gas.
(C) The change in average kinetic energy of the gas molecules.
(D) The change in the temperature of the gas.

Answers: (C) and (D). The change in average kinetic energy of the gas molecules and the change in the temperature of the gas. The temperature of the gas depends on the point on the PV diagram, and is independent of the path taken. As the temperature is related to the average kinetic energy of the molecules of the gas, the average kinetic energy of the gas molecules must also be path independent.

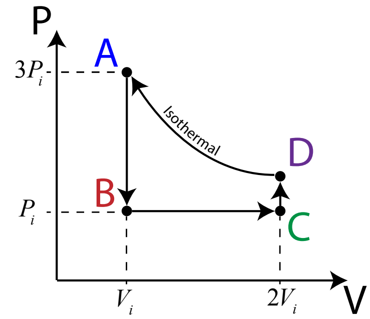
EK: 5.B.7 The first law of thermodynamics is a specific case of the law of conservation of energy involving the internal energy of a system and the possible transfer of energy through work and/or heat. 7.A.2 The temperature of a system characterizes the average kinetic energy of its molecules.

SP: 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

LO: 5.B.7.3 The student is able to use a plot of pressure versus volume for a thermodynamic process to make calculations of internal energy changes, heat, or work, based upon conservation of energy principles (i.e., the first law of thermodynamics). 7.A.2.1 The student is able to qualitatively connect the average of all kinetic energies of molecules in a system to the temperature of the system.

AP2 Thermal Physics

A set amount of an ideal gas is taken through a thermodynamic cycle as shown in the PV diagram at right (not drawn to scale). Process DA is isothermal.



(a) Find the temperature at point C (T_C) in terms of the temperature at point B (T_B).

(b) Find the pressure at point D (P_D) in terms of P_i.

(c) Find the work done by the gas in moving from State A to State B to State C in terms of P_i and V_i.

(d) In which process or processes is heat taken from the gas? Explain.

Answers:

(a) The pressure at Point B is the same at the pressure at Point C, which is equal to P_i, therefore the ratio of the temperatures to the volumes at B and C must be equal:

$$P_B = P_C \rightarrow \frac{T_B}{V_B} = \frac{T_C}{V_C} \rightarrow T_C = \frac{V_C T_B}{V_B} = \frac{2V_i T_B}{V_i} = 2T_B$$

(b) Since Points A and D are on an isothermal line, they have the same temperature, so the product of their pressure and volume must be equal:

$$T_A = T_D \rightarrow P_A V_A = P_D V_D \rightarrow 3P_i V_i = P_D (2V_i) \rightarrow P_D = \tfrac{3}{2} P_i$$

(c) Work is the area under the graph, which is $P_i(2V_i - V_i) = P_i V_i$

AB and DA. Examine each path separately:

AB: ΔU=Q+W, but W=0, so ΔU=Q. Temperature decreases from A to B, so ΔU must be negative, therefore Q must be negative. This implies that heat is taken from the gas.

BC: The gas is expanding so W is negative, and temperatureis increasing, so ΔU is increasing while W is negative, therefore Q must be positive, therefore heat is added to the gas.

CD: ΔU=Q+W, but W=0, so ΔU=Q. Temperature increases from C to D so Q is positive, therefore heat is added to the gas.

DA: ΔU is zero because DA is an isotherm, therefore Q=-W. The gas is compressed, so W is positive, therefore Q must be negative, indicating that heat is taken from the gas.

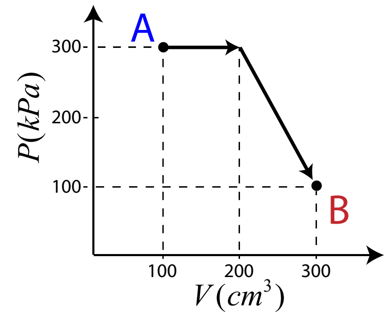
EK: 5.B.7 The first law of thermodynamics is a specific case of the law of conservation of energy involving the internal energy of a system and the possible transfer of energy through work and/or heat.

SP: 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

LO: 5.B.7.1 The student is able to predict qualitative changes in the internal energy of a thermodynamic system involving transfer of energy due to heat or work done and justify those predictions in terms of conservation of energy principles. 5.B.7.3 The student is able to use a plot of pressure versus volume for a thermodynamic process to make calculations of internal energy changes, heat, or work, based upon conservation of energy principles (i.e., the first law of thermodynamics).

AP2 Thermal Physics

An ideal gas moves from State A to State B following the path depicted in the PV diagram at right. How much work was done **on** the gas during this process?



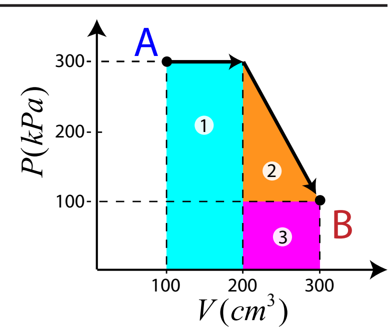
Answer: -50 J. The gas is expanding, therefore the gas is doing work. The answer to the question asked, then, how much work was done on the gas, must be negative. You can find the work done by taking the area under the graph, breaking the graph up into geometric shapes, as shown at right.

$$A_1 = lw = (1\times10^{-4}\,m^3)(300{,}000\,Pa) = 30J$$

$$A_2 = \tfrac{1}{2}bh = \tfrac{1}{2}(1\times10^{-4}\,m^3)(200{,}000\,Pa) = 10J$$

$$A_3 = lw = (1\times10^{-4}\,m^3)(100{,}000\,Pa) = 10J$$

$$W_{total} = -(A_1 + A_2 + A_3) = -50J$$



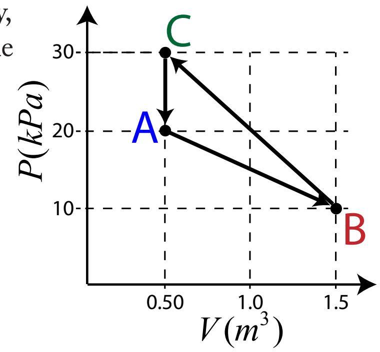
EK: 5.B.7 The first law of thermodynamics is a specific case of the law of conservation of energy involving the internal energy of a system and the possible transfer of energy through work and/or heat.

SP: 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

LO: 5.B.7.3 The student is able to use a plot of pressure versus volume for a thermodynamic process to make calculations of internal energy changes, heat, or work, based upon conservation of energy principles (i.e., the first law of thermodynamics).

AP2 Thermal Physics

A cylinder filled with an ideal gas is fitted with a movable frictionless piston. Initially, the gas is in state A at 20 kPa, 400K, and 0.5 m^3. The gas is taken through a reversible thermodynamic cycle as shown in the PV diagram at right (not drawn to scale).



(a) Determine how many moles of gas are in the cylinder.

(b) Calculate the temperature of the gas at the following states:

i. State B

ii. State C

(c) Determine the net work done on the gas during the cycle.

(d) Explain whether heat was added to the gas or removed from the gas during the cycle. Justify your answer.

AP2 Thermal Physics

Answers:

(a) At State A, T=400K, so you can use the ideal gas law to solve for the number of moles of gas:

$$PV = nRT \rightarrow n = \frac{PV}{RT} = \frac{(20{,}000Pa)(0.5m^3)}{(8.31 \tfrac{J}{mol \cdot K})(400K)} = 3.0\ moles$$

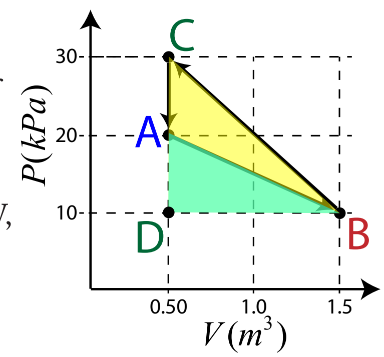
(b) Knowing the quantity of the gas, these become straightforward ideal gas law applications:

$$T_B = \frac{P_B V_B}{nR} = \frac{(10{,}000Pa)(1.5m^3)}{(3.0mol)(8.31 \tfrac{J}{mol \cdot K})} = 600K$$

$$T_C = \frac{P_C V_C}{nR} = \frac{(30{,}000Pa)(0.5m^3)}{(3.0mol)(8.31 \tfrac{J}{mol \cdot K})} = 600K$$

(c) The net work done on the gas is the area enclosed by triangle ABC, and is positive as the gas cycle is counter-clockwise. You can determine the area of triangle ABC by finding the area of triangle BCD and subtracting the area of triangle ABD as shown at right.

$$A_{BCD} - A_{ABD} = \tfrac{1}{2}(1m^3)(20{,}000Pa) - \tfrac{1}{2}(1m^3)(10{,}000Pa) = 5000J$$



(d) The work done on the gas is positive, and in a complete cycle ΔU=0, so Q=-W, therefore Q must have the opposite sign of W, and must be negative, indicating that **heat was removed** from the gas.

EK: 5.B.7 The first law of thermodynamics is a specific case of the law of conservation of energy involving the internal energy of a system and the possible transfer of energy through work and/or heat. 7.A.3 In an ideal gas, the macroscopic (average) pressure (P), temperature (T), and volume (V), are related by the equation PV = nRT.

SP: 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

LO: 5.B.7.1 The student is able to predict qualitative changes in the internal energy of a thermodynamic system involving transfer of energy due to heat or work done and justify those predictions in terms of conservation of energy principles. 5.B.7.3 The student is able to use a plot of pressure versus volume for a thermodynamic process to make calculations of internal energy changes, heat, or work, based upon conservation of energy principles (i.e., the first law of thermodynamics). 7.A.3.3 The student is able to analyze graphical representations of macroscopic variables for an ideal gas to determine the relationships between these variables and to ultimately determine the ideal gas law PV = nRT.

AP2 Thermal Physics

Absolute zero is the theoretical extrapolation of a volume-temperature plot for an ideal gas when the pressure becomes zero. Practically, you cannot reach absolute zero with an ideal gas because at very low temperatures, gases liquify. It is also challenging in a basic lab setting to adjust the volume of an ideal gas. However, by extrapolating the Pressure-Temperature plot of an ideal gas kept at a constant volume, you can arrive at a good approximation of absolute zero.

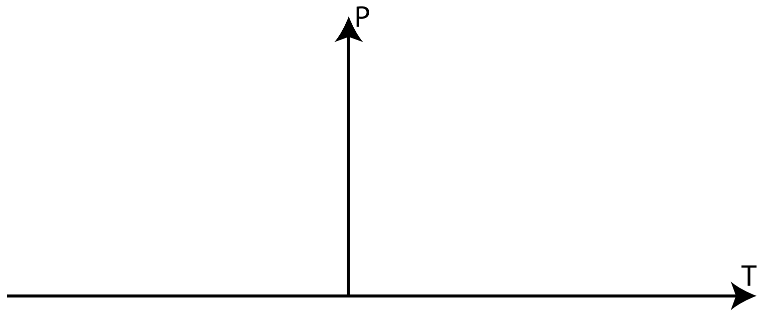
Students are presented with an enclosed sample of an ideal gas inside a closed 100 cm^3 container.

(a) What data would you need to collect in order to approximate absolute zero? Justify your answer.

(b) Describe the equipment you would need to undertake this experiment. You may assume that probes can be placed into the container of gas without affecting the gas or its characteristics.

(c) Design a plan for collecting this data.

(d) Sketch an approximation of what you expect your best-fit line to look like on the axes below. Indicate the portions of the graph where you anticipate gathering actual data, and portions of the graph where your line must be extrapolated.



(e) How can you determine the quantity of gas in the container from your graph?

(f) How can you determine absolute zero from your graph?

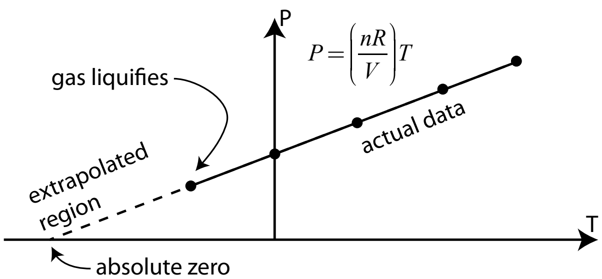
Answers:

(a) You would need to collect data on the pressure of the gas at varying temperatures in order to create the Pressure-Temperature plot.

(b) A digital thermometer to measure the temperature of the ideal gas inside the container, and a pressure gauge to measure the pressure inside the container would be required. In addition, you would need a means of adjusting the temperature of the gas inside the container (heating / cooling equipment of some sort).

(c) Starting at the minimum or maximum available temperature, read and record the pressure inside the container. Adjust the temperature and repeat until you reach the limits of the equipment and/or the gas liquifies.

(d)



(e) The slope of your line is equal to nR/V, therefore you can determine the number of moles of gas by rearranging for n such that n=slope*V/R.

(f) Absolute zero can be found at the x-intercept of your P-T plot as shown above.

EK: 7.A.3 In an ideal gas, the macroscopic (average) pressure (P), temperature (T), and volume (V), are related by the equation PV = nRT.

SP: 2.1 The student can justify the selection of a mathematical routine to solve problems. 3.3 The student can evaluate scientific questions. 4.1 The student can justify the selection of the kind of data needed to answer a particular scientific question. 4.2 The student can design a plan for collecting data to answer a particular scientific question. 5.3 The student can evaluate the evidence provided by data sets in relation to a particular scientific question. 6.1 The student can justify claims with evidence. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

LO: 7.A.3.1 The student is able to extrapolate from pressure and temperature or volume and temperature data to make the prediction that there is a temperature at which the pressure or volume extrapolates to zero. 7.A.3.2 The student is able to design a plan for collecting data to determine the relationships between pressure, volume, and temperature, and amount of an ideal gas, and to refine a scientific question concerning a proposed incorrect relationship between the variables.