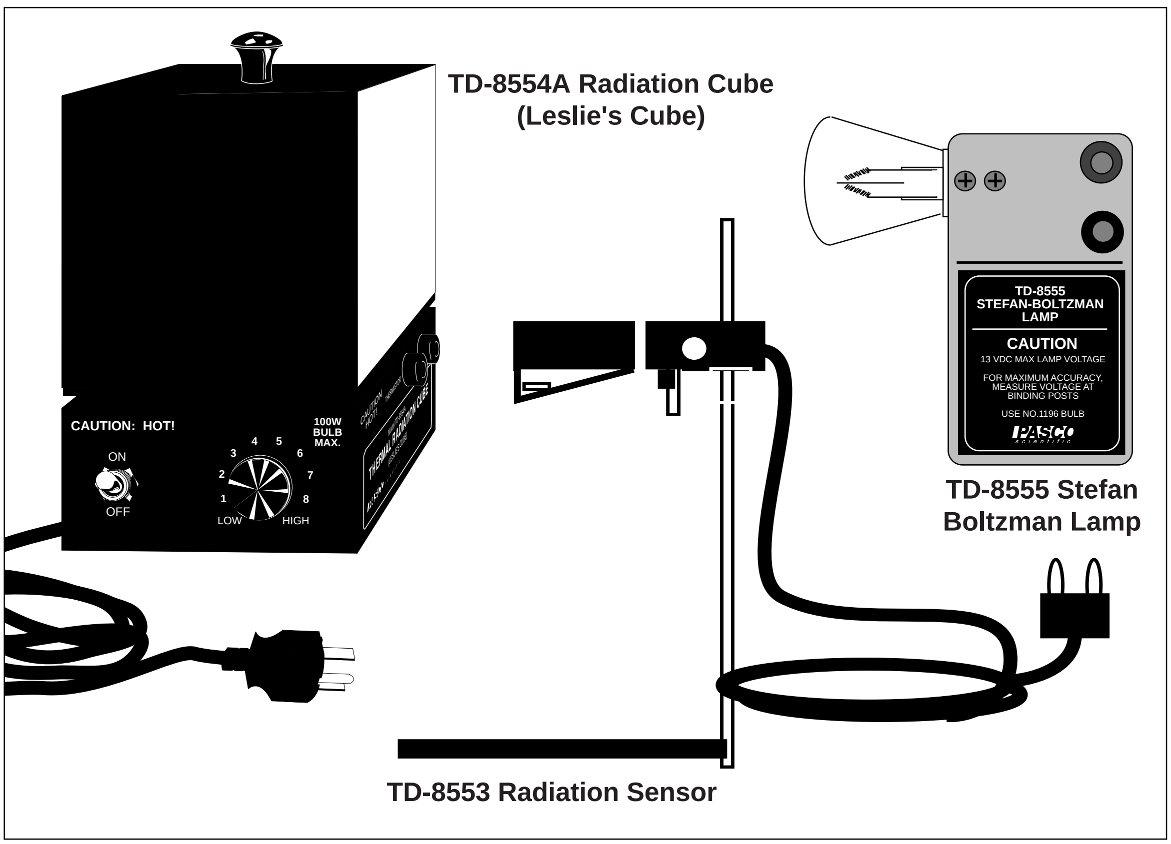
Includes Teacher's Notes and Typical Experiment Results

Instruction Manual and Experiment Guide for the PASCO scientific Model TD-8553/8554A/8555

012-04695D

03/99

THERMAL RADIATION SYSTEM



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Introduction

The PASCO Thermal Radiation System includes three items: the TD-8553 Radiation Sensor, the TD-8554A Radiation Cube (Leslie's Cube), and the TD-8555 Stefan-Boltzmann Lamp. This manual contains operating instructions for each of these items plus instructions and worksheets for the following four experiments:

① Introduction to Thermal Radiation,

② Inverse Square Law,

③ Stefan-Boltzmann Law* (at high temperatures),

④ Stefan-Boltzmann Law* (at low temperatures).

* The Stefan-Boltzmann law states that the radiant energy per unit area is proportional to the fourth power of the temperature of the radiating surface.

In addition to the equipment in the radiation system, several standard laboratory items, such as power supplies and meters are needed for most experiments. Check the experiment section of this manual for information on required equipment.

If you don't have all the items of the radiation system, read through the operating instructions for the equipment you do have, then check the experiment section to determine which of the experiments you can perform. (A radiation sensor is required for all the experiments.)

Radiation Sensor

The PASCO TD-8553 Radiation Sensor (Figure 1) measures the relative intensities of incident thermal radiation. The sensing element, a miniature thermopile, produces a voltage proportional to the intensity of the radiation. The spectral response of the thermopile is essentially flat in the infrared region (from 0.5 to 40 µm), and the voltages produced range from the microvolt range up to around 100 millivolts. (A good millivolt meter is sufficient for all the experiments described in this manual. See the current PASCO catalog for recommended meters.)

The Sensor can be hand held or mounted on its stand for more accurate positioning. A spring-clip shutter is opened and closed by sliding the shutter ring forward or back. During experiments, the shutter should be closed when measurements are not actively being taken. This helps reduce temperature shifts in the thermopile reference junction which can cause the sensor response to drift.

➤ **NOTE:** When opening and closing the shutter, it is possible you may inadvertently change the sensor position. Therefore, for experiments in which the sensor position is critical, such as Experiment 3, two small sheets of opaque insulating foam have been provided. Place this heat shield in front of the sensor when measurements are not actively being taken.

The two posts extending from the front end of the Sensor protect the thermopile and also provide a reference for positioning the sensor a repeatable distance from a radiation source.

Specifications

Temperature Range: -65 to 85 °C.
Maximum Incident Power: 0.1 Watts/cm^2.
Spectral Response: .6 to 30µm.
Signal Output: Linear from 10^{-6} to 10^{-1} Watts/cm^2.

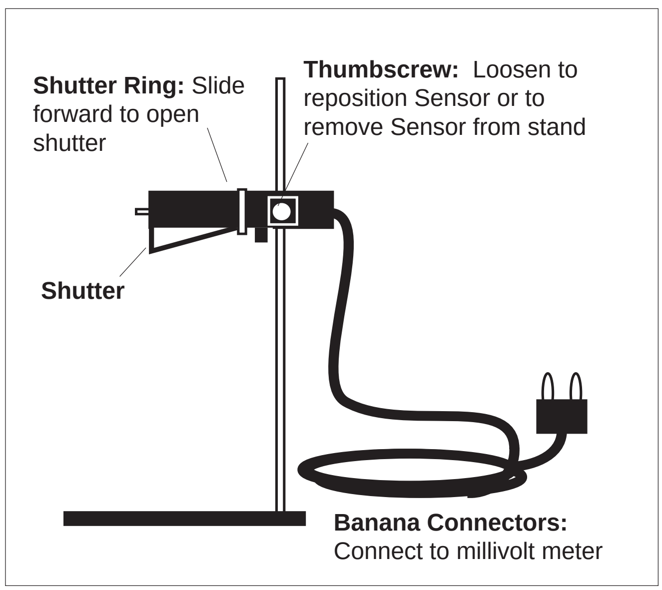


Figure 1 Radiation Sensor

Thermal Radiation Cube (Leslie's Cube)

The TD-8554A Radiation Cube (Figure 2) provides four different radiating surfaces that can be heated from room temperature to approximately 120 °C. The cube is heated by a 100 watt light bulb. Just plug in the power cord, flip the toggle switch to “ON”, then turn the knob clockwise to vary the power.

Measure the cube temperature by plugging your ohmmeter into the banana plug connectors labeled THERMISTOR. The thermistor is embedded in one corner of the cube. Measure the resistance, then use Table 1, below, to translate the resistance reading into a temperature measurement. An abbreviated version of this table is printed on the base of the Radiation Cube.

➤ **NOTE:** For best results, a digital ohmmeter should be used. (See the current PASCO catalog for recommended meters.)

➤ **IMPORTANT:** When replacing the light bulb, use a 100-Watt bulb. Bulbs of higher power could damage the cube.

CAUTION: Cube may be HOT!

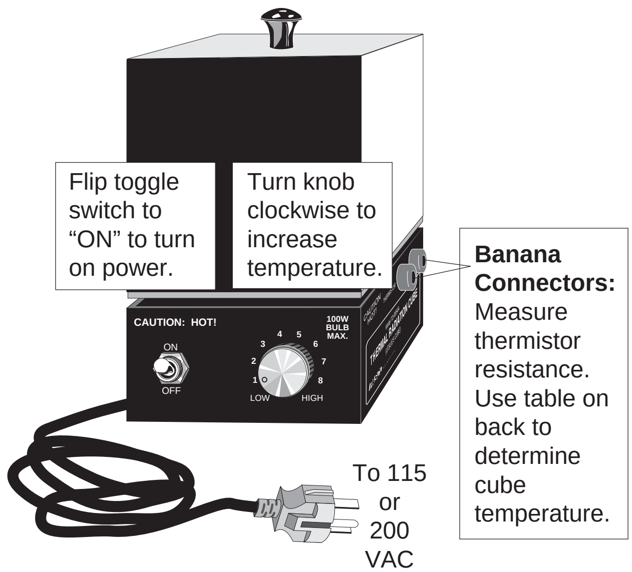


Figure 2 Radiation Cube (Leslie's Cube)

Table 1

Resistance versus Temperature for the Thermal Radiation Cube

Therm. Res. (Ω)	Temp. (°C)	Therm. Res. (Ω)	Temp. (°C)	Therm. Res. (Ω)	Temp. (°C)	Therm. Res. (Ω)	Temp. (°C)	Therm. Res. (Ω)	Temp. (°C)	Therm. Res. (Ω)	Temp. (°C)
207,850	10	66,356	34	24,415	58	10,110	82	4,615.1	106	2,281.0	130
197,560	11	63,480	35	23,483	59	9,767.2	83	4,475.0	107	2,218.3	131
187,840	12	60,743	36	22,590	60	9,437.7	84	4,339.7	108	2,157.6	132
178,650	13	58,138	37	21,736	61	9,120.8	85	4,209.1	109	2,098.7	133
169,950	14	55,658	38	20,919	62	8,816.0	86	4,082.9	110	2,041.7	134
161,730	15	53,297	39	20,136	63	8,522.7	87	3,961.1	111	1,986.4	135
153,950	16	51,048	40	19,386	64	8,240.6	88	3,843.4	112	1,932.8	136
146,580	17	48,905	41	18,668	65	7,969.1	89	3,729.7	113	1,880.9	137
139,610	18	46,863	42	17,980	66	7,707.7	90	3,619.8	114	1,830.5	138
133,000	19	44,917	43	17,321	67	7,456.2	91	3,513.6	115	1,781.7	139
126,740	20	43,062	44	16,689	68	7,214.0	92	3,411.0	116	1,734.3	140
120,810	21	41,292	45	16,083	69	6,980.6	93	3,311.8	117	1,688.4	141
115,190	22	39,605	46	15,502	70	6,755.9	94	3,215.8	118	1,643.9	142
109,850	23	37,995	47	14,945	71	6,539.4	95	3,123.0	119	1,600.6	143
104,800	24	36,458	48	14,410	72	6,330.8	96	3,033.3	120	1,558.7	144
100,000	25	34,991	49	13,897	73	6,129.8	97	2,946.5	121	1,518.0	145
95,447	26	33,591	50	13,405	74	5,936.1	98	2,862.5	122	1,478.6	146
91,126	27	32,253	51	12,932	75	5,749.3	99	2,781.3	123	1,440.2	147
87,022	28	30,976	52	12,479	76	5,569.3	100	2,702.7	124	1,403.0	148
83,124	29	29,756	53	12,043	77	5,395.6	101	2,626.6	125	1,366.9	149
79,422	30	28,590	54	11,625	78	5,228.1	102	2,553.0	126	1,331.9	150
75,903	31	27,475	55	11,223	79	5,066.6	103	2,481.7	127		
72,560	32	26,409	56	10,837	80	4,910.7	104	2,412.6	128		
69,380	33	25,390	57	10,467	81	4,760.3	105	2,345.8	129		

Stefan-Boltzmann Lamp

> **IMPORTANT:** The voltage into the lamp should **NEVER exceed 13 V**. Higher voltages will burn out the filament.

The TD-8555 Stefan-Boltzmann Lamp (Figure 3) is a high temperature source of thermal radiation. The lamp can be used for high temperature investigations of the Stefan-Boltzmann Law. The high temperature simplifies the analysis because the fourth power of the ambient temperature is negligibly small compared to the fourth power of the high temperature of the lamp filament (see Experiments 3 and 4). When properly oriented, the filament also provides a good approximation to a point source of thermal radiation. It therefore works well for investigations into the inverse square law.

By adjusting the power into the lamp (13 Volts max, 2 A min, 3 A max), filament temperatures up to approximately 3,000 °C can be obtained. The filament temperature is determined by carefully measuring the voltage and current into the lamp. The voltage divided by the current gives the resistance of the filament.

Equipment Recommended

AC/DC LV Power Supply (SF-9584) or equivalent capable of 13 V @ 3 A max

$$T = \frac{R - R_{ref}}{\alpha R_{ref}} + T_{ref}$$

For small temperature changes, the temperature of the tungsten filament can be calculated using **a**, the temperature coefficient of resistivity for the filament:

where,

- T = Temperature
- R = Resistance at temperature T
- T_{ref} = Reference temperature (usually room temp.)
- R_{ref} = Resistance at temperature T_{ref}
- α = Temperature coefficient of resistivity for the filament ($\alpha = 4.5 \times 10^{-3}\ K^{-1}$ for tungsten)

For large temperature differences, however, **a** is not constant and the above equation is not accurate.

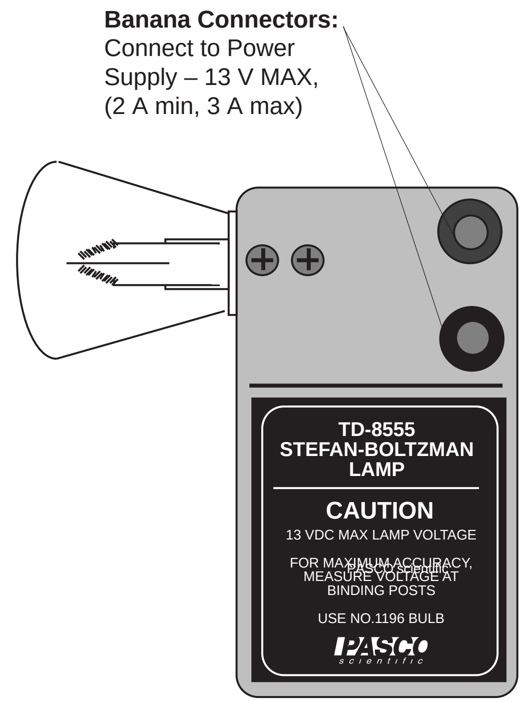


Figure 3 Stefan-Boltzmann Lamp

> **REPLACEMENT BULB:** GE Lamp No. 1196, available at most auto parts stores.
> ➤ **NOTE:** When replacing the bulb, the leads should be soldered to minimize resistance.

For large temperature differences, therefore, determine the temperature of the tungsten filament as follows:

① Accurately measure the resistance (R_{ref}) of the tungsten filament at room temperature (about 300 °K). Accuracy is important here. A small error in R_{ref} will result in a large error in your result for the filament temperature.

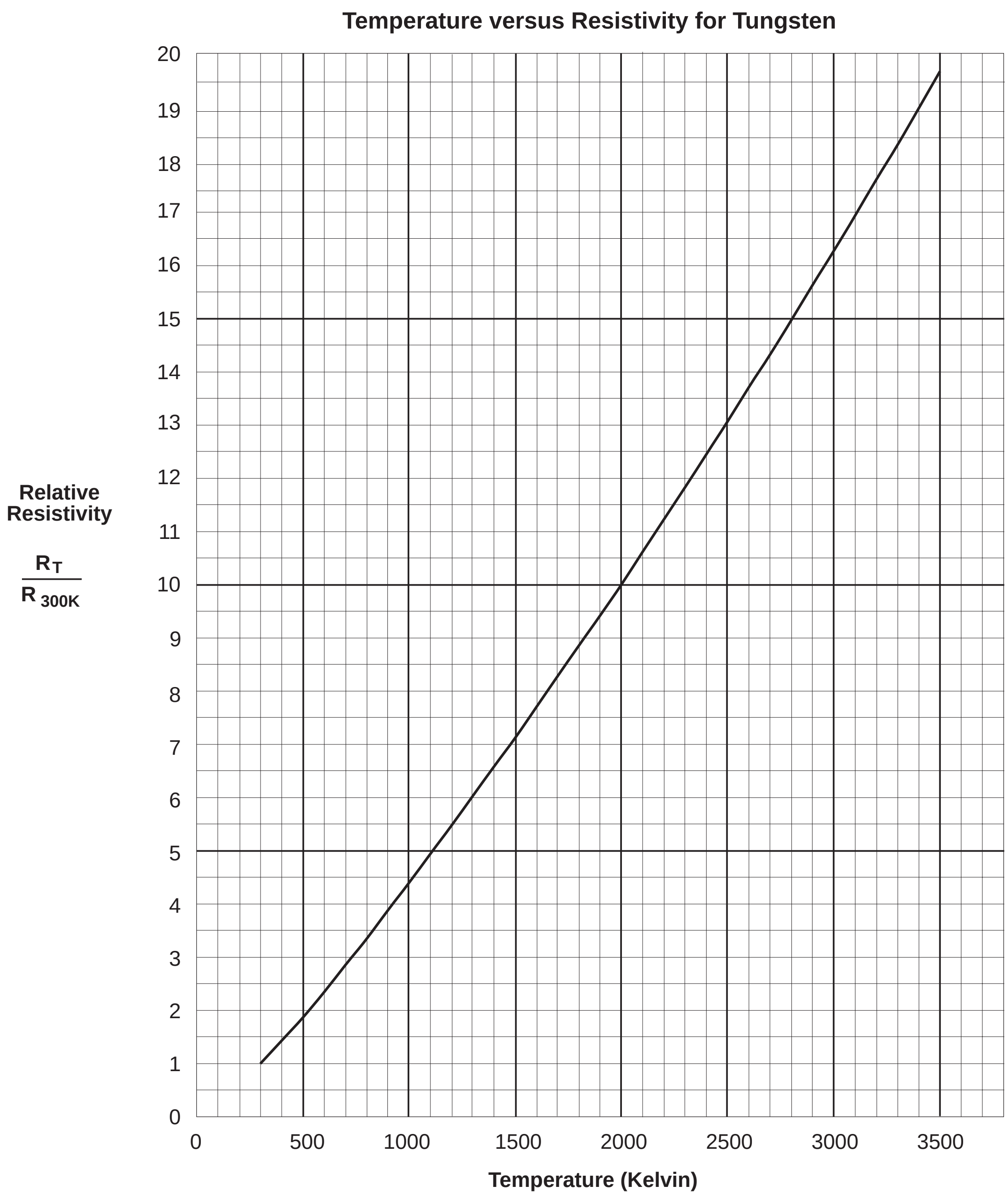
② When the filament is hot, measure the voltage and current into the filament and divide the voltage by the current to measure the resistance (R_T).

③ Divide R_T by R_{ref} to obtain the relative resistance (R_T/R_{ref}).

④ Using your measured value for the relative resistivity of the filament at temperature T, use Table 2 on the following page, or the associated graph, to determine the temperature of the filament.

Table 2 Temperature and Resistivity for Tungsten

R/R_{300K}	Temp °K	Resistivity μΩ cm	R/R_{300K}	Temp °K	Resistivity μΩ cm	R/R_{300K}	Temp °K	Resistivity μΩ cm	R/R_{300K}	Temp °K	Resistivity μΩ cm
1.0	300	5.65	5.48	1200	30.98	10.63	2100	60.06	16.29	3000	92.04
1.43	400	8.06	6.03	1300	34.08	11.24	2200	63.48	16.95	3100	95.76
1.87	500	10.56	6.58	1400	37.19	11.84	2300	66.91	17.62	3200	99.54
2.34	600	13.23	7.14	1500	40.36	12.46	2400	70.39	18.28	3300	103.3
2.85	700	16.09	7.71	1600	43.55	13.08	2500	73.91	18.97	3400	107.2
3.36	800	19.00	8.28	1700	46.78	13.72	2600	77.49	19.66	3500	111.1
3.88	900	21.94	8.86	1800	50.05	14.34	2700	81.04	26.35	3600	115.0
4.41	1000	24.93	9.44	1900	53.35	14.99	2800	84.70			
4.95	1100	27.94	10.03	2000	56.67	15.63	2900	88.33			



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Experiment 1: Introduction to Thermal Radiation

EQUIPMENT NEEDED:

— Radiation Sensor, Thermal Radiation Cube
— Millivoltmeter
— Window glass
— Ohmmeter.

➤ **NOTES:**

① If lab time is short, it's helpful to preheat the cube at a setting of 5.0 for 20 minutes before the laboratory period begins. (A very quick method is to preheat the cube at full power for 45 minutes, then use a small fan to reduce the temperature quickly as you lower the power input. Just be sure that equilibrium is attained with the fan off.)

② Part 1 and 2 of this experiment can be performed simultaneously. Make the measurements in Part 2 while waiting for the Radiation Cube to reach thermal equilibrium at each of the settings in Part 1.

③ When using the Radiation Sensor, always shield it from the hot object except for the few seconds it takes to actually make the measurement. This prevents heating of the thermopile which will change the reference temperature and alter the reading.

Radiation Rates from Different Surfaces

Part 1

① Connect the Ohmmeter and Millivoltmeter as shown in Figure 1.1.

② Turn on the Thermal Radiation Cube and set the power switch to "HIGH". Keep an eye on the ohmmeter reading. When it gets down to about 40 kΩ, reset the power switch to 5.0. (If the cube is preheated, just set the switch to 5.0.)

③ When the cube reaches thermal equilibrium—the ohmmeter reading will fluctuate around a relatively fixed value—use the Radiation Sensor to measure the radiation emitted from each of the four surfaces of the cube. Place the Sensor so that the posts on its end are in contact with the cube surface (this ensures that the distance of the measurement is the same for all surfaces). Record your measurements in the appropriate table on the following page. Also measure and record the resistance of the thermistor. Use the table on the base of the cube to determine the corresponding temperature.

④ Increase the power switch setting, first to 6.5, then to 8.0, then to "HIGH". At each setting, wait for the cube to reach thermal equilibrium, then repeat the measurements of step 1 and record your results in the appropriate table.

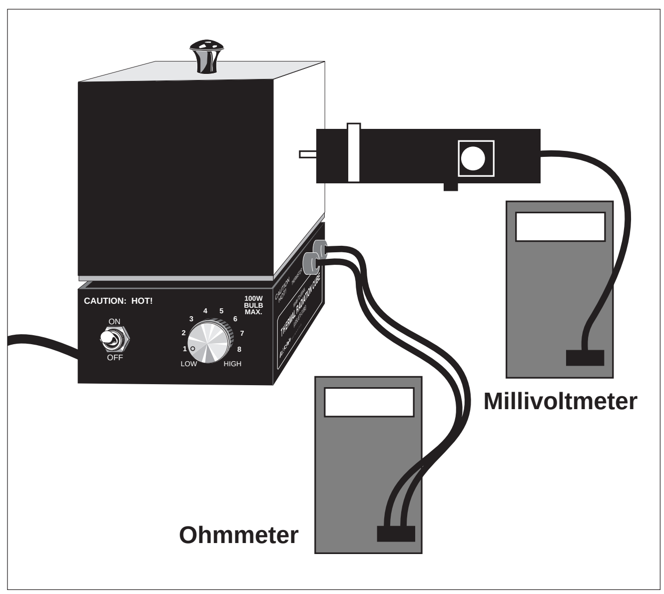

Figure 1.1 Equipment Setup

Part 2

Use the Radiation Sensor to examine the relative magnitudes of the radiation emitted from various objects around the room. On a separate sheet of paper, make a table summarizing your observations. Make measurements that will help you to answer the questions listed below.

Absorption and Transmission of Thermal Radiation

① Place the Sensor approximately 5 cm from the black surface of the Radiation Cube and record the reading. Place a piece of window glass between the Sensor and the bulb. Does window glass effectively block thermal radiation?

② Remove the lid from the Radiation Cube (or use the Stefan-Boltzmann Lamp) and repeat the measurements of step 1, but using the bare bulb instead of the black surface. Repeat with other materials.

Radiation Rates from Different Surfaces

Data and Calculations

Power Setting 5.0

Therm. Res. ________ Ω
Temperature ________ °C

Surface	Sensor Reading (mV)
Black	
White	
Polished Aluminum	
Dull Aluminum	

Power Setting 6.5

Therm. Res. ________ Ω
Temperature ________ °C

Surface	Sensor Reading (mV)
Black	
White	
Polished Aluminum	
Dull Aluminum	

Power Setting 8.0

Therm. Res. ________ Ω
Temperature ________ °C

Surface	Sensor Reading (mV)
Black	
White	
Polished Aluminum	
Dull Aluminum	

Power Setting 10.0

Therm. Res. ________ Ω
Temperature ________ °C

Surface	Sensor Reading (mV)
Black	
White	
Polished Aluminum	
Dull Aluminum	

Questions (Part 1)

① List the surfaces of the Radiation Cube in order of the amount of radiation emitted. Is the order independent of temperature?

② It is a general rule that good absorbers of radiation are also good emitters. Are your measurements consistent with this rule? Explain.

Questions (Part 2)

① Do different objects, at approximately the same temperature, emit different amounts of radiation?

② Can you find materials in your room that block thermal radiation? Can you find materials that don't block thermal radiation? (For example, do your clothes effectively block the thermal radiation emitted from your body?)

Absorption and Transmission of Thermal Radiation

Questions

① What do your results suggest about the phenomenon of heat loss through windows?

② What do your results suggest about the Greenhouse Effect?

Experiment 2: Inverse Square Law

EQUIPMENT NEEDED:

— Radiation Sensor
— Stefan-Boltzmann Lamp, Millivoltmeter
— Power Supply (12 VDC; 3 A), meter stick.

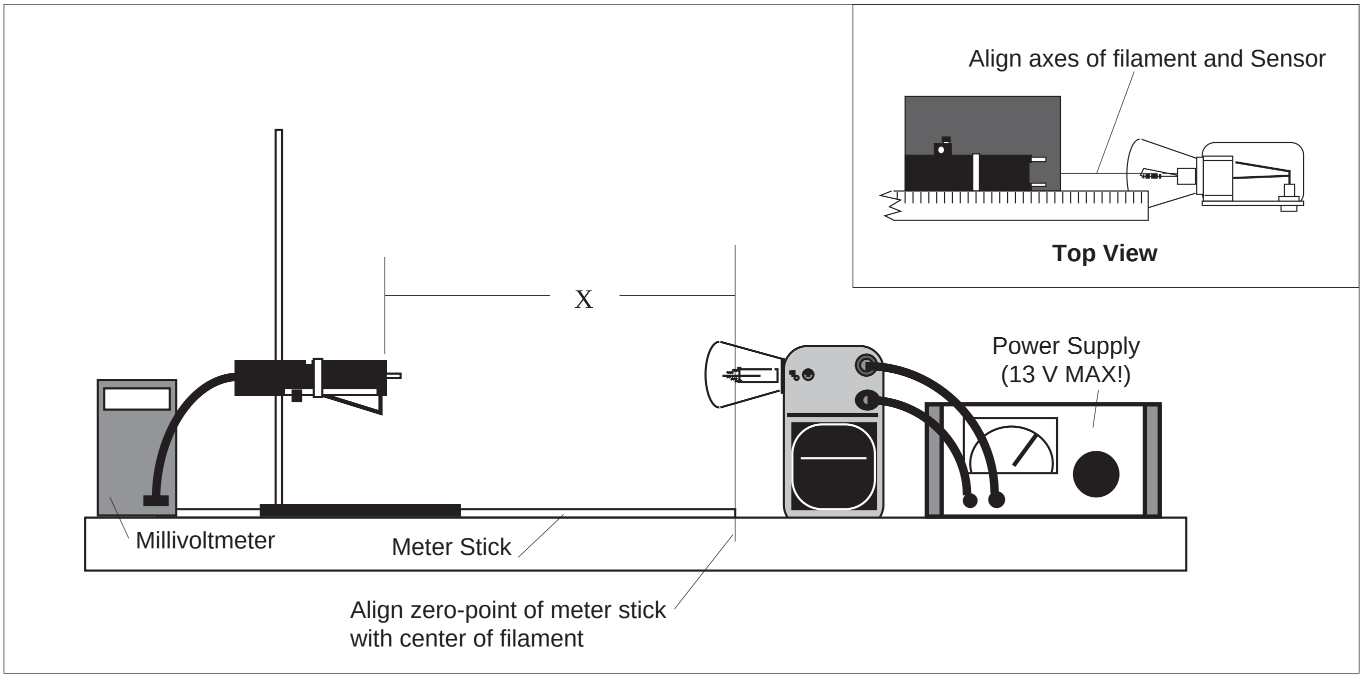

Figure 2.1 Equipment Setup

① Set up the equipment as shown in Figure 2.1.

a. Tape a meter stick to the table.

b. Place the Stefan-Boltzmann Lamp at one end of the meter stick as shown. The zero-point of the meter stick should align with the center of the lamp filament.

c. Adjust the height of the Radiation Sensor so it is at the same level as the filament of the Stefan-Boltzmann Lamp.

d. Align the lamp and sensor so that, as you slide the Sensor along the meter stick, the axis of the lamp aligns as closely as possible with the axis of the Sensor.

e. Connect the Sensor to the millivoltmeter and the lamp to the power supply as indicated in the figure.

② With the lamp OFF, slide the sensor along the meter stick. Record the reading of the millivolt-meter at 10 cm intervals. Record your values in Table 2.1 on the following page. Average these values to determine the ambient level of thermal radiation. You will need to subtract this average ambient value from your measurements with the lamp on, in order to determine the contribution from the lamp alone.

③ Turn on the power supply to illuminate the lamp. Set the voltage to approximately 10 V.

➤ **IMPORTANT:** Do not let the voltage to the lamp exceed 13 V.

④ Adjust the distance between the Sensor and the lamp to each of the settings listed in Table 2.2. At each setting, record the reading on the millivoltmeter.

➤ **IMPORTANT:** Make each reading quickly. Between readings, move the Sensor away from the lamp, or place the reflective heat shield between the lamp and the Sensor, so that the temperature of the Sensor stays relatively constant.

X (cm)	Ambient Radiation Level (mV)
10	
20	
30	
40	
50	
60	
70	
80	
90	
100	
Average Ambient Radiation Level =	

Table 2.1
Ambient Radiation Level

X (cm)	Rad (mV)	$1/X^2$ (cm^{-2})	Rad - Ambient (mV)
2.5			
3.0			
3.5			
4.0			
4.5			
5.0			
6.0			
7.0			
8.0			
9.0			
10.0			
12.0			
14.0			
16.0			
18.0			
20.0			
25.0			
30.0			
35.0			
40.0			
45.0			
50.0			
60.0			
70.0			
80.0			
90.0			
100.0			

Table 2.2
Radiation Level versus Distance

Calculations

① For each value of X, calculate $1/X^2$. Enter your results in Table 2.2.

② Subtract the Average Ambient Radiation Level from each of your Rad measurements in Table 2.2. Enter your results in the table.

③ On a separate sheet of paper, make a graph of Radiation Level versus Distance from Source, using columns one and four from Table 2.2. Let the radiation level be the dependent (y) axis.

④ If your graph from part 3 is not linear, make a graph of Radiation Level versus $1/X^2$, using columns three and four from table 2.2.

Questions

① Which of the two graphs is more linear? Is it linear over the entire range of measurements?

② The inverse square law states that the radiant energy per unit area emitted by a point source of radiation decreases as the square of the distance from the source to the point of detection. Does your data support this assertion?

③ Is the Stefan-Boltzmann Lamp truly a point source of radiation? If not, how might this affect your results? Do you see such an effect in the data you have taken?

Experiment 3: Stefan-Boltzmann Law (high temperature)

EQUIPMENT NEEDED:

— Radiation Sensor
— Ohmmeter
— Voltmeter (0-12 V)
— Ohmmeter
— Stefan-Boltzmann Lamp
— Ammeter (0-3 A)
— Millivoltmeter
— Thermometer.

Introduction

The Stefan-Boltzmann Law relates R, the power per unit area radiated by an object, to T, the absolute temperature of the object. The equation is:

$$R = \sigma T^4; \quad \left(\sigma = 5.6703 \quad x\ 10^{-8} \frac{W}{m^2 K^4}\right)$$

In this experiment, you will make relative measurements of the power per unit area emitted from a hot object, namely the Stefan-Boltzmann Lamp, at various temperatures. From your data you will be able to test whether the radiated power is really proportional to the fourth power of the temperature.

Most of the thermal energy emitted by the lamp comes from the filament of the lamp. The filament temperature can be determined using the procedure given on pages 3 and 4 of this manual.

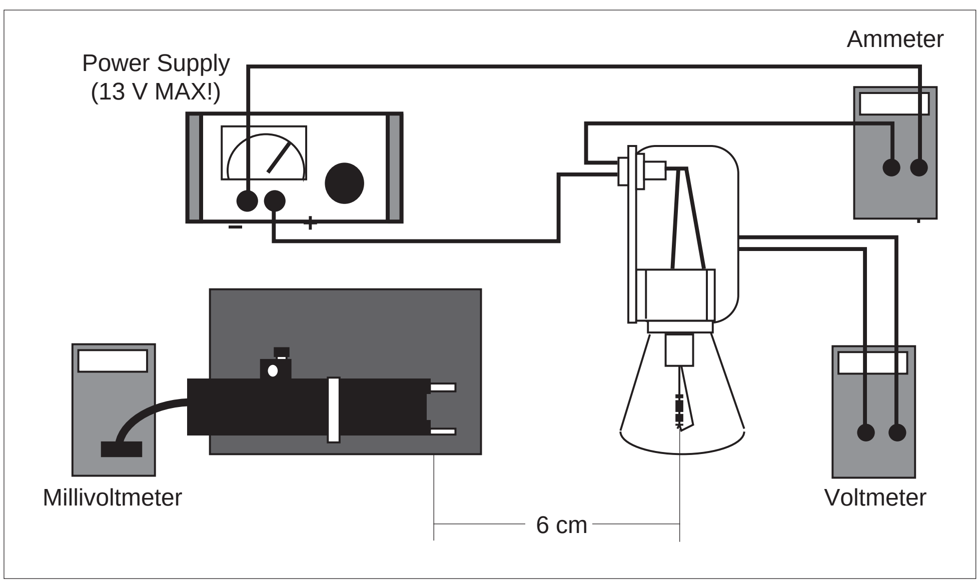

Figure 3.1 Equipment Setup

Procedure

➤ **IMPORTANT:** The voltage into the lamp should NEVER exceed 13 V. Higher voltages will burn out the filament.

① **BEFORE TURNING ON THE LAMP**, measure T_{ref}, the room temperature in degrees Kelvin, (K=°C + 273) and R_{ref}, the resistance of the filament of the Stefan-Boltzmann Lamp at room temperature. Enter your results in the spaces on the following page.

② Set up the equipment as shown in Figure 3.1. The voltmeter should be connected directly to the binding posts of the Stefan-Boltzmann Lamp. The Sensor should be at the same height as the filament, with the front face of the Sensor approximately 6 cm away from the filament. The entrance angle of the thermopile should include no close objects other than the lamp.

③ Turn on the power supply. Set the voltage, V, to each of the settings listed in Table 3.1 on the following page. At each voltage setting, record I, the ammeter reading, and Rad, the reading on the millivoltmeter.

➤ **IMPORTANT:** Make each Sensor reading quickly. Between readings, place both sheets of insulating foam between the lamp and the Sensor, with the silvered surface facing the lamp, so that the temperature of the Sensor stays relatively constant.

Data and Calculations

① Calculate R, the resistance of the filament at each of the voltage settings used ($R = V/I$). Enter your results in Table 3.1.

② Use the procedure on pages 3 and 4 of this manual to determine T, the temperature of the lamp filament at each voltage setting. Enter your results in the table.

③*Calculate T^4 for each value of T and enter your results in the table.

④*On a separate sheet of paper, construct a graph of Rad versus T^4. Use Rad as your dependent variable (y-axis).

*In place of calculations ① and , some may prefer to perform a power regression on Rad versus T to determine their relationship, or graph on log-log paper and find the slope.

Questions

① What is the relationship between Rad and T? Does this relationship hold over the entire range of measurements?

② The Stefan-Boltzmann Law is perfectly true only for ideal, black body radiation. A black body is any object that absorbs all the radiation that strikes it. Is the filament of the lamp a true black body?

③ What sources of thermal radiation, other than the lamp filament, might have influenced your measurements? What affect would you expect these sources to have on your results?

$\alpha = 4.5 \times 10^{-3}\ K^{-1}$

T_{ref} (room temperature) = _______ K (K = °C + 273)

R_{ref} (filament resistance at T_{ref}) = ________Ω

Table 3.1

Data			Calculations		
V (Volts)	I (Amps)	Rad (mV)	R (Ohms)	T (K)	T^4 (K^4)
1.00					
2.00					
3.00					
4.00					
5.00					
6.00					
7.00					
8.00					
9.00					
10.00					
11.00					
12.00					

Instruction Manual and
Experiment Guide for the
PASCO scientific
Model TD-8572

HEAT ENGINE/ GAS LAW APPARATUS

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Introduction

The PASCO TD-8572 Heat Engine/Gas Law Apparatus is used for quantitative experiments involving the Ideal Gas Law (as described below) and for investigations of a working heat engine. The equipment allows the amount of work done by thermal energy to be measured.

The heart of this apparatus is a nearly friction-free piston/cylinder system. The graphite piston fits snugly into a precision-ground Pyrex cylinder so that the system produces almost friction-free motion and negligible leakage.

Equipment

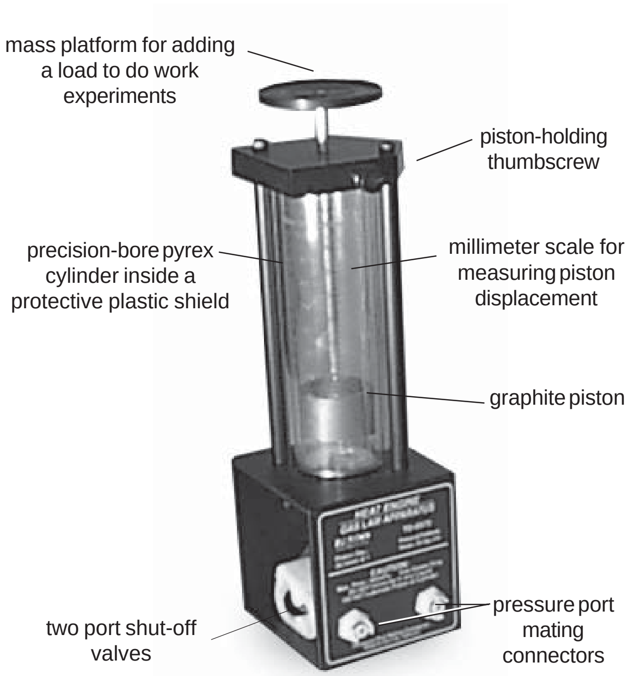


Figure 1. Base apparatus

The Heat Engine/Gas Law Apparatus is designed with two pressure ports with quick-connect fittings for connecting to the air chamber tubing.

The apparatus can be connected to a Low Pressure Sensor for use with PASCO computer interfaces.

> Do not apply lubricant to the piston or cylinder.

> Do not immerse the base apparatus in liquid.

> Note: Use only non-caustic/non-toxic gases such as air or helium.

The apparatus includes the following equipment

- base apparatus (Figure 1)
  - piston diameter: 32.5 mm ± 0.1
  - mass of piston and platform: 35.0 g ± .06
- air chamber (Figure 2)
- 3 hose configurations: one with one-way check valves and one with a clamp (Figure 2), and one plain piece of tubing (not shown)
- 1 each, one-holed and two-holed rubber stopper

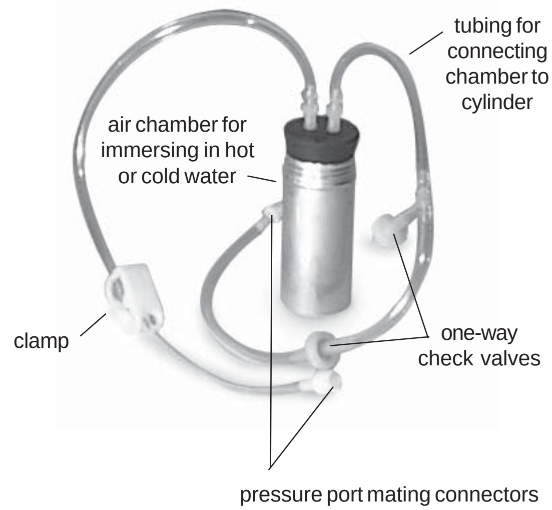


Figure 2. Air chamber and tubing

> Always release the tubing clamps prior to storage to avoid permanently deforming the tubing.

> Maximum Pressure: 345 kPa.

Experiment 2: Charles' Law

Equipment Required:	
• Heat Engine/Gas Law Apparatus	• container of hot water
• thermometer	• ice

Theory

Charles' law states that at a constant pressure, the volume of a fixed mass or quantity of gas varies directly with the absolute temperature:

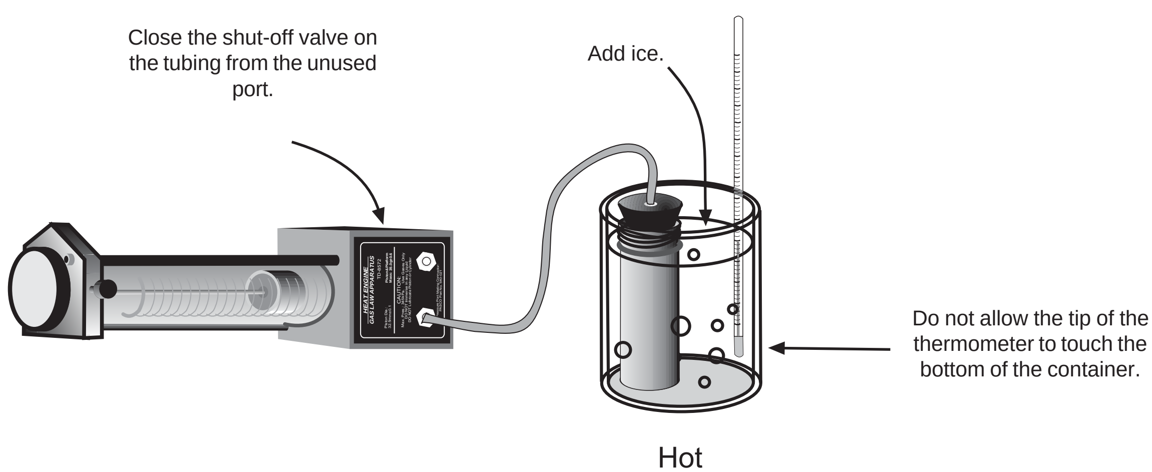
$$V = cT \qquad \text{(at constant } P \text{ and where } T \text{ is expressed in degrees Kelvin)}$$

Setup

① Using the one-holed stopper and plain tubing, connect the base apparatus and the air chamber.

② Close the shut-off valve on the tubing from the unused port.

③ Turn the base apparatus on its side. (In this position, the force acting on the apparatus is the atmospheric pressure and is equal throughout the range of operation of the piston.)



Procedure

① Place the air chamber in a container of hot water. After the chamber equilibrates to the temperature, record the temperature and the height of the piston.

② Add ice to the container and record the temperature and pressure at regular time intervals.

③ Calculate the gas volumes at the various piston positions you measured and make a graph of plots of temperature versus volume. (Hint: The diameter of the piston is 32.5 mm.)

Experiment 3: Boyle's Law

Equipment Required:	
• Heat Engine/Gas Law Apparatus	• *Science Workshop* computer interface*
• Pressure Sensor (CI-6532)	

*For details on setting up and operating the Pressure Sensor with *Science Workshop*, please consult the instruction sheet for the Pressure Sensor and the User's Guide for *Science Workshop.*

Theory

Boyle's law states that the product of the volume of a gas times its pressure is a constant at a fixed temperature:

$$PV = a$$

Therefore, at a fixed temperature, the pressure will be inversely related to the volume, and the relationship will be linear:

$$P = \frac{a}{V}$$

Setup

① With the platform raised to its uppermost position, connect the Pressure Sensor to a port on the base apparatus with a short piece of tubing (Figure 3.1).

② Close the shut-off valve on the tubing from the unused port.

③ Connect the Pressure Sensor to the computer interface and set up Science Workshop to record pressure. Be sure that you set up the keyboard sampling option so you can enter height data by hand. (Consult the *Science Workshop User's Guide*, "Keyboard Sampling," for details.)

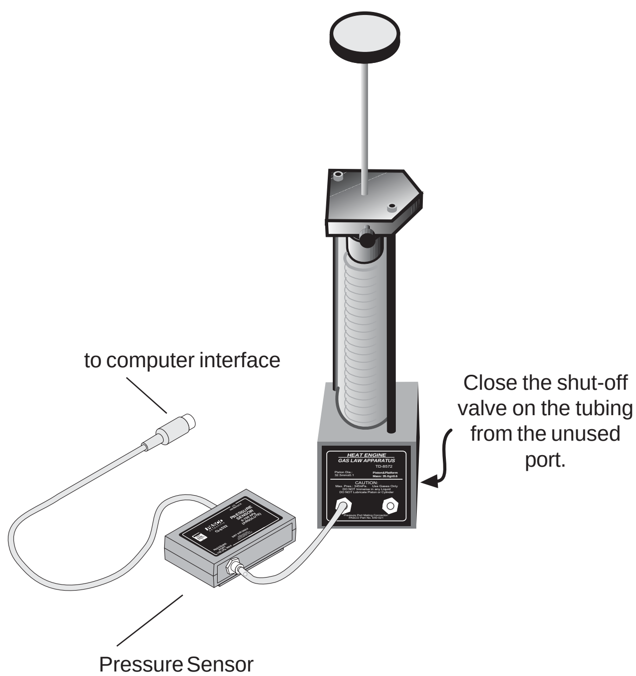


Figure 3.1. Experimental setup

Procedure

① Record the height of the piston and the pressure when the platform is raised to its highest position.

② Press the platform down to a series of levels and record the height and pressure at each level.

③ Convert the height measurements to gas volume measurements. (Hint:
The diameter of the piston is 32.5 mm.)

④ Prepare a graph of pressure versus volume.

➤ Note: The relationship between pressure and volume may not be linear at pressures greater than 120 kPa because of air leakage from the valves and ports at higher pressures.

Experiment 4: Combined Gas Law (Gay-Lussac's)

Equipment Required:	
• Pressure Sensor (CI-6532)	• hot plate
• *Science Workshop* computer interface*	• Pyrex beaker with water
• Temperature Sensor (CI-6505)	• ice

*For details on setting up and operating the Pressure Sensor and the Temperature Sensor with *Science Workshop*, please consult the instruction sheets for the Pressure Sensor and the Temperature Sensor and the User's Guide for *Science Workshop*.

Theory

Charles' law states that V is proportional to T, and Boyle's law states that V is proportional to $1/P$. Combining these, we have:

$$V = \frac{aT}{P}$$

The combined gas law predicts that for a given mass of gas, if V is held constant, P is proportional to T.

Setup

① The Gas Law Apparatus is not used in this experiment. Use a short piece of tubing to connect the pressue sensor to the air chamber fitted with the 2-hole stopper.

② Insert the Temperature Sensor into the other hole of the rubber stopper.

③ Connect the Pressure Sensor and the Temperature Sensor to the computer interface, and set up the *Science Workshop* program to graph temperature versus pressure.

> Use a silicon lubricant on the end of the Temperature Probe to aid insertion and to prevent damage to the probe.

④ Place the air chamber in the Pyrex container and turn on the hot plate.

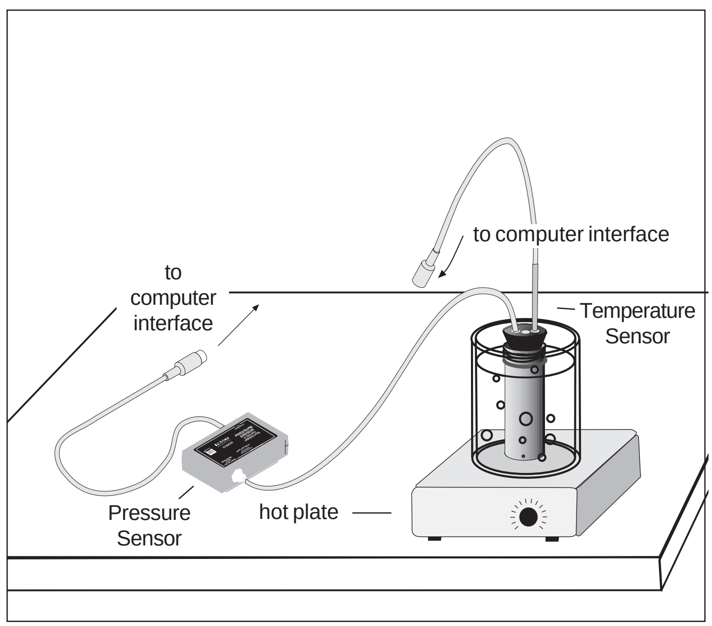


Figure 4.1. Experimental setup

> ➤ Note: You can substitute a thermometer in the water container for the Temperature Sensor. Be sure to keep the tip of the thermometer from touching the bottom of the container.

Procedure

① Record the temperature and pressure as the water heats.

② Display a graph of temperature versus pressure in Science Workshop.

Experiment 5: The Mass Lifter Heat Engine[1]

The Heat Engine/Gas Law Apparatus is ideal for use in the calculus-based experiment 18.10 of the *Workshop Physics Activity Guide*. Following is a slightly modified reprint of the experiment:

Equipment Required:	
• Heat Engine/Gas Law Apparatus	• 1 calipers
• 2 Pyrex beakers, 1000 ml (to use as reservoirs)	• 1 mass set, 20 g, 50 g, 100 g, 200 g
• 1 ruler	• 1 hot plate
• 1 barometer pressure gauge	• 1 vat to catch water spills

Optional:
- a computer-based laboratory system with barometer sensor

Your working group has been approached by the Newton Apple Company about testing a heat engine that lifts apples that vary in mass from 100 g to 200 g from a processing conveyer belt to the packing conveyer belt that is 10 cm higher. The engine you are to experiment with is a "real" thermal engine that can be taken through a four-stage expansion and compression cycle and that can do useful mechanical work by lifting small masses from one height to another. In this experiment we would like you to verify experimentally that the useful mechanical work done in lifting a mass, *m*, through a vertical distance, *y*, is equal to the net thermodynamic work done during a cycle as determined by finding the enclosed area on a *P*-*V* diagram. Essentially you are comparing useful mechanical "ma_gy" work (which we hope you believe in and understand from earlier studies) with the accounting of work in an engine cycle as a function of pressure and volume changes given by the expression:

$$W_{net} = \oint PdV$$

Although you can prove mathematically that this relationship holds, the experimental verification will allow you to become familiar with the operation of a real heat engine.

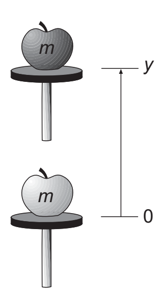


Figure 5.1. Doing useful mechanical work by lifting a mass, *m*, through a height, *y*.

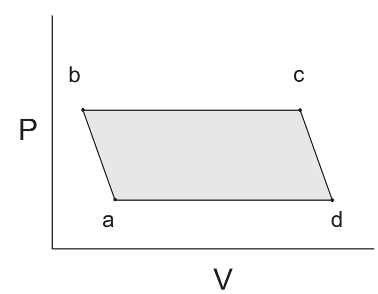


Figure 5.2 Doing thermodynamic work in a heat engine cycle.

[1]Priscilla W. Laws, et al. *Workshop Physics Activity Guide*, 1996 by John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.

The Incredible Mass Lifter Engine

The heat engine consists of a hollow cylinder with a graphite piston that can move along the axis of the cylinder with very little friction. The piston has a platform attached to it for lifting masses. A short length of flexible tubing attaches the cylinder to an air chamber (consisting of a small can sealed with a rubber stopper that can be placed alternately in the cold reservoir and the hot reservoir. A diagram of this mass lifter is shown in Figure 5.2.

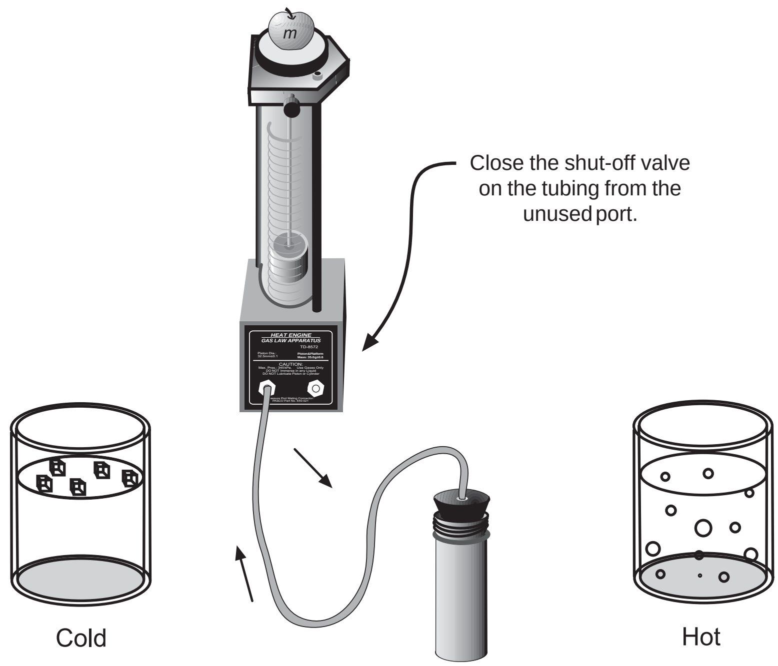


Figure 5.2. A schematic diagram of the incredible mass lifter heat engine.

If the temperature of the air trapped inside the cylinder, hose, and can is increased, then its volume will increase, causing the platform to rise. Thus, you can increase the volume of the trapped air by moving the can from the cold to the hot reservoir. Then, when the apple has been raised through a distance *y*, it can be removed from the platform. The platform should then rise a bit more as the pressure on the cylinder of gas decreases a bit. Finally, the volume of the gas will decrease when the air chamber is returned to the cold reservoir. This causes the piston to descend to its original position once again. The various stages of the mass lifter cycle are shown in Figure 5.3.

Before taking data on the pressure, air volume, and height of lift with the heat engine, you should set it up and run it through a few cycles to get used to its operation. A good way to start is to fill one container with room temperature water and another with hot tap water or preheated water at about 60–70°C. The engine cycle is much easier to describe if you begin with the piston resting above the bottom of the cylinder. Thus, we suggest you raise the piston a few centimeters before inserting the rubber stopper firmly in the can. Also, air does leak out of the cylinder slowly. If a large mass is being lifted, the leakage rate increases, so we suggest that you limit the added mass to something between 100 g and 200 g. After observing a few engine cycles, you should be able to describe each of the points *a*, *b*, *c*, and *d* of a cycle carefully, indicating which of the transitions between points are approximately adiabatic and which are isobaric. You can observe changes in the volume of the gas directly and you can predict how the pressure exerted on the gas by its surroundings ought to change from point to point by using the definition of pressure as force per unit area.

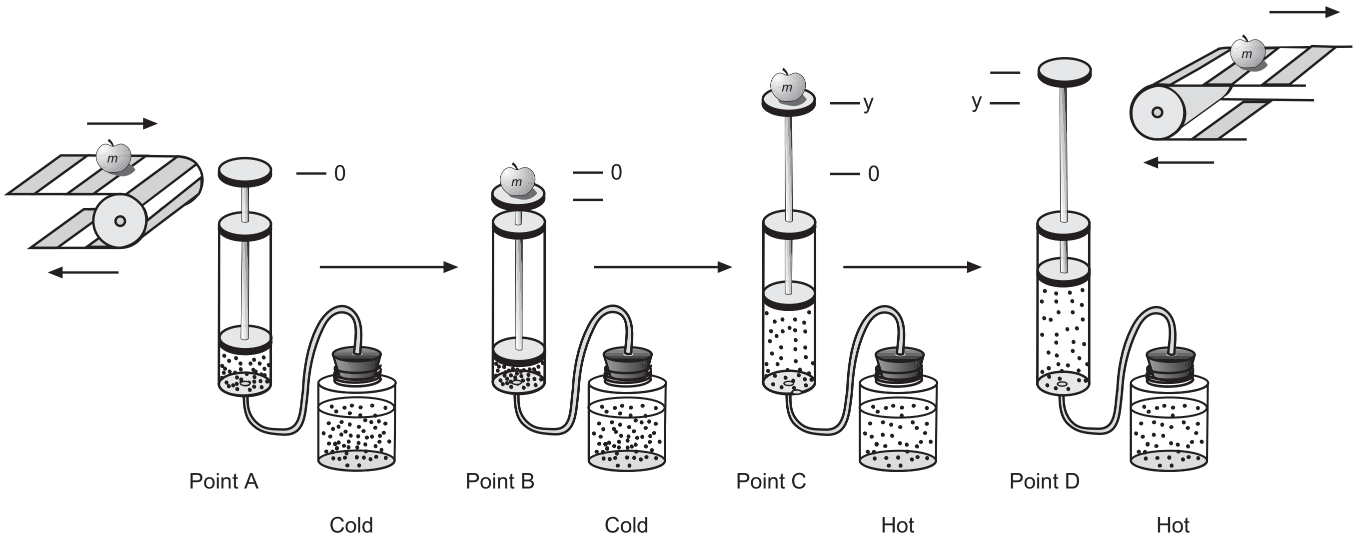


Figure 5.3. A simplified diagram of the mass lifter heat engine at different stages of its cycle.

5.1 Activity: Description of the Engine Cycle

a. Predicted transition *a*→*b*: Close the system to outside air but leave the can in the cold reservoir. Make sure the rubber stopper is firmly in place in the can. What should happen to the height of the platform when you add a mass? Explain the basis of your prediction.

b. Observed transition *a*→*b*: What happens when you add the mass to the platform? Is this what you predicted?

c. Predicted transition *b*→*c*: What do you expect to happen when you place the can in the hot reservoir ?

d. Observed transition *b*→*c*: Place the can in the hot reservoir and describe what happens to the platform with the added mass on it. Is this what you predicted? (This is the engine power stroke!)

e. Predicted transition *c*→*d*: Continue to hold the can in the hot reservoir and predict what will happen if the added mass that is now lifted is removed from the platform and moved onto an upper conveyor belt. Explain the reasons for your prediction.

f. Observed transition $c \rightarrow d$: Remove the added mass and describe what actually happens. Is this what you predicted?

g. Predicted transition $d \rightarrow a$: What do you predict will happen if you now place the can back in the cold reservoir? Explain the reasons for your prediction.

h. Observed transition $d \rightarrow a$: Now it's time to complete the cycle by cooling the system down to its original temperature for a minute or two before placing a new mass to be lifted on it. Place the can in the cold reservoir and describe what actually happens to the volume of the trapped air. In particular, how does the volume of the gas actually compare to the original volume of the trapped air at point a at the beginning of the cycle? Is it the same or has some of the air leaked out?

i. Theoretically, the pressure of the gas should be the same once you cool the system back to its original temperature. Why?

Determining Pressures and Volumes for a Cycle

In order to calculate the thermodynamic work done during a cycle of this engine, you will need to be able to plot a *P-V* diagram for the engine based on determinations of the volumes and pressures of the trapped air in the cylinder, tubing, and can at the points *a*, *b*, *c*, and *d* in the cycle.

5.2 Activity: Volume and Pressure Equations

a. What is the equation for the volume of a cylinder that has an inner diameter of *d* and a length *L*?

b. Use the definition of pressure to derive the equation for the pressure on a gas being contained by a vertical piston of diameter *d* if the total mass on the piston including its own mass and any added mass is denoted as *M*. **Hints:** (1) What is the definition of pressure? (2) What is the equation needed to calculate the gravitational force on a mass, *M*, close to the surface of the Earth? (3) Don't forget to add in the atmospheric pressure, P_{atm}, acting on the piston and hence the gas at sea level.

Now that you have derived the basic equations you need, you should be able to take your engine through another cycle and make the measurements necessary for calculating both the volume and the pressure of the air and determining a *P-V* diagram for your heat engine. Instead of calculating the pressures, if you have the optional equipment available, you might want to measure the pressures with a barometer or a barometer sensor attached to a computer-based laboratory system.

5.3 Activity: Determining Volume and Pressure

a. Take any measurements needed to determine the volume and pressure of air in the system at all four points in the engine cycle. You should do this rapidly to avoid air leakages around the piston and summarize the measurements with units in the space below.

b. Next you can use your measurements to calculate the pressure and volume of the system at point *a*. Show your equations and calculations in the space below and summarize your results with units. Don't forget to take the volume of the air in the tubing and can into account!

$P_a =$

$V_a =$

c. Use the measurements at point *b* to calculate the total volume and pressure of the air in the system at that point in the cycle. Show your equations and calculations in the space below and summarize your results with units.

$P_b =$

$V_b =$

d. What is the height, *y*, through which the added mass is lifted in the transition from *b* to *c*?

e. Use the measurements at point *c* to calculate the total volume and pressure of the air in the system at that point in the cycle. Show your equations and calculations in the following space and summarize your results with units.

$P_c =$

$V_c =$

f. Remove the added mass and make any measurements needed to calculate the volume and pressure of air in the system at point *d* in the cycle. Show your equations and calculations in the space below and summarize your results with units.

$P_d =$

$V_d =$

g. We suspect that transitions from $a \to b$ and from $c \to d$ are approximately adiabatic. Explain why.

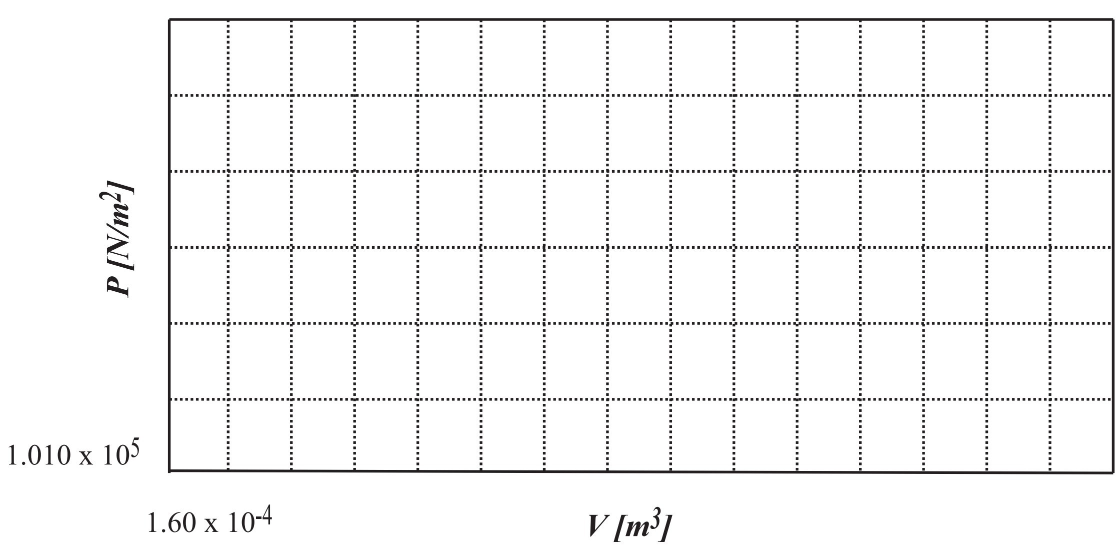
h. You should have found that the transitions from $b \to c$ and from $d \to a$ are isobaric. Explain why this is the case.

Finding Thermodynamic Work from the Diagram

In the next activity you should draw a *P- V* diagram for your cycle and determine the thermodynamic work for your engine.

5.4 Activity: Plotting and Interpreting a *P-V* Diagram

a. Fill in the appropriate numbers on the scale on the graph frame that follows and plot the *P-V* diagram for your engine cycle. Alternatively, generate your own graph using a computer graphing routine and affix the result in the space below.



b. On the graph in part a, label each of the points on the cycle (*a*, *b*, *c*, and *d*). Indicate on the graph which of the transitions ($a \rightarrow b$, $b \rightarrow c$, etc.) are adiabatic and which are isobaric.

Next you need to find a way to determine the area enclosed by the *P*- *V* diagram. The enclosed area doesn't change very much if you assume that *P* is approximately a linear function of *V* for the adiabatic transitions. By making this approximation, the figure is almost a parallelogram so you can obtain the enclosed area using one of several methods. Three of the many possibilities are listed below. *Creative students have come up with even better methods than these, so you should think about your method of analysis carefully*.

Method I

Since the pressure doesn't change from point *b* to point *c*, you can take the pressure of those two points as a constant pressure between points. The same holds for the transition from *d* to *a*. This gives you a figure that is approximately a parallelogram with two sets of parallel sides. You can look up and properly apply the appropriate equation to determine the net thermodynamic work performed.

Method II

Display your graph with a grid and count the boxes in the area enclosed by the lines connecting points *a*, *b*, *c*, and *d*. Then multiply by the number of joules each box represents. You will need to make careful estimates of fractions of a box when a "leg" of a cycle cuts through a box.

Method III

$$\oint PdV = \int_a^b PdV + \int_b^c PdV + \int_c^d PdV + \int_d^a PdV$$

Fit a straight line to each of the starting and ending points for the four transitions in the cycle. Each equation will give you a function relating *P* and *V*. Perform an integral for each of these equations, since

5.5 Activity: Comparing the Thermodynamic and Useful Mechanical Work

a. Choose a method for computing the thermodynamic work in joules, describe it in the space below, and show the necessary calculations. Report the result in joules.

b. What is the equation you need to use to calculate the useful mechanical work done in lifting the mass from one level to another?

c. Use the result for the height that the mass is lifted in the power stroke of the engine to calculate the useful mechanical work performed by the heat engine.

d. How does the thermodynamic work compare to the useful mechanical work? Please use the correct number of significant figures in your comparison (as you have been doing all along, right?)

The Incredible Mass Lifter Engine Is Not So Simple

Understanding the stages of the engine cycle on a *P-V* diagram is reasonably straightforward. However, it is difficult to use equations for adiabatic expansion and compression and the ideal gas law to determine the temperature (and hence the internal energy of the air throughout the cycle. There are several reasons for this. First, air is not an ideal gas. Second, the mass lifter engine is not well insulated and so the air that is warmed in the hot reservoir transfers heat energy through the cylinder walls. Thus, the air in the can and in the cylinder are probably not at the same temperature. Third, air does leak out around the piston, especially when larger masses are added to the platform. This means that the number of moles of air decreases over time. You can observe this by noting that in the transition from point *d* to point *a*, the piston can actually end up in a lower position than it had at the beginning of the previous cycle. However, the Incredible Mass Lifter Engine does help us understand typical stages of operation of a real heat engine.

➤ Note: The previous experiment was intended to help students consolidate the concepts of pressure and volume by taking their own data for height and mass in each part of the cycle and then calculating the pressures using the basic definition of pressure vs. force per unit area. An alternate method for doing this experiment is to use the *Science Workshop* computer interface with the Pressure Sensor (CI-6532) in conjunction with either a Motion Sensor (CI-6529) or Rotary Motion Sensor (CI-6538) to detect pressure, volume, and height automatically with a computer.