

MATRIX

Thermodynamics principles



MATRIX
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Contents

Thermodynamics

	Introduction	3
Worksheet 1 -	Pressure vs volume	5
Worksheet 2 -	Pressure vs temp.	7
Worksheet 3 -	Black vs silver - 1	9
Worksheet 4 -	Black vs silver - 2	11
Worksheet 5 -	Thermal expansion	13
Worksheet 6 -	Specific heat capacity of metals	15
Worksheet 7 -	Specific heat capacity of water	17
	Student Handbook	19
	Instructor Guide	28

The measuring instruments

The energy meter:



First, a review of the quantities which it can measure:

- Energy:**
- makes things happen - moving, heating, lighting etc.;
 - is measured in joules (J).
- Power:**
- is how much energy is delivered each second;
 - is measured in watts (W).
- Average Power:**
- 'Average' means 'smooth out the variations'.
- Voltage:**
- measures the force pushing the electricity around the circuit;
 - is like the size of the pump forcing water through a pipe.
- Current:**
- measures how much electricity flows around the circuit;
 - is measured in amps (A).

The energy meter is powered from a 5V DC plug top power supply. via its micro USB connector.

The maximum voltage that can be measured is $\pm 25V$ while the maximum current is $\pm 7A$.

An internal fuse protects against currents over 7A.

The smallest values that can be displayed are:

- energy 100nJ;
- power 100nW;
- voltage 1mV;
- current 100 μ A.

The display is refreshed every 0.5 seconds. The values displayed represent the values of current and voltage averaged over the 0.5 second period before the display is refreshed.

Energy meter views

The Energy Meter offers different operating modes, selected by pressing the function button:

Measuring energy

The display shows the energy transferred through it in the time shown.

The 'Start/Pause' and 'Reset' buttons control the measurement.

```
Energy 110J
Time 62s ▶
```

Measuring power

The display shows the power transferred each instant.

```
Power 1.83W
```

Measuring average power

The display gives the average power over the time shown and the values used to calculate it .

```
Av.Pwr | 4.65J
232mW | 20s ◻
```

Measuring voltage, current and power

The display shows the voltage, current and power at each instant.

```
V 9.43V | Power
I 3.59A | 33.9W
```

Using the energy meter

- Connect the energy meter between the power supply carrier and the load device.
- Plug in the energy meter power supply, and switch on.
The display shows the word 'Initialising...' for a few seconds
- Press the right-hand button to step through the measurement functions available - energy, power, average power over the duration of the measurement and the voltage and current delivered to the load.
- Select energy measurement.
- Press the 'Start / Pause' button. The meter starts to record the energy transferred from the power supply to the load. At the lower right-hand corner of the display, an arrow '▶' shows that the meter is continuing to measure.
- Press the 'Start / Pause' button again. The display freezes and the arrow turns to a 'P' to show that the meter has paused.
- To clear the energy and power readings, press the 'Reset' button.

Some measurements come with 'm' in front, meaning 'milli' - 'one thousandth'. One **milliamp (mA)** is the same as one-thousandth of an amp and so 1 joule = 1000mJ and 1 watt = 1000mW.

In the same way, 'μ' means 'micro' - 'one millionth' and 'n' means 'nano' - 'one thousand millionth'.

The temperature indicator:

The Extech temperature indicator offers a digital readout of temperature, accurate to the nearest 1°C, over a temperature range from -40°C to +70°C.

It takes a temperature reading every 15s or so and holds that value on the display until the next reading.

It has the ability to record the maximum or minimum reading taken (since the last reset) and to hold the current reading.

Alarm temperature levels (high or low) can be set to cause an audible alert if exceeded.

When using the temperature indicator, be aware that it updates the display every 15s or so and will not follow rapidly changing temperatures.



The pressure gauge

The Bourdon-type pressure gauge contains a curved, sealed tube, which straightens when the pressure of the air inside increases. A lever system moves the pointer across the scale as a result.

It is an absolute pressure gauge, meaning that it would show a reading of zero if exposed to a perfect vacuum.

The pressure is shown in both imperial units - pounds per square inch (psi) and SI units - pascals (Pa). Standard atmospheric pressure is around 100,000 Pa or 15 psi.

We use SI units of pressure, shown by the red scale. On this, '1' indicates 100,000 (or 1×10^5) Pa. Each small division on the scale represents a change in air pressure of 10,000 Pa.



Worksheet 1 -option 1

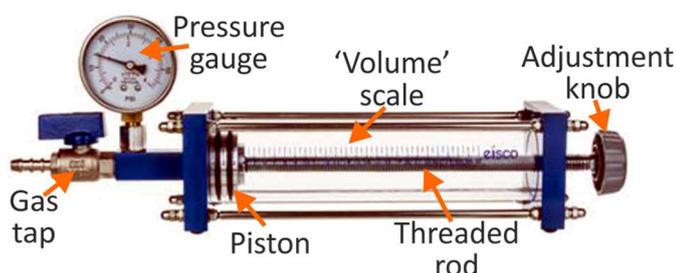
Pressure vs volume

Thermodynamics



Why do air bubbles from the diver expand as they rise through the water?
 Why do divers suffer from 'bends' if they ascend too quickly?
 How does a syringe work?
 Why do your ears 'pop' when your aeroplane takes off?
 Why does it make crisp packets inflate?
 All of these are consequences of the effect investigated here.

The apparatus:



At its heart is a transparent tube. In it, a mass of air is trapped between a gas tap and a moveable piston .

The scale from 0 to 27, marked on the tube is a measure of the volume of air trapped by the piston. A threaded rod allows the piston to be moved inside the tube, changing the volume of trapped air.

With the gas tap open, the pressure gauge reads atmospheric pressure. When closed, the volume and pressure of the trapped air can be changed by moving the piston.

Over to you:

- Open the gas tap to allow air to enter or leave the transparent tube.
- Turn the adjustment knob until the piston face sits at the '25' mark.
- Now close the gas tap so that the air inside the tube cannot escape.
- In the first row of the table in the Student Handbook, record the air pressure (pressure gauge) reading, **P** .
- Next turn the knob **slowly** to increase the air pressure to 110,000Pa (i.e. '**1.1**' on the gauge).
- Record the new 'volume **V**' of the trapped air.
- Continue increasing air pressure, **P**, in steps of 10,000Pa as shown in the table.
- Record the resulting volume '**V**' of trapped air in the table.

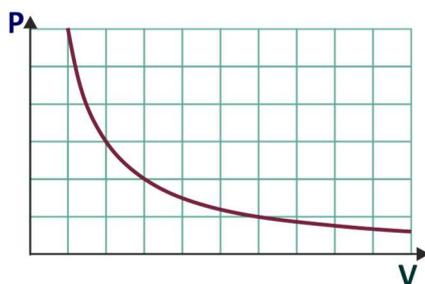
Worksheet 1 -option 1

Pressure vs volume

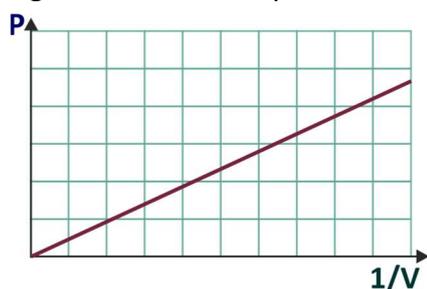
Thermodynamics

So what:

- In the Student Handbook, complete the third column of the table by calculating ' $1/V$ ' for each row.
- Were you to plot a graph of air pressure ' P ' against volume ' V ', the result would not be particularly helpful:



- However, using your results to plot a graph of air pressure ' P ' against ' $1/V$ ', the pattern of the plotted points should suggest a straight line relationship.



Air pressure P	Air volume V	1 / V
	25	0.04
1.2		
1.3		
1.4		
1.5		
1.6		
1.7		
1.8		
1.9		
2.0		
2.1		
2.2		
2.3		
2.4		
2.5		
2.6		
2.7		
2.8		
2.9		
3.0		

- Put into words, this result suggests that the air pressure is directly proportional to the inverse of its volume (i.e. $1/V$.) 'Directly proportional' means that when you double one quantity, the other doubles too. When you quarter one, the other one is quartered too etc.

This result is known as **Boyle's law**:

The pressure of a fixed mass of an ideal gas, at constant temperature, is inversely proportional to its volume.

It results in the formula: **pressure \times volume = constant**, or $p_1V_1 = p_2V_2$

- Answer the questions raised in the Student Handbook.

Challenge

Modify the investigation to see the effect of lowering the air pressure below atmospheric.

- Set the piston initially at the '10' mark with the gas valve open.
- Close the valve and progressively reduce the pressure to 50,000Pa in steps of 10,000Pa.
- For each value of pressure, record the resulting 'volume' of the air.
- Analyse the results in the same way as in the first part of the investigation and add them to the graph.

Worksheet 1 -option 2

Pressure vs volume

Thermodynamics



Why do air bubbles from the diver expand as they rise through the water?
 Why do divers suffer from 'bends' if they ascend too quickly?
 How does a syringe work?
 Why do your ears 'pop' when your aeroplane takes off?
 Why does it make crisp packets inflate?
 All of these are consequences of the effect investigated here.

The apparatus:



At its heart is a 2.5mL syringe filled with air.

The LCD display shows the pressure in the syringe which changes with every 0.1mL change in volume. The volume of air in the syringe can be measured using the markings on the side of the syringe

Over to you:

- Remove the syringe from the apparatus.
- Adjust the volume in the syringe to 2mL.
- Replace the syringe on the apparatus.
- In the first row of the table in the Student Handbook, record the air pressure (pressure gauge) reading, **P** .
- Next push the syringe in to increase the pressure
- Take readings of pressure and volume as you increase the pressure until the syringe is at 0.5mL volume of air.

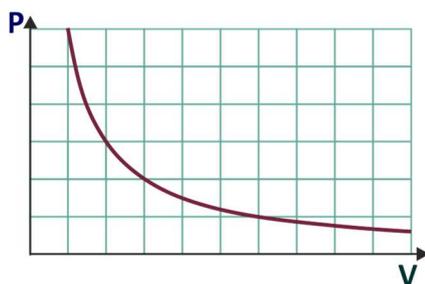
Worksheet 1 -option 2

Pressure vs volume

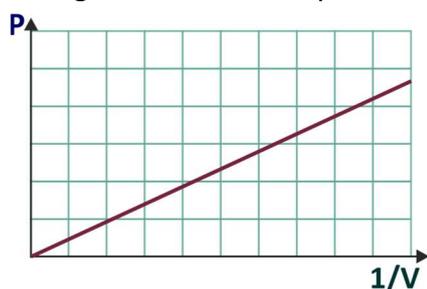
Thermodynamics

So what:

- In the Student Handbook, complete the third column of the table by calculating ' $1/V$ ' for each row.
- Were you to plot a graph of air pressure ' P ' against volume ' V ', the result would not be particularly helpful:



- However, using your results to plot a graph of air pressure ' P ' against ' $1/V$ ', the pattern of the plotted points should suggest a straight line relationship.



Air volume V	Air pressure P	$1/V$
2		
1.9		
1.8		
1.7		
1.6		
1.5		
1.4		
1.3		
1.2		
1		
0.9		
0.8		
0.7		
0.6		
0.5		

- Put into words, this result suggests that the air pressure is directly proportional to the inverse of its volume (i.e. $1/V$.) 'Directly proportional' means that when you double one quantity, the other doubles too. When you quarter one, the other one is quartered too etc.

This result is known as **Boyle's law**:

The pressure of a fixed mass of an ideal gas, at constant temperature, is inversely proportional to its volume.

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- Answer the questions raised in the Student Handbook.

Challenge

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- Set the piston initially at the '10' mark with the gas valve open.
- Close the valve and progressively reduce the pressure to 50,000Pa in steps of 10,000Pa.
- For each value of pressure, record the resulting 'volume' of the air.
- Analyse the results in the same way as in the first part of the investigation and add them to the graph.

Worksheet 2

Pressure vs temp

Thermodynamics



Advice

- **Always check tyre pressures *before* you set off, not later!**

After driving for a while, the tyres heat up. The volume of air trapped in the tyre hardly changes but its pressure does.

- **Don't try to freeze crisps to keep them fresh!**

Filled with nitrogen, the packets are sealed to stop the crisps from going stale and from being crushed. The volume of gas inside them is fixed, but the pressure changes when the packet is placed in the freezer. Result - limp packet!



The investigation looks at the relationship between the temperature of air and its pressure.

The apparatus:

The apparatus is simply a thick-walled sphere attached to a Bourdon pressure gauge by a gas-tight seal.

Over to you:

- Place the apparatus in the 1 litre plastic beaker.
- ***Taking appropriate steps to avoid a scald***, add hot water until the metal sphere is covered to a depth of 1cm or so.
(It floats - you need to hold it down while you add the hot water.)
- Lower the temperature probe to the same depth as the centre of the metal sphere.
- Switch on the temperature indicator and record the water temperature and the pressure of the air in the sphere, in the table in the Student Handbook.
- Allow the water to cool until the air pressure has dropped to the next red mark on the gauge. Now record the water temperature and new air pressure.
- Repeat this process until the air pressure has dropped to normal atmospheric pressure.
If necessary, this process can be speeded up by adding a small quantity of cold water each time to lower the temperature. However, you should then stir the water and allow a few minutes for the air in the sphere to adjust before taking readings.



Worksheet 2

Pressure vs temp

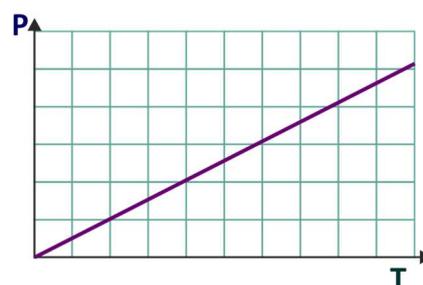
Thermodynamics

So what:

- Record your measurements in the first two columns of the table in the Student Handbook.
- Convert the temperatures to the absolute (Kelvin) temperature scale by adding 273 to the Celsius temperature. Complete the third column of the table with your results .

Vessel pressure P	Vessel temperature t in °C	Vessel temperature T in K
	t_1	$t_1 + 273$
	t_2	$t_2 + 273$
⋮	⋮	⋮

- Plot a graph of pressure, **P**, against temperature **T** (in K).
(Once again, you could use Microsoft Excel or a similar application.)



The graph should suggest a straight line relationship. However, be careful!

Doubling the temperature in the Celsius temperature scale does not double the pressure.

Using the absolute temperature scale, doubling the temperature doubles the pressure.

This relationship, known as the 'Pressure law' or Gay-Lussac's law, leads to the formula:

$$p_1 / T_1 = p_2 / T_2$$

For example:

A fixed quantity of air at an initial temperature, T_1 , of 200K has a pressure, p_1 , of 80 000Pa.

When the temperature is raised to 300K, (T_2) the new pressure, p_2 , will be:

$$\begin{aligned} p_2 &= p_1 \times T_2 / T_1 \\ &= 80\,000 \times 300 / 200 = 120\,000\text{Pa} \end{aligned}$$

Providing that this relationship is maintained, the graph suggests that when air is cooled sufficiently, its pressure falls to zero.

Challenge:

- Extend the range of readings by replacing the water with ice.
Take new temperature and pressure readings by allowing the ice to melt.
- Use the graph to estimate the temperature at which the pressure would fall to zero.

Worksheet 3

Black vs silver - 1

Thermodynamics



Shouldn't polar bears be black?

Shame that tarmac roads are black: they melt in summer and freeze in winter!

Why is kitchen foil shiny?

Why are there no black glaciers?

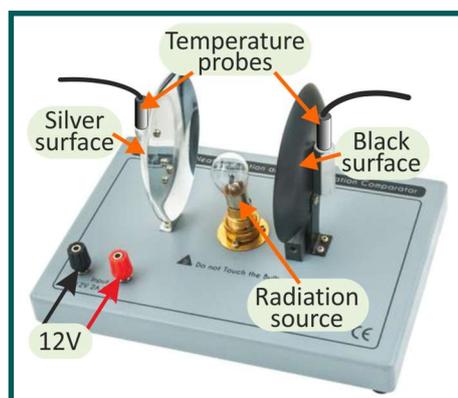
Why do cricketers wear white clothing?

Couldn't solar panels be a more attractive colour than black ?



This investigation shows that the colour of a surface affects how well it absorbs heat radiation.

The apparatus:



The apparatus consists of two identical curved reflectors, one polished silver and the other matt black, positioned at equal distances on opposite sides of a 12V lamp.

Metal blocks on the backs of the reflectors house temperature probes to monitor the temperatures of the reflectors.

A filament lamp acts as a source of heat radiation when switched on.

Over to you:

- Insert temperature probes into the blocks attached to each reflector.
- Switch on the temperature indicators.
- Connect the lamp to a 12V supply.
- Switch on the lamp and at the same time start the stopwatch.
- Record the initial temperatures of the reflectors in the table in the Student handbook.
- After one minute, measure and record the temperatures again.
- Repeat this process each minute for ten minutes.

Caution! - Do not touch the lamp or the reflectors. They get very hot!

Worksheet 3

Black vs silver - 1

Thermodynamics

So what:

The table in the Student Handbook shows the results of the investigation.

Time in mins	Temperature of silver reflector in $^{\circ}\text{C}$	Temperature of black reflector in $^{\circ}\text{C}$
0		
1		
2		
⋮	⋮	⋮
8		
9		
10		

Challenge:

- Repeat the experiment to confirm that this effect is due to the colour of the surfaces by covering the black reflector with aluminium kitchen foil.
- Record your findings in the Student Handbook.
- Answer the questions posed in the Student Handbook.

Worksheet 4

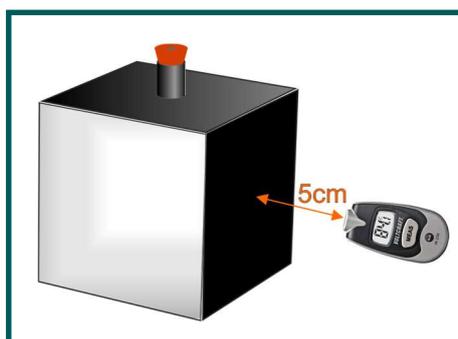
Black vs silver - 2

Thermodynamics

- What is the best colour for a radiator?
- Why do people stick aluminium foil behind radiators?
- Why are emergency blankets made from shiny foil?
- Why are the fins on the back of the fridge always black?
- Why does a vacuum flask have shiny metal surfaces?



The apparatus:



This investigation uses a metal box with different-coloured faces, known as Leslie's cube, to find out if some colours are better at radiating infra-red radiation than others. The cube, a hollow, water-tight metal cube, has faces coloured matt black, polished black, white and unpainted (silver-like).

An infra-red thermometer compares how well each face radiates heat energy. The reading on the thermometer is a measure of how much thermal radiation emitted from that face of the cube.

The amount of radiation intercepted by the thermometer depends on its distance from the hot body. To make it a fair test for all colours, this distance must be monitored carefully to keep it constant for all readings. For the same reason, the thermometer's front face (and so sensor) is kept parallel to the surface under investigation.

Over to you:

- **Taking appropriate steps to avoid a scald**, fill the cube with hot water.
- Check that the I-R thermometer is set to read temperature in the Celsius scale.
(See the instruction manual for details of how to do this.)
- Position the thermometer at a distance of 5cm, pointing at the centre of the matt black face.
- Tilt the thermometer up and down to find the maximum temperature reading at this distance.
(You may find it easier to use the 'max' function on the instrument - again see the instruction manual for details of how to do this.)
- Record the measurement in the table in the Student Handbook.
- Now repeat the process for the other faces of the cube, with the thermometer at the same distance.

Worksheet 4

Black vs silver - 2

Thermodynamics

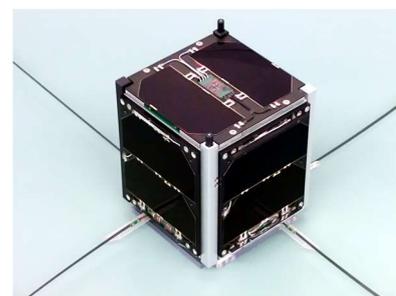
So what:

The table in the Student Handbook shows the results of the investigation.

Colour of face	Thermometer reading in °C
Matt black	
Shiny black	
White	
Unpainted	

Challenge:

- What is the effect of using a different separation between cube and thermometer?
What is the optimum distance?
- In November 2013, AMSAT (**AM**ateur Radio **SAT**ellite), a world-wide organisation, launched a satellite called FUNcube 1. In reality, it was a Leslie's cube in space.
Find out as much as you can about the project and create a report from your findings.



Worksheet 5

Thermal expansion

Thermodynamics



When objects heat up, they expand.

The forces involved are enormous, as the photograph shows. It's not easy to bend steel railway lines!

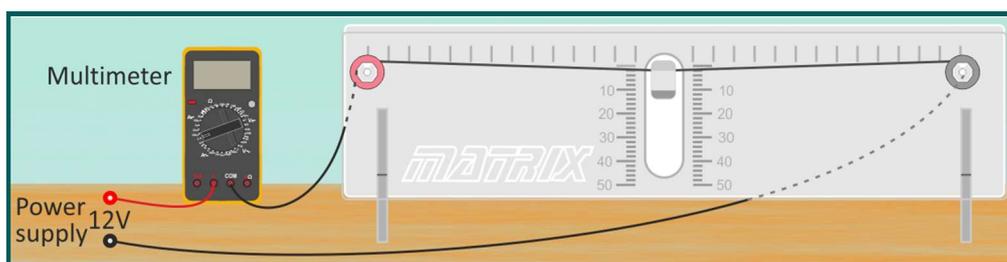
Engineering solutions include loops in metal pipelines and expansion joints for bridges, where they are subject to high temperatures.

Different materials ex-

pand at different rates. The linear expansivity of a substance describes how much it expands when heated. It is defined as the *fractional* increase in length per unit rise in temperature.



The apparatus:



The apparatus is shown above. It consists of a length of 32 s.w.g. nichrome wire mounted on a baseboard. At its centre is a small weight to keep the wire taut. Two 4mm sockets, connected to the ends of the wire allow it to be connected easily to a power supply and multimeter. The measured current heats up the wire. The temperature of the wire can be estimated using engineering data given on the next page. (Nichrome is an alloy of nickel and chromium.)

Over to you:

- Connect the wire to a 12V power supply and multimeter.
- With no current flowing, read the vertical position of the wire on the scale.
- Switch on the power supply and note the value of current flowing through the wire.
- As the wire heats up, it expands. **Caution! - the wire gets very hot! Do not touch it!**
- Note the new position of the wire on the vertical scale.
- Record your measurements in the Student Handbook and follow the procedure outlined there to obtain an estimate of the linear expansivity of nichrome.

Worksheet 5

Thermal expansion

Thermodynamics

So what:

Linear expansivity is defined as the *fractional* increase in length per unit rise in temperature.

Steps in the calculation:

- original length of the wire, L , is known;
- change in vertical position of wire, h , is known;
- use Pythagoras' theorem to calculate expanded length of wire, L , (from $L^2 = L^2 + h^2$);
- calculate the increase in length, (from $L - L$);
- calculate the fractional increase in length, (from $[L - L] / L$);
- The following table shows the approximate temperature, in Celsius, of a 32 gauge nichrome wire when a current, in Amps, passes through it in a room at 20C. Use a power supply to develop a current of 2.5 Amps. Use the table to estimate the heated temperature, T , of the wire at this current;

Current (A)	1.0	1.3	1.5	1.8	2.2	2.5	2.9	3.3	3.8	4.2
Temperature (°C)	200	300	400	500	600	700	800	900	1000	1100

- assume that the initial temperature of the wire, T , is room temperature, 20°C;
- calculate the increase in temperature (from $T - T$);
- calculate the *fractional* increase in length per unit rise in temperature, (from $([L - L] / L) / T - T$)

This is your estimate for the linear expansivity of nichrome.

Challenge:

- Repeat the measurements using a different value for the current through the wire.
- Look up the expansion of Nichrome on the web. Discuss why your results may differ from the real value of linear expansivity of Nichrome.

Worksheet 6

Specific heat capacity of metals

Thermodynamics

Energy is needed to raise the temperature of a body, (make its particles move faster.) How much energy depends on:

- its mass - the bigger its mass, the greater the energy needed;
- the temperature rise - the greater this is, the greater the energy needed;
- what it is made from - some substances need more energy than others.

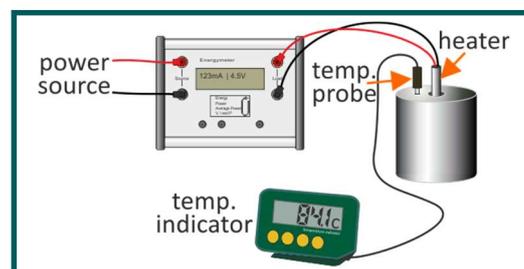


In our kitchens, we want the utensils to heat up quickly. With rising energy costs, it is important to make the most of the energy from the Sun. Modern building design seeks to do this by incorporating 'thermal batteries' such as large blocks of concrete beneath the building that can store heat energy during hot weather and release it when needed.



The apparatus:

The solid, a metal cylinder, is heated by a 12V electrical heater. A temperature probe monitors its temperature. The electrical energy delivered is measured by the energy meter.



Over to you:

- Connect the energy meter to its plug-top 9V power supply and switch on.
- Press the mode button to select energy measurement. If necessary, press the 'Reset' button to clear any previous measurements.
- Place the immersion heater in one of the metal cylinders. Place the temperature probe in the same cylinder.
- Connect the energy meter to a 12V power supply, through the energy meter, as shown, and switch it on at the same time as you press the 'START' button on the energy meter.
- Record the initial temperature of the cylinder in the table in the Student Handbook.
- **Take care! The heater is now hot! Hold it by the cables when you move it and do not leave it unattended.**
- Continue heating until the energy meter shows that 10kJ of energy have been supplied.
- Watch the temperature indicator and record the highest temperature reached by the cylinder.
- Remove the heater from the cylinder and store it back in a safe spot when the experiment is over.

Worksheet 6

Specific heat capacity of metals

Thermodynamics

The results are stored in a table like that shown below:

Name of metal	
Initial energy meter reading	
Initial cylinder temperature	
Final energy meter reading	
Final cylinder temperature	

So what:

Use the approach in the Student Handbook to calculate the specific heat capacity of the metal.

An alternative approach uses the formula:

$$Q = m \cdot c \cdot T$$

where: **Q** = quantity of energy delivered;
m = mass of substance heated;
c = specific heat capacity;
T = temperature rise produced.

For example, suppose that a metal cylinder has a mass of 0.5kg. When 3000J of electrical energy are supplied, its temperature rises by 45°C.

Substituting these values into the formula:

$$3000 = 0.5 \times c \times 45$$

so that specific heat capacity **c** = 0.13kJ/kg/°C

Challenges:

- Repeat the investigation for the other cylinders and record the results in the Student Handbook.
- One problem with this investigation is that heat is lost to the surroundings. Investigate the effect of insulating the cylinder with materials such as bubble-wrap, cardboard or polystyrene beads. If you have time carry out the same experiment over a longer of period of time and compare the results.
- Look up the specific heat capacity of the various metals. Discuss why your results differ from the real values and how you could get a more accurate reading.

Record your results in the Student Handbook.

Worksheet 7

Specific heat capacity of water

Thermodynamics

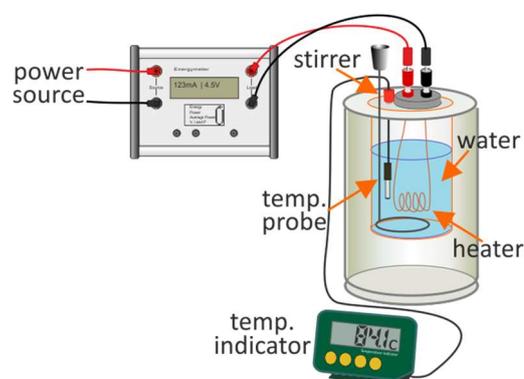
This investigation shows how to measure the specific heat capacity of a liquid - water in this case.

Water has a particularly high value of specific heat capacity - it requires a lot of energy to warm it up and releases a lot of energy when it cools.

This has significant implications for the Earth's climate.



The apparatus:



The apparatus consists of an insulated can, housing an electrical heater and a stirrer.

A temperature probe and indicator measure the temperature of the liquid inside.

The energy meter measures the electrical energy delivered to the water.

Over to you:

- Set up the apparatus as shown in the right-hand diagram. You will need a 5V power supply. Add 150ml of cold water to the insulated can and lower the temperature probe into it.
- Connect the energy meter to its plug-top power supply and switch it on.
- Press the mode button to select energy measurement.
If necessary, press the 'Reset' button to clear any previous measurements.
- Switch on the temperature indicator and record the initial water temperature in the table in the Student Handbook.
- Switch on the 5V power source and press the 'Start' button on the energy meter simultaneously. As the water warms stir it occasionally using the stirrer to distribute the heat in the vessel.
- Continue heating the water until the temperature has risen by around 5⁰C.
- Record the temperature reached and the energy supplied to achieve this. Repeat for 10C and 15C.
- Use the approach outlined in the Student Handbook to calculate the specific heat capacity of water.

Worksheet 7

Specific heat capacity of water

Thermodynamics

So what:

$$\begin{aligned} \text{Volume of water heated} &= 150\text{ml} = 0.15 \times 10^{-3} \text{ m}^3 \\ \text{Density of water} &= 997\text{kg}\cdot\text{m}^{-3} \\ \text{Mass of water heated, } m &= \text{water volume} \times \text{density} \\ &= 0.15 \times 10^{-3} \times 997 \\ &= 0.15\text{kg} \end{aligned}$$

$$\text{Energy delivered to water} = Q$$

$$\text{Resulting temperature rise} = T$$

$$\text{Rearranging the formula gives } Q = m \cdot c \cdot T$$

$$c = Q / (m \times T)$$

Your results can be used to calculate a value for the specific heat capacity of water. Follow the guide given in the Student Handbook to obtain your estimate of the specific heat capacity of water.

Challenge:

Verify the specific heat capacity for different temperature rises.

Investigate the effect on specific heat capacity of adding salt to the water?

Thermodynamics

Thermodynamics

Student Handbook

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For your records

Student Handbook **Thermodynamics**

Introduction:

First, a review of some related quantities:

- Energy:**
- makes things happen - moving, heating, lighting etc.;
 - is measured in joules (J).
- Power:**
- is how much energy is delivered each second;
 - is measured in watts (W).
- Average Power:**
- 'Average' means 'smooth out the variations'.
- Voltage:**
- measures the force pushing the electricity around the circuit;
 - is like the size of the pump forcing water through a pipe.
- Current:**
- measures how much electricity flows around the circuit;
 - is measured in amps (A).

The energy meter:

The energy meter is powered from a 5V DC plug top power supply. via its micro USB connector. The maximum voltage it can be measure is $\pm 25V$, while the maximum current is $\pm 7A$.

The smallest values that can be displayed are:

- energy 100nJ;
- power 100nW;
- voltage 1mV;
- current 100 μ A.



The display is refreshed every 0.5 seconds. The values displayed represent the values of current and voltage averaged over the 0.5 second period before the display is refreshed.

The temperature indicator:

The Extech temperature indicator offers a digital readout of temperature, accurate to the nearest $1^{\circ}C$, over a temperature range from $-40^{\circ}C$ to $+70^{\circ}C$.

It takes a temperature reading every 15s or so and holds that value on the display until the next reading.

It has the ability to record the maximum or minimum reading taken (since the last reset) and to hold the current reading.

Alarm temperature levels (high or low) can be set to cause an audible alert if exceeded.

When using the temperature indicator, be aware that it updates the display every 15s or so and will not follow rapidly changing temperatures.



The pressure gauge

The Bourdon-type pressure gauge contains a curved, sealed tube, which straightens when the pressure of the air inside increases. A lever system moves the pointer across the scale as a result.

It is an absolute pressure gauge, meaning that it would show a reading of zero if exposed to a perfect vacuum.

The pressure is shown in both imperial units - pounds per square inch (psi) and SI units - pascals (Pa). Standard atmospheric pressure is around 100,000 Pa or 15 psi.

We use SI units of pressure, shown by the red scale. On this, '1' indicates 100,000 (or 1×10^5) Pa. Each small division on the scale represents a change in air pressure of 10,000 Pa.

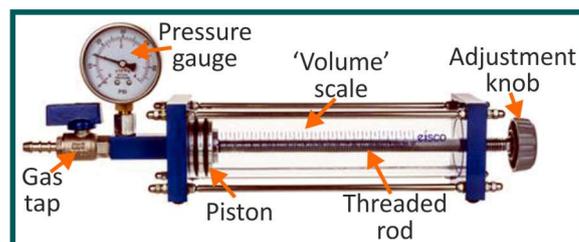


Student Handbook Thermodynamics

Worksheet 1 - Pressure vs volume

The apparatus is shown in the diagram:

The volume of trapped air is changed *slowly* and the resulting pressure is measured. The measurements are shown in the table.



Step 1 - Complete the third column of the table by calculating '1/V' for each value of volume 'V'.

Step 2 - Plot a graph of **P** against 1/V.

The graph should suggest a straight line relationship, meaning that the pressure is doubled when 1/V is **doubled**, i.e. when V is halved, and so on. This result is known as Boyle's law.

The pressure of a fixed mass of an ideal gas, at constant temperature, is inversely proportional to its volume.

It results in the formula: **pressure x volume = constant**,

$$\text{or } p_1V_1 = p_2V_2$$

Example:

When the pressure is 120 000Pa, a fixed mass of air has a volume of 0.5m³. What volume will it have when the pressure is 100 000Pa?

Using $p_1V_1 = p_2V_2$:

$$120\,000 \times 0.5 = 100\,000 \times V_2$$

$$V_2 = 120\,000 \times 0.5 / 100\,000$$

$$= 0.6\text{m}^3$$

- Explain why the volume should be changed *slowly*:

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In a similar experiment, the volume of air was 40 units when the pressure was 150 000Pa. Assuming that the air obeys Boyle's law:

- At what pressure would the volume be 20 units?

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- When the pressure is 120 000Pa, what would be the volume?

Challenge results:

Do your results suggest the same kind of behaviour as that described above?

Give reasons to support your answer.

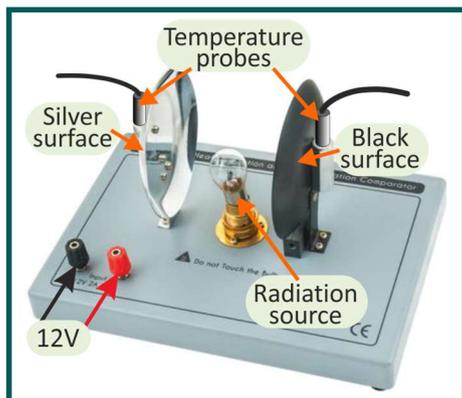
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Air pressure P	Air volume V	1 / V
	25	0.04
1.2		
1.3		
1.4		
1.5		
1.6		
1.7		
1.8		
1.9		
2.0		
2.1		
2.2		
2.3		
2.4		
2.5		
2.6		
2.7		
2.8		
2.9		
3.0		

Student Handbook Thermodynamics

Worksheet 3 - Black vs silver - 1

This investigation aims to show that the colour of a surface determines how well it absorbs infra-red (heat) radiation. The apparatus is shown below. The radiation source, (the lamp) is turned on and the temperature of the two reflectors is taken every minute for ten minutes. The results are shown in the table.



Time in mins	Temperature of silver reflector in °C	Temperature of black reflector in °C
0		
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		

Which of the two colours was better at absorbing radiation?

Which of the two colours was better at reflecting radiation?

Implications:

Why do people sometimes spread ash from a fire onto snowy surfaces?

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What is the best colour for a car to keep it cool on hot sunny days?

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Why are satellites often covered in shiny foil?

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Challenge results:

Describe the results of the challenge. What do they show about the absorption of infra-red radiation?

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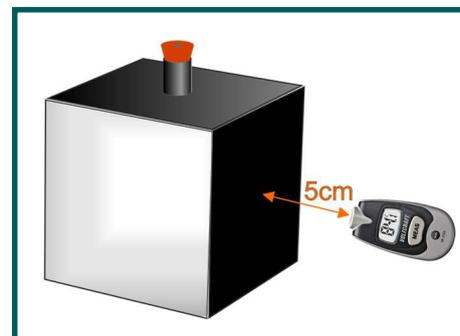
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Worksheet 4 - Black vs silver - 2

This investigation uses Leslie's cube, a metal box with different-coloured faces, to find out if some colours are better at radiating infra-red radiation than others.

Results:

Colour of face	Thermometer reading in °C
Matt black	
Shiny black	
White	
Unpainted	



All faces of the cube are at virtually the same temperature.

Why did the thermometer reading vary from face to face?

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Why was it important to keep the distance from the cube to the thermometer constant throughout the experiment?

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Describe the results of the 'Challenges' and their significance:

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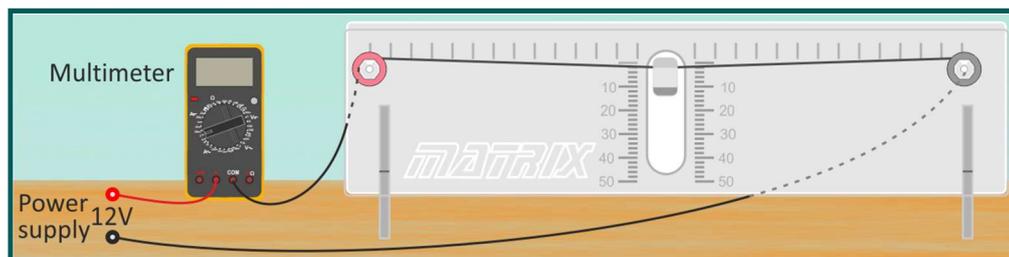
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Worksheet 5 - Thermal expansion

When objects heat up, they expand. The forces involved are enormous, as the photograph shows.



The apparatus consists of a length of 32 s.w.g. nichrome wire fastened to a baseboard and connected to a power supply. At its centre, a small weight keeps the wire taut.



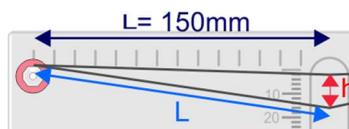
Linear expansivity is defined as the *fractional* change in length (increase in length / original length) occurring when the temperature rises by 1°C .

Measurements:

Original length of wire = $0.3\text{m} = 300\text{mm}$.

Original length $L = 0.15\text{m} = 150\text{mm}$

Distance fallen by weight, $h = \dots\dots\dots\text{mm}$



Final length of wire, $L = \sqrt{(150^2 + h^2)} = \dots\dots\dots\text{mm}$

Increase in length, $L - L = \dots\dots\dots\text{mm}$

Fractional increase in length = $\frac{\text{Increase in length}}{\text{Original length}} = \frac{L - L}{L} = \dots\dots\dots$

Current through wire = $\dots\dots\dots\text{A}$

Initial temperature of wire, $T = 20^{\circ}\text{C}$ (estimate)

Final temperature of wire, $T = \dots\dots\dots^{\circ}\text{C}$ (estimate from current measurement)

Temperature rise, $T - T = \dots\dots\dots^{\circ}\text{C}$

Linear expansivity = fractional increase in length / temperature rise = $\dots\dots\dots/^{\circ}\text{C}$

Describe two industrial uses of expansion.

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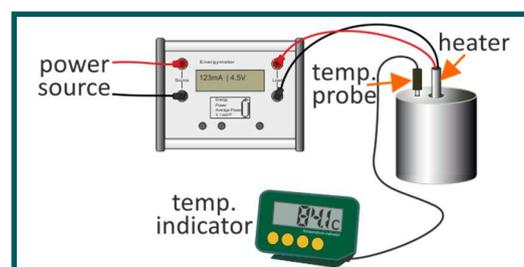
Student Handbook Thermodynamics

Worksheet 6 - Specific heat capacity of metals

Energy is needed to raise the temperature of a body, (make its particles move faster.) The bigger its mass, the greater the energy needed. Similarly, the bigger the temperature rise, the greater the energy needed. Some substances need more energy than others.

Specific heat capacity spells out how much energy is needed to raise the temperature of 1kg of a substance by 1^oC.

The investigation involves measuring the temperature rise produced in a 1kg metal cylinder when it is supplied with 10kJ (=10 000J) of energy.



Results:

Aluminium		Brass	
Initial energy meter reading		Initial energy meter reading	
Initial cylinder temperature		Initial cylinder temperature	
Final energy meter reading		Final energy meter reading	
Final cylinder temperature		Final cylinder temperature	
Copper (not supplied in standard kit)		Steel	
Initial energy meter reading		Initial energy meter reading	
Initial cylinder temperature		Initial cylinder temperature	
Final energy meter reading		Final energy meter reading	
Final cylinder temperature		Final cylinder temperature	

To calculate specific heat capacity:

Each block has a mass of 1kg so we don't have to take mass into account. Instead, simply divide the energy supplied (10 000J) by the resulting temperature rise.

Complete the following table with your results.

Challenge :

Carry out the same procedure with your results from the investigation using insulation.

Record your results in the following table.

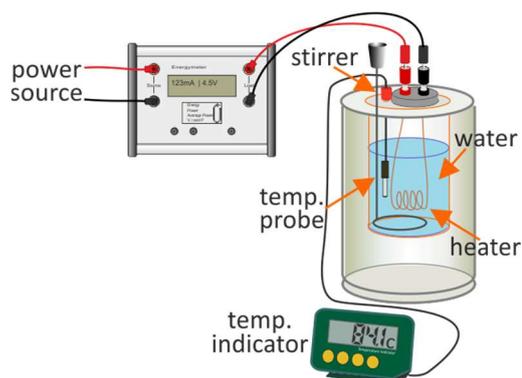
Compare your results with real values for the metals. Why is there a difference between practical and real results?

Results for uninsulated cylinders		
Metal	Temp.rise in ^o C	S.H.C. (= temp.rise / 10 000) in J / kg ^o C
Aluminium		
Brass		
Copper		
Steel		

Results for insulated cylinders		
Metal	Temp.rise in ^o C	S.H.C. (= temp.rise / 10 000) in J / kg ^o C
Aluminium		
Brass		
Copper		
Steel		

Student Handbook Thermodynamics

Worksheet 7- Specific heat capacity of water



The apparatus consists of an insulated can, housing an electrical heater and a stirrer. A temperature probe and indicator measure the temperature of the liquid inside.

The energy meter measures the electrical energy delivered to the water.

Your results:

$$\begin{aligned} \text{Volume of water heated} &= 150\text{ml} = 0.15 \times 10^{-3} \text{ m}^3 \\ \text{Density of water} &= 997\text{kg}\cdot\text{m}^{-3} \\ \text{Mass of water heated, } m &= \text{water volume} \times \text{density} \\ &= 0.15 \times 10^{-3} \times 997 \\ &= 0.15\text{kg} \end{aligned}$$

$$\text{Energy delivered to water, } Q = \dots\dots\dots\text{J}$$

$$\text{Resulting temperature rise, } T = \dots\dots\dots^{\circ}\text{C}$$

$$\begin{aligned} \text{Rearranging the formula} & \quad Q = m \cdot c \cdot T \\ \text{gives} & \quad c = Q / (m \times T) \end{aligned}$$

$$\begin{aligned} \text{Substituting your results:} & \quad c = \frac{\dots\dots\dots}{\dots\dots\dots \times \dots\dots\dots} \\ & = \dots\dots\dots \text{ J}\cdot\text{kg}^{-1}\cdot^{\circ}\text{C}^{-1} \end{aligned}$$

Challenge results:

What is the effect on specific heat capacity of adding salt to water?

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Water has a high value of specific heat capacity. What is the significance of this in our everyday lives?

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Thermodynamics

Thermodynamics

Instructor Guide

Instructor Guide **Thermodynamics**

About this course

Introduction

The course is essentially a practical one. The equipment makes it simple to conduct experiments designed to encourage clear understanding of thermodynamics. Where possible, practical implications and applications of the theory are highlighted to make the course more relevant to the students.

A Student Handbook is included to give students a concise record of their studies.

Aim

Thermodynamics is at the core of our everyday lives.

It is the science behind all processes involving heat exchange - all fossil-fuelled engines, power stations, refrigerators, air conditioning, wind generators etc. It even explains why we sweat!

Prior Knowledge

It is recommended that students have followed a general science or physical science course up to GCSE level and have the ability to perform simple mathematical operations.

Learning Objectives

On successful completion of this course the student will be able to:

- distinguish between and relate the terms 'energy' and 'power';
- distinguish between and relate the terms 'voltage' and 'current';
- state the units in which energy, power, voltage and current are measured;
- explain what is meant by the prefixes 'milli', 'micro' and 'nano';
- use an energy meter to measure the energy delivered to a load;
- use an Extech temperature indicator to monitor the temperature of a body;
- state the SI unit of pressure and measure it using a Bourdon gauge;
- investigate the relationship between the pressure of a gas and its volume;
- state Boyle's law and recall an equation derived from it;
- investigate the relationship between the pressure of a gas and its temperature;
- state Gay-Lussac's law and recall an equation derived from it;
- use the results of this experiment to predict the absolute zero of temperature;
- investigate the effect of colour of a surface on its ability to absorb thermal radiation;
- describe three implications for everyday life of the way in which different colours absorb thermal radiation in different ways;
- use Leslie's cube to investigate the effect of surface on a body's ability to radiate thermal energy;
- give an everyday example to illustrate the forces involved in thermal expansion;
- set up a demonstration of the expansion of a metal wire when heated;
- use given data to calculate linear expansivity;
- list three factors which determine the amount of energy needed to raise the temperature of a body;
- use the formula $Q = m.c.T$ to calculate the energy needed to raise the temperature of a body;
- set up an experiment to measure the specific heat capacity of a metallic solid;
- devise an experiment to test the effectiveness of an insulating material on the determination of specific heat capacity;
- set up an experiment to measure the specific heat capacity of a liquid;
- use the formula $Q = m.c.T$ to calculate the specific heat capacity of water, given appropriate data;
- explain the significance of the high value of specific heat capacity for water on the Earth's climate.

Instructor Guide **Thermodynamics**

What the student will need:

To complete the thermodynamics course, the student will need the following equipment:

1	LK8591	Energy Meter
1	HP5540	Deep tray
1	HP4039	Tray Lid
1	LK5603	Lead, red, 500mm, 4mm to 4mm stackable
1	LK5604	Lead, black, 500mm, 4mm to 4mm stackable
1	HP9061	Digital Thermometer
1	HP3140	Leslie Cube
1	HP1586	Infrared Thermometer
1	HP3658	Jolly Bulb
1	HP0010	Measuring beaker
1	HP3519	Boyle's Law apparatus
1	HP7880	Heat Absorption apparatus
1	HP1233	Thermocouple K type 1m length
1	HP4566	Duratool thermometer
1	HP8187	Steel Block calorimeter
1	HP3761	Aluminium Block calorimeter
1	HP6809	Brass Block calorimeter
1	HP7758	Calorimeter
1	HP6457	Thermal expansion of Metals apparatus
1	HP8119	1 metre 32SWG Nichrome wire.

In addition to this students will need a 12V bench top supply capable of delivering up to 4 Amps.

Using this course:

The experiments in this course should be integrated with teaching to introduce the theory behind it, and reinforced with written examples, assignments and calculations.

The worksheets should be printed / photocopied / laminated, preferably in colour, for the students' use. They should make their own notes to enhance those provided in the Student Handbook. They are unlikely to need their own permanent copy of the worksheets.

This format encourages self-study, with students working at a rate that suits their ability. The instructor should monitor that students' understanding keeps pace with their progress through the worksheets. One way to do so is to 'sign off' each worksheet, as a student completes it, and in doing so have a brief chat with the student to assess grasp of the ideas involved in the exercises it contains.

Students would benefit from using Excel to plot graphs. Failing this they should be provided with additional graph paper for making plots as appropriate.

Time:

It should take students between 3 and 5 hours to complete the worksheets. It is expected that a similar length of time will be needed to support the learning that takes place as a result.

Scheme of Work **Thermodynamics**

Worksheet	Notes for the Instructor	Time
Introduction	<p>The introduction begins with a review of physical quantities, such as energy and power and their measurement units. Depending on students' understanding and experience, the instructor may need to expand on what is given here.</p> <p>It continues with details of how to use the energy meter and how to interpret the screen contents.</p> <p>It gives an introduction to the other measuring instruments used in the course. One important feature of the temperature meter is that it samples temperature, rather than monitoring it continuously. This has implications for the design of experiments.</p> <p>The instructor may wish to go into more detail about air pressure - its units, the distinction between absolute and relative pressure readings and how the Bourdon pressure gauge works, or students could research these topics.</p>	15 - 25 mins
1	<p>This investigation looks at one of the fundamental properties of a gas and leads to Boyle's law. This is also known as Boyle-Mariotte's law, as it was crafted separately by Robert Boyle, and Edme Mariotte in the 17th century.</p> <p>It describes the relationship between pressure and volume in a fixed mass of gas kept at a steady temperature.</p> <p>The apparatus uses a Bourdon gauge to monitor pressure. Students may need help with the scales on the gauge, which include scientific (Pascal) and engineering (PSI) units.</p> <p>The volume of the cylinder-shaped mass of air trapped in the tube is equal to the length of the air cylinder multiplied by its cross-sectional area. Here, it is measured in relative units, using a linear scale on the transparent tube. This is valid provided the cross-section of the tube is constant along its length.</p> <p>Changes to the volume should be made relatively slowly to avoid heating up the gas. (This is one of the questions in the Student Handbook.) Readings should then be taken quite quickly as the seal around the piston will slowly leak.</p> <p>The Challenge is to extend the range of readings below atmospheric pressure.</p> <p>Where facilities are available and students have the ability, a spreadsheet program such as 'Excel' makes an excellent graph-plotting tool and may address IT-related objectives for the course.</p>	20 - 30 mins
2	<p>This investigation explores another classic relationship - between gas pressure and temperature in a fixed mass of gas. Known as Gay-Lussac's law (though others were also involved in its formulation,) it applies only when the temperature is measured in the absolute (Kelvin) scale. The instructor may need to elaborate on this.</p> <p style="text-align: center;">Safety! The experiment involves near-boiling water.</p> <p style="text-align: center;">The instructor must ensure that measures are taken to avoid scalds!</p> <p>Students could be invited to design appropriate methods to control the temperature of the water and hence trapped air, as there are a number of possible approaches. The sphere is made from metal, a good conductor of heat, but nevertheless there will be a time lag between a change in the water temperature and the resulting change in the temperature of the air.</p> <p>Ideally, the volume of trapped air remains unchanged throughout the experiment. The thick-walled sphere helps towards this, but there will be some expansion. Students could be invited to suggest how this would affect the readings and graph.</p> <p>Once again, a spreadsheet program could be used to generate a graph of the results.</p>	20 - 30 mins

Scheme of Work **Thermodynamics**

Worksheet	Notes for the Instructor	Time
3	<p>Another topic within thermodynamics is the effect of surface colour on the absorption and reflection of radiation. This investigation provides an introduction to that topic. One of the two surfaces is matt black, the other polished. Equally spaced from the source of radiation, a lamp, both are subjected to the same intensity of radiation. The extent to which they absorb or reflect that radiation is assessed by measuring the temperature rise resulting from the radiation.</p> <p style="text-align: center;">Safety! The lamp and reflectors get very hot! Students must be instructed not to touch them.</p> <p>The Challenge involves another experiment design, to devise an experiment to confirm that the results are the effect of surface rather than some other cause.</p>	20 - 30 mins
4	<p>This investigation looks at the other aspect of the black vs silver debate - the ability to radiate energy. Another classic piece of kit, Leslie's cube has each side finished in a different colour. Heated with hot water, all faces of the metal cube have the same temperature. However, an infra-red thermometer perceives them to be at different temperatures because they radiate more or less energy.</p> <p>The thermometer reading is a measure of how much thermal radiation is emitted from that face of the cube. The optical system of the thermometer collects infra-red energy from a circular field of view, or 'measurement spot' and focuses it on the detector. It should be placed at such a distance that the face of the cube fills the field of view. Then, the reading is a true measure of the radiation from that surface. If the thermometer is too far away, it will 'see' other objects as well.</p> <p style="text-align: center;">Safety! The experiment involves near-boiling water. The instructor must ensure that measures are taken to avoid scalds!</p> <p>For the reasons just given, it is important that all measurements are made at the same distance from the cube and with the sensor at the same angle to it. Students must design their method to address these factors.</p> <p>The first part of the Challenge explores the effect of distance.</p> <p>The second part invites students to do some on-line research to learn about the 'FUNcube' project. In November 2013, AMSAT (AMateur Radio SATellite) launched a satellite called FUNcube 1. In reality, it is a Leslie's cube in space, whose output can be accessed by educational institutions.</p>	20 - 30 mins
5	<p>This investigation can be approached at two levels. At its simplest, it is a quick and reliable demonstration that hot solids expand. Where students are reasonably adept at manipulating mathematical equations, it provides an 'engineering' approach to estimating the linear expansivity of the wire, using look-up table to obtain an estimate of the temperature of the wire.</p> <p style="text-align: center;">Safety! The wire gets extremely hot and must not be touched.</p> <p>The instructor may choose to plot a graph of the data given in the look-up table to provide the students with another means of obtaining the temperature.</p> <p>The value of expansivity obtained is always going to be only an estimate as the exact composition of the material in the wire is usually uncertain.</p> <p>The Student Handbook asks for the results of a brief piece of research into industrial uses of expansion. The instructor may wish to add further structure to this task.</p> <p>Note that repeated use and over current may damage the wire which is standard Ni-chrome 32 SWG wire and is a consumable in this kit. There is a spare 1m coil in your kit and this is readily available for electrical suppliers.</p>	20 - 30 mins

Scheme of Work **Thermodynamics**

Worksheet	Notes for the Instructor	Time
6	<p>The introduction hints at some kinetic theory - that particles in hot substances move faster on average than those in cold substances. The significant point here is that energy must be supplied to raise the temperature of a material.</p> <p>Some require more energy than others, just by virtue of their structure. The greater the mass of the substance, the greater the energy required to raise its temperature - it probably has more particles in it to speed up! The greater the temperature rise needed, the greater the energy needed.</p> <p>The approach used is simple and direct. The metal cylinder has a mass of 1kg - specific heat capacity is quoted for a mass of 1kg. It is supplied with a quantity of electrical energy, measured on the energy meter. The resulting temperature rise is measured. The specific heat capacity is defined as the energy to raise 1kg of a substance by 1^oC. The measurements lead to a value for this.</p> <p>In the basic version of the experiment, the cylinder is not insulated and so some heat energy is lost to the surroundings. The students could be asked how this will affect the result. To minimise these losses, the temperature rise is kept small. Students could repeat the process for greater quantities of energy to see the effect of increased heat loss. (The hotter a body, the greater its heat loss.)</p> <p>The experiment is repeated for other metals. To save time, different groups could be given different metals.</p> <p>The Challenge invites them to insulate the cylinders and repeat the process. Different groups of students could be given different insulators or different thicknesses of insulation. Each could report on its findings to the rest of the class.</p>	30 - 40 mins
7	<p>Water has one of the highest values of specific heat capacity of all liquids. One consequence is that seas and lakes act as reservoirs for heat energy, giving nearby areas a mild climate. On the coast, sand has a lower specific heat capacity and so heats up more quickly than the sea. This results in land and sea breezes. Farmers and gardeners often spray plants with water when temperatures fall in winter to stop the plants from freezing and being damaged as a result.</p> <p>The approach is the same as in the previous investigation - to supply a known mass of water with a measured quantity of electrical energy and measure the resulting temperature rise. From these measurements, the specific heat capacity of water can be deduced.</p> <p>Once again, there is a time lag between the electrical heater warming up and the water responding. The answer is frequent stirring and looking for the highest temperature reached.</p> <p>The Student Handbook guides the students through the calculations needed to obtain the specific heat capacity of water.</p> <p>The Challenge is to carry out the same experiment using salt water, to find its specific heat capacity. The instructor could direct different groups to use amounts of salt.</p>	30 - 40 mins

Version control

Thermodynamics

27 10 20 Added an alternative worksheet 1 for new pressure/volume apparatus as original large syringe no longer available.

24 11 21 BOM changes for Thermal expansion of metals parts and Heat capacity of metals parts.

19 05 22 Nichrome wire added as consumable.