# CPL Theory
# Aircraft Systems (CSYA)

## CSYA 1 – Piston Engines

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## 3. Disclaimer

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# TYPES OF PISTON ENGINES

## Engine Manufacturers

- Light aircraft manufacturers usually do not produce their own engines
- Engines manufactured by Lycoming or Continental are typically fitted to Cessna, Piper and other popular makes. These engines have changed little in over 50 years

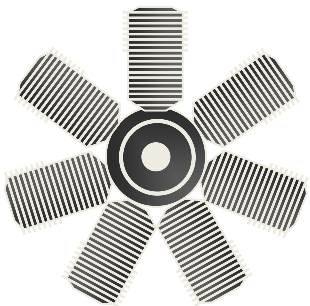
**CAE C172 Fleet is fitted with Lycoming IO-360, which is rated at 180HP at 2700RPM**

# Can you name these engine types?

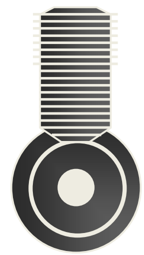

# Piston Engine Configurations

- Light aircraft typically use a piston engine (reciprocating)

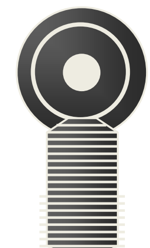
- The piston engine is configured based on the location of the pistons and the crankshaft



Radial Engine

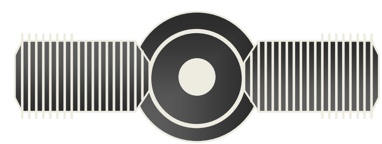


Inline upright



Inline inverted

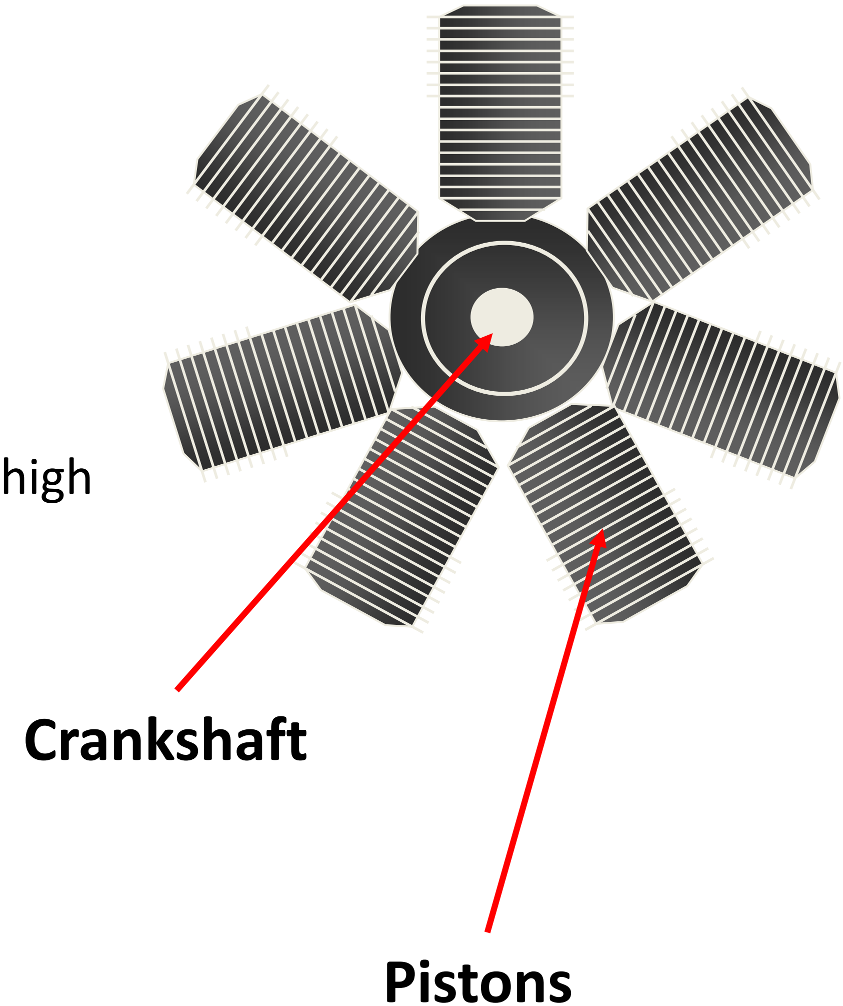
Vee



Horizontally opposed

# Radial Engine

- Used on older aircraft
- Pistons were arranged radically around the crankshaft
- Excellent power to weight ratio
- Good airflow for cooling
- However the large frontal area created high amounts of drag and poor visibility

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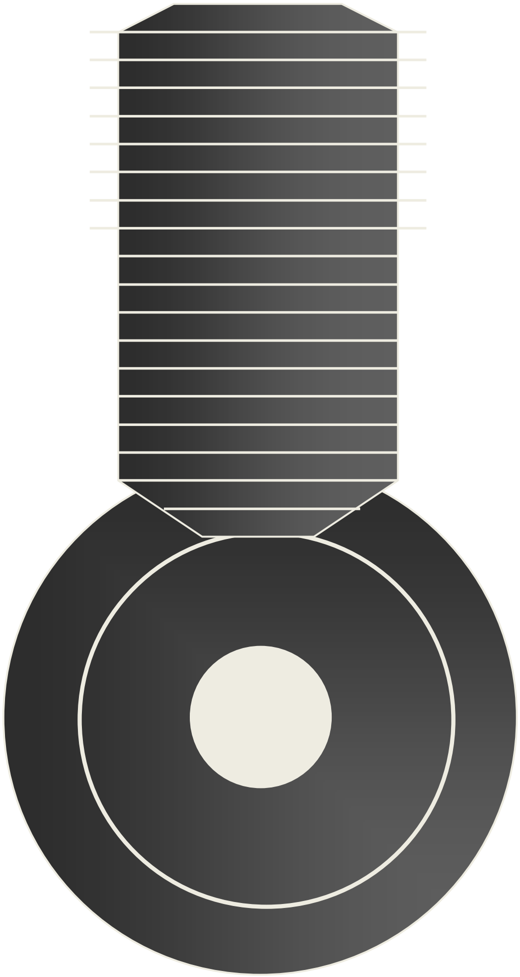
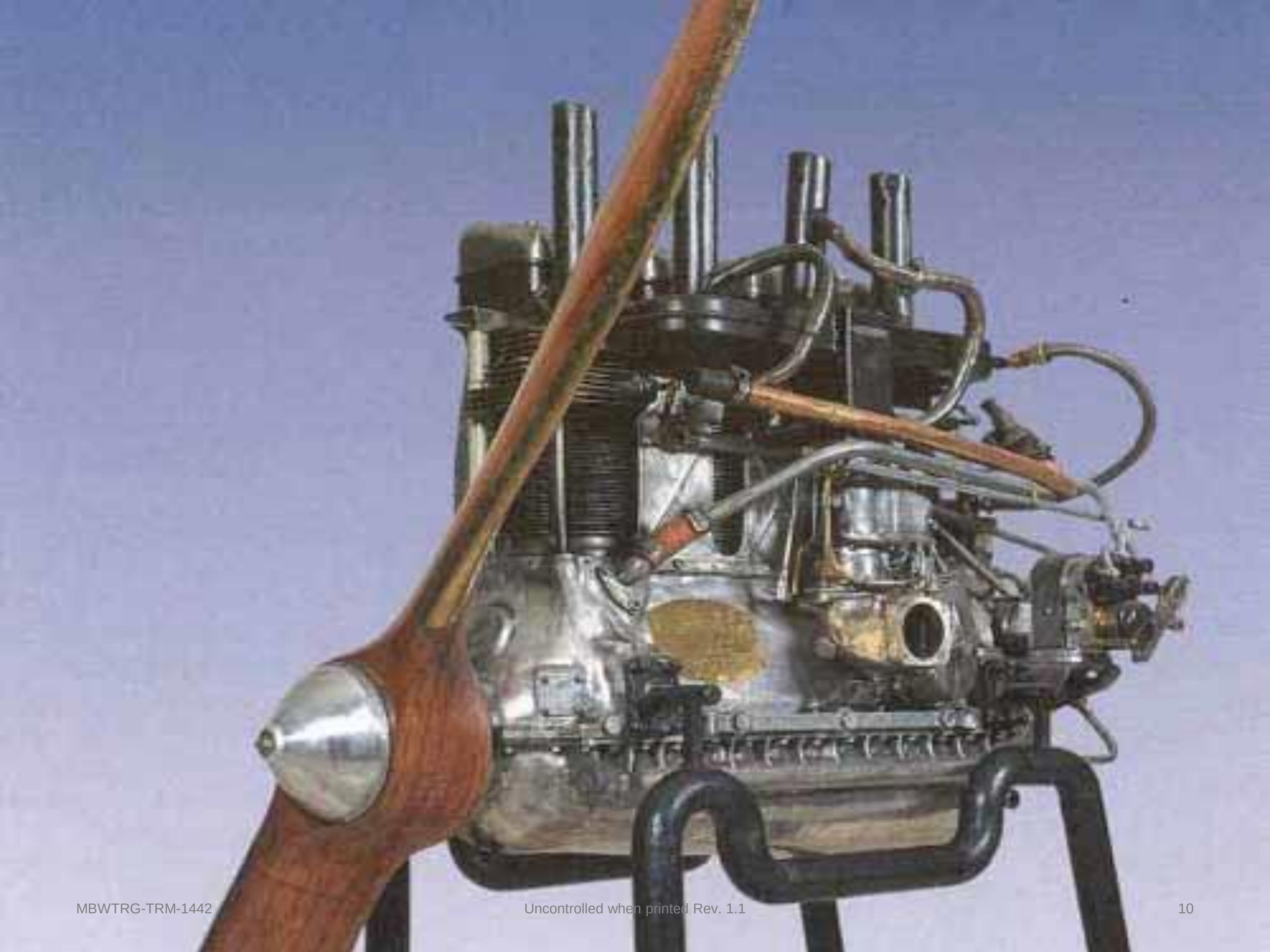
JACK

## Inline Upright

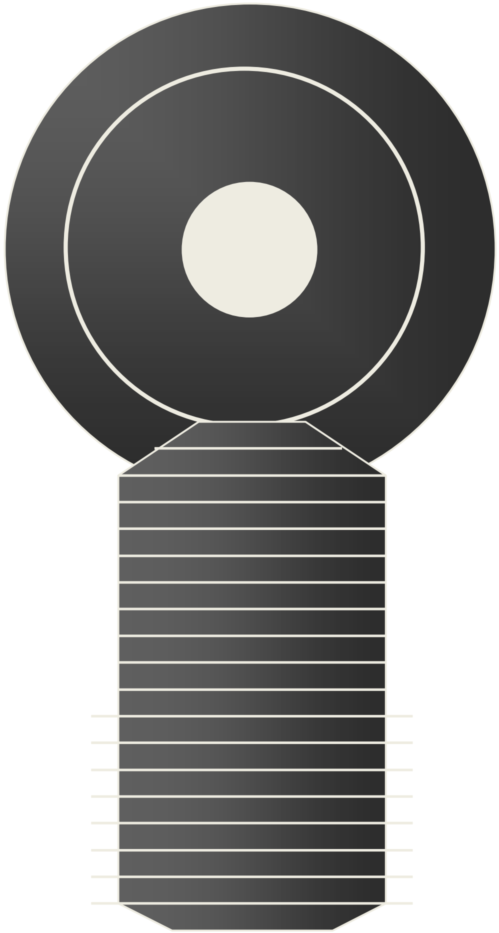
- Rarely used on aircraft, mainly on early model cars
- The cylinders provide poor visibility
- The location of the crankshaft meant the propellers were close to the ground





# Inline Upright

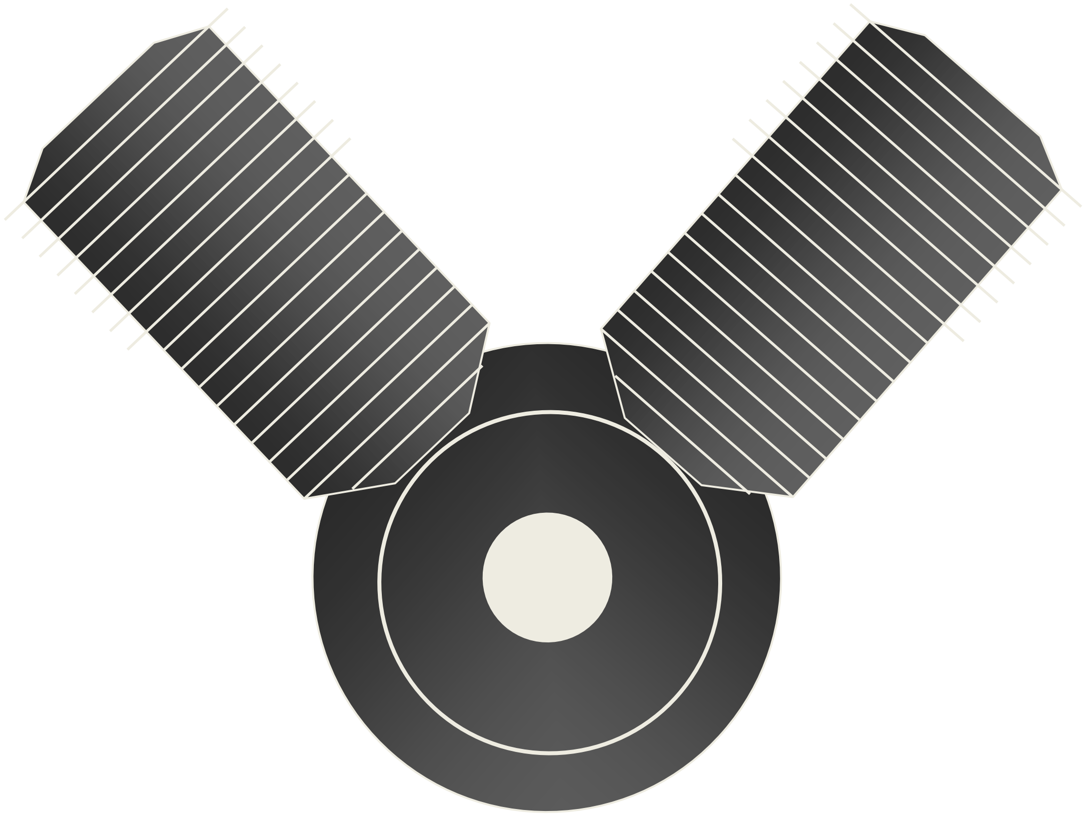
- The propeller is clear of ground and visibility is increased
- However, oil can drip into head overnight. Could damage head on startup
- Solution was to pull propeller through by hand and if jamming, hold until oil drained out a valve

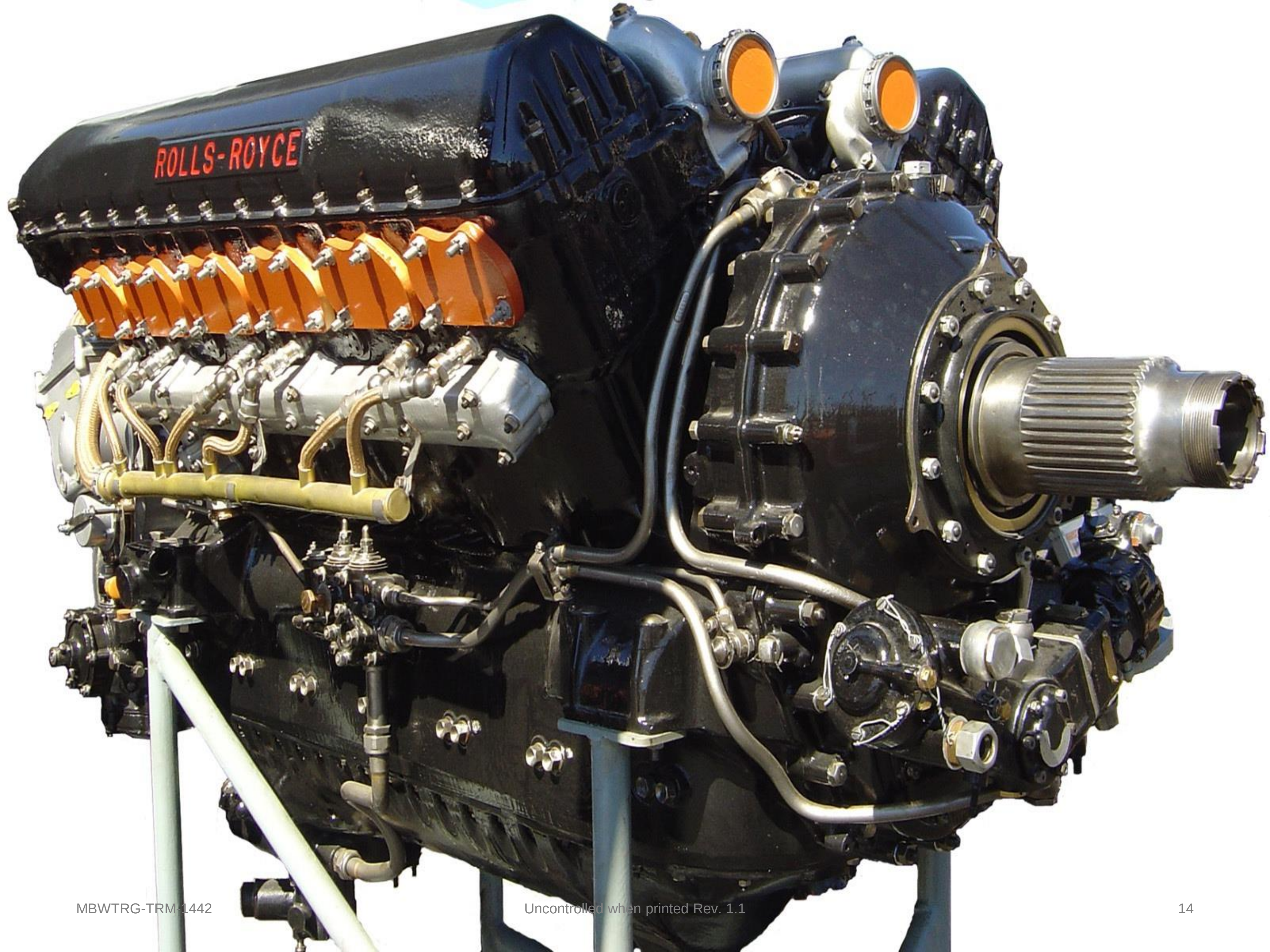



SC002

# Vee

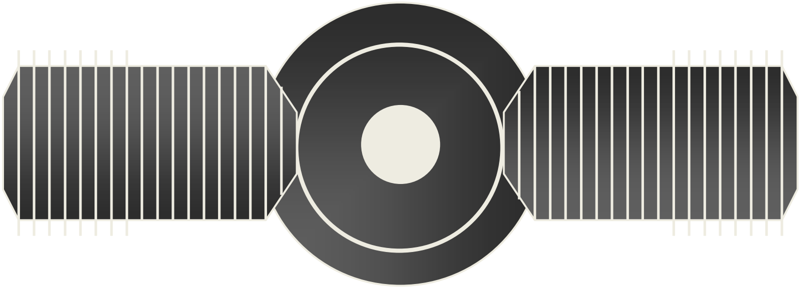
- Used in modern car designs
- Reduces the required length of the engine bay




ROLLS-ROYCE

# Horizontally Opposed

- Most common light aircraft engine
- C172 has 4 cylinders horizontally opposed



# WHAT DOES AN ENGINE DO?

# What does an engine do?

An engine simply burns fuel and harnesses the energy produced. To create a fire three things are needed:

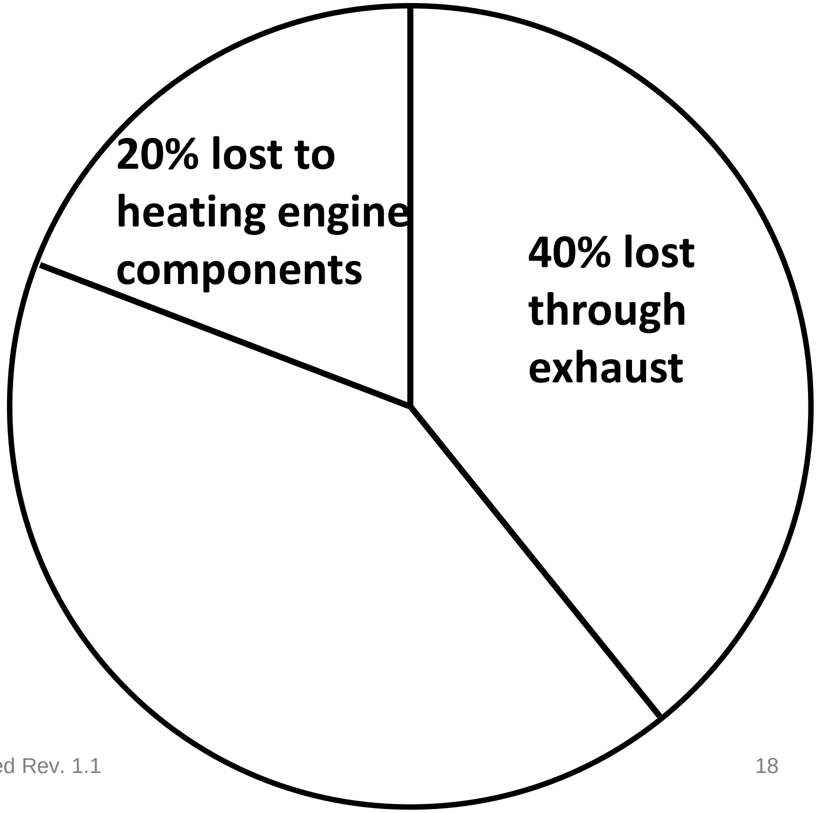
- Air
- Fuel
- Source of ignition

## What does an engine do?

- Another way to define an engine's function is simply to say that it produces **power**
- This power is then converted into **thrust** via the **propeller**
- However, is all of the power (heat energy) converted into thrust via the propeller?
- The answer – **definitely not!**
- **Engine thermal efficiency** compares the total heat energy released within the combustion chamber with the energy that is actually delivered to the piston
- **Around half** the heat energy is actually wasted as it:

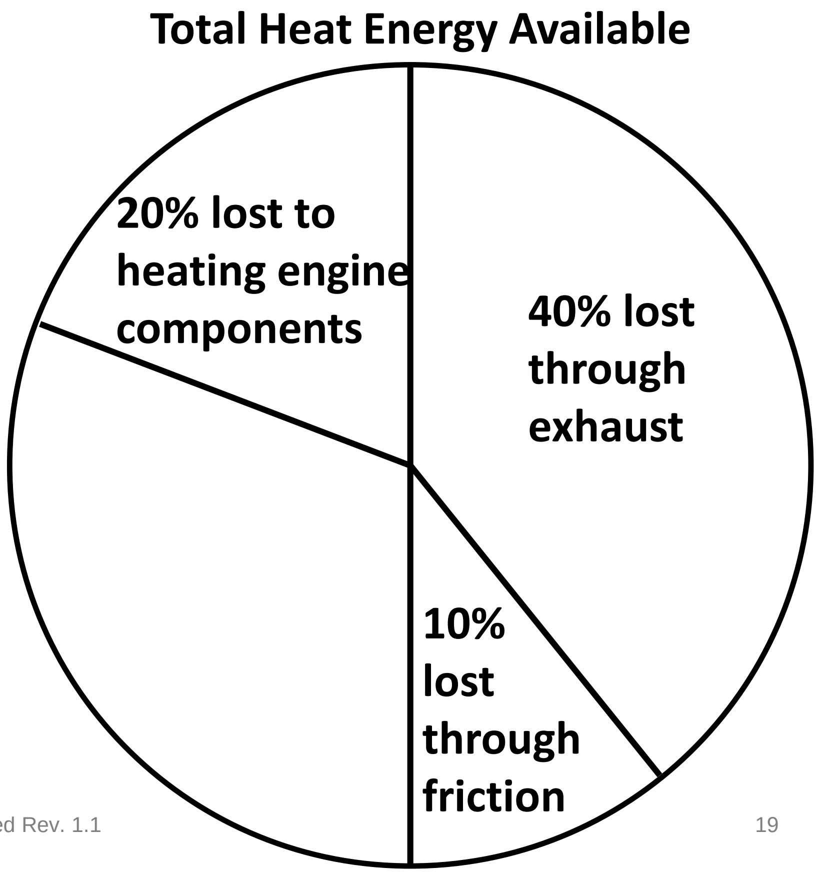
1. Passes out as **exhaust gas** through the exhaust system
2. Heats engine components – particularly the cylinder heads

**Total Heat Energy Available**



## What does an engine do?

- The remaining energy provides the power that is actually delivered to the piston to push it down on the power stroke – this is referred to as **Indicated Horse Power (IHP)**
- A further 10% is then lost to:
  1. Friction inside the cylinders
  2. Running engine accessories
     - Magnetos
     - Fuel Pump
     - Oil Pump
     - Superchargers
- This lost power is called **Friction Horse Power (FHP)** and good engine lubrication and design keeps this at around 10%
- Friction loss determines the **mechanical efficiency** of the engine



# What does an engine do?

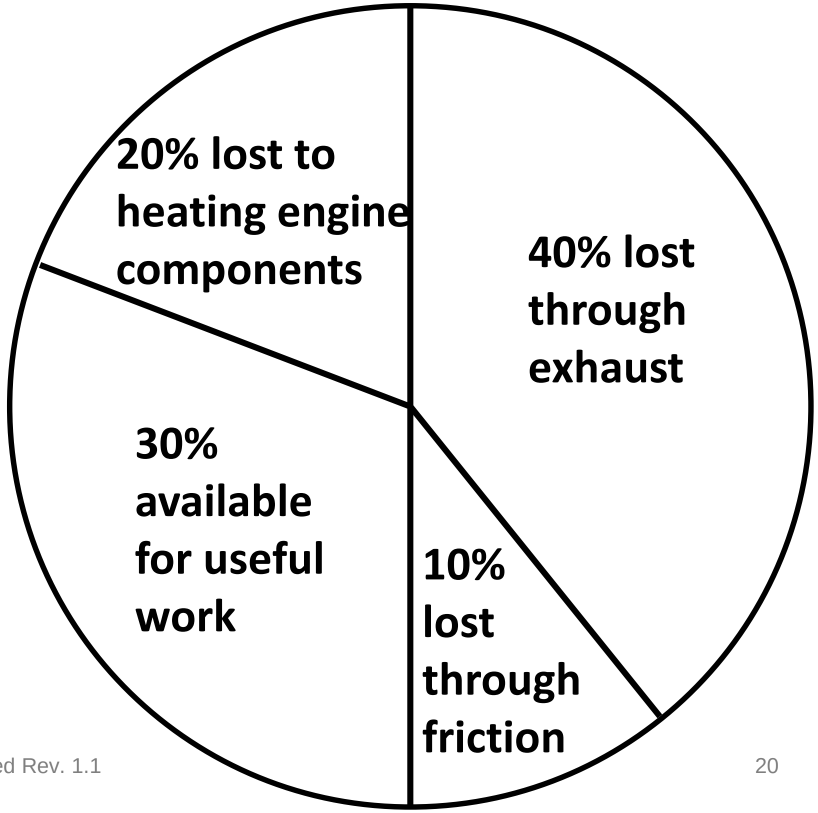
- The power that remains will be available to do useful work – i.e. turn the crankshaft
- This is known as **Brake Horse Power (BHP).** In summary:

**1. Total Heat Energy – Exhaust Losses – Engine Heating Losses = Indicated Horse Power**

**2. IHP – FHP = BHP**

**3. BHP is around 30% of the total power originally available from a light engine aircraft**

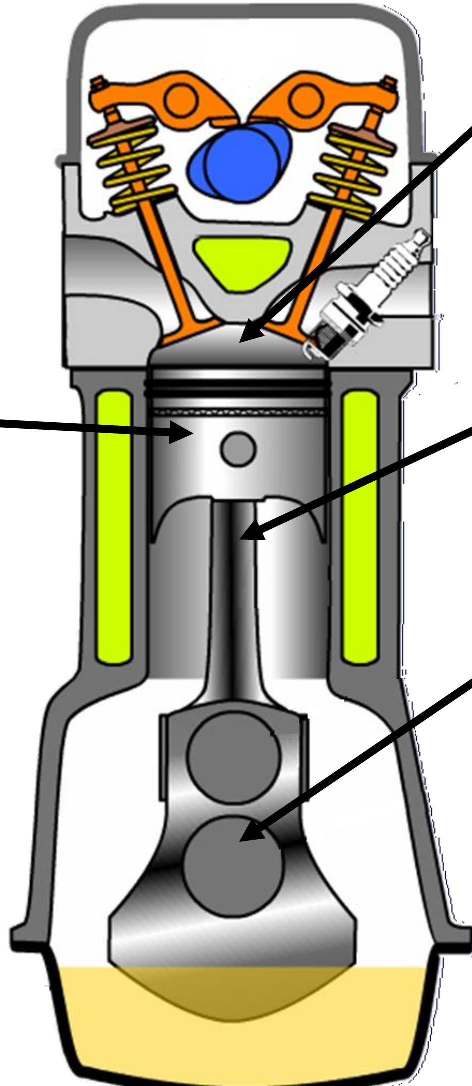
**Total Heat Energy Available**




- We must also consider the further losses due to **aerodynamic efficiency** of the propeller – losses due to drag and friction
- This means that possibly as little as 20% of the original total energy may actually be converted into thrust!
- This is known as **Thrust Horsepower (THP)**

# 4 STROKE CYCLE

# 4 Stroke Cycle



## PISTON

Is free to move within the cylinder and forms one of the walls of the combustion chamber

Has 3 piston rings which:

- seal the piston in the cylinder and prevents leakage (loss of power)
- lubricate the cylinder

## COMBUSTION CHAMBER

Area of the cylinder above the piston head in which the fuel/air is compressed and burned

## CONNECTING ROD

Forms a link between the piston and the crankshaft

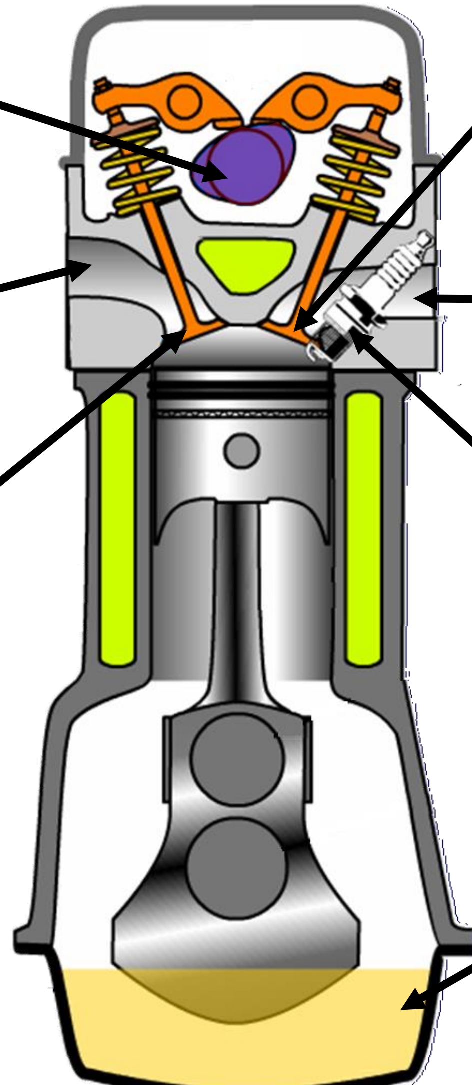
## CRANKSHAFT

Changes the straight line motion of the piston to a rotary turning motion required for the propeller

The propeller is attached directly to the crankshaft

# 4 Stroke Cycle

# 4 Stroke Cycle



**CAMSHAFT**

Provides the timing sequence for the intake and exhaust valves (driven by the crankshaft)

**INTAKE MANIFOLD**

Where the gas flows through INTO the cylinder

**INTAKE VALVE**

Is required to allow the fuel/air mixture to enter the cylinder

**EXHAUST VALVE**

Is required to allow the exhaust gases to exit the cylinder

**OUTLET MANIFOLD**

Where the gas flows through OUT of the cylinder

**SPARK PLUG**

Provides the spark required for combustion

**OIL SUMP**

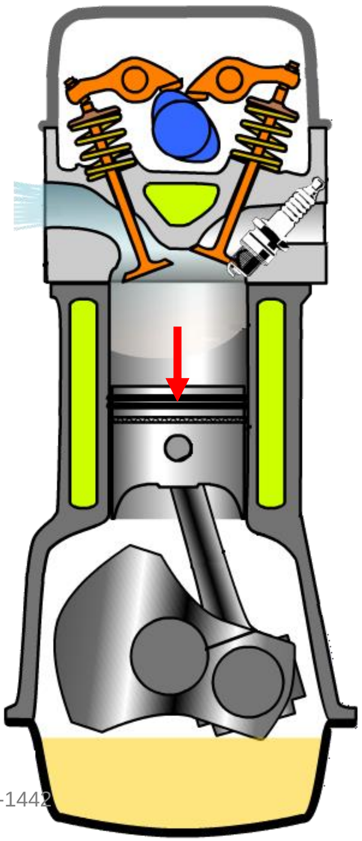
Oil lubricates the engine as the crankshaft is rotated

# 4 Stroke Cycle

# 4 Stroke Cycle

- A complete cycle of a piston engine comprises of four strokes known as the OTTO cycle, (named after the inventor Nikolaus Otto)

- The four strokes are:



**1** **Intake (or induction)**

- Piston travels down towards the crankshaft (from Top Dead Centre to Bottom Dead Centre)
- As the piston moves down, a low pressure is created inside the cylinder
- This causes a fresh charge of fuel/air mixture to be drawn into the combustion chamber (like a syringe)

# 4 Stroke Cycle

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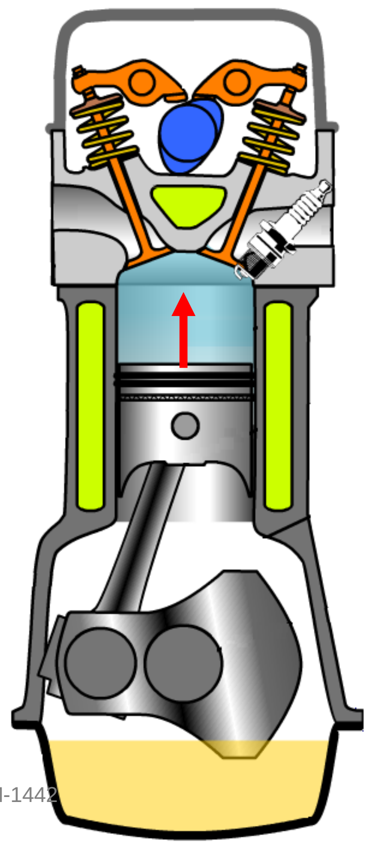
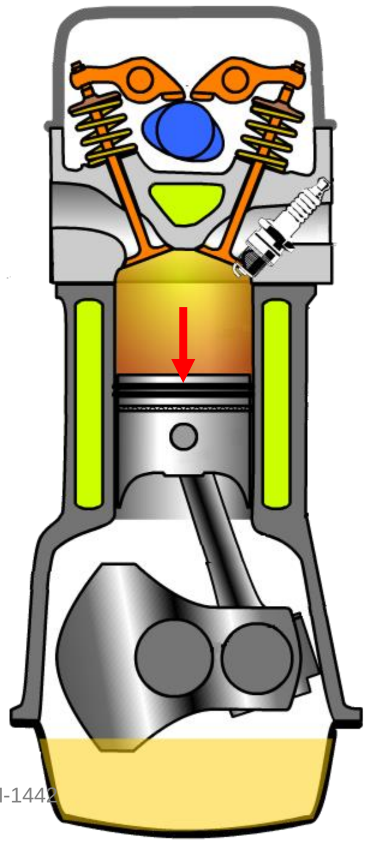


1. **Intake (or induction)**
2. **Compression**
   - Piston travels upwards away from the crankshaft (from Bottom Dead Centre to Top Dead Centre)
   - This compresses the fuel/air mixture to approximately 1/8th its original density
   - Towards the end of the compression stroke, the spark plugs fire and the fuel/air mixture is ignited

# 4 Stroke Cycle

- A complete cycle of a piston engine comprises of four strokes known as the OTTO cycle, (named after the inventor Nikolaus Otto)

- The four strokes are:

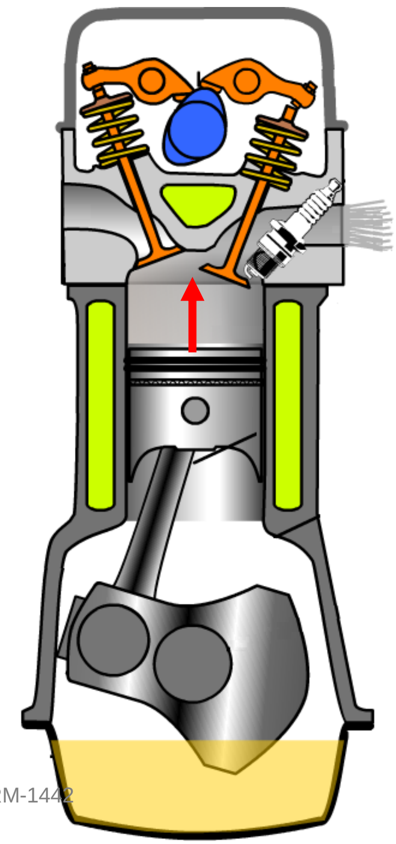


1. **Intake (or induction)**
2. **Compression**
3. **Power or Combustion**
   - The pressure of combustion forces the piston down the barrel towards the crankshaft (from Top Dead Centre to Bottom Dead Centre)
   - This rapid downwards movement of the piston rotates the crankshaft which in turn rotates the propeller

# 4 Stroke Cycle

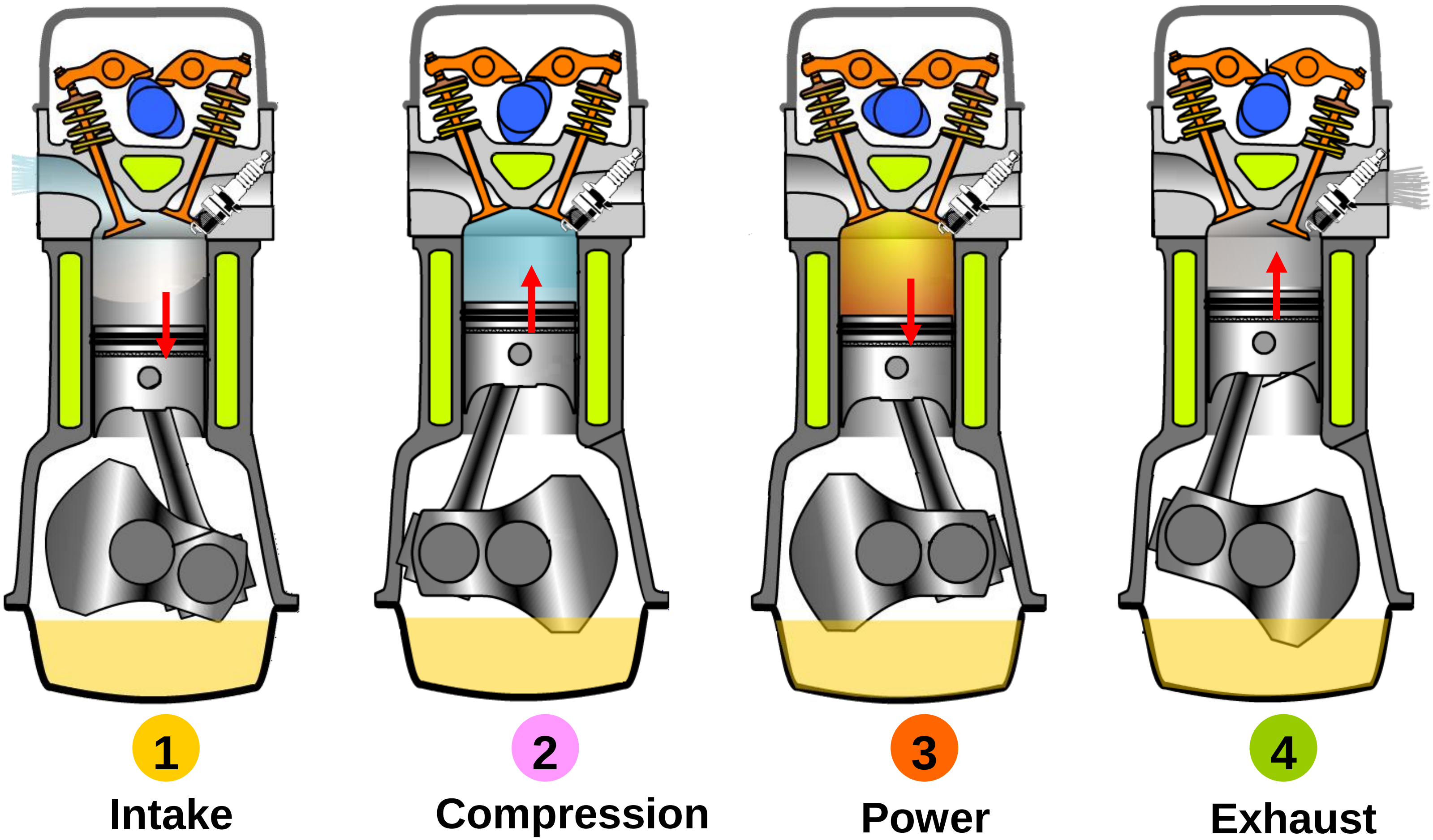
- A complete cycle of a piston engine comprises of four strokes known as the OTTO cycle, (named after the inventor Nikolaus Otto)

- The four strokes are:



1. **Intake (or induction)**
2. **Compression**
3. **Power or Combustion**
4. **Exhaust**
   - The piston is forced back up the barrel (from Bottom Dead Centre to Top Dead Centre)
   - This expels the spent gases through the exhaust valve
   - The cycle then starts again

# 4 Stroke Cycle



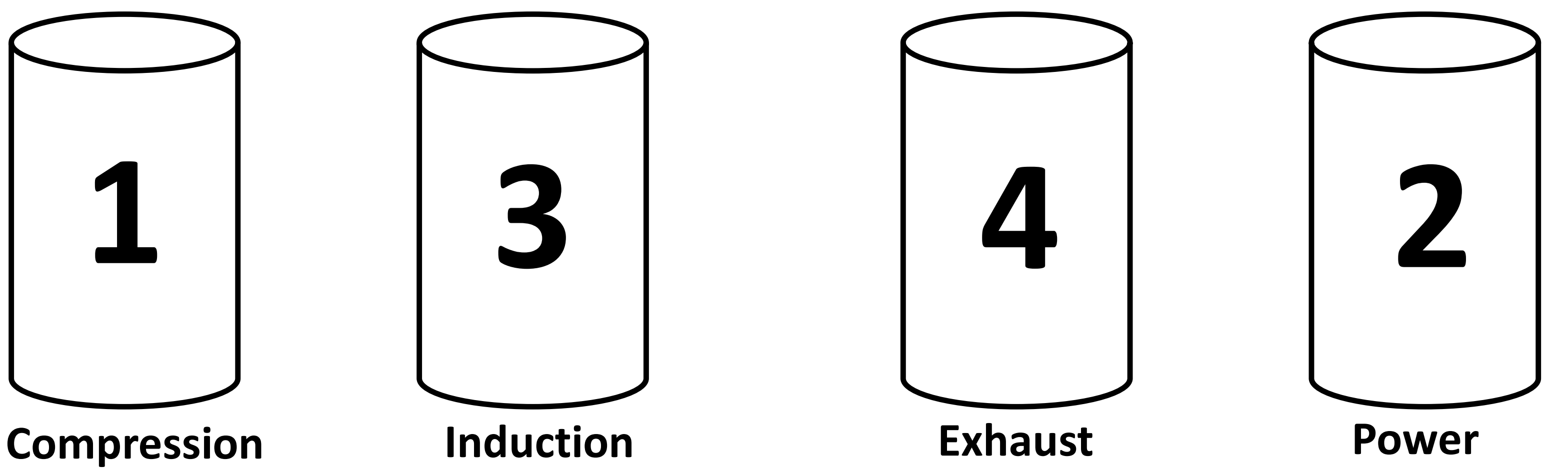

- 4 strokes of the piston generates **2 revolutions of the crankshaft** and **one revolution of the camshafts**

# FIRING ORDER

# Firing Order

- Now that we know the 4 stroke cycle, we can work out what stroke any particular piston is carrying out at any given time

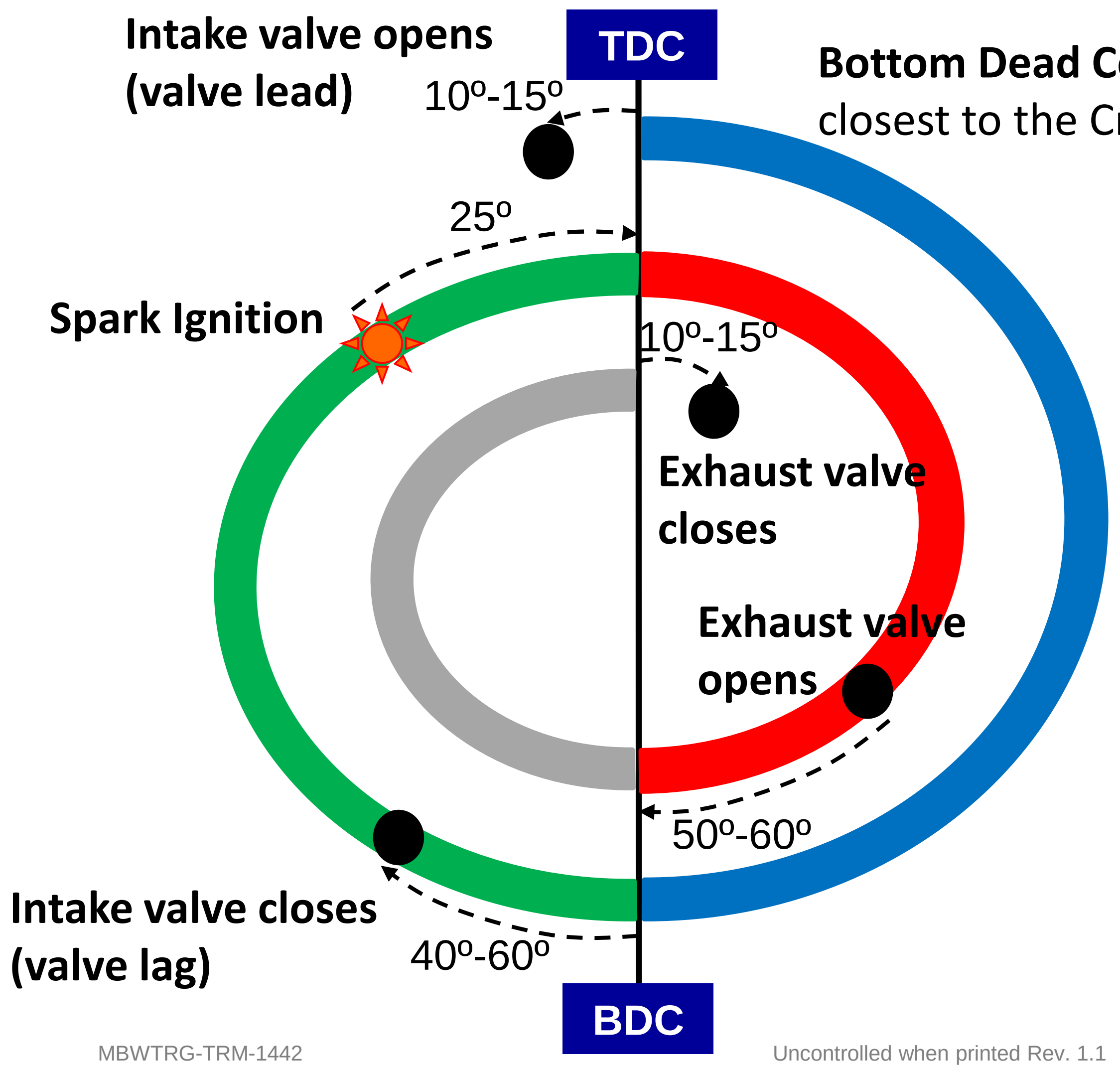
*Example: The firing order of a four-stroke engine is 1-3-4-2. If Number 1 Piston is on the compression stroke, which stroke is Number 2 on?*




- Number 2 Piston is on the power stroke

# VALVE TIMING

# 4 Stroke Cycle




**Top Dead Centre:** Piston is furthest from the Crankshaft

**Bottom Dead Centre:** Piston is closest to the Crankshaft



- The intake valve opens just prior to TDC **(valve lead)** and remains open until after BDC **(valve lag)** to allow maximum fuel/air intake
- Ignition is before TDC as it takes time for flame front to spread across the whole chamber
- Exhaust valve opens before BDC as the "push" is already complete
- Exhaust valve remains open until after TDC as the intake fuel/air helps to push out any remaining exhaust gas **(valve overlap)**

# VOLUMETRIC EFFICIENCY

# Volumetric Efficiency

- We have already seen that roughly only 30% of the total heat energy produced by an engine can be used for useful work

- Whilst we may not be able to eliminate losses due to friction and heating of engine components and exhaust, we can still increase an engine's power output by increasing an engine's **volumetric efficiency**

- If we can increase the volume of fuel-air mixture drawn into the cylinders during the induction stroke, we can increase the total heat energy produced during the power stroke – thus increasing power output

- **Volumetric Efficiency** is simply a measure of how much mixture is drawn into the cylinder during the induction stroke compared to how far the piston actually moves

# Volumetric Efficiency

- Volumetric Efficiency will be affected by:

**Air Density:**

- An increase in ambient air density causes air molecules to be closer together, meaning more mixture can be drawn into the volume of the cylinder
- An increase in density therefore increases volumetric efficiency

**Throttle Position:**

- Full throttle produces maximum flow of the mixture into the cylinders
- Volumetric efficiency is at its best when the engine is operating at full throttle

**Engine RPM:**

- Whilst the above is true, an increase in engine RPM also gives rise to increased friction inside the cylinders and around the ports and valves
- The inlet valve is also open for a shorter time at high RPM so there is less opportunity for mixture to enter the cylinder

# Volumetric Efficiency

**Temperature of the Mixture:**

- High engine temperatures or the use of carburettor heat could also heat the mixture on its way to the engine

- Hot fuel is less dense so once again, less fuel molecules would enter the cylinder during the induction stroke

**Supercharging:**

- This compresses air before it enters the cylinders, producing a higher mass flow

- Supercharging is a fantastic way to increase volumetric efficiency!

# COMPRESSION RATIO

# Compression Ratio

- Another method of determining engine power output is to examine the degree of compression the mixture is subject to during the compression stroke

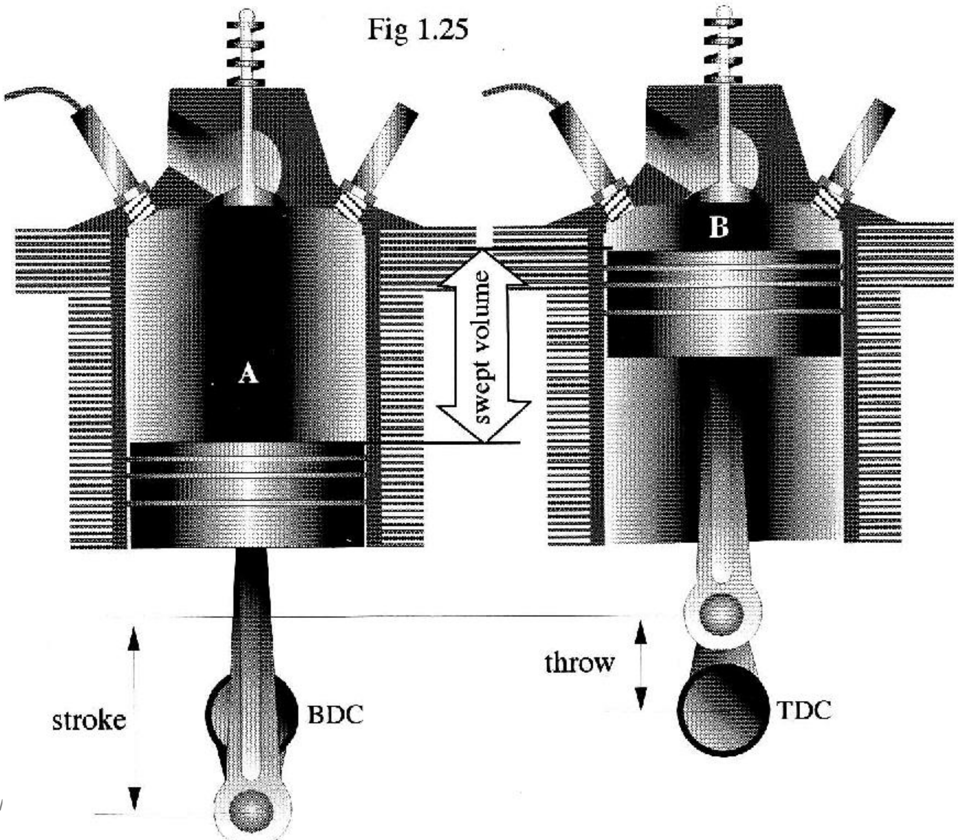
- This is determined by the decrease in volume of the mixture as the piston travels from BDC to TDC – the greater the compression, the greater the power output

- At the beginning of the compression stroke, the piston is at BDC. The volume of mixture inside the combustion chamber is measured, labelled A

- At the end of the compression stroke, the volume has been reduced to B

- Compression ratio is A ÷ B

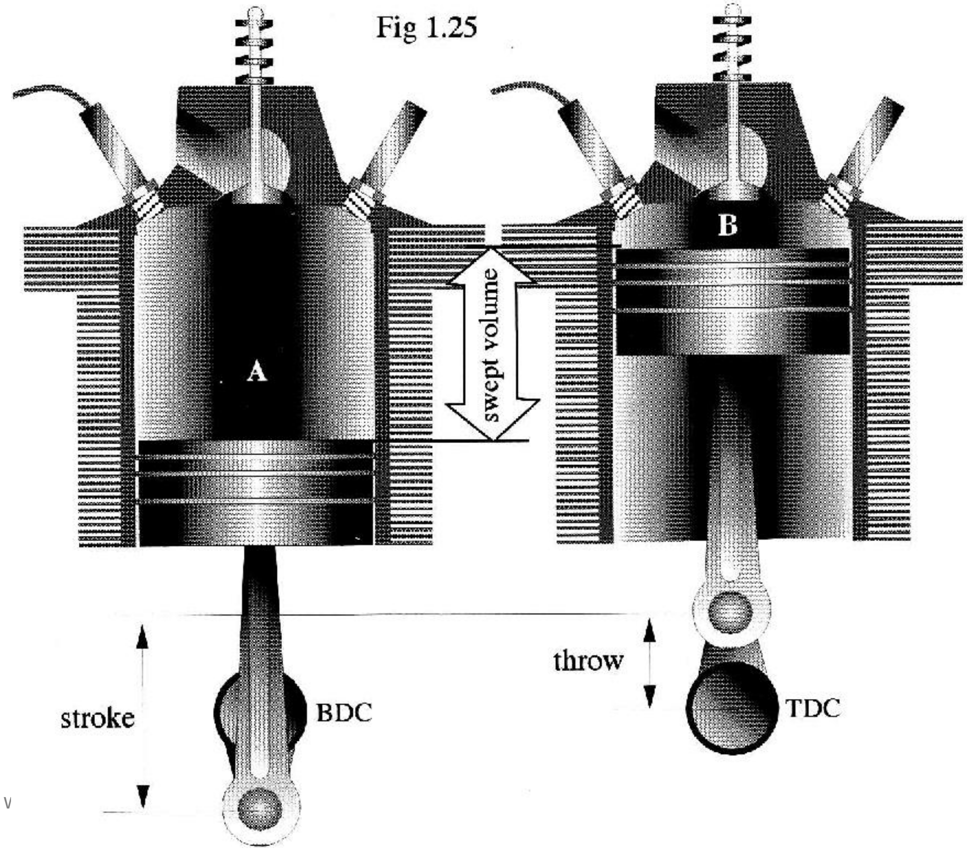
Fig 1.25



# Compression Ratio

- The distance the piston travels from BDC to TDC is also known as the **swept volume**
- The volume of the combustion chamber when the piston is at TDC is known as the **clearance volume**
- Therefore, another way to describe compression ratio is:

$$\frac{\textbf{Clearance Volume + Swept Volume}}{\textbf{Clearance Volume}}$$



# TACHOMETER

# Tachometer

- In a fixed pitch propeller aircraft like the C172, Engine RPM is measured using a tachometer
- This gives the pilot an indication of engine power output
- The stronger the "push" on the piston during the power stroke, the higher the engine RPM

**Green Arc:**
Normal Operating Range


**Red Line:**
Maximum permissible RPM of an engine

# Tachometer

- At higher altitudes, the air becomes less dense
- This will affect the engine power output (you will notice a decrease in RPM)
- To counter this, the throttle must be regularly increased to maintain RPM
- Eventually, you may reach an altitude at which full throttle is required to maintain a given RPM. **This is known as full throttle height**

**Green Arc:**
Normal Operating Range


**Red Line:**
Maximum permissible RPM of an engine

# MAXIMUM CONTINUOUS POWER

# Maximum Continuous Power

- Engine power output is usually expressed as a percentage of the Maximum Continuous Power (MCP) the engine is rated to produce
- The definition is quite simple – MCP is the maximum power that can be used continuously
- Some larger aircraft have power settings that are actually beyond MCP – but these are approved for only short-term use – usually between **3 to 5 minutes**
- Power settings beyond MCP are usually known as **take-off power or take-off/go-around (TOGA) power–** in addition to the time limit, other conditions such as airspeed limitations and mixture settings may apply to ensure adequate engine cooling
- You may come across a term known as **METO power**
- This means **Maximum Except Take-Off Power** and means the **same thing as MCP**

# CARBURETTOR

## Carburettor

- The device used to mix fuel to air to obtain a burnable mixture for the engine

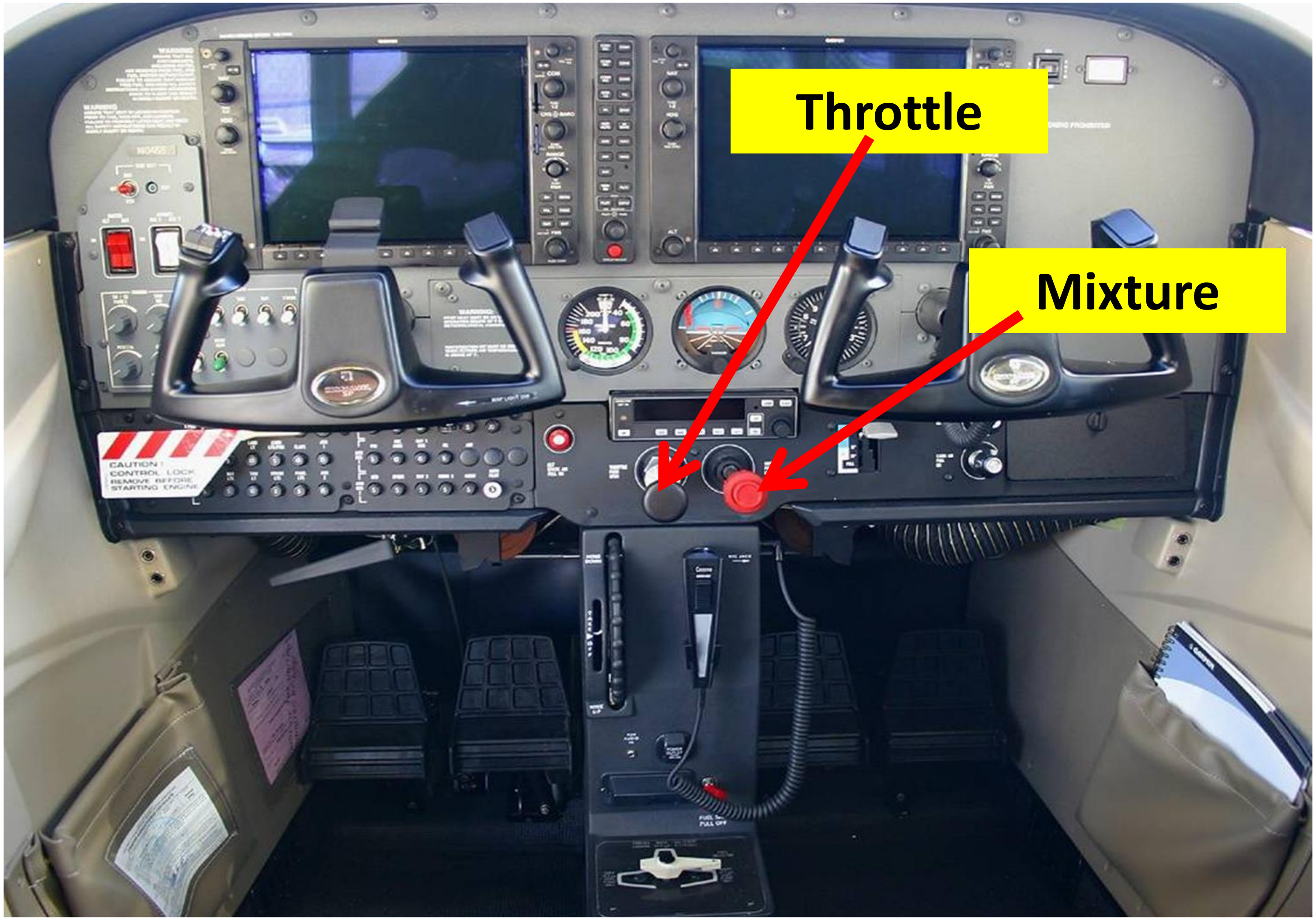
# Carburettor

- The device used to mix fuel (avgas) to air to obtain a burnable mixture for the engine
- The mixture of fuel to air is called the **fuel/air ratio** and is reasonably correct at 1:12
- Combustion can occur with a fuel/air ratio between:

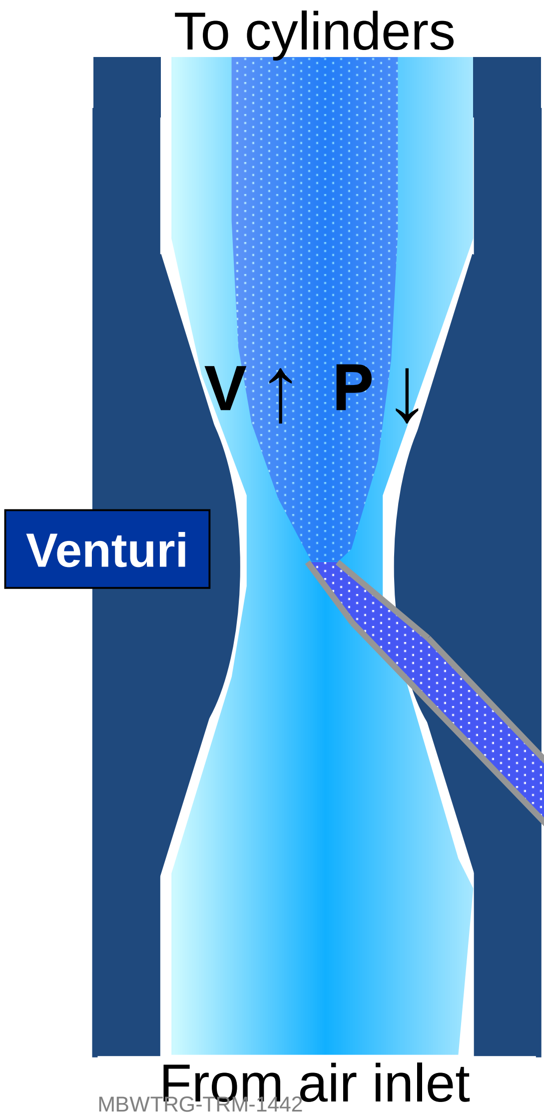
  1. **1:8 (RICH)**
  2. **1:20 (LEAN)**

- The ideal mixture is called the **Chemically Correct Mixture (CCM)** and is where **all the fuel is being burnt with all the air**
- For gasoline, this occurs at a ratio of **1:15** and is called the **"Stoichiometric Mixture"**
- We can adjust the amount of fuel in the mixture using the Mixture Control Lever

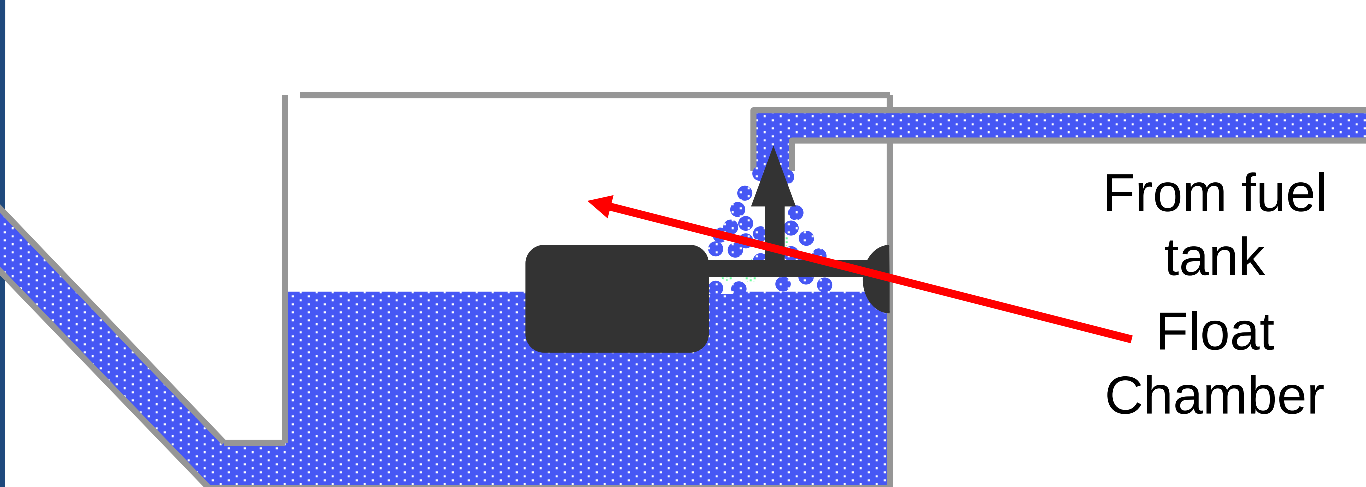
# Carburettor



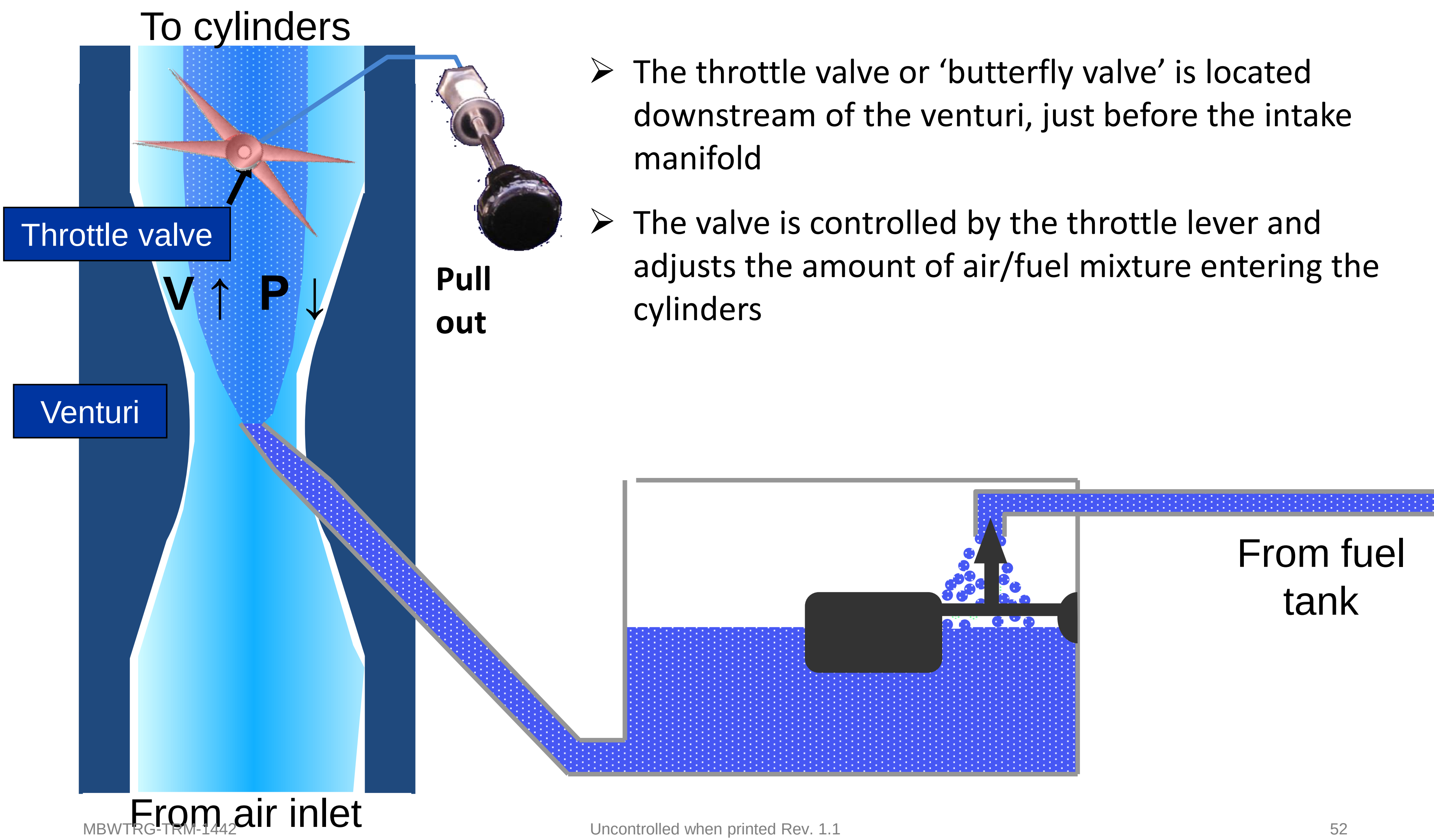
# Carburettor




- On its way to the cylinders the air flows through a venturi (a narrow tube)
- As it does so, fuel is sucked into the airflow from the float chamber
- The carburetor is designed to provide a constant flow of fuel according to the speed of the airflow through the venturi (the faster the air the more fuel is added)

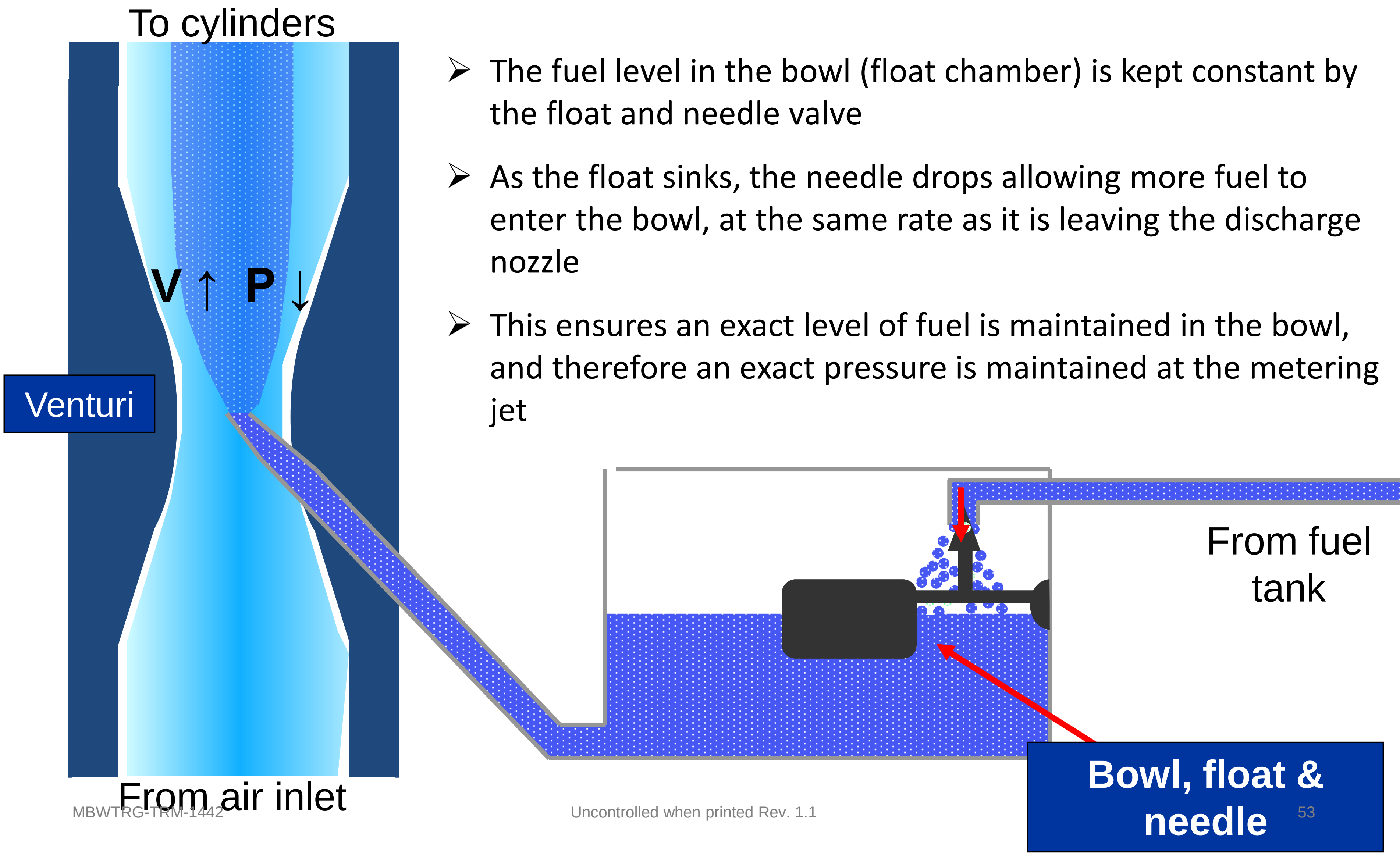


# Carburettor




- The throttle valve or 'butterfly valve' is located downstream of the venturi, just before the intake manifold
- The valve is controlled by the throttle lever and adjusts the amount of air/fuel mixture entering the cylinders

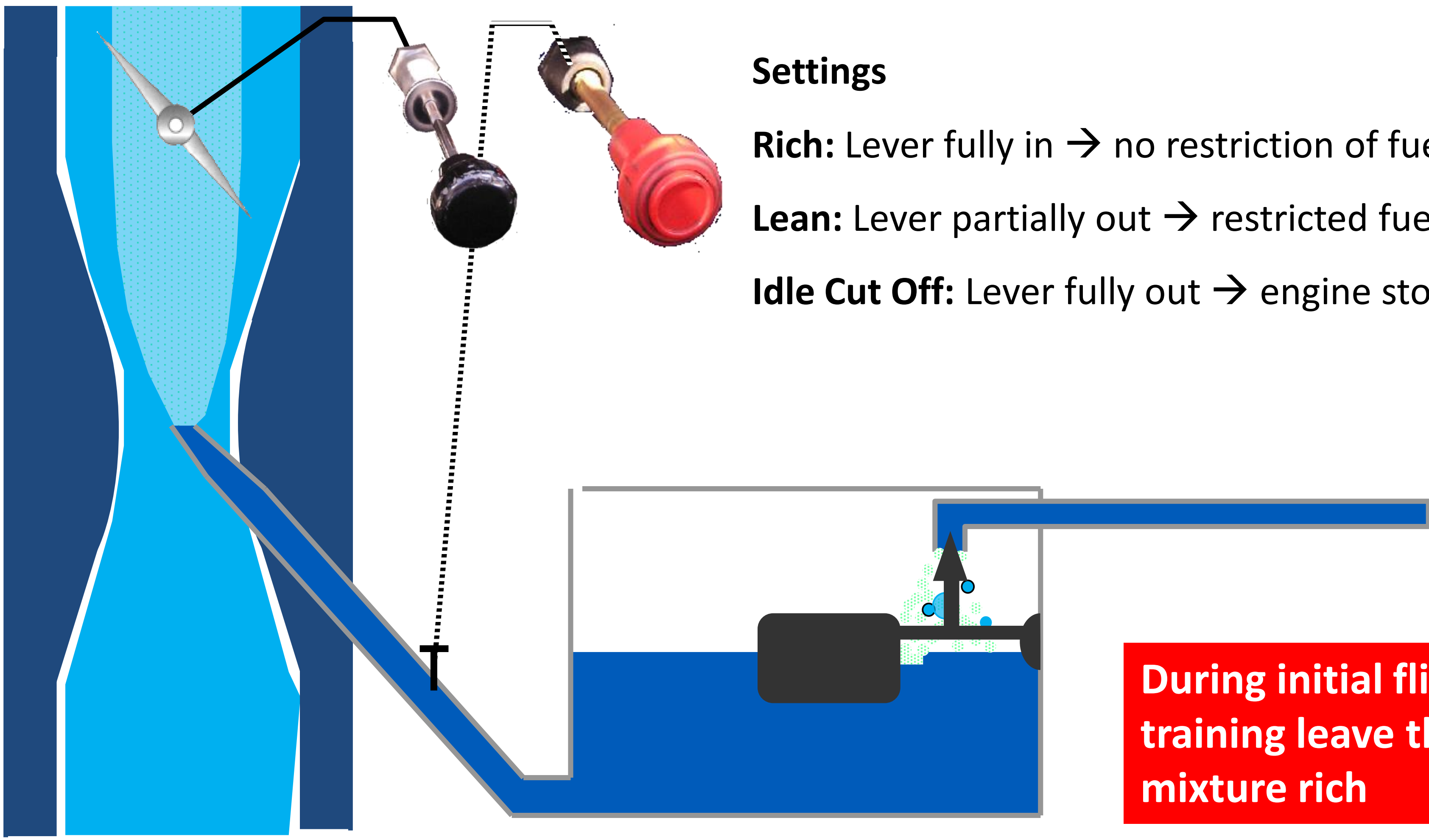
# Carburettor




- The fuel level in the bowl (float chamber) is kept constant by the float and needle valve
- As the float sinks, the needle drops allowing more fuel to enter the bowl, at the same rate as it is leaving the discharge nozzle
- This ensures an exact level of fuel is maintained in the bowl, and therefore an exact pressure is maintained at the metering jet

# Carburettor

- The mixture restrictor valve is located in the carburettor



**Settings**

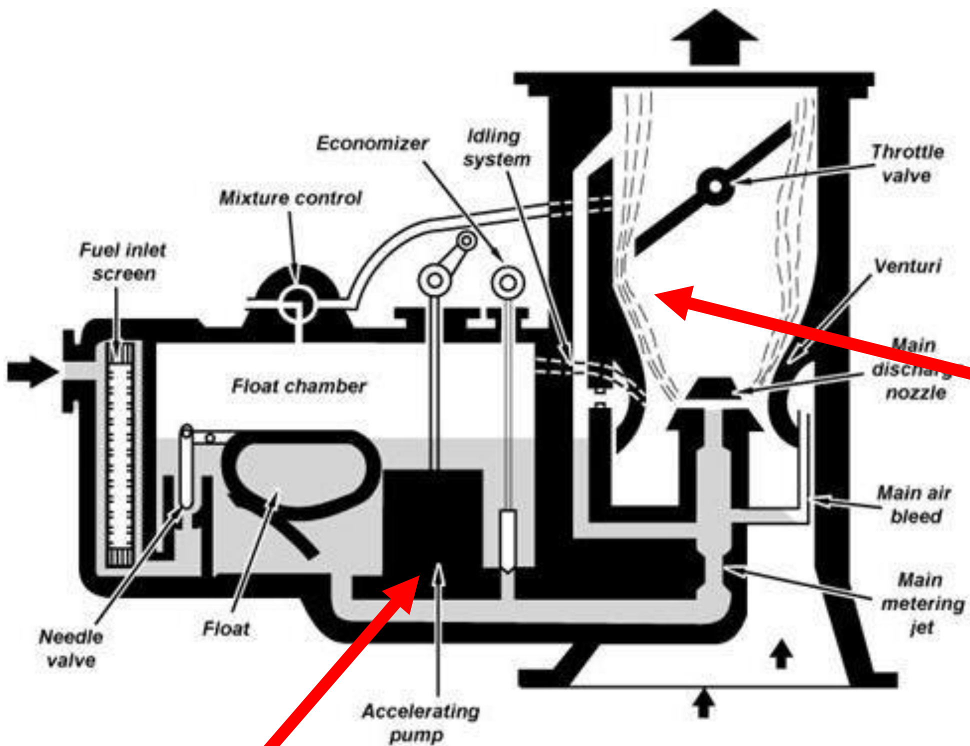
**Rich:** Lever fully in → no restriction of fuel flow

**Lean:** Lever partially out → restricted fuel flow

**Idle Cut Off:** Lever fully out → engine stops

**During initial flight training leave the mixture rich**

# Carburettor




- When the engine is idling, the butterfly valve is almost closed, there is not enough suction to draw fuel from the main jet
- A small idling jet is fitted which has sufficient suction to keep fuel flowing by itself
- This keeps the engine idling at low RPM instead of cutting out
- When the throttle is suddenly opened, the airflow increases but there is a lag in the fuel flow increase, resulting in too lean a mixture
- An **accelerator pump** is fitted to provide an extra spurt of fuel as the throttle is quickly and fully opened

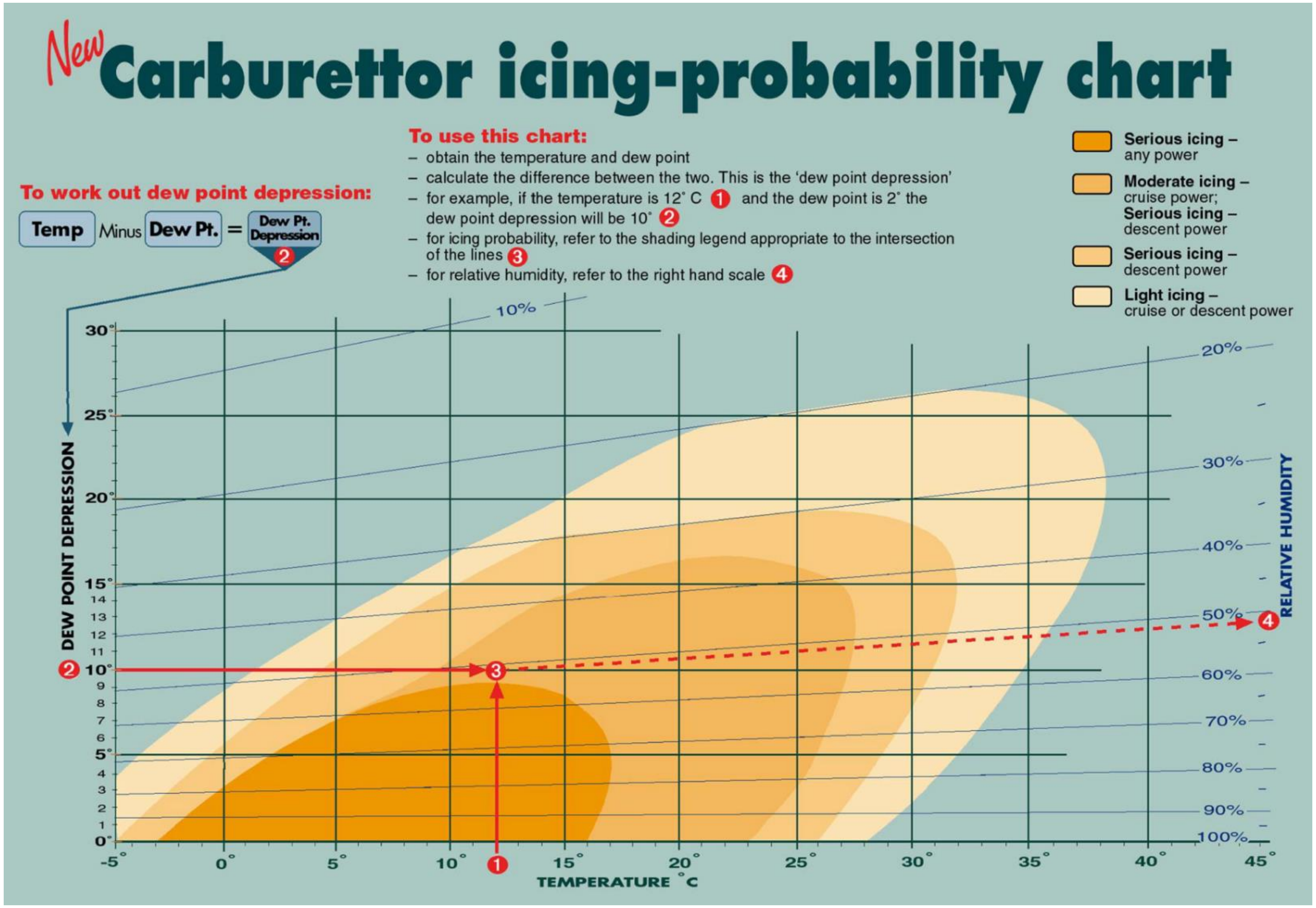
# CARBURETTOR ICING

# Carburettor Icing

- The air accelerating through the Carburettor Venturi creates a low pressure (to allow fuel to be drawn in)
- One consequence of this is that the temperature also decreases (as much as 25-30° C)
- If the air contains moisture, then as it cools, ice may form
- This will reduce the power available and may even stop the engine

# Carburettor Icing

- Generally, icing is most likely at +10 to +20° C in conditions of high humidity and with low power settings (does not require presence of cloud or rain)



## Carburettor Icing – Types

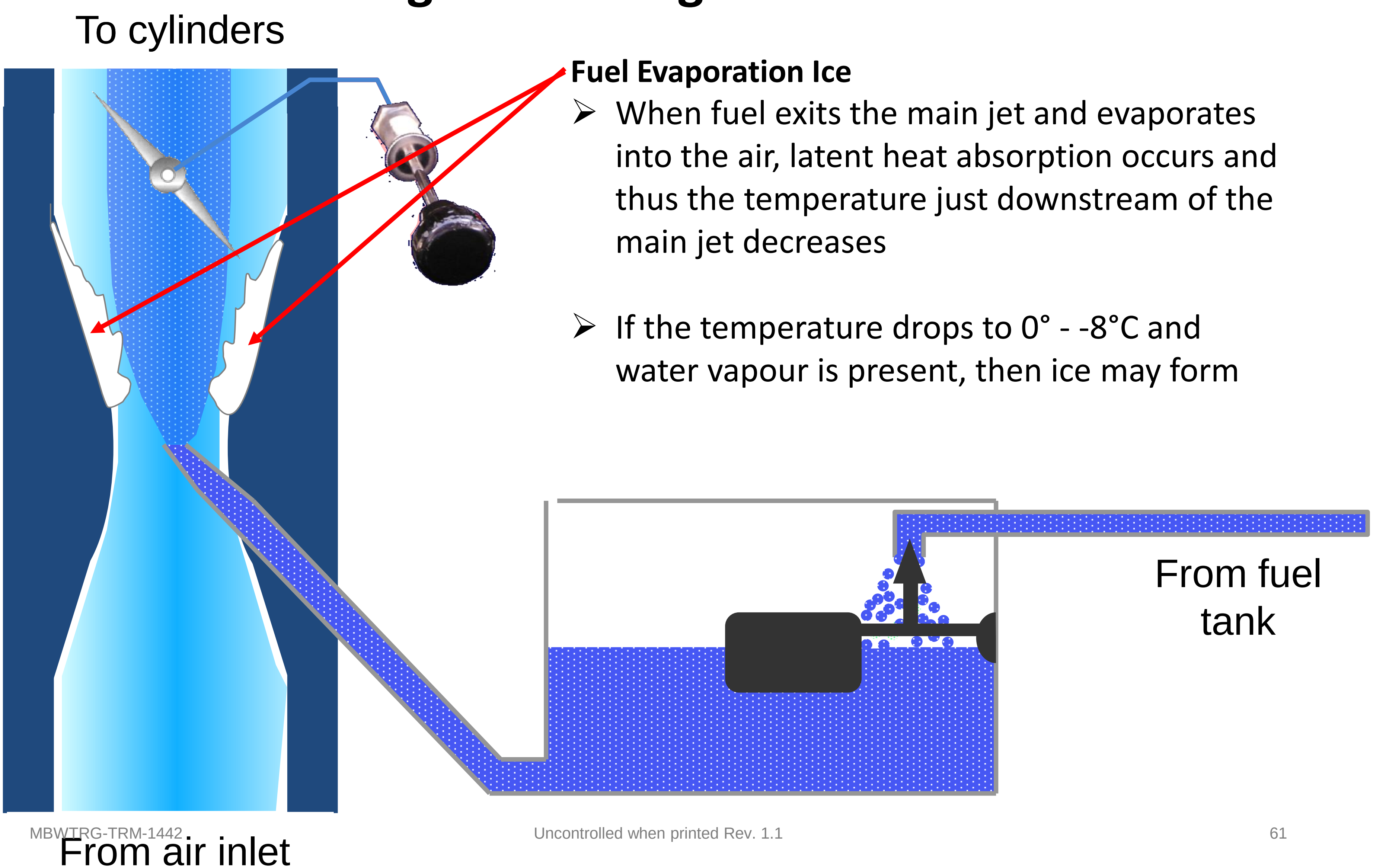
- There are 3 types of Carburettor Icing with which we need to be concerned:

1. **Impact Icing**
2. **Fuel Icing**
3. **Throttle Icing**

# Carburettor Icing – Impact Icing

- This is not technically carburettor ice as it doesn't occur inside the carburettor
- It occurs when super-cooled water droplets impact on the filter or metal surfaces of the air inlet
- These water droplets freeze on impact and can block or partially block the air intake duct into the carburettor
- This is the same process as ice formation on the wings of an aircraft and occurs when the OAT is near or below 0° C

# Carburettor Icing – Fuel Icing



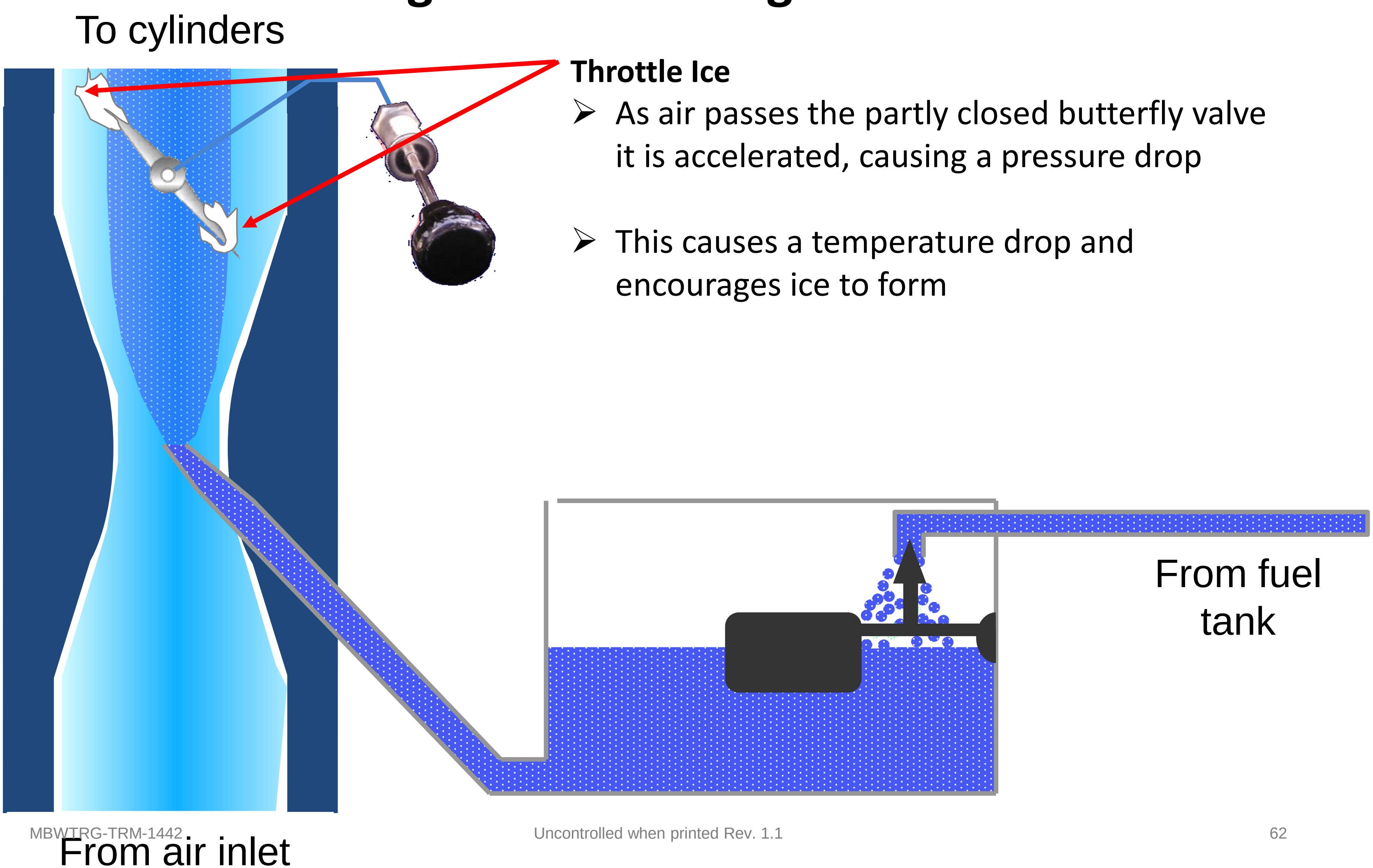

**Fuel Evaporation Ice**

- When fuel exits the main jet and evaporates into the air, latent heat absorption occurs and thus the temperature just downstream of the main jet decreases
- If the temperature drops to 0° - -8°C and water vapour is present, then ice may form

# Carburettor Icing – Throttle Icing

**Throttle Ice**

- As air passes the partly closed butterfly valve it is accelerated, causing a pressure drop
- This causes a temperature drop and encourages ice to form



# Carburettor Icing

**Signs of Carburettor Ice:**

- A build up of ice is similar to slowly closing the throttle
- In a fixed pitch propeller aircraft there will be:

**1. A reduction in RPM (even though the throttle position stays constant)**

**2. A reduction in power**

**3. Rough running**

**4. Possible complete engine failure if ice build up continues**

# Carburettor Icing

**Pilot Actions on Recognition of Carburettor Ice:**

- Apply full Carburettor Heat (can be used to prevent or remove icing)

**Application**

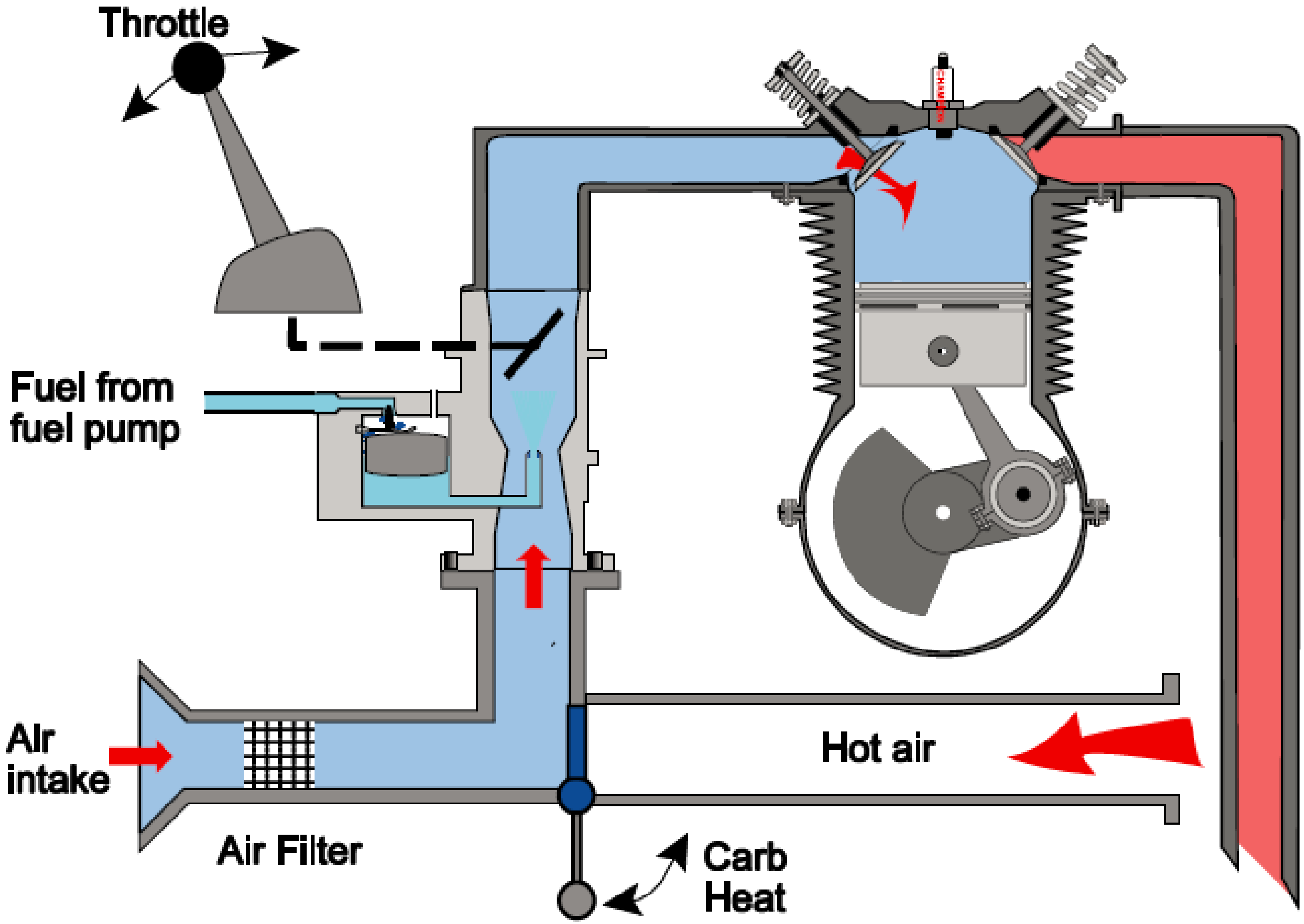
- When selected to ‘hot’, a valve directs hot air from around the exhaust through the carburettor to melt the ice

- When applying carburettor heat the RPM will decrease further as hot air is less dense (therefore less air will enter the cylinders for combustion, and the mixture becomes richer)

- When the ice has melted the RPM will increase again

**Glide Descents**

- There would be no symptoms of icing when gliding since the butterfly valve is closed – apply carburettor heat before and during glides as a precaution


Throttle
Fuel from fuel pump
Air intake
Air Filter
Hot air
Carb Heat

# Carburettor Icing

## Carburettor Heat Checks:

- During pre-take off checks, the carburettor heat must be checked to ensure it is working
- When the carburettor heat is applied there should be a drop in RPM as the less dense hot air reduces volumetric efficiency and causes the mixture to become richer
- Operation on the ground should be avoided (except testing), to prevent dust and other particles entering the cylinders
- If the air filter becomes blocked, carburettor heat can act as an alternate air supply to the engine in case of emergency

# ENGINE COOLING

# Engine Cooling

- Almost half the heat resulting from combustion is removed through exhaust gases
- However, this still leaves a large amount of heat remaining. It must be removed to ensure proper engine function.
- Most light aircraft engines are air-cooled. This is achieved through several different means:

## 1. Cooling fins on cylinders

## 2. Air-cooled oil systems

## 3. Cowl flaps

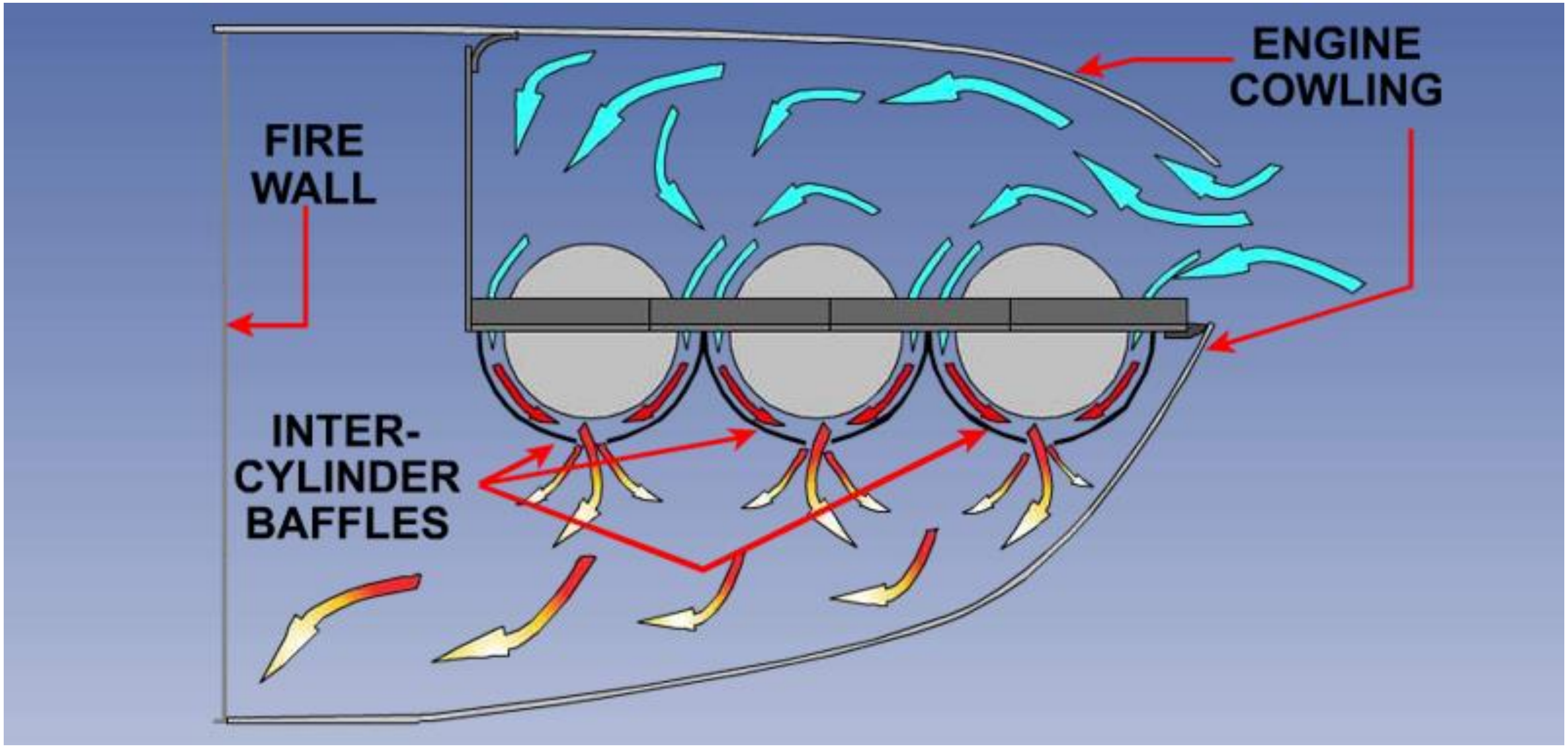
# Engine Cooling

- Air inlets either side of the propeller hub allow airflow to enter the engine bay


**Air inlets**

# Engine Cooling

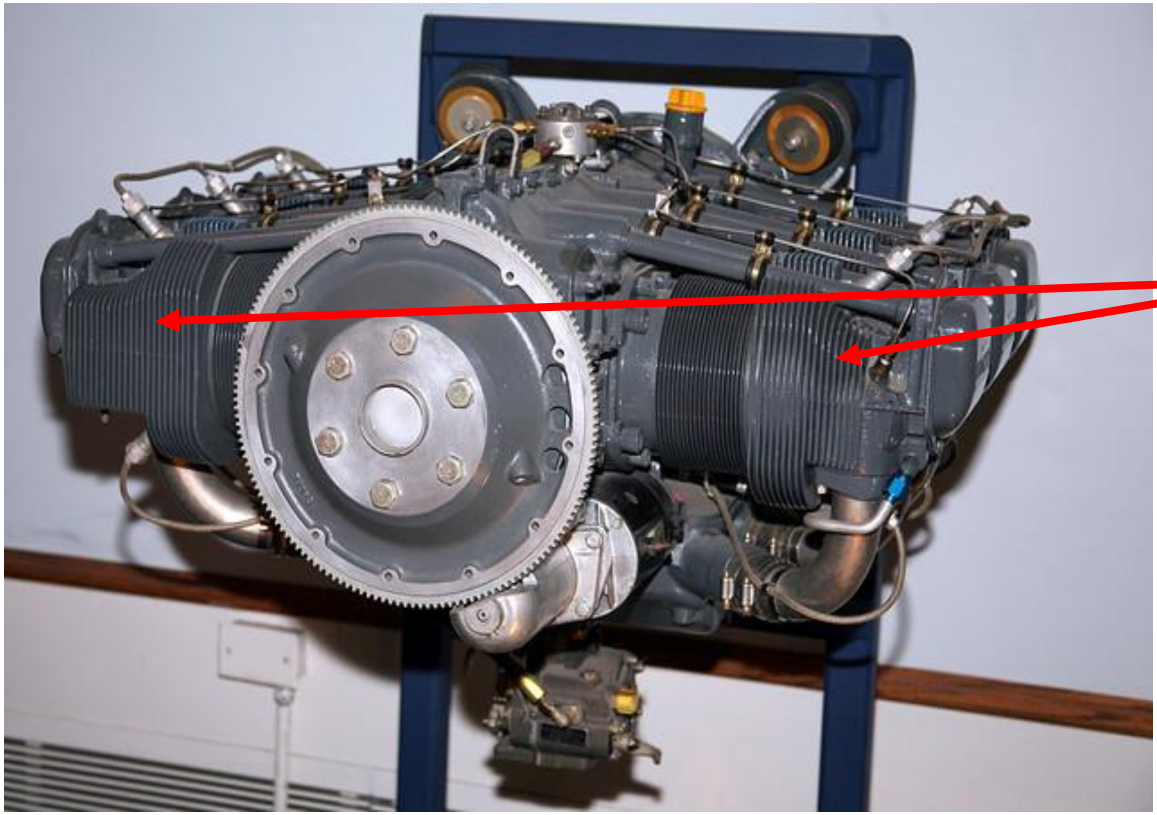
- Inside the cowling, baffles are used to direct the airflow onto the cylinders



# Engine Cooling

- Heat is conducted through the cylinder walls to the cylinder cooling fins

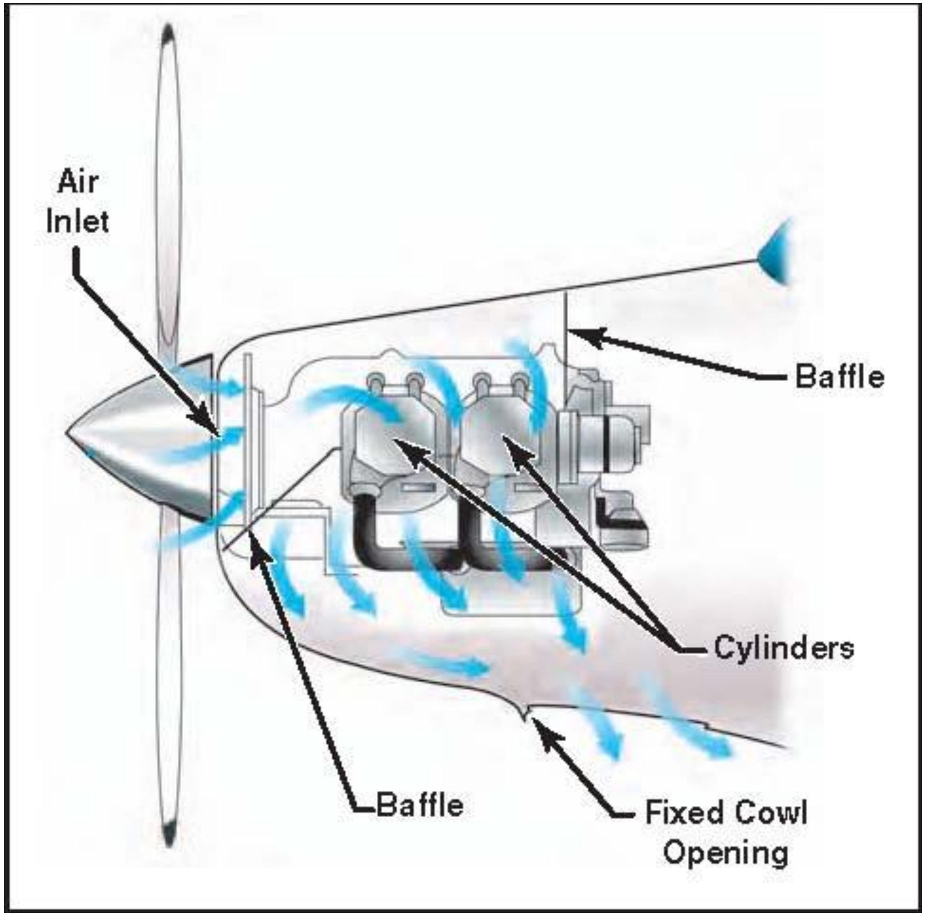
- There are many cooling fins on each cylinder to maximise the surface area exposed to the airflow, increasing the cooling effect



Cooling fins

# Engine Cooling

- Heat is transferred from the cylinder cooling fins and oil cooler to the air passing through the engine cowling which then exits through a fixed cowl opening, removing the heat from the engine bay



# Engine Cooling

- On larger aircraft where operating temperatures are higher, cowl flaps may also be used
- These are flaps that open beneath the engine cowling and increase airflow through the engine


# Engine Cooling

- Cowl flaps are operated from the cockpit via a lever

- Generally, cowl flaps are only opened during take-off and climb at low altitude, where power settings are high and airspeed is relatively low

- They are generally closed during cruise and descent as the increased airflow provides adequate cooling

- If cowl flaps are left open unnecessarily, they can cause a large increase in drag and a reduction in airspeed

# ENGINE ACCESSORY GEARBOX

# Engine Accessory Gearbox

- The accessory gearbox (gears at the rear of the engine) drives the following:

  1. **Magnetos – supply a spark to the spark plugs**

  2. **Oil Pump – pumps oil through the oil system**

  3. **Mechanical Fuel Pump – pumps fuel through the fuel system**

  4. **Vacuum Pump – provides suction for the gyroscopic flight instruments**

  5. **Tacho Generator – supplies an RPM indication**

- Note: Gear-driven alternators also run off the accessory gearbox, but not belt-driven alternators

# ANNUNCIATIONS

# Annunciations

- Most modern aircraft will be fitted with an annunciator panel
- This is located in an easily visible location and will 'announce' to the pilot that a system has failed (via a flashing warning light)
- Items featuring on the annunciator panel may include, but are not limited to:

1. **VAC – vacuum pump failure**
2. **ALT – alternator failure**
3. **OIL – oil pump failure**

- G1000 specific annunciations can be located on page 7-48 of the Cessna 172 Manual

# MIXTURE CONTROL

# Mixture Control

- Air density decreases as altitude increases, so without a mixture control, the fuel/air mixture would become progressively more rich
- This would lead to rough running and excessive fuel consumption
- The aircraft is fitted with a mixture knob to allow us to reduce the amount of fuel used

**During Take-off & Climb:**

- Set the mixture to full rich (the excess fuel is used to help cool the engine)
- Take-off from aerodromes above 2000’ AMSL may require a leaner setting for T/O

**Once Cruise Level is Reached:**

- The aircraft should be leaned out for more efficient engine operation and better fuel economy
- Correct leaning can reduce fuel consumption by up to 25%

# Mixture Control

**During Take-off & Landing**

- Set the mixture to full rich (to protect against detonation, pre-ignition and overheating in the cylinders)

**How to Lean:**

1. **Gradually lean the engine. The RPM will gradually increase, peak and then decrease with possible rough running. Enrich the mixture until smooth running is achieved. You will now be on the rich side of peak EGT**

2. **If we have an EGT gauge (such as on the G1000) we can lean to peak EGT. It is normal to operate the engine around 50º rich of peak EGT**

# Mixture Control

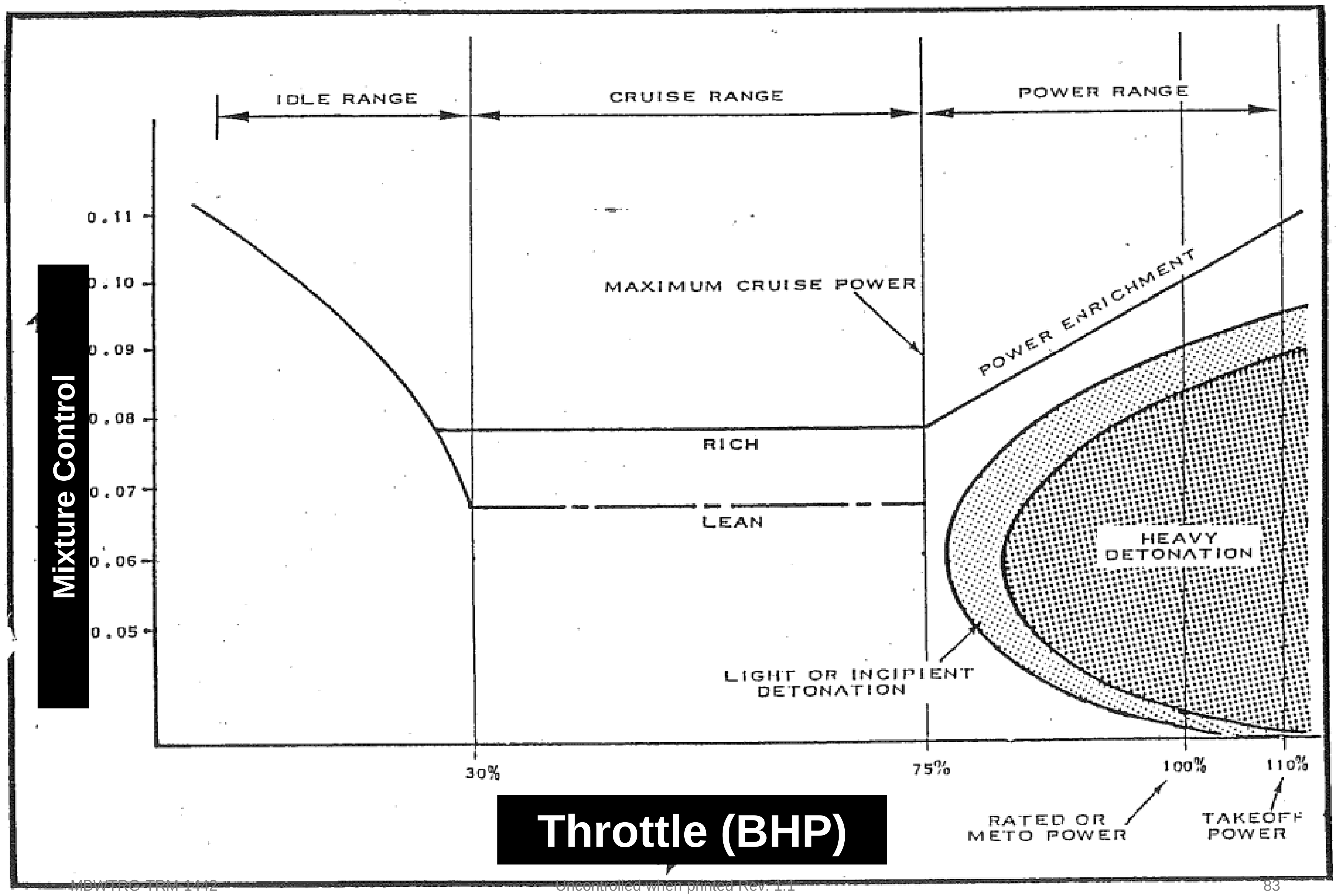
**Dangers of an Over-Rich Mixture:**

- Loss of power
- High fuel consumption
- Spark plug fouling
- Formation of carbon on piston heads and valves

**Dangers of an Over-Lean Mixture:**

- Excessively high Cylinder Head Temperature
- Detonation
- Possible engine failure

# Mixture Vs Power Setting Relationship



# EXHAUST SMOKE INDICATIONS

# Exhaust Smoke Indications

- After firing is the burning of fuel in the exhaust system, which is normally accompanied by visible flames and smoke coming out of the exhaust system

- Possible causes are:

  1. **Ignition not taking place**

  2. **Excessively rich mixture**

- The colour of the smoke will indicate the conditions of the fuel/air mixture:

**Black Smoke** – An over rich mixture

**White Smoke** – A lean mixture (often hard to see)

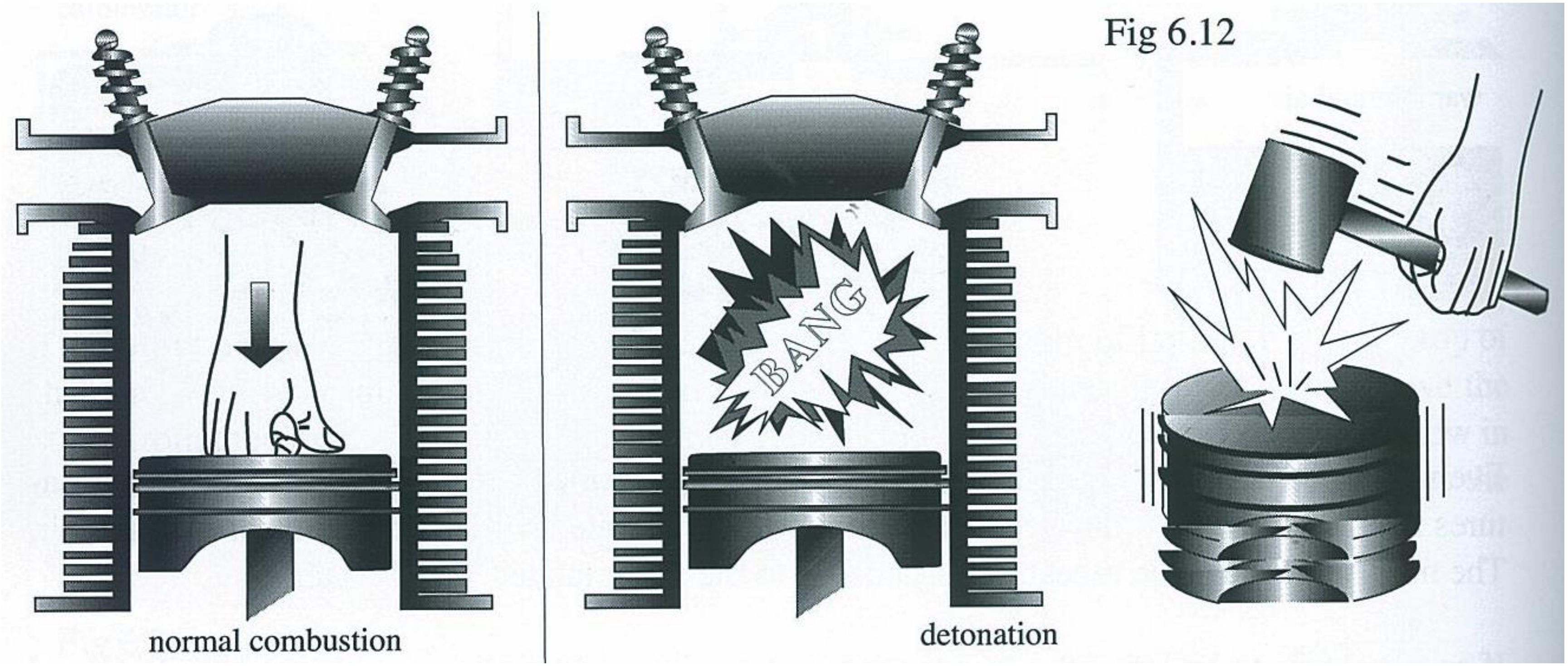
**Blue Smoke** – Oil is being burnt → sign of imminent engine problem

# DETONATION

# Detonation

- Detonation is the explosive combustion of the fuel/air mixture rather than a controlled burn

- This can cause severe damage to pistons, valves and spark plugs, resulting in a loss of power and possible engine failure



# Detonation

**Causes of Detonation:**

1. Using a lower fuel grade than recommended or time expired fuel
2. An over-lean mixture
3. Over boosting (more on this later in the course) (too high a Manifold Pressure for a set RPM)
4. An overheated engine
5. Using AVTUR

**Symptoms of Detonation:**

- Rough running
- High Cylinder Head Temperature

**The Cure:**

- **Enrich the mixture**
- **Reduce pressure in the cylinder (throttle back – reduce power)**
- **Increase airspeed to help reduce CHT (lower the nose)**

# Pre-Ignition

- Not to be confused with detonation, pre-ignition refers to the ignition of the mixture before the spark plug fires

- Pre-ignition will usually occur in one cylinder or a group whereas detonation is a function of the fuel/air mixture being supplied to all cylinders

**Causes:**

- A hot-spot of carbon on the cylinder wall that ignites the mixture too early
- High power settings when the mixture is too lean

**Symptoms:**

- Rough running
- Possible backfiring (explosion of the mixture in the induction system)
- Possible sudden rise in CHT

**Pilot Actions:**

- Set mixture to full rich (excess fuel will help cool the cylinders)
- Decrease power

# WHAT NOT TO DO!

# What Not To Do!

**Prolonged Idling:**

- The main danger of prolonged idling (particularly at rich mixture settings) is spark plug fouling

- This could be due to lead, carbon or oil build-ups around the spark plugs which hinder their ability to spark properly

- This is avoided by maintaining 1000 RPM minimum whilst on the ground

- Prolonged Idling of the engine may occur during a glide descent as part of your Forced Landings without Power training and could also cause:

1. **Spark plug fouling**
2. **Possible uneven cooling of the engine**

# WHAT TO DO!

# What To Do!

**Leaning on the Ground:**

- This can reduce the likelihood of spark plug fouling and save fuel
- However, for initial training sorties, ground operations require a full rich setting

**Warming the Engine During a Prolonged Descent:**

- Increasing the power every 1000ft or so during a descent can reduce the likelihood of spark plug fouling and uneven cooling of cylinders
- It may also blast any lead build ups out the exhaust system