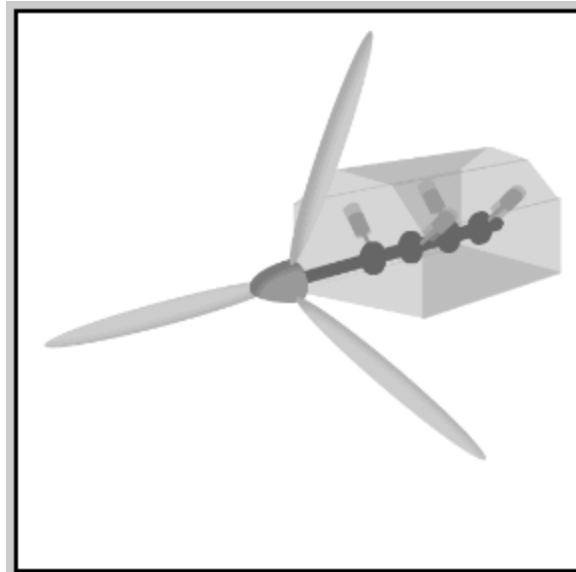


Propulsion

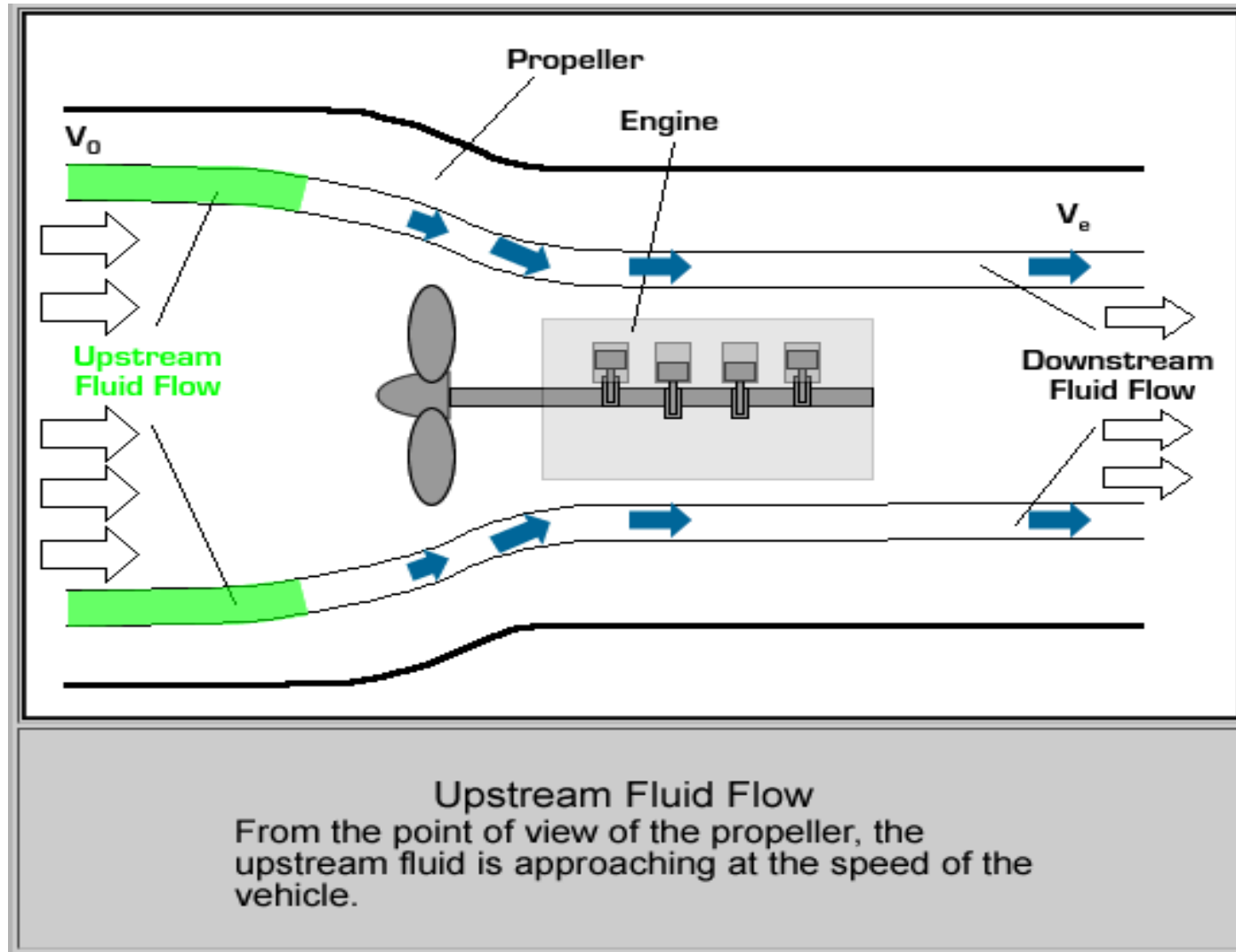
Unit –III	08 Hrs
Drones Propulsion Systems: Thrust Generation, Powered Lift, Sources of Power for UAVs- Piston, Rotary, Gas turbine engines, electric or battery powered UAVs.	

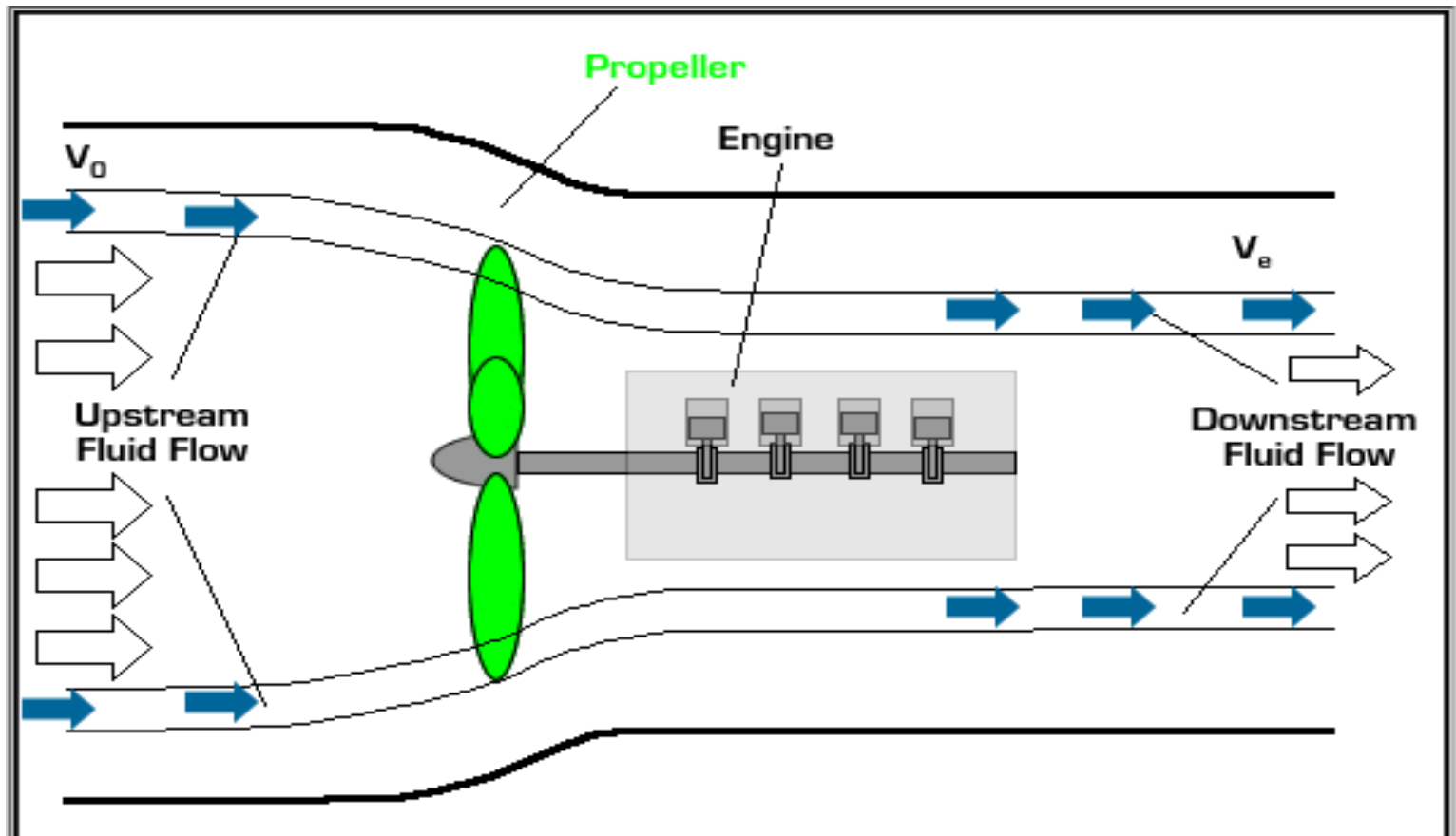
Thrust generation via propellers

- Propellers are used on boats, submarines, and small aircraft. Propellers are simple, revolving hubs with blades placed evenly along the edges (usually 2 to 4 blades on a propeller, but more are possible).
- A mechanical engine attached to the propeller converts fuel or other stored energy into mechanical power which turns the propeller at a high rate of speed.



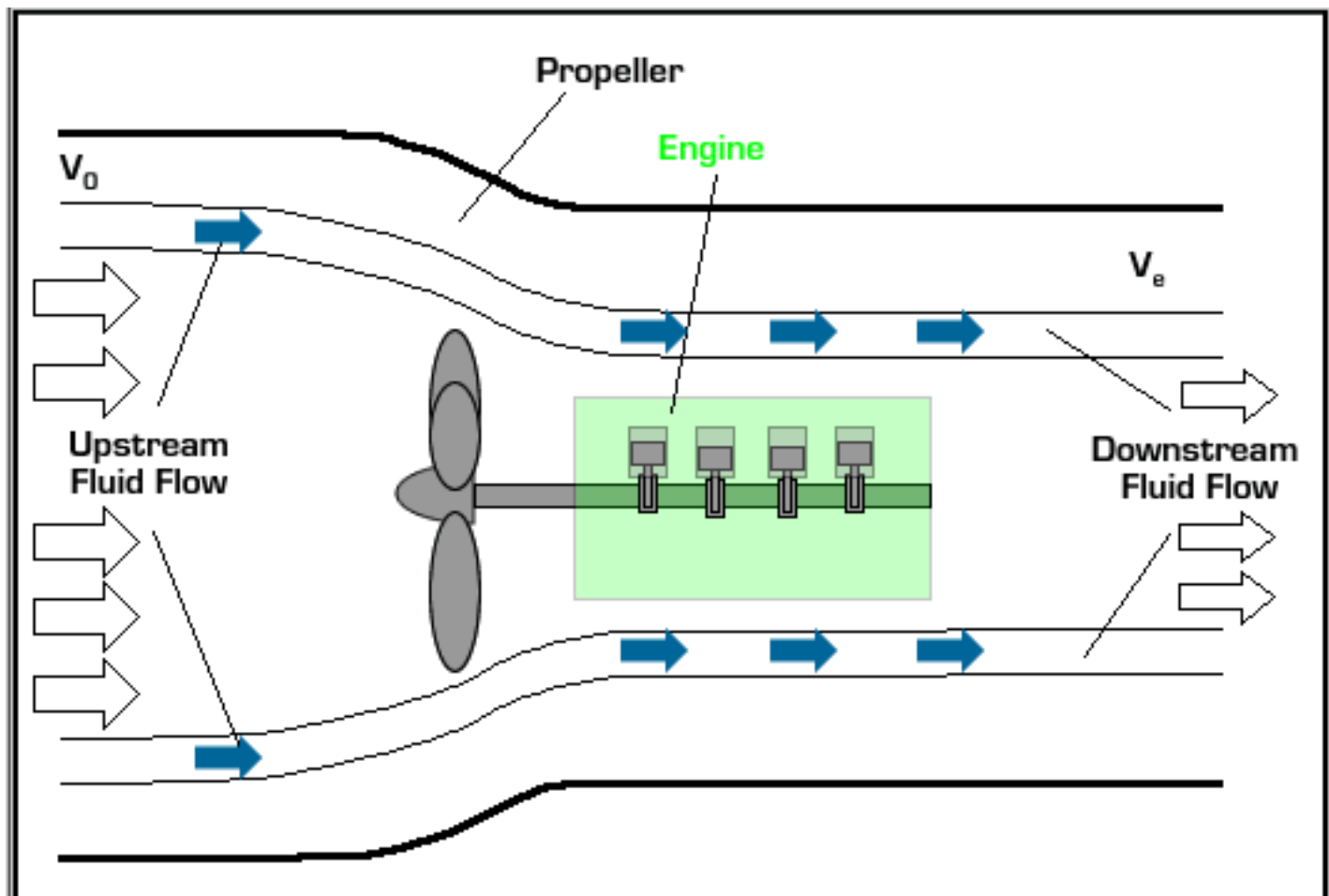
In small aircraft, the propeller is normally powered by a piston engine as shown above. In larger vessels like nuclear submarines, the propeller may be powered by a nuclear power plant. The basic operation of a propeller propulsion system is described in the interactive animation below.





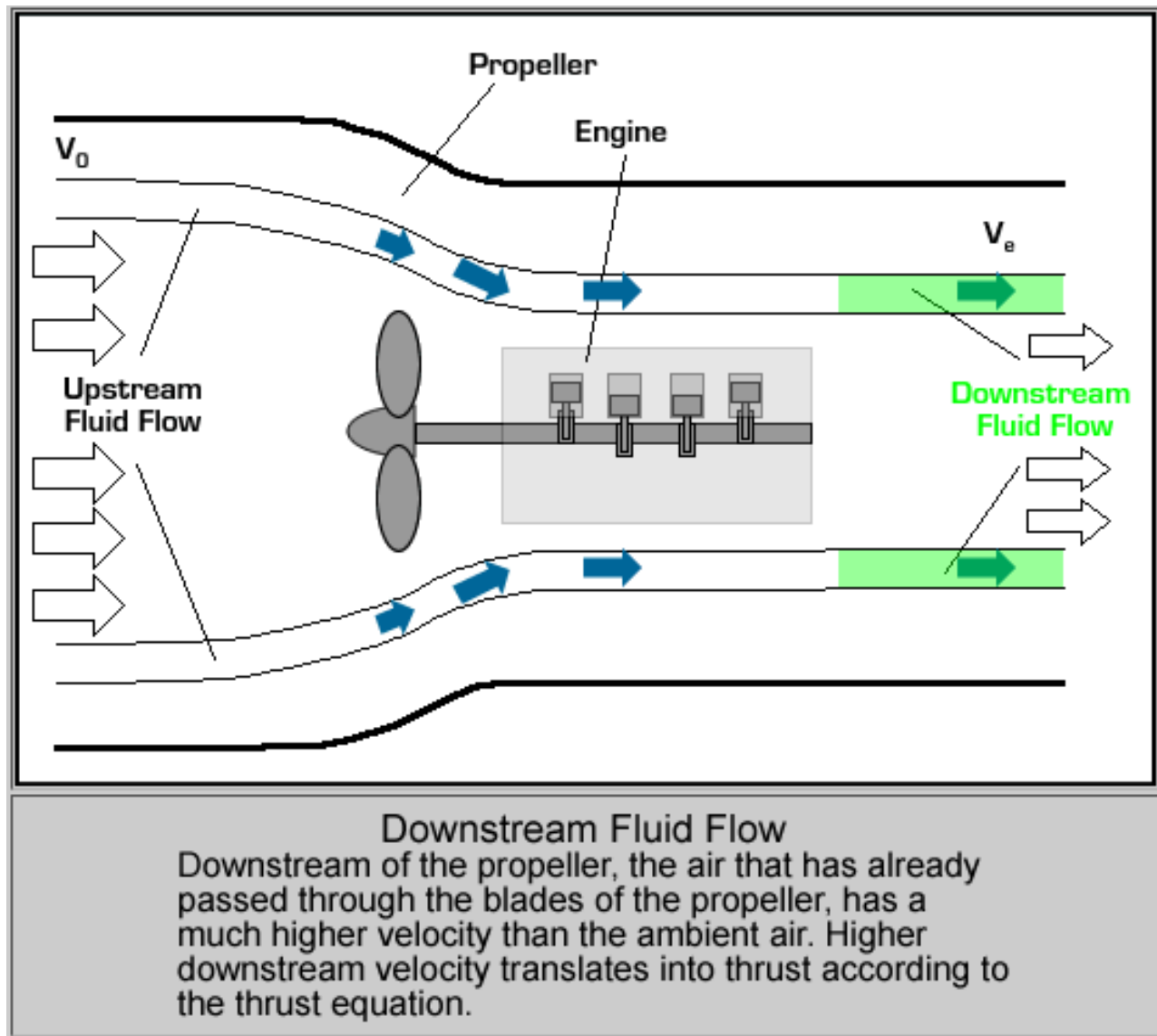
Propeller

The propeller is like a spinning wing. As the upstream fluid approaches, the blades accelerate the fluid creating thrust in the same manner that a wing creates lift as it moves through the air.



Engine

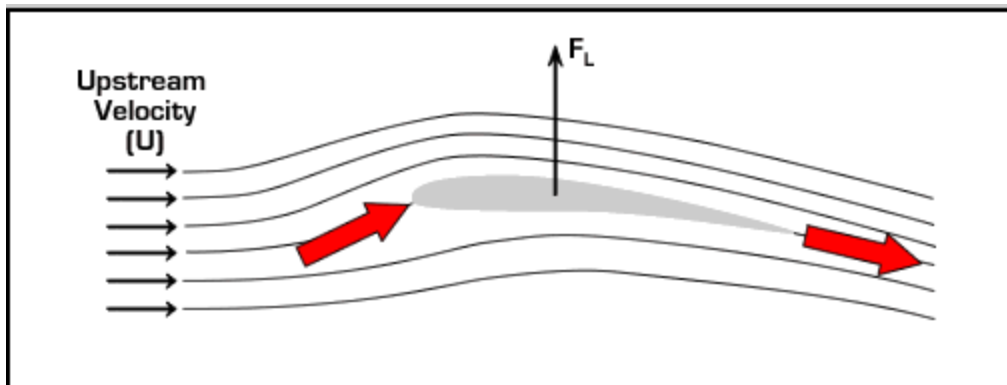
The engine is often an internal combustion engine that converts chemical fuel energy into mechanical power. The mechanical power turns a driveshaft and spins the propeller.



The design of a propeller is crucial for this system to generate thrust efficiently. A propeller may be thought of as a **spinning wing**. Wings have a very special shape in order to direct the flow around them in a specific way.

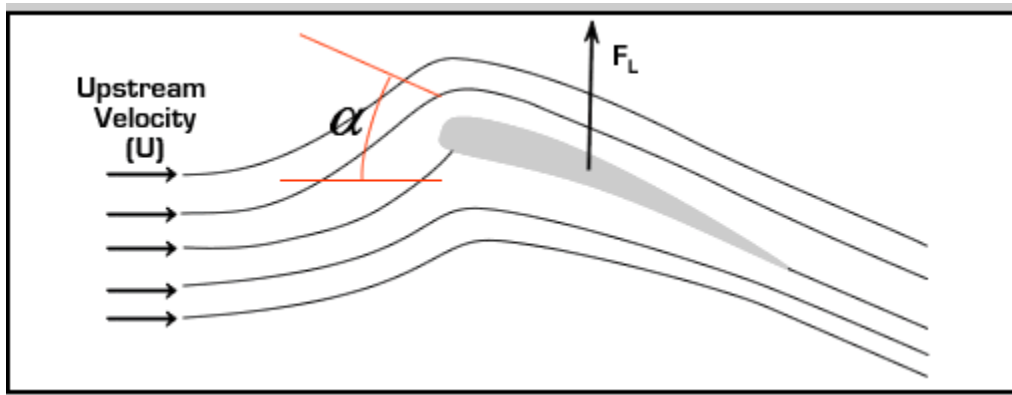
Lift production for an airfoil or wing

- In the figure below, it can be seen that **near the back a wing has a slightly steeper slope on the top as compared to the bottom**. As a result, the fluid flowing over the wing tends to flow down and away from the wing as it passes the end or "trailing edge" of the wing. Near the front of the wing, the curvature of the top of the wing adds to this effect because the flow must curve up as it approaches the wing in order to flow smoothly over the hump on the top of the wing. The net effect is a change in flow direction from upward to downward by the wing. **Because the flow is accelerated down** (the direction of the fluid velocity is changed to the downward direction), Newton's Third Law requires there be an upward reaction force on the wing..



Lift @ higher angle of attack

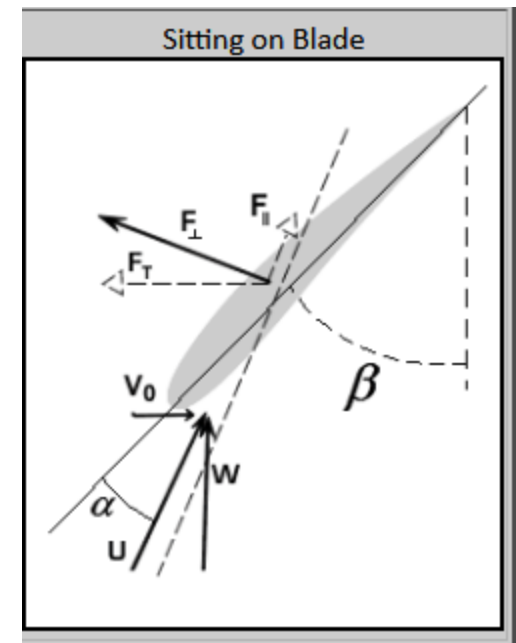
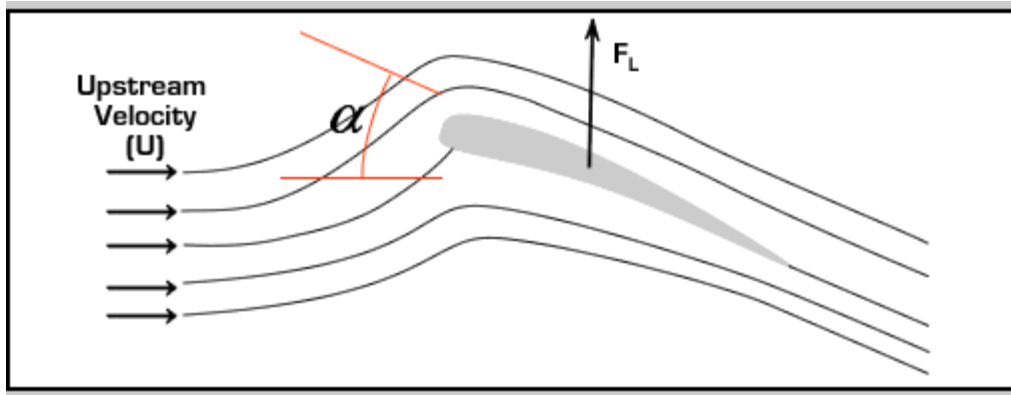
- The vertical force acting on the wing is called lift and it is what keeps airplanes aloft. If the angle of the wing relative to the oncoming flow (angle of attack, α) is increased, **the downward acceleration of the flow is enhanced and lift is increased** (as long as α is not too large).
- In general, the lift force can be computed from the equation where ρ is the fluid density, U is the upstream flow speed, and A is the wing area. C_L is called the lift coefficient and it depends on the wing geometry and α .

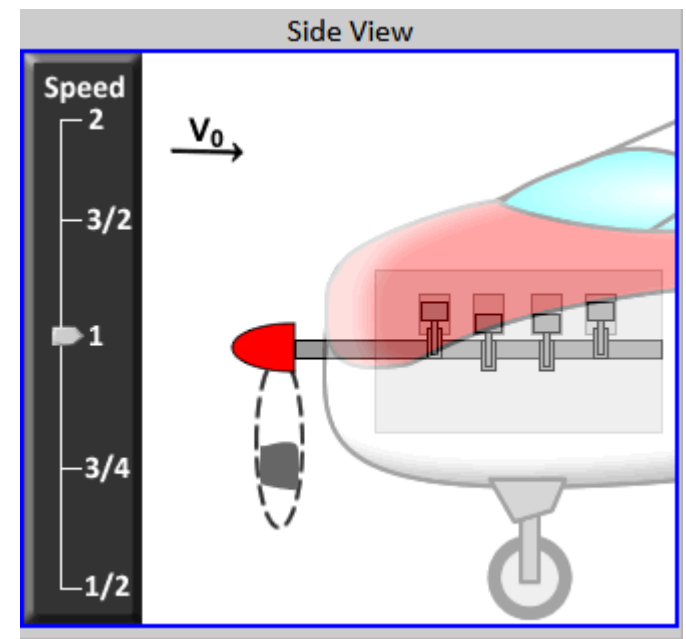
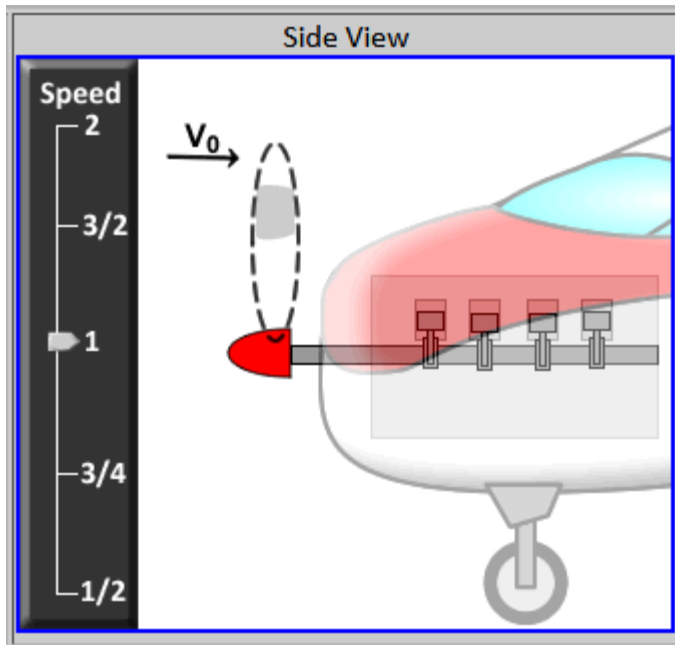
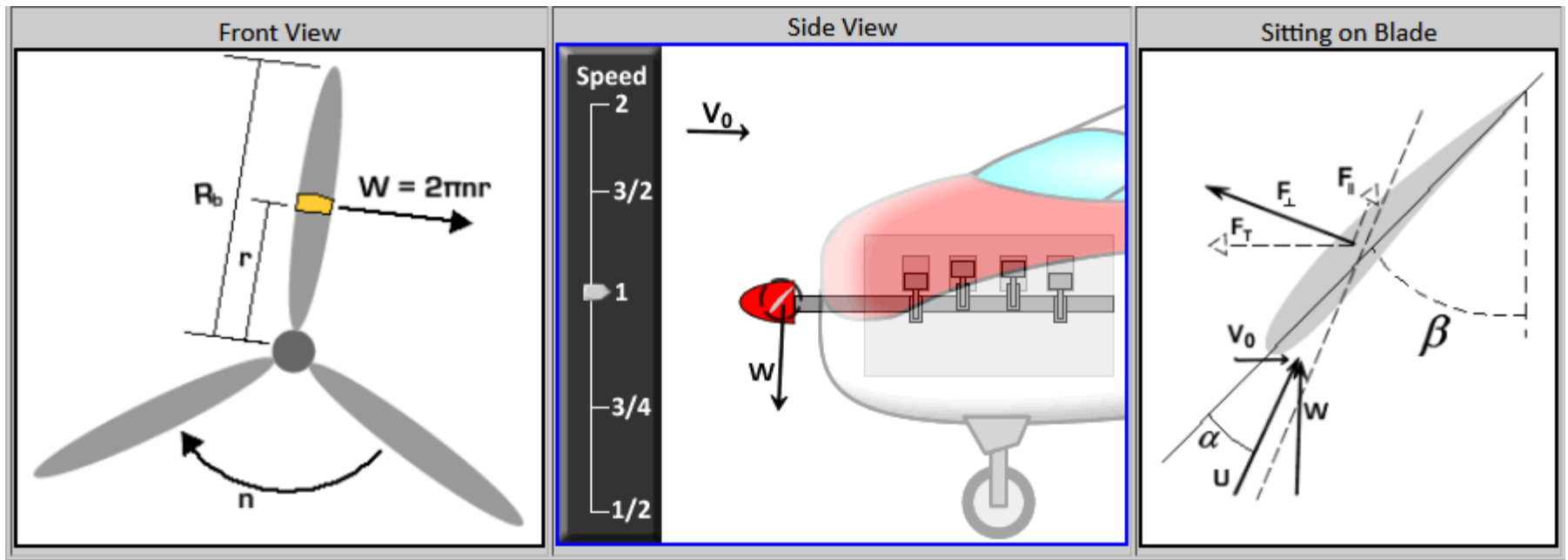


$$F_L = \frac{1}{2} C_L \rho A U^2$$

Thrust from propeller blade

- Now, envision the above scenario rotated 90° counter clockwise so that the top of the wing is facing forward. The force on the wing is now pointed forward, creating thrust instead of lift. In this orientation, we call the wing a propeller "blade".





- Just rotating the wing 90° **isn't enough to turn lift into thrust.**
- The propeller blade **must also be spun** around its axis.
- **Spinning the blade induces the fluid to flow over the blade in a manner similar to the flow over a wing, but rotated 90° to generate thrust.**
- In the center of the figure below is a side view of a spinning propeller blade. Only a slice of the blade is shown so you can see the wing-like shape of the propeller blade moving through the oncoming flow. **For future reference, let's say the chosen slice of the blade is a distance r from the hub (see the picture on the left in the figure).**
- On the right of the figure is the flow seen from the point of view of someone sitting on the propeller blade. In this view, the flow moves past the propeller blade in a manner similar to that illustrated for the wing above.
- **Notice that the angle of the oncoming flow (α) is determined by (a) the speed of the aircraft (V_0), and (b) the vertical speed of the propeller, namely, $W = 2\pi nr$ where n is the rotation rate of the propeller in revolutions per minute (rpm).**
- As with the wing, the propeller blade accelerates the oncoming flow away from it, generating **force (F_{\perp}) in a direction perpendicular to the oncoming flow** as shown. (Here we call the "lift" force generated by the blade F_{\perp} instead of F_L because F_{\perp} is not perpendicular to the motion of the airplane as is the case for lift on a wing.)

- The horizontal component of F_{\perp} points forward, giving the desired thrust (F_T).
- Notice also that there is a vertical force component that resists the motion of the blade and must be overcome by the motor that spins the blade. That is, work must be done by the motor to generate thrust. There is also a "drag" force on the blade parallel to the oncoming flow (F_{\parallel}). This parallel force tends to reduce thrust and increase the work required from the motor, but for a well-designed propeller, this effect is small.
- Thrust can be increased by increasing r , which can in turn be increased by increasing the oncoming flow speed (U) and α in the same way that lift on a wing is increased.
- Since U is the vector sum (addition) of V_0 and W , both U and α can be increased by increasing W , which increases with propeller rotation rate n . Thus, simply revving the engine to make the propeller spin faster will generate more thrust.
- Unfortunately, increasing W also increases the drag that resists propeller motion that requires more power from the motor to spin the propeller.
- From the point of view of the thrust equation introduced in the Principles section, as

$$F_T = \dot{m}_0(V_e - V_0)$$

$$\text{Thrust} = F = \dot{m}_e V_e - \dot{m}_0 V_0$$

$$\dot{m}_e = \dot{m}_0 = r V_p A$$

$$F = r V_p A (V_e - V_0)$$

let's break down the difference between momentum thrust and pressure thrust in a jet engine in a simple way:

Momentum Thrust:

Idea: Imagine you're standing on a skateboard, and you throw a heavy ball away from you. The force that pushes you backward is similar to momentum thrust.

In a Jet Engine: The jet engine takes in air, adds fuel, and then throws the hot and fast-moving exhaust gases out the back. The reaction to this action is what propels the airplane forward. It's like the engine is throwing something backward to go forward.

Pressure Thrust:

Idea: Think of blowing up a balloon and then letting it go. The air rushing out of the balloon creates a force that propels the balloon in the opposite direction. This force is somewhat like pressure thrust.

In a Jet Engine: Inside the engine, the burning of fuel creates high-pressure, hot gases. As these gases exit through the nozzle at the back of the engine, they expand and accelerate, creating an additional push or thrust. It's like controlled pressure release, and this push helps move the airplane forward.

In simple terms, momentum thrust is about throwing things backward to move forward, while pressure thrust is about harnessing the force created by hot, pressurized gases expanding and rushing out. Both of these forces work together to propel the jet forward through the sky.

"For every action, there is an equal and opposite reaction."



Equilibrium



REACTION

ACTION

Rocket Propulsion:
Thrust = Mass Flow x Velocity

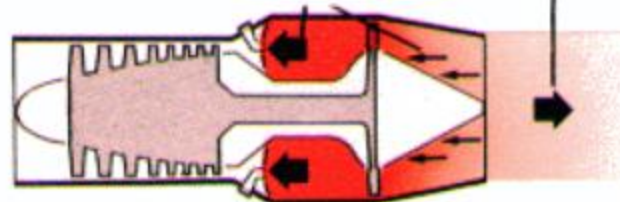


Equilibrium



REACTION

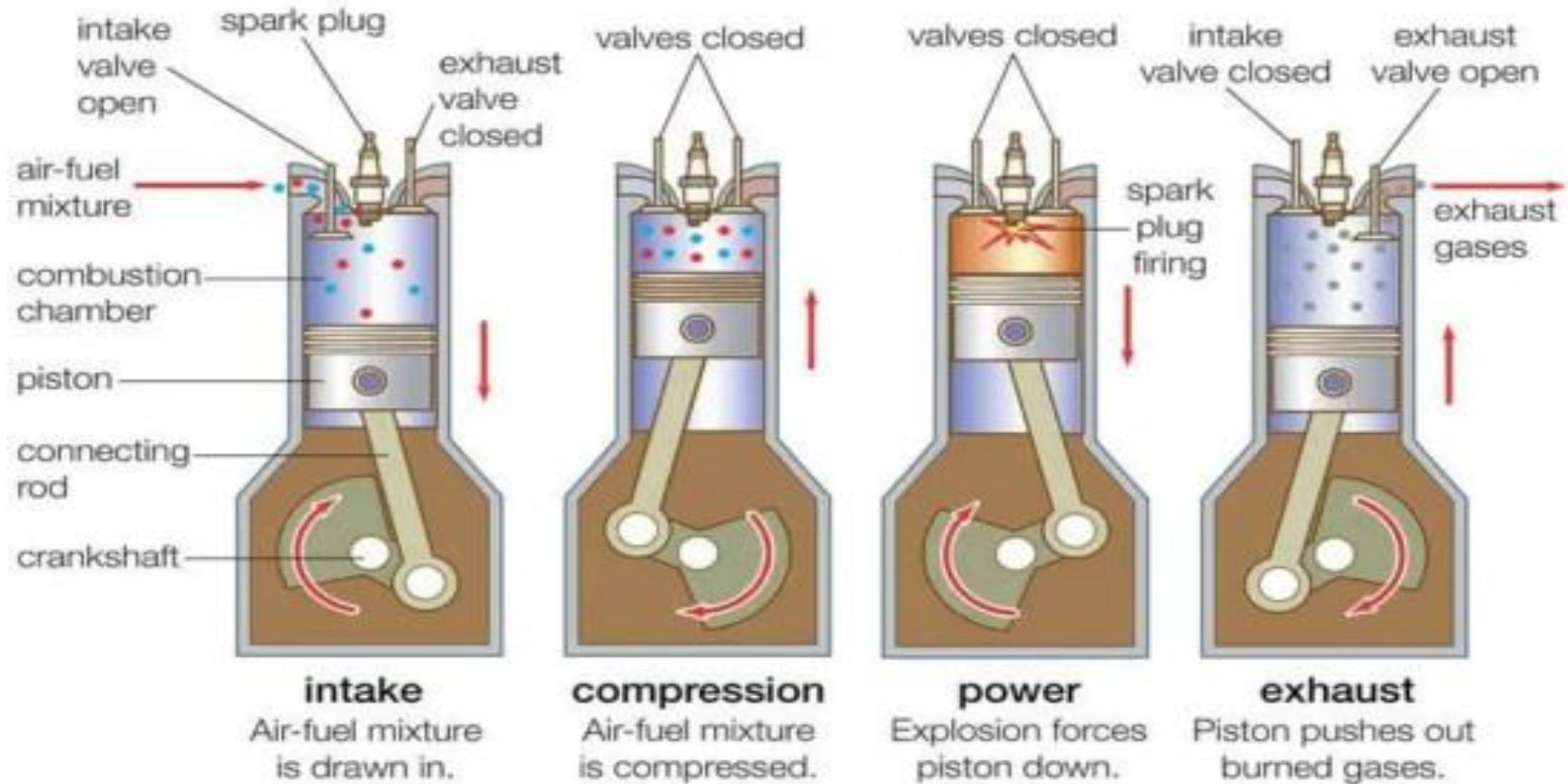
ACTION



Jet Propulsion:
Thrust = (Mass Flow x Velocity) + (Pressure x Exit Area)

Source of power for UAVs

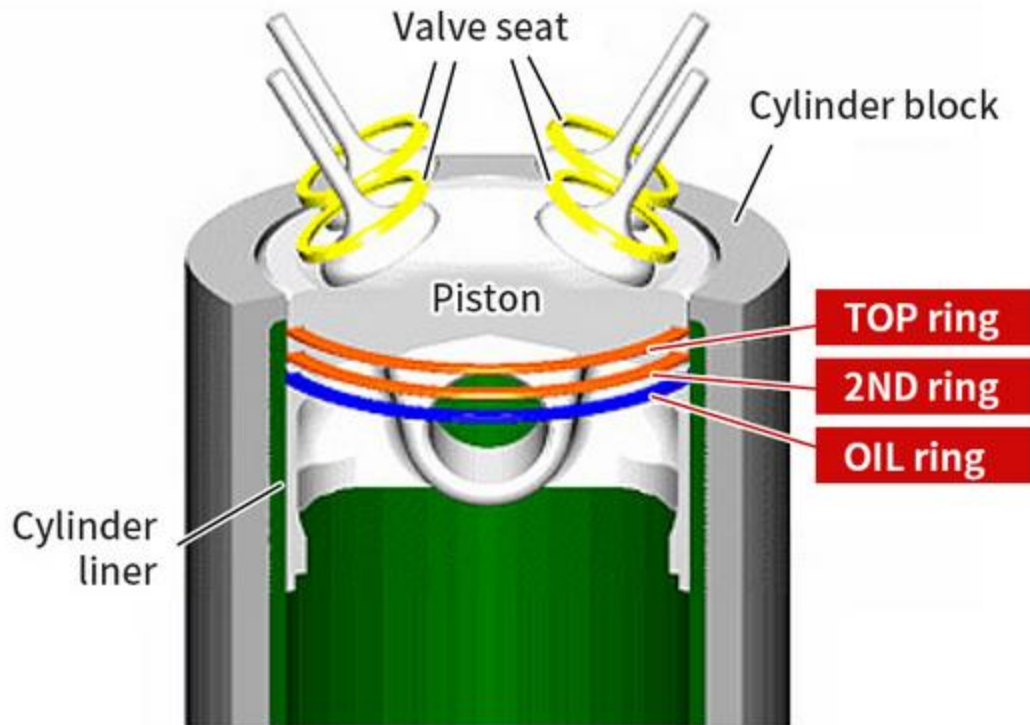
4 stroke piston engine



Construction

- Four-stroke engines consist of the following parts:
- **Cylinder:** It is the heart of the engine. The piston reciprocates in the cylinder.
- **Cylinder head:** It is the top cover of the cylinder, towards TDC, which is called the cylinder head.
- **Piston:** It is the reciprocating member of the engine. It reciprocates in the cylinder.
- **Piston rings:** Two or three piston rings are provided on the piston. It seals the gap between the cylinder liner and piston.
- **Crank:** It is a rotating member. It makes a circular motion inside the crankcase.
- **Crankcase:** It is the housing of crank and other engine parts. It is also used as the sump of lubricating oil.
- **Connecting rod:** It is used to convert the reciprocating motion of the piston to rotary motion of the crankshaft.
- **Crankshaft:** It is the rotating member, which connects the crank.
- **Cooling fins or Water jackets:** It is used for cooling purposes.
- **Cam and Camshaft:** It is provided to operate the **opening and closing** of the Inlet and Exhaust valve and also operate the fuel injection pump in the Diesel engine.
- **Inlet valve:** This valve controlled the admission of charge or air inside the engine cylinder.
- **Exhaust valve:** This valve controls the removal of burnt gas after combustion.
- **Intake manifold:** This is a passage that carries the fresh charge or air.
- **Exhaust manifold:** This a passage through which the exhaust gas goes out of the engine cylinder.
- **Spark plug:** It is used in a Petrol engine or SI engine to ignite the fuel.
- **Fuel injector:** It is used in a Diesel engine or CI engine to sprayed the fuel inside the cylinder. engine
- **Carburetor:** It is used in a Petrol engine to mix the air-fuel properly.

Piston rings

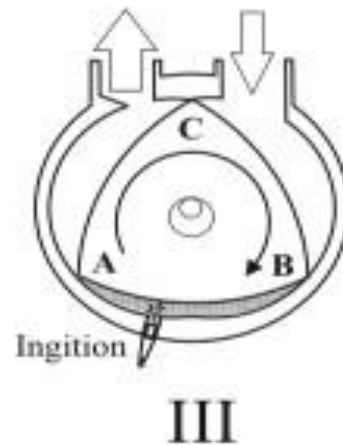
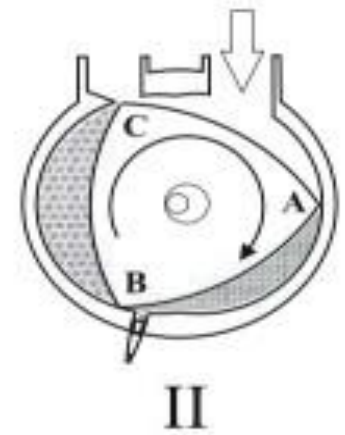
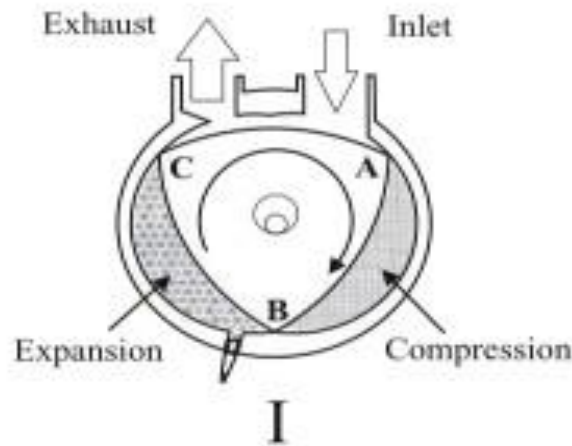
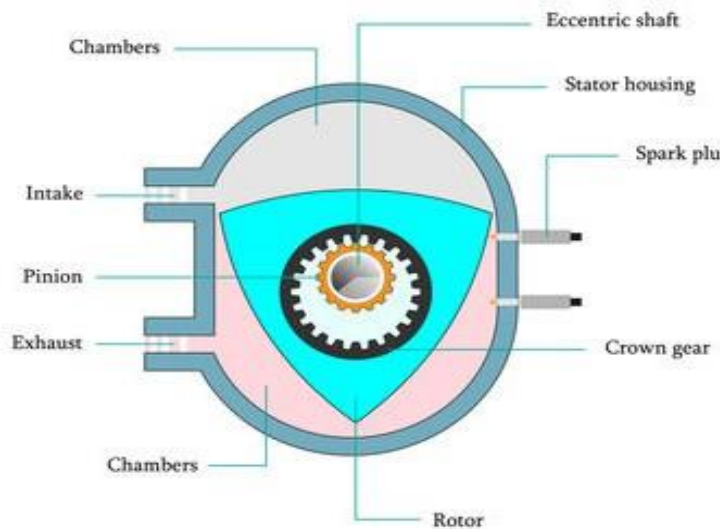


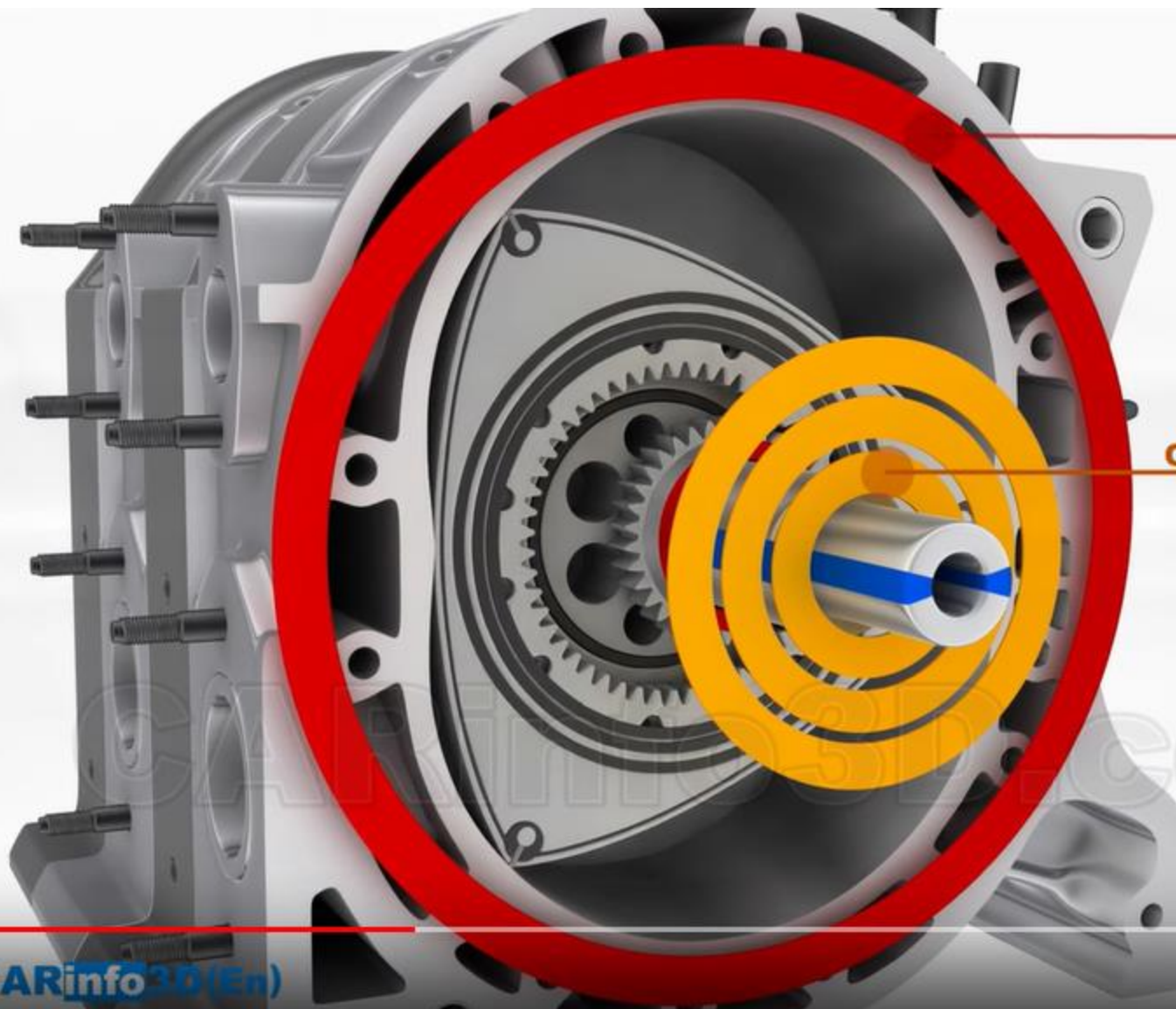
The piston rings **act to carry heat away from the hot piston into the cooled cylinder wall/block of the engine.** Heat energy flows from the piston groove into the piston ring and then into the cylinder wall, where it eventually will be transferred into the engine coolant.

Working

- A four-stroke engine delivers one power stroke for every two cycles of the piston (or four-piston strokes). Intake stroke: The piston moves downward to the bottom; this increases the volume to allow a fuel-air mixture to enter the chamber.
- Compression stroke: The intake valve is closed, and the piston moves up the chamber to the top. This compresses the fuel-air mixture. At the end of this stroke, a spark plug provides the compressed fuel with the activation energy required to begin combustion.
- Power Stroke: As the fuel reaches the end of its combustion, the heat released from combusting hydrocarbons increases the pressure which causes the gas to push down on the piston and create the power output.
- Exhaust stroke: As the piston reaches the bottom, the exhaust valve opens. The remaining exhaust gas is pushed out by the piston as it moves back upwards.

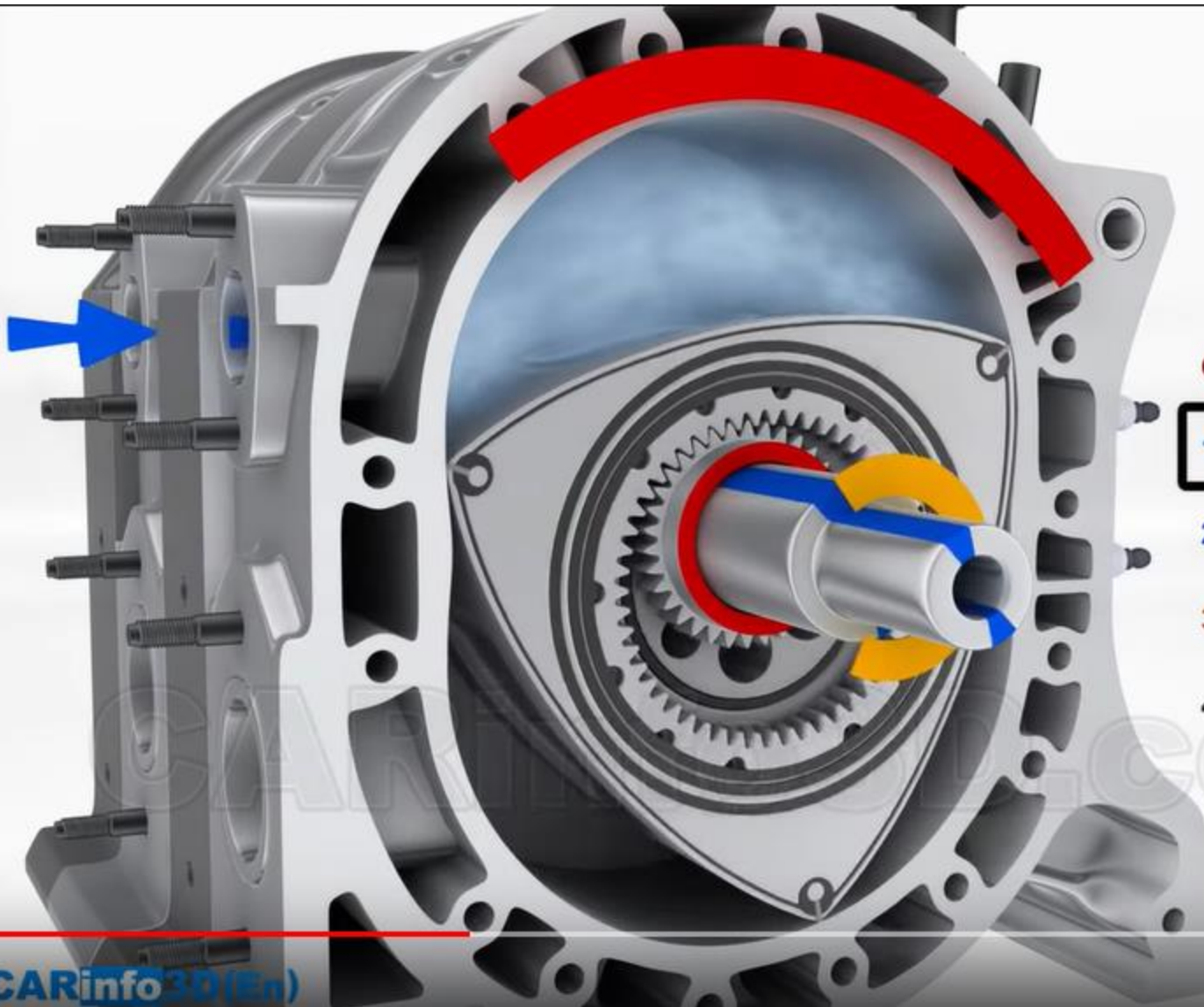
Rotary engine: Working animated video





**ONE REVOLUTION
OF THE ROTOR**

**THREE REVOLUTIONS
OF THE ECCENTRIC SHAFT**



OPERATION CYCLE:

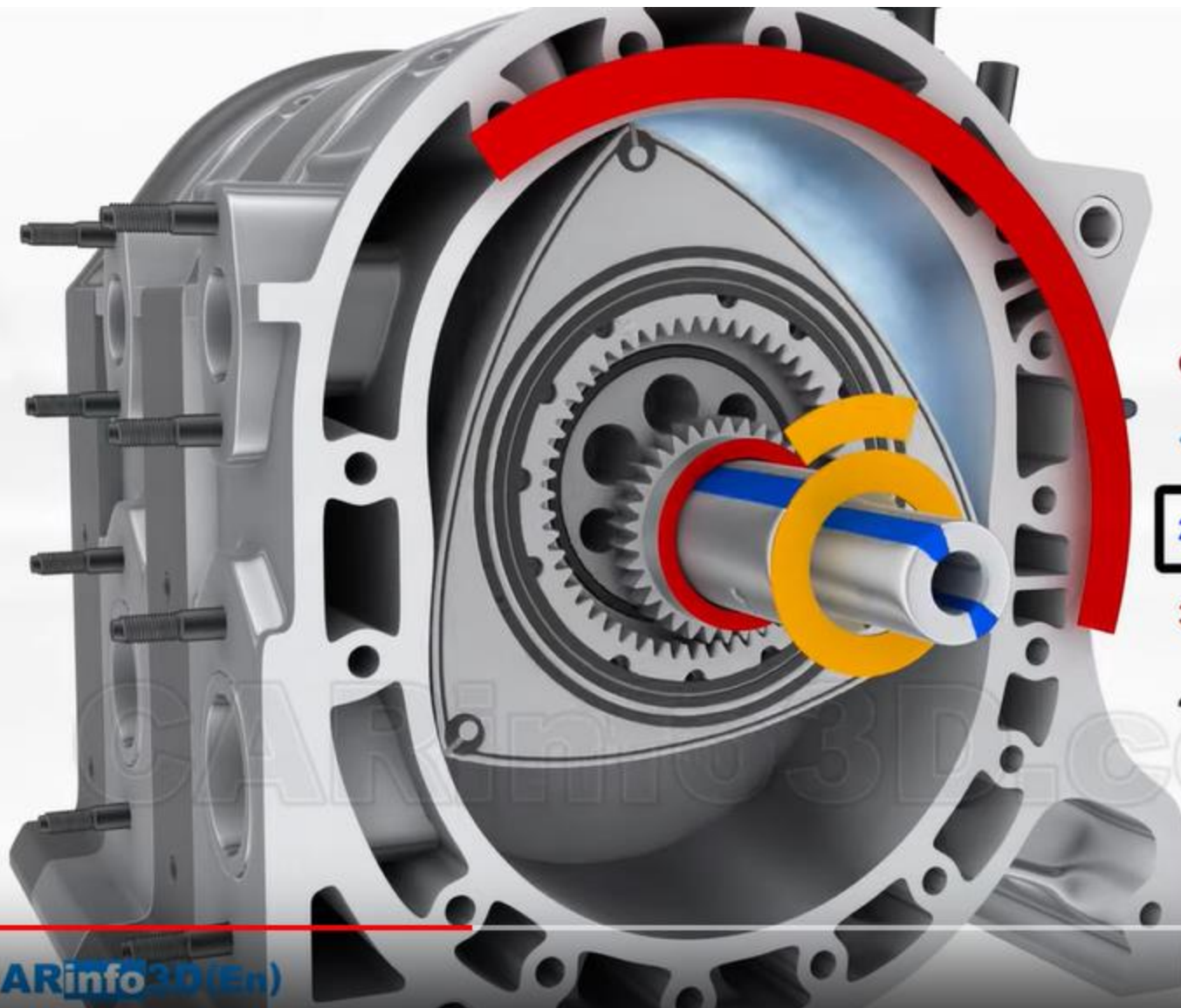
1 - INTAKE

2 - COMPRESSION

3 - POWER (COMBUSTION)

4 - EXHAUST





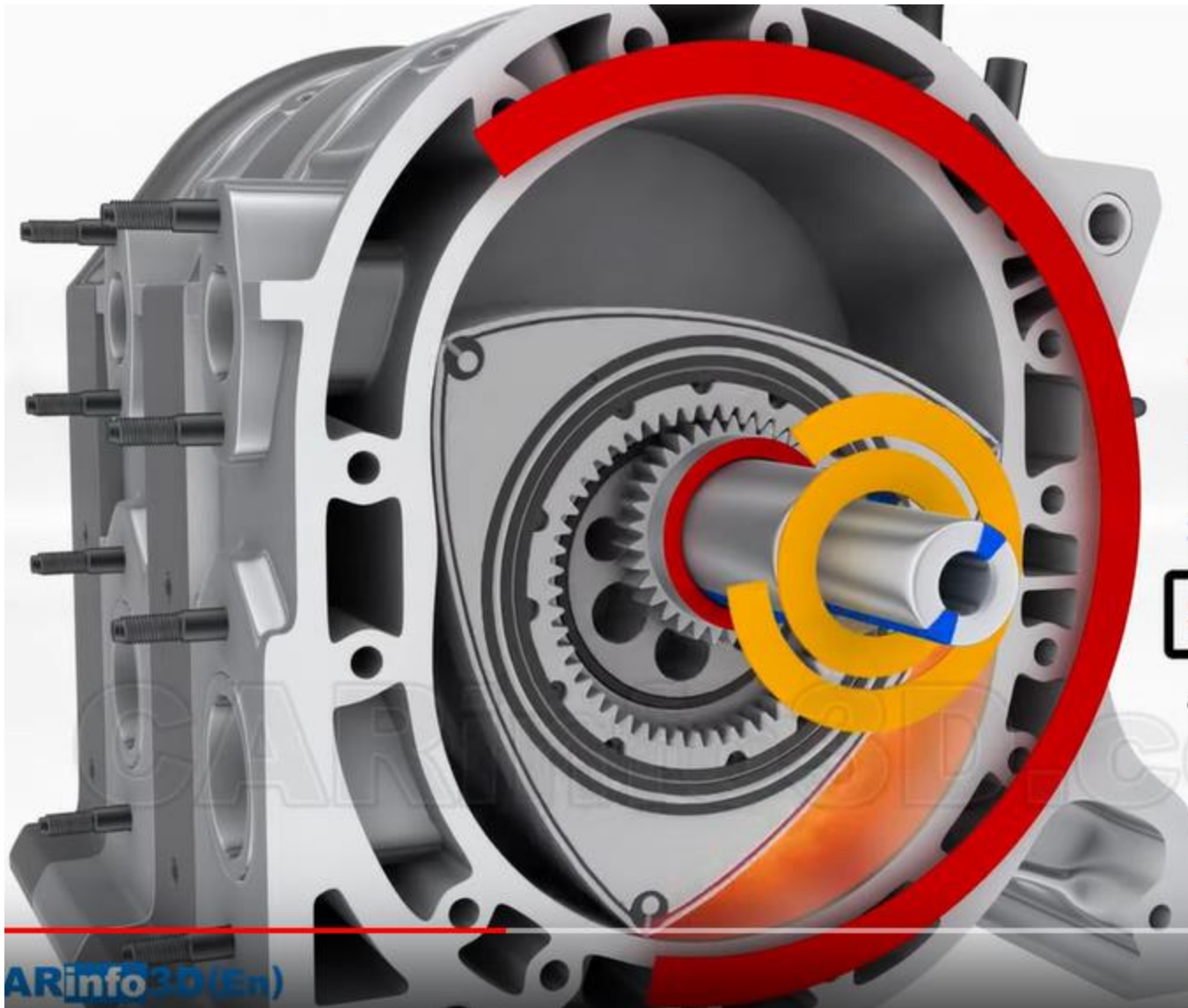
OPERATION CYCLE:

1 - INTAKE

2 - COMPRESSION

3 - POWER (COMBUSTION)

4 - EXHAUST



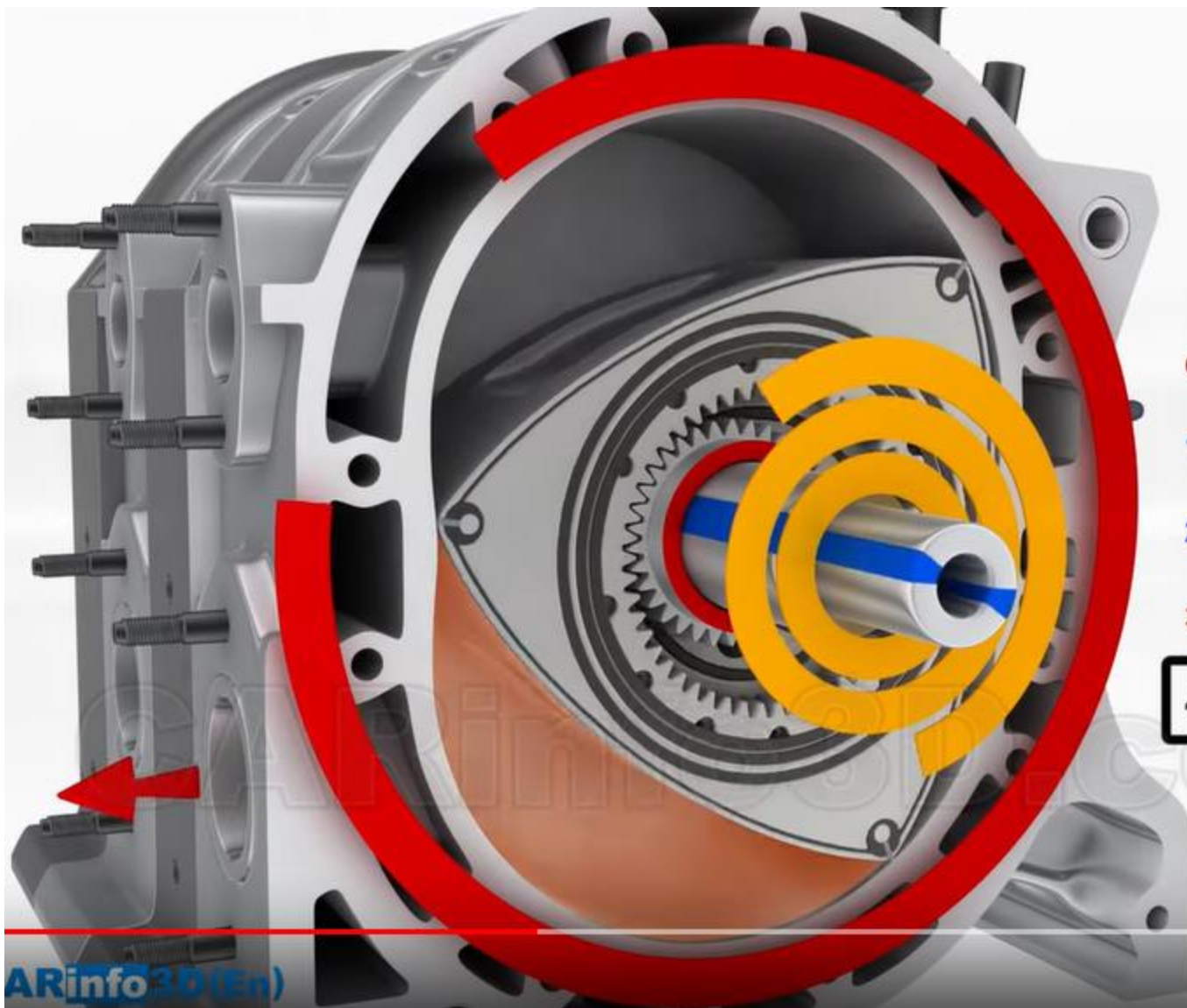
OPERATION CYCLE:

1 - INTAKE

2 - COMPRESSION

3 - POWER (COMBUSTION)

4 - EXHAUST



OPERATION CYCLE:

1 - INTAKE

2 - COMPRESSION

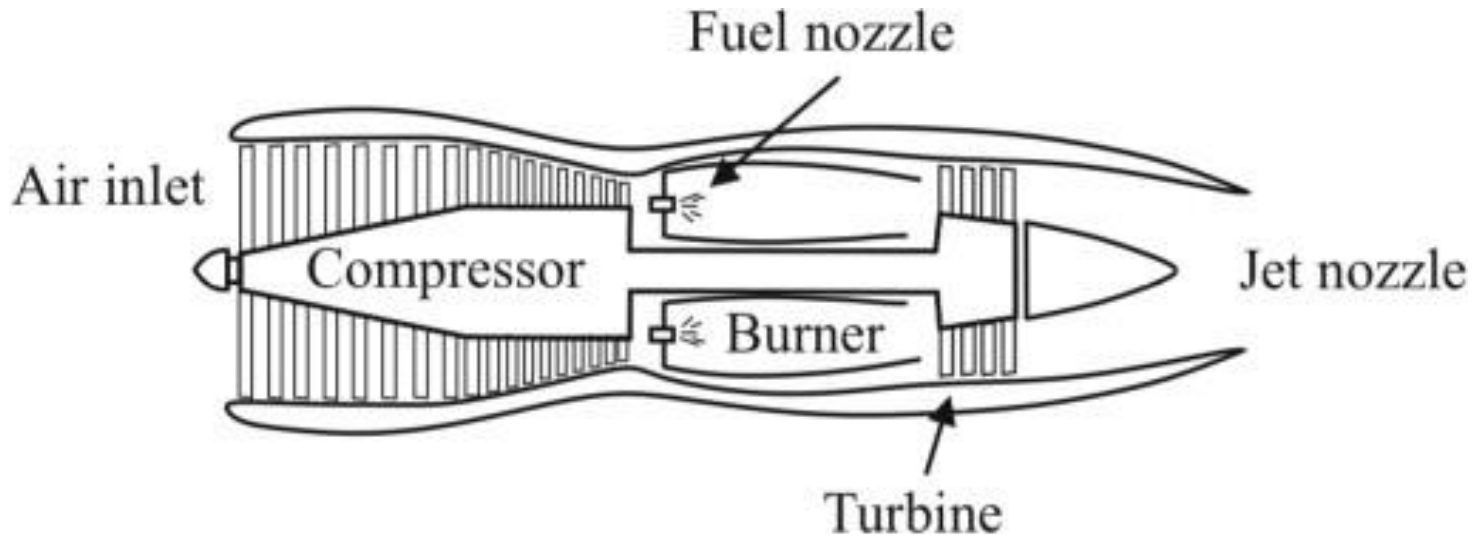
3 - POWER (COMBUSTION)

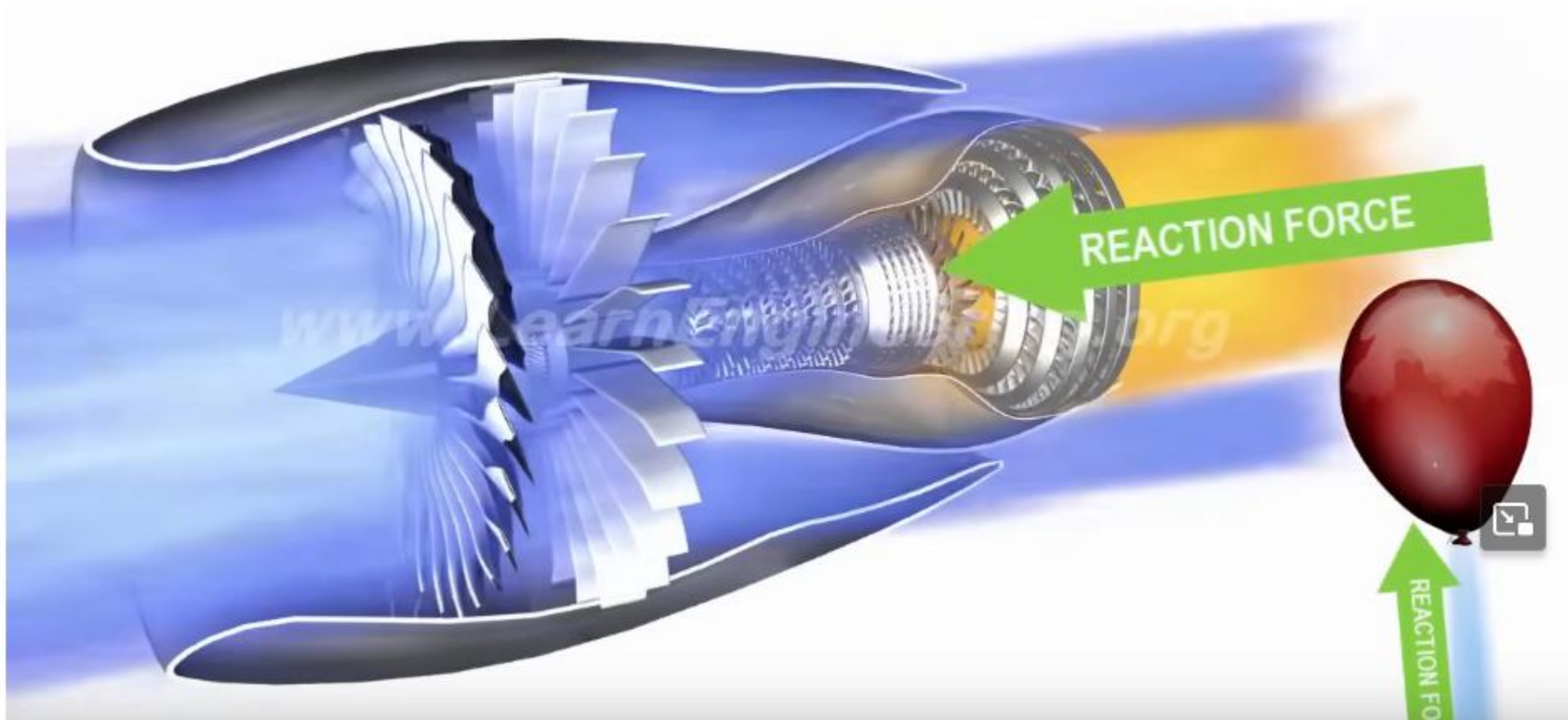
4 - EXHAUST

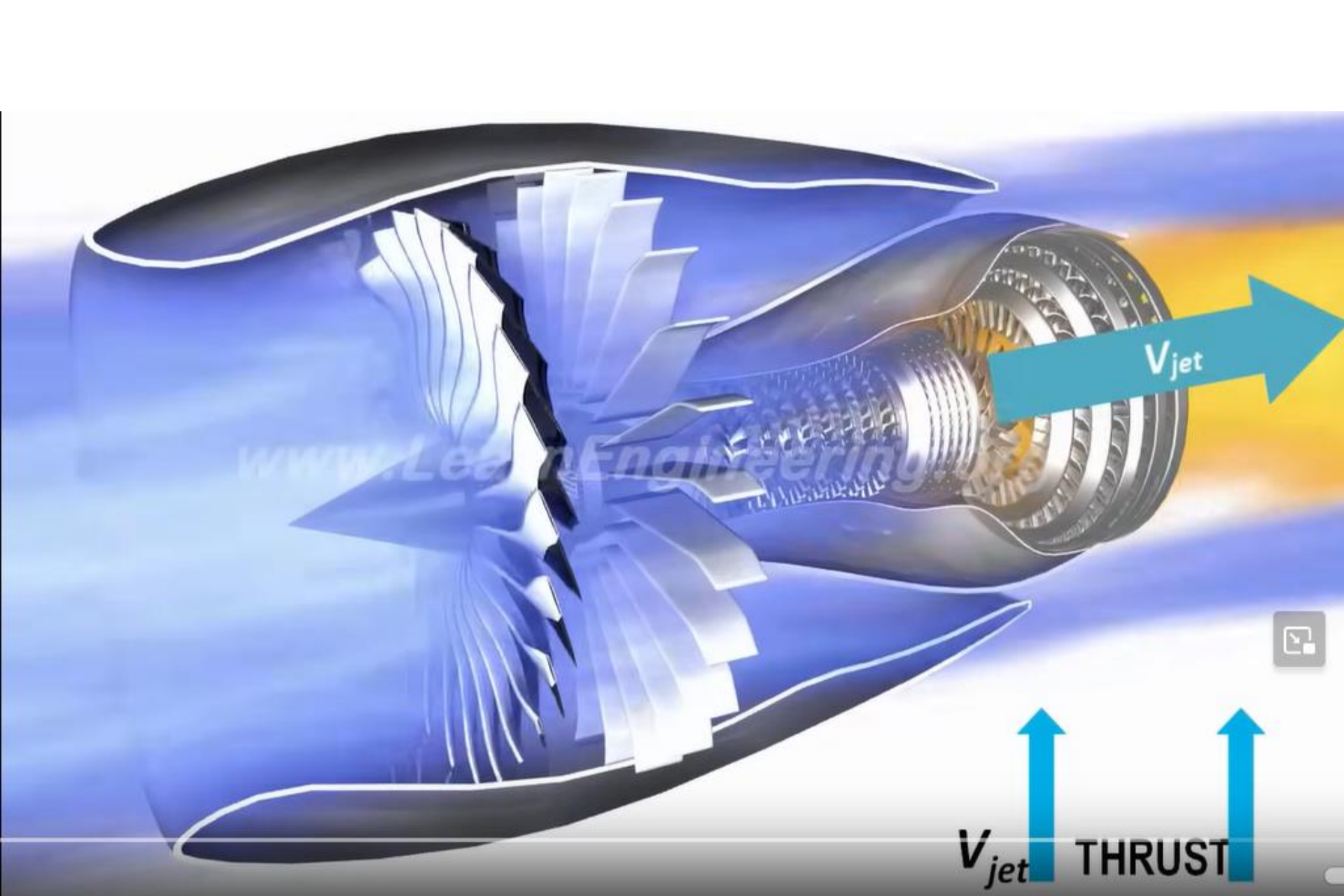
- The principle of operation of the rotary engine is based on the rotation of a three-sided geometrical shape within a two-lobe geometrical stator. The rotor revolves within this stator such that its three apices make continuous contact with the stator. The stator is an epitrochoid curve based on the path of a point on the radius of a circle that rolls on the outside of a fixed circle.
- Each face of the rotor completes a four-cycle process identical to the four-cycle engine: intake, compression, combustion, and exhaust.
- The cycle takes place during one rotation of the rotor, so one can consider a single bank rotary engine as a three-cylinder engine. As we shall see there is no reciprocating motion, so vibration can be very low. The end of the rotor is usually provided with an internal gear, concentric with its center, that rotates around a smaller fixed pinion gear mounted on the side cover of the casing

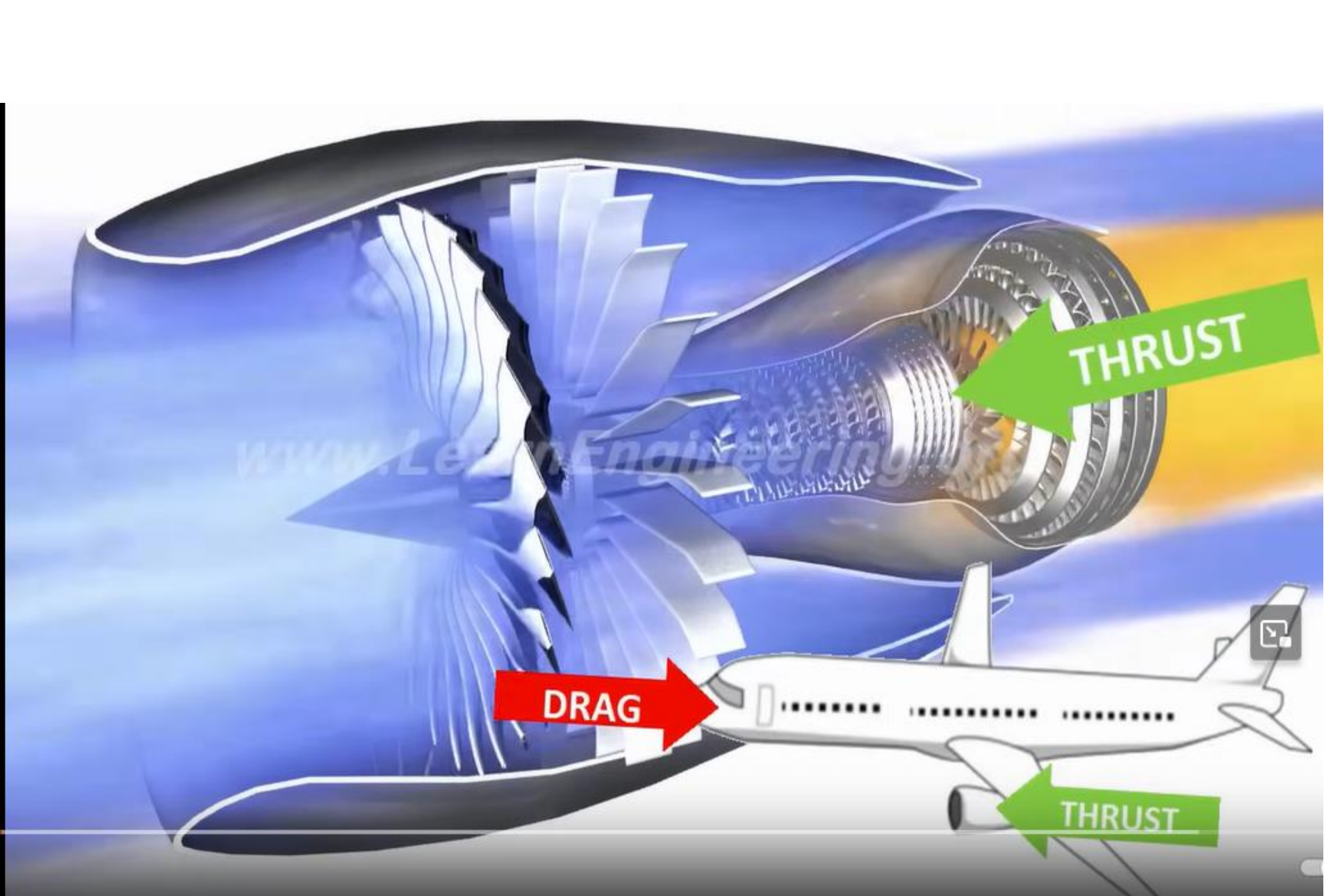
- In diagram I, the exhaust and inlet ports are shown to be open, just ending one cycle of exhaust and starting input of a fresh fuel–air mixture to the segment adjacent to side C–A, while the mixture previously drawn into the segment adjacent to side A–B is starting to be compressed. This process continues in diagram II. In diagram III, the mixture adjacent to side A–B has reached its maximum compression and is ignited by a spark. At the same time, the segment adjacent to side B–C, which has been expanding and driving the rotor, is opened to the exhaust port.
- The burning mixture in the segment adjacent to side A–B now expands and drives the rotor, while the fresh mixture that has been drawn into the segment adjacent to side C–A begins to be compressed, and the combustion products in the segment adjacent to side B–C are expelled through the exhaust port and replaced by a fresh fuel–air mixture entering through the inlet port.
- Thus, in one revolution three, four-cycle Otto cycles have been completed, one in each segment

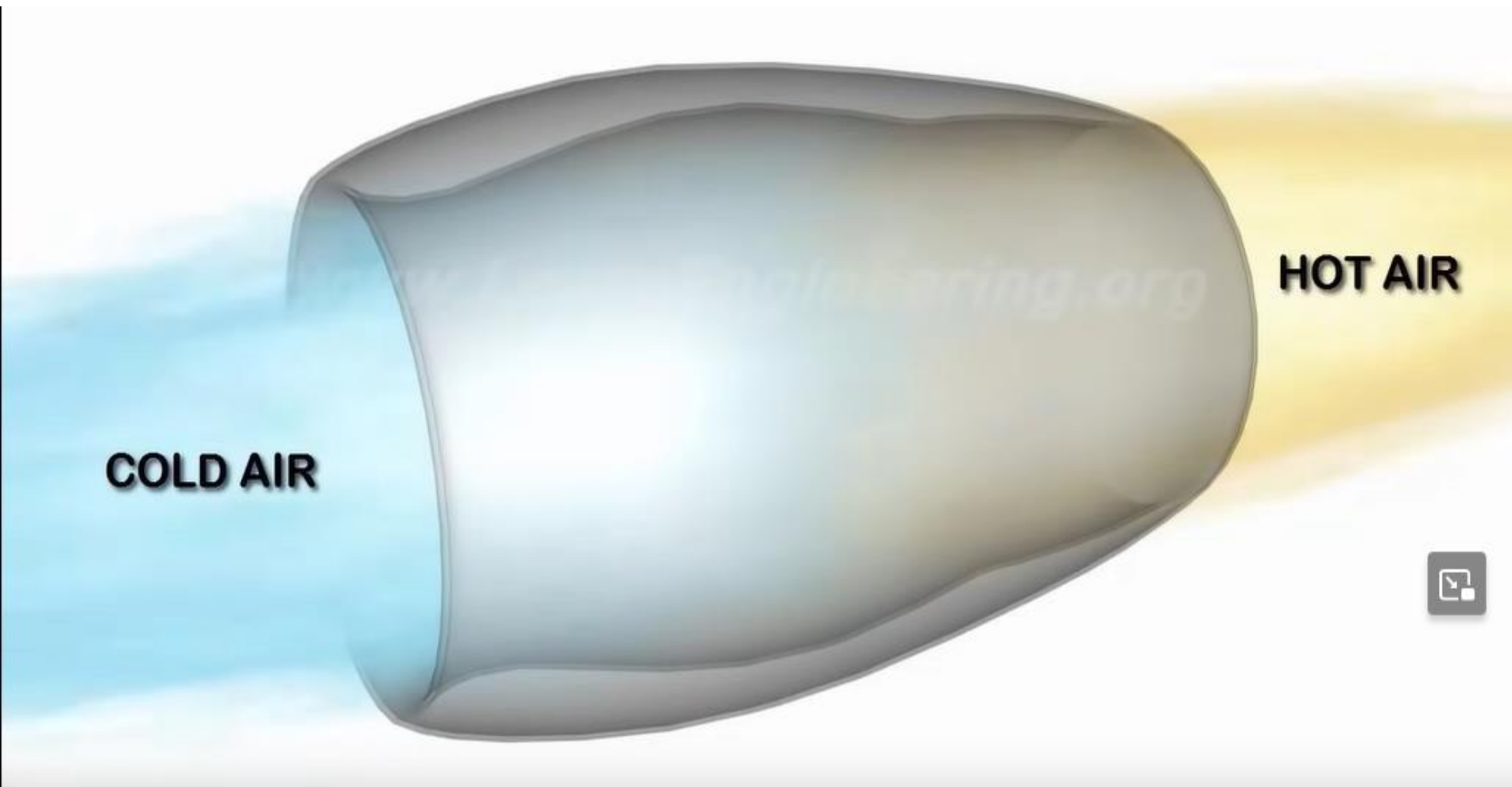
The Gas Turbine Engine

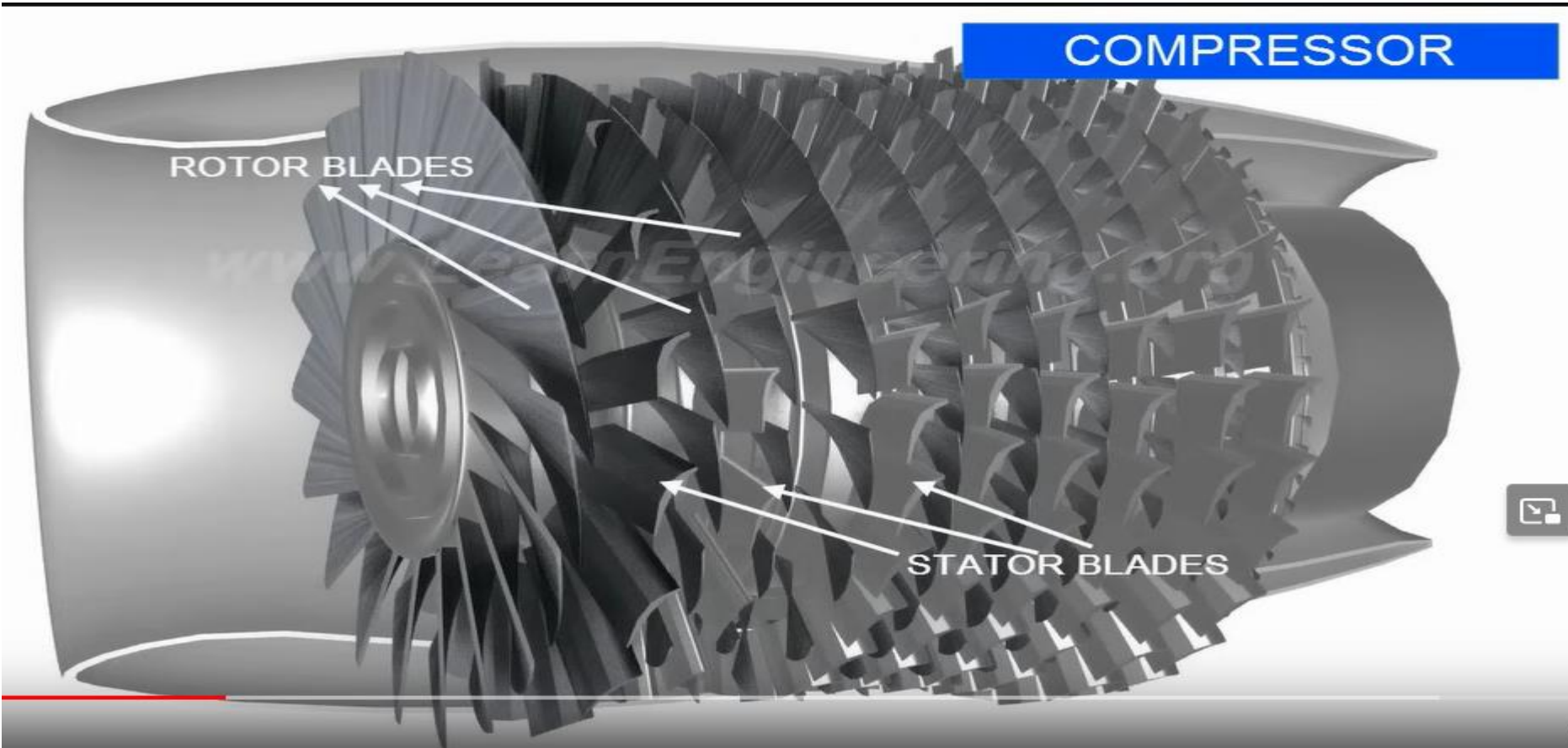
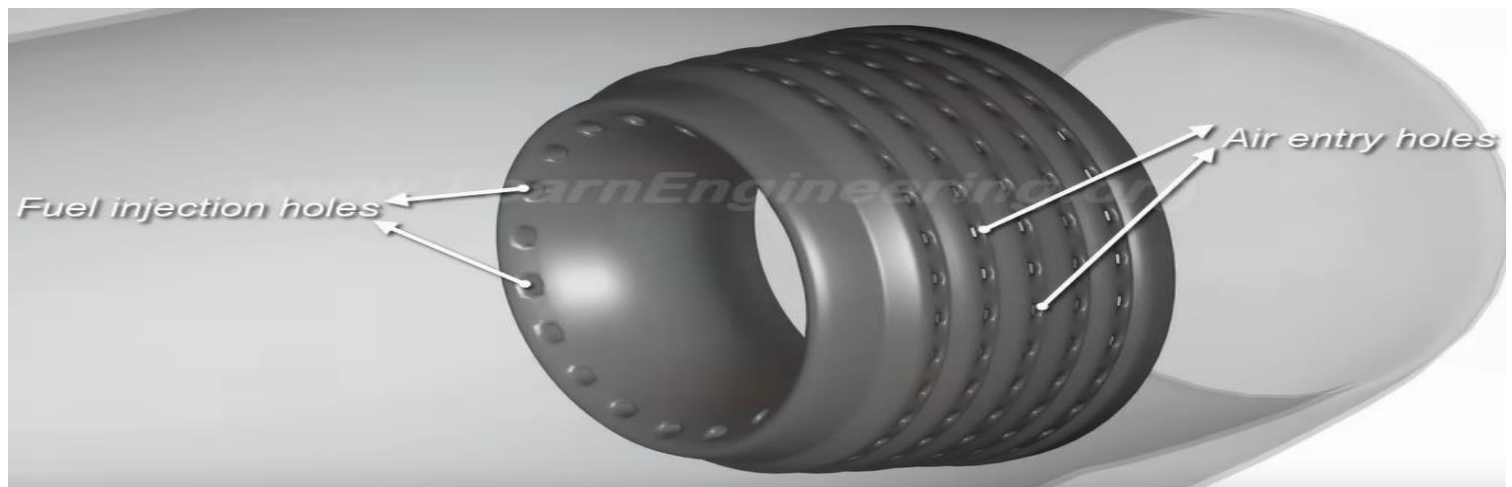


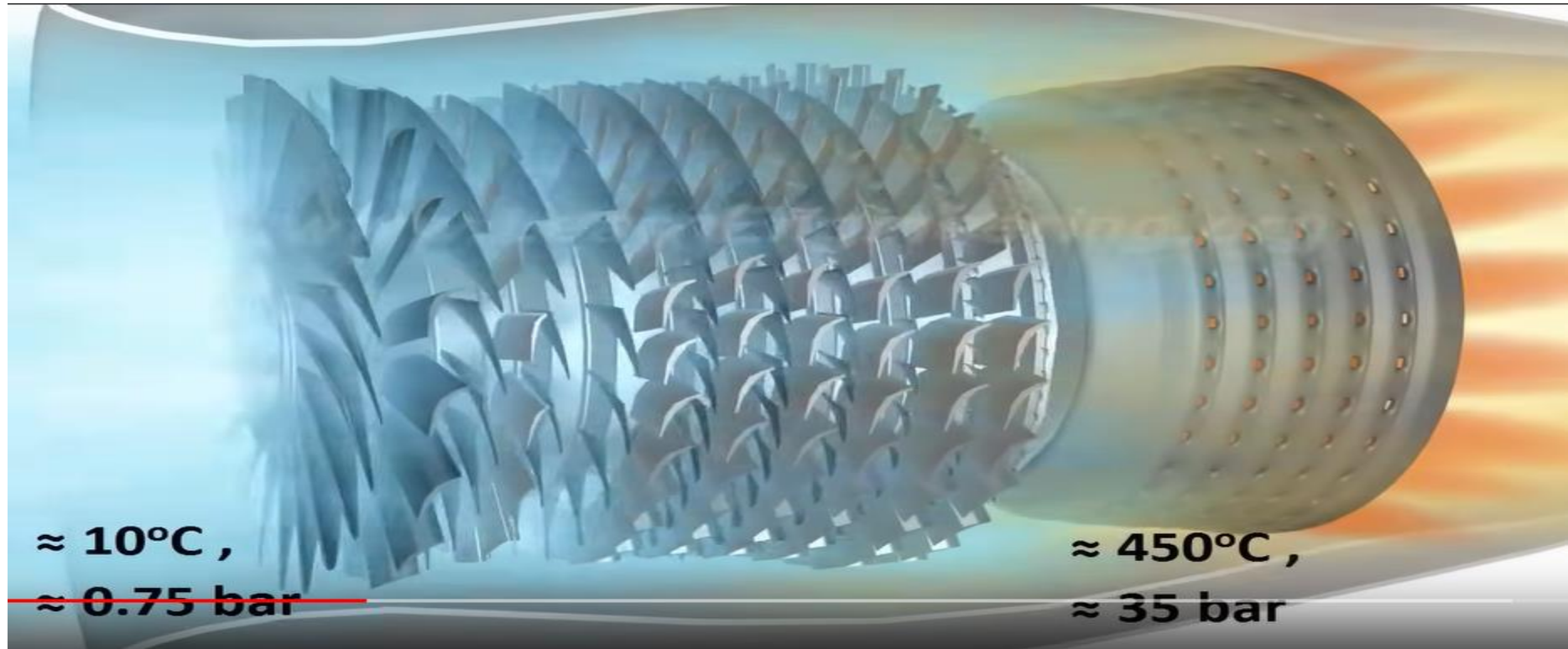




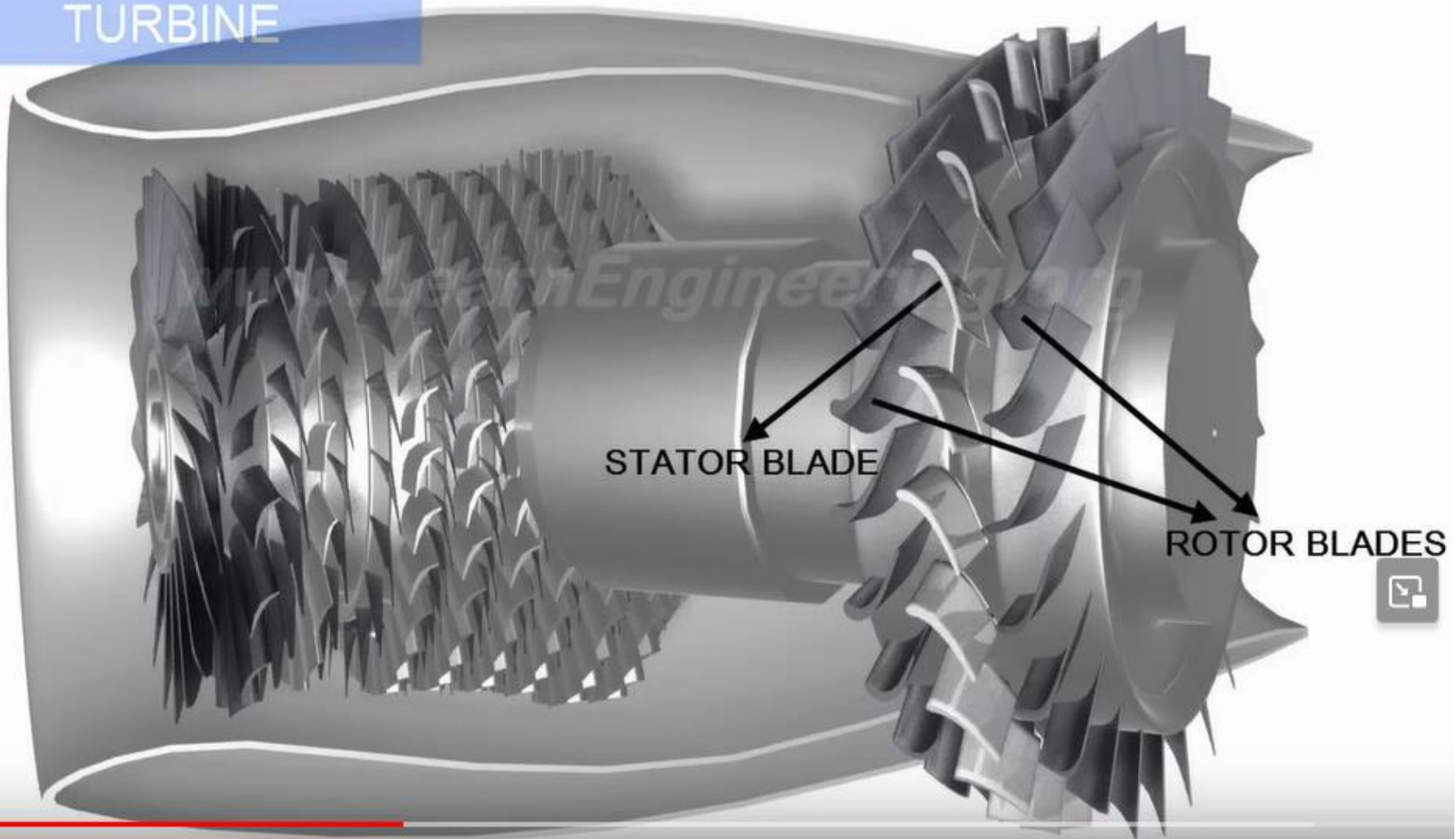


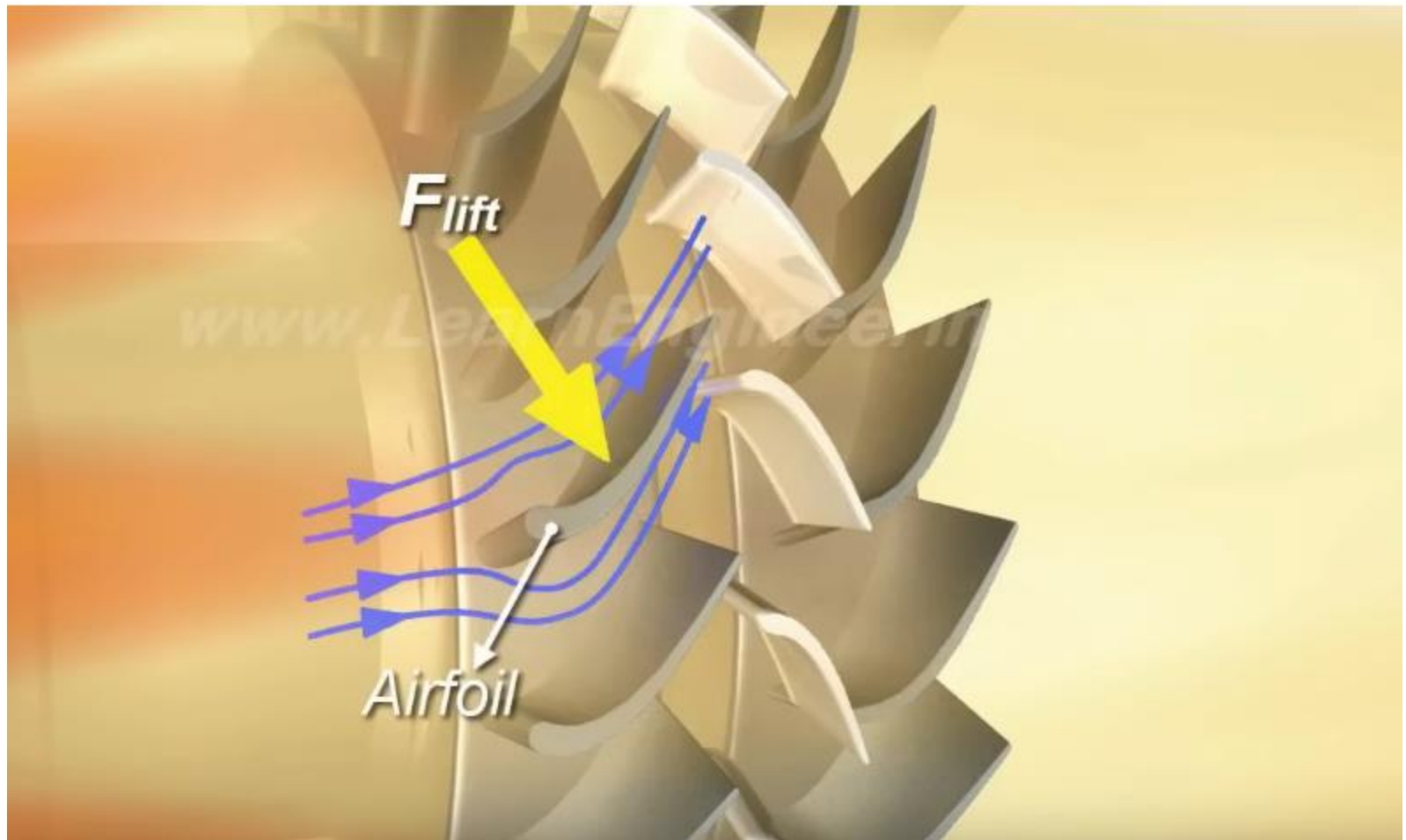






TURBINE







PRESSURE

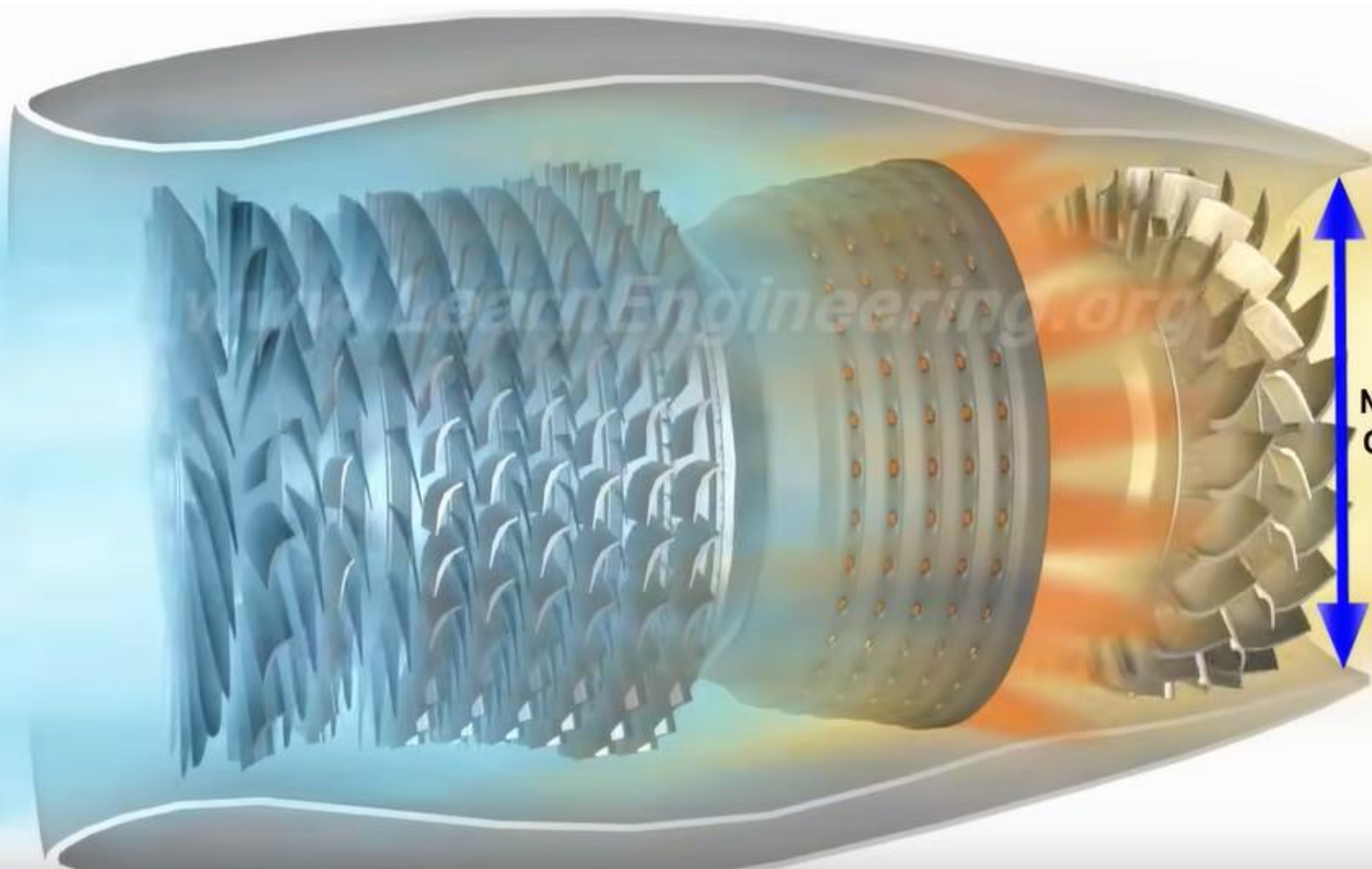
**$\approx 1600^{\circ}\text{C}$,
 $\approx 35 \text{ bar}$**

**$\approx 350^{\circ}\text{C}$,
 $\approx 0.75 \text{ bar}$**

$\approx 10^{\circ}\text{C}$

$\approx 350^{\circ}\text{C}$





**NARROW
OUTLET**



Air inlet: The air inlet duct must provide clean and unrestricted airflow to the engine. Clean and undisturbed inlet airflow extends engine life by preventing erosion, corrosion, and foreign object damage (FOD).

Compressor: The compressor is responsible for providing the turbine with all the air it needs in an efficient manner. In addition, it must supply this air at high static pressures. In an axial flow compressor, each stage incrementally boosts the pressure from the previous stage. A single stage of compression consists of a set of rotor blades attached to a rotating disk, followed by stator vanes attached to a stationary ring. The flow area between the compressor blades is slightly divergent.

Combustion chamber : combustion section has the difficult task of controlling the burning of large amounts of fuel and air. It must release the heat in a manner that the air is expanded and accelerated to give a smooth and stable stream of uniformly-heated gas at all starting and operating conditions. Maximum combustion section outlet temperature (turbine inlet temperature) in this engine is about 1070 degree Celsius.

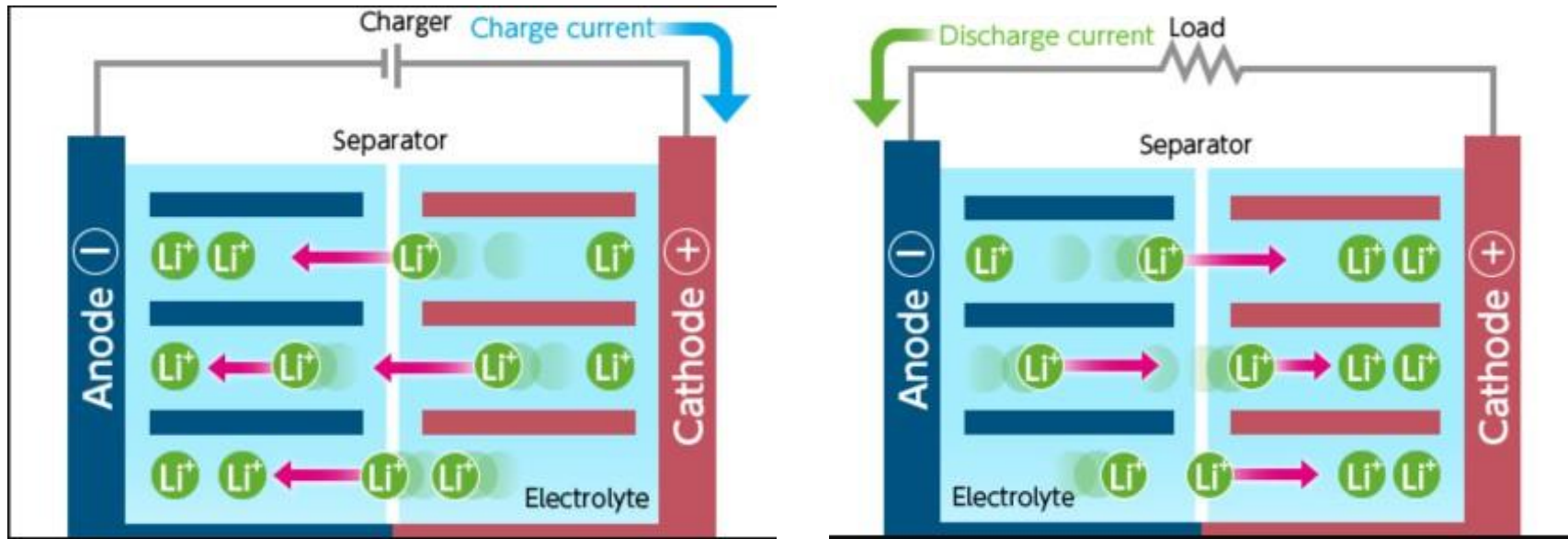
Turbine : The turbine converts the gaseous energy of the air/burned fuel mixture out of the combustor into mechanical energy to drive the compressor, driven accessories, and, through a reduction gear, the propeller. The turbine converts gaseous energy into mechanical energy by expanding the hot, high-pressure gases to a lower temperature and pressure

Nozzle: It is a device that is used to accelerate the hot gas from the turbine. It expands the gas to higher velocity and generates a jet thrust. It is found at the rear of the engine.

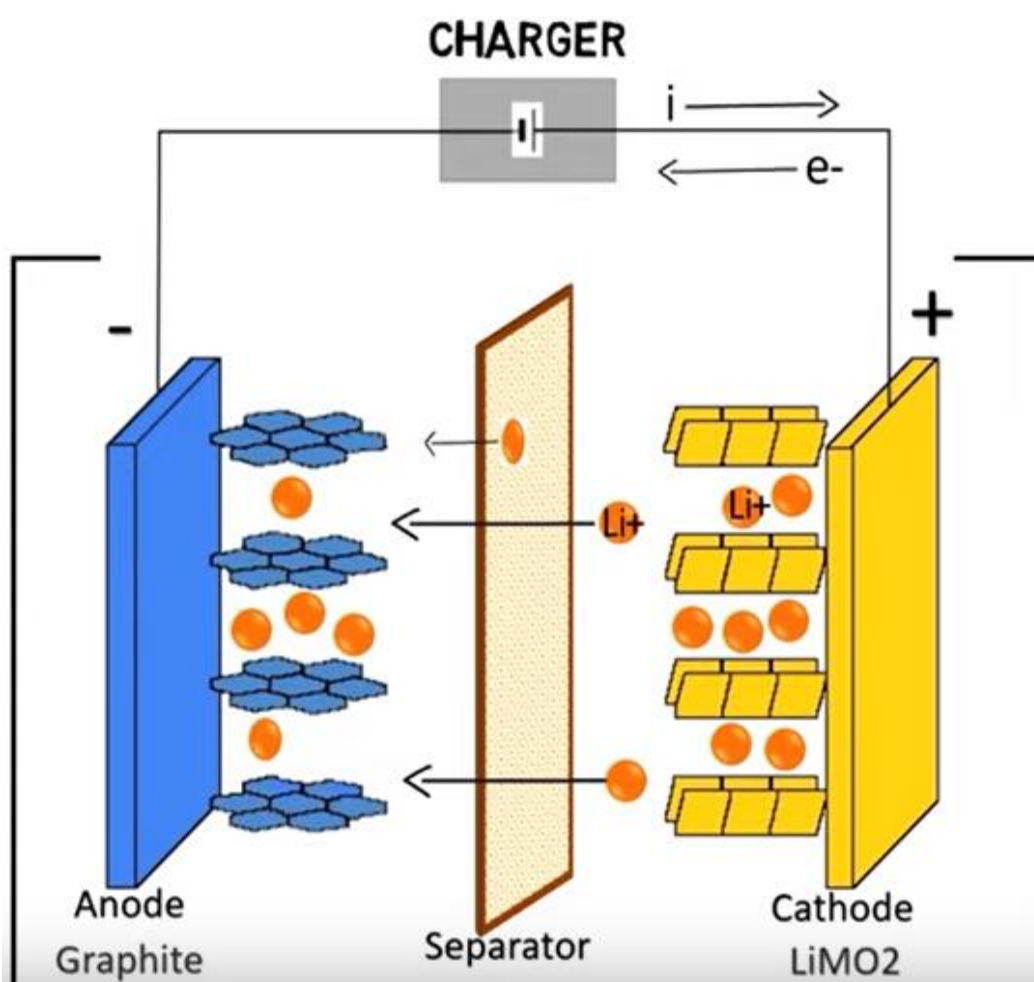
Fan : The turbojet engine fitted with fan at the front end of engine is called as turbofan engine. The rotation of fan pushes an incoming air rearward resulting in forward Fan thrust. This design is not suitable for supersonic flight.

Turbofan thrust = Fan thrust + Jet thrust

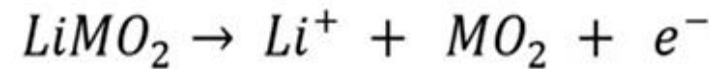
Lithium ion battery



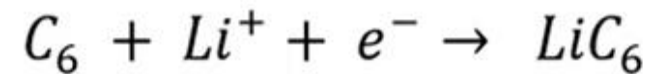
The most common electrolyte in lithium batteries is a lithium salt solution such as **lithium hexafluorophosphate (LiPF_6)** Ref: <https://www.energy.gov/energysaver/articles/how-lithium-ion-batteries-work>



AT CATHODE



AT ANODE

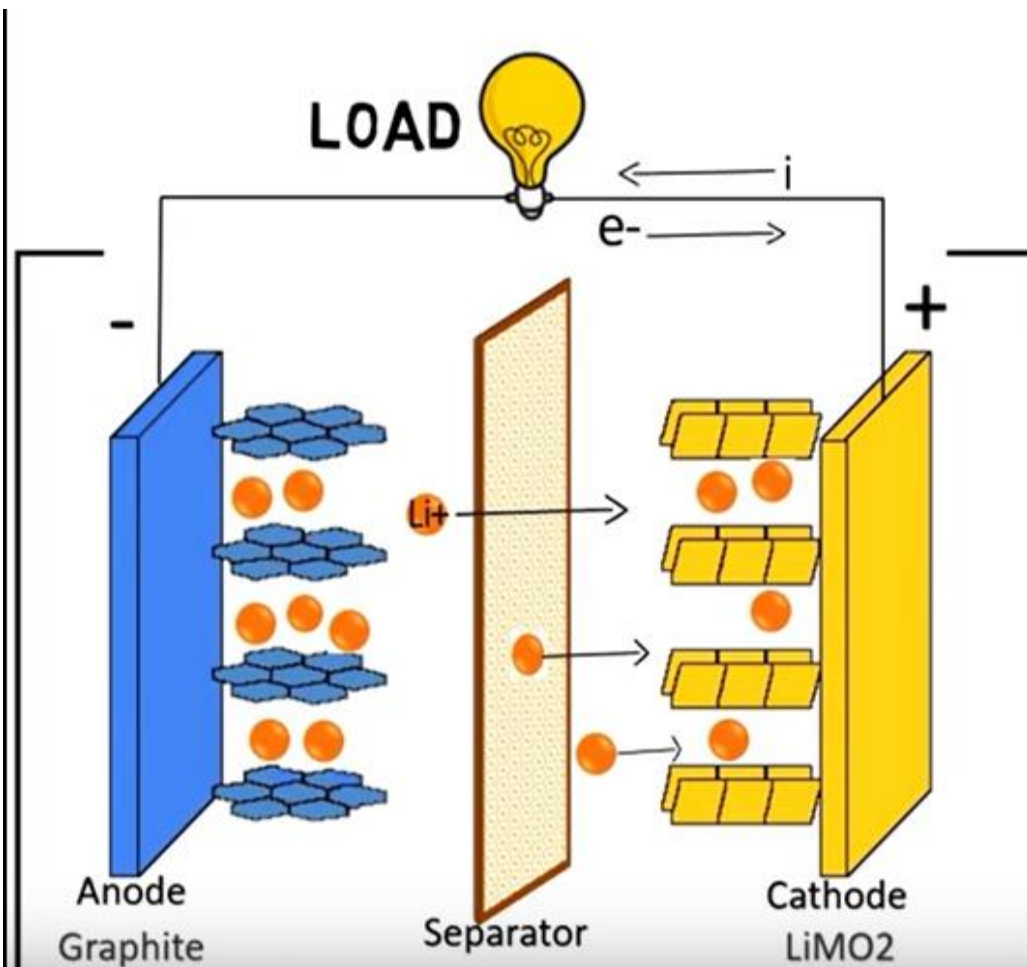


CELL REACTION:

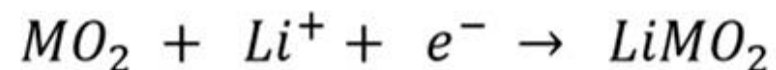


LiC₆—lithiated carbon and LiMO₂—Lithium metal oxide and **mobile battery is 100% if lithium is loaded at anode between graphite(carbon) layers. Electric current is used to drive the non-spontaneous redox reaction through this electrolytic cell**

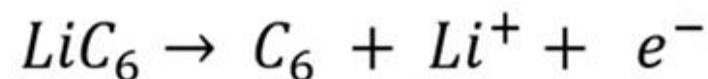
For reference: to know electrochemical cell and electrolytic cell working and how spontaneous redox reaction drive electric current and how electric current drives non-spontaneous redox reaction: <https://www.youtube.com/watch?v=1tvvSUySfls>



AT CATHODE



AT ANODE



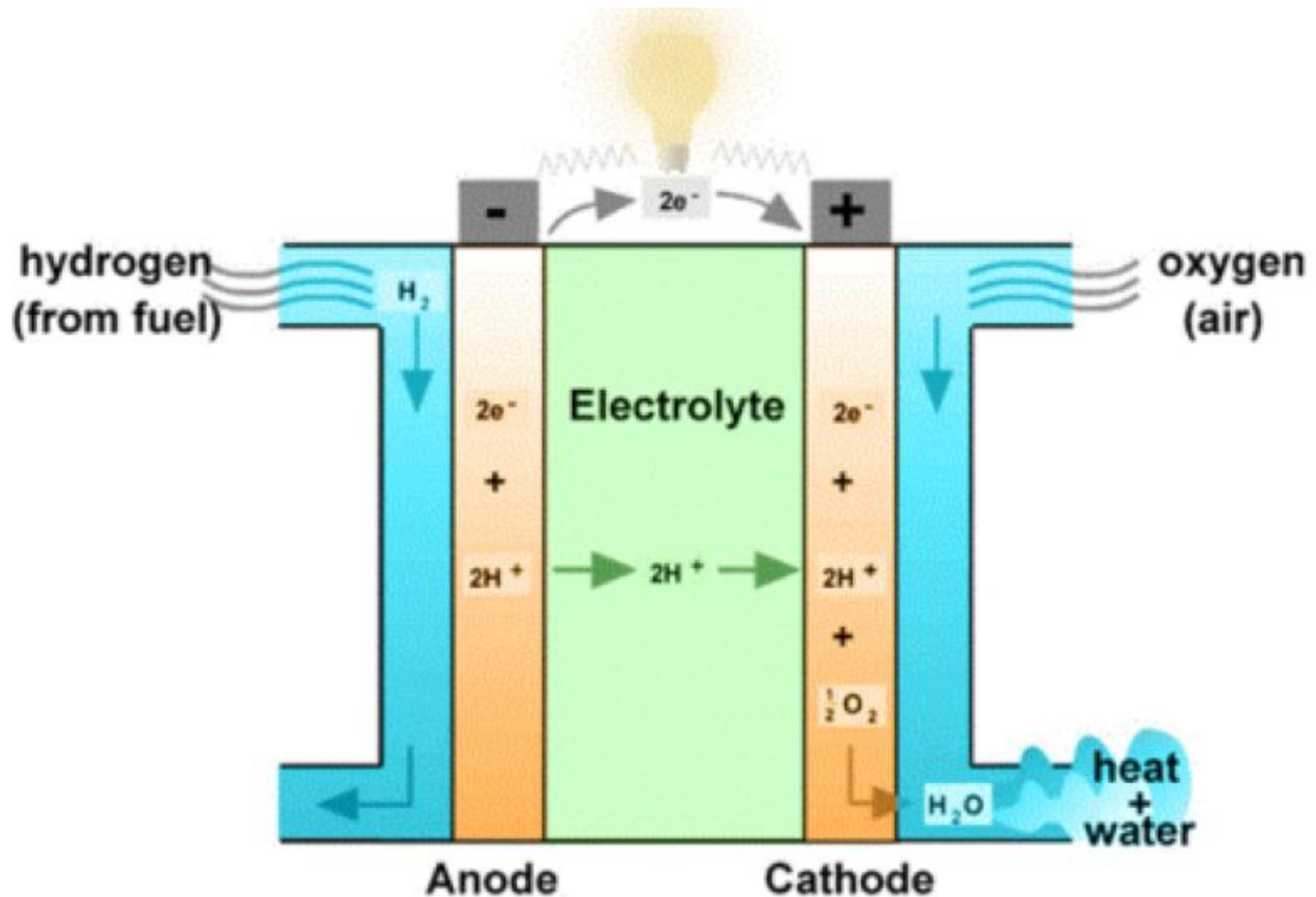
CELL REACTION



Mobile battery is **empty(0%)** if there is no lithium ions at the anode to move. Lithium is a reactive metal and thus **spontaneous redox reaction** takes place to loose electrons at the anode. Lithium ion will transfer through separator where electron will drive and electric current.

- The rechargeable lithium-ion battery is made of one or more power-generating compartments called cells. Each cell has essentially three components.- positive electrode, negative electrode and electrolyte.
- A positive electrode connects to the battery's positive or + terminal. A negative electrode connects to the negative or – terminal. And a chemical called an electrolyte is in between them.
- The positive electrode is typically made from a chemical compound called lithium-cobalt oxide (LiCoO_2) or lithium iron phosphate (LiFePO_4). The negative electrode is generally made from carbon (graphite). The electrolyte varies from one type of battery to another.
- The electrolyte carries positively charged lithium ions from the anode to the cathode. The movement of the lithium ions creates free electrons in the anode which creates a charge at the positive current collector. The electrical current then flows from the current collector through a device being powered (cell phone, computer, etc.) to the negative current collector. The separator blocks the flow of electrons inside the battery.
- While the battery is discharging and providing an electric current, the anode releases lithium ions to the cathode, generating a flow of electrons from one side to the other. When plugging in the device, the opposite reaction happens, the cathode releases lithium ions and anode receives them. This is how the Lithium-ion battery works

Fuel cells: Play video





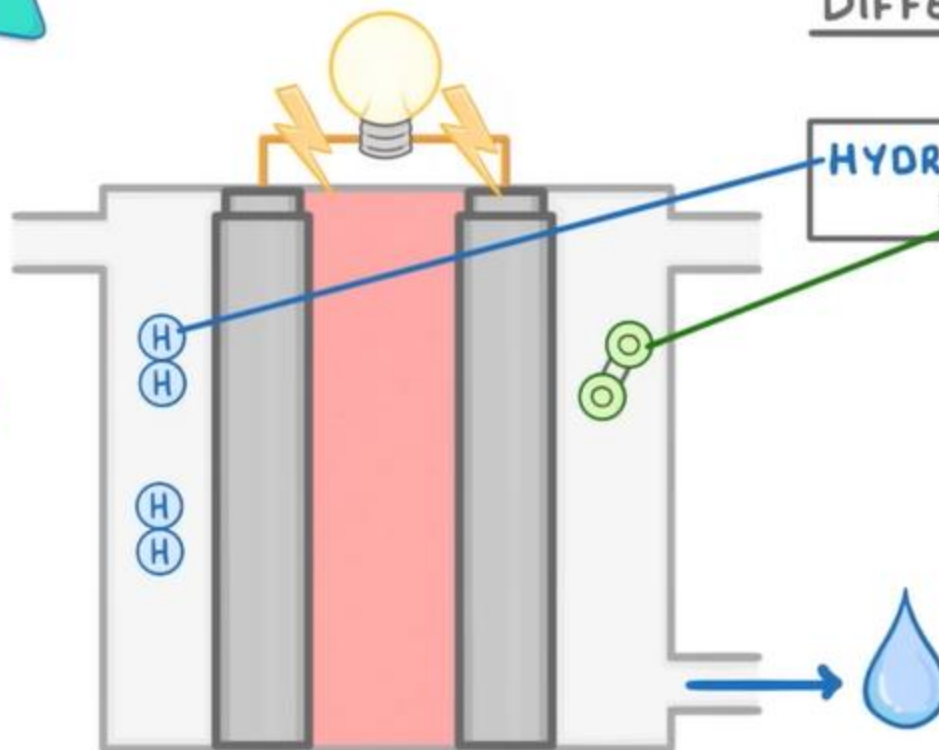
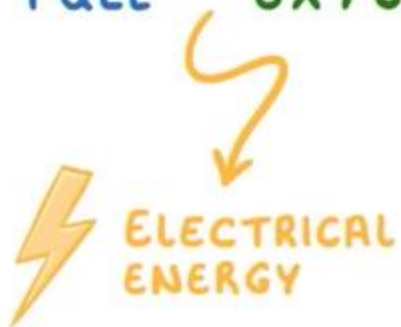
FUEL CELLS

DIFFERENT TYPES:



FUEL

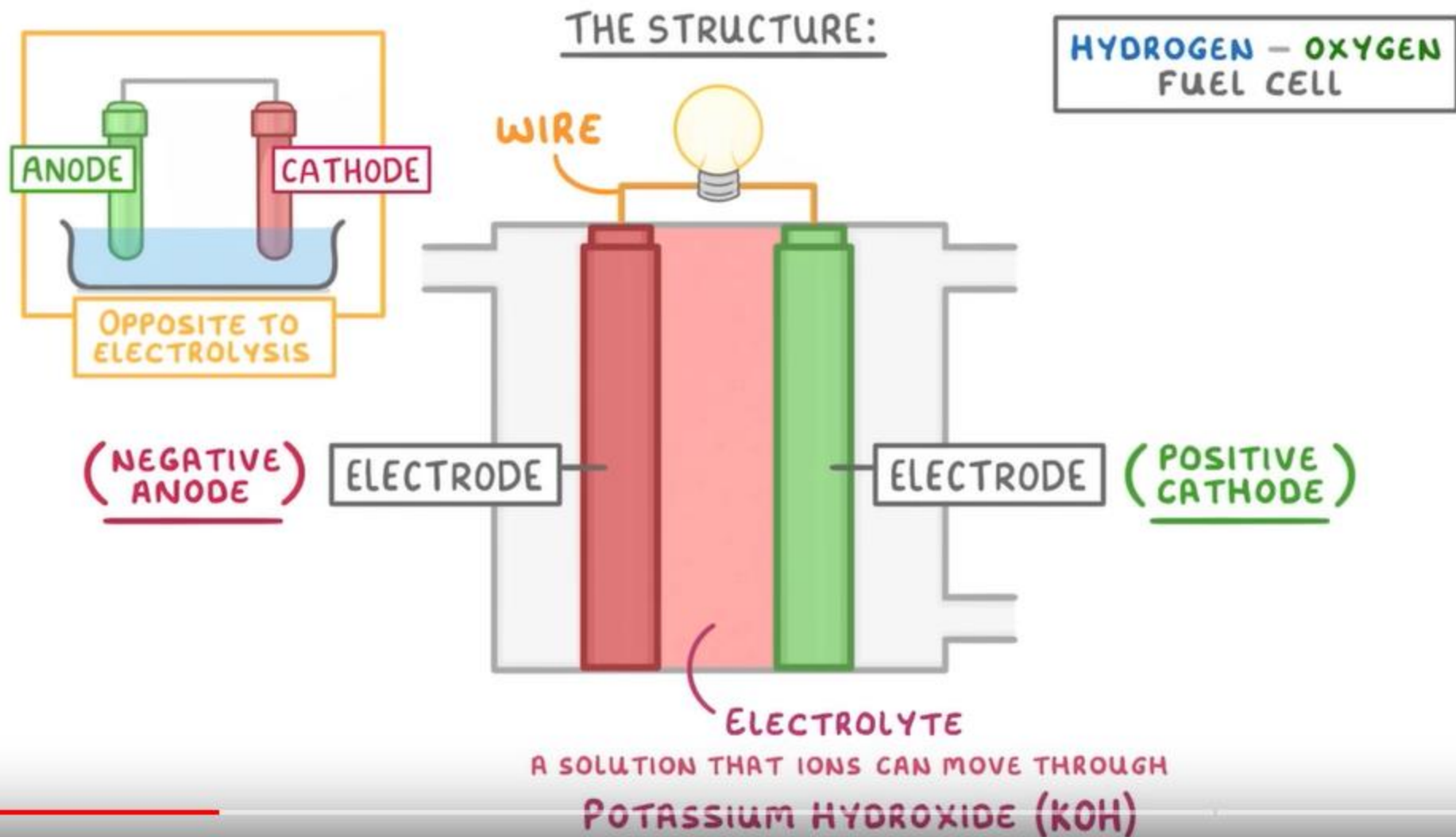
OXYGEN



HYDROGEN - OXYGEN
FUEL CELL

ELECTROCHEMICAL CELL





PROS

HYDROGEN - OXYGEN FUEL CELL

CONS



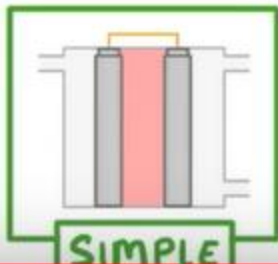
HYDROGEN

ONLY REQUIRE:



OXYGEN

DON'T PRODUCE ANY
AS WASTE



↳ LAST LONGER THAN
BATTERIES

↳ LESS POLLUTING
TO DISPOSE OF

HYDROGEN IS
A GAS



↳ MORE SPACE TO STORE
THAN FOSSIL FUELS
OR BATTERIES

↳ EXPLOSIVE WHEN MIXED
WITH AIR



STORAGE IS DANGEROUS



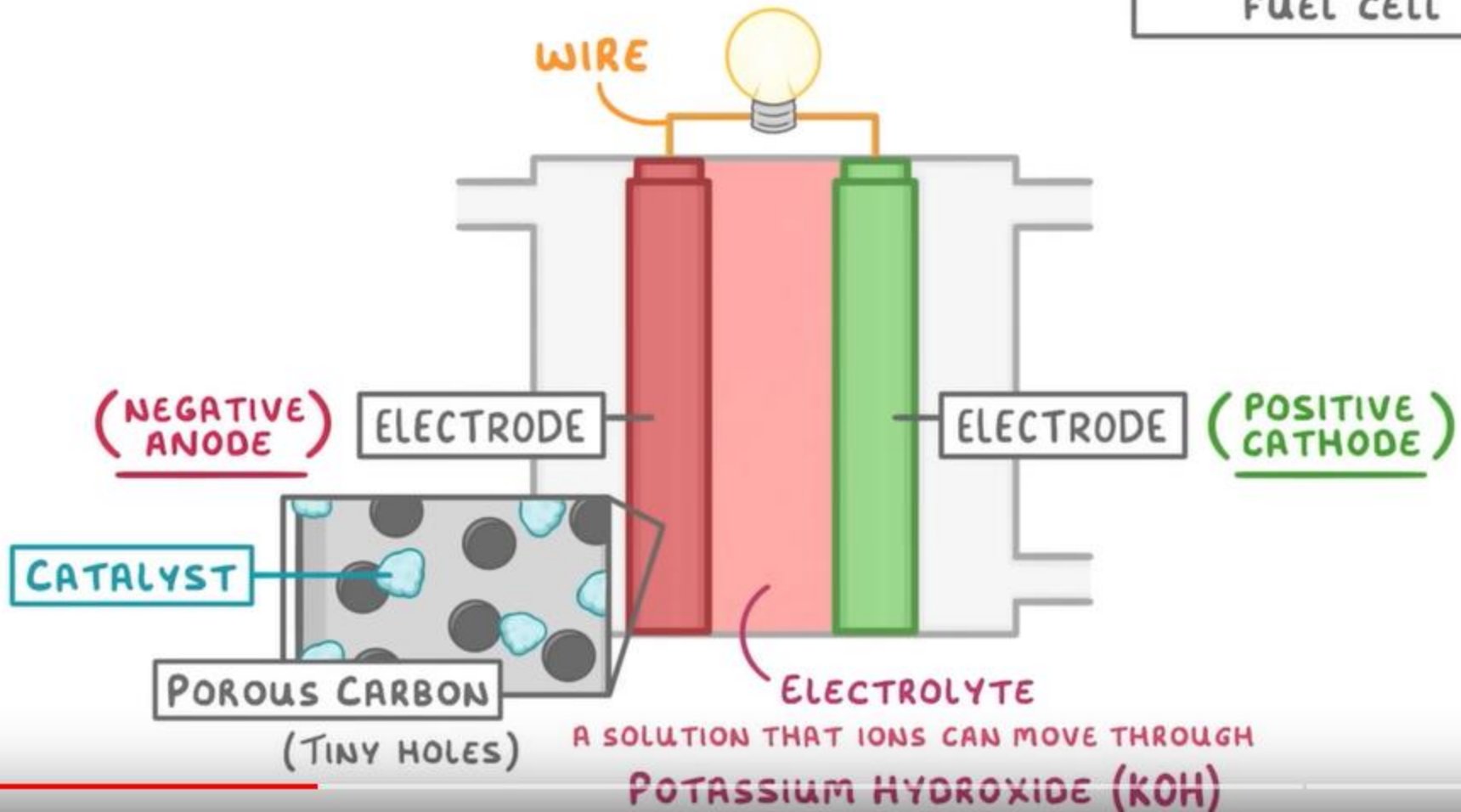
REQUIRES
ENERGY



FOSSIL FUELS

THE STRUCTURE:

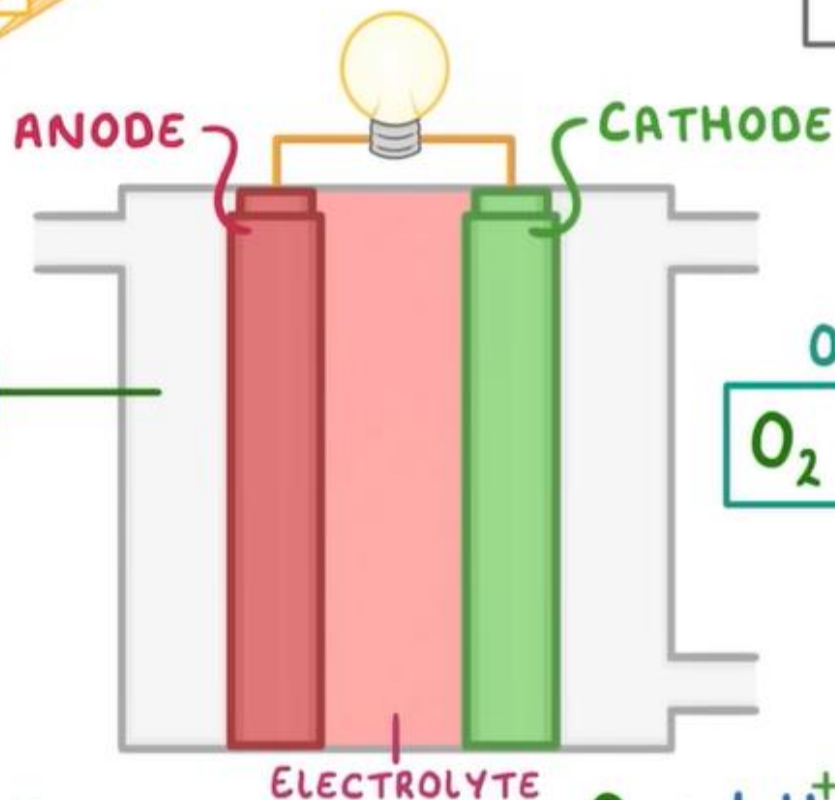
**HYDROGEN – OXYGEN
FUEL CELL**



ELECTRICAL ENERGY

HOW IT WORKS

HYDROGEN – OXYGEN
FUEL CELL



OVERALL EQUATION:



OXIDATION OF
HYDROGEN

HALF EQUATION:



loss

REDUCTION OF
OXYGEN

HALF EQUATION:



gain

HOW IT WORKS

↳ IN EXAMS:

SETS UP A POTENTIAL DIFFERENCE
ACROSS THE CELL

↳ DRIVES THE ELECTRONS
AROUND THE CIRCUIT

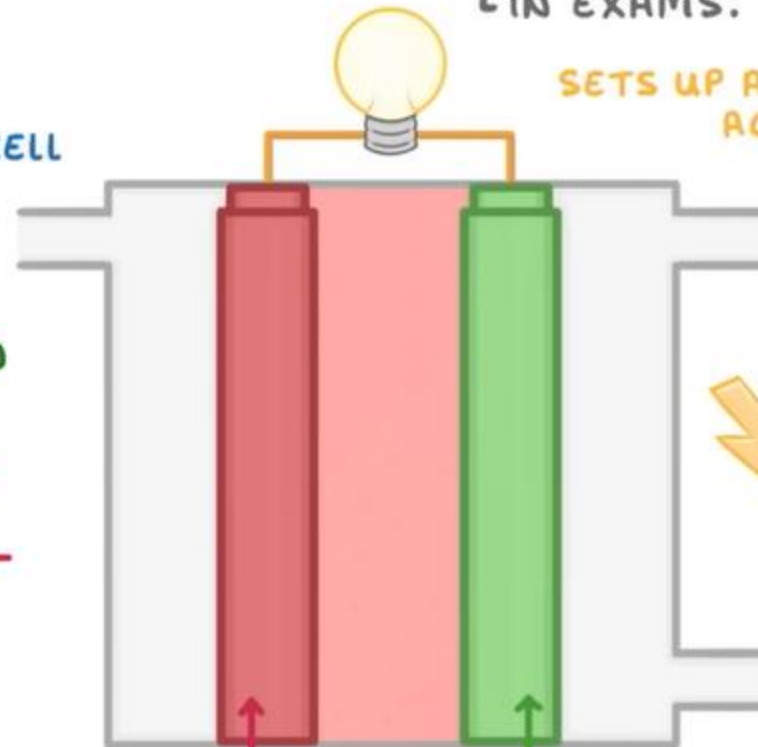
GENERATE ELECTRICITY

DIFFERENCE
IN CHARGE

AS FUEL ENTERS THE CELL

BECOMES OXIDISED

LOSES ELECTRONS:



- In fuel cell the chemical energy is converted into electrical energy in a reaction that eliminates the combustion of the fuel.
- Fuel cells allow the direct conversion of energy stored in a fuel into electricity.
- Instead of combining the hydrogen with oxygen from the air, the fuel cell uses a catalyst to facilitate the ionization of the hydrogen at the anode, creating positively charged hydrogen ions and free electrons. It then uses an electrolyte to pass the hydrogen ions to a cathode that is in contact with oxygen gas. This gives the anode a positive charge and creates a voltage potential between the cathode and anode that drives the free electrons through an external circuit. When the electrons get to the cathode, they combine with the oxygen atoms to form water molecules.
- The choice of the electrolyte is very important. Some of the electrolytes that work well in fuel cells need to operate at temperatures as high as 1,000 C. This clearly requires significant packaging to insulate the cell from its surroundings. For use in a UAS, the more attractive electrolytes are solid organic polymers and solutions of potassium hydroxide in a “matrix.”
- In this context, one could think of the matrix as a layer of some absorbing material that can be permeated by the liquid electrolyte and avoids the issues related to an unrestrained liquid electrolyte.
- A fuel cell is not a battery and cannot directly be “recharged.” However, if it uses hydrogen as a fuel, the resulting water can be saved and electrolyzed to turn it back into oxygen and hydrogen gas. This makes a fuel cell an attractive way to store and recover energy on an electrically propelled UAV that uses solar cells to provide power during the day but must store energy to remain aloft at night

Powered Lift

For an un-ducted rotor, ambient air is sucked into the disk defined by the spinning fan, and passes through it with a velocity v_d and continues to accelerate to a final exit velocity v_e . It is well known and easily proved that:

$$v_d = \frac{v_e}{2} \quad (6.7)$$

and the mass flow is:

$$\frac{dm}{dt} = \rho A v_d = \frac{1}{2} \rho A v_e \quad (6.8)$$

where A is the area of the disk, so the lift of the disk is:

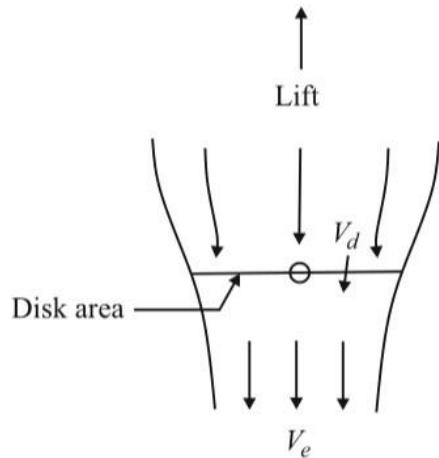
$$L = \frac{dm}{dt} v_e = \frac{\rho A v_e^2}{2} \quad (6.9)$$

The induced power is:

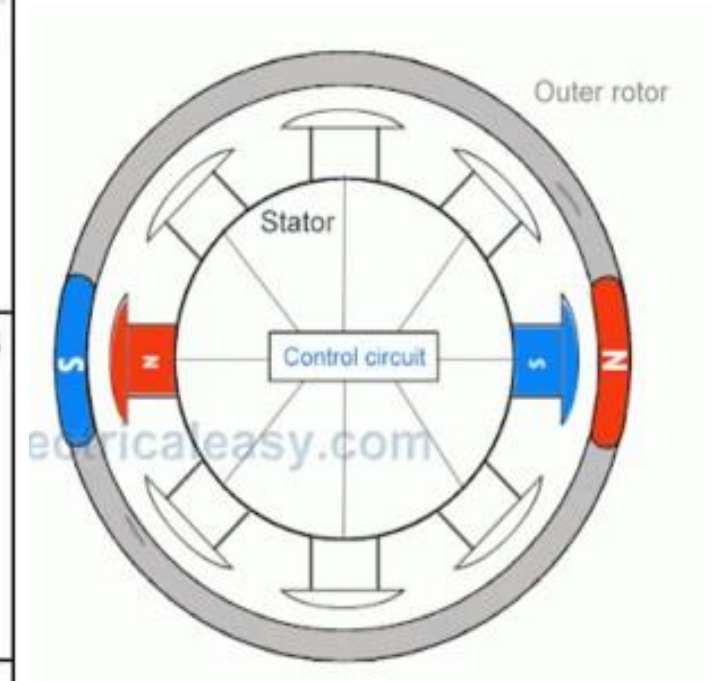
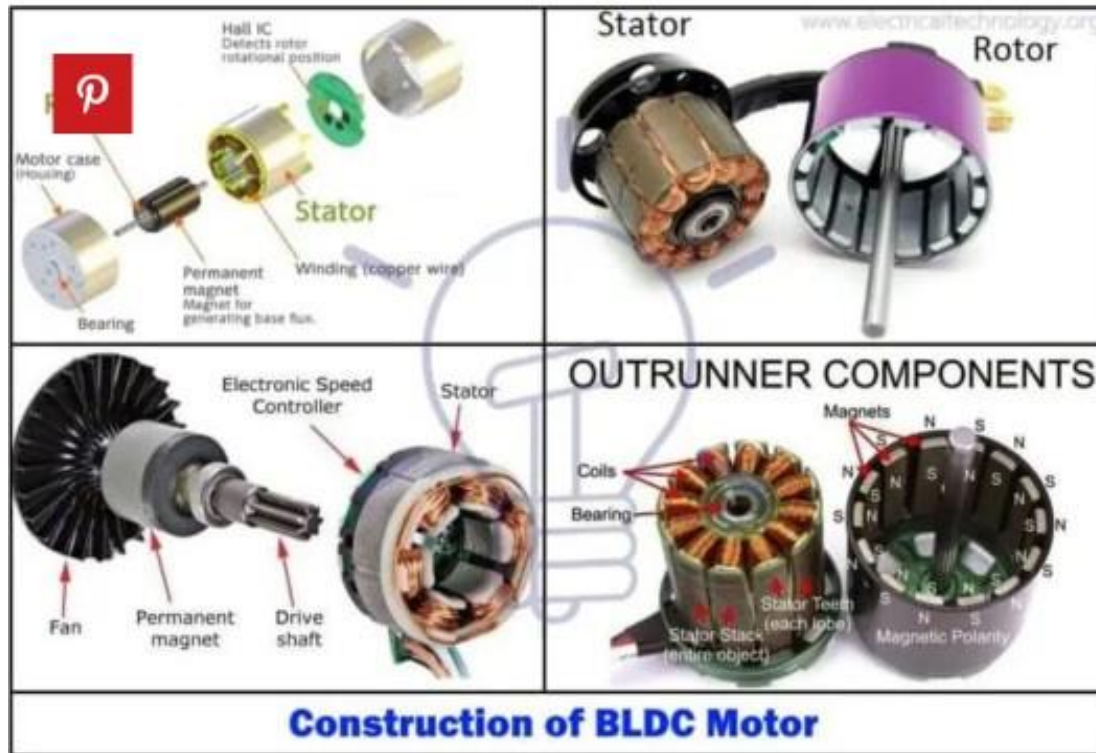
$$P = \frac{1}{2} \frac{dm}{dt} v_e^2 \quad (6.10)$$

and by substituting for dm/dt from Equation (6.8) and for v_e^3 from Equation (6.9), we find that:

$$P = \frac{L^{3/2}}{\sqrt{2\rho A}} \quad (6.11)$$



Brushless DC motor



Construction: BLDC motor consists of two main parts a stator and a rotor. Permanent magnets are mounted on the rotor of a BLDC motor, and the stator is wound for a specific number of poles. Also, a control circuit is connected to the stator winding. Most of the times, the inverter/control circuit or controller is integrated into the stator assembly.

Working: Stator windings of a BLDC motor are connected to a ~~Working~~ circuit (an integrated switching circuit or inverter circuit). The control circuit energizes proper winding at the proper time, in a pattern which rotates around the stator. Permanent magnets on the rotor try to align with the energized electromagnets of the stator, and as soon as it aligns, the next electromagnets are energized. Thus, the rotor keeps running.

Batteries

The key characteristics of a battery are as follows:

- Capacity—The electrical charge effectively stored in a battery and available for transfer during discharge. Expressed in ampere-hours (Ah) or milliampere-hours (mAh).
- Energy Density—Capacity/Weight or Ah/weight.
- Power Density—Maximum Power/Weight in Watts/weight.
- Charging/Discharging rate (C rate)—The maximum rate at which the battery can be charged or discharged, expressed in terms of its total storage capacity in Ah or mAh. A rate of 1C means transfer of all of the stored energy in 1 h; 0.1C means 10% transfer in 1 h, or full transfer in 10 h.



Battery types

6.4.5.1.1 Nickel–Cadmium Battery

The nickel–cadmium (NiCd) battery uses nickel hydroxide as the positive electrode (anode) and cadmium/cadmium hydroxide as the negative electrode (cathode). Potassium hydroxide is used as the electrolyte. Among rechargeable batteries, NiCd is a popular choice but contains toxic metals. NiCd batteries have generally been used where long life and a high discharge rate is important.

6.4.5.1.2 Nickel–Metal Hydride Battery

The nickel–metal hydride (NiMH) battery uses a hydrogen-absorbing alloy for the negative electrode (cathode) instead of cadmium. As in NiCd cells, the positive electrode (anode) is nickel hydroxide.

The NiMH has a high-energy density and uses environmentally friendly metals. The NiMH battery offers up to 40% higher energy density compared to NiCd. The NiMH has been replacing the NiCd in recent years. This is due both to environmental concerns about the disposal of used batteries and the desirability of the higher energy density.



6.4.5.1.3 Lithium-Ion Battery

The lithium-ion (Li-ion) battery is a fast growing battery technology because it offers high-energy density and low weight. Although slightly lower in energy density than lithium metal, the energy density of the Li-ion is typically higher than that of the standard NiCd. Li-ion batteries are environmentally friendly for disposal.

Li-ion batteries typically use a graphite (carbon) anode and an anode made of LiCoO_2 or LiMn_2O_4 . LiFePO_4 also is used. The electrolyte is a lithium salt in an organic solvent. These materials are all relatively environmentally friendly.

Li-ion is the presently used technology for most electric and hybrid ground vehicles and its maturity and cost are likely to be driven by the large commercial demand.

6.4.5.1.4 Lithium-Polymer Battery

The lithium-polymer (Li-poly) battery uses LiCoO_2 or LiMn_2O_4 for the cathode and carbon or lithium for the anode.

The Li-poly battery is different than other batteries because of the type of electrolyte used. The polymer electrolyte replaces the traditional porous separator, which is soaked with a liquid electrolyte.

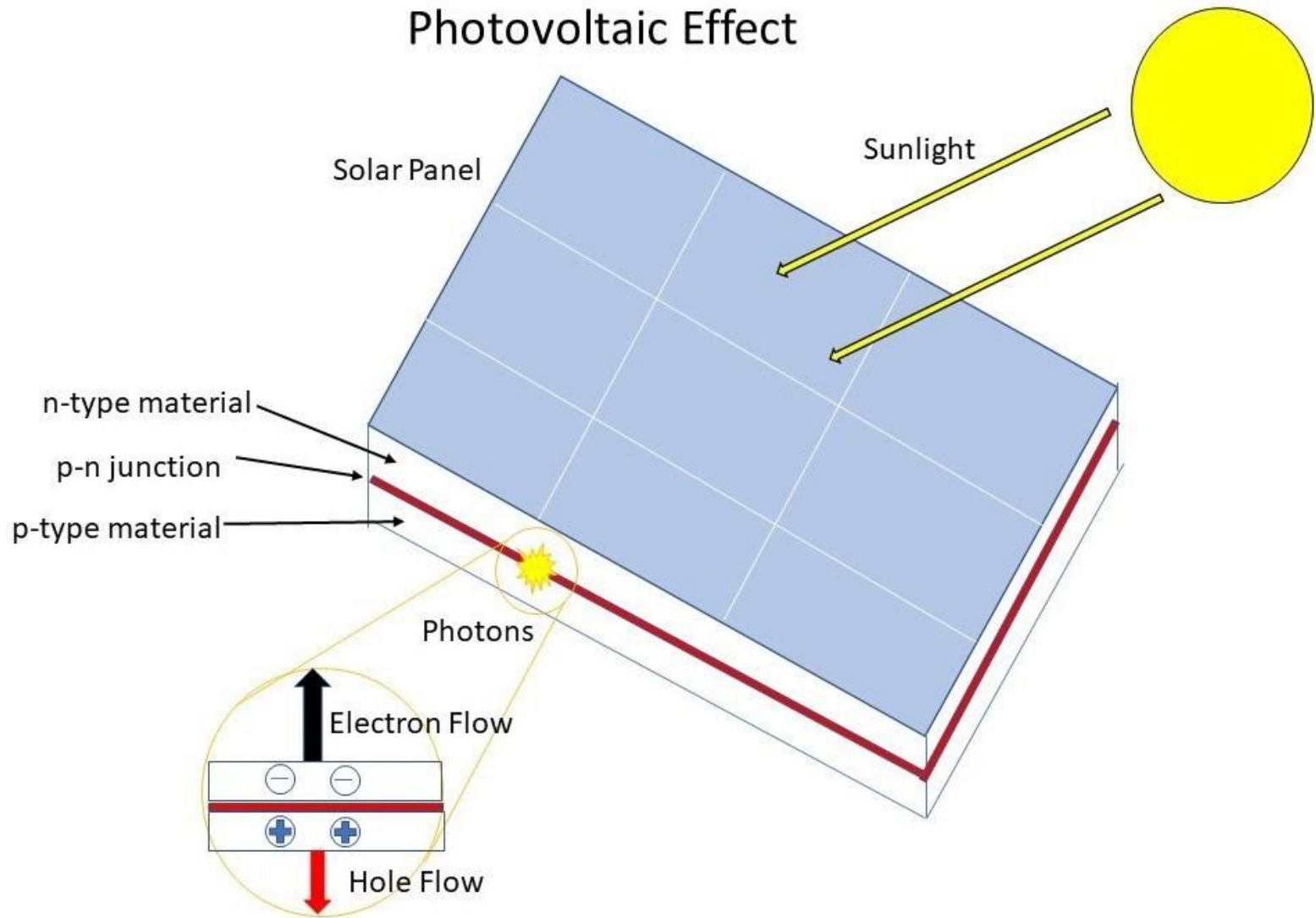
The dry polymer design offers simplifications with respect to fabrication, ruggedness, safety and thin-profile geometry. The major reason for switching to the Li-ion polymer is form factor. It allows great freedom to choose the shape of the battery, including wafer-thin geometries.

Solar Cells

- **The basic principle of a solar cell is that a photon from the sun (or any other light source) is absorbed by an atom in the valence band of semiconductor material and an electron is excited into the conduction band of the material. In order for this to happen, the photon must have enough energy to allow the electron to jump through an “energy gap” that separates the conduction band from the valence band and is due to quantum mechanical effects that create “forbidden” energy states in a crystalline material.**



Photovoltaic Effect



- The most common type of solar cell is a silicon positive-intrinsic-negative (PIN) diode.
- This is created by doping small amounts of selected impurities into a silicon crystal so that it has somewhat higher energy bands than pure silicon (positive doped or “P” material) and then adding additional doping to the surface of the crystal that lowers the energy bands near the surface relative to the undoped material (negative doped or N material). In the region where the doping is intermediate, the energy bands pass through the levels of pure silicon, and the crystal is neither positive nor negative, but “intrinsic” or “I” material
- The doping of the junction creates a potential difference in the crystal that causes the electron to move toward the surface and contact on the “N” side and the hole to move to the surface and contact on the P side, so that if these two contacts are connected through a load, a current will flow through that load



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