Piston Engine

Technologies and Configurations
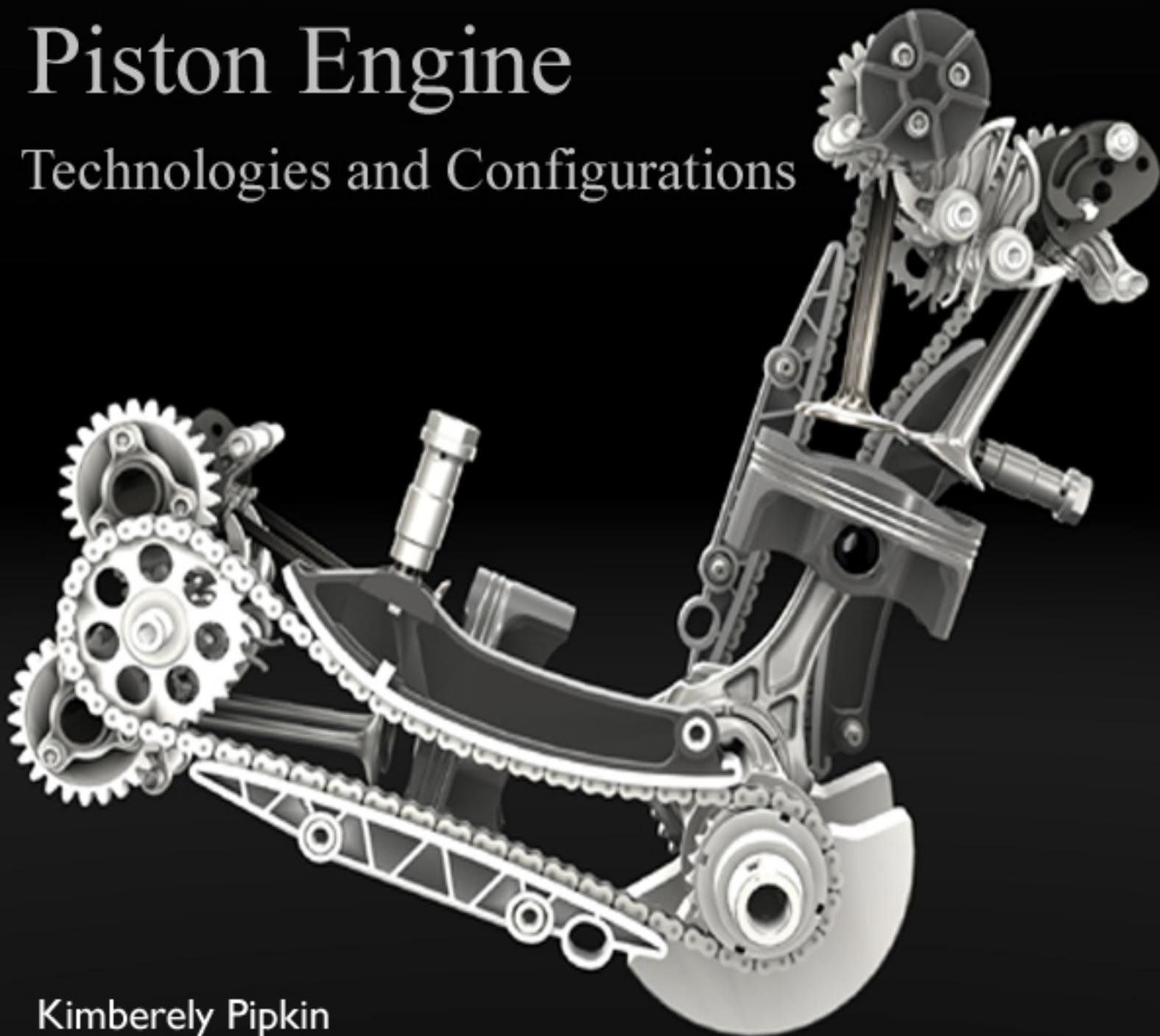
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Reciprocating Engine

Internal combustion piston engine
Components of a typical, four stroke cycle, internal combustion piston engine.
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S - Spark plug
V - Valves

P - Piston
R - Connecting rod
C - Crankshaft
W - Water jacket for coolant flow

A **reciprocating engine**, also often known as a **piston engine**, is a heat engine that uses one or more reciprocating pistons to convert pressure into a rotating motion. This is describes the common features of all types. The main types are: the internal combustion engine, used extensively in motor vehicles; the steam engine, the mainstay of the Industrial Revolution; and the niche application Stirling engine.

Common features in all types

There may be one or more pistons. Each piston is inside a cylinder, into which a gas is introduced, either already hot and under pressure (steam engine), or heated inside the cylinder either by ignition of a fuel air mixture (internal combustion engine) or by contact with a hot heat exchanger in the cylinder (Stirling engine). The hot gases expand, pushing the piston to the bottom of the cylinder. The piston is returned to the cylinder top (Top Dead Centre) either by a flywheel or the power from other pistons connected to the same shaft. In most types the expanded or "exhausted" gases are removed from the cylinder by this stroke. The exception is the Stirling engine, which repeatedly heats and cools the same sealed quantity of gas.

In some designs the piston may be powered in both directions in the cylinder in which case it is said to be double acting.
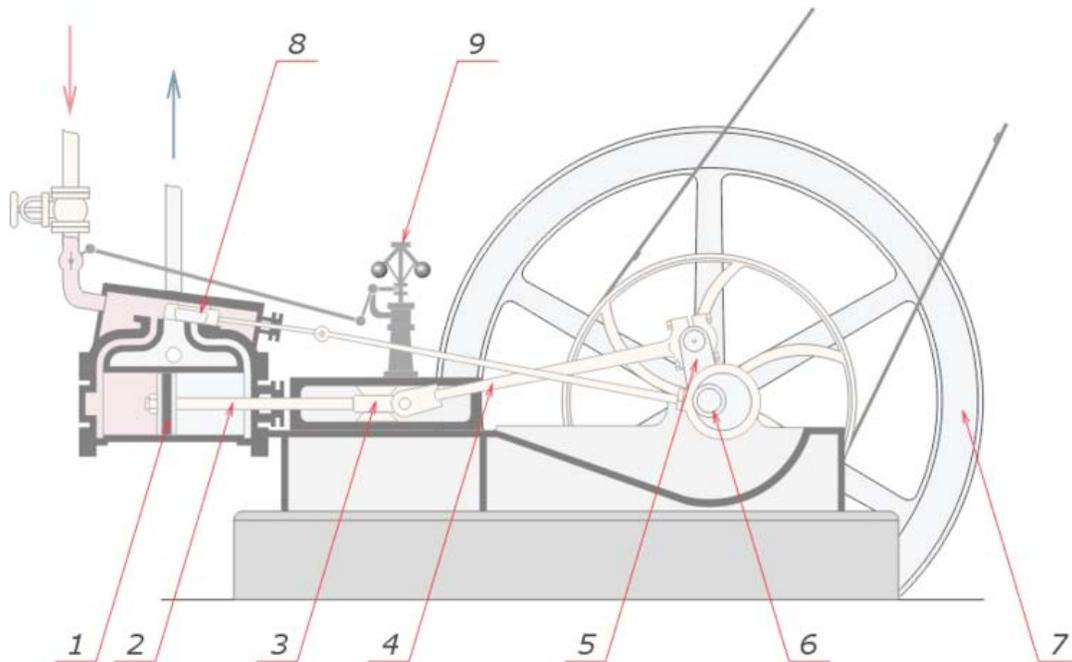
Steam piston engine
A labeled schematic diagram of a typical single cylinder, simple expansion, double-acting high pressure steam engine. Power takeoff from the engine is by way of a belt.
1 - Piston
2 - Piston rod
3 - Crosshead bearing
4 - Connecting rod
5 - Crank
6 - Eccentric valve motion
7 - Flywheel
8 - Sliding valve
9 - Centrifugal governor.

In all types, the linear movement of the piston is converted to a rotating movement via a connecting rod and a crankshaft or by a swashplate. A flywheel is often used to ensure smooth rotation. The more cylinders a reciprocating engine has, generally, the more vibration-free (smoothly) it can operate. The power of a reciprocating engine is proportional to the volume of the combined pistons' displacement.

A seal needs to be made between the sliding piston and the walls of the cylinder so that the high pressure gas above the piston does not leak past it and reduce the efficiency of the engine. This seal is provided by one or more piston rings. These are rings made of a hard metal which are sprung into a circular groove in the piston head. The rings fit tightly in the groove and press against the cyinder wall to form a seal.

It is common for such engines to be classified by the number and alignment of cylinders and the total volume of displacement of gas by the pistons moving in the cylinders usually measured in cubic centimetres (cm³ or cc) or litres (l) or (L) (US:liter). For example for internal combustion engines, single and two-cylinder designs are common in smaller vehicles such as motorcycles, while automobiles typically have between four and eight, and locomotives, and ships may have a dozen cylinders or more. Cylinder capacities may range from 10 cm³ or less in model engines up to several thousand cubic centimetres in ships' engines.

The compression ratio is a measure of the performance in an internal-combustion engine or a Stirling Engine. It is the ratio between the volume of the cylinder, when the piston is at the bottom of its stroke, and the volume when the piston is at the top of its stroke.

The bore/stroke ratio is the ratio of the diameter of the piston, or "bore", to the length of travel within the cylinder, or "stroke". If this is around 1 the engine is said to be "square", if it is greater than 1, i.e. the bore is larger than the stroke, it is "oversquare". If it is less than 1 , i.e. the stroke is larger than the bore, it is "undersquare".

Cylinders may be aligned in line, in a V configuration, horizontally opposite each other , or radially around the crankshaft. Opposed-piston engines put two pistons working at

opposite ends of the same cylinder and this has been extended into triangular arrangements such as the Napier Deltic.
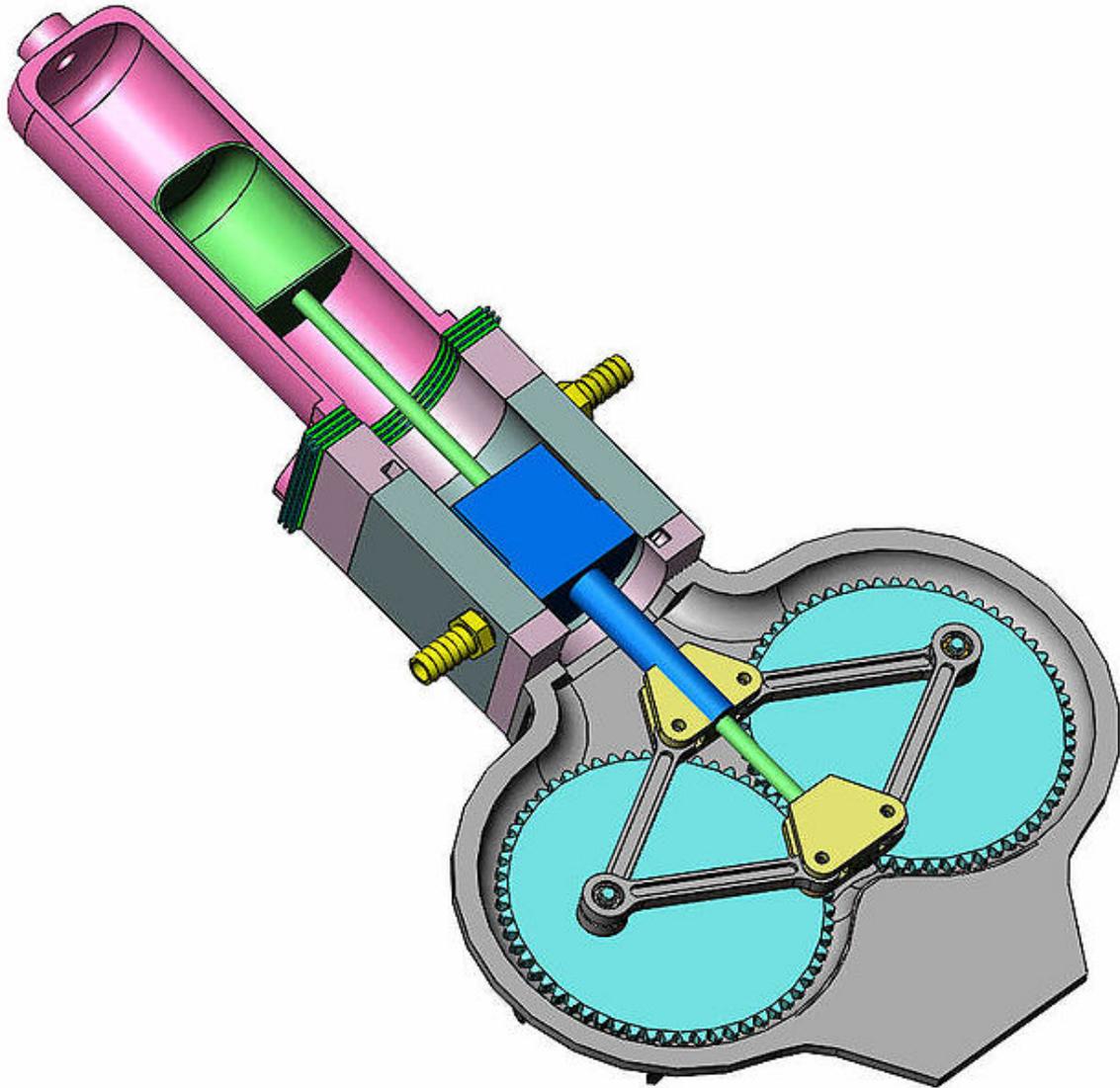
Stirling piston engine
Rhombic Drive Beta Stirling Engine Design showing the second displacer piston (green) within the cylinder which shunts the working gas between the hot and cold ends , but produces no power itself.
Pink - Hot cylinder wall,
Dark grey - Cold cylinder wall,
Green - Displacer piston,
Dark blue - Power piston,
Light blue - Flywheels

In steam engines and internal combustion engines, valves are required to allow the entry and exit of gasses at the correct time in the piston's cycle. These are worked by cams or

cranks driven by the shaft of the engine. Early designs used the D slide valve but this has been largely superseded by Piston valve or Poppet valve designs. In steam engines the point in the piston cycle at which the steam inlet valve closes is called the cutoff and this can often be controlled to adjust the torque supplied by the engine.

Internal combustion engines operate through a sequence of strokes which admit and remove gases to and from the cylinder. These operations are repeated cyclically and an engine is said to be 2-stroke, 4-stroke or 6-stroke depending on the number of strokes it takes to complete a cycle.

In some steam engines, the cylinders may be of varying size with the smallest bore cylinder working the highest pressure steam. This is then fed through one or more, increasingly larger bore cylinders successively, to extract power from the steam at increasingly lower pressures. These engines are called Compound engines.

History

An early known example of rotary to reciprocating motion can be found in a number of Roman saw mills (dating to the 3rd to 6th century AD) in which a crank and connecting rod mechanism converted the rotary motion of the waterwheel into the linear movement of the saw blades. Another early example was the reciprocating piston pump of Al-Jazari in 1206.

The reciprocating engine developed in Europe during the 18th century, first as the atmospheric engine then later as the steam engine. These were followed by the Stirling engine and internal combustion engine in the 19th century. Today the most common form of reciprocating engine is the internal combustion engine running on the combustion of petrol, diesel, Liquefied petroleum gas (LPG) or compressed natural gas (CNG) and used to power motor vehicles.

One of the most advanced reciprocating engines ever made was the 28-cylinder, 3,500 hp (2,600 kW) Pratt & Whitney R-4360 "Wasp Major" radial engine which powered the last generation of large piston-engined planes before the jet engine and turboprop took over from 1944 onward. It had a total engine capacity of 71.5 litres (2.52 cu ft).

The largest reciprocating engine in production at present, but not the largest ever built, is the Wärtsilä-Sulzer RTA96-C turbocharged two-stroke diesel engine of 2006 built by Japan's Diesel United, Ltd. It is used to power the largest modern container ships such as the Emma Mærsk. It is five stories high (13.5 m/44 ft), 27 metres (89 ft) long, and weighs over 2,300 metric tons (2,500 short tons) in its largest 14 cylinders version producing more than 84.42 MW (114,800 bhp). Each cylinder has a capacity of 1,820 litres (64 cu ft), making a total capacity of 25,480 litres (900 cu ft) for the largest versions.

Engine capacity

For piston engines, an engine's capacity is the engine displacement, in other words the volume swept by all the pistons of an engine in a single movement. It is generally measured in litres (L) or cubic inches (c.i.d. *or* cu in *or* in³) for larger engines, and cubic centimetres (abbreviated cc) for smaller engines. Engines with greater capacities are more powerful and provide greater torque at lower speed (rpm) and consumption of fuel increases accordingly.

Other modern non-internal combustion types

Reciprocating engines that are powered by compressed air, steam or other hot gases are still used in some applications such as to drive many modern torpedoes or as pollution-free motive power. Most steam-driven applications use steam turbines, which are more efficient than piston engines.

The French-designed FlowAIR vehicles use compressed air stored in a cylinder to drive a reciprocating engine in a pollution-free urban vehicle.

Torpedoes may use a working gas produced by high test peroxide or Otto fuel II, which pressurise without combustion. The 230 kg (510 lb) Mark 46 torpedo, for example, can travel 11 km (6.8 mi) underwater at 74 km/h (46 mph) fuelled by Otto fuel without oxidant.

Chapter 2

Cam-In-Block

The **cam-in-block** valvetrain layout of piston engines is one where the camshaft is placed within the cylinder block, usually beside and slightly above the crankshaft in a straight engine or directly above the crankshaft in the V of a V engine. This contrasts with an overhead camshaft (OHC) design which places the camshafts within the cylinder head and drives the valves directly or through short rocker arms.

Placing the camshaft inside the engine block has a long history in its use in valve-in-block engines, in straight and V configurations, the Ford flathead being exemplary of the type. Pushrod overhead valve engines with the cam in the block were long used in Chevrolet and Buick straight engines from the 1930s through the mid 1950s and in various similar six cylinder engines until the extensive employment of the V6 configuration in the 1980s.

There are three main cam-in-block designs:

- L-head, also known as *L-block*, *flathead* or *sidevalve*
- F-head
- I-head, also known as overhead valve (OHV)

L-head

flathead V twin engine, modified for power, depicted on cover of Hot Rod magazine. The "flat head" is evident. In this version the camshaft directly operates the distributor, the black object on the front face of the block (the red object)

L-head (*flathead*) refers to the pushrod valvetrain configuration in which the valves are placed in the engine block beside the pistons. The design was common on early engine designs, but has since fallen from use.

Generally L-head engines use a small chamber on one side of the cylinder to carry the valves. This has a number of advantages, primarily in that it makes the cylinder head much simpler. It also means that the valve can be operated by pushing directly up on it, as opposed to needing some sort of mechanical arrangement to push the valves down. It may also lead to slightly easier cooling, as the valves and operating rods are out of the way of the cylinder, making a cooling jacket simpler to construct. The line of intakes along the side of the engine lead to the name L-head, due to the cylinders having the shape of an upside-down L. This configuration is also known as sidevalve, as the valves are located be*side* the cylinders.

On the downside, the L-head engine also requires the airflow to make at least a 90° turn to enter the cylinder, which makes it less efficient; colloquially it's said that such an

engine has poorer "breathing". Breathing was not greatly emphasized in past production cars because engines could not run long and reliably at high speed due to other factors. This was a minor concern given the benefits in simplicity.

Although L-head inline 4 and 6 cylinder engines were frequently used for automobiles, tractors, etc., the best known L-head automotive engine is the early 20th century Ford V-8, which has both sets of valves (intake and exhaust) located on the inside of the "Vee," and which are all operated by a single camshaft located above the crankshaft. The exhaust follows a lengthy path to leave the engine. This virtually guarantees that the engine will need an unusually large coolant radiator to avoid overheating under sustained heavy use. A flathead design in a V engine, with the air intake/fuel system and all of the exhaust and intake valves inside of the "V" requires that the exhaust gas be passed between the cylinders to outside of the V to the exhaust system. Exhaust heat is thus passed to the coolant (as it exits the engine between the cylinders). In the Ford V-8 flathead design, manufactured from 1932 through 1952, the center exhaust port on the outside of the block exhausts the gasses from two cylinders, exacerbating the high heat problem. This "very hot in the middle" problem makes this particular engine prone to heat-related stress and cracks in the cylinder block. In line engine exhaust gas exits the block more directly and does not cross between the cylinders and is a more temperature-stable design. Whenever exhaust ports and valves are in the cylinder head, exhausting heat has far less time to heat the coolant, and such engines are more durable under high load conditions and a similar sized engine will require less coolant radiator capacity than a flathead V-8.

Due to the heating and efficiency problems, L-head engines fell from high power uses such as aircraft engines fairly quickly, prior to World War I. They lived on for some time in the automotive world and were used in the World War II Jeep, for instance. L-heads are no longer used in automobile engines, although they remain in common use for small-engine applications in lawnmowers and generators. Because of their heat-retaining design, the size of valves and the compression ratio are limited (the valve/combustion chamber is away from the piston top typically creating a larger combustion space--a lower compression ratio), which in turn reduces available power and economy. Not all L-heads are cam-in-block engines; the location of the camshaft varies in this layout.

T-head

In some flathead engines, the exhaust valves were in a second set of similar chambers on the other side of the cylinder and driven by a second camshaft. This crossflow layout is referred to as a T-head.

F-head

The F-head layout can be thought of as a combination of L-head and I-head: the intake manifold and its valves are located atop the cylinders (in the cylinder head, as in an I-head design) and are operated by pushrods, but the exhaust manifold and its valves are located beside the cylinders (in the block, as in an L-head design). The exhaust valves are

either roughly or exactly parallel with the pistons; their faces point upwards and they are not operated by pushrods, but by direct contact with a lifter contacting the camshaft. Reverse variation of F-head with side intake and in head exhaust were also made- the Ford V8 overhead exhaust valve conversions to flathead engines were to decrease the overheating under load problems in commercial service. The Indian/Henderson 4 cylinder motorcycle engine family used both designs- the overhead exhaust was again an overheating consideration design.

This was a more expensive engine design. Its advantages over competing L-head engines included more power from its higher compression, better intake mixture flow, less susceptibility to pinging, and greater reliability from its cooling of the exhaust valve and its spring (and having half the number of pushrods of an OHV engine). With only one valve in the head, and one in the block, larger valves can be used than in an OHV engine, to offset the poorer airflow of a side exhaust valve.

For years the British motor car firms Rolls-Royce and Rover used this arrangement. From 1927-1929, the American firm Hudson used a 6-cylinder engine of this form as well, but this engine is not to be confused with that of the race-winning Hudsons of the 1950s. The last major use was the Willys Hurricane engine, used in civilian Jeeps in the 1950s and 1960s. It was replaced by the I-head design.

I-head

The I-head design is one in which the entry and exit valves and ports are contained in the cylinder head. It was developed by the Scottish-American David Dunbar Buick. It employed pushrod-actuated valves parallel to the pistons and is still in use today in some designs (notably several engines produced by General Motors).

It has several advantages over L- and F-head designs, but the most notable is the fact that the intake charge and exhaust gases have a more direct path into and out of the combustion chambers, increasing power, improving fuel efficiency and reducing noxious exhaust emissions.

Chapter 3

Compression Ratio

The **compression ratio** of an internal-combustion engine or external combustion engine is a value that represents the ratio of the volume of its combustion chamber from its largest capacity to its smallest capacity. It is a fundamental specification for many common combustion engines.

In a piston engine it is the ratio between the volume of the cylinder and combustion chamber when the piston is at the bottom of its stroke, and the volume of the combustion chamber when the piston is at the top of its stroke.

Picture a cylinder and its combustion chamber with the piston at the bottom of its stroke containing 1000 cc of air (900 cc in the cylinder plus 100 cc in the combustion chamber). When the piston has moved up to the top of its stroke inside the cylinder, and the remaining volume inside the head or combustion chamber has been reduced to 100 cc, then the compression ratio would be proportionally described as 1000:100, or with fractional reduction, a 10:1 compression ratio.

A high compression ratio is desirable because it allows an engine to extract more mechanical energy from a given mass of air-fuel mixture due to its higher thermal efficiency. High ratios place the available oxygen and fuel molecules into a reduced space along with the adiabatic heat of compression–causing better mixing and evaporation of the fuel droplets. Thus they allow increased power at the moment of ignition and the extraction of more useful work from that power by expanding the hot gas to a greater degree.

Higher compression ratios will however make gasoline engines subject to engine knocking if lower octane-rated fuel is used, also known as detonation. This can reduce efficiency or damage the engine if knock sensors are not present to retard the timing. However, knock sensors have been a requirement of the OBD-II specification used in 1996 model year vehicles and newer.

Diesel engines on the other hand operate on the principle of compression ignition, so that a fuel which resists autoignition will cause late ignition which will also lead to engine knock.

Formula

The ratio is calculated by the following formula:

$$CR = \frac{\frac{\pi}{4}b^2 s + V_c}{V_c}$$, where

b = cylinder bore (diameter)
s = piston stroke length
V_c = clearance volume. It is the volume of the combustion chamber (including head gasket). This is the minimum volume of the space at the end of the compression stroke, i.e. when the piston reaches top dead center (TDC). Because of the complex shape of this space, it is usually measured directly rather than calculated.

Typical compression ratios

Petrol (gasoline) engine

Due to pinging (detonation), the compression ratio in a gasoline or petrol-powered engine will usually not be much higher than 10:1, although some production automotive engines built for high-performance from 1955–1972 had compression ratios as high as 13.0:1, which could run safely on the high-octane leaded gasoline then available.

A technique used to prevent the onset of knock is the high "swirl" engine that forces the intake charge to adopt a very fast circular rotation in the cylinder during compression that provides quicker and more complete combustion. Recently, with the addition of variable valve timing and knock sensors to delay ignition timing, it is possible to manufacture gasoline engines with compression ratios of over 11:1 that can use 87 MON (octane rating) fuel.

In engines with a 'ping' or 'knock' sensor and an electronic control unit, the CR can be as high as 13:1 (2005 BMW K1200S). In 1981, Jaguar released a cylinder head that allowed up to 14:1 compression; but settled for 12.5:1 in production cars. The cylinder head design was known as the "May Fireball" head; it was developed by a Swiss engineer Michael May.

Petrol/gasoline engine with pressure-charging

In a turbocharged or supercharged gasoline engine, the CR is customarily built at 9.32:1 or lower.

Petrol/gasoline engine for racing

Motorcycle racing engines can use compression ratios as high as 14:1, and it is not uncommon to find motorcycles with compression ratios above 12.0:1 designed for 86 or 87 octane fuel.

Ethanol and methanol engines

Ethanol and methanol can take significantly higher compression ratios than gasoline. Racing engines burning methanol and ethanol fuel often incorporate a CR of 14.5-16:1, with F1 engines coming closer to 17:1(which is very critical for maximizing volumetric/fuel efficiency at around 18000 rpm)

Gas-fueled engine

In engines running exclusively on LPG or CNG, the CR may be higher, due to the higher octane rating of these fuels.

Diesel engine

In an auto-ignition diesel engine, (no electrical sparking plug—the hot air of compression lights the injected fuel) the CR will customarily exceed 14:1. Ratios over 22:1 are common. The appropriate compression ratio depends on the design of the cylinder head. The figure is usually between 14:1 and 16:1 for direct injection engines and between 18:1 and 23:1 for indirect injection engines.

Fault finding and diagnosis

Measuring the compression pressure of an engine, with a pressure gauge connected to the spark plug opening, gives an indication of the engine's state and quality. There is, however, no formula to calculate compression ratio based on cylinder pressure.

If the nominal compression ratio of an engine is given, the pre-ignition cylinder pressure can be estimated using the following relationship:

$$p = p_0 \times \mathrm{CR}^\gamma$$

where p_0 is the cylinder pressure at bottom dead center which is usually at 1 atm, CR is the compression ratio, and γ is the specific heat ratio for the working fluid, which is about 1.4 for air, and 1.3 for methane-air mixture.

For example, if an engine running on gasoline has a compression ratio of 10:1, the cylinder pressure at top dead center is

$$p_{\mathrm{TDC}} = 1 \ \mathrm{bar} \times 10^{1.4} = 25.1 \ \mathrm{bar}$$

This figure, however, will also depend on cam (i.e. valve) timing. Generally, cylinder pressure for common automotive designs should at least equal 10 bar, or, roughly estimated in pounds per square inch (psi) as between 15 and 20 times the compression ratio, or in this case between 150 psi and 200 psi, depending on cam timing. Purpose-built racing engines, stationary engines etc. will return figures outside this range.

Factors including late intake valve closure (relatively speaking for camshaft profiles outside of typical production car range, but not necessarily into the realm of competition engines) can produce a misleadingly low figure from this test. Excessive connecting rod clearance, combined with extremely high oil pump output (rare but not impossible) can sling enough oil to coat the cylinder walls with enough oil to facilitate reasonable piston ring seal artificially give a misleadingly high figure, on engines with compromised ring seal.

This can actually be used to some slight advantage. If a compression test does give a low figure, and it has been determined it is not due to intake valve closure/camshaft characteristics, then one can differentiate between the cause being valve/seat seal issues and ring seal by squirting engine oil into the spark plug orifice, in a quantity sufficient to disperse across the piston crown and the circumference of the top ring land, and thereby effect the mentioned seal. If a second compression test is performed shortly thereafter, and the new reading is much higher, it would be the ring seal that is problematic, whereas if the compression test pressure observed remains low, it is a valve sealing (or more rarely head gasket, or breakthrough piston or rarer still cylinder wall damage) issue.

If there is a significant (greater than 10%) difference between cylinders, that may be an indication that valves or cylinder head gaskets are leaking, piston rings are worn or that the block is cracked.

If a problem is suspected then a more comprehensive test using a leak-down tester can locate the leak.

Saab variable-compression engine

Because cylinder bore diameter, piston stroke length and combustion chamber volume are almost always constant, the compression ratio for a given engine is almost always constant, until engine wear takes its toll.

One exception is the experimental Saab Variable Compression engine (SVC). This engine, designed by Saab Automobile, uses a technique that dynamically alters the volume of the combustion chamber (V_c), which, via the above equation, changes the compression ratio (CR).

To alter V_c, the SVC 'lowers' the cylinder head closer to the crankshaft. It does this by replacing the typical one-part engine block with a two-part unit, with the crankshaft in the lower block and the cylinders in the upper portion. The two blocks are hinged together at one side (imagine a book, lying flat on a table, with the front cover held an inch or so

above the title page). By pivoting the upper block around the hinge point, the V_c (imagine the air between the front cover of the book and the title page) can be modified. In practice, the SVC adjusts the upper block through a small range of motion, using a hydraulic actuator.

Variable Compression Ratio (VCR) engines

The SAAB SVC is an advanced and workable addition to the world of VCR engines, the first being built and tested by Harry Ricardo in the 1920s. This work led to him devising the octane rating system that is still in use today. SAAB has recently been involved in working with the 'Office of Advanced Automotive Technologies', to produce a modern petrol VCR engine that showed an efficiency comparable with that of a Diesel. Many companies have been carrying out their own research in to VCR Engines, including Nissan, Volvo, PSA/Peugeot-Citroën and Renault but so far with no publicly demonstrated results.

The Atkinson cycle engine was one of the first attempts at variable compression. Since the compression ratio is the ratio between dynamic and static volumes of the combustion chamber the Atkinson cycle's method of increasing the length of the powerstroke compared to the intake stroke ultimately altered the compression ratio at different stages of the cycle.

Cortina Variable Compression engine

American inventor Paul Cortina is the latest entry into variable compression engine development. The Cortina engine is the only variable compression concept that slides the entire reciprocating assembly toward and away from the cylinder head. The advantage of this approach is that there is no complication to the workings of the reciprocating assembly itself, nor is there any complication outside of the engine. The way this is accomplished is by sliding the reciprocating assembly on a splined output shaft that is positioned perpendicular to a typical engine's output orientation. The novel use of a barrel cam in place of a tradition crankshaft uses fewer parts than competing designs and adds the option of a true Atkinson cycle. It also has a more favorable leverage curve than a traditional crankshaft. Since the connecting rods stay straight, with a barrel cam cycling the pistons, it also is possible to box in the lower cylinder for use as an internal supercharger.

Dynamic compression ratio

The calculated compression ratio, as given above, presumes that the cylinder is sealed at the bottom of the stroke, and that the volume compressed is the actual volume.

However: intake valve closure (sealing the cylinder) always takes place after BDC, which may cause some of the intake charge to be compressed backwards out of the cylinder by the rising piston at very low speeds; only the percentage of the stroke after intake valve closure is compressed. Intake port tuning and scavenging may allow a greater mass of

charge (at a higher than atmospheric pressure) to be trapped in the cylinder than the static volume would suggest (This "corrected" compression ratio is commonly called the "*dynamic compression ratio*".

This ratio is higher with more conservative (i.e., earlier, soon after BDC) intake cam timing, and lower with more radical (i.e., later, long after BDC) intake cam timing, but always lower than the static or "nominal" compression ratio.

The actual position of the piston can be determined by trigonometry, using the stroke length and the connecting rod length (measured between centers). The absolute cylinder pressure is the result of an exponent of the dynamic compression ratio. This exponent is a polytropic value for the ratio of variable heats for air and similar gases at the temperatures present. This compensates for the temperature rise caused by compression, as well as heat lost to the cylinder. Under ideal (adiabatic) conditions, the exponent would be 1.4, but a lower value, generally between 1.2 and 1.3 is used, since the amount of heat lost will vary among engines based on design, size and materials used, but provides useful results for purposes of comparison. For example, if the static compression ratio is 10:1, and the dynamic compression ratio is 7.5:1, a useful value for cylinder pressure would be $(7.5)^{1.3} \times$ atmospheric pressure, or 13.7 bar. ($\times$ 14.7 psi at sea level = 201.8 psi. The pressure shown on a gauge would be the absolute pressure less atmospheric pressure, or 187.1 psi.)

The two corrections for dynamic compression ratio affect cylinder pressure in opposite directions, but not in equal strength. An engine with high static compression ratio and late intake valve closure will have a DCR similar to an engine with lower compression but earlier intake valve closure.

Additionally, the cylinder pressure developed when an engine is running will be higher than that shown in a compression test for several reasons.

- The much higher velocity of a piston when an engine is running versus cranking allows less time for pressure to bleed past the piston rings into the crankcase.

- a running engine is coating the cylinder walls with much more oil than an engine that is being cranked at low RPM, which helps the seal.

- the higher temperature of the cylinder will create higher pressures when running vs. a static test, even a test performed with the engine near operating temperature.

- A running engine does not stop taking air & fuel into the cylinder when the piston reaches BDC; The mixture that is rushing into the cylinder during the downstroke develops momentum and continues briefly after the vacuum ceases (in the same respect that rapidly opening a door will create a draft that continues after movement of the door ceases). This is called scavenging. Intake tuning, cylinder head design, valve timing and exhaust tuning determine how effectively an engine scavenges.

Compression ratio versus overall pressure ratio

Compression ratio and overall pressure ratio are interrelated as follows:

Compression ratio	2:1	3:1	5:1	10:1	15:1	20:1	25:1	35:1
Pressure ratio	2.64:1	4.66:1	9.52:1	25.12:1	44.31:1	66.29:1	90.60:1	145.11:1

The reason for this difference is that compression ratio is defined via the volume reduction:

$$CR = \frac{V_1}{V_2},$$

while pressure ratio is defined as the pressure increase:

$$PR = \frac{P_2}{P_1}.$$

In calculating the pressure ratio, we assume that an adiabatic compression is carried out (i.e. that no heat energy is supplied to the gas being compressed, and that any temperature rise is solely due to the compression). We also assume that air is a perfect gas. With those two assumptions we can define the relationship between change of volume and change of pressure as follows:

$$P_1 V_1^{\gamma} = P_2 V_2^{\gamma} \Rightarrow \frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{\gamma}$$

where γ is the ratio of specific heats for air (approximately 1.4). The values in the table above are derived using this formula. Note that in reality the ratio of specific heats changes with temperature and that significant deviations from adiabatic behavior will occur.

Chapter 4

Engine Configuration

Engine configuration is an engineering term for the layout of the major components of a reciprocating piston internal combustion engine. These components are the cylinders and crankshafts in particular but also, sometimes, the camshaft(s).

Many apparently 'standard' names for configurations are historic, arbitrary, or overlapping. For example, the 180° V engine is so named because the crankshaft is related to a V engine more closely than it is related to other opposed-piston engines such as the boxer. Others would consider it a flat engine because of its shape.

The names *W engine* and *rotary engine* have each been used for several unconnected designs. The *H-4* and *H-6* engines produced by Subaru are not H engines at all, but boxer engines.

Categorisation by piston motion

Horizontally-Opposed Engines   In-Line Engines   V-Type Engines
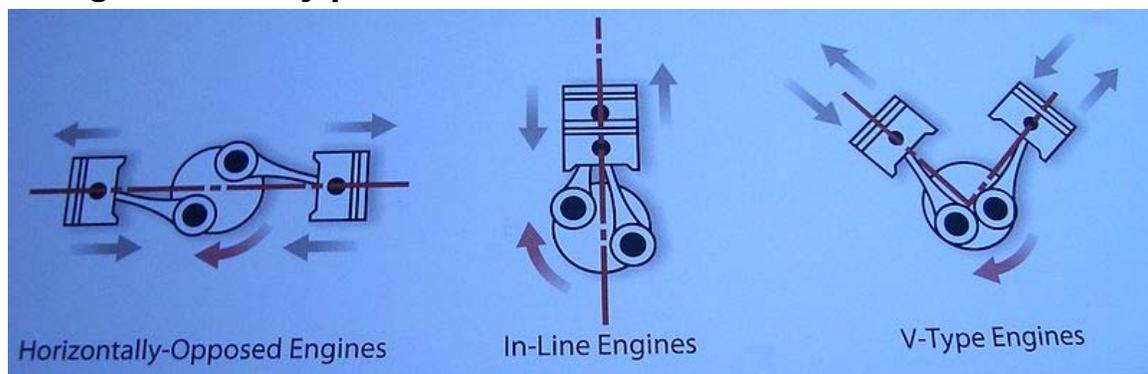
Engine types include:

- Single cylinder engines
- Inline engine designs:
    o Straight engine, with all of the cylinders placed in a single row

- U engine, two separate straight engines with crankshafts linked by a central gear.
  - The **square four** is a U engine where the two straight engines have two cylinders each.
  - V engine, with two banks of cylinders at an angle, most commonly 60 or 90 degrees.
  - Flat engine, two banks of cylinders directly opposite each other on either side of the crankshaft.
    - H engine, two crankshafts.
  - W engine. Combination of V and straight, giving 3 banks, or two V's intertwined giving 4 banks.
  - Opposed piston engine, with multiple crankshafts, an example being:
    - Delta engines, with three banks of cylinders and three crankshafts
  - X engine.
- Radial designs, including most:
  - Rotary engine designs. Mostly seen on pre-WWII aircraft.
- Pistonless rotary engines, notably:
  - Wankel engine.

The standard names for some configurations are historic, arbitrary, or both, with some overlap. For example, the cylinder banks of a 180° V engine do not in any way form a V, but it is regarded as a V engine because of its crankshaft and big end configuration, which result in performance characteristics similar to a V engine. But it is also considered a flat engine because of its shape. On the other hand, some engines which have none of the typical V engine crankshaft design features and consequent performance characteristics are also regarded as V engines, purely because of their shape. Similarly, the Volkswagen Group VR6 engine is a hybrid of the V engine and the straight engine, and can not be definitively labeled as either.

Other categorisations

By valve placement

The majority of four stroke engines have poppet valves, although some aircraft engines have sleeve valves. Valves may be located in the cylinder block (side valves), or in the cylinder head (overhead valves). Modern engines are invariably of the latter design. There may be two, three, four or five valves per cylinder, with the intake valves outnumbering the exhaust valves in case of an odd number.

By camshaft placement

Poppet valves are opened by means of a camshaft which revolves at half the crankshaft speed. This can be either chain, gear or toothed belt driven from the crankshaft, and can be located in the crankcase (where it may serve one or more banks of cylinders) or in the cylinder head.

If the camshaft is located in the crankcase, a valve train of pushrods and rocker arms will be required to operate overhead valves. Mechanically simpler are side valves, where the valve stems rested directly on the camshaft. However, this gives poor gas flows within the cylinder head as well as heat problems and fell out of favor for automobile use.

The majority of modern automobile engines place the camshaft on the cylinder head in an overhead camshaft (OHC) design. There may be one or two camshafts in the cylinder head; a single camshaft design is called single overhead camshaft (SOHC). A design with two camshafts per cylinder head is called double overhead camshaft (DOHC). Note that the camshafts are counted per cylinder head, so a V engine with one camshaft in each of its two cylinder heads is still an SOHC design, and a V engine with two camshafts per cylinder head would be described as 2xDOHC, or informally as a 'quad cam' engine.

With overhead camshafts, the valvetrain will be shorter and lighter, as no pushrods are required. Some single camshaft designs still have rocker arms; this facilates adustment of mechanical clearances.

If there are two camshafts in the cylinder head, the cams can sometimes bear directly on cam followers on the valve stems. This is the usual arrangement for a four-valves-per-cylinder design. This latter arrangement is the most inertia free, allows the most unimpeded gas flows in the engine and is the usual arrengement for high performance automobile engines. It also permits the spark plug to be located in the centre of the cylinder head, which promotes better combustion characteristics.

Very large engines (e.g. marine engines) can have either extra camshafts or extra lobes on the camshaft to enable the engine to run in either direction.

A disadvantage of overhead cams is that a much longer chain (or belt) is needed to drive the cams than with a camshaft located in the cylinder block, usually a tensioner is also needed. A break in the belt may destroy the engine if pistons touch open valves at top dead centre.

Chapter 5

Stroke Ratio

In a reciprocating piston engine, the **stroke ratio**, defined by either **bore/stroke ratio** or **stroke/bore ratio**, is a term which is used to describe the ratio between the diameter of the cylinder bore and the length of the piston stroke within its cylinders. This can be used for either an internal combustion engine, such as a petrol- or diesel engine, where the fuel is burned within the cylinders of the engine, or external combustion engine, such as a steam engine, where the combustion of the fuel takes place *outside* the working cylinders of the engine.

While the stroke ratio can provide insight into the goals of an engine's designer, it has no direct effect on the speed at which an engine reaches maximum torque: holding displacement constant, lengthening the crank throw reduces the piston area by an exactly corresponding amount.

Conventions

In a piston engine, there are two different ways of describing the *stroke ratio* of its cylinders, and these are often mixed together causing confusion. These are: *bore/stroke* ratio, and *stroke/bore* ratio.

Bore/stroke ratio

Bore/stroke is the most commonly used term, which is mainly used in the North America, Europe, United Kingdom, Asia, Australia, and some other countries.

The diameter of the cylinder bore is divided by the length of the piston stroke to give the ratio.

Stroke/bore ratio

Stroke/bore ratio is generally more rare than **bore/stroke** ratio, but is used in some countries, like in Finland for example.

The length of the piston stroke is divided by the diameter of the cylinder bore to give the ratio.

Stroke/bore ratio is similar to the bore/stroke ratio with the following exception:

When stroke/bore value is over 1:1 the engine is long-stroke or undersquare and when the stroke/bore value is under 1:1 the engine is short-stroke or oversquare. The square engine has a value of 1:1 in both cases.

For example an engine with 110 millimetres (4.33 in) stroke and 80 millimetres (3.15 in) bore, stroke/bore value 1.375, is an undersquare or long-stroke engine. An engine that has 70 millimetres (2.76 in) stroke and 100 millimetres (3.94 in) bore, stroke/bore value 0.7, is oversquare or short-stroke.

Square, undersquare and oversquare engines

The following terms describe the naming conventions for the various configurations of the relationship ratio between the diameter of the cylinder bore and the length of the piston stroke within the cylinders of a piston engine.

Square engine

An engine is described as a **square engine** when it has equal bore *and* stroke dimensions, giving a bore/stroke value of exactly 1:1.

For example an engine which has 95 millimetres (3.74 in) bore, and an identical 95 millimetres (3.74 in) stroke, has a bore/stroke value of:

      95 mm / 95 mm = 1.00

Usually engines that have a bore/stroke ratio of 0.95 to 1.04 are referred as square engines.

Square engine examples

The Volkswagen Group W16 engine as used in the Bugatti Veyron is an example of a square engine - with an identical bore and stroke of 86.0 millimetres (3.39 in). Another example of a square engine is the 1970s Ford 400M with a 4.00" bore and stroke.

The Mercedes-Benz M117 engine with a displacement of 5547 cubic centimeters is an example of a nearly square engine with a bore of 96.5 millimeters and a stroke of 94.8 millimeters.

The Cadillac 500-V8 manufactured from 1970-1976 is a nearly square engine with a 4.300 inch bore and a 4.304 inch stroke.

Nissan's SR20DE is a square engine, with a bore and stroke of 86mm.

The 1973-1976 Kawasaki Z-1 and KZ(Z)900 had a 66 mm bore and a 66 mm stroke, also making it a square engine.

Oversquare, or short-stroke engine

An engine is described as **oversquare** or **short-stroke** if its cylinders have a greater bore diameter than its stroke length - giving a ratio value of greater than 1:1.

For example an engine which has 100 millimetres (3.94 in) bore and 80 millimetres (3.15 in) stroke has a bore/stroke value of:

$$100 \text{ mm} / 80 \text{ mm} = 1.25:1$$

An oversquare engine allows for more and larger valves in the head of the cylinder, lower friction losses (due to the reduced distance travelled during each engine rotation) and lower crank stress (due to the lower peak piston speed relative to engine speed). Because these characteristics favor higher engine speeds, oversquare engines are often tuned to develop peak torque at a relatively high speed.

The reduced stroke length allows for a shorter cylinder and sometimes a shorter connecting rod, generally making oversquare engines less tall than undersquare engines of similar engine displacement but wider and longer (for engines with vertical cylinder axes).

By changing the crankshaft and modifying the connecting rod(s), piston(s) and/or engine block an engine can be "de-stroked". This reduces the displacement and consequently the torque of the engine, but can allow it to run at higher speeds and in fact develop greater peak power.

Oversquare engine examples

Oversquare engines are extremely common, including both Chevrolet and Ford small block V8s. Most Boxer (horizontally-opposed) engines (such as those built by Volkswagen, Porsche, and Subaru) feature oversquare designs since any increase in stroke length would result in twice the increase in overall engine size.

This is particularly crucial in Subaru's front-engine layout, where the steering angle of the front wheels is limited largely by the size of the engine. Although oversquare engines have a reputation for being high-strung, low-torque machines, the Subaru EJ engine develops peak torque at speeds as low as 3200 RPM.

Extreme examples of oversquare engine designs are found in Formula One race cars, whose rules tightly limit displacement and thereby require that power be achieved

through high engine speeds. Stroke ratios of 2.5:1 are typical, with engines capable of 19,000 RPM.

Undersquare, or long-stroke engine

An engine is described as **undersquare** or **long-stroke** if its cylinders have a smaller bore (width, diameter) than its stroke (length of piston travel) - giving a ratio value of less than 1:1.

For example an engine which has 90 millimetres (3.54 in) bore and 120 millimetres (4.72 in) stroke has a bore/stroke value of:

$$90 \text{ mm} / 120 \text{ mm} = 0.75:1$$

At a given engine speed, a longer stroke increases engine friction (since the piston travels a greater distance per stroke) and increases stress on the crankshaft (due to the higher peak piston speed). The smaller bore also reduces the area available for valves in the cylinder head, requiring them to be smaller or fewer in number. Because these factors favor lower engine speeds, undersquare engines are most often tuned to develop peak torque at relatively low speeds.

An undersquare engine will typically be more compact in the directions perpendicular to piston travel but larger in the direction parallel to piston travel.

An engine can be "stroked" by replacing the crankshaft with a so-called "stroker" crankshaft and modifying the connecting rod(s), piston(s) or engine block to accommodate the increased piston travel. This increases the displacement and therefore the torque of the engine, but may reduce the peak speed at which it is safe to run.

Undersquare engine examples

Many inline engines, particularly those mounted transversely in front-wheel-drive cars, utilize an undersquare design. The smaller bore allows for a shorter engine that increases room available for the front wheels to steer. Examples of this include many Volkswagen, Honda, and Mazda engines. Some rear-wheel-drive cars that borrow engines from front-wheel-drive cars (such as the Mazda Miata) use an undersquare design.

Despite their reputation as low-speed torque machines, some undersquare engines are designed for quite high speeds. The Honda Integra Type R's B18C5 engine has one of the highest redlines of any production engine, yet features an undersquare design. The 2011 Ford Coyote engine is a modern undersquare engine with a 7,000 rpm redline.

Many British automobile companies used undersquare designs through the 1950s, largely because of a motor tax system that taxed cars by their cylinder bore. This includes the Austin A-Series engine, and many Nissan derivatives.

The Chrysler Slant-6 engine, in its most common 225 cubic inch (3.7 litre) version, is a massively undersquare engine, with a 86 millimetres (3.39 in) bore and a 105 millimetres (4.13 in) stroke, producing most of its power right on the peak of its torque curve. The Achilles heel of this engine, otherwise known for its exceptional durability, is being over-revved by inexperienced drivers. Red line for a factory engine is under 4,500 revolutions per minute (rpm); red line with aftermarket connecting rods is about 5,500 rpm. On the other hand, a well-maintained Slant-6 can be made to idle as low as 75 rpm (though this is *not* a recommended speed - neither the alternator nor the oil pump will function adequately). In some circles, the Slant-6 is nicknamed "The Stump-Puller" for its diesel engine-like low-speed torque. Appropriate gearing and driving skill is required for performance use.

Willys also used mostly undersquare engines; in fact the L134 and F134 engines, with their fairly small 79.4 millimetres (3.13 in) bore and 111.1 millimetres (4.37 in) stroke, are probably the most undersquare engines ever built (for Jeeps).

The Dodge Power Wagon, among other vehicles, used a straight-six Chrysler Flathead engine of 230 cubic inches (3.8 litre) with a bore of 83 millimetres (3.27 in) and a stroke of 117 millimetres (4.61 in), yielding a substantially under-square stroke ratio of 0.70.

Virtually all piston aircraft engines used in military aircraft were long stroke engines. The PW R-2800, Wright R-3350, PW R-4360, Rolls-Royce Merlin (1650), Allison V-1710, and Hispano-Suiza 12Y-Z are only a few of more than a hundred examples.

Chapter 6

Cutoff (Steam Engine)

In a steam engine, **cutoff** is the point in the piston stroke at which the inlet valve is closed. On a steam locomotive, the cutoff is controlled by the reverser.

The point at which the inlet valve closes and stops the entry of steam into the cylinder from the boiler plays a crucial role in the control of a steam engine. Once the valve has closed, steam trapped in the cylinder expands adiabatically. The steam pressure drops as it expands. A late cutoff delivers full steam pressure to move the piston through its entire stroke, for maximum start-up forces. But, since there will still be unexploited pressure in the cylinder at the end of the stroke, this is achieved at the expense of engine efficiency. In this situation the steam will still have considerable pressure remaining when it is exhausted resulting in the characteristic "chuff chuff" sound of a steam engine. An early cutoff has greater thermodynamic efficiency but provides less average force on the piston and is used for running the engine at higher speeds. The steam engine is the only thermodynamic engine design that can provide its maximum torque at zero revolutions.

Explanation
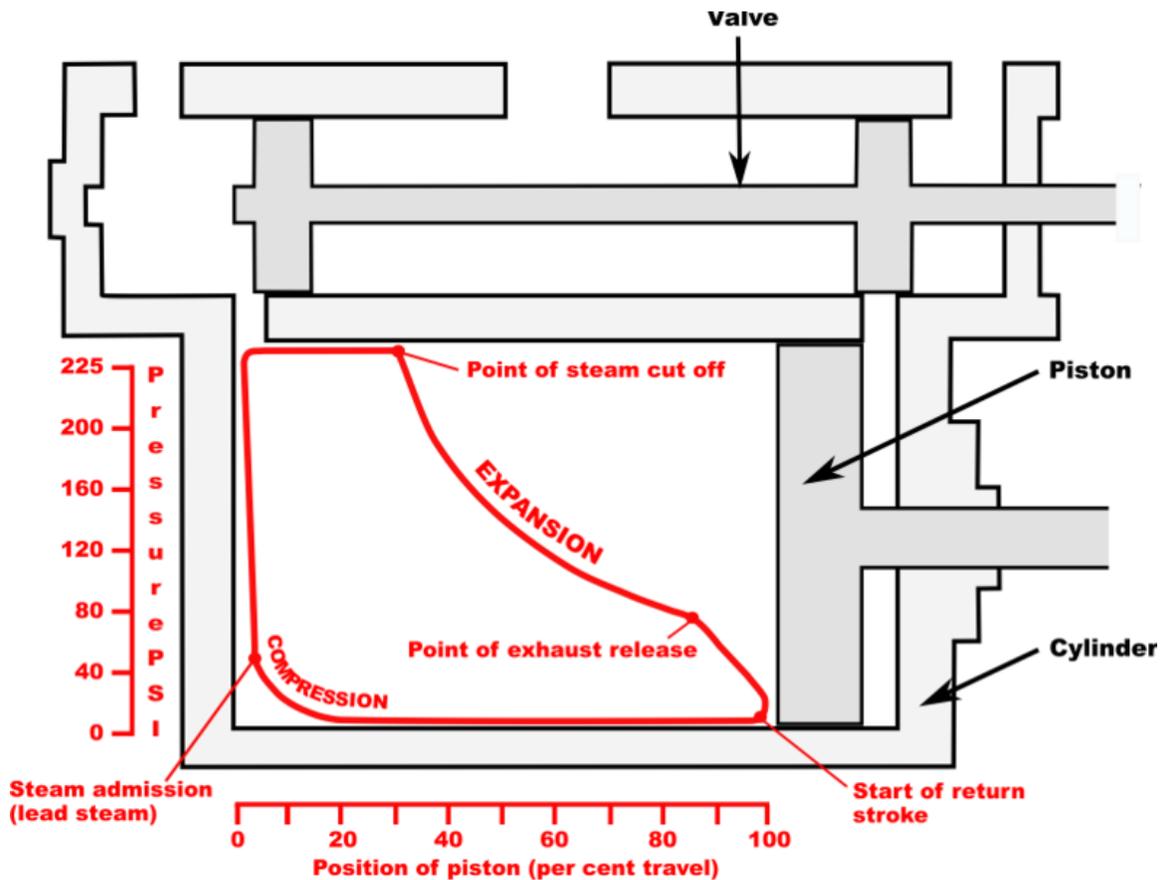
Schematic Indicator diagram of pressure in a steam locomotive cylinder. The pressure in the cylinder declines after cutoff as the steam pushes the piston down its bore

Cutoff is one of the four valve events. Early cutoff is used to increase the efficiency of the engine by allowing the steam to expand for the rest of the power stroke, yielding more of its energy and conserving steam. This is known as expansive working. Late cutoff is used to provide maximum torque to the shaft at the expense of efficiency and is used to start the engine under load.

Cutoff is conventionally expressed as percentage of the power stroke of the piston; if the piston is at a quarter of its stroke at the cutoff point, the cutoff is stated as 25%.

Smaller stationary steam engines generally have a fixed cutoff point while, in large ones, the speed and power output is generally governed by altering the cutoff, frequently under governor control using an expansion valve or trip gear. In steam engines for transport, it is desirable to be able to alter the cutoff over a wide range. For starting and at low speed and heavy load, the cylinders need steam supply at maximum pressure for almost the full length of the stroke. In a two-cylinder locomotive, for example, the maximum or 'full gear' cutoff is typically about 85%. At high speeds, the cutoff may be 15% percent of the

piston stroke or less. Steam engines used in boats and ships operate under a constant, unvarying load through the propeller and so have a fixed cutoff, with speed being controlled through the regulator.

Providing variable cutoff is an important function of the valve gear. Most valve gear designs provide it, the exception being early Stephenson valve gear.

Control mechanism on locomotives

Reversing lever

This is the most common form of reverser. It consists of a long lever mounted, parallel to the direction of travel, on the driver's side of the cab. It has a handle and sprung trigger at the top and is pivoted at the bottom so as to pass between two notched sector plates. The reversing rod, which connects to the valve gear, is attached to this lever, either above or below the pivot, in such a position as to give good leverage. A square pin is arranged so as to engage with the notches in the plates and hold the lever in the desired position when the trigger is released.

The advantages of this design are that change between forward and reverse gear can be made very quickly as is needed in, for example, a shunting engine. Disadvantages are that, because the lever must rest at one of the notches, fine adjustment of the cutoff to offer best running and economy is not possible. On large locomotives it can be difficult to prevent the mechanism from jumping into full forward gear ("nose-diving") when adjusting the cutoff once the locomotive has gathered speed: with such engines it was the practice of drivers to select an appropriate degree of cutoff before opening the regulator and to leave it in that position for the duration of the journey.
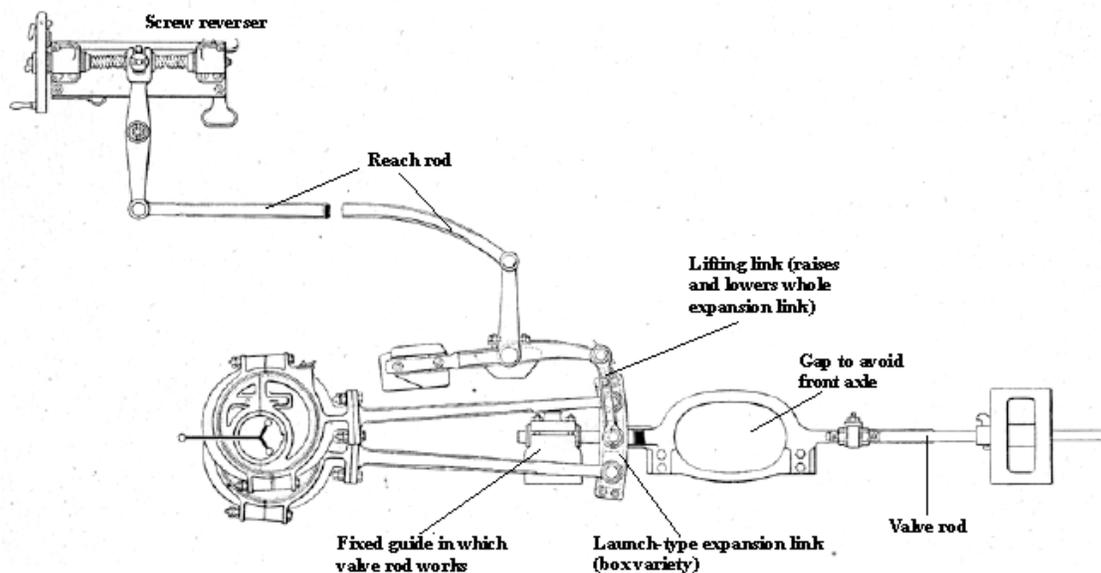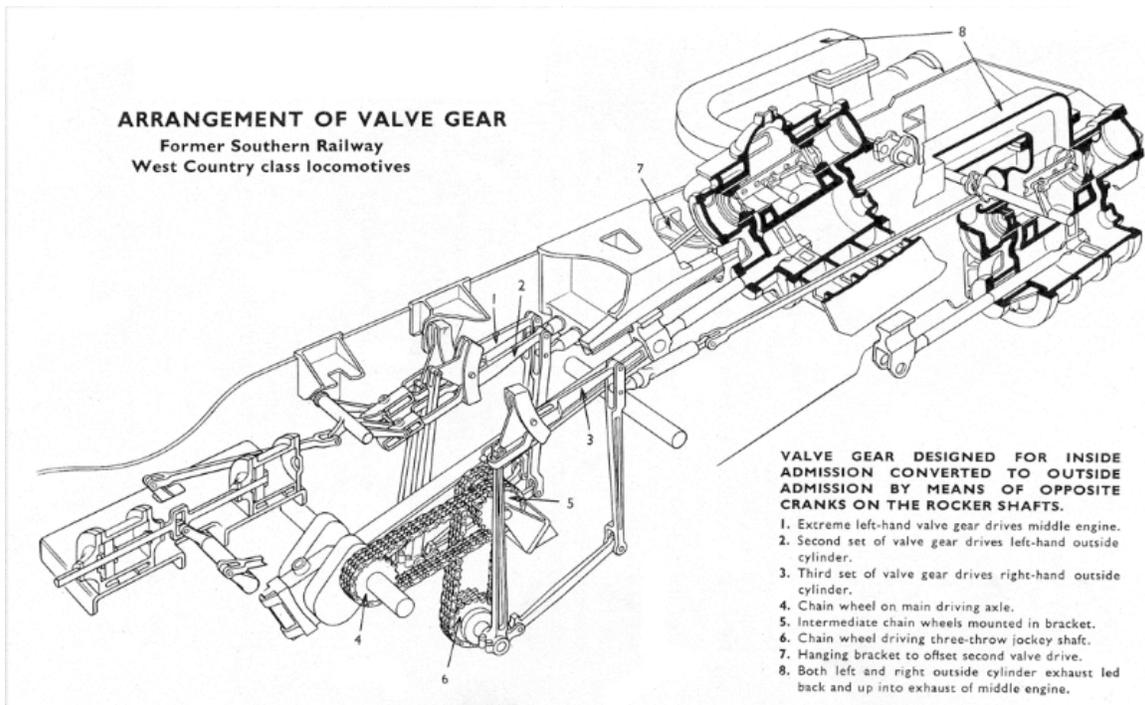
Screw reverser

Diagram of Stephenson valve gear controlled by a screw reverser

In this mechanism the reversing rod is controlled by a screw and nut, worked by a wheel in the cab. The nut either operates on the reversing rod directly or through a lever, as above. The screw and nut may be cut with a double thread and a coarse pitch to move the mechanism as quickly as possible. The wheel is fitted with a locking lever to prevent creep and there is an indicator to show the percentage of cutoff in use. This method of altering the cutoff offers finer control than the sector lever, but it has the disadvantage of slow operation. It is most suitable for long-distance passenger engines where frequent changes of cutoff are not required and where fine adjustments offer the most benefit. On locomotives fitted with Westinghouse air brake equipment and Stephenson valve gear, it was common to use the screw housing as an air cylinder, with the nut extended to form a piston. Compressed air from the brake reservoirs was applied to one side of the piston to reduce the effort required to lift the heavy expansion link, with gravity assisting in the opposite direction.

ARRANGEMENT OF VALVE GEAR
Former Southern Railway
West Country class locomotives

VALVE GEAR DESIGNED FOR INSIDE ADMISSION CONVERTED TO OUTSIDE ADMISSION BY MEANS OF OPPOSITE CRANKS ON THE ROCKER SHAFTS.
1. Extreme left-hand valve gear drives middle engine.
2. Second set of valve gear drives left-hand outside cylinder.
3. Third set of valve gear drives right-hand outside cylinder.
4. Chain wheel on main driving axle.
5. Intermediate chain wheels mounted in bracket.
6. Chain wheel driving three-throw jockey shaft.
7. Hanging bracket to offset second valve drive.
8. Both left and right outside cylinder exhaust led back and up into exhaust of middle engine.

The two pistons of the steam reverser can be seen at the extreme left on this Bulleid *Merchant Navy* class

Power reverse gear

With larger engines, the linkages involved in controlling cutoff and direction grew progressively heavier and there was a need for power assistance in adjusting them. Steam (or later, compressed air) powered reversing gear were developed in the late 19th and early 20th centuries.

In smaller engines, the screw or lever used to control the cutoff and reversing linkages directly indicated the position of those linkages. The first power reversing gear separated

the control and indicator functions. Typically, the operator worked a valve that admitted steam to one side or the other of a cylinder until the indicator showed the intended position. A second mechanism was required to lock the linkages in position.

Henszey's reversing gear, patented in 1882, illustrates a typical early solution. Henszey's device consists of two pistons mounted on a single piston rod. Both pistons are double-ended. One is a steam piston to move the rod as required. The other, containing oil, holds the rod in a fixed position when the steam is turned off. Control is by a small three-way steam valve ("forward", "stop", "back") and a separate indicator showing the position of the rod and thus the percentage of cutoff in use. When the steam valve is at "stop", an oil cock connecting the two ends of the locking piston is also closed, thus holding the mechanism in position. The piston rod connects by levers to the reversing gear, which operates in the usual way, according to the type of valve gear in use.
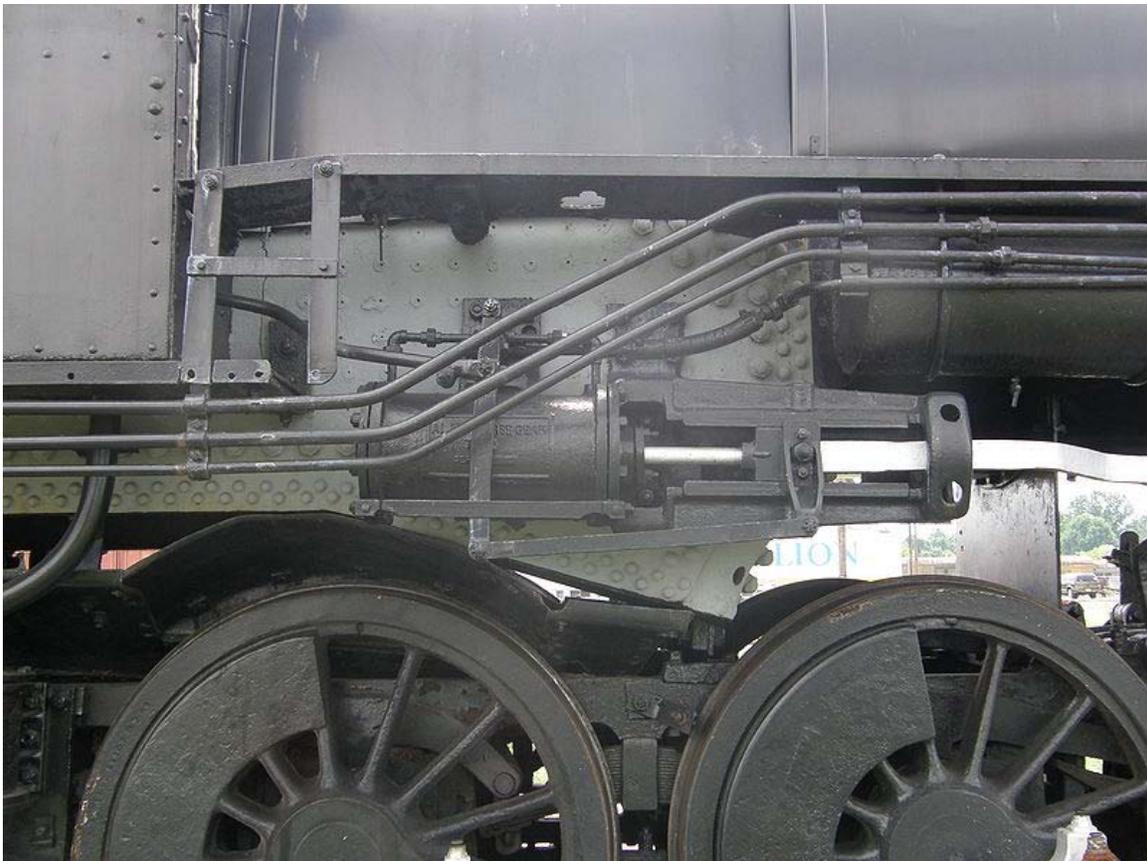
Steam reverser on a Southern Railway 2-8-0.

The first locomotive engineer to fit such a device was James Stirling of the South Eastern Railway in 1876. Several engineers then tried them, including William Dean of the GWR and Vincent Raven of the North Eastern Railway, but they found them little to their liking, mainly because of maintenance difficulties: any oil leakage from the locking cylinder, either through the piston gland or the cock, allowed the mechanism to creep, or worse "nose-dive", into full forward gear while running. However Harry Wainwright of

the SER's successor company the South Eastern and Chatham Railway incorporated them into most of his designs, which were in production about thirty years after Stirling's innovation. Later still the forward-looking Southern Railway engineer Oliver Bulleid fitted them to his famous Merchant Navy Class of locomotives, but they were mostly removed at rebuild.

The Ragonnet power reverse, patented in 1909, was a true feedback controlled servomechanism. The power reverse amplified small motions of reversing lever in the locomotive cab made with modest force into much larger and more forceful motions of the reach rod that controlled the engine cutoff and direction. It was usually air powered, but could also be steam powered. The term *servomotor* was explicitly used by the developers of some later power reverse mechanisms. The use of feedback control in these later power reverse mechanisms eliminated the need for a second cylinder for a hydraulic locking mechanism, and it restored the simplicity of a single operating lever that both controlled the reversing linkage and indicated its position.

The development of articulated locomotives was a major impetus to the development of power reverse systems, because these typically had two or even three sets of reverse gear, instead of just one on a simple locomotive. The Baldwin Locomotive Works used the Ragonnet reversing gear, and other American builders generally abandoned positive locking features. In British use, locking cylinders remained in use. The Hadfield reversing gear, patented in 1950, was in most particulars a Ragonnet reversing gear with added locking cylinder. Most Beyer Garratt locomotives used the Hadfield system.
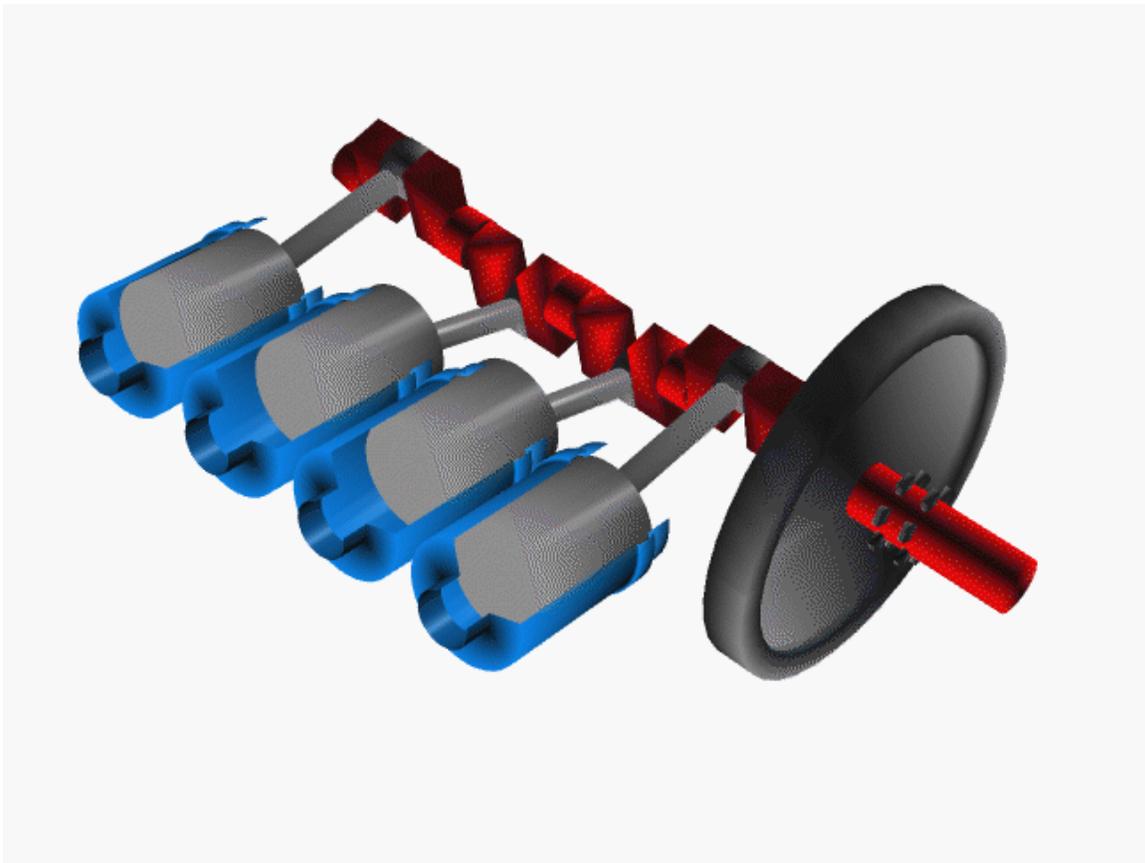
Many American locomotives were built, or retro-fitted, with power reverse, e.g. PRR K4s, PRR N1s, PRR B6, PRR L1s.

Enginemen's terminology

In the UK, a screw reverser is sometimes called a "bacon slicer", particularly the type fitted to BR Standard locomotives. In the US, a reversing lever is called a "Johnson bar".
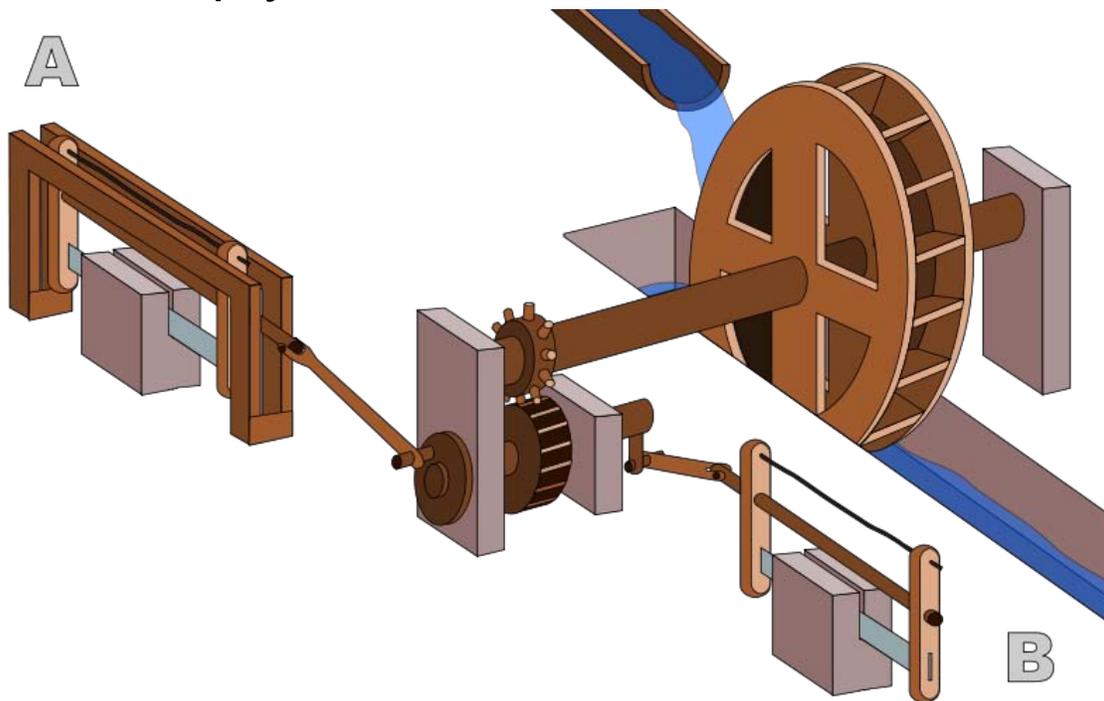
Chapter 7

Crankshaft

Crankshaft (red), pistons (gray) in their cylinders (blue), and flywheel (black)

The **crankshaft**, sometimes casually abbreviated to *crank*, is the part of an engine which translates reciprocating linear piston motion into rotation. To convert the reciprocating motion into rotation, the crankshaft has "crank throws" or "crankpins", additional bearing surfaces whose axis is offset from that of the crank, to which the "big ends" of the connecting rods from each cylinder attach.

It typically connects to a flywheel, to reduce the pulsation characteristic of the four-stroke cycle, and sometimes a torsional or vibrational damper at the opposite end, to reduce the torsion vibrations often caused along the length of the crankshaft by the cylinders farthest from the output end acting on the torsional elasticity of the metal.

History

Classical Antiquity

Roman Hierapolis sawmill from the 3rd century AD, the earliest known machine to combine a crank with a connecting rod.

The earliest evidence for the crank as part of a machine, that is in combination with a connecting rod, anywhere in the world appears in the late Roman Hierapolis sawmill from the 3rd century AD and two Roman stone sawmills at Gerasa, Roman Syria, and Ephesus, Asia Minor (both 6th century AD). On the pediment of the Hierapolis mill, a waterwheel fed by a mill race is shown powering via a gear train two frame saws which cut rectangular blocks by the way of some kind of connecting rods and, through mechanical necessity, cranks. The accompanying inscription is in Greek.

The crank and connecting rod mechanisms of the other two archaeologically attested sawmills worked without a gear train. In ancient literature, we find a reference to the workings of water-powered marble saws close to Trier, now Germany, by the late 4th century poet Ausonius; about the same time, these mill types seem also to be indicated by the Christian saint Gregory of Nyssa from Anatolia, demonstrating a diversified use of water-power in many parts of the Roman Empire. The three finds push back the date of the invention of the crank and connecting rod back by a full millennium; for the first

time, all essential components of the much later steam engine were assembled by one technological culture:

With the crank and connecting rod system, all elements for constructing a steam engine (invented in 1712) — Hero's aeolipile (generating steam power), the cylinder and piston (in metal force pumps), non-return valves (in water pumps), gearing (in water mills and clocks) — were known in Roman times.

Middle Ages

In the 9th century, the non-manual crank appears in several of the hydraulic machines described by the Banu Musa brothers in their *Book of Ingenious Devices*. Two of them contain an action which approximates to that of a crankshaft and only a small modification would have required to convert it to a crankshaft.

In reality, however, these devices made only partial rotations and could only be lightly loaded, while the historian of technology Lynn White did not classify them even as the simplest application of a crank.

The first known use of a crankshaft in a chain pump was in one of Al-Jazari's (1136–1206) saqiya machines. The concept of minimizing intermittent working is also first implied in one of al-Jazari's *saqiya* chain pumps, which was for the purpose of maximising the efficiency of the saqiya chain pump Al-Jazari also constructed a water-raising saqiya chain pump which was run by hydropower rather than manual labour, though the Chinese were also using hydropower for chain pumps prior to him. Saqiya machines like the ones he described have been supplying water in Damascus since the 13th century up until modern times, and were in everyday use throughout the medieval Islamic world. Al-Jazari described a crank and connecting rod system in a rotating machine in two of his water-raising machines. His twin-cylinder pump incorporated a crankshaft, but the device was unnecessarily complex indicating that he still did not fully understand the concept of power conversion. Citing the Byzantine siphon used for discharging Greek fire as an inspiration, Al-Jazari went on to describe the first suction pipes, suction pump, double-action pump, and made early uses of valves and a crankshaft-connecting rod mechanism, when he invented a twin-cylinder reciprocating piston suction pump. This pump is driven by a water wheel, which drives, through a system of gears, an oscillating slot-rod to which the rods of two pistons are attached. The pistons work in horizontally opposed cylinders, each provided with valve-operated suction and delivery pipes. The delivery pipes are joined above the centre of the machine to form a single outlet into the irrigation system. This water-raising machine had a direct significance for the development of modern engineering. This pump is remarkable for three reasons:

- The first known use of a true suction pipe (which sucks fluids into a partial vacuum) in a pump.
- The first application of the double-acting principle.

- The conversion of rotary to reciprocating motion, via the crank-connecting rod mechanism.

Al-Jazari's suction piston pump could lift 13.6 m (45 ft) of water, with the help of delivery pipes. This was more advanced than the suction pumps that appeared in 15th-century Europe, which lacked delivery pipes. It was not, however, any more efficient than a noria commonly used by the Muslim world at the time.

The Italian physician Guido da Vigevano (c. 1280−1349), planning for a new crusade, made illustrations for a paddle boat and war carriages that were propelled by manually turned compound cranks and gear wheels (center of image). The Luttrell Psalter, dating to around 1340, describes a grindstone which was rotated by two cranks, one at each end of its axle; the geared hand-mill, operated either with one or two cranks, appeared later in the 15th century;

Taqi al-Din incorporated a crankshaft in a six-cylinder pump in 1551.

In China, the potential of the crank of converting circular motion into reciprocal one never seems to have been fully realized, and the crank was typically absent from such machines until the turn of the 20th century.

Renaissance

The first depictions of the compound crank in the carpenter's brace appear between 1420 and 1430 in various northern European artwork. The rapid adoption of the compound crank can be traced in the works of the Anonymous of the Hussite Wars, an unknown German engineer writing on the state of the military technology of his day: first, the connecting-rod, applied to cranks, reappeared, second, double compound cranks also began to be equipped with connecting-rods and third, the flywheel was employed for these cranks to get them over the 'dead-spot'.

In Renaissance Italy, the earliest evidence of a compound crank and connecting-rod is found in the sketch books of Taccola, but the device is still mechanically misunderstood. A sound grasp of the crank motion involved demonstrates a little later Pisanello who painted a piston-pump driven by a water-wheel and operated by two simple cranks and two connecting-rods.

One of the drawings of the Anonymous of the Hussite Wars shows a boat with a pair of paddle-wheels at each end turned by men operating compound cranks. The concept was much improved by the Italian Roberto Valturio in 1463, who devised a boat with five sets, where the parallel cranks are all joined to a single power source by one connecting-rod, an idea also taken up by his compatriot Francesco di Giorgio.

Crankshafts were also described by Konrad Kyeser (d. 1405), Leonardo da Vinci (1452–1519) and a Dutch "farmer" by the name Cornelis Corneliszoon van Uitgeest in 1592. His wind-powered sawmill used a crankshaft to convert a windmill's circular motion into a

back-and-forward motion powering the saw. Corneliszoon was granted a patent for his crankshaft in 1597.

From the 16th century onwards, evidence of cranks and connecting rods integrated into machine design becomes abundant in the technological treatises of the period: Agostino Ramelli's *The Diverse and Artifactitious Machines* of 1588 alone depicts eighteen examples, a number which rises in the *Theatrum Machinarum Novum* by Georg Andreas Böckler to 45 different machines, one third of the total.

Design
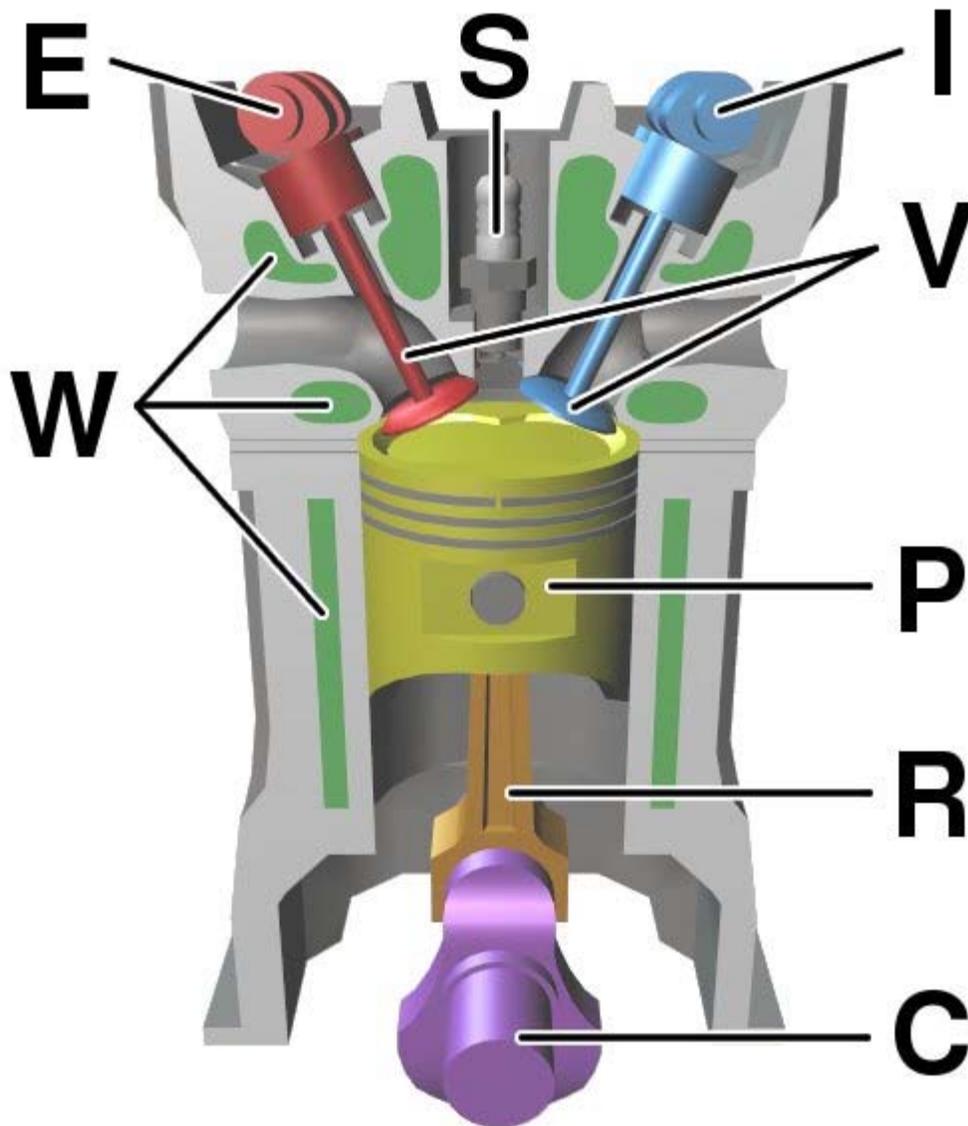
Components of a typical, four stroke cycle, DOHC piston engine. (E) Exhaust camshaft, (I) Intake camshaft, (S) Spark plug, (V) Valves, (P) Piston, (R) Connecting rod, (C) Crankshaft, (W) Water jacket for coolant flow.

Large engines are usually multicylinder to reduce pulsations from individual firing strokes, with more than one piston attached to a complex crankshaft. Many small engines, such as those found in mopeds or garden machinery, are single cylinder and use only a single piston, simplifying crankshaft design. This engine can also be built with no riveted seam.

Bearings

The crankshaft has a linear axis about which it rotates, typically with several bearing journals riding on replaceable bearings (the main bearings) held in the engine block. As the crankshaft undergoes a great deal of sideways load from each cylinder in a multicylinder engine, it must be supported by several such bearings, not just one at each end. This was a factor in the rise of V8 engines, with their shorter crankshafts, in preference to straight-8 engines. The long crankshafts of the latter suffered from an unacceptable amount of flex when engine designers began using higher compression ratios and higher rotational speeds. High performance engines often have more main bearings than their lower performance cousins for this reason.

Piston stroke

The distance the axis of the crank throws from the axis of the crankshaft determines the piston stroke measurement, and thus engine displacement. A common way to increase the low-speed torque of an engine is to increase the stroke, sometimes known as "shaft-stroking." This also increases the reciprocating vibration, however, limiting the high speed capability of the engine. In compensation, it improves the low speed operation of the engine, as the longer intake stroke through smaller valve(s) results in greater turbulence and mixing of the intake charge. For this reason, even such high speed production engines as current Honda engines are classified as "under square" or long-stroke, in that the stroke is longer than the diameter of the cylinder bore. As such, finding the proper balance between shaft-stroking speed and length will lead to more optimal results.

Engine configuration

The configuration and number of pistons in relation to each other and the crank leads to straight, V or flat engines. The same basic engine block can be used with different crankshafts, however, to alter the firing order; for instance, the 90° V6 engine configuration, in older days sometimes derived by using six cylinders of a V8 engine with what is basically a shortened version of the V8 crankshaft, produces an engine with an inherent pulsation in the power flow due to the "missing" two cylinders. The same engine, however, can be made to provide evenly spaced power pulses by using a crankshaft with an individual crank throw for each cylinder, spaced so that the pistons are actually phased 120° apart, as in the GM 3800 engine. While production V8 engines use four crank throws spaced 90° apart, high-performance V8 engines often use a "flat" crankshaft with throws spaced 180° apart. The difference can be heard as the flat-plane crankshafts result in the engine having a smoother, higher-pitched sound than cross-plane

(for example, IRL IndyCar Series compared to NASCAR Nextel Cup, or a Ferrari 355 compared to a Chevrolet Corvette).

Engine balance

For some engines it is necessary to provide counterweights for the reciprocating mass of each piston and connecting rod to improve engine balance. These are typically cast as part of the crankshaft but, occasionally, are bolt-on pieces. While counter weights add a considerable amount of weight to the crankshaft, it provides a smoother running engine and allows higher RPMs to be reached.

Rotary engines

Many early aircraft engines (and a few in other applications) had the crankshaft fixed to the airframe and instead the cylinders rotated, known as a rotary engine design. Rotary engines such as the Wankel engine are referred to as pistonless rotary engines.

In the Wankel engine, also called a rotary engine, the rotors drive the eccentric shaft, which could be considered the equivalent of the crankshaft in a piston engine.

Construction
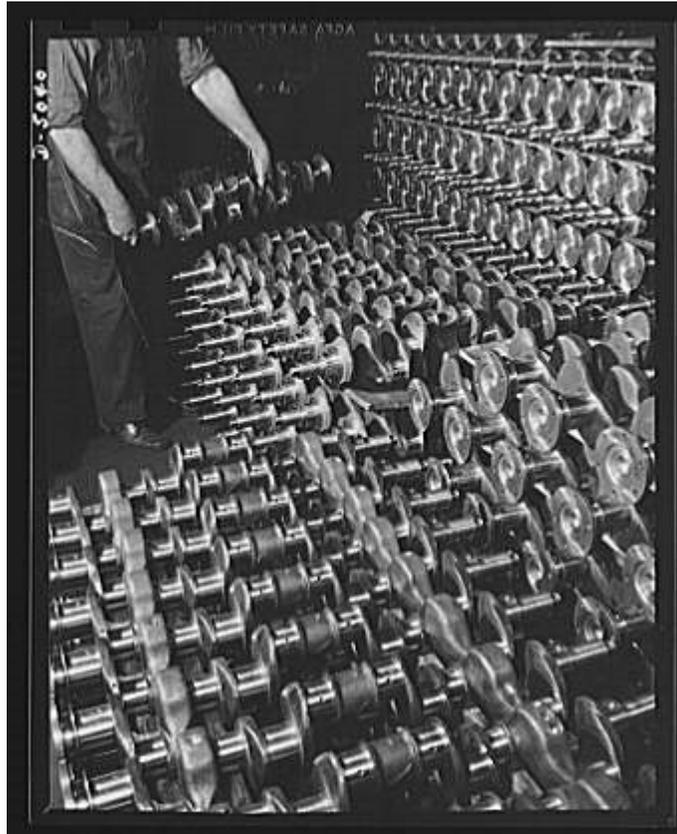
Continental engine marine crankshafts, 1942

Crankshafts can be monolithic (made in a single piece) or assembled from several pieces. Monolithic crankshafts are most common, but some smaller and larger engines use assembled crankshafts.

Forging and casting

Crankshafts can be forged from a steel bar usually through roll forging or cast in ductile steel. Today more and more manufacturers tend to favor the use of forged crankshafts due to their lighter weight, more compact dimensions and better inherent dampening. With forged crankshafts, vanadium microalloyed steels are mostly used as these steels can be air cooled after reaching high strengths without additional heat treatment, with exception to the surface hardening of the bearing surfaces. The low alloy content also makes the material cheaper than high alloy steels. Carbon steels are also used, but these require additional heat treatment to reach the desired properties. Iron crankshafts are today mostly found in cheaper production engines (such as those found in the Ford Focus diesel engines) where the loads are lower. Some engines also use cast iron crankshafts for low output versions while the more expensive high output version use forged steel.

Machining

Crankshafts can also be machined out of a billet, often using a bar of high quality vacuum remelted steel. Even though the fiber flow (local inhomogeneities of the material's chemical composition generated during casting) doesn't follow the shape of the crankshaft (which is undesirable), this is usually not a problem since higher quality steels which normally are difficult to forge can be used. These crankshafts tend to be very expensive due to the large amount of material removal which needs to be done by using lathes and milling machines, the high material cost and the additional heat treatment required. However, since no expensive tooling is required, this production method allows small production runs of crankshafts to be made without high costs.

Fatigue strength

The fatigue strength of crankshafts is usually increased by using a radius at the ends of each main and crankpin bearing. The radius itself reduces the stress in these critical areas, but since the radii in most cases are rolled, this also leaves some compressive residual stress in the surface which prevents cracks from forming.

Hardening

Most production crankshafts use induction hardened bearing surfaces since that method gives good results with low costs. It also allows the crankshaft to be reground without having to redo the hardening. But high performance crankshafts, billet crankshafts in particular, tend to use nitridization instead. Nitridization is slower and thereby more costly, and in addition it puts certain demands on the alloying metals in the steel, in order to be able to create stable nitrides. The advantage with nitridization is that it can be done at low temperatures, it produces a very hard surface and the process will leave some

compressive residual stress in the surface which is good for the fatigue properties of the crankshaft. The low temperature during treatment is advantageous in that it doesn't have any negative effects on the steel, such as annealing. With crankshafts that operate on roller bearings, the use of carburization tends to be favored due to the high Hertzian contact stresses in such an application. Like nitriding, carburization also leaves some compressive residual stresses in the surface.

Counterweights

Some expensive, high performance crankshafts also use heavy-metal counterweights to make the crankshaft more compact. The heavy-metal used is most often a tungsten alloy but depleted uranium has also been used. A cheaper option is to use lead, but compared with tungsten its density is much lower.

Stress on crankshafts

The shaft is subjected to various forces but generally needs to be analysed in two positions. Firstly, failure may occur at the position of maximum bending; this may be at the centre of the crank or at either end. In such a condition the failure is due to bending and the pressure in the cylinder is maximal. Second, the crank may fail due to twisting, so the conrod needs to be checked for shear at the position of maximal twisting. The pressure at this position is the maximal pressure, but only a fraction of maximal pressure.

Chapter 8

Bourke Engine

The **Bourke Engine** was designed by Russell Bourke in the 1920s, as an improved two stroke engine. Despite finishing his design and building several working engines, the onset of World War II, lack of test results, and the poor health of his wife compounded to prevent his engine from ever coming successfully to market. The main claimed virtues of the design are that it has only two moving parts, is light weight, powerful, has two power pulses per revolution, and does not need oil mixed into the fuel.

Overview

The Bourke engine is basically a two stroke design, with one horizontally opposed piston assembly using two pistons that move in the same direction at the same time, so that their operations are 180 degrees out of phase. The pistons are connected to a Scotch Yoke mechanism in place of the more usual crankshaft mechanism, which slightly reduces the acceleration of the pistons so that the hydrogen will detonate. The incoming charge is compressed in a chamber under the pistons, as in a conventional crankcase-charged two stroke engine. The connecting-rod seal prevents the fuel from contaminating the bottom-end lubricating oil.

Operation

The operating cycle is very similar to that of a current production spark ignition two-stroke with crankcase compression, with two modifications:

1. The fuel is injected directly into the air as it moves through the transfer port.
2. The engine is designed to run without using spark ignition once it is warmed up. This is known as auto-ignition or dieseling, and the air/fuel mixture starts to burn due to the high temperature of the compressed gas, and/or the presence of hot metal in the combustion chamber.

Design features

The following design features have been identified

Mechanical features

- Scotch yoke instead of connecting rods to translate linear motion to rotary motion
- Fewer moving parts (only 2 moving assemblies per opposed cylinder pair) and the opposed cylinders are combinable to make 2, 4, 6, 8, 10, 12 or any even number of cylinders
- Smoother operation due to elimination of crank and slider mechanism
- The piston is connected to the Scotch yoke through a slipper bearing (a type of hydrodynamic tilting-pad fluid bearing)
- Mechanical fuel injection.
- Ports rather than valves.
- Easy maintenance (top overhauling) with simple tools.
- The Scotch yoke does not create lateral forces on the piston, reducing friction, vibration and piston wear.
- O-rings are used to seal joints rather than gaskets.
- The use of the Scotch Yoke reduces vibration from the motions of the connecting rod—for example, the peak acceleration in a Scotch yoke is 25% less than the acceleration in a conventional crank and slider arrangement.
- The Scotch Yoke makes the pistons dwell very slightly longer at top dead center, so the fuel burns more completely in a smaller volume.

Gas flow and thermodynamic features

- Low exhaust temperature (below that of boiling water) so metal exhaust components are not required, plastic ones can be used if strength is not required from exhaust system
- Extremely fast hydrogen detonation burn time of the lean mixture so the engine can be considered to be a hydrogen detonation (i.e., explosion not deflagration) engine.
- 15:1 to 24:1 compression ratio for high efficiency and it can be easily changed as required by different fuels and operation requirements.
- Fuel is vaporised when it is injected into the transfer ports, and the turbulence in the intake manifolds and the piston shape above the rings stratifies the fuel air mixture into the combustion chamber.
- Lean burn for increased efficiency and reduced emissions.

Lubrication

- This design uses oil seals to prevent the pollution from the combustion chamber (created by piston ring blow-by in four-strokes and just combustion in two-strokes) from polluting the crankcase oil, extending the life of the oil as it is used slowly for keeping the rings full of oil to hold and use to lubricate. Oil was shown

to be used slowly by the dropfull as needed, but checking the quantity and cleanness of it was still recommended by Russell Bourke, its creator.

- The lubricating oil in the base is protected from combustion chamber pollution by an oil seal over the connecting rod.
- The piston rings are supplied with oil from a small supply hole in the cylinder wall at bottom dead center.

Claimed and measured performance

- **Efficiency** 0.25 (lb/h)/hp is claimed - about the same as the best diesel engine, or roughly twice as efficient as the best two strokes. This is equivalent to a thermodynamic efficiency of 55.4%, which is an exceedingly high figure for a small internal combustion engine. In a test witnessed by a third party, the **actual** fuel consumption was 1.1 hp/(lb/h), or 0.9 (lb/h)/hp, equivalent to a thermodynamic efficiency of about 12.5%, which is typical of a 1920s steam engine.

- **Power to weight** 0.9 to 2.5 hp/lb is claimed, although no independently witnessed test to support this has been documented. The upper range of this is roughly twice as good as the best four stroke production engine shown here, or 0.1 hp/lb better than a Graupner G58 two stroke. The lower claim is unremarkable, easily exceeded by production four stroke engines, never mind two strokes.

- **Emissions** Achieved virtually no hydrocarbons (80 ppm) or carbon monoxide (less than 10 ppm) in published test results, however no power output was given for these results, and NOx was not measured.

- **Low Emissions** The engine is claimed to be able to operate on hydrogen or any hydro-carbon fuel without any modifications, producing only water vapor and carbon dioxide as emissions.

Engineering critique of the Bourke engine

The Bourke Engine has some interesting features, but the extravagant claims for its performance are unlikely to be borne out by real tests. Many of the claims are contradictory.

1) Seal friction from the seal between the air compressor chamber and the crankcase, against the connecting rod, will reduce the efficiency.

2) Efficiency will be reduced due to pumping losses, as the air charge is compressed and expanded twice but energy is only extracted for power in one of the expansions per piston stroke.

3) Engine weight is likely to be high because it will have to be very strongly built to cope with the high peak pressures seen as a result of the rapid high temperature combustion.

4) Each piston pair is highly imbalanced as the two pistons move in the same direction at the same time, unlike in a boxer engine. This will limit the speed range and hence the power of the engine, and increase its weight due to the strong construction necessary to react the high forces in the components.

5) High speed two-stroke engines tend to be inefficient compared with four-strokes because some of the intake charge escapes unburnt with the exhaust.

6) When the charge is transferred from the compressor chamber to the combustion chamber it will cool down, reducing the efficiency of the engine.

7) Use of excess air will reduce the torque available for a given engine size.

8) Forcing the exhaust out rapidly through small ports will incur a further efficiency loss.

9) Operating an internal combustion engine in detonation reduces efficiency due to heat lost from the combustion gases being scrubbed against the combustion chamber walls by the shock waves.

10) Emissions - although some tests have shown low emissions in some circumstances, these were not necessarily at full power. As the scavenge ratio (i.e. engine torque) is increased more HC and CO will be emitted.

11) Increased dwell time at TDC will allow more heat to be transferred to the cylinder walls, reducing the efficiency.

12) When running in auto-ignition mode the timing of the start of the burn is controlled by the operating state of the engine, rather than directly as in a spark ignition or diesel engine. As such it may be possible to optimize it for one operating condition, but not for the wide range of torques and speeds that an engine typically sees. The result will be reduced efficiency and higher emissions.

13) If the efficiency is high, then combustion temperatures must be high, as required by the Carnot cycle, and the air fuel mixture must be lean. High combustion temperatures and lean mixtures cause nitrogen dioxide to be formed.

Chapter 9

Flathead Engine

Harley-Davidson flathead engine

A **flathead engine** or **sidevalve engine** (sometimes called a **flatty**) is an internal combustion engine with valves placed in the engine block beside the piston, instead of in the cylinder head, as in an overhead valve engine. The design was common on early engine designs, but has since fallen from favor.

Advantages

Generally the flathead's valves are carried on one side of the cylinder. A chamber is recessed into the underside of the head to allow the poppet valves to alternately rise from their seats to admit the fuel-air mixture and for the exhaust gases to escape the combustion chamber. This has a number of advantages, primarily making the valve gear simpler, without either long push rods and rocker arms to work overhead valves from a cam shaft mounted near the crank shaft or a long chain, belt or gear train to drive one or more overhead cam shafts. The head of a flathead engine commonly consists of only a single piece of cast metal.

Each valve is operated by pushing directly up on it, as opposed to needing some sort of mechanical arrangement to transfer the motion from the crank case to the cylinder head, as in an overhead valve engine. The line of intakes along the side of the engine leads to the alternate name **L-block** (or **L-head**), due to the cylinders having the shape of an upside-down L. This configuration is also known as (Ford) sidevalve engine. A great advantage to this design was that limited damage occurred if a valve dropped, unlike the overhead design in which serious damage could occur. One could still continue to travel even with a broken valve.

Because the intake and exhaust pass through the same small passage between the block and head, and because the light valve gear allows the valves to open and close quickly, flatheads are designed with very little "overlap", part of the cycle when both intake and exhaust valves are open. This gives better low rotation speed performance than is typical of push rod overhead valve engines or overhead cam engines tuned for high speed power. On the other hand, the light valve gear allows the engine to function at high speed, though with little power. The torque and power curves are therefore broad, making it easier for the manual transmission and driver or for the automatic transmission. This flexibility is returning to cars in the form of electric motors.

Disadvantages

The flathead configuration requires the intake and exhaust gases to make at least a 90-degree turn and to pass between the block and head to enter and leave the cylinder, which makes it less efficient, colloquially called poorer "breathing". Breathing was not greatly important for early production cars because engines could not run long and reliably at high speed, and few roads allowed sustained high speeds, so this was a minor concern given the benefits in simplicity. The maximum compression ratio is also low at only about 7:1, further reducing efficiency (although it means the engine can run well on low-octane fuel.) This is mainly because the combustion chamber must include the space for the valve movement and the space for the gas flow.

A compromise used by Willys (Jeep),Rover and Rolls-Royce in the mid 20th century was the F-head or intake over exhaust configuration, in which there is one side valve and one overhead valve per cylinder.

The greatest advancements to flathead engine technology were developed in the 1920s through experimentation by Sir Harry Ricardo of Great Britain, who improved the performance and efficiency by intently studying their flow characteristics. He published his findings, and obtained patents, in 1927. Primarily, his **Ricardo head** can be recognized on sight, because he moved the exhaust valve farther from the center of the cylinder than the intake valve (they had previously been symmetrical). He also paid careful attention to the form of the intake and exhaust tracts cast into the cylinder block as regarded turbulence in the intake stream and within the combustion chamber.

Another concern is that because the exhaust follows a more complicated path to leave the engine, there is increased tendency for the engine to overheat under sustained heavy use. This is especially true if the exhaust is routed between the cylinders, as in the Ford flathead. It is possible to arrange the sidevalve engine layout so exhaust will be taken away through a valve and an exhaust tract located on the opposite side of the cylinder from the intake valve, in which case the layout is referred to as a **T-block** or **T-head**. American LaFrance famously powered their production fire engines with T-head engines from the 1920s to the 1950s. The Cleveland Motorcycle Company produced a four-cylinder in-line motorcycle engine using the T-head configuration in the 1920s. Very early Stutz engines were T heads. This requires two passages between the block and head, within the combustion chamber, and it loses some of the simplicity.

The flathead design also greatly reduced the ability to overbore the engine for performance purposes. Since the piston, exhaust valve, and intake valve were all next to each other, the piston cylinder bore could only be slightly increased, if at all, or it would encroach upon the radii of the intake and exhaust valves, and also cause thin and weak cylinder walls.

History and applications

Although flathead in-line 4 and 6 cylinder engines were frequently used for automobiles, tractors, and other products, the best known flathead automotive engine is the early 20th century Ford V-8, which has both sets of valves (intake and exhaust) located on the inside of the "Vee," and which are all operated by a single camshaft located above the crankshaft. Other common configurations included in-line ("straight") eights and a V 12 Lincoln version of the Ford V 8.

Due to cooling and efficiency problems, flathead engines fell out of favor in "high power" applications, such as aircraft engines, prior to World War I. However they lived on for some time in the automotive world and were used on the Jeep for instance. Flatheads are no longer in common use for automobiles (except in some rodding and customizing circles), although they are still used for some small-engine applications like lawnmowers. Because of their design, the size of valves and the compression ratio are limited, which in turn reduces available power and economy.

Harley-Davidson motorcycle flathead engines

The flathead engine saw service in Harley-Davidson motorcycles beginning with the "Sport Model" opposed twin produced from 1919 to 1923, and continuing in 1924 with single cylinder export-model 21 cubic inches (340 cc) and 30.5 cubic inches (500 cc) singles and continued in the Servi-Cars until 1973. In the domestic U.S. market, the 45 cubic inches (740 cc) DL model (1929 to 1931) and its technical descendant, the RL model (1932 to 1936), started Harley's side valve tradition in the 45 cubic inch displacement class. The DL and RL models featured a total loss oiling system and were succeeded in 1937 by the WL 45, which had recirculating oil lubrication. The WL went on to serve in WWII as the U.S. and Canadian Army's primary two-wheeled mount and subsequently as a civilian middleweight through 1952. The engine continued virtually unchanged with various G-based designations in the three wheeled "Servi-Car" until production ceased in 1973.

In 1952, the K series flatheads was introduced, selling in parallel with the W series (which was discontinued after 1952), designed to compete with British sporting motorcycles of the time, as the American motorcycle Association allowed the 750 cc sidevalves to compete against 500 cc overhead-valve bikes. The K models featured a unit construction engine and transmission case, right side foot shift and left side foot brake, and evolved from 45 cubic inch (1952 to 1953) to 55 cubic inches by a 0.75 inches (19 mm) increase in stroke length (1954 to 1956) over its five year retail market run. The K series was replaced by the overhead valve Sportster series in the retail market in 1957. However, racing versions of the 750 cc K model, designated KR, continued to be produced in very limited numbers for some time after, winning both roadraces and dirt track events against overhead valve bikes limited to 500 cc through 1969, when the American Motorcycle Association finally decided to change the rules and make the venerable flatheads uncompetitive. The K racers were replaced first by the iron-head XR 750cc overhead valve engine, and two years later by the alloy-head XR, which continues in service in flat track racing to this day.

In 1930, the 74 cubic inches (1,210 cc) VL flathead replaced the JD Big Twin, which had featured intake-over-exhaust (IoE) valve configuration. The VL had a single downtube frame and total loss oiling, culminating in an 80 cubic inches (1,300 cc) version (VLH) in 1935. In 1937, that engine was redesigned to include a recirculating lubrication system, and designated the model U, and it went into the same frame and running gear configuration as the model E Knucklehead, which had originated in 1936. The U continued to be produced in varying configurations as a 74& cubic inch U & UL (1937 to 1948), and 80 cubic inch UH & ULH engine (1937 to 1941). By that time, the first year of the aluminum-head Panhead, it had been thoroughly superseded and outsold in the marketplace by the superior performance of the overhead valve model Big Twins.

Oil Burner (Engine) and Fluidyne Engine

Oil burner

Darjeeling Himalayan Railway Locomotive No.787 after conversion to oil firing.

An **oil burner engine** is a steam engine that uses oil as its fuel. The term is often used with reference to a locomotive or ship engine that burns oil, to heat water, to produce steam which drives the pistons, or turbines, from which the power is derived. Some

engines of this form were originally designed to be coal powered and were converted. An early pioneer of this form of engine was James Holden.

This is mechanically very different from a diesel engine that is a form of internal combustion engine, which is sometimes colloquially referred to as an oil burner .

Conversion

When a coal-burning steam locomotive is converted to oil-burning, various modifications are usual:

1. the grate is covered with broken firebrick to act as a reservoir of heat. If the oil flame is blown out (e.g. by a downdraft when entering a tunnel) the hot firebrick will re-ignite it
2. the lower part of the inner firebox is lined with firebrick
3. shorter superheater elements are fitted

Changes 2 & 3 are needed because oil firing produces higher temperatures than coal firing and can cause rapid erosion of metal. For a similar reason, the smokebox is sometimes painted with silver-coloured heat-resisting paint.

Oil-fired steam locomotives

- Darjeeling Himalayan Railway
- LNER Class U1
- Snowdon Mountain Railway
- Union Pacific 737
- Mount Washington Cog Railway
- most cab forward locomotives
- some Fairlie locomotives
- Advanced steam technology locomotives

Oil-fired steamships
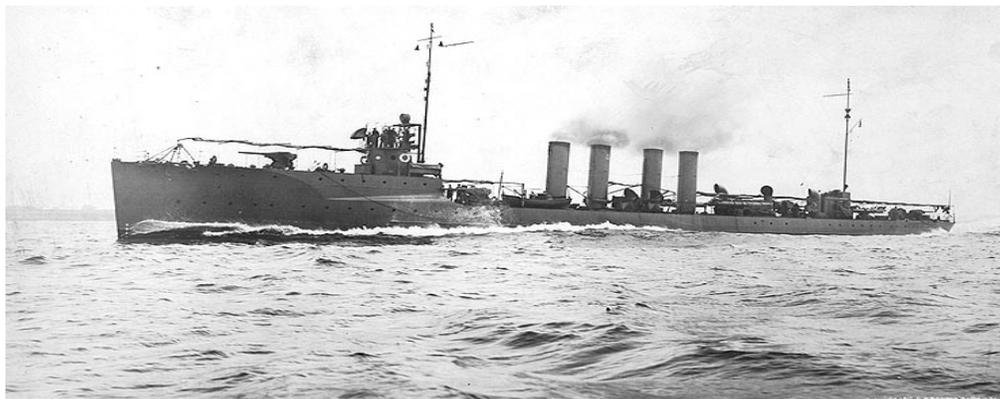
USS Trippe, an oil burner powered ship

- USS Drayton (DD-23)
- USS Terry (DD-25)
- USS Perkins (DD-26)
- USS Sterett (DD-27)
- USS McCall (DD-28)
- USS Warrington (DD-30)
- USS Burrows (DD-29)
- USS Monaghan (DD-32)
- USS Trippe (DD-33)
- USS Walke (DD-34)
- USS Ammen (DD-35)
- USS Jarvis (DD-38)
- USS Henley (DD-39)
- USS Jouett (DD-41)
- USS Jenkins (DD-42)
- USS George Washington (1908)

Fluidyne Engine
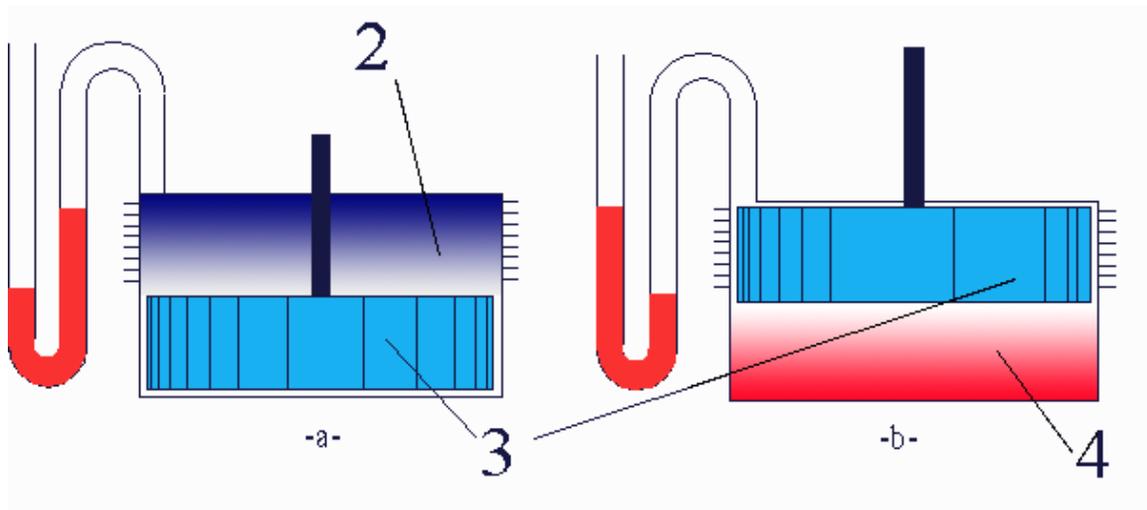
This is a Fluidyne variant with a solid displacer piston (3). In figure -a-, as the displacer moves from the cold compression space (2), to the hot expansion space (4) in figure -b-, the temperature of the gaseous working fluid is increased. This increases the pressure of the gaseous working fluid, and as it expands, work is done on the (red) liquid piston as it is pushed through the tube.
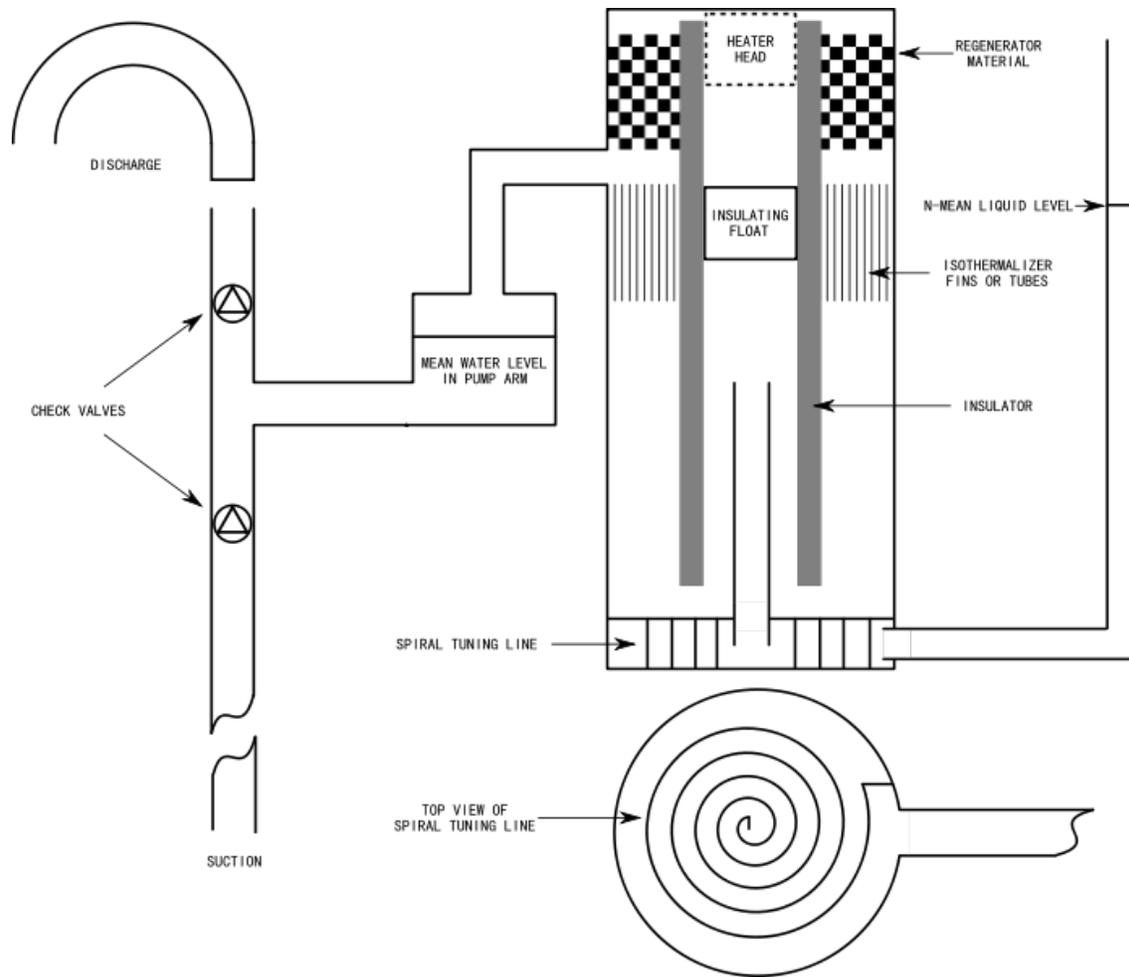
A Concentric-cylinder Fluidyne Pumping engine

A **Fluidyne engine** is an alpha or gamma type Stirling engine with one or more liquid pistons. It contains a working gas (often air), and either two liquid pistons or one liquid piston and a displacer.

Engine operation

Working gas in the engine is heated, and this causes it to expand and push on the water column. This expansion cools the air which contracts, at the same time being pushed back by the weight of the displaced water column. Cycle then repeats.

Engine as a pump

In the classic configuration, the work produced via the water pistons is integrated with a water pump. The simple pump is external to the engine, and consists of two check valves, one on the intake and one on the outlet. In the engine, the loop of oscillating liquid can be thought of as acting as a displacer piston. The liquid in the single tube extending to the pump acts as the power piston. Traditionally the pump is open to the atmosphere, and the

hydraulic head is small, so that the absolute engine pressure is close to atmospheric pressure.
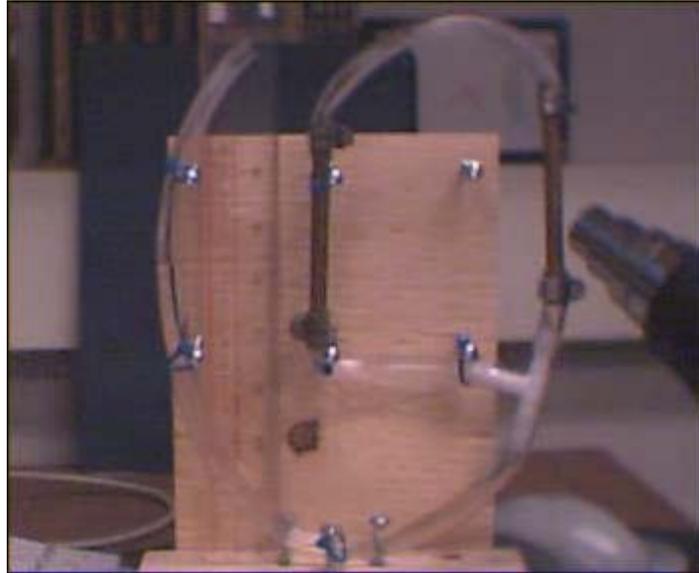
Test of a model fluidyne engine.

Detail of a water level displacement in a leftmost vertical tube.

This shows operation of a model fluidyne engine. Hot pipe is heated by a heat gun, and water column oscillation builds up to a steady-state level. Second image shows a detail of the actual water displacement.

Chapter 11

Ericsson Cycle
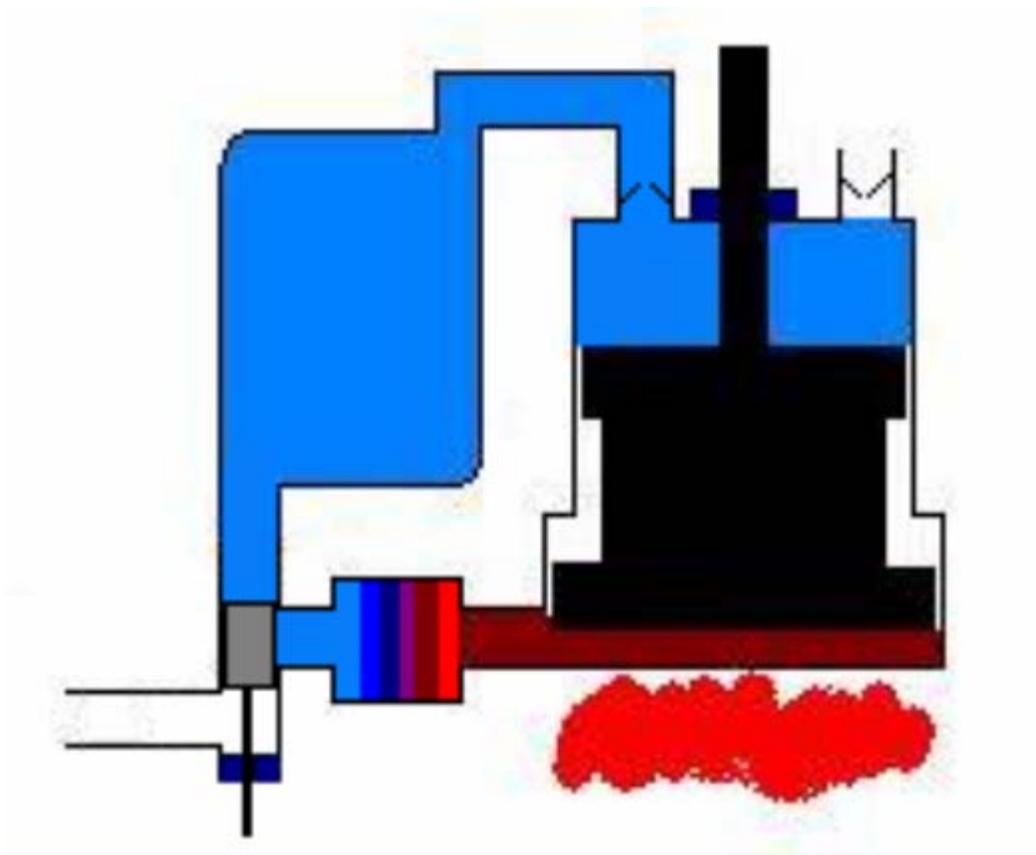
Rendering of an Ericsson engine

The **Ericsson cycle** is named after inventor John Ericsson, who designed and built many unique heat engines based on various thermodynamic cycles. He is credited with inventing two unique heat engine cycles and developing practical engines based on these cycles. His *first* cycle is very similar to what is now called the "Brayton cycle", with the exception that it uses external combustion. His second cycle is now called the Ericsson cycle.

Ideal Ericsson cycle

The following is a list of the four processes that occur between the four stages of the ideal Ericsson cycle:

- Process 1 -> 2: Isothermal compression. The compression space is assumed to be intercooled, so the gas undergoes isothermal compression. The compressed air flows into a storage tank at constant pressure. In the ideal cycle, there is no heat transfer across the tank walls.
- Process 2 -> 3: Isobaric heat addition. From the tank, the compressed air flows through the regenerator and picks up heat at a high constant-pressure on the way to the heated power-cylinder.
- Process 3 -> 4: Isothermal expansion. The power-cylinder expansion-space is heated externally, and the gas undergoes isothermal expansion.
- Process 4 -> 1: Isobaric heat removal. Before the air is released as exhaust, it is passed back through the regenerator, thus cooling the gas at a low constant pressure, and heating the regenerator for the next cycle.

Comparison with Stirling and Carnot cycles

The Ericsson cycle is often compared to the Stirling cycle, since the engine designs based on these respective cycles are both external combustion engines with regenerators. The Ericsson is perhaps most similar to the so called "double-acting" type of Stirling engine, in which the displacer piston also acts as the power piston. Theoretically, both of these cycles have so called *ideal* efficiency, which is the highest allowed by the second law of thermodynamics. The most well known ideal cycle is the Carnot cycle, although a real *Carnot engine* is not known to have been invented. The theoretical efficiencies for both, Ericsson and Stirling cycles acting in the same limits are equal to the Carnot Efficiency for same limits.

Comparison with the Brayton cycle

The first cycle Ericsson developed is now called the "Brayton cycle", commonly applied to the rotary jet engines for airplanes.

The second Ericsson cycle is the cycle most commonly referred to as simply the "Ericsson cycle". The (second) Ericsson cycle is also the limit of an ideal gas-turbine Brayton cycle, operating with multistage intercooled compression, and multistage expansion with reheat and regeneration. Compared to the Brayton cycle which uses adiabatic compression and expansion, the second Ericsson cycle uses isothermal compression and expansion, thus producing more net work per stroke. Also the use of regeneration in the Ericsson cycle increases efficiency by reducing the required heat input.

Cycle/Process	Compression	Heat addition	Expansion	Heat rejection
Ericsson (First, 1833)	adiabatic	isobaric	adiabatic	isobaric
Ericsson (Second, 1853)	isothermal	isobaric	isothermal	isobaric
Brayton (Turbine)	adiabatic	isobaric	adiabatic	isobaric

Ericsson engine

The Ericsson engine is based on the Ericsson cycle, and is known as an "external combustion engine", because it is externally heated. To improve efficiency, the engine has a regenerator or recuperator between the compressor and the expander. The engine can be run open- or closed-cycle. Expansion occurs simultaneously with compression, on opposite sides of the piston.

Regenerator

Ericsson coined the term "regenerator" for his independent invention of the mixed-flow counter-current heat exchanger. However, Rev. Robert Stirling had invented the same device, prior to Ericsson, so the invention is credited to Stirling. Stirling called it an "economiser" or "economizer", because it increased the fuel economy of various types of heat processes. The invention was found to be useful, in many other devices and systems, where it became more widely used, since other types of engines became favored over the Stirling engine. The term "regenerator" is now the name given to the component in the Stirling engine.

The term "recuperator" refers to a separated-flow, counter-current heat exchanger. As if this weren't confusing enough, a mixed-flow regenerator is sometimes used as a quasi-separated-flow recuperator. This can be done through the use of moving valves, or by a rotating regenerator with fixed baffles, or by the use of other moving parts. When heat is recovered from exhaust gases and used to preheat combustion air, typically the term recuperator is used, because the two flows are separate.

History

In 1791, before Ericsson, Barber proposed a similar engine. The Barber engine used a bellows compressor and a turbine expander, but it lacked a regenerator/recuperator. There are no records of a working Barber engine. Ericsson invented and patented his first engine using an external version of the Brayton cycle in 1833 (number 6409/1833 British). This was 18 years before Joule and 43 years before Brayton. Brayton engines were all piston engines and for the most part, internal combustion versions of the un-recuperated Ericsson engine. The "Brayton Cycle" is now known as the gas turbine cycle, which differs from the original "Brayton Cycle" in the use of a turbine compressor and expander. The gas turbine cycle is used for all modern gas turbine and turbojet engines, however simple cycle turbines are often recuperated to improve efficiency and these recuperated turbines more closely resemble Ericsson's work.

Ericsson eventually abandoned the open cycle in favor of the traditional closed Stirling cycle.

Ericsson's engine can easily be modified to operate in a closed-cycle mode, using a second, lower-pressure, cooled container between the original exhaust and intake. In closed cycle, the lower pressure can be significantly above ambient pressure, and He or H2 working gas can be used. Because of the higher pressure difference between the upward and downward movement of the work-piston, specific output can be greater than of a valveless Stirling engine. The added cost is the valve. Ericsson's engine also minimizes mechanical losses: the power necessary for compression does not go through crank-bearing frictional losses, but is applied directly from the expansion force. The piston-type Ericsson engine can potentially be the highest efficiency heat engine arrangement ever constructed. Admittedly, this has yet to be proven in practical applications.

The Ericsson-cycle engine (the second of the two discussed here) was used to power a 2,000-ton ship, the caloric ship *Ericsson*, and ran flawlessly for 73 hours. The combination engine produced about 300 horsepower (220 kW). It had a combination of four dual-piston engines; the larger expansion piston/cylinder, at 14 feet (4.3 m) in diameter, was perhaps the largest piston ever built. Rumor has it that tables were placed on top of those pistons (obviously in the cool compression chamber, not the hot power chamber) and dinner was served and eaten, while the engine was running at full power. At 6.5 RPM the pressure was limited to 8 psi (55 kPa). According to the official report it only consumed 4200 kg coal per 24 hours (original target was 8000 kg, which is still better than contemporary steam engines). The one sea trial proved that even though the engine ran well, the ship was underpowered. Sometime after the trials, the *Ericsson* sank. When it was raised, the Ericsson-cycle engine was removed and a steam engine took its place.

Ericsson designed and built a very great number of engines running on various cycles including steam, Stirling, Brayton, externally heated diesel air fluid cycle. He ran his engines on a great variety of fuels including coal and solar heat.

Ericsson was also responsible for an early use of the screw propeller for ship propulsion, in the USS *Princeton*, built in 1842–43.

Today's potential

The Ericsson cycle (and the similar Brayton cycle) receives renewed interest today to extract power from the exhaust heat of gas (and producer gas) engines and solar concentrators. An important advantage of the Ericsson cycle over the widely known Stirling engine is often not recognized: the volume of the heat exchanger does not adversely effect the efficiency. For medium and large engines the cost of valves can be small compared to this advantage. Turbocompressor plus turbine implementations seem favorable in the MWe range, positive displacement compressor plus turbine for Nx100 kWe power, and positive displacement compressor+expander below 100 kW.

With high temperature hydraulic fluid, both the compressor and the expander can be liquid ring pump even up to 400°C, with rotating casing for best efficiency.

Chapter 12

Connecting Rod
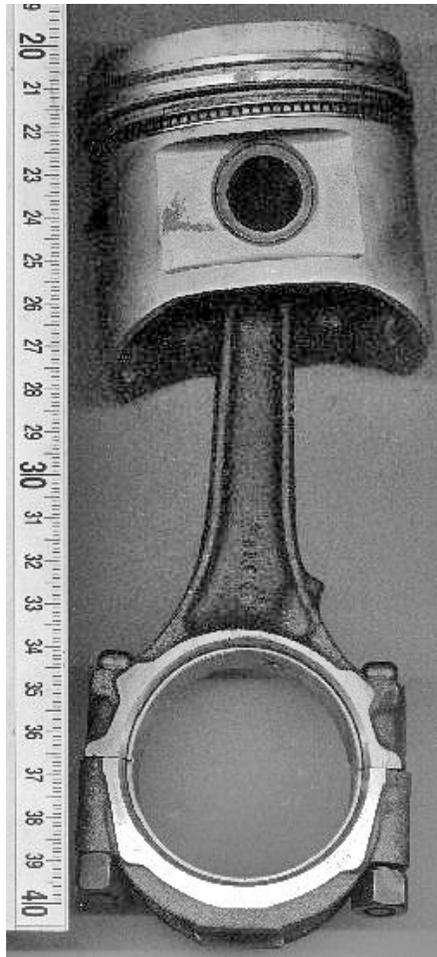
piston (top) and connecting rod from typical automotive engine (scale is in centimetres)

In a reciprocating piston engine, the **connecting rod** or **conrod** connects the piston to the crank or crankshaft. Together with the crank, they form a simple mechanism that converts linear motion into rotating motion.

Connecting rods may also convert rotating motion into linear motion. Historically, before the development of engines, they were first used in this way.

As a connecting rod is rigid, it may transmit either a push or a pull and so the rod may rotate the crank through both halves of a revolution, i.e. piston pushing and piston pulling. Earlier mechanisms, such as chains, could only pull. In a few two-stroke engines, the connecting rod is only required to push.

Today, connecting rods are best known through their use in internal combustion piston engines, such as car engines. These are of a distinctly different design from earlier forms of connecting rods, used in steam engines and steam locomotives.

History
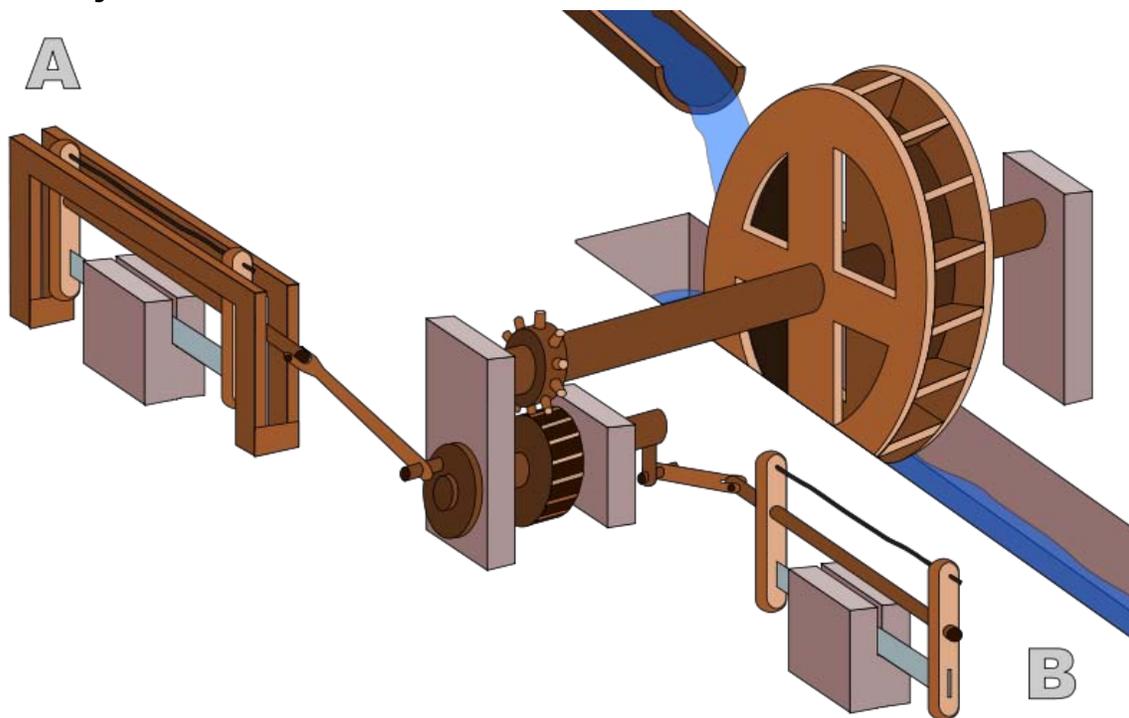
Scheme of the Roman Hierapolis sawmill, the earliest known machine to combine a connecting rod with a crank.

The earliest evidence for a connecting rod appears in the late 3rd century AD Roman Hierapolis sawmill. It also appears in two 6th century Eastern Roman saw mills excavated at Ephesus respectively Gerasa. The crank and connecting rod mechanism of these Roman watermills converted the rotary motion of the waterwheel into the linear movement of the saw blades.

Sometime between 1174 and 1206, the Arab inventor and engineer Al-Jazari described a machine which incorporated the connecting rod with a crankshaft to pump water as part

of a water-raising machine, but the device was unnecessarily complex indicating that he still did not fully understand the concept of power conversion.

In Renaissance Italy, the earliest evidence of a − albeit mechanically misunderstood − compound crank and connecting-rod is found in the sketch books of Taccola. A sound understanding of the motion involved displays the painter Pisanello (d. 1455) who showed a piston-pump driven by a water-wheel and operated by two simple cranks and two connecting-rods.

By the 16th century, evidence of cranks and connecting rods in the technological treatises and artwork of Renaissance Europe becomes abundant; Agostino Ramelli's *The Diverse and Artifactitious Machines* of 1588 alone depicts eighteen examples, a number which rises in the *Theatrum Machinarum Novum* by Georg Andreas Böckler to 45 different machines.

Steam engines

Beam engine, with twin connecting rods (almost vertical) between the horizontal beam and the flywheel cranks

The first steam engines, Newcomen's atmospheric engine, was single-acting: its piston only did work in one direction, and so these used a chain rather than a connecting rod. Their output rocked back and forth, rather than rotating continuously.
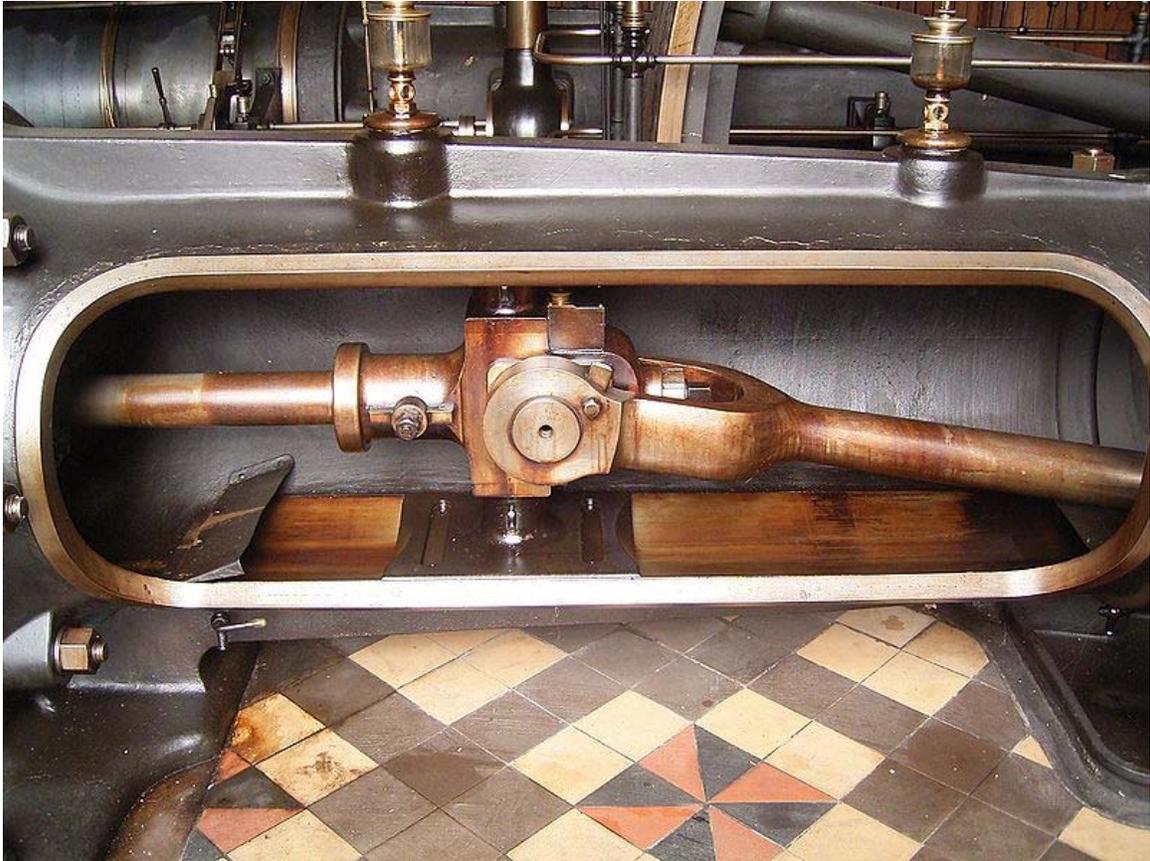
Crosshead of a stationary steam engine: piston rod to the left, connecting rod to the right

Steam engines after this are usually double-acting: their internal pressure works on each side of the piston in turn. This requires a seal around the piston rod and so the hinge between the piston and connecting rod is placed outside the cylinder, in a large sliding bearing block called a crosshead.
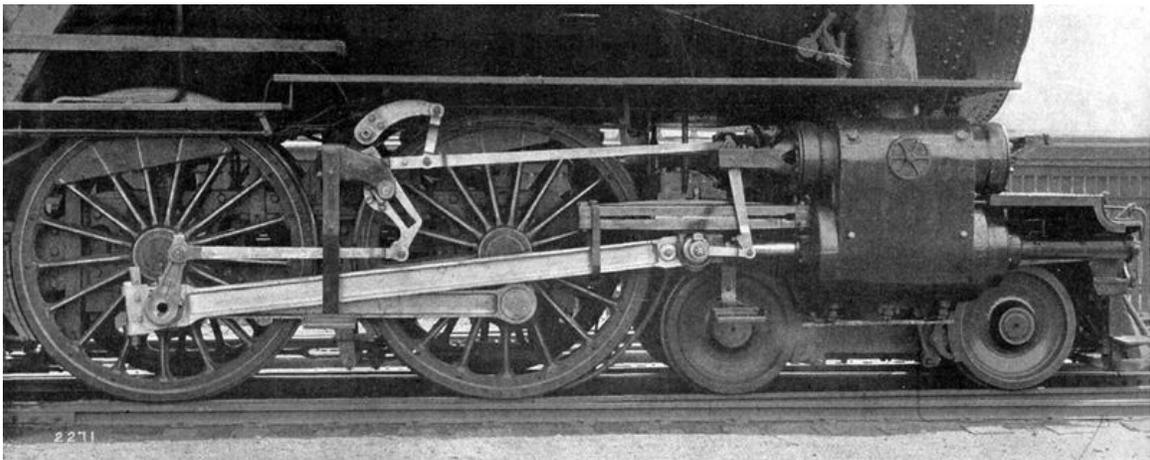
Steam locomotive rods, the large angled rod being the connecting rod

In a steam locomotive, the crank pins are usually mounted directly on one or more pairs of driving wheels, and the axle of these wheels serves as the crankshaft. The connecting rods, also called the **main rods** (*in US practice*), run between the crank pins and crossheads, where they connect to the piston rods. Crossheads or trunk guides are also used on large diesel engines manufactured for marine service. The similar rods between driving wheels are called **coupling rods** (*in British practice*).

The connecting rods of smaller steam locomotives are usually of rectangular cross-section but, on small locomotives, marine-type rods of circular cross-section have occasionally been used. Stephen Lewin, who built both locomotive and marine engines, was a frequent user of round rods. Gresley's A4 Pacifics, such as *Mallard, had an alloy steel connecting rod with a web that was only 3/8" thick.*

On Western Rivers steamboats, the connecting rods are properly called **pitmans**, and are sometimes incorrectly referred to as pitman arms.

Internal combustion engines

Failure of a connecting rod is one of the most common causes of catastrophic engine failure.

In modern automotive internal combustion engines, the connecting rods are most usually made of steel for production engines, but can be made of T6-2024 and T651-7075

aluminum alloys (for lightness and the ability to absorb high impact at the expense of durability) or titanium (for a combination of lightness with strength, at higher cost) for high performance engines, or of cast iron for applications such as motor scooters. They are not rigidly fixed at either end, so that the angle between the connecting rod and the piston can change as the rod moves up and down and rotates around the crankshaft. Connecting rods, especially in racing engines, may be called "billet" rods, if they are machined out of a solid billet of metal, rather than being cast.

The **small end** attaches to the piston pin, gudgeon pin or wrist pin, which is currently most often press fit into the connecting rod but can swivel in the piston, a "floating wrist pin" design. The **big end** connects to the bearing journal on the crank throw, in most engines running on replaceable bearing shells accessible via the *connecting rod bolts* which hold the bearing "cap" onto the big end. Typically there is a pinhole bored through the bearing and the big end of the connecting rod so that pressurized lubricating motor oil squirts out onto the thrust side of the cylinder wall to lubricate the travel of the pistons and piston rings. Most small two-stroke engines and some single cylinder four-stroke engines avoid the need for a pumped lubrication system by using a rolling-element bearing instead, however this requires the crankshaft to be pressed apart and then back together in order to replace a connecting rod.

The connecting rod is under tremendous stress from the reciprocating load represented by the piston, actually stretching and being compressed with every rotation, and the load increases to the square of the engine speed increase. Failure of a connecting rod, usually called "throwing a rod" is one of the most common causes of catastrophic engine failure in cars, frequently putting the broken rod through the side of the crankcase and thereby rendering the engine irreparable; it can result from fatigue near a physical defect in the rod, lubrication failure in a bearing due to faulty maintenance, or from failure of the rod bolts from a defect, improper tightening. Re-use of rod bolts is a common practice as long as the bolts meet manufacturer specifications. Despite their frequent occurrence on televised competitive automobile events, such failures are quite rare on production cars during normal daily driving. This is because production auto parts have a much larger factor of safety, and often more systematic quality control.

When building a high performance engine, great attention is paid to the connecting rods, eliminating stress risers by such techniques as grinding the edges of the rod to a smooth radius, shot peening to induce compressive surface stresses (to prevent crack initiation), balancing all connecting rod/piston assemblies to the same weight and Magnafluxing to reveal otherwise invisible small cracks which would cause the rod to fail under stress. In addition, great care is taken to torque the connecting rod bolts to the exact value specified; often these bolts must be replaced rather than reused. The big end of the rod is fabricated as a unit and cut or cracked in two to establish precision fit around the big end bearing shell. Therefore, the big end "caps" are not interchangeable between connecting rods, and when rebuilding an engine, care must be taken to ensure that the caps of the different connecting rods are not mixed up. Both the connecting rod and its bearing cap are usually embossed with the corresponding position number in the engine block.

Recent engines such as the Ford 4.6 liter engine and the Chrysler 2.0 liter engine, have connecting rods made using powder metallurgy, which allows more precise control of size and weight with less machining and less excess mass to be machined off for balancing. The cap is then separated from the rod by a fracturing process, which results in an uneven mating surface due to the grain of the powdered metal. This ensures that upon reassembly, the cap will be perfectly positioned with respect to the rod, compared to the minor misalignments which can occur if the mating surfaces are both flat.

A major source of engine wear is the sideways force exerted on the piston through the connecting rod by the crankshaft, which typically wears the cylinder into an oval cross-section rather than circular, making it impossible for piston rings to correctly seal against the cylinder walls. Geometrically, it can be seen that longer connecting rods will reduce the amount of this sideways force, and therefore lead to longer engine life. However, for a given engine block, the sum of the length of the connecting rod plus the piston stroke is a fixed number, determined by the fixed distance between the crankshaft axis and the top of the cylinder block where the cylinder head fastens; thus, for a given cylinder block longer stroke, giving greater engine displacement and power, requires a shorter connecting rod (or a piston with smaller compression height), resulting in accelerated cylinder wear.

Compound rods

Fig. 5. — Bielles et Biellettes.
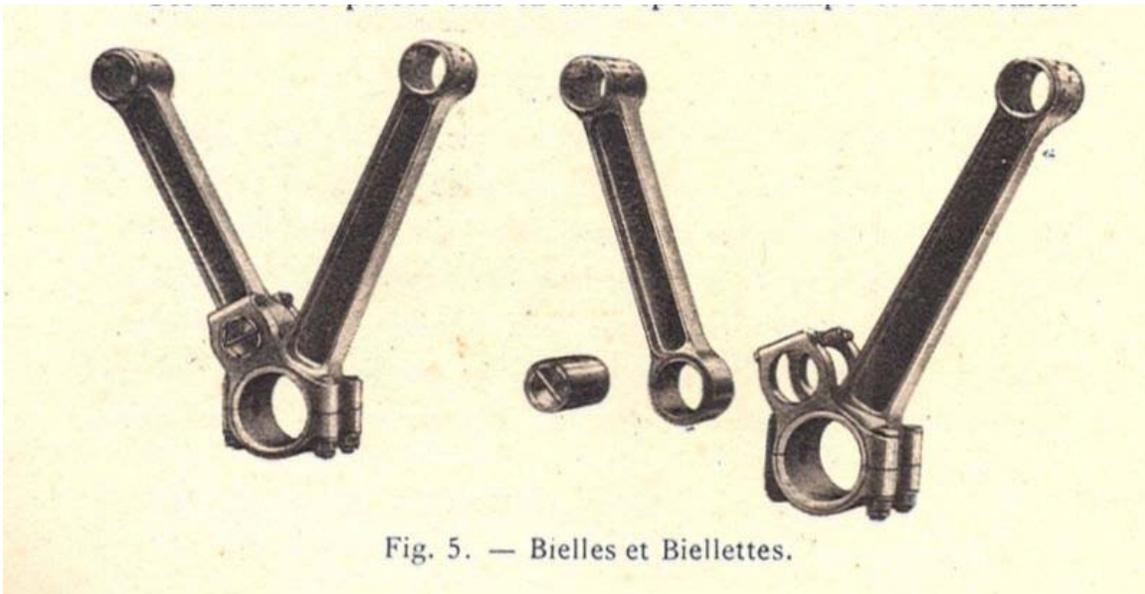
Articulated connecting rods

Many-cylinder multi-bank engines such as a V12 layout have little space available for many connecting rod journals on a limited length of crankshaft. This is a difficult compromise to solve and its consequence has often led to engines being regarded as failures (Sunbeam Arab, Rolls-Royce Vulture).

The simplest solution, almost universal in road car engines, is to use simple rods where cylinders from both banks share a journal. This requires the rod bearings to be *narrower*, increasing bearing load and the risk of failure in a high-performance engine. This also means the opposing cylinders are not exactly in line with each other.

In certain engine types, master/slave rods are used rather than the simple type shown in the picture above. The master rod carries one or more ring pins to which are bolted the much smaller big ends of slave rods on other cylinders. Certain designs of V engines use a master/slave rod for each pair of opposite cylinders. A drawback of this is that the stroke of the subsidiary rod is slightly shorter than the master, which increases vibration in a vee engine, catastrophically so for the Sunbeam Arab.

BMW 132 radial aero engine rods

Radial engines typically have a master rod for one cylinder and multiple slave rods for all the other cylinders in the same bank.
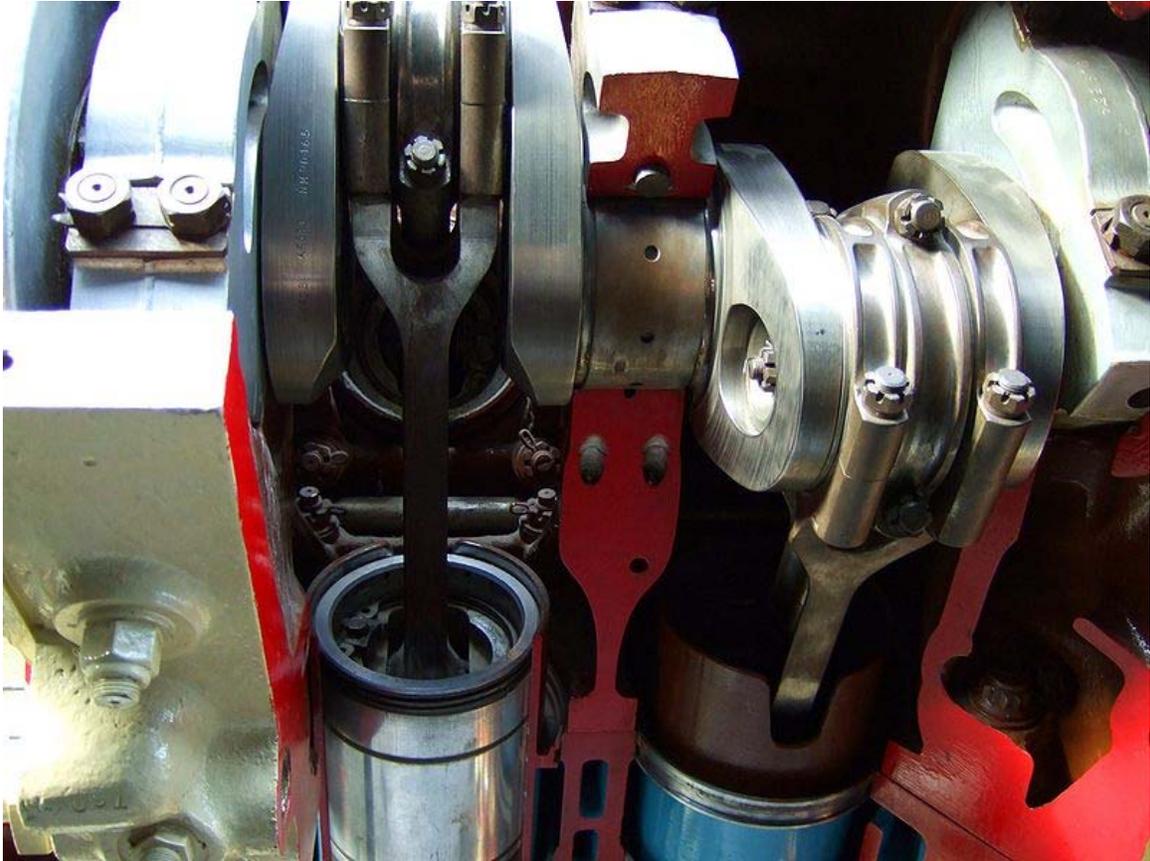
Fork and blade rods of a Napier Deltic

The usual solution for high-performance aero-engines is a "forked" connecting rod. One rod is split in two at the big end and the other is thinned to fit into this fork. The journal is still shared between cylinders. The Rolls-Royce Merlin used this "fork-and-blade" style.
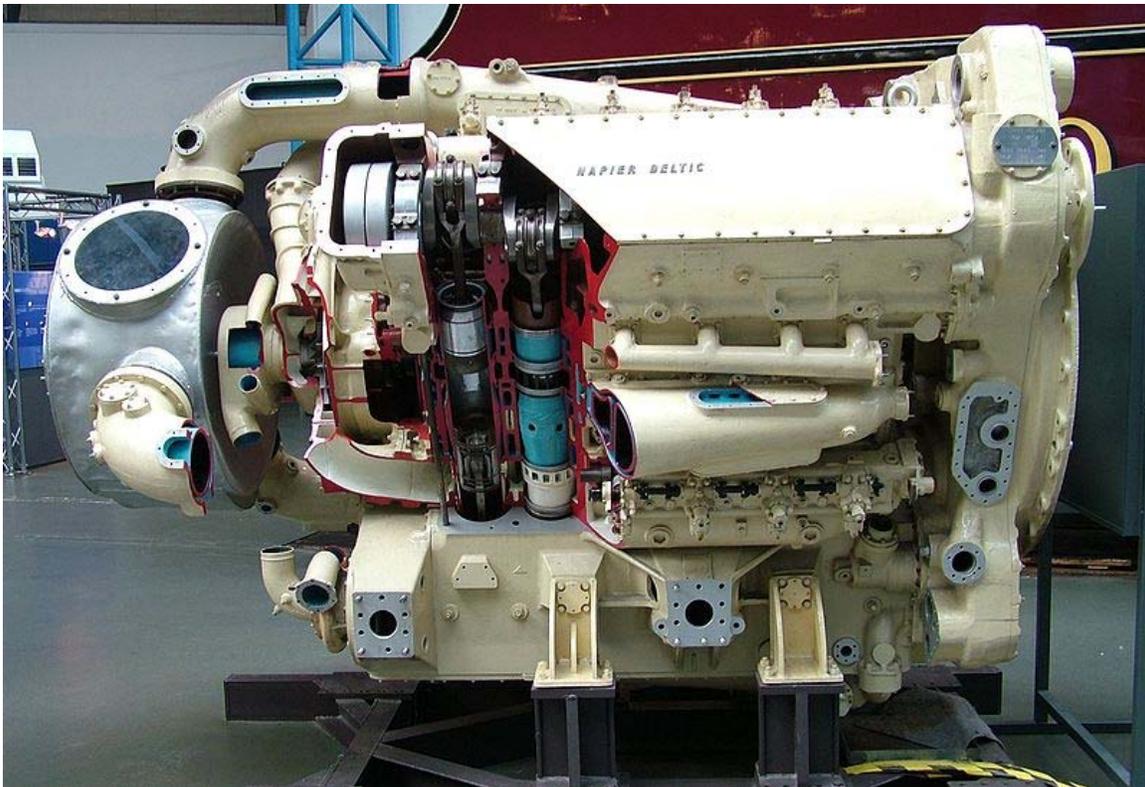
Napier Deltic

Napier Deltic engine at the National Railway Museum, York, UK

The **Napier Deltic** engine was a British opposed-piston valveless, two-stroke diesel engine used in marine and locomotive applications, designed and produced by Napier & Son. The cylinders were divided in three blocks in a triangular arrangement, the blocks forming sides with crankcases located in each apex of the triangle.

The term Deltic (meaning in the form of the Greek letter Delta) is used to refer to both the *Deltic E.130* opposed-piston high-speed diesel engine and the locomotives produced by English Electric using these engines, including their demonstrator locomotive named

DELTIC and the production version for British Railways, who designated these as (TOPS) Class 55.

A single half-sized, turbocharged Deltic power unit also featured in the English Electric-built Type 2 locomotive, designated as the Class 23. Both locomotive and engine became better known as the "Baby Deltic".

History and design

The Deltic story began in 1943 when the British Admiralty set up a committee to develop a high-power, lightweight diesel engine for Motor Torpedo Boats. Hitherto in the Royal Navy, such boats had been driven by petrol engines but this fuel is highly flammable, making them vulnerable to fire, and at a disadvantage compared with the German diesel-powered E-boats.

Until this time, diesel engines had poor power-to-weight ratio and low speed. Before the war, Napier had been working on an aviation diesel design known as the Culverin after licensing versions of the Junkers Jumo 204. The Culverin was an opposed-piston two-stroke design. Instead of each cylinder having a single piston and being closed at one end with a cylinder head, the Jumo-based design used an elongated cylinder containing two pistons moving in opposite directions towards the centre. This negates the need for a heavy cylinder head, as the opposing piston filled this role. On the downside, the layout required separate crankshafts on either end of the engine, and some form of gearing to take off power and combine it back into a single shaft. The primary advantage of the design was that it led to a rather "flat" engine, intended to be buried in the wings of large aircraft.
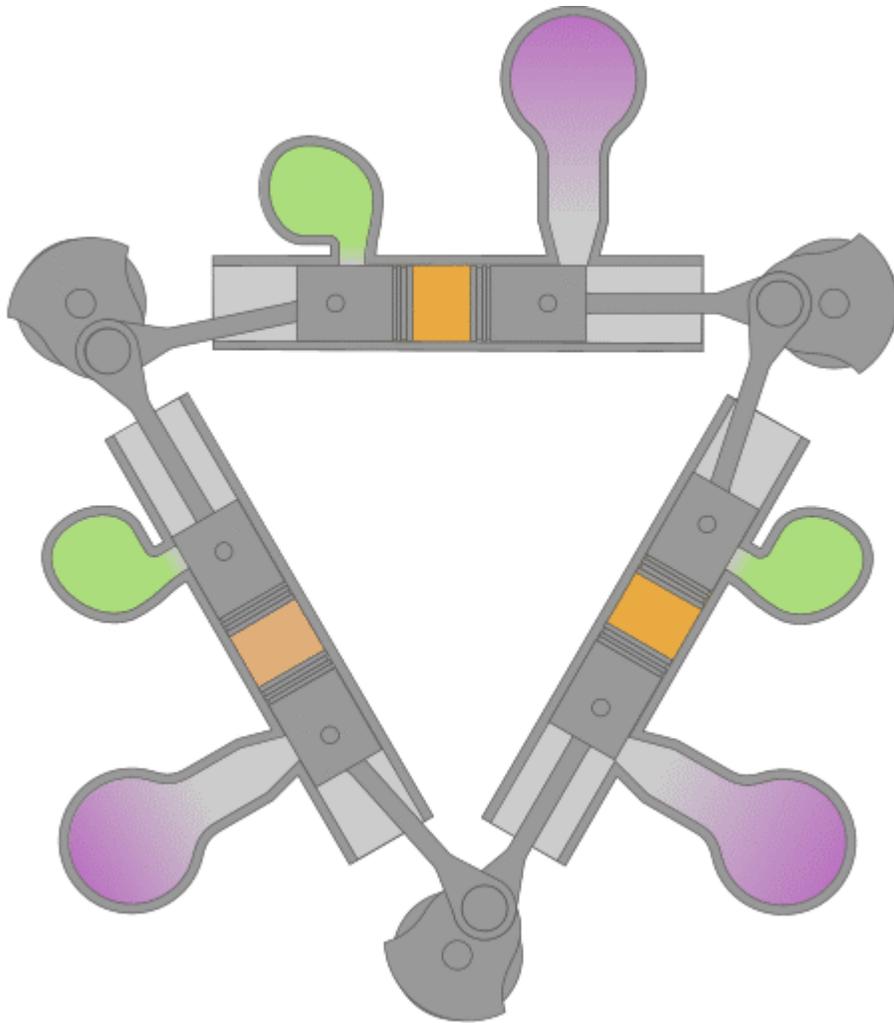
Diagram of Deltic engine layout
Note: The bottom left input and output ports are shown incorrectly as reversed

The Admiralty required a much more powerful engine, and knew about Junkers' designs for multi-crankshaft engines of triangular- and diamond-form. The Admiralty felt these would be a reasonable starting point for the larger design it required. The result was a triangle, the cylinder banks forming the sides, and tipped by three crankshafts, one at each apex. The crankshafts were connected with phasing gears to drive one output shaft. In this arrangement, there were six banks of pistons driving three crankshafts, the same as three separate V-engines of the same overall size. Various models of Deltic engine could be produced with varying numbers of cylinders, though nine and eighteen cylinders were the most common, having three and six cylinders per bank respectively. In 1946, the Admiralty placed a contract with the English Electric Company, parent of Napier, to develop this engine.

One feature of the engine was the way the crankshaft-phasing was arranged to allow for exhaust port lead and inlet port lag. These engines are called 'uniflow' designs because

the flow of gas into and out of the cylinder is one way, assisted by mild supercharging to improve cylinder exhaust scavenging. The inlet/outlet port order is In/Out/In/Out/In/Out going around the triangular ring (i.e. the inlet and outlet manifold arrangements have C_3 rotational symmetry).

Earlier attempts at designing such an engine failed because of the difficulty in arranging the pistons to move in the correct manner, for all three cylinders in one delta, and this was the problem which caused Junkers Motorenbau to leave behind work on the delta-form while continuing to prototype of a diamond-form four-crankshaft 24-cylinder Junkers Jumo 223. Mr. N. Penwarden of the Admiralty Engineering Laboratory solved this problem by suggesting that one crankshaft needed to revolve anti-clockwise to achieve the correct piston-phasing, so Napier designers produced the necessary gearing in order that one of them rotated in the opposite direction to the other two.

In an opposed-piston design with no inlet or exhaust valves, and no ability to vary the port positions, the Deltic design arranged each crankshaft to connect two adjacent pistons operating in different cylinders in the same plane, using "fork and blade" connecting rods, the latter an 'inlet' piston used to open and close the inlet port, and the former an 'exhaust' piston in the adjacent cylinder to open and close the exhaust port.

Crankshaft connecting-rod journals were arranged so that each cylinder's exhaust piston 'led' its inlet piston by 20 degrees of crankshaft rotation. This allowed the exhaust port to be opened well before the inlet port, and allowed the inlet port to be closed after the exhaust port, which led to both good scavenging of exhaust gas, and good volumetric efficiency for the fresh air charge. It also led to Deltics' even, buzzing exhaust note, with a charge ignition every 20 degrees of crankshaft revolution, and a lack of torsional vibration, ideal for use in mine-hunting vessels.

Although the engine was cylinder-ported and required no poppet valves, it did still have camshafts, with each bank having a separate camshaft, driven at crankshaft speed. This was used solely to drive the fuel injection pumps, each cylinder having its own injector and pump, driven by its own cam lobe.

Uses

Naval service

The Deltic-powered Hunt class Mine Countermeasures Vessel HMS *Ledbury*

Development began in 1947 and the first Deltic unit was produced in 1950. By January 1952 six engines were available, enough for full development and endurance trials. S212, a captured ex-German E-Boat powered by three Mercedes-Benz diesel engines, was selected for these trials, since its power units were of approximately equal power to the new 18-cylinder Deltic engines. Two of the three Mercedes-Benz engines were replaced with Napier Deltics, the compactness of the Deltic being graphically illustrated: they were half the size of the original engines. The Deltic weighed one fifth of its contemporaries of equivalent power.

Proving successful, Deltic diesel engines became a common powerplant in small and fast naval craft. The Royal Navy used them first in the Dark class fast attack craft. Subsequently they were used in a number of other smaller attack craft. The low magnetic signature lent itself to use in mine countermeasures vessels and the Deltic was selected to power the Ton class minesweeper. The Deltic engine is still in service in the Hunt class. These versions are de-rated to reduce engine stress.

Deltic diesels served in MTBs and PT Boats built for other navies. Particularly notable was the Norwegian *Tjeld* or *Nasty* class, which was also sold to Germany, Greece, and the United States Navy. *Nasty* class boats served in the Vietnam War, largely for covert operations.

Smaller nine-cylinder *Deltic 9* engines were used as marine engines, notably by minesweepers. The Ton class vessels were powered by a pair of Deltic 18s and used an additional Deltic 9 for power generation for their magnetic influence sweep. The Hunt class used three Deltic 9s, two for propulsion and again one for power generation, but this time with a hydraulic pump integrated as well to power bow-thrusters for slow-speed manœuvring.

Railway use

Napier Deltic powered British Rail Class 55 *Alycidon*, at the National Railway Museum, York, UK

The 'Deltic' engines were used in two types of British rail locomotive: classes 55 and 23, built in the 1960s—both earned the *nom-de-plume* or nickname from the type of engines—"Deltics" and "Baby Deltics" respectively.

The Class 55 used two deltic engines: mechanically-blown 18-cylinder engines, the Class 23 used a single less powerful nine-cylinder turbocharged T9-29 Deltic of 1,100 hp (820 kW).

Reliability in service

While the Deltic engine was successful and very powerful for its size and weight, it was a highly-strung unit, requiring careful maintenance. This led to a policy of unit replacement rather than repair in situ. Deltic engines were easily removed after breakdown, generally being sent back to the manufacturer for repair, although after initial contracts expired both the Royal Navy and British Railways set up their own workshops for overhauls.

Turbo-compound Deltic

The *E.185* or *Compound Deltic* turbo-compound variant was planned and a single protoype was built in 1956 and tested in 1957. This capitalised on Napier's experience with both the *Nomad* and their increasing involvement with gas turbines. It used the Deltic as the gas generator inside a gas turbine, with both a twelve-stage axial compressor and a three stage gas turbine. Unlike the Nomad, this turbine was not mechanically coupled to the crankshaft but merely drove the compressor. It was hoped to produce 6,000 horsepower, with fuel economy and power-to-weight ratio "second to none". Predictions by the engineers closely connected with it were that connecting rod failure would be the limit on this power, failing at around 5,300 bhp. On test it actually produced 5,600 bhp, before throwing a connecting rod through the crankcase just as predicted. Naval interest had waned by 1958 in favour of the pure gas turbine, despite its heavier fuel consumption, and no further development was carried out.

Chapter 14

Crank (Mechanism)
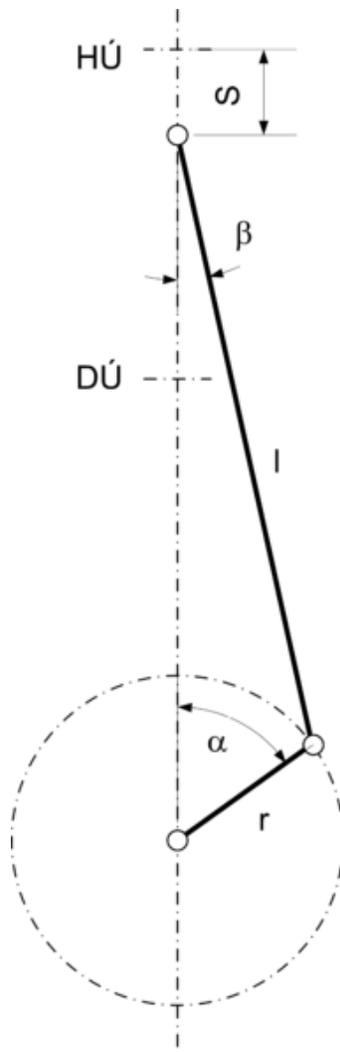
A **crank** is an arm attached at right angles to a rotating shaft by which reciprocating motion is imparted to or received from the shaft. It is used to change circular into

reciprocating motion, or reciprocating into circular motion. The arm may be a bent portion of the shaft, or a separate arm attached to it. Attached to the end of the crank by a pivot is a rod, usually called a connecting rod. The end of the rod attached to the crank moves in a circular motion, while the other end is usually constrained to move in a linear sliding motion, in and out.

The term often refers to a human-powered crank which is used to manually turn an axle, as in a bicycle crankset or a brace and bit drill. In this case a person's arm or leg serves as the connecting rod, applying reciprocating force to the crank. Often there is a bar perpendicular to the other end of the arm, often with a freely rotatable handle on it to hold in the hand, or in the case of operation by a foot (usually with a second arm for the other foot), with a freely rotatable pedal.

Examples
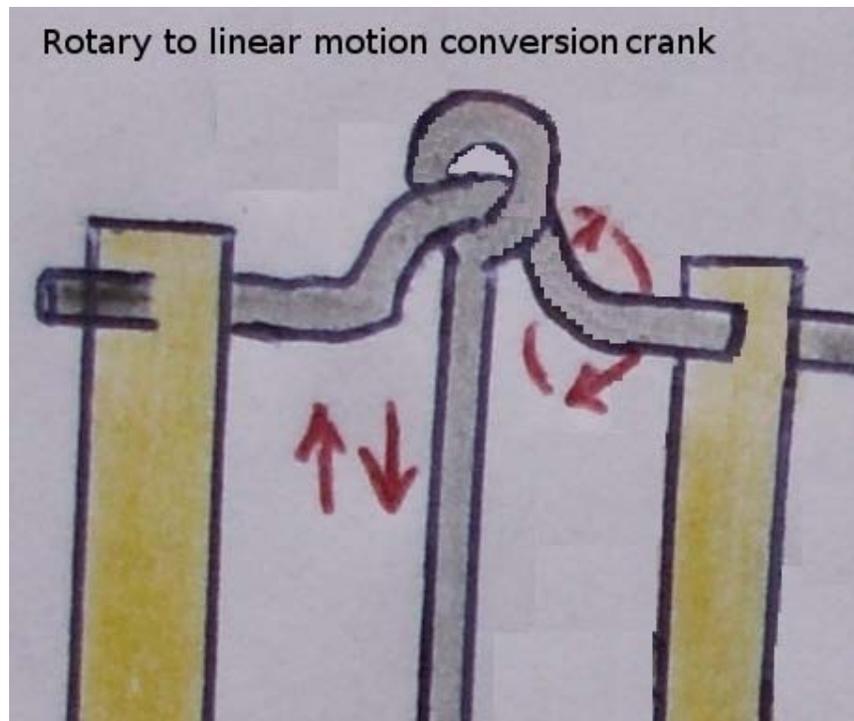
Rotary to linear motion conversion crank

A crank

Hand crank on a pencil sharpener

Familiar examples include:

Hand-powered cranks

- Mechanical pencil sharpener
- Fishing reel and other reels for cables, wires, ropes, etc.
- Manually operated car window
- The crank set that drives a trikke through its handles.

Foot-powered cranks

- The crankset that drives a bicycle via the pedals.
- Treadle sewing machine

Engines

Almost all reciprocating engines use cranks to transform the back-and-forth motion of the pistons into rotary motion. The cranks are incorporated into a crankshaft.

Mechanics

The displacement of the end of the connecting rod is approximately proportional to the cosine of the angle of rotation of the crank, when it is measured from top dead center (TDC). So the reciprocating motion created by a steadily rotating crank and connecting rod is approximately simple harmonic motion:

$$x = l + r \cos \alpha$$

where x is the distance of the end of the connecting rod from the crank axle, l is the length of the connecting rod, r is the length of the crank, and α is the angle of the crank measured from top dead center (TDC). Technically, the reciprocating motion of the connecting rod departs slightly from sinusoidal motion due to the changing angle of the connecting rod during the cycle.

The mechanical advantage of a crank, the ratio between the force on the connecting rod and the torque on the shaft, varies throughout the crank's cycle. The relationship between the two is approximately:

$$\tau = Fr \sin \alpha$$

where τ is the torque and F is the force on the connecting rod. For a given force on the crank, the torque is maximum at crank angles of $\alpha = 90°$ or $270°$ from TDC. When the crank is driven by the connecting rod, a problem arises when the crank is at top dead centre ($0°$) or bottom dead centre ($180°$). At these points in the crank's cycle, a force on the connecting rod causes no torque on the crank. Therefore if the crank is stationary and happens to be at one of these two points, it cannot be started moving by the connecting

rod. For this reason, in steam locomotives, whose wheels are driven by cranks, the two connecting rods are attached to the wheels at points 90° apart, so that regardless of the position of the wheels when the engine starts, at least one connecting rod will be able to exert torque to start the train.
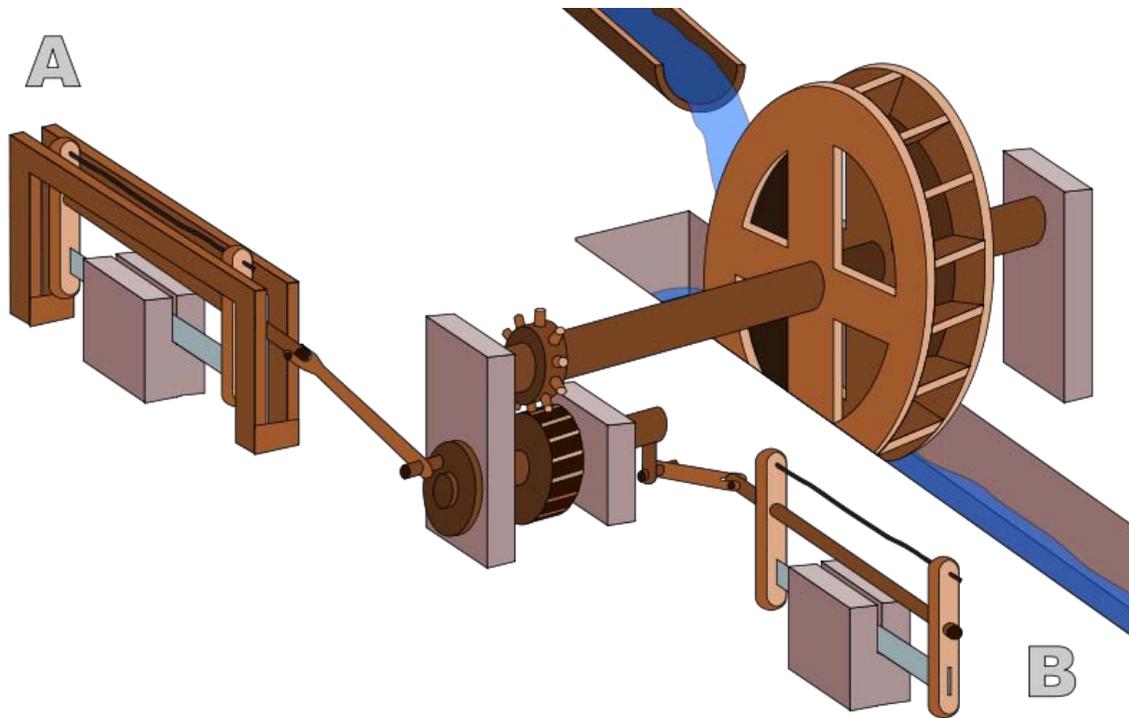
History

Western World

Classical Antiquity

Roman crank handle from Augusta Raurica, from before 250 AD

The eccentrically mounted handle of the rotary handmill which appeared in 5th century BC Celtiberian Spain and ultimately spread across the Roman Empire constitutes a crank. A ca. 40 cm long true iron crank was excavated, along with a pair of shattered mill-stones of 50−65 cm diameter and diverse iron items, in Aschheim, close to Munich. The crank-operated Roman mill is dated to the late 2nd century AD.

A Roman iron crank handle was excavated in Augusta Raurica, Switzerland. The 82.5 cm long piece with a 15 cm long handle is of yet unknown purpose and dates to no later than ca. 250 AD. An often cited modern reconstruction of a bucket-chain pump driven by hand-cranked flywheels from the Nemi ships has been dismissed though as "archaeological fantasy".

Roman Hierapolis sawmill from the 3rd century AD, the earliest known machine to combine a crank with a connecting rod.

The earliest evidence for the crank as part of a machine, that is in combination with a connecting rod, anywhere in the world appears in the late Roman Hierapolis sawmill from the 3rd century AD and two Roman stone sawmills at Gerasa, Roman Syria, and Ephesus, Asia Minor (both 6th century AD). On the pediment of the Hierapolis mill, a waterwheel fed by a mill race is shown powering via a gear train two frame saws which cut rectangular blocks by the way of some kind of connecting rods and, through mechanical necessity, cranks. The accompanying inscription is in Greek.

The crank and connecting rod mechanisms of the other two archaeologically attested sawmills worked without a gear train. In ancient literature, we find a reference to the workings of water-powered marble saws close to Trier, now Germany, by the late 4th century poet Ausonius; about the same time, these mill types seem also to be indicated by the Christian saint Gregory of Nyssa from Anatolia, demonstrating a diversified use of water-power in many parts of the Roman Empire The three finds push back the date of the invention of the crank and connecting rod back by a full millennium; for the first time, all essential components of the much later steam engine were assembled by one technological culture:

With the crank and connecting rod system, all elements for constructing a steam engine (invented in 1712) — Hero's aeolipile (generating steam power), the cylinder and piston (in metal force pumps), non-return valves (in water pumps), gearing (in water mills and clocks) — were known in Roman times.

Middle Ages

Vigevano's war carriage

A rotary grindstone − the earliest representation thereof − which is operated by a crank handle is shown in the Carolingian manuscript *Utrecht Psalter*; the pen drawing of around 830 goes back to a late antique original. A musical tract ascribed to the abbot Odo of Cluny (ca. 878−942) describes a fretted stringed instrument which was sounded by a resined wheel turned with a crank; the device later appears in two 12th century illuminated manuscripts. There are also two pictures of Fortuna cranking her wheel of destiny from this and the following century.

The use of crank handles in trepanation drills was depicted in the 1887 edition of the *Dictionnaire des Antiquités Grecques et Romaines* to the credit of the Spanish Muslim surgeon Abu al-Qasim al-Zahrawi; however, the existence of such a device cannot be confirmed by the original illuminations and thus has to be discounted. The Benedictine monk Theophilus Presbyter (c. 1070−1125) described crank handles "used in the turning of casting cores".

The Italian physician Guido da Vigevano (c. 1280−1349), planning for a new crusade, made illustrations for a paddle boat and war carriages that were propelled by manually turned compound cranks and gear wheels (center of image). The *Luttrell Psalter*, dating to around 1340, describes a grindstone which was rotated by two cranks, one at each end of its axle; the geared hand-mill, operated either with one or two cranks, appeared later in the 15th century;

Medieval cranes were occasionally powered by cranks, although more often by windlasses.

Renaissance
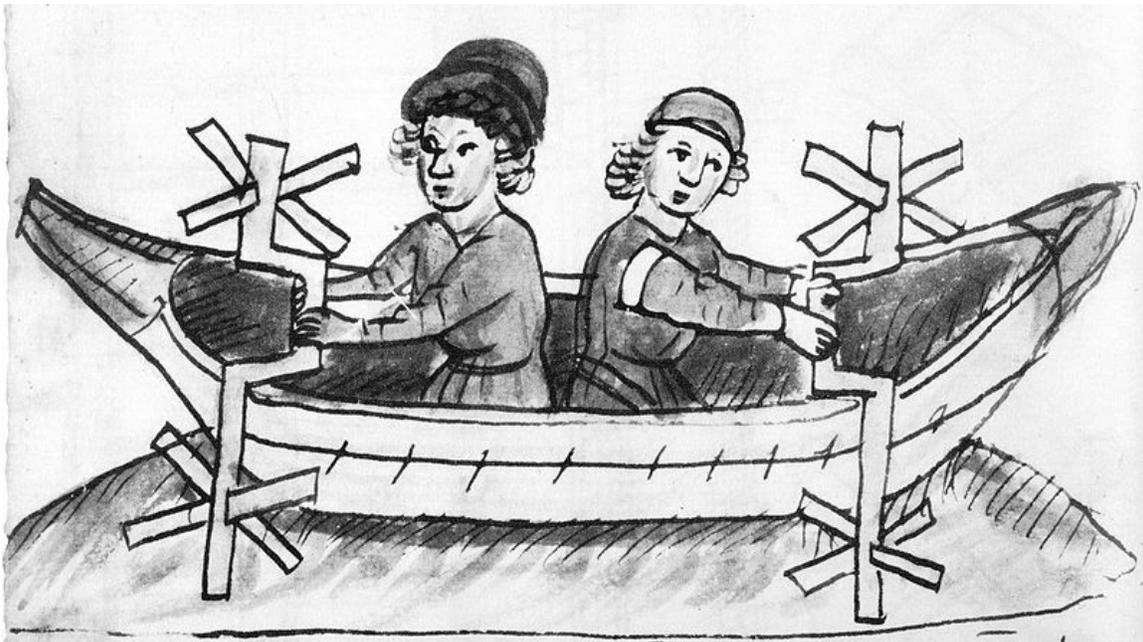
15th century paddle-wheel boat whose paddles are turned by single-throw crankshafts (Anonymous of the Hussite Wars)

The crank became common in Europe by the early 15th century, often seen in the works of those such as the German military engineer Konrad Kyeser. Devices depicted in Kyeser's *Bellifortis* include cranked windlasses (instead of spoke-wheels) for spanning siege crossbows, cranked chain of buckets for water-lifting and cranks fitted to a wheel of bells. Kyeser also equipped the Archimedes screws for water-raising with a crank handle, an innovation which subsequently replaced the ancient practice of working the pipe by

treading. The earliest evidence for the fitting of a well-hoist with cranks is found in a miniature of c. 1425 in the German *Hausbuch of the Mendel Foundation*.

The first depictions of the compound crank in the carpenter's brace appear between 1420 and 1430 in various northern European artwork. The rapid adoption of the compound crank can be traced in the works of the Anonymous of the Hussite Wars, an unknown German engineer writing on the state of the military technology of his day: first, the connecting-rod, applied to cranks, reappeared, second, double compound cranks also began to be equipped with connecting-rods and third, the flywheel was employed for these cranks to get them over the 'dead-spot'.

One of the drawings of the Anonymous of the Hussite Wars shows a boat with a pair of paddle-wheels at each end turned by men operating compound cranks. The concept was much improved by the Italian Roberto Valturio in 1463, who devised a boat with five sets, where the parallel cranks are all joined to a single power source by one connecting-rod, an idea also taken up by his compatriot Francesco di Giorgio.

Water-raising pump powered by crank and connecting rod mechanism (Georg Andreas Böckler, 1661)

In Renaissance Italy, the earliest evidence of a compound crank and connecting-rod is found in the sketch books of Taccola, but the device is still mechanically misunderstood. A sound grasp of the crank motion involved demonstrates a little later Pisanello who painted a piston-pump driven by a water-wheel and operated by two simple cranks and two connecting-rods.

The 15th century also saw the introduction of cranked rack-and-pinion devices, called cranequins, which were fitted to the crossbow's stock as a means of exerting even more force while spanning the missile weapon. In the textile industry, cranked reels for winding skeins of yarn were introduced.

Around 1480, the early medieval rotary grindstone was improved with a treadle and crank mechanism. Cranks mounted on push-carts first appear in a German engraving of 1589.

From the 16th century onwards, evidence of cranks and connecting rods integrated into machine design becomes abundant in the technological treatises of the period: Agostino Ramelli's *The Diverse and Artifactitious Machines* of 1588 alone depicts eighteen examples, a number which rises in the *Theatrum Machinarum Novum* by Georg Andreas Böckler to 45 different machines, one third of the total.

Far East

Tibetan operating a quern (1938). The perpendicular handle of such rotary handmills works as a crank.

The earliest true crank handle in Han China occurs, as Han era glazed-earthenware tomb models portray, in a agricultural winnowing fan, dated no later than 200 AD. The crank was used thereafter in China for silk-reeling and hemp-spinning, in the water-powered flour-sifter, for hydraulic-powered metallurgic bellows, and in the well windlass. However, the potential of the crank of converting circular motion into reciprocal one never seems to have been fully realized in China, and the crank was typically absent from such machines until the turn of the 20th century.

Middle East

While the US-American historian of technology Lynn White could not find "firm evidence of even the simplest application of the crank until al-Jazari's book of A.D. 1206", the crank appears according to Beeston in the mid-9th century in several of the hydraulic devices described by the Banū Mūsā brothers in their *Book of Ingenious Devices*. These devices, however, made only partial rotations and could not transmit much power, although only a small modification would have been required to convert it to a crankshaft.

Al-Jazari (1136–1206) described a crank and connecting rod system in a rotating machine in two of his water-raising machines. His twin-cylinder pump incorporated a crankshaft, but the device was unnecessarily complex indicating that he still did not fully understand the concept of power conversion. Another other machine of al-Jazari incorporated the first known crank-slider mechanism.

After al-Jazari, according to White, cranks in Islamic technology are not traceable until an early 15th century copy of the *Mechanics* of the ancient Greek engineer Hero of Alexandria.

Cranks were formerly common on some machines in the early 20th century; for example almost all phonographs before the 1930s were powered by clockwork motors wound with cranks, and internal combustion engines of automobiles were usually started with cranks (known as *starting handles* in the UK), before electric starters came into general use.

Chapter 15

Flat Engine
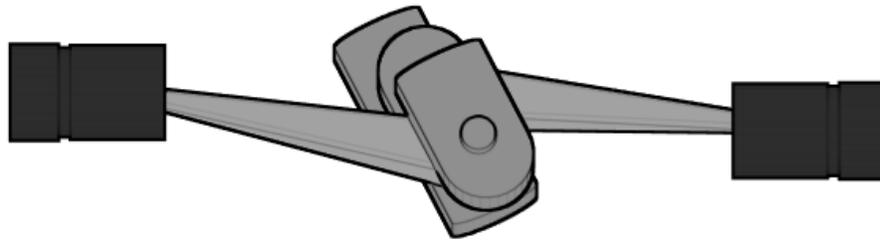
The boxer engine was first patented by German engineer Karl Benz.

A **flat engine** is an internal combustion engine with multiple pistons that move in a horizontal plane. Typically, the layout has cylinders arranged in two banks on either side of a single crankshaft and is generally known as the **boxer**, or horizontally-opposed engine—not to be confused with opposed-piston engines, which are mechanically different. This is the concept patented in 1896 by engineer Karl Benz, eight years after he started producing the world's first successful automobiles.

Another widely used form of flat engine consists of a straight engine with two, three, four or more cylinders canted 90 degrees into the horizontal plane, however this is not generally considered significantly different from other straight engines.

Configuration

1954 BMW "Boxer" motorcycle engine. The two cylinders cannot be directly opposite each other.
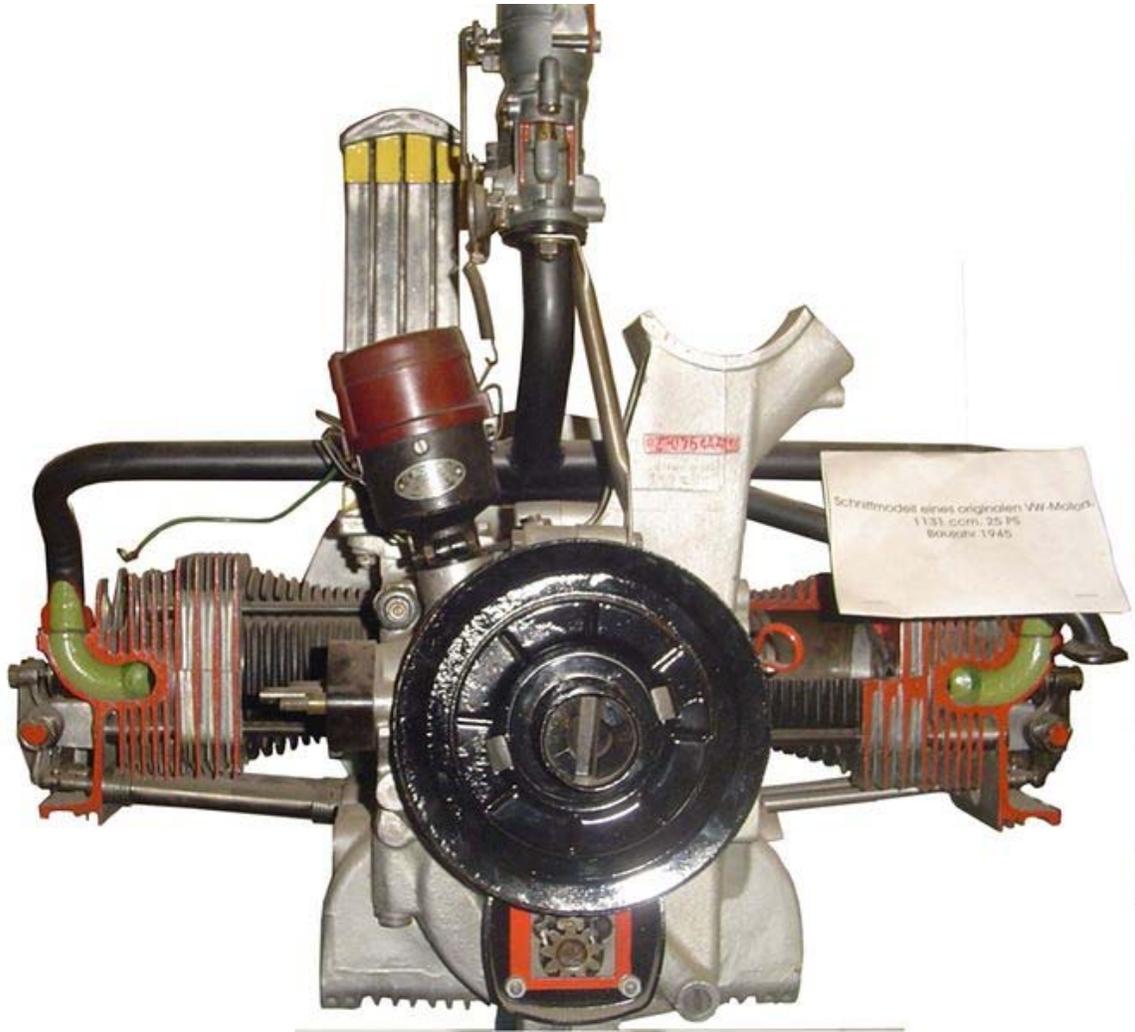
The Flat-4 Volkswagen air cooled engine
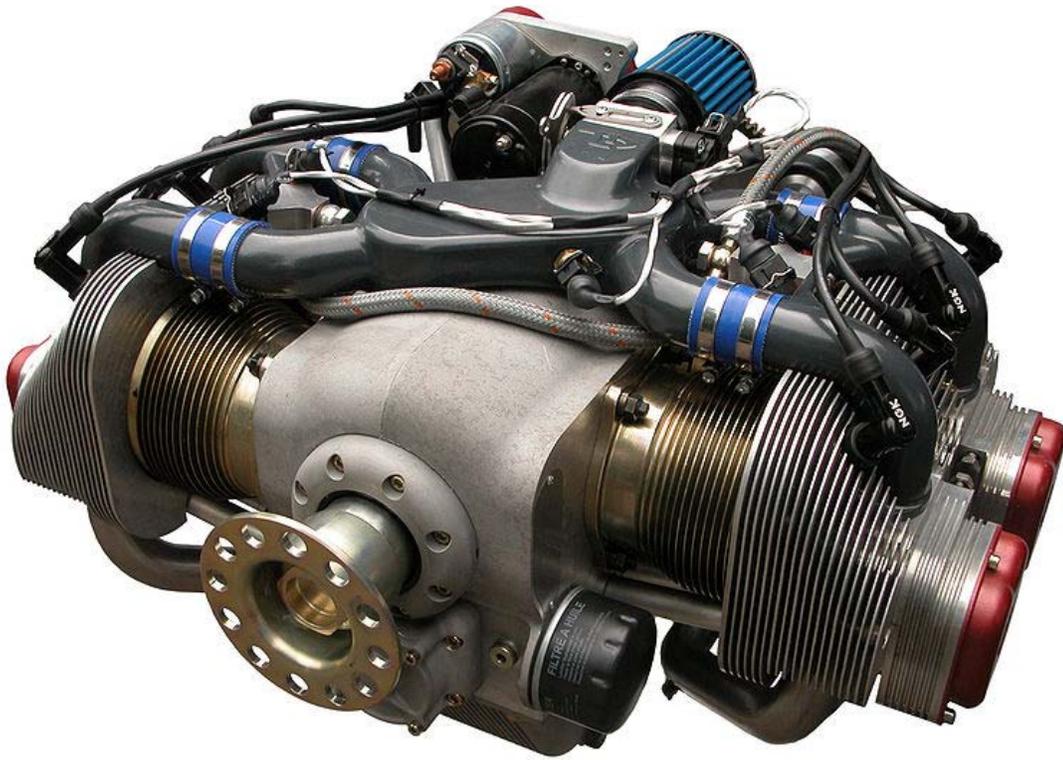
UL260i Flat-4 aircraft engine

Flat engines offer a low centre of gravity and thereby may offer a drive configuration with better stability and control. They are also wider than other engines configurations, presenting complications with the fitment of the engine within the engine bay of a front-engined car. With motorcycles, the flat engine's width may restrict cornering. Flat engines lend themselves well to aircraft engines.

Front-mounted air-cooled flat-twin engines were used in Tatra 11 and Tatra 30, by Citroën in their model 2CV and its derivatives, while the GS and GSA. Oltcit used a flat-four and a flat-six was proposed for the Citroën DS but rejected. BMW Motorrad used an air-cooled flat-twin in almost all of its motorcycles from 1921 until 1980 and still depends heavily on this layout, using it in many models to the present day. Cars such as the Porsche 911 use a flat-engine (in that particular case a six-cylinder) at the rear of the car, where its extra width does not interfere with the steering of the front wheels and there is a weight-saving since no prop-shaft is required.

All versions of the Subaru Impreza, Forester, Tribeca, Legacy, Outback and SVX use either a flat-4 or flat-6 engine.

True boxers have each crankpin controlling only one piston/cylinder while 180° engines, which superficially appear very similar, share crankpins.

- The boxer engine (the true horizontally opposed engine) has corresponding pistons reaching top dead centre (TDC) simultaneously.

- The 180° V engine has corresponding pistons sharing a crankpin on the crankshaft and reaching TDC half a crankshaft revolution apart. They may use regular connecting rods side by side, or use a master/slave system, or a fork-and-blade system. Flat engines with more than eight cylinders are most commonly V engines.

Boxer engines must not be confused with opposed-piston engines, which are essentially the inverse, with two pistons compressing a single combustion space. These can be used in vehicles such as tanks.

Boxer engines

1969 Hino Motors DS140 12 cylinder boxer diesel engine

Boxer engines got their name because each pair of pistons moves simultaneously in and out rather than alternately, like boxers showing they are ready by clashing their gloved fists against each other before a fight. Boxer engines of up to eight cylinders have proved highly successful in automobiles and up to six cylinders in motorcycles and continue to be popular for light aircraft engines.

Boxers are one of only three cylinder layouts that have a natural dynamic balance; the others being the straight-6 and the V12. These engines can run very smoothly and free of

unbalanced forces with a four-stroke cycle and do not require a balance shaft or counterweights on the crankshaft to balance the weight of the reciprocating parts, which are required in other engine configurations. Note that this is generally true of boxer engines regardless of the number of cylinders (assumed to be even), but not true for all V or inline engines. However, in the case of boxer engines with fewer than six cylinders, unbalanced moments (a reciprocating torque also known as a "rocking couple") are unavoidable due to the "opposite" cylinders being slightly out of line with each other.

Boxer engines (and flat engines in general) tend to be noisier than other common engines for both intrinsic and other reasons, e.g., in cars, valve clatter from under the hood is not damped by large air filters and other components. Boxers need no balance weights on the crankshaft, which should be lighter and fast-accelerating - but, in practice (e.g. in cars), they need a flywheel to run smoothly at low speeds and this negates the advantage. They have a characteristic smoothness throughout the rev range and offer a low centre of gravity. When combined with a mounting position immediately ahead of the rear axle (e.g. Porsche Boxster and Cayman but not Porsche 911 nor Volkswagen Beetle), they have largely neutral handling.

Notable flat engines

Subaru Boxer Turbodiesel engine cutaway display

- In 1896, Karl Benz invented the first internal combustion engine with horizontally opposed pistons.
- In 1923 Max Friz designed the first BMW motorcycles, choosing a 500 cc boxer engine and unit transmission with shaft drive. This engine type is still in production today. The BMW 247 engine, known as an airhead due to its air cooling, was produced until 1995. BMW replaced it with the oilhead engine with partial oil cooling and four valves per cylinder, but still retaining the same boxer twin configuration.

- In 1948 Preston Tucker modified a helicopter flat-6 to be rear mounted in his Tucker Torpedo
- The Volkswagen air-cooled flat-4 engine used in the Volkswagen Beetle, SP2 and Karmann Ghia, and later developed further for the Volkswagen Type 2 (Bus) transporters and Volkswagen Type 3 cars. VW was rumoured to have worked on a Diesel version of the aircooled boxer but abandoned this engine due to noise and heat issues. The latest version of the VW boxer was watercooled and thus dubbed the 'Wasserboxer' or waterboxer by enthusiasts. This engine included many developments of the earlier engines. It was offered in capacities of 1.9 and 2.1 litres was used to power T3 buses and transporters.
- The Citroën 2CV and Panhard air-cooled flat-2 engines, both influenced by the flat-2s of BMW
- The air-cooled Chevrolet Corvair OHV flat-6
- In 1960 Lancia's flat-4 water-cooled engine debuted for the Lancia Flavia model, first Italian front-wheel drive car, like 1500 cc 90 PS (66 kW) coupé version and during the years become a 2000 cc with 142 bhp (106 kW) when was mounted the first electronic Injection by Bosch in 1970 in a flat four engine, Lancia also rebuild a new big flat-4 engine in 1976, 2484 cc, for his upper size model Lancia Gamma. It was produced until 1984 and was Lancia's last flat-4 engine.
- The flat-4 engines in Alfa Romeo's Alfasud, Sprint, 33 and early versions of the 145. The last of the line was a 1712 cc flat-4, 16 valves, producing up to 137 PS (101 kW).
- The water-cooled front-mounted flat-4 and flat-6 engines used by Subaru in all of its mid-sized cars. Subaru refers to these as boxer engines in publicity commentary, and include a variety of naturally aspirated and turbo driven engines from 1966, when the Subaru 1000 was introduced to current; both closed and semi-closed short blocks have been used. A print add for the 1973 Subaru GL coupe referred to the engine as "quadrozontal" The EJ series of 4 cylinder engines released first in 1990 has been the focus for the development of the Boxer engine in the late 20th century. Ranging from 1.6-2.5 litres, this engine in its 2 litre turbo arrangement has been the power behind World Rally Championship winning cars. Subaru also offers a boxer turbodiesel, called the Subaru EE series, the world's first to be fitted into a passenger car.
- Since its introduction in 1975, the Honda Goldwing has utilized a boxer engine, a 4-cylinder until 1987, and 6-cylinders since. The water-cooled SOHC 1832 cc flat-6 is fitted to the Honda Goldwing from 2001 on.
- The air-cooled flat-4, flat-6 and flat-8 engines were used for many years in early Porsches. The flat-12 in the 917 model is a 180° V-engine and not a boxer.
- The water-cooled flat-6 engines in the Porsche Boxster, Cayman and later 911 models
- General aviation aircraft often use air-cooled flat-4 and flat-6 engines made by companies such as Lycoming, Continental. Ultralight and microlight aircraft often use engines such as the Rotax 912 or Jabiru 2200.
- Ferrari made use of a flat-12 design in several models, including the Berlinetta Boxer, the Testarossa and its derivatives, such as the 512TR and the F512 M,

although this engine design is technically a V12 that has been flattened down to a 180° configuration, and therefore cannot be regarded as a true boxer engine.
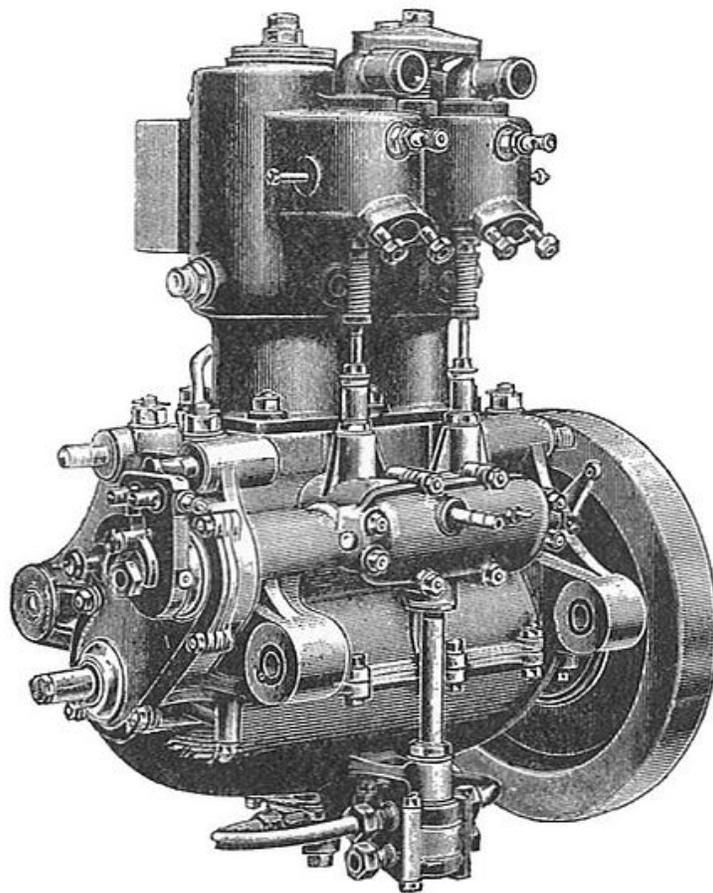
Flat engine designs

- Flat-twin
- Flat-4
- Flat-6
- Flat-8
- Flat-10
- Flat-12
- Flat-16
- H engine
- Controlled Combustion Engine

Other engine designs

- X engine
- V engine
- W engine
- Straight engine
- Rotary engine

Chapter 16

Monobloc Engine

De Dion-Bouton engine with monobloc cylinder heads, c. 1905

A *monobloc* or *en bloc* **engine** is an internal-combustion piston engine where some of the major components: cylinder head, cylinder block, or crankcase are formed, usually by

casting, as a single integral unit, rather than being assembled later. This has the advantages of improving mechanical stiffness, and also improving the reliability of the sealing between them.

Monobloc techniques date back to the beginnings of the internal combustion engine. Use of the term has changed over time, usually to address the most pressing mechanical problem affecting the engines of its day. There have thus been three distinct uses of the technique:

- Cylinder head and cylinder
- Cylinder block
- Cylinder block and crankcase

In most cases, any use of the term describes a deliberate single-unit construction, opposed to the more common contemporary practice. Where the monobloc technique has later become the norm, the specific term falls from favour. It is now usual and un-noteworthy practice to use monobloc cylinders and crankcases, but a monobloc head (for a water-cooled inline engine at least) would be regarded as peculiar and obsolescent.

Cylinder head
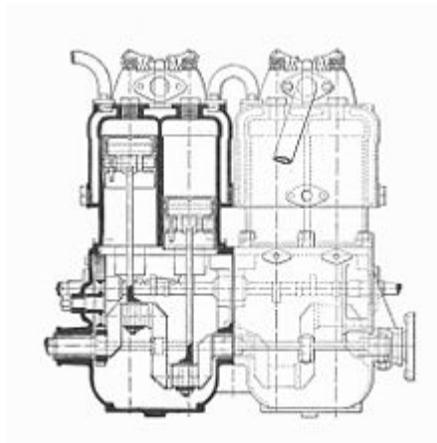
Napier engine, with monobloc head
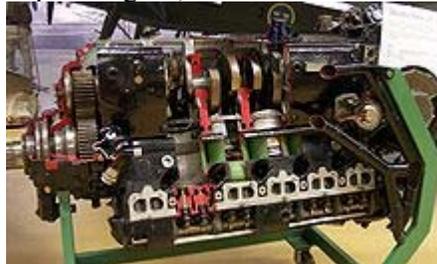
DB 605 inverted aircraft engine of WW2, with monobloc cylinder blocks and heads
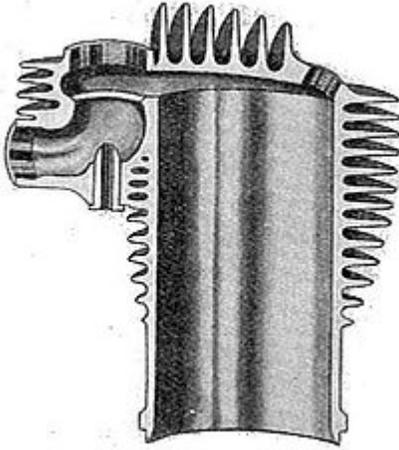
Sectioned view of an air-cooled single cylinder, with monobloc head and access plug above the side valve

The head gasket is the most highly-stressed static seal in an engine and was a source of considerable trouble in early years. The monobloc cylinder head forms both cylinder and head in one unit, thus avoiding the need for a seal.

Along with head gasket failure, one of the least reliable parts of the early petrol engine was the exhaust valve, which tended to fail by overheating and burning. A monobloc head could provide good water cooling, thus reduced valve wear, as it could extend the water jacket uninterrupted around both head and cylinder. Engines with gaskets required a metal-to-metal contact face here, disrupting water flow.

The drawback to the monobloc head is that access to the inside of the combustion chamber (the upper volume of the cylinder) becomes difficult. Access through the cylinder bore is restricted for machining the valve seats, or simply for inserting angled valves. An even more serious restriction is that for the maintenance task of de-coking and re-grinding the valve seats, a regular task on older engines. Rather than removing the cylinder head from above, the mechanic must now remove pistons, connecting rods and the entire crankshaft from beneath.

One solution to this for side-valve engines was to place a screwed plug directly above each valve, and to access the valves through this (illustrated). The tapered threads of the screwed plug provided a reliable seal. For low-powered engines this was a popular solution for some years. It was difficult to cool this plug, as the water jacket didn't extend into the plug. As performance increased, it also became important to have better combustion chamber designs with less "dead space". One solution was to place the spark plug in the centre of this plug, which at least made use of the space. However this also placed the spark plug further away from the main combustion chamber, leading to long flame paths and slower ignition.

During World War 1, development of the internal combustion engine progressed enormously. After the war, as civilian car production recommenced, the monobloc

cylinder head was required less frequently. Only high-performance cars such as the Leyland Eight of 1920 persisted with it. Bentley and Bugatti were other racing marques who notably adhered to them, through the 1920s and into the 1930s.

Aircraft engines at this time were beginning to use high supercharging pressures, increasing the stress on their head gaskets. Engines such as the Rolls-Royce Buzzard used monobloc heads for reliability.

The last engines to make widespread use of monobloc cylinder heads were large air-cooled aircraft radial engines, such as the Wasp Major. These have individual cylinder barrels, so access as a monobloc is less restricted than on inline engine. As they are also of high specific power and require the utmost reliability, the advantages of the monobloc remained attractive.

The difficulties of machining, and maintaining, a monobloc cylinder head were always a severe drawback to it. As head gaskets became able to handle the heat and pressure necessary, the technique went out of use. It is almost unknown today.
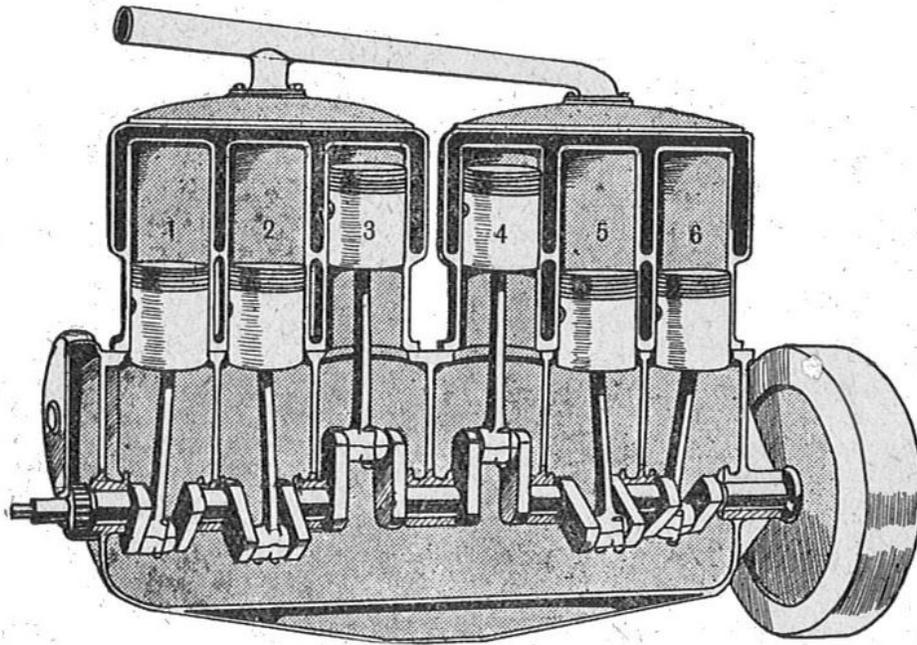
Cylinder block
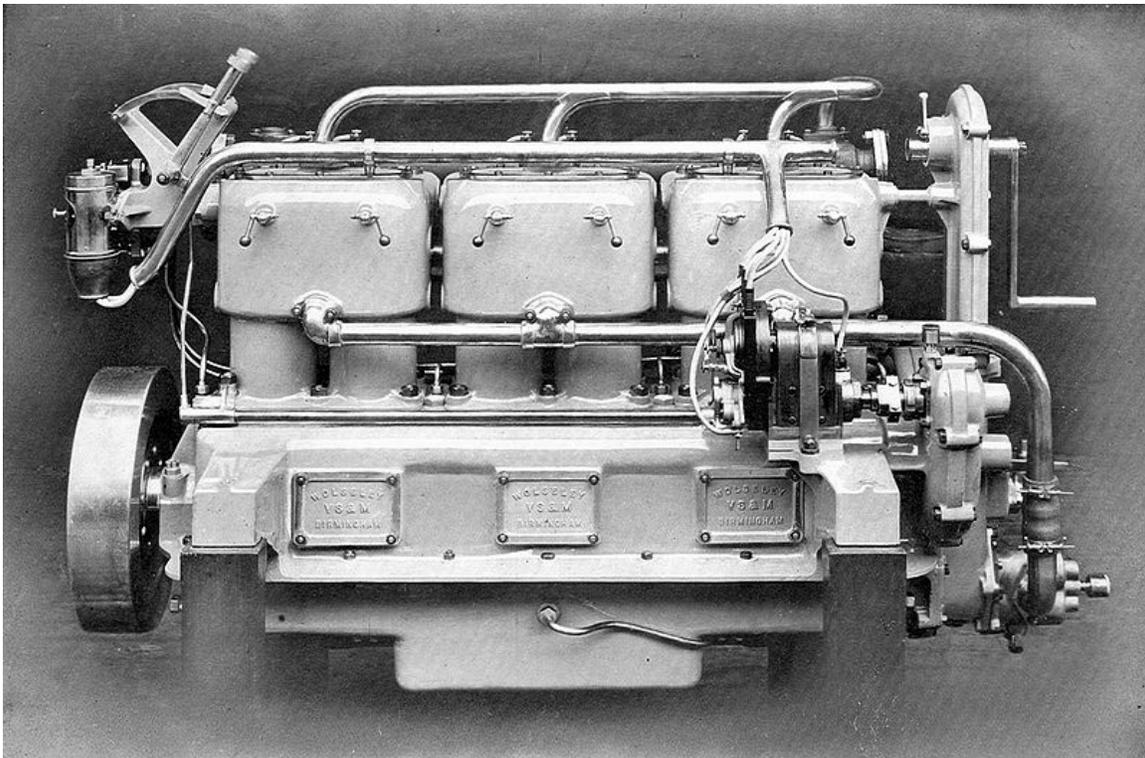
Non-monobloc engine: cylinders are cast in three pairs
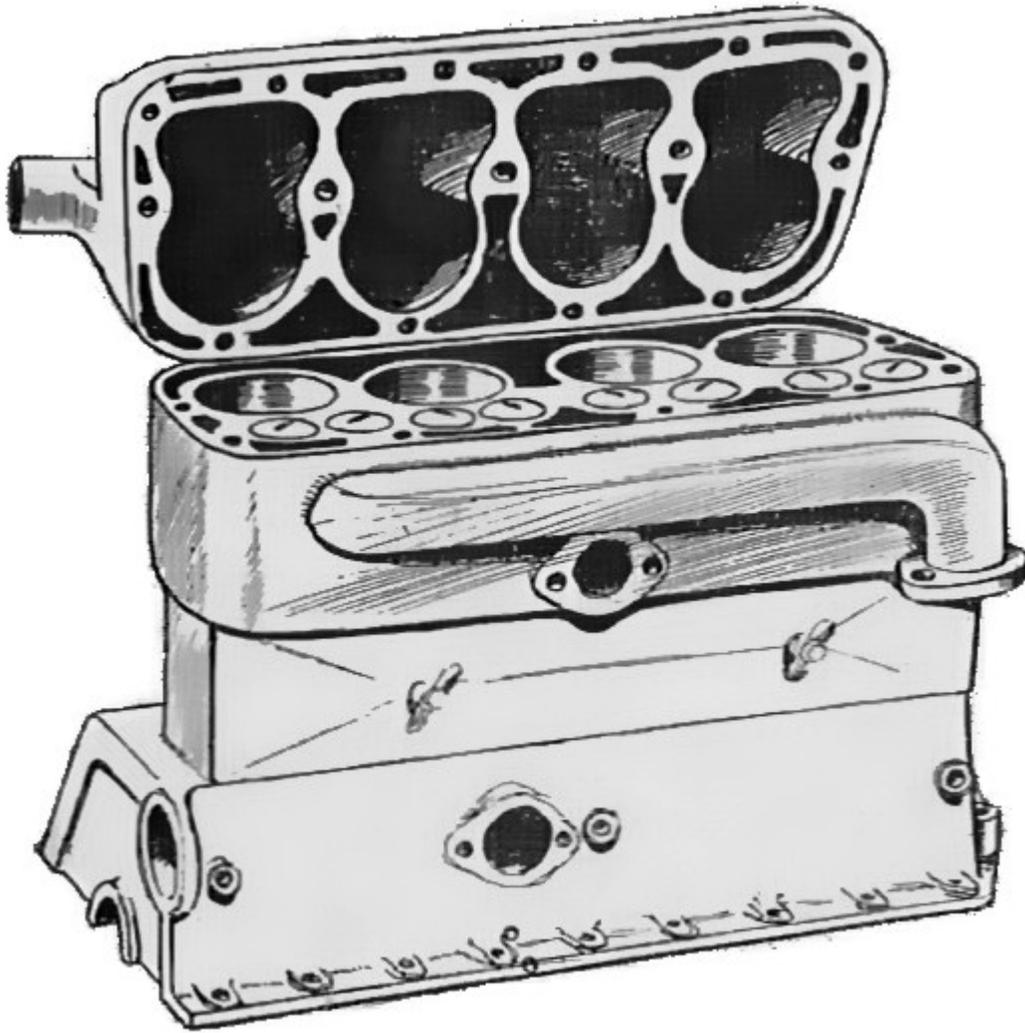
Early monobloc engine: All cylinders are cast together with the crankcase

Non-monobloc engine: cylinders are cast in two blocks of three

Casting technology at the dawn of the internal combustion engine could reliably cast either large castings, or castings with complex internal cores to allow for water jackets, but not both simultaneously. Most early engines, particularly those with more than four cylinders, had their cylinders cast as pairs or triplets of cylinders, then bolted to a single crankcase.

As casting techniques improved, the entire cylinder block of four, six or even eight cylinders could be cast as one. This was a simpler construction, thus cheaper to make, and the communal water jacket permitted closer spacing between cylinders. This also improved the mechanical stiffness of the engine, against bending and the increasingly important torsional twist, as cylinder numbers and engine lengths increased.

V engines remained with a separate block casting for each bank. For economy, some engines were designed to use identical castings for each bank, left and right. The complex ducting required for inlet manifolds between the banks were too complicated to cast otherwise. Some rare engines, such as the Lancia 22½° narrow-angle V12 of 1919, did use a single block casting for both banks.

Modern cylinders, except for air-cooled engines and V engines, are now universally cast as a single cylinder block.

Crankcase
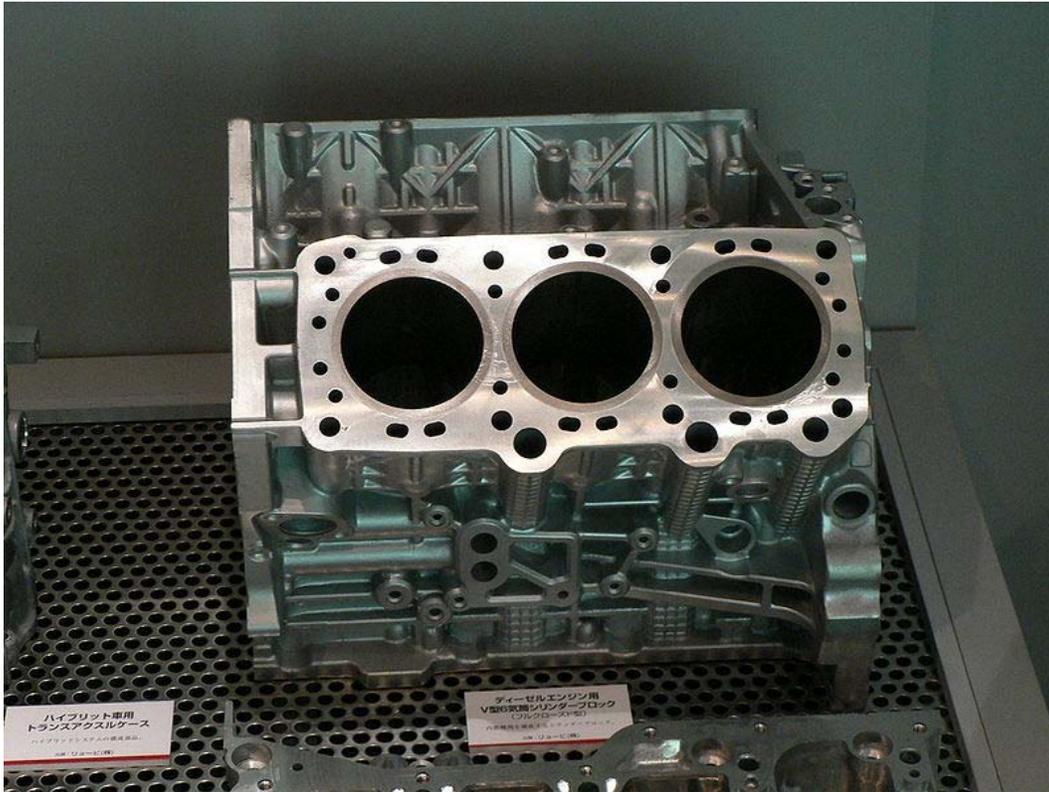
A V6 diesel engine, with both blocks and crankcase formed *en bloc*

As casting improved and cylinder blocks became a monobloc, it also became possible to cast both cylinders and crankcase as one unit. The main reason for this was to improve stiffness of the engine construction, reducing vibration and permitting higher speeds.

Most engines, except some V engines, are now a monobloc of crankcase and cylinder block.

Modern engines - Combined block, head and crankcase

Light-duty consumer-grade Honda GC-family small engines use a monobloc design where the cylinder head, block, and half the crankcase share the same casting, termed 'uniblock' by Honda. One reason for this, apart from cost, is to produce an overall lower engine height. Being an air-cooled OHC design, this is possible thanks to current aluminum casting techniques and lack of complex hollow spaces for liquid cooling. The valves are vertical, so as to permit assembly in this confined space. On the other hand, performing basic repairs becomes so time-consuming that the engine can be considered disposable. Commercial-duty Honda GX-family engines (and their many popular knock-offs) have a more conventional design of a single crankcase and cylinder casting, with a separate cylinder head.

Honda produces many other head-block-crankcase monoblocs under a variety of different names, such as the GXV-series. They may all be externally identified by a gasket which would bisect the crankshaft on an approximately 45° angle.

Exhaust valve failure is common and, owing to the monobloc design, so labour-intensive to repair that the engine is normally discarded.
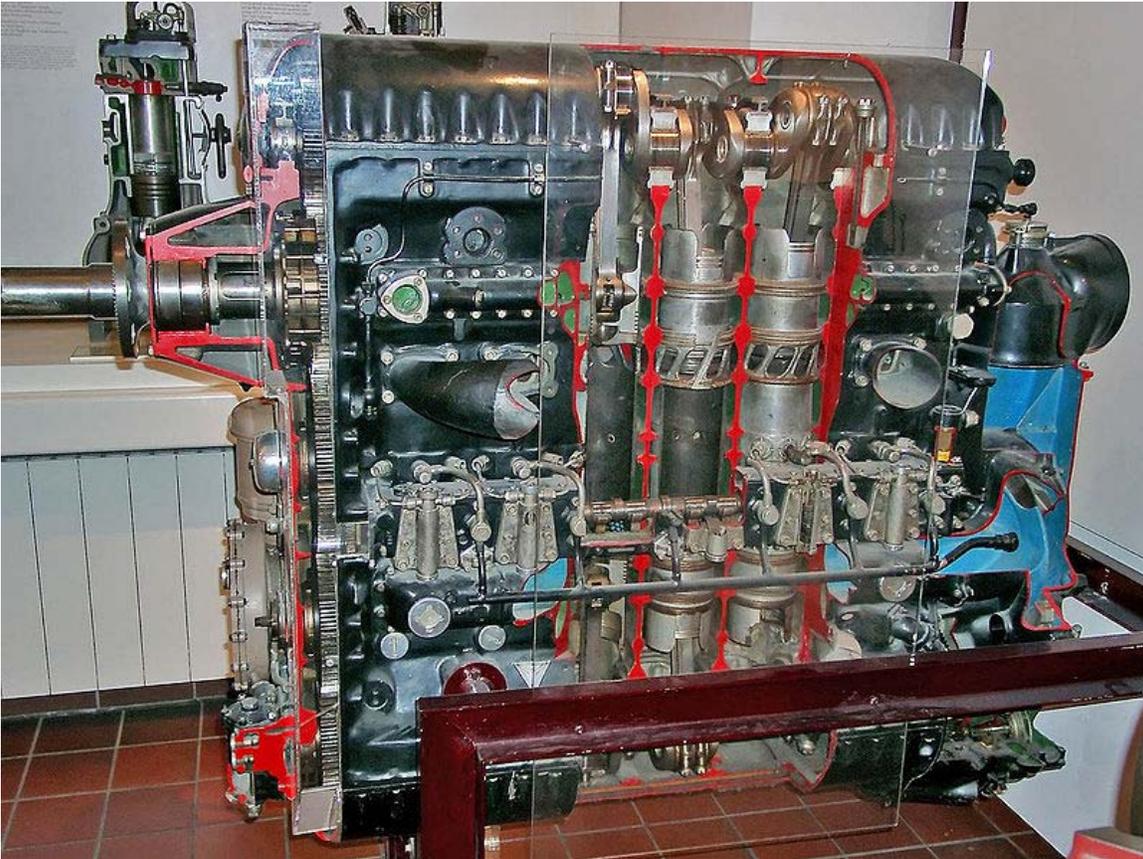
Chapter 17

Opposed-Piston Engine

Fairbanks-Morse opposed-piston diesel engines on the submarine *USS Pampanito*.

An **opposed-piston engine** is one in which the cylinders are double-ended, with a piston at each end and no cylinder head.

Configurations

Junkers Jumo 205 aircraft engine

Some variations of the Opposed Piston or OP designs use a single crankshaft like the Doxford ship engines and the Commer OP truck engines. They should not be confused with flat engines. Though flat engines are sometimes referred to as horizontally opposed, they are very different mechanically.

A more common layout uses two crankshafts, with the crankshafts geared together, or even three geared crankshafts in the Napier Deltic diesel engines. The Deltic uses three crankshafts serving three banks of double-ended cylinders arranged in an equilateral triangle, with the crankshafts at the corners. These were used in railway locomotives and to power fast patrol boats. Both types are now largely obsolete, although the Royal Navy still maintains some Deltic-powered Hunt class mine countermeasure vessels.

The first opposed-piston diesel engines were developed in the beginning of 20th century. In 1907, Raymond Koreyvo, the engineer of Kolomna Works, built an opposed-piston two-stroke diesel with two crankshafts connected by gearing. Although Koreyvo patented his engine in France in November, 1907, the management would not go on to manufacture opposed-piston engines.

An April, 1950 print advertisement for Fairbanks-Morse opposed-piston engines, touting their greater thermodynamic efficiency and lower maintenance cost than standard configurations

The first Junkers engines had one crankshaft, the upper pistons having long connecting rods outside the cylinder. These engines were the forerunner of the Doxford marine engine, and this layout was also used for two- and three-cylinder car engines from around 1900-1922 by Gobron-Brillié. There is currently a resurgence of this design in a boxer configuration as a small diesel aircraft engine, and for other application, called the 'OPOC' engine by Advanced Propulsion Technologies, Inc. of California. Later Junkers engines like the Junkers Jumo 205 diesel aircraft engine, use two crankshafts, one at either end of a single bank of cylinders. There are efforts to reintroduce the opposed-

piston diesel aircraft engine with twin geared crankshafts for General aviation applications, by both Dair and PowerPlant Developments in the UK.

This configuration has also been used for marine auxiliary generators and for larger marine propulsion engines, notably Fairbanks-Morse diesel engines used in both conventional and nuclear US submarines. Fairbanks-Morse also used it in diesel locomotives starting in 1944. With the addition of a supercharger or turbocharger, opposed-piston designs can make very efficient two-stroke cycle Diesel engines. Attempts were made to build non-diesel 4-stroke engines, but as there is no cylinder head, the bad location of the valves and the spark plug makes them inefficient.

Koreyvo, Jumo and Deltic engines used one piston per cylinder to expose an intake port, and the other to expose an exhaust port. Each piston is referred to as either an *intake piston* or an *exhaust piston* depending on its function in this regard. This layout gives superior scavenging, as gas flow through the cylinder is axial rather than radial, and simplifies design of the piston crowns. In the Jumo 205 and its variants, the upper crankshaft serves the exhaust pistons, and the lower crankshaft the intake pistons. In designs using multiple cylinder banks, such as the Junkers Jumo 223 and the Deltic, each big end bearing serves one inlet and one exhaust piston, using a forked connecting rod for the exhaust piston.

The Doxford Engine Works of the UK designed and built very large opposed-piston engines for marine use. These engines differ in design from Jumo and Fairbanks-Morse engines by having external connecting rods outside the cylinder linking the upper and lower pistons, thus requiring only a single crankshaft. The first engine of this type was developed by Karl Otto Keller in 1912. Doxford obtained a sole UK license from Oechelhauser and Junkers to build this design of engine. After World War I, these engines were produced in a number of models, such as the P and J series, with outputs as high as 20,000 horsepower (15,000 kW). Certain models were license-built in the US. Production of Doxford engines in the UK ceased in 1980.

Assembly and function
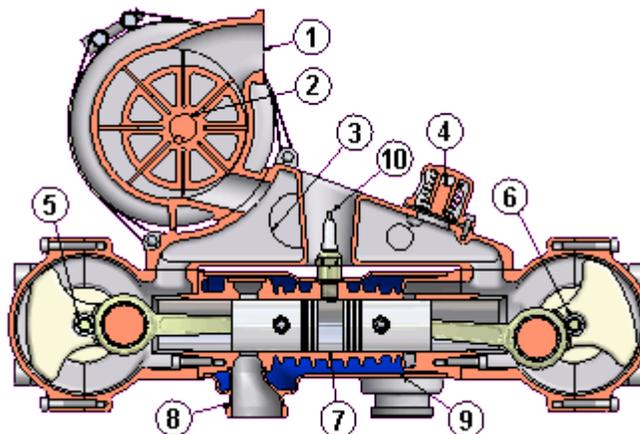
An example of an opposed-piston engine.
1 intake for the fuel-air mixture
2 supercharger (here: rotary vane pump; original: Centrix)
3 airbox to buffer and distribute the mixture
4 waste valve to limit the pressure level
5 outlet crank mechanism (runs app. 20° past the outlet to achieve an asymmetric control diagram)
6 inlet crank mechanism
7 cylinder with inlet and outlet slots
8 exhaust
9 water cooling jacket
10 sparkplug

Shown (at right) is the layout of a two-stroke engine similar to the one developed by engineer Kurt Bang at the Prüssing Office on the basis of the prewar DKW race engine. There existed two versions: one with a displacement of 250 cm^3 (15 cu in), and one with 350 cm^3 (21 cu in) displacement. The engine had two cylinders with four pistons, two crankshafts and a supercharger. The crankshafts were connected by gears.

The supercharger takes in the fuel-air mixture, compressing it and pushing it into the airbox. From here it reaches the crank housings. On the outlet side it cools the thermally high loaded piston. After ignition the pistons move outwards, performing the power stroke. At first, the outlet piston opens its slots in the cylinder. The remaining pressure accelerates the gas column towards the exhaust. Then the other piston opens the inlet slots. The pressurized fresh mixture pushes the remaining waste gas out. While the inlet is still opened, the outlet is closed. The supercharger forces additional gas into the cylinder until the inlet slots are closed by the piston. Then the compression stroke starts and the cycle repeats. This type of two cycle system is similar to the famous Grey Marine Diesel, later to be known as the GM Diesel (Detroit Diesel). Production ceased in 1998 but the U.S. and British Militaries still purchase remanufactured engines on occasion.

Free-piston engine

An interesting variation on the opposed-piston engine is the free-piston engine which was patented in 1934 by Raúl Pateras de Pescara. It has no crankshaft and the pistons are returned after each firing stroke by compression and expansion of air in a separate cylinder. Early applications were for use as an air compressor or as a gas generator for a gas turbine, such as the Pratt & Whitney PT1 design. There is now renewed interest in it for powering vehicles by using it to drive a linear alternator.

Other notable opposed-piston engines

- Junkers Jumo 205.
- Commer TS3 "The Commer Knocker" commercial vehicle engine.
- Leyland L60 tank engine, used in the Chieftain tank.Similar in layout to the Junkers Jumo 205 and Napier Culverin.
- Rolls-Royce K60 engine, smaller and improved version of the L60 used in the FV430 series armoured fighting vehicles and Swedish tank Strv 103.
- Napier Deltic.

- Soviet engine 5TDF used on tank T-64.
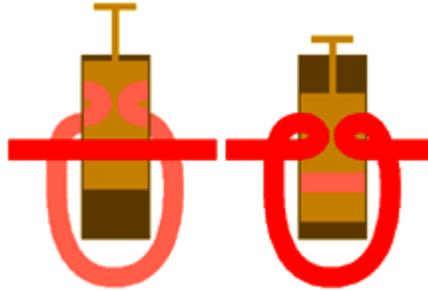- Soviet engine 6TD used on tanks T-80UD, T-84 and Al-Khalid.

Piston Valve & H Engine

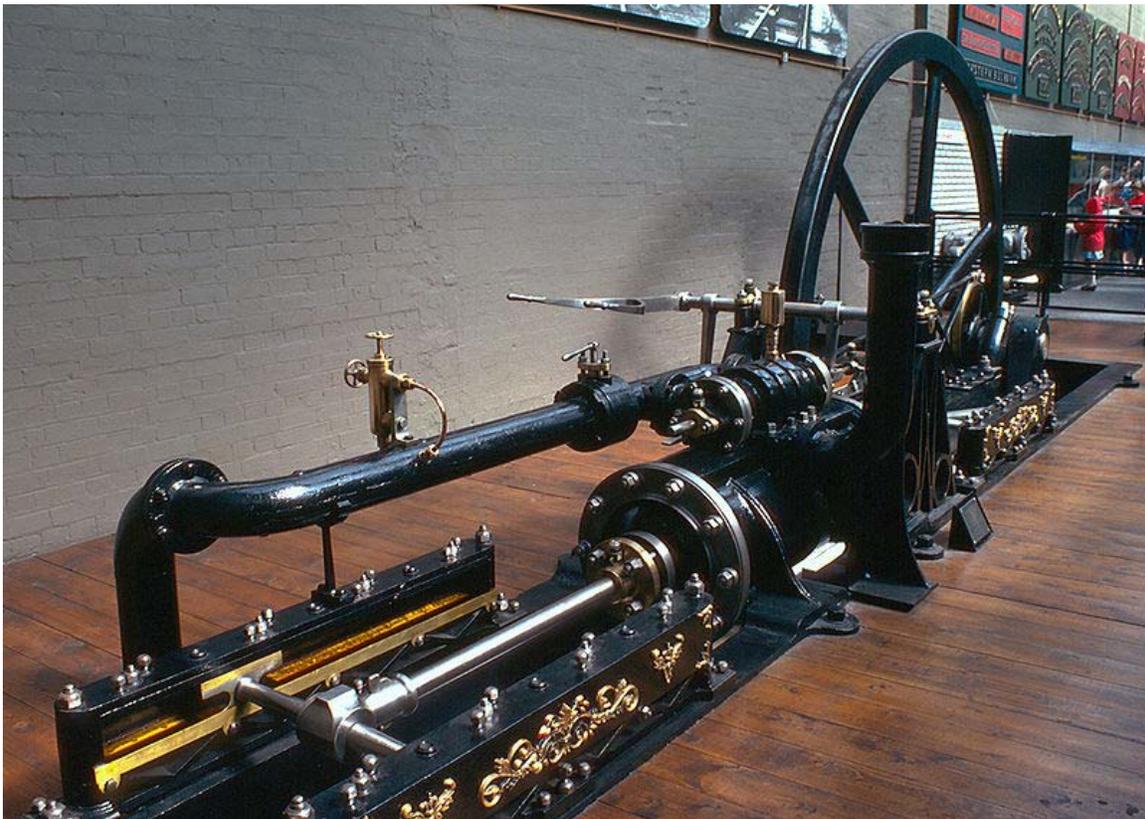## Piston Valve

Piston check valve

Piston valve in a brass instrument

A '**piston valve**' is a device used to control the motion of a fluid along a tube or pipe by means of the linear motion of a piston within a chamber or cylinder.

Examples of piston valves are:

- The valves used in the valve gear of many stationary steam engines and most steam locomotives.
- The valves used in many brass instruments.
- The valves used in pneumatic cannons.

Steam engines

The Swannington incline winding engine of 1833 incorporated a piston valve

The Swannington incline winding engine on the Leicester and Swannington Railway, manufactured by The Horsely Coal & Iron Company in 1833, shows a very early use of the piston valve. Piston valves had been used a year or two previously in the horizontal engines manufactured by Taylor and Martineau of London, but did not become general for stationary or locomotive engines until the end of the 19th century.

In the 19th century, most steam locomotives used slide valves to control the flow of steam into and out of the cylinders. In the 20th century, slide valves were gradually superseded by piston valves, particularly in engines using superheated steam. There were two reasons for this:

- With piston valves, the steam passages can be made shorter. This reduces resistance to the flow of steam and improves efficiency
- It is difficult to lubricate slide valves adequately in the presence of superheated steam

The usual locomotive valve gears, *e.g.*, the Stephenson valve gear, Walschaerts valve gear, and Baker valve gear, can be used with either slide valves or piston valves. Where poppet valves are used, a different gear, such as Caprotti valve gear is needed.

Brass instruments

First piston valve of a B♭ trumpet

Cylindrical piston valves called Perinet valves (after their inventor, François Perinet), are used to change the length of tube in the playing of most brass instruments, particularly the trumpet-like members of the family (cornet, flugelhorn, saxhorn, etc.).

Other brass instruments use rotary valves. notably the orchestral horns and many tuba models, but also a number of rotary-valved variants of those brass instruments which more commonly employ piston valves.

The first piston-valved musical instruments were developed just after the start of the 19th century. The Stölzel valve (invented by Heinrich Stölzel in 1814) was an early variety. In the mid 19th century the Vienna valve was an improved design. However most professional musicians preferred rotary valves for quicker, more reliable action, until better designs of piston valves were mass manufactured in towards the end of the 19th century.

Pneumatic cannons

A Piston valve can also refer to a 2-way 2-position, pilot operated valve. The term is extremely popular among spud gun enthusiasts who often build homemade piston valves for use in pneumatic cannons. Valves are typically constructed primarily from pipe fittings and machined plastics or metals. The inside of a piston valve contains a piston that blocks the output when the valve is pressurized, and a volume of air behind the piston. When the pressure behind the piston is released the piston is pushed back by the force of the pressure from the input. This allows the valve to be opened by a much smaller pilot valve, with speeds faster than possible with just a manually operated valve. Functionally these types of valves are comparable to quick exhaust valves.

This type of piston valve is also sometimes referred to as a back-pressure valve.

H Engine
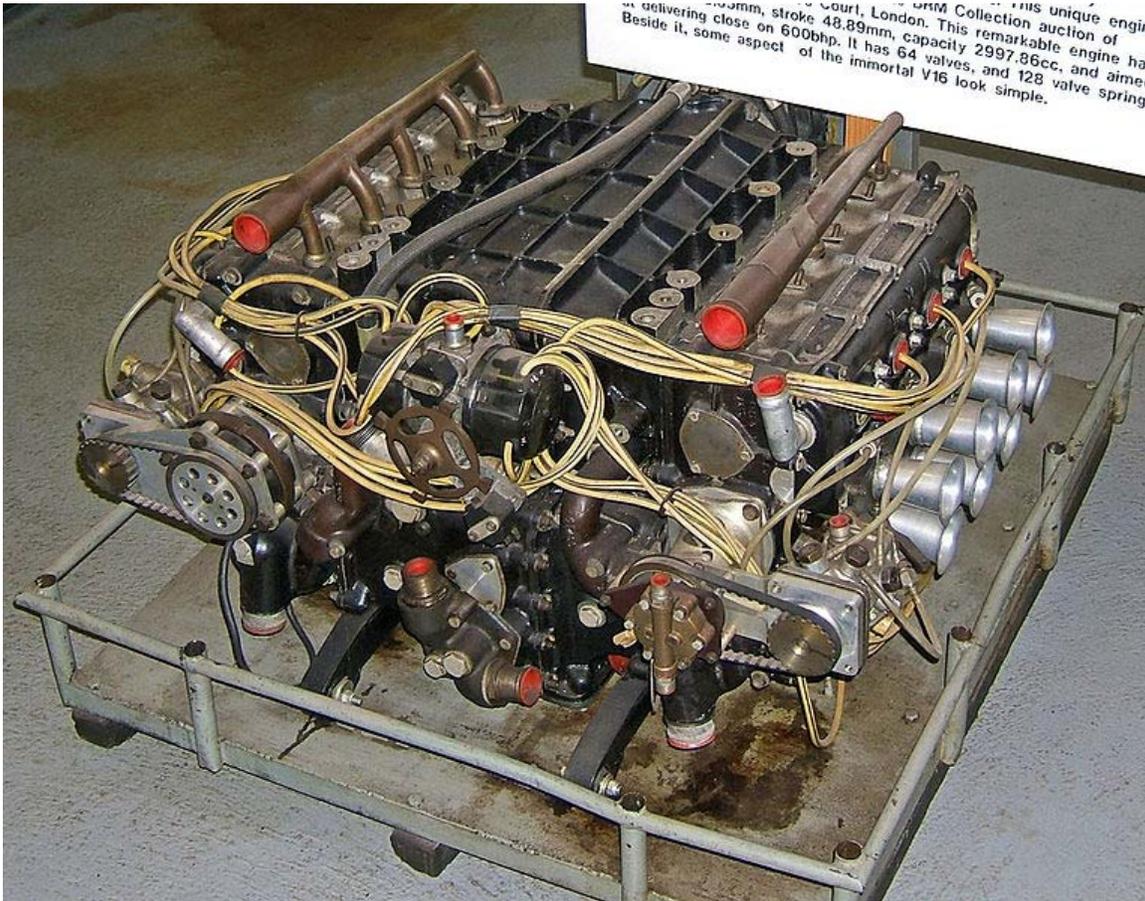
The BRM H16 Formula One engine in its final, 64-valve incarnation.

An **H engine** (or H-block) is an engine configuration in which the cylinders are aligned so that if viewed from the front, they appear to be in a vertical or horizontal letter H.

An H engine can be viewed as two flat engines, one atop or beside the other. The "two engines" each have their own crankshaft, which are then geared together at one end for power-take-off. The H configuration allows the building of multi-cylinder engines that are shorter than the alternatives, sometimes delivering advantages on aircraft. For race-car applications there is the disadvantage of a higher center of gravity, not only because one crankshaft is located atop the other, but also because the engine must be high enough off the ground to allow clearance underneath for a row of exhaust pipes. The power-to-weight ratio is not as good as simpler configurations employing one crankshaft. There is excellent mechanical balance, especially desirable and otherwise difficult to achieve in a four cylinder engine.

Two straight engines can be similarly joined to provide a U engine.

H engines

Aircraft engines
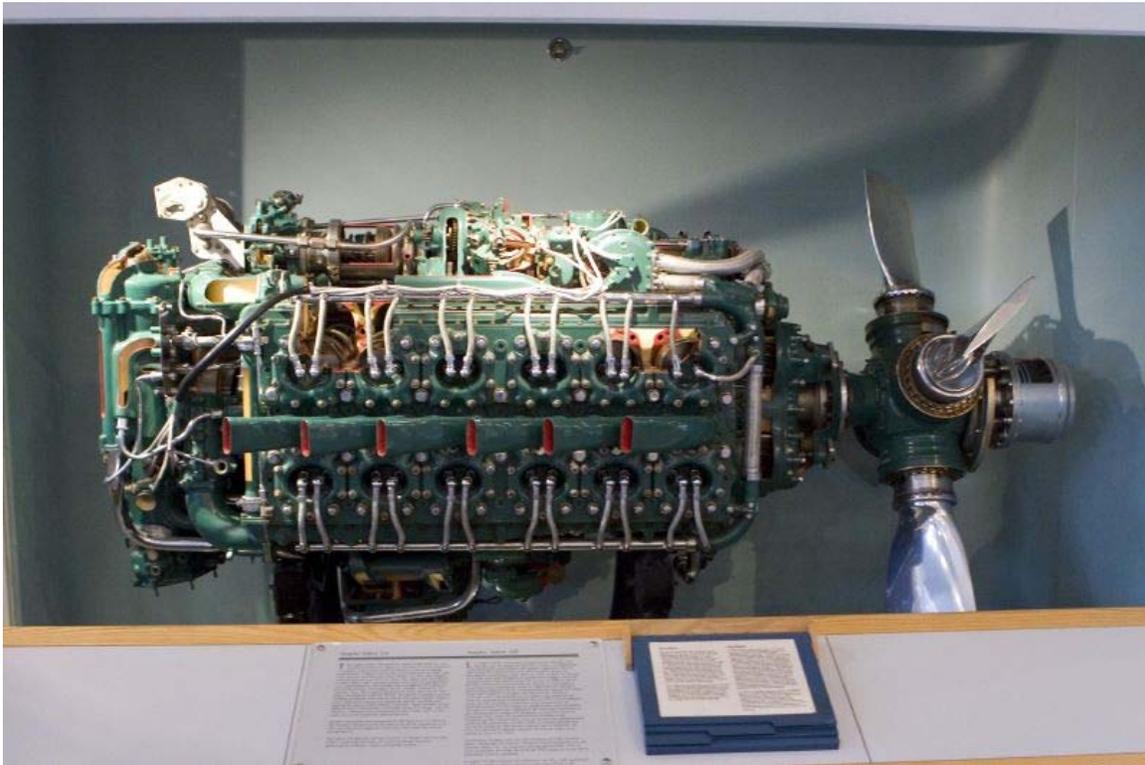
Napier Sabre H-24 engine. The two starboard 6-cylinder banks can be seen in this view

- Lycoming H 2470 "hyper engine".
- Fairey Aviation
    - Fairey Prince (H-16) (1939) - 1,500 hp
    - Fairey Monarch (1939) - H-24 2,240 hp
- Napier & Son, UK.
    - Rapier (1929) - H-16 air-cooled vertical, 8.83 litres 340 hp
    - Dagger (1934) - H-24, air-cooled vertical, 16.85 litres 890 hp, a development of the Rapier
    - Sabre (1938) - H-24, water cooled horizontal sleeve valves, 36.7 litres 3,500 hp. By 1944 in the Hawker Typhoon, the most powerful inline configuration piston engine ever.
- Rolls-Royce Eagle (1944) - H-24, 46.2 litres, 3,200 hp.

Other engines

Brough Superior H-4 motorcycle engine

A BRM H16 engine, mounted in the back of a BRM P83 Formula One car.

- The British Racing Motors (BRM) H-16 Formula One engine won the 1966 US Grand Prix with Jim Clark in a Lotus 43. As a racing-car engine it was hampered by a high center of gravity, and it was heavy and complex, with gear-driven twin overhead cams for each of four cylinder heads, two gear-coupled crankshafts, and mechanical fuel injection.
- The Brough Superior Golden Dream motorcycle, first shown in 1938. A 1,000 cc H-4 design and a few units were produced in early 1939. Any development planned was interrupted by WWII and subsequent years of austerity.
- Wooler built a motorcycle prototype with a similar configuration to the Brough Superior Golden Dream and exhibited it at the British International Motor Show at Earls Court in 1948 and again in 1951. This was replaced by a flat-4-engined prototype at the 1953 show.

Other uses of H term

Subaru produces water-cooled flat-4 and flat-6 "Horizontal" engines that are marketed as H-4 and H-6 (also thought to represent the configuration of the cylinders from a 'top down' POV as opposed to the traditional 'head-on' POV).

Chapter 19

Controlled Combustion Engine

REVETEC X4v2 Prototype Engine

Controlled Combustion Engine (CCE) is a term used by Revetec, an engine design company, to identify a type of experimental internal combustion engine (ICE) designed by Brad Howell-Smith. It uses two counter-rotating cams instead of a crankshaft. Pairs of cylinders oppose each other in a boxer flat engine or "X" arrangement.

History

The idea came to Howell-Smith, an automotive engineer residing in Australia, during REM sleep in 1995. He designed five different engine layouts with variations on each and established Revolution Engine Technologies Pty Ltd in 1996 with a budget of A$2000. The first working prototype was built by father-in-law Peter Koch in Howell-Smith's garage. Howell-Smith founded a company named Revetec Limited and set up a research and development site in Sydney. The prototype was displayed at the 1996 Sydney International Motor Show which brought public awareness to the design. Work began on a second prototype intended for use in generators and pumps, however interest expressed by the Middle East automotive market shifted focus towards automotive applications.

Engine description

The REVETEC Engine design consists of two counter-rotating "trilobate" (three lobed) cams geared together, so both cams contribute to forward motion. Two bearings run along the profile of both cams (four bearings in all) and stay in contact with the cams at all times. The bearings are mounted on the underside of the two inter-connected pistons, which maintain the desired clearance throughout the stroke.

The two cams rotate and raise the piston with a scissor-like action to the bearings. Once at the top of the stroke the air/fuel mixture is fired. This is the power stroke during which the maximum mechanical advantage is reached after the piston has moved approximately 5% of its travel from top dead centre (approx. 10° ATDC), which makes better use of the high cylinder pressures at this point in the cycle. In comparison a conventional engine reaches its maximum mechanical advantage after the piston has moved approximately 40% of its travel from top dead centre (approx. 60° ATDC). A side effect of this is a CCE can idle at a much lower RPM.

Because the piston assembly only moves in one dimension (unlike the case in an engine with connecting rods), contact with the cylinder wall is minimised, which reduces wear and lubrication requirements. The cams create less piston shock, which allows ceramic components to be used. The engine can run in either direction if symmetrical lobes are used.

The effective cranking distance is determined by the length from the point of bearing contact to the centre of the output shaft (not the stroke).

The dual bearings contact the two cams in the opposite side which cancels the side forces out. The piston assembly does not experience any side force which will reduce wear and lubrication requirements at the cylinder contact. One module which consists of a minimum of five moving components, produces six power strokes per revolution. Increasing the number of lobes on each cam to five produces ten power strokes without increasing the number of components.

Claimed Advantages

The following advantages are claimed for the CCE engine at.

- Predicted production power to dressed weight ratio is 0.40 bhp/lb. For comparison a Continental 100 hp (75 kW) engine is 0.465 hp/lb, dressed
- Efficiency - Recent tests gave good results, for a gasoline engine, when running lean.
- fewer moving and total components. As a result of fewer components, more easily manufactured than conventional engines.
- identical cylinder head assembly ("top end") to conventional engines. Most existing head technology can be either adapted or utilised.
- Flexible design - can be four-stroke, two-stroke, petrol, diesel or gas, natural or forced aspiration.
- Eliminated irregularly reciprocating components such as connecting rods. No second order balancing required.
- Output shaft can be run in either direction if multilobed cams with symmetrical lobes are employed.
- The CCE can be designed to operate at greatly reduced operating speeds while delivering high torque output.
- Substantial reduction in stroke reduces heat loss through cylinder wall.
- Extended piston dwell is possible because engine design allows a lower than normal compression ratio to be used reducing power loss from compression cycle.
- Able to fire on a leaner mixture than conventional engines.
- Maximum mechanical advantage can be applied to output shaft at only 20 degrees ATDC utilising high cylinder pressure early in the stroke, compared to around 60 degrees ATDC for conventional engines.
- Lower emissions can be achieved due to increased control over combustion.
- Low idle speed due to increase in mechanical efficiency at the top of the stroke.
- Little or no bore contact/piston side thrust, which reduces wear on cylinder bore.
- Can have different port timing on compression stroke than power stroke allowing better control.
- Lower centre of gravity on the boxer design.
- Due to controlled piston acceleration rates the CCE reduces engine vibration.
- A hollow output shaft can be utilised for specialty applications, such as peristaltic pumps.

Disadvantages

The following have yet to be verified independently.

- Vibration
- Reliability, especially when running lean as is required for good economy.
- Emissions

Patents

U.S. Patent 5,992,356 "Opposed piston combustion engine "; November 30, 1999; Howell-Smith; Bradely David (Worongary, AU).

Revetec has a PCT patent application pending for the "X" design lodged late 2006.

Performance

A dyno graph of the Revetec 1.38litr engine is shown on their development page, shows a flat torque curve.

Test results (11 November 2007) on the X4v2 engine showing torque and power curves and the fuel injection map.

In April 2008, Revetec completed their first Independently Certified Test Report carried out by Orbital Australia, achieving a repeatable BSFC figure of 212g/kW-h (38.6% efficiency) with a best tested figure of 207g/kW-h (39.5% efficiency).

Chapter 20

Corliss Steam Engine
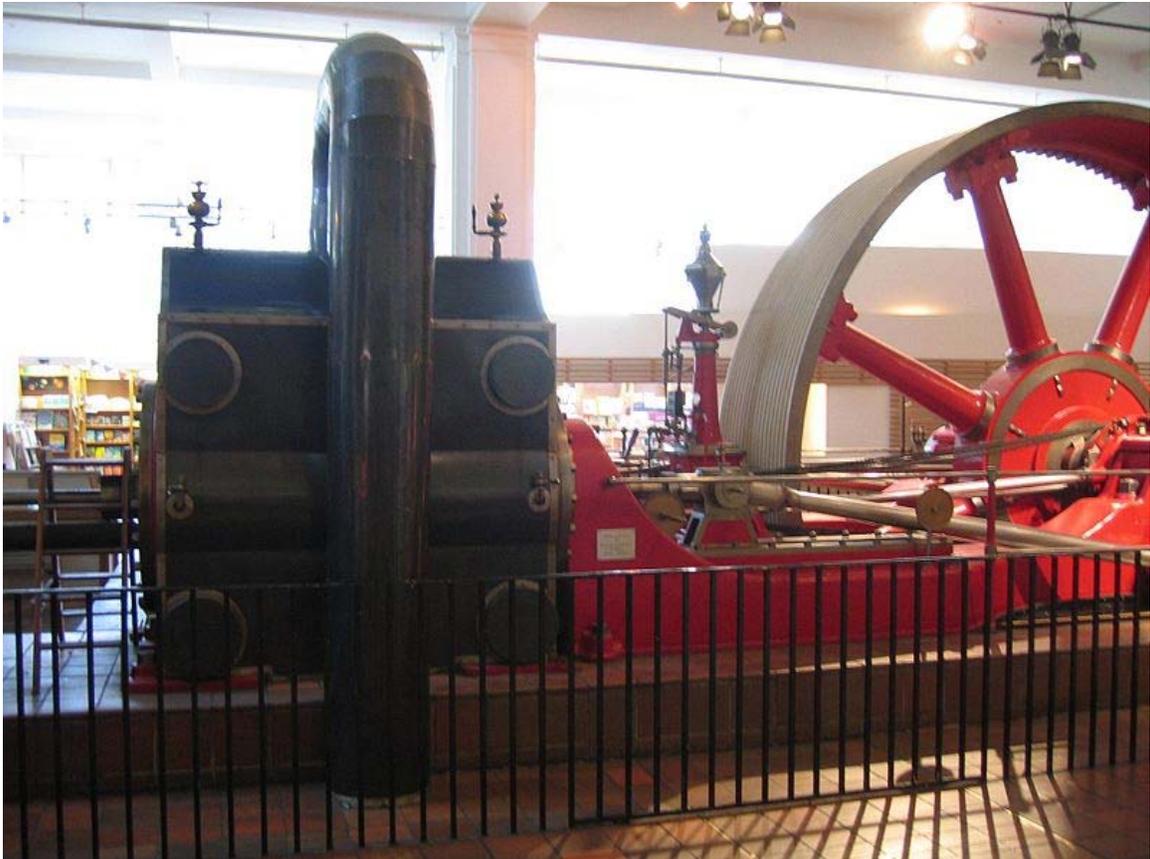
Horizontal mill engine, and valve covers

A **Corliss steam engine** (or **Corliss engine**) is a steam engine, fitted with rotary valves and with variable valve timing patented in 1849, invented by and named after the American engineer George Henry Corliss.

Engines fitted with Corliss valve gear offered the best thermal efficiency of any type of stationary steam engine until the refinement of the uniflow steam engine and steam

turbine in the 20th century. Corliss engines were generally about 30 percent more fuel efficient than conventional steam engines with fixed cutoff. This increased efficiency made steam power more economical than water power, allowing industrial development away from millponds.

Corliss engines were typically used as stationary engines to provide mechanical power to line shafting in factories and mills and to drive dynamos to generate electricity. Many were quite large, standing several stories tall, and developing several hundred horsepower, albeit at low speed, turning massive flywheels weighing several tons at about 100 revolutions per minute. Some of these engines had unique roles as mechanical legacy systems and because of their relatively high efficiency and low maintenance requirements, some remain in service in early 21st century (see, for example, the engines at the Hook Norton Brewery and the *Distillerie Dillon* in the list of operational engines).

Corliss engine mechanisms
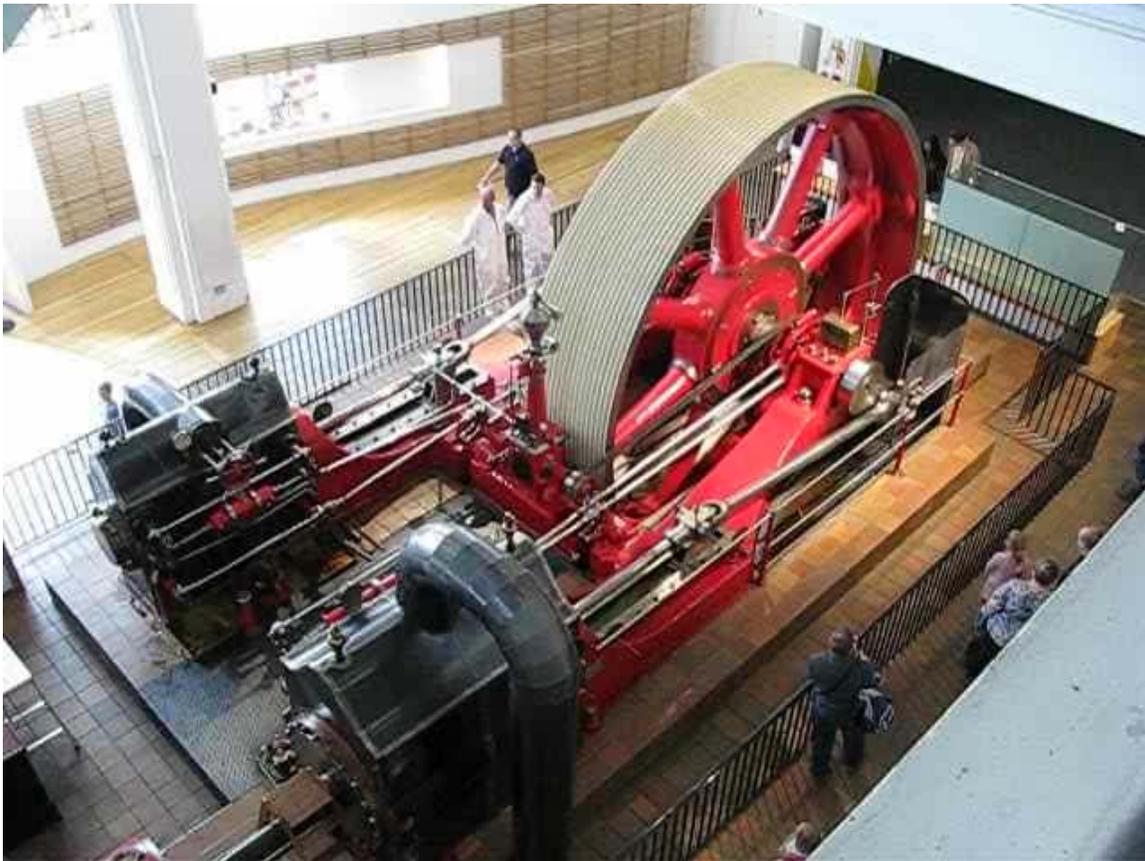
Corliss steam engine in motion

Corliss engines have four valves for each cylinder, with steam and exhaust valves located at each end. Corliss engines incorporate distinct refinements in both the valves themselves and in the valve gear, that is, the system of linkages that operate the valves.

The use of separate valves for admission and exhaust means that neither the valves nor the steam passages between cylinders and valves need to change temperature during the power and exhaust cycle, and it means that the timing of the admission and exhaust valves can be independently controlled. In contrast, conventional steam engines have a slide or piston valve that alternately feeds and exhausts through passages to each end of the cylinder. These passages are exposed to wide temperature swings during engine operation, and there are high temperature gradients within the valve mechanism itself.
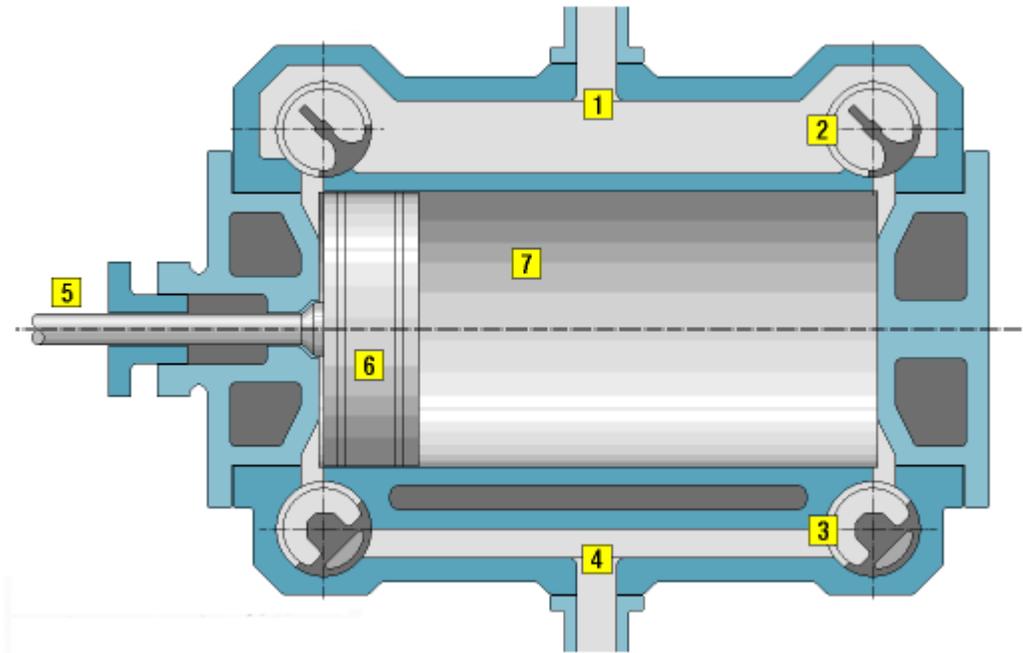
Corliss valve gear

George Corliss received US Patent 6162 for his valve gear on March 10, 1849. This patent covered the use of a *wrist-plate* to convey the valve motion from a single eccentric to the four valves of the engine, and it covered the use of trip valves with variable cutoff under governor control that characterize Corliss Engines. Unlike later engines, most of which were horizontal, this patent describes a vertical cylinder beam engine, and it used individual slide valves for admission and exhaust at each end of the cylinder.

The inlet valves are pulled open with an eccentric-driven pawl; when the pawl trips, the rapid closure is damped using a dashpot. In many engines, the same dashpot acts as a vacuum spring to pull the valves closed, but Corliss's early engines were slow enough that it was the weight of the dashpot piston and rod that closed the valve.

The speed of a Corliss engine is controlled by varying the cutoff of steam during each power stroke, while leaving the throttle wide open at all times. To accomplish this, the centrifugal governor is linked to a pair of cams, one for each admission valve. These cams determine the point during the piston stroke that the pawl will release, allowing that valve to close.

As with all steam engines where the cutoff can be regulated, the virtue of doing so lies in the fact that most of the power stroke is powered by the expansion of steam in the cylinder after the admission valve has closed. This comes far closer to the ideal Carnot cycle than is possible with an engine where the admission valve is open for the length of the power stroke and speed is regulated by a throttle valve.

Corliss valves

Sectioned cylinder, showing rotating valves

Corliss valves open directly into the cylinder. The valves connect the cylinder to separate steam and exhaust plenums. Initially, Corliss used slide valves with linear actuators, but by 1851, Corliss had shifted to rotary valve actuators, as documented in U.S. Patent 8253. In this engine, the wrist plate was moved to the center of the cylinder side, as on later Corliss engines. This was still a beam engine, however, and the rotary valve actuators operated linear slide valves inside the four valve chests of the engine.

Corliss valves are in the form of a minor circular segment, rotating inside a cylindrical valve-face. Their actuating mechanism is off along the axis of the valve, thus they have little "dead space" such as the stem of a poppet valve and the entire port area can be used efficiently for gas flow.

As the area of a Corliss valve is small compared to the port area, the effects of gas flow generate relatively little torque on the valve axle compared to some other sorts of valve. These advantages have led to the Corliss form of valve being used in other roles, apart from steam engines with Corliss gear.

The Rolls-Royce Merlin aero-engine used a rectangular butterfly valve as a throttle. Gas-flow forces acting asymmetrically on this butterfly could lead to poor control of the power in some circumstances. Late models, from the 134, used a Corliss throttle valve instead to avoid this problem.

Barring and barring engines

A common feature of large Corliss engines is one or two sets of narrow gear teeth in the rim of the flywheel. These teeth allow the flywheel to be *barred*, that is, turned with the aid of a crowbar. This may be needed during engine maintenance, for example, to set the cutoff and admission valve timing, and it may be needed during engine starting.

The need for barring the engine during starting is most obvious on single cylinder engines, where a careless engine operator might stop the engine with piston in dead center. Once stopped in dead center, the engine cannot be started under its own power, so it must be barred to a more favorable position for starting.

Large Corliss engines cannot be safely started cold, so it is common to admit low-pressure steam to both sides of the cylinder to warm up the metalwork. Turning the engine slowly during this process ensures that the entire engine is uniformly warmed, and it ensures that oil is uniformly distributed through the mechanism before applying power. Again, barring may be used to do this, although operators sometimes do this by careful manual manipulation of the valves.

For large engines, muscle powered barring is sufficiently difficult that *barring engines* are frequently installed. These are small engines with gear teeth cut to mate with the teeth on the flywheel. Generally, the drive gears of the barring engine are designed to automatically disengage if the engine begins running under its own power while the barring gears are engaged.

Company history

The Corliss Steam Engine Company was originally known as Fairbanks, Clark & Co. in the 1830s. In 1843 it was renamed Fairbanks, Bancroft & Co. when Edward Bancroft joined the company. In 1846 it was renamed Bancroft, Nightingale & Co. when George H. Corliss joined the company, and in 1847 it was renamed Corliss, Nightingale and Co. In 1848 the company moved to the Charles Street Railroad Crossing in Providence, Rhode Island.

In 1857 the company was renamed for the last time to Corliss Steam Engine Company. By 1864 Corliss bought out his partners and was the sole owner of the company. In 1900 the Corliss Steam Engine Company was purchased by the International Power Company. In 1905 it was purchased by the American and British Manufacturing Company. In 1925 the company merged into Franklin Machine Company. By then Franklin Machine Company was already owned by the William A. Harris Steam Engine Company.
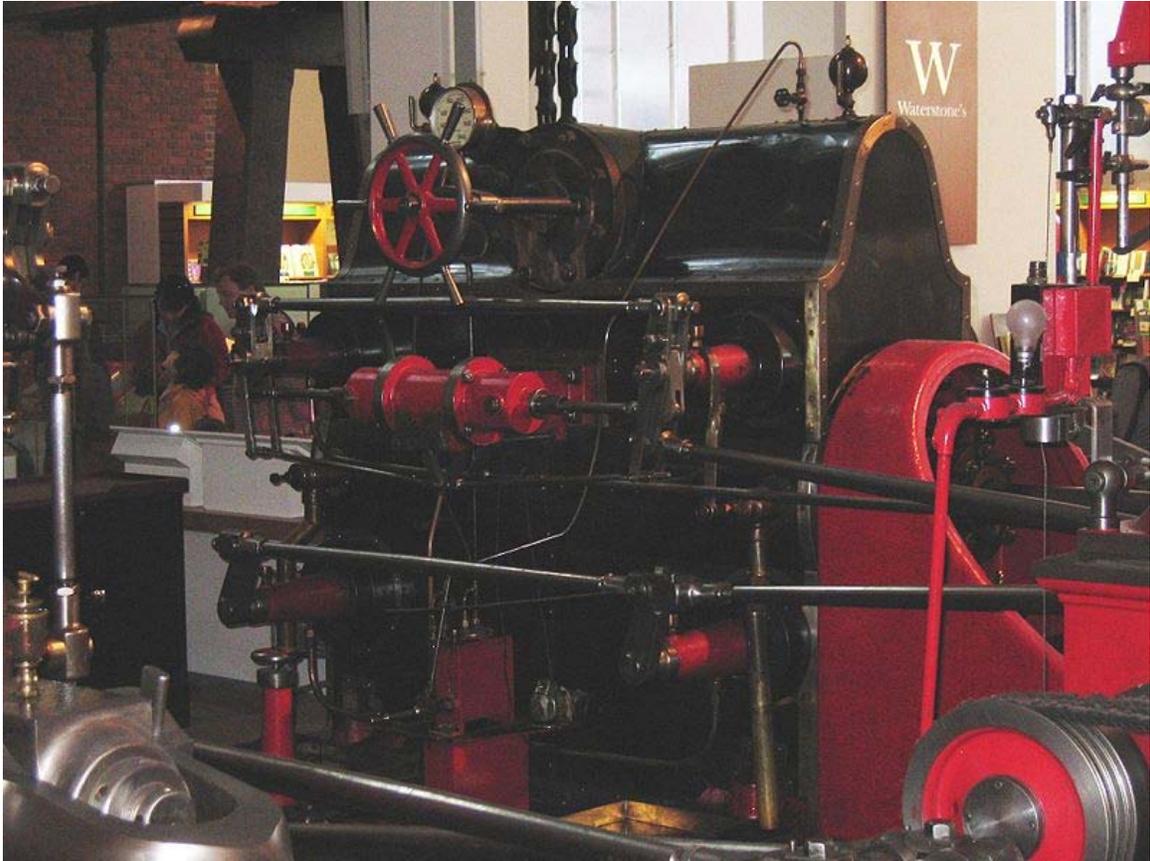
Valve gear typical of engines developed by Corliss competitors. The horizontal arrangement of the dashpots and the lack of a wrist plate avoided key claims in the Corliss patents.

By 1859, all of the key features of what we now know as the Corliss engine were in place. Patents granted to Corliss and others incorporated rotary valves and crank shafts in-line with the cylinders. See, for example, Corliss' U.S. Patent 24,618, granted July 5, 1859. Competing inventors worked hard to invent alternatives to Corliss' mechanisms; they generally avoided Corlis's use of a wrist plate and adopted alternative releasing mechanisms for the steam valves, as in Jamieson's U.S. Patent 19,640, granted March 16, 1858.

Corliss' 1849 patent expired in 1870; the term of this patent had been extended by U.S. Patent reissue 200 on May 13, 1851 and U.S. Patent reissues 758 and 763 on July 12, 1859. After 1870, numerous other companies began to manufacture Corliss engines. Among them, the William A. Harris Steam Engine Company , the Worthington Pump and Machinery Company , and Allis-Chalmers . In general, these machines were referred to as Corliss engines regardless of who made them.

Centennial Engine
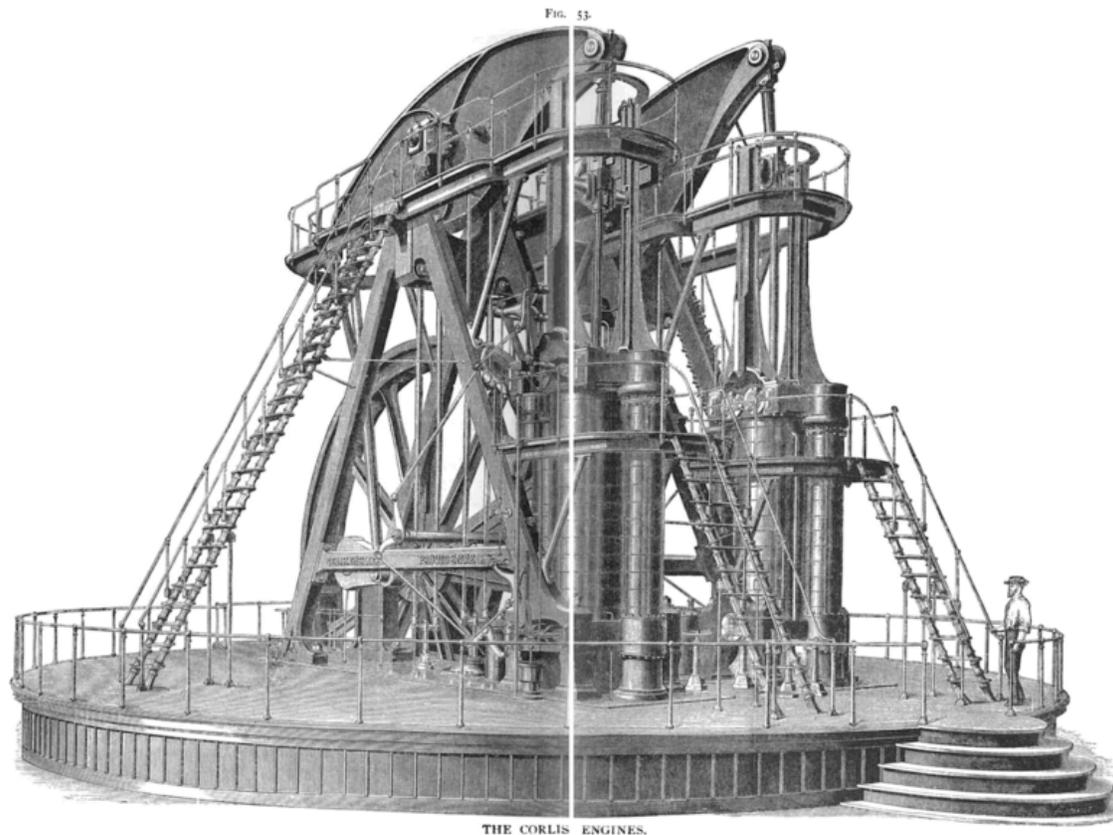
The Centennial Engine

The Corliss Centennial Engine was an all-inclusive, specially-built rotative beam engine that powered virtually all of the exhibits at the Centennial Exposition in Philadelphia in 1876 through shafts totaling over a mile in length. Switched on by President Ulysses Grant and Emperor Dom Pedro of Brazil, the engine was in public view for the duration of the fair.

The engine was configured as two cylinders side-by-side. Each cylinder was bored to 44 inches (1.1 m) with a stroke of 10 feet (3.0 m), making it the largest engine of the nineteenth century. The Centennial Engine was 45 feet (14 m) tall, had a flywheel 30 feet (9.1 m) in diameter, and produced 1,400 hp. After the fair it was disassembled and shipped back to Corliss's plant in Providence. Seven years later it was sold and powered a Chicago factory owned by George Pullman until 1910, when it was sold as scrap.

This engine became a cultural icon, so much so that to many modern historians the term **Corliss Engine** (or **Corliss Steam Engine**) refers to this specific engine and not to the broad class of engines fitted with Corliss valve gear.

Chapter 21

Sleeve Valve
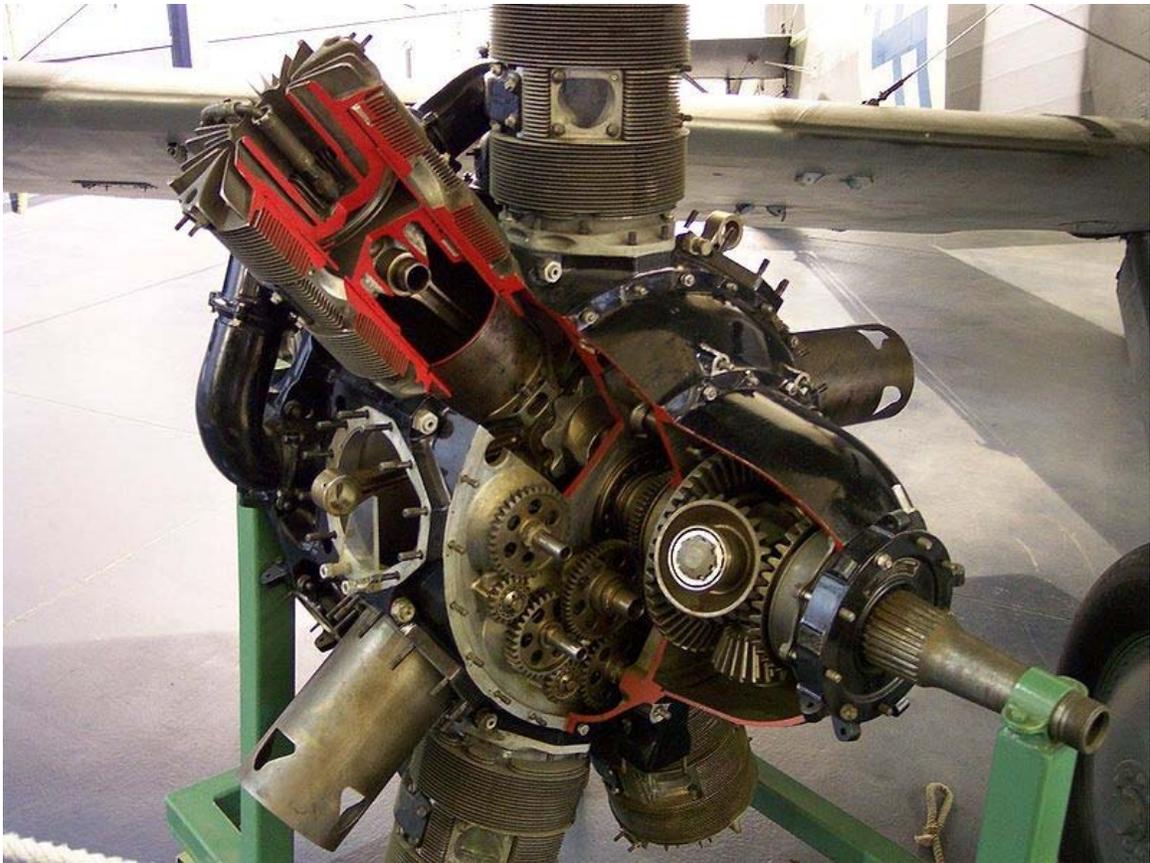
Bristol Perseus

The **sleeve valve** is a type of valve mechanism for piston engines, distinct from the more common poppet valve. Sleeve-valve engines saw use in a number of pre-World War II luxury cars, sports cars, the Willys-Knight car and light truck, the British Daimler and French Avions Voisin luxury cars, also used the same Willys-Knight double-sleeve system. They subsequently fell from use due to advances in poppet-valve technology (sodium cooling) and to their tendency to burn a lot of lubricating oil or to seize due to

lack of it. The Scottish Argyll company used its own, much simpler and efficient, single-sleeve system in its cars, a system which, after extensive development, saw substantial use in aircraft engines of the 1940s, such as the Napier Sabre and Bristol Hercules and Centaurus, only to be supplanted by the jet engine.

Description

A sleeve valve takes the form of one or more machined sleeves. It fits between the piston and the cylinder wall in the cylinder of an internal combustion engine where it rotates and/or slides, ports (holes) in the side of the valve(s) aligning with the cylinder's inlet and exhaust ports at the appropriate stages in the engine's cycle.

Types of sleeve valve
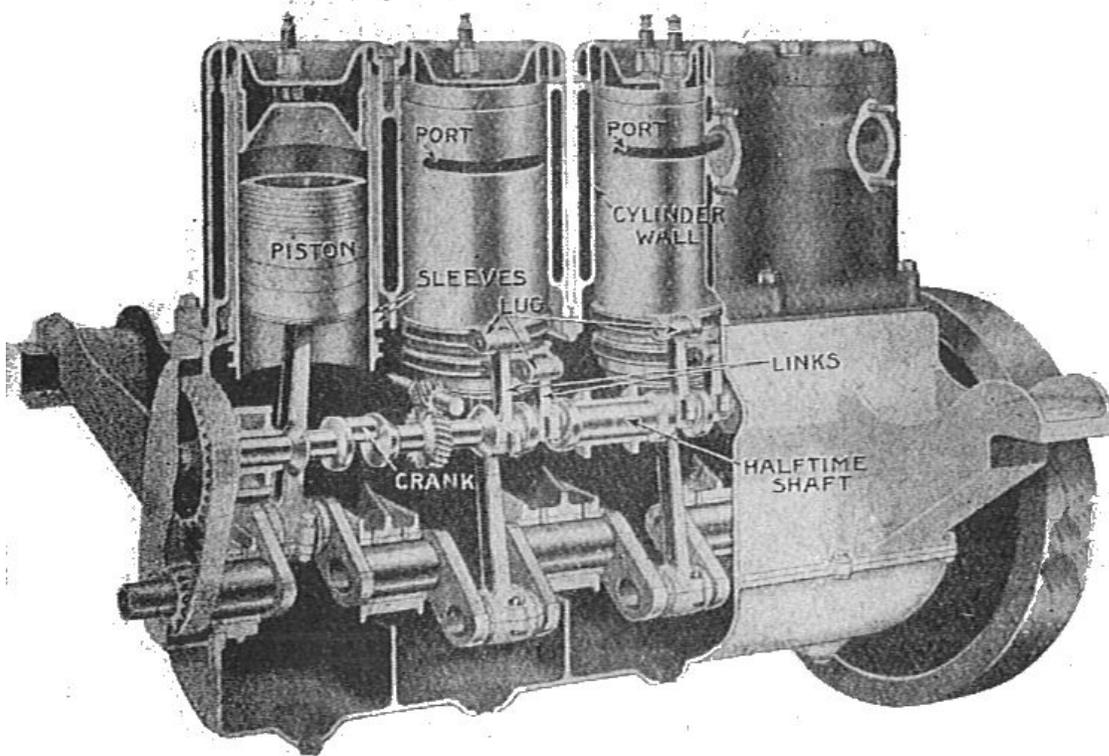
Knight sleeve valve engine

The first successful sleeve valve was patented by Charles Yale Knight, and used twin alternating sliding sleeves. It was used in some luxury automobiles, notably Daimler, but was noted for its high oil consumption.
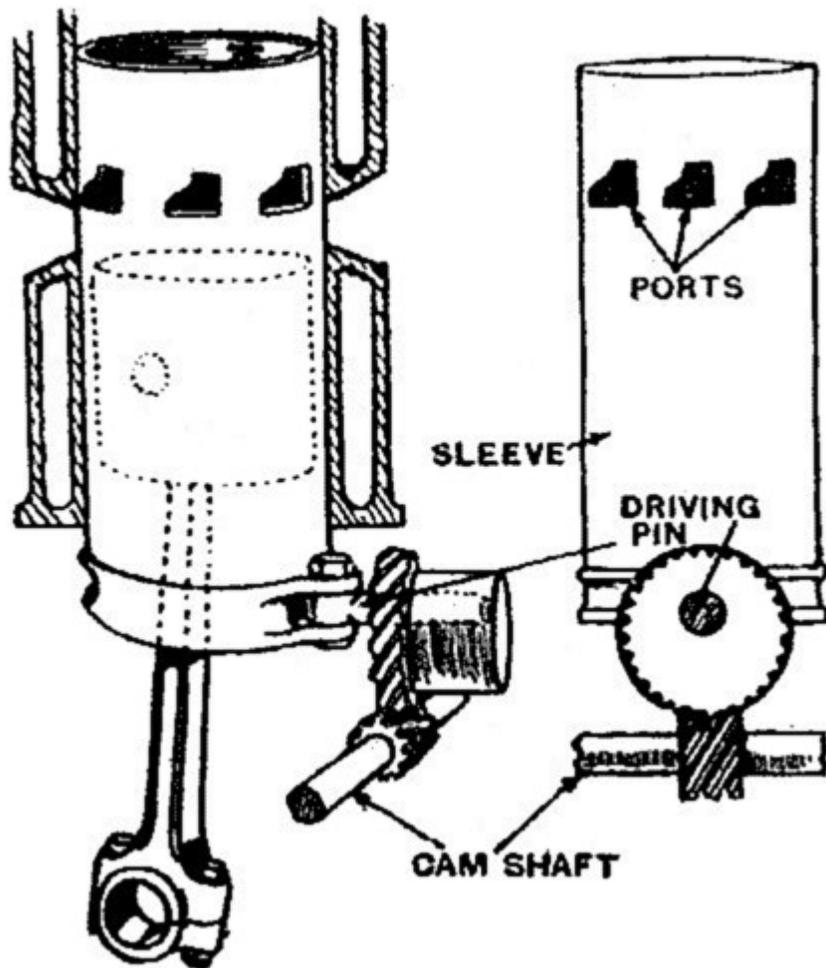
Argyll single sleeve valve

The Burt-McCollum sleeve valve, as used by the Scottish company Argyll for its cars, and later adopted by Bristol for its radial aircraft engines, used a single sleeve which rotated around a timing axle set at 90 degrees to the cylinder axle. Mechanically simpler and more rugged, the Burt-McCollum valve had the additional advantage of reducing oil consumption (compared to other sleeve valve designs), while retaining the rational combustion chambers and big, uncluttered, porting area possible in the Knight system.

A small number of designs used a "cuff" sleeve in the cylinder head instead of the cylinder proper, providing a more "classic" layout compared to traditional poppet valve engines. This design also had the advantage of not having the piston within the sleeve, although in practice this appears to have had little practical value. On the downside, this arrangement limited the size of the ports to that of the cylinder head, whereas in-cylinder sleeves could have much larger ports.

Advantages/disadvantages

Advantages

The main advantages of the sleeve valve engine are:

- Increased volumetric efficiency due to very large port openings. Sir Harry Ricardo also demonstrated better mechanical efficiency. An additional advantage of the system is that the size of the ports can be readily controlled. This is important when an engine operates over a wide RPM range, since the speed at which air can enter and exit the cylinder is defined by the size of the duct leading to the cylinder, and varies according to the cube of the RPM. In other words, at higher RPM the engine typically requires larger ports that remain open for a greater proportion of the cycle, which is fairly easy to achieve with sleeve valves, but difficult in a poppet valve system.

- Good exhaust scavenging and controllable swirl of the inlet air/fuel mixture in single-sleeve designs. When the intake ports open, the fuel air mixture can be made to enter tangentially to the cylinder. This helps scavenging when exhaust/inlet timing overlap is used and a wide speed range required, whereas poor poppet valve exhaust scavenging can dilute the fresh air/fuel mixture intake to a greater degree, being more speed dependent (relying principally on exhaust/inlet system resonant tuning to separate the two streams). Greater freedom of combustion chamber design (few constraints other than the spark plug positioning) means that fuel/air mixture swirl at TDC can also be more controlled allowing improved ignition and flame travel which as demonstrated by Ricardo, at least one extra unit of compression ratio before detonation c.f. the poppet valve engine.

- The combustion chamber formed with the sleeve at the top of its stroke is ideal for complete, detonation-free combustion of the charge, as it does not have to contend with compromised chamber shape and hot exhaust (poppet) valve(s).

- No springs are involved in the sleeve valve system, therefore the power needed to operate the valve remains largely constant with the engine's RPM, meaning that the system can be used at very high speeds with no penalty for doing so. A problem with high-speed engines which use poppet valves is that as engine speed increases, the speed at which the valve moves also has to increase. This in turn increases the loads involved due to the inertia of the valve, which has to be opened quickly, brought to a stop, then reversed in direction and closed and brought to a stop again. Large valves that allow good air-flow have considerable mass and require a strong spring to overcome the opening inertia. At some point, the valve spring reaches its resonance frequency, causing a compression wave to oscillate within the spring, which in turn causes it to become effectively weaker and unable to properly close the valve. This valve float can result in the valve not closing quickly, and it may strike the top of the rising piston. In addition,

camshaft, pushrods, and valve rockers can be eliminated in a sleeve valve design, as the sleeve valves are generally driven by a single gear powered from the crankshaft. In an aircraft engine this provided reductions in weight and complexity.

- Longevity, as demonstrated in early automotive applications of the Knight engine. Prior to the advent of leaded gasolines, poppet-valve engines typically required grinding of the valves and valve seats after 20,000 to 30,000 miles (32,000 to 48,000 km) of service. Sleeve valves did not suffer from the wear and recession caused by the repetitive impact of the poppet valve against its seat. Sleeve valves were also subjected to less intense heat buildup than poppet valves, owing to their greater area of contact with other metal surfaces. In the Knight engine, carbon build-up actually helped to improve the sealing of the sleeves, the engines being said to "improve with use", in contrast to poppet valve engines, which lose compression and power as valves and valve stems/guides wear. Due to the continued motion of the sleeve (Burt-McCollum type), the high wear points linked to poor lubrication in the TDC/BDC of piston course are suppressed, therefore rings and cylinders lasted much longer.

- Cylinder head is not required to house valves, allowing the spark plug to be placed in the best possible location for efficient ignition of the combustion mixture. For very big engines, where flame propagation speed limits both size and speed, the swirl induced by ports as described by Ricardo can be an additional advantage.

Most of these advantages were evaluated and established during the 1920s by Sir Harry Ricardo, possibly the sleeve-valve engine's greatest advocate. He conceded that some of these advantages were significantly eroded as fuels improved up to and during World War II and as sodium-cooled exhaust valves were introduced in high output aircraft engines.

Disadvantages

The sleeve valve's one major disadvantage is that perfect sealing is difficult to achieve. In a poppet valve engine, the piston possesses piston rings (often at least three and sometimes as many as eight) which form a seal with the cylinder bore. During the "breaking in" period (known as "running-in" in the UK) any imperfections in one are scraped into the other, resulting in a good fit. This type of "breaking in" is not possible on a sleeve valve engine, however, because the piston and sleeve move in different directions and in some systems even rotate in relation to one another. Unlike a traditional design, the imperfections in the piston do not always line up with the same point on the sleeve. In the 1940s this was not a major concern because the poppet valves of the time typically leaked appreciably more than they do today, so that oil consumption was significant in either case.

The high oil consumption problem associated with the Knight double sleeve valve was fixed with the Burt-McCollum single sleeve valve, as perfected by Bristol. At top dead center (TDC), the single sleeve valve rotates in relation to the piston. This prevents boundary lubrication problems, as piston ring ridge wear at TDC and bottom dead center (BDC) does not occur. The Hercules overhaul time was rated at 3,000 hr at wide open throttle. An inherent disadvantage may be that the piston in its course partially obscures the ports, thus making it difficult for gases to flow during the crucial overlap between the intake and exhaust valve timing usual in modern engines. The German engineer Max Bentele, after studying a British sleeve valve aero engine (probably a Hercules), complained that the arrangement required more than 100 gearwheels for the engine, too many for his taste.

History

Charles Yale Knight

In 1901 Knight bought an air-cooled, single cylinder three-wheeler whose noisy valves annoyed him. He believed that he could design a better engine and did so, inventing his double sleeve principle in 1904. Backed by Chicago entrepreneur L.B. Kilbourne, a number of engines were constructed followed by the "Silent Knight" touring car which was shown at the 1906 Chicago Auto Show.

Knight's design had two cast-iron sleeves per cylinder, one sliding inside the other with the piston inside the inner sleeve. The sleeves were operated by small connected rods actuated by an eccentric shaft. They had ports cut out at their upper ends. The design was remarkably quiet, and the sleeve valves needed little attention. It was, however, more expensive to manufacture due to the precision grinding required on the sleeves' surfaces. It also used more oil at high speeds and was harder to start in cold weather.

Although he was initially unable to sell his Knight Engine in the United States, a trip to Europe secured several luxury car firms as customers willing to pay his expensive premiums. He first patented the design in Britain in 1908. As part of the licensing agreement, "Knight" was to be included in the car's name.

Among the companies using Knight's technology were Gabriel Voisin (in his Avions Voisin cars), Daimler (in their V-12 "Double Six", from 1909–1930), Panhard (1911–39), Mercedes (1909–24), Willys (as the Willys-Knight, plus the associated Falcon-Knight), Stearns, Mors, Peugeot, and Belgium's Minerva company, some thirty companies in all. Itala also experimented with sleeve valves.

Upon Knight's return to America he was able to get some firms to use his design; here his brand name was "Silent Knight" (1905–1907) — the selling point was that his engines were quieter than those with standard poppet valves. The best known of these were the F.B. Stearns Company of Cleveland, which sold a car named the Stearns-Knight, and the Willys firm which offered a car called the Willys-Knight, which was produced in far greater numbers than any other sleeve-valve car.

Burt-McCollum

The Burt-McCollum sleeve valve consisted of a single sleeve, which was given a combination of up-and-down and partial rotary motion. It was developed in about 1909 and was first used in the 1911 Argyll car. Argyll went out of business after high expenses of a litigation with the Knight patent holders. Its greatest success was in Bristol's large aircraft engines, and was also used in the Napier Sabre and Rolls-Royce Eagle aircraft engines. The single valve system also cured the high oil consumption associated with the Knight double sleeve valve.

A number of sleeve valve aircraft engines were developed following a seminal 1927 research paper from the RAE by Harry Ricardo. This paper outlined the advantages of the sleeve valve, and suggested that poppet valve engines would not be able to offer power outputs much beyond 1500 hp (1,100 kW). Napier and Bristol began the development of sleeve valve engines that would eventually result in two of the most powerful piston engines in the world: the Napier Sabre and Bristol Centaurus.

Potentially the most powerful of all sleeve-valve engines (though it never reached production) was the Rolls-Royce Crecy V-12 (oddly, using a 90 degree V-angle), two-stroke, direct-injected, force-scavenged (turbocharged) aero-engine of 26.1 litres capacity. It achieved a very high specific output, and surprisingly good specific fuel consumption (SFC). In 1945 the single cylinder test-engine (E65) produced the equivalent of 5,000 HP (192 BHP/Litre) when water injected, although the full V12 would probably have been initially type rated at circa 2,500 hp (1,900 kW). Sir Harry Ricardo, who specified the layout and design goals, felt that a reliable 4,000 HP military rating would be possible. Ricardo was constantly frustrated during the war with Rolls-Royce's (RR) efforts. Hives & RR were very much focused on their Merlin, Griffon, then Eagle and finally Whittle's jets, which had a clearly defined production purpose. Ricardo and Tizard eventually realized that the Crecy would never get the development attention it deserved unless it was specified for installation in a particular aircraft, but by 1945, their "Spitfire on steroids" concept of a rapidly-climbing interceptor powered by the lightweight Crecy engine had become an aircraft without a purpose.

Following World War II the sleeve valve disappeared from use, as the previous problems with sealing and wear on poppet valves had been remedied by the use of better materials, and the inertia problems with the use of large valves were reduced by using several smaller valves instead, giving increased flow area and reduced mass. Up to that point, the single sleeve valve had won every contest against the poppet valve hands down in comparison of power to displacement. The difficulty of nitride hardening, then finish grinding the sleeve valve for truing the circularity, may have been a factor in its lack of commercial application.

Modern usage

The sleeve valve has begun to make something of a comeback, due to modern materials, dramatically better engineering tolerances and modern construction techniques, which

produce a sleeve valve that leaks very little oil. However, most advanced engine research is concentrated on improving other internal combustion engine designs, such as the Wankel.

Mike Hewland and Keith Duckworth experimented with a single-cylinder sleeve-valve test engine when looking at Cosworth DFV replacements. Hewland claimed to have obtained 72 hp (54 kW) from a 500 cc single cylinder engine, with a specific fuel consumption of 170 gr/HP/hr -.45 to .39 lb/hp/hr-, the engine being able to work on creosote, with no specific lubrication supply for the sleeve. Hewland reported also that the highest temperature measured in the cylinder head didn't exceed 150°C, sleeve temperatures were around 140°C,T was 270°C in the center of cylinder and 240°C in the edge.

A recent SAE paper deals with a high speed, small displacement sleeve valve engine, calculated, but not experimentally shown, to have a higher SFC than the poppet valve alternative, a non-surprising result, considering the difficulty in obtaining the high intake and exhaust overlap that very fast-running engines require, additional work compares two different side opening intake strategies for sleeve valve engines.

An unusual form of four stroke model engine to use what is essentially a sleeve-valve format, is the British RCV series of "SP" model engines, which use a rotating cylinder liner driven through a bevel gear at the cylinder liner's "bottom", and even more unusually have the propeller shaft emerging from what would normally be the cylinder's "top", at the extreme front of the engine, achieving a 2:1 gear reduction ratio compared to the vertically oriented crankshaft's rotational speed. The same firm's "CD" series of model engines use a conventional upright single cylinder instead, with the crankshaft used to directly spin the propeller, and also use the rotating cylinder valve. As a parallel with the earlier Charles Knight-designed sleeve-valved automotive powerplants, any RCV sleeve-valved model engine that is run on model glow engine fuel using castor oil as a small percentage (about 2% to 4% content) of the lubricant in the fuel allows the "varnish" created through engine operation to provide a better pneumatic seal between the rotating cylinder valve and the unitized engine cylinder/head castings, initially formed while the engine is being broken-in.

Steam engine

Sleeve valves have occasionally been used on steam engines, for example the SR Leader class.