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How the radial aircraft engine works

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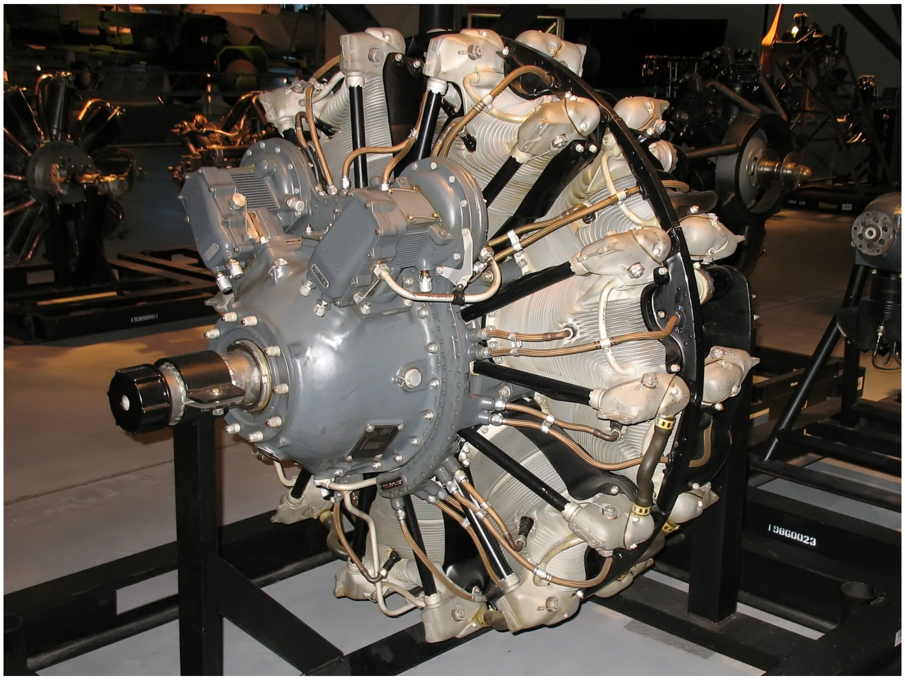
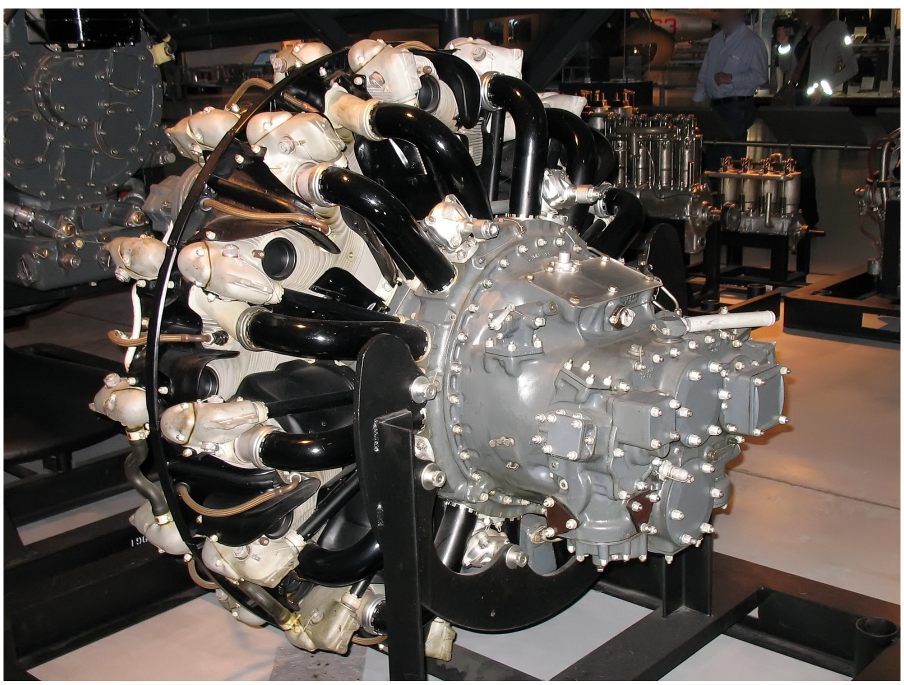
Pratt & Whitney R-2000 radial engine





How the radial aircraft engine works.

In the early days, automobile engines were modified for use in flying machines. The designs are:
Inline, as in most car engines today – and in older aircraft engines (think DH Gipsy Major);
Vee engines, such as pioneered by the Ford V-8 – and the Rolls-Royce Merlin; and
Horizontally-opposed auto engines, think Porsche – and the modern Continental aero engines.
Radial engines were not used in automobiles, although there were land and marine applications.

The radial engine is a reciprocating type, internal combustion engine configuration in which the cylinders 'radiate' outward from a central crankcase like the spokes of a wheel. The radial configuration was very commonly used for aircraft engines before turbine engines became predominant.

History

C. M. Manly constructed a water-cooled five-cylinder radial engine in 1901, a conversion of one of Stephen Balzer's rotary engines, for Langley's Aerodrome aircraft. Manly's engine produced 52 hp (39 kW) at 950 rpm. In 1903–1904 Jacob Ellehammer used his experience constructing motorcycles to build the world's first air-cooled radial engine, a three-cylinder engine that he used as the basis for a more powerful five-cylinder model in 1907. This was installed in his triplane and made a number of short free-flight hops.

Another early radial engine was the three-cylinder Anzani, one of which powered Louis Blériot's Blériot XI across the English Channel. Before 1914, Alessandro Anzani had developed radial engines ranging from 3 cylinders (spaced 120° apart) to a massive 20-cylinder engine of 200 hp (150 kW), with its cylinders arranged in four rows of five cylinders apiece.

The Rotary engine

From 1909 to 1919 the radial engine was overshadowed by its close relative, the rotary engine — which differed from the so-called 'stationary' radial in that the crankcase and cylinders revolved with the propeller. Mechanically it was identical in concept to the later radial except that the propeller was bolted to the engine, and the crankshaft to the airframe. The problem of the cooling of the cylinders, a major factor with the early 'stationary' radials, was solved by the engine generating its own cooling airflow. The rotating cylinders also acted as a flywheel for the slow-revving engine.

A fuel-metering carburetor was attached to the hollow fixed crankshaft. Air, fuel and castor oil (for lubrication), were drawn into the crankcase then passed through the intake pipes to the cylinders. The exhaust was timed to exit at the bottom of the engine to minimize interference with the pilot.

In World War I, many French and other Allied aircraft flew with Gnome, Le Rhône, Clerget and Bentley rotary engines, the ultimate examples of which reached 240 hp (180 kW).

By the end of the war the rotary engine had reached the limits of the design, particularly in regard to the amount of fuel and air that could be drawn into the cylinders through the hollow crankshaft, while advances in both metallurgy and cylinder cooling finally allowed stationary radial engines to supersede rotary engines.

This is a completely different design to the Wankel Rotary car engine developed in the 1970s.

The Radial engine

By 1918, the potential advantages of air-cooled radials over the water-cooled inline engine and air-cooled rotary engine that had powered World War I aircraft were appreciated but remained unrealized. In the 1920s British designers at the Bristol Aeroplane Company and Armstrong Siddeley produced reliable air-cooled radials such as the Bristol Jupiter and the Armstrong Siddeley Jaguar.

In the United States, the National Advisory Committee for Aeronautics (NACA) noted in 1920 that air-cooled radials could offer an increase in the power-to-weight ratio and reliability, and by 1921 the U.S. Navy had announced it would only order aircraft fitted with air-cooled radials. Charles Lawrance's J-1 engine was developed in 1922 with Navy funding, and using aluminum cylinders with steel liners ran for an unprecedented 300 hours, at a time when 50 hours endurance was normal. At the urging of the Army and Navy the Wright Aeronautical Corporation bought Lawrance's company, and subsequent engines were built under the Wright name.

Wright's 225 hp (168 kW) J-5 Whirlwind radial engine of 1925 was widely acknowledged as 'the first truly reliable aircraft engine.' The J-5 was used on many advanced aircraft of the day, including Charles Lindbergh's Spirit of St. Louis with which he made the first solo trans-Atlantic flight.

In 1925, the American rival firm to Wright's radial engine production efforts, Pratt & Whitney, was founded. The P & W firm's initial offering, the Pratt & Whitney R-1340 Wasp, test run later that year, began the evolution of the many models of Pratt & Whitney radial engines, among them the 14-cylinder, twin-row R-1830 Twin Wasp, the most-produced aviation engine of any single design, with a total production quantity of nearly 175,000 engines. (R = radial, number = cubic inch displacement).

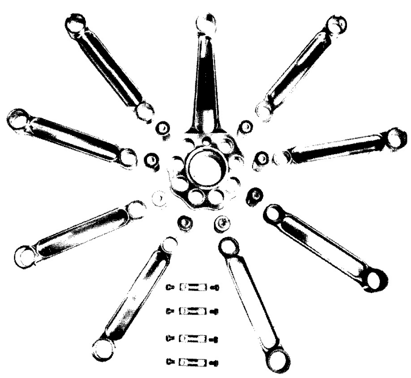
In the United Kingdom the Bristol Aeroplane Company was developing radial engines such as the Jupiter, Mercury and sleeve-valve Hercules. France, Germany, Russia and Japan largely built licenced or locally improved versions of the Armstrong Siddeley, Bristol, Wright, or Pratt & Whitney radials.

Sleeve-valve radial engines

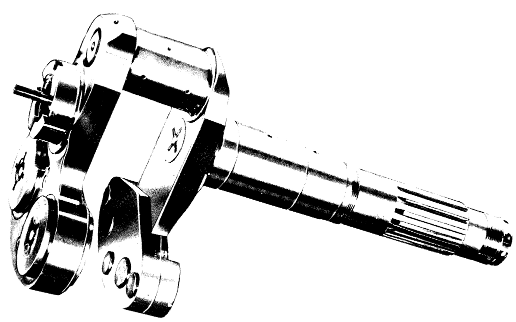
The Bristol radial engines used sleeve-valves rather than traditional poppet valves. Poppet valves get in the way of incoming gas, and hot exhaust valves limit compression and the octane rating of the fuel. Sleeve-valves use a ring or sleeve traveling up and down in the cylinder with the piston. A turning motion of the sleeve as it rises and falls aligns a hole in the sleeve wall with intake or exhaust ports and proper timing lets in gas and air, and lets out exhaust gases. Bristol built the 14-cylinder Bristol Hercules and the 18-cylinder Bristol Centaurus – Britain's most powerful radial that generated 2,500 hp. These engines were of increased complexity and required tighter manufacturing tolerances.

Engine operation

Since the axes of the cylinders are coplanar, the connecting rods cannot all be directly attached to the crankshaft. Instead, the pistons are connected to the crankshaft with a master-and-articulating-rod assembly. One piston has a master rod with a direct attachment to the crankshaft. The remaining pistons pin their connecting rods' attachments to rings around the edge of the master rod. Extra 'rows' of radial cylinders are added in order to increase the output of the engine without adding to its diameter.



Masterod and Linkrod assembly



Crankshaft

Four-stroke radials have an odd number of cylinders per row, so that a consistent every-other-piston firing order can be maintained, providing smooth operation. For example, on a five-cylinder engine the firing order is 1, 3, 5, 2, 4 and back to cylinder 1. Moreover, this always leaves a one-piston gap between the piston on its combustion stroke and the piston on compression. The active stroke directly helps compressing the next cylinder to fire, so making the motion more uniform. If an even number of cylinders were used, the equally timed firing cycle would not be feasible. The radial Zoche aero-diesels have an even number of cylinders, either four or eight; but this is not problematic, because they are two-stroke engines, with twice the number of power strokes as a four-stroke engine.

The radial engine normally uses fewer cams compared to other types. As with most four-strokes, the crankshaft takes two revolutions to complete the four strokes of each piston (intake, compression, combustion, exhaust). The camshaft ring is geared to spin slower and in the opposite direction to the crankshaft. The cam lobes are placed in two rows for the intake and exhaust. For the example, four cams serve all five cylinders, whereas 10 would be required for a typical inline engine with the same number of cylinders and valves.

Most radial engines use overhead poppet valves driven by pushrods and lifters on a cam plate that is concentric with the crankshaft, with a few smaller radials, like the Kinner B-5, using individual camshafts within the crankcase for each cylinder.

Radial versus inline debate

Pros

Weight: Air-cooled radial engines often weigh less than equivalent liquid-cooled inline engines.

Damage tolerance: Liquid cooling systems are generally more vulnerable to battle damage. Minor shrapnel damage easily results in a loss of coolant and consequent engine seizure, while an air-cooled radial might be largely unaffected by small damage.

Simplicity: Radials have shorter and stiffer crankshafts, a single bank radial needing only two crankshaft bearings as opposed to the seven required for a liquid-cooled six-cylinder inline engine of similar stiffness.

Reliability: The shorter crankshaft also produces less vibration and hence higher reliability through reduced wear and fatigue.

Smooth running: It is typically easier to achieve smooth running with a radial engine

Cons

Cooling: While a single bank radial permits all cylinders to be cooled equally, the same is not true for multi-row engines where the rear cylinders can be affected by the heat coming off the front row, and air flow being masked.

Drag: Having all the cylinders exposed to the airflow increases drag considerably, adding turbulence that can destroy the laminar airflow over the fuselage and adjacent wings.

Power: Because each cylinder on a radial engine has its own head, it is impractical to use a multi-valve valvetrain on a radial engine. Therefore, almost all radial engines use a two valve pushrod-type valvetrain which may result in less power for a given displacement than multi-valve inline engines.

Visibility: Pilot visibility is often poorer due to the bulk of the engine

Installation: The designer can be limited in engine placement, having to ensure adequate cooling air, which can be a challenge in a buried engine installation or pusher configurations.

The answer to some of the drag issues was the addition of specially designed cowlings with baffles to force the air over the cylinders. The first effective drag reducing cowling that didn’t impair engine cooling was the British Townend ring or ‘drag ring’ which formed a narrow band around the engine covering the cylinder heads, not only reducing drag, but adding a small amount of thrust. The National Advisory Committee for Aeronautics then studied the problem, developing the NACA cowling which further reduced drag, increased thrust and improved cooling. Nearly all aircraft radial engine installations since have used NACA type cowlings. Tight fitting cowlings also tended to reduce the bulk of engine installations and improve visibility, particularly for single-engined fighter aircraft.

The German BMW firm came up with an innovation for their World War II-produced BMW 801 twin-row, 14-cylinder radial engine by integrating the 801’s oil cooler within the forward cowl’s structure. BMW designed the cowls used for every example of the 801 ever built, all with the integral oil cooler present in the forward section of the cowl. This made it an appropriate choice for a powerplant to be ‘unitized’ in the effort to produce a rapidly interchangeable aviation engine for maintenance purposes in front-line combat conditions, within the so-called German Kraftei (power-egg) unitized engine installation design philosophy. The BMW 801 ended up being the Third Reich’s most-produced radial engine of any type, with some 28,000 examples built.

While inline liquid-cooled engines were common in new designs until late in World War II, radial engines dominated until overtaken by jet engines, with the late-war Hawker Sea Fury and Grumman Bearcat, two of the fastest production piston-engined aircraft ever built, using radial engines.

Multi-row radials

Originally radial engines had one row of cylinders, but as engine sizes increased it became necessary to add extra rows. The first known radial-configuration engine to use a twin-row design was the 160 hp Gnôme ‘Double Lambda’ rotary engine of 1912, designed as a 14-cylinder twin-row version of the firm’s 80 hp Lambda single-row seven-cylinder rotary.

Two-row designs began to appear in large numbers during the 1930s, when aircraft size and weight grew to the point where single-row engines of the required power were simply too large to be practical. Two-row designs often had cooling problems with the rear bank of cylinders, but a variety of baffles and fins were introduced that largely eliminated these problems. The downside was a relatively large frontal area that had to be left open to provide enough airflow, which increased the amount of drag. This led to significant arguments in the industry in the late 1930s about the possibility of using radials for high-speed aircraft like modern fighters.

The solution was introduced with the BMW 801 14-cylinder twin-row radial. Kurt Tank designed a new cooling system for this engine that used a high-speed fan to blow compressed air into channels that carry air to the middle of the banks, where a series of baffles directed the air over all of the cylinders. This allowed the cowling to be tightly fit around the engine, reducing drag, while still providing enough cooling air to the rear to keep the engine working well.

A major study into the airflow around radials using wind tunnels and other systems was carried out in the US and demonstrated that ample airflow was available through careful design. Pratt & Whitney produced the R-4360 Wasp Major, which had 28 cylinders arranged in a 4-row ‘corncob’ configuration and an output of 4300 hp. The engine was used on large post-World War II American aircraft.

Large radials continued to be built for other uses, although they are no longer common. One example is the Zvezda diesel boat engine series with 56 cylinders or 112-cylinders in 8 or 16 rows of 7 cylinders each displacing 383 litres (23,931 cu in) and producing 10,000 hp (7,500 kW). These were used on fast attack craft, such as Osa class missile boats.

Radials in helicopters

To fill the requirement for greater load carrying the P&W R-1340 radial engine was used in the Piasecki HRP-1 twin-rotor helicopter in 1945 the and Sikorsky S-55 in 1949. A unique design feature of the S-55 was to incline the radial engine in a special mount in the nose to give a large obstruction-free cabin. A later development, the H-34 (civilian S-58) used a 1,500 hp Wright engine and could transport 16 troops. It was used extensively in the Vietnam war and was licence-built in France and Britain. Many were later converted to turbine power (as the S-58T) using a Pratt & Whitney Canada PT6T-3 Twin-Pac turboshaft engine in an extended nose fairing.

Diesel radials

While most radial engines have been produced for gasoline, there have been diesel radial engines. Two major advantages favour diesel engines — lower fuel consumption and reduced fire risk.

Packard designed and built a 9-cylinder 980 cubic inch (16,000 cc) displacement diesel radial aircraft engine, the 225 horsepower (168 kW) DR-980, in 1928. On 28 May 1931, a DR-980 powered Bellanca CH-300, with 481 gallons of fuel, set a record for staying aloft for 84 hours and 32 minutes without being refueled. In 1932 the French company Clerget developed the 14D, a 14-cylinder two-stroke diesel radial engine. After a series of improvements, in 1938 the 14F2 model produced 520 hp (390 kW) at 1910 rpm cruise power, with a power-to-weight ratio near that of contemporary gasoline engines and a specific fuel consumption of roughly 80% that for an equivalent gasoline engine.

Use in tanks

In the years leading up to World War II, as the need for armored vehicles was realized, designers were faced with the problem of how to power the vehicles, and turned to using aircraft engines, among them radial types. The radial aircraft engines provided greater power-to-weight ratios and were more reliable than conventional inline vehicle engines available at the time.

The Continental R-670, a 7-cylinder radial aero engine that first flew in 1931, became a widely used tank powerplant. The Guiberson T-1020, a 9-cylinder radial diesel aero engine, and the Continental R-975 saw service in armoured vehicles.

Modern radials

A number of companies continue to build radial engines today. Vedeneyev produces the M-14P radial of 360–450 hp (270–340 kW) as used on Yakovlev and Sukhoi aerobatic aircraft. The M-14P is also used by builders of homebuilt aircraft, such as the Culp Special, and Culp Sopwith Pup, Pitts S12 ‘Monster’ and the Murphy ‘Moose’. 110 hp (82 kW) 7-cylinder and 150 hp (110 kW) 9-cylinder engines are available from Australia’s Rotec Engineering. HCI Aviation offers the R180 5-cylinder (75 hp (56 kW)) and R220 7-cylinder (110 hp (82 kW)), available ‘ready to fly’ and as a build-it-yourself kit. Verner Motor of the Czech Republic builds radial engines ranging in power from 25 to 150 hp (19 to 112 kW).

Frequently Asked Questions About Radial Engines

Why does a Radial Engine always have an odd number of cylinders?

Any four-stroke engine, regardless of construction, must fire all of the cylinders in two revolutions of the crankshaft.

- Unlike an automobile engine, a radial engine has only one crankshaft throw for all the cylinders in a bank. An 18-cylinder engine is just two 9-cylinder banks, set 180 degrees to each other.
- The firing order starts with the #1 cylinder at the top and proceeds around the engine in a counter clockwise direction as viewed from the front. The firing order progresses from the #1 cylinder, skips #2 cylinder and fires #3 cylinder. So in the first revolution of the crank, the firing order would be #1, #3, #5, #7 and #9.
- Using this skip and fire technique, the next cylinder to skip on the second revolution of the crankshaft, would be the #1 cylinder. On the second revolution of the crank, the firing order would be #2, #4, #6, #8. Again using the skip and fire technique, the #9 cylinder is skipped and the #1 cylinder is again ready to start the whole process over again. If there were an even number of cylinders, half would never be fired.

How does the cam work?

- Consider a nine cylinder radial as an example. In a 9 cylinder, there are 40 degrees between the cylinders. Referring to the firing order explanation, the crank progresses two cylinders between firings, or 80 degrees.
- The cam drive gears are designed to run the cam 1/8 speed in the opposite direction to the crankshaft. This is accomplished with two-stage gear reduction. A single jackshaft using a spur gear set makes a 2 to 1 reduction. On the other end of the jackshaft, a second stage reduction of 4 to 1 is made using an internal tooth ring gear mounted along the inside diameter of the cam ring. Other gearing combinations are possible, but are difficult to package in the limited space available in the crankcase.
- While the crankshaft is turning counter-clockwise, as seen from the front, through 80 degrees, at the same time the cam ring is turning 10 degrees in the opposite direction. The combination is 80 + 10 degrees. So there are four lobes, each at 90 degrees on both the intake and exhaust cam rows.

How do the pistons connect to the crankshaft?

- As shown in the picture, one cylinder is equipped with a 'master rod.' On the crank throw end the master rod has two rings with holes to receive a pin from other rods. The remaining pistons have a connecting rod that is pinned to the two rings of the master rod.

How is oil kept out of the lower cylinders?

- Radial engines incorporate a 'dry-sump' oil system. In addition, the cylinder skirts extend into the crankcase inside diameter. This keeps the oil from easily entering the cylinder bore. The oil is directed from the crankcase into the oil sump between the two lower cylinders and returned to the tank.
- With these provisions, the two lower cylinders still require constant attention. When allowed to stand, without running, the oil can accumulate in the combustion chambers. When the piston reaches top dead center (TDC) there is no place for the oil to go. This is known as hydraulic lock. If steps are not taken to drain the oil, severe engine damage can result.

How does the ignition system work?

All aircraft engines have a dual ignition system for safety reasons – if one system fails the engine will continue to operate. Most have dual magnetos, with each magneto providing the spark to one of the two spark plugs in each cylinder. Usually the magnetos are mounted on the accessory drive at the back of the engine with a wiring harness threading its way between the cylinders to each spark plug. A magneto switch in the cockpit allows the pilot to cut out one ignition system at a time to check the magnetos before takeoff. The Jacobs engines have one magneto and one coil ignition system.

How does the fuel get to the cylinders?

Smaller radial engines have the carburetor on the bottom of the engine with the fuel-air mixture passing through internal passages and intake pipes to each cylinder. Larger engines may have a top-mounted carburetor with the mixture flowing directly into the supercharger and then to each cylinder.

The P&W R-2800 does not mix fuel and air in the carburetor, instead metering the fuel according to the throttle setting, then sending fuel directly to the supercharger inlet for distribution to the cylinders.

Smaller radials are usually ‘normally aspirated’ while medium and larger engines incorporate a supercharger driven from the gear case at the rear of the engine – at up to 10x engine speed. This allows sea-level performance of the engine up to much higher altitudes. The supercharger may be single or two-speed, and may have one or two stages. Some radials incorporate a power-recovery turbine in the exhaust stream that directs power back to the engine. To achieve a higher takeoff power, fuel with octane ratings up to 145 was used and a water injection system, known as the anti-detonant injection (ADI), directed a water-alcohol spray into the air stream.

What is power-weight ratio?

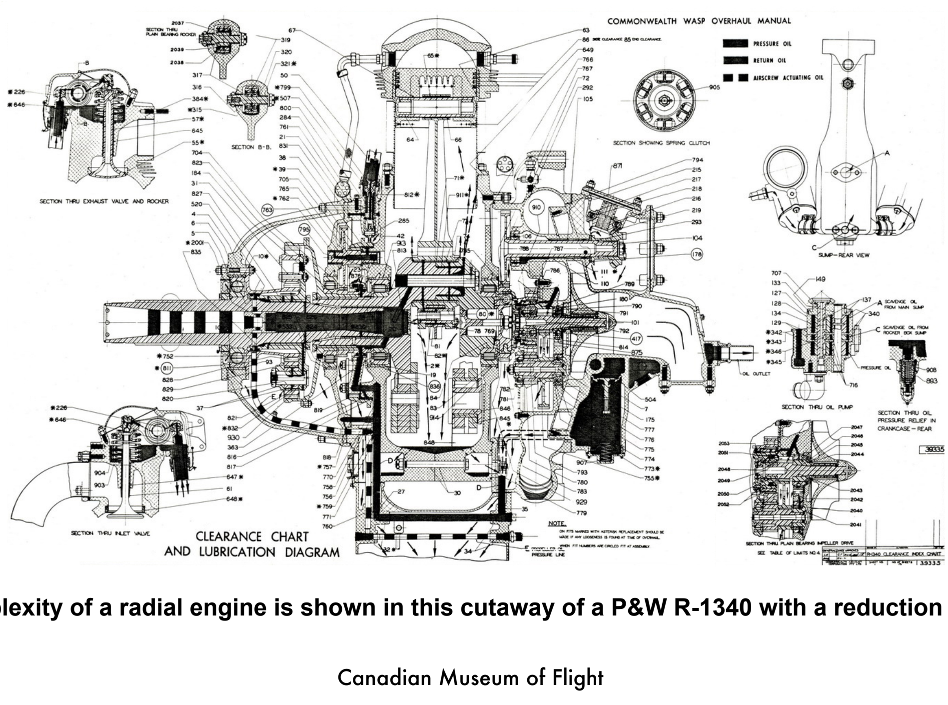
Aircraft engines must produce as much power as possible while weighing as little as possible. This is usually expressed in terms of pounds per horsepower (lb/hp). One way to make an engine more powerful is to make it bigger, but this also makes it heavier. Moreover, if metal is shaved away to make it lighter, parts start to break and generally become less reliable. Another option is to get more power from a given size. Engine size is usually expressed in cubic inches (cu in) of swept volume (the volume displaced by all the pistons going up and down). If the engine gets more horsepower per cubic inch (hp/in), it has been made lighter. The Curtiss OX-5 (1915) displaced 503 cu/in, weighed about 390 pounds and produced 90 hp (0.18 hp/in, 4.33 lb/hp). By contrast, the P&W R-1340 (1925) produced 600 hp from 1340 cu/in and weighed 930 lb (0.45 hp/in, 1.55 lb/hp) and the Wright R-3350 (1937) displaced 3350 cu in, weighed 3670 lb., and produced as much as 3700 hp (1.10 hp/in, 0.99 lb/hp), improvements of six-fold in hp per cubic inch and over four-fold in power-to-weight ratio.

The Wright brothers decided to design and build the engine for their aircraft. They finished it in eight weeks with the aid of Charles Taylor, a mechanic and machinist, but without drawings. The 12-hp, four-cylinder engine weighed 179 lb, giving a p/w ratio of 14.9 lb/hp. Their later production engines were 30 hp and 180 lb (6 lb/hp). In WW1 the Bentley BR2 rotary engine generated 230 hp and weighed 500 lb. (2.2 lb/hp) and the V12, water-cooled Liberty 12-A of 1918 had an output of 410 hp for a weight of 786 lb. (1.9 lb/hp). The famous Wright J-5 Whirlwind used by Charles Lindbergh on his trans-Atlantic flight had an output of 220 hp for a weight of 510 lb (2.3 lb/hp). However, this air-cooled engine did away with the plumbing of liquid-cooled engines with consequent improvement in reliability.

The Pratt & Whitney Twin Wasp of 1932 put out 1,200 hp and weighed 1,467 lb (1.2 lb/hp); the Bristol Centaurus of 2520 hp was 2695 lb. (1.1 lb/hp); the P&W R-2800 2000 hp, 2350 lb (1.2 lb/hp).

For the big Vee engines the power-to-weight race was very competitive as well; the Rolls-Royce Merlin 61, 1580 hp and 1640 lb (1.03 lb/hp), the Griffon 65 at 2220 hp and 1980 lb (0.9 lb/hp) and the Allison V-1710-F30 at 1500 hp and 1395 lb (0.9 lb/hp).

By contrast, the modern PT-6A-6 turbo-prop with an output of 578 hp weighs only 270 lb (0.47 lb/hp).



The complexity of a radial engine is shown in this cutaway of a P&W R-1340 with a reduction gearbox.