OX-5s to Turbo-Compounds: A Brief Overview of Aircraft Engine Development

By Kimble D. McCutcheon

During the period between the World Wars, aircraft engines improved dramatically and made possible unprecedented progress in aircraft design. Engine development in those days, and to a large extent even today, is a very laborious, detailed process of building an engine, running it to destruction, analyzing what broke, designing a fix, and repeating the process. No product ever comes to market without some engineer(s) having spent many long, lonely, anxious hours perfecting that product. This is especially true of aircraft engines, which by their very nature push all the limits of ingenuity, materials, and manufacturing processes.

Aircraft Engine Requirements and Measures of Performance

In order to compare engines, we must discuss the special requirements of aircraft engines and introduce some measures of performance. The requirements are in some ways contradictory, and therein lies the engineering challenge. For the purpose of this discussion, we will compare the Curtiss OX-5 to the Wright R-3350. The OX-5, though hardly state-of-the-art at the end of WWI, was the first U.S. aircraft engine to be mass-produced and was produced in such quantities that war surplus ones powered aircraft for the next twenty years. The Wright R-3350, completely state-of-the-art at the end of WWII, had been developed for the Boeing B-29 (the aircraft that dropped the atomic bomb on Japan) and was widely used in airline service through the middle sixties.

RELIABILITY

The first and most important requirement for an aircraft engine is that it must be reliable. At the end of WWI, the Curtis OX-5 regularly failed after only 30 hours of operation. During the 1950's, airlines often ran Wright R-3350s 3000 hours. This hundred-fold increase in reliability is one of the fascinating subjects of this discussion. These values are usually expressed in Time Between Overhaul (TBO), but are not really directly comparable. Pilots often ran OX-5s to failure and forced landings were common. Airlines, on the other hand, figured a forced landing might scare their passengers, so they put on multiple engines, kept good records about how long particular engines could be expected to last, and presumably overhauled them <u>before</u> they failed. The point, however, is that engines got much, much better during the period of our interest.

POWER-TO-WEIGHT RATIO

Secondly, 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 you shave away metal to make it lighter, parts start to crack, break, and generally become less reliable. You can see the conflicting objectives faced by the engineer. 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 you can make an engine get more horsepower per cubic inch (hp/in), then you have made it lighter. The OX-5 displaced 503 cu/in, weighed about 390 pounds and produced 90 HP (0.18 hp/in, 4.33 lb/hp). By contrast, the R-3350 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 horsepower per cubic inch and over four-fold in power-to-weight ratio.

FUEL CONSUMPTION

Finally, an aircraft engine must be fuel-efficient. A great deal of the take-off weight of an airplane is dedicated to fuel. So if one can make the engine(s) more fuel efficient, less fuel must be carried to go the same distance, and more bombs, passengers or freight can be carried instead. Fuel usage is expressed in terms called Brake Specific Fuel Consumption (BSFC). This is the number of pounds of fuel an engine uses per horsepower per operating hour (lb/hp/hr). Fuel is measured in pounds because a pound of fuel is always the same amount of fuel, while a gallon of fuel at 100 degrees weighs less than a gallon of fuel at 20 degrees. BSFC for the OX-5 was about .53 lb/hp/hr, while the R-3350 was about .38 lb/hp/hr. If one could compare a ten hour flight under similar conditions and power settings, one would have to carry 371 pounds of fuel for the OX-5 verses 257 pounds of fuel for the R-3350, or a savings of 114 pounds. This may not seem like much of a difference, but again, it is an unrealistic comparison because of the huge difference in the output of the two engines. In reality, tens of thousands of pounds of fuel were carried in the huge transports of the 1950's, and improvements in fuel consumption made significant differences in overall aircraft capability. Indeed, ocean-crossing airliners such as the Lockheed Super Constellation and

Douglas DC-7 would have not been economically feasible without the superb fuel consumption of advanced engines.

Areas of Improvement

So how were these remarkable improvements made? They were done by systematically improving seven areas of engine design and construction: Arrangement, materials, cooling, induction, lubrication, fuels, and operation. Most of these are necessarily interrelated, as we shall see.

In addition to engine improvements, there were also important advances in aircraft and propeller design. Perhaps the greatest engine-related airframe advance was the development of the NACA cowl that reduced the cooling drag of air-cooled radial engines to levels that were competitive with liquid-cooled engines. The greatest propeller advance was the introduction in the 1930s of controllable pitch and later automatically controlled constant speed. Constant-speed propellers allow engines to produce maximum take-off power by turning maximum RPM due to fine blade pitch, and then cruise at efficient lower RPM through the selection of a coarse blade pitch.

We will now briefly discuss each of these areas of improvement. Many of the engines have companion articles that go into greater technical detail.

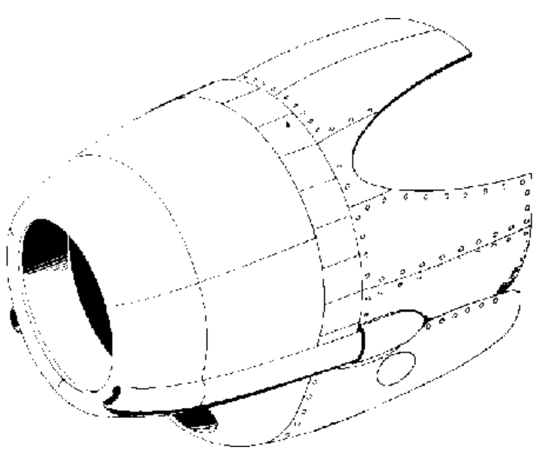


Figure 1. The NACA low-drag cowl

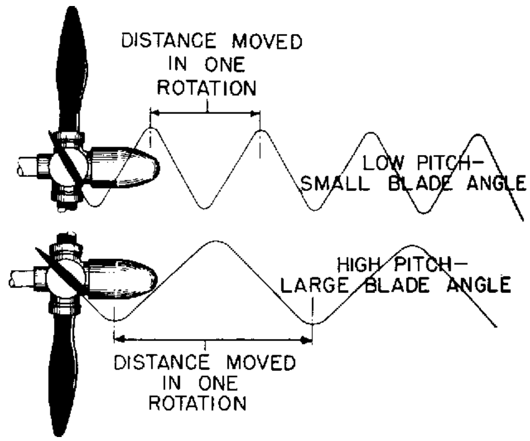


Figure 2. The variable pitch propeller

Arrangement

Engine arrangement refers to the organization of multiple cylinders around the crankshaft. There are really only two ways of doing this - to put them all in a row along the length of the crankshaft, as in the in-line engine, or to put them around a single throw of the crankshaft like spokes in a wheel, as in radial engines. For a long time, aircraft designers were overly concerned with frontal area of engines, because this had to be accounted for in the design of the airframe, and produced drag. In-line, opposed, and V-type engines provide the least frontal area because cylinders are “stacked” one behind the other. Unfortunately, any engine flexes as it runs and must be stiff enough so that it does not crack its components. This requires a very heavy crankcase and crankshaft. The radial configuration avoids this problem by having a short, stiff crankcase and crankshaft.

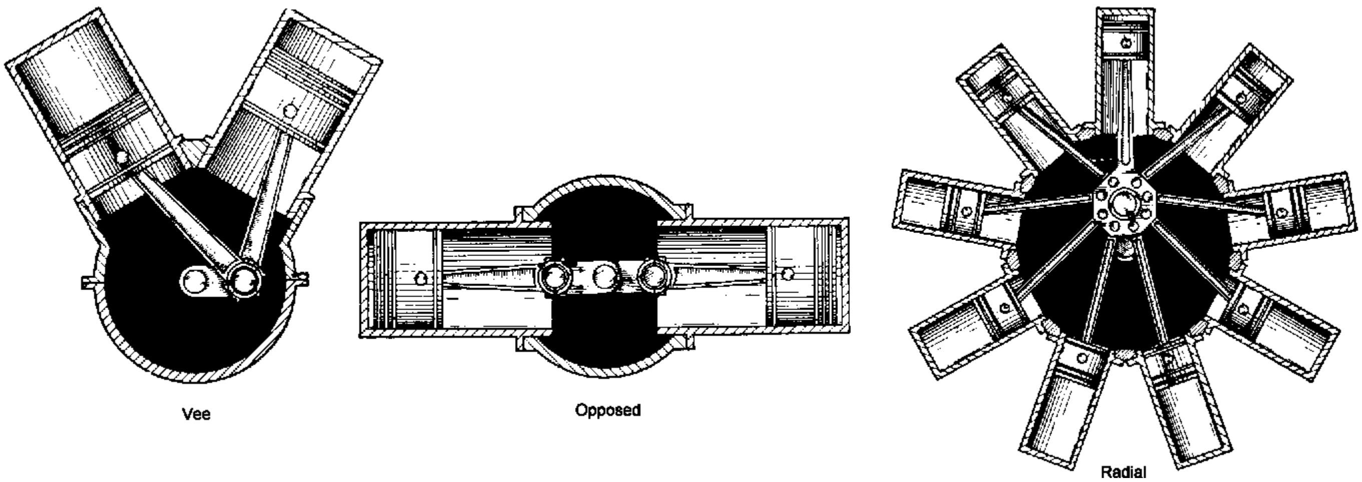


Figure 3. Engine arrangements

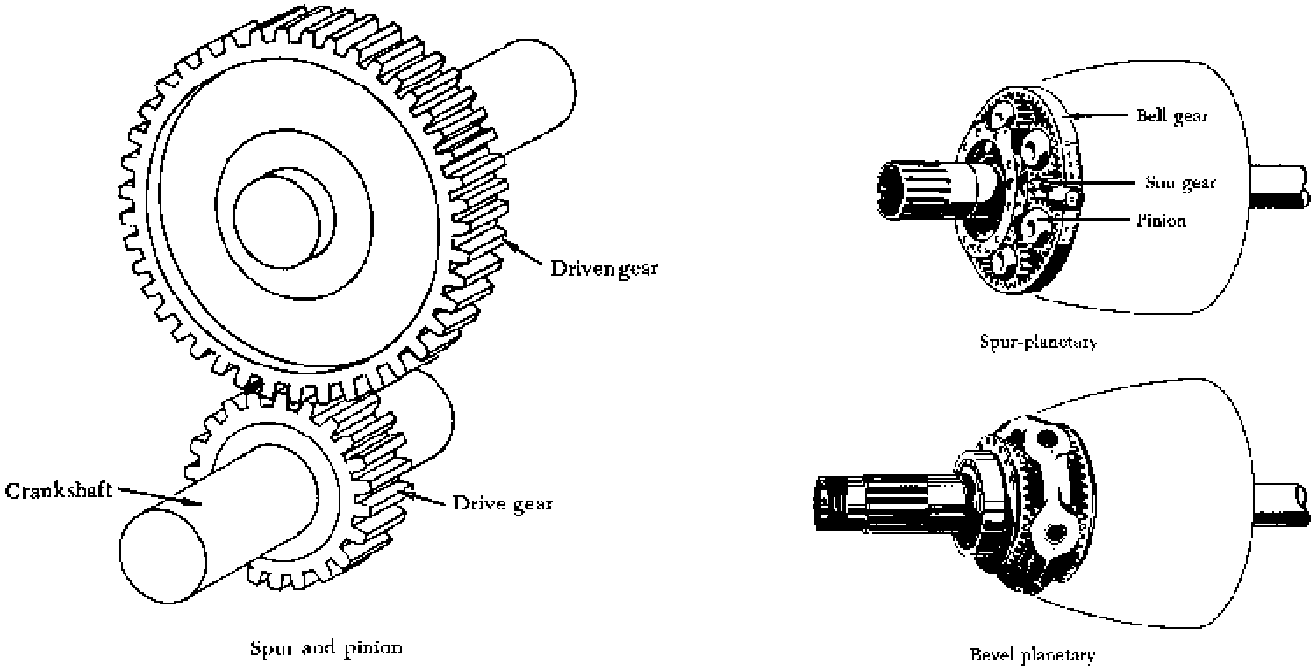


Figure 4. Propeller reduction gearing

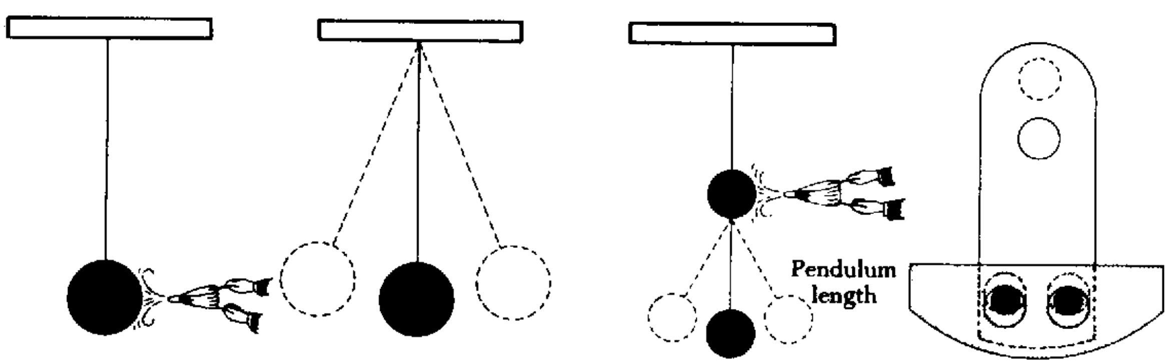
Over time, designers learned to stack multiple rows of radial cylinders together, and since this had the best power-to-weight ratio, it became the preferred configuration for high-power engines. Advances in cowl design all but eliminated any frontal area advantage of the in-line and V-type engine. Many other configurations were tried, but none ever equaled the multi-row radial engine for power-to-weight ratio.

The Curtiss OX-5, Rolls-Royce Merlin (V-1610), and Ranger V-770 are examples of V-type engines. There are many examples of multi-row radial engines, with the Wright R-3350 and Pratt & Whitney R-4360 being the latest and most highly refined. There are also many examples of opposed engines.

While engines are able to achieve higher power by turning higher RPM, propeller RPM is limited by tip speed. In order to remain efficient, propeller tips must remain below the speed of sound. Otherwise, engine power is wasted overcoming the excess drag of propeller tips making shock waves and noise. The logical answer to this paradox lies in the use reduction gearing, allowing the engine to turn faster than the propeller. Propeller reduction gearing was a feature of the 1903 Wright "Flyer", but it took a considerable amount of work to sort out the details of reduction gearing for high-powered radial engines, particularly multi-row radials. Each power stroke of the engine tends to slightly wind up the crankshaft. The propeller resists this winding, or torsion. When the power stroke subsides, the somewhat springy crankshaft unwinds producing a phenomenon called torsional vibration. This plagued early engines, was not very well understood, and was generally fixed by resorting to huge spur or helical-cut gears with massive teeth that could resist the shock loads imposed on the reduction gearing by torsional vibration. Later engines saw the development of planetary reduction gears with very close tolerances that mitigated some of the effects of torsional vibration.

It all came to a head when controllable-pitch propellers fitted to early Wright R-1820 Cyclones began breaking propeller shafts. It turned out that the greater weight of controllable-pitch propellers increased the effective mass of the propeller and allowed vibrations of certain frequencies to actually fatigue the propeller shaft until it broke. The solution was to fit tuned dynamic torsional vibration absorbers in the form of massive dynamic counterweights loosely attached to the crankshaft so they were free to move slightly in the plane of rotation. Weight and pendulum length were calculated so that the dynamic counterweight vibrated at the same frequency as the power strokes of the engine, but out of phase so as to cancel out the effect of the torsional vibration.

Both the Wright R-3350 and Pratt & Whitney R-2800 encountered another vibration-related problem. These were the first multi-row radials with nine cylinders per row, and they too began breaking engine parts early in development. The problem in this case was traced to a different mechanism, but was still vibration related. Radial engines with the master /articulating rod system produce slightly different motions for each piston/rod combination, and can never have perfect balance. This becomes more of a problem as the number of cylinders per row increases. The unbalance tends to make the engine move in a circle in the same plane as the cylinders. Because two-row radials have a two-throw crankshaft, two such motions acting at twice crankshaft speed tend to cause the engine to wobble about its center main bearing. This wobble causes the propeller change its plane of rotation, and eventually fatigues the propeller shaft to the breaking point. The solution is rotate correctly sized counterbalances at twice crankshaft speed and in same direction as crankshaft rotation.



If a simple pendulum is given a series of regular impulses at a speed corresponding to its natural frequency (using a bellows to simulate a power impulse in an engine) it will commence swinging, or vibrating, back and forth from the impulses. Another pendulum, suspended from the first, would absorb the impulses and swing itself, leaving the first stationary. The dynamic damper is a short pendulum hung on the crankshaft and tuned to the frequency of the power impulses to absorb vibration in the same manner.

Figure 5. Principle of tuned dynamic torsional vibration absorber

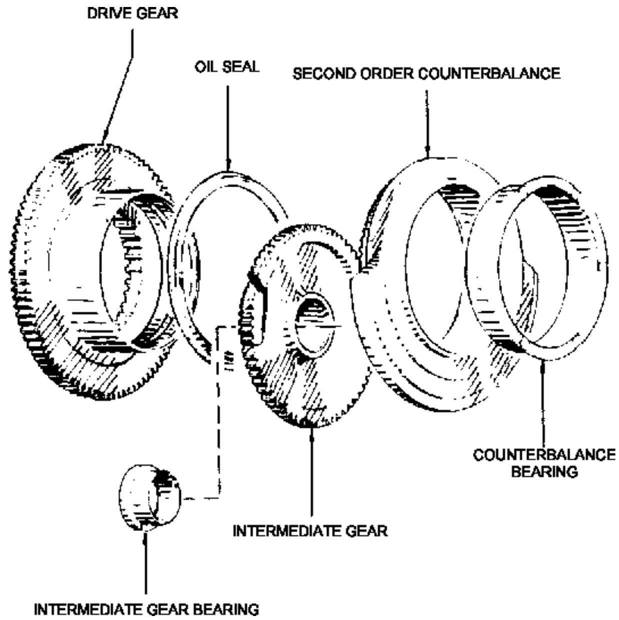


Figure 6. Second order counterbalance

Materials

An engine designer, always striving for low weight, typically makes everything out of the lightest material that is practical. This usually translates into the use of aluminum for the bulky components (such as pistons, cylinder heads, and crankcases) and steel for the highly stressed components (such as crankshafts, connecting rods, and gears). Over time, designers created lighter and stronger alloys, developed ways to harden materials so they lasted longer, and most importantly, learned ways of forming metal components so that the "grain" of the metal (metals have grain just like wood) was correctly aligned to handle the stresses imposed on the part. This process, called forging, vastly improved the strength of almost all engine components. Consider the strength of a crankshaft carved from a single plank of wood. Though the grain of the wood is in line with the bearing journals of the crankshaft, the throws of the crankshaft would be cut across the grain and would be quite weak. This was the precise problem of early engines. Crankshafts were machined from giant chunks of steel that had been hot-rolled so that all the grain of the metal was in one direction. The forging process takes a hot chunk of metal and hammers it into roughly the final shape. The metal grain is forced to conform to the final shape and is much stronger. Nearly all engines made after 1920 used forged crankshafts, connecting rods, and pistons. As forging processes became better understood and huge hammer forges became available, larger engine parts such as crankcases were forged. The Pratt & Whitney R-1340 "Wasp" was the first American radial to use a forged crankcase.

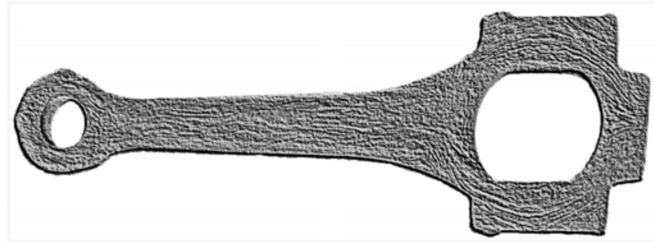


Figure 7. Etched connecting rod rough forging showing metal flow lines

Further benefits were obtained by improving the art of casting large chunks of aluminum. In the early days, crankcases with integral cylinders could not be cast because no one knew how to make such large castings without flaws. In-line and V-type engines with the cylinders separate from the crankcase could never be as stiff as a single large casting, and consequently, were heavier than necessary. The Curtiss OX-5 is an example of a separate-cylinder engine while the Rolls-Royce Merlin is an example of a one-piece block.

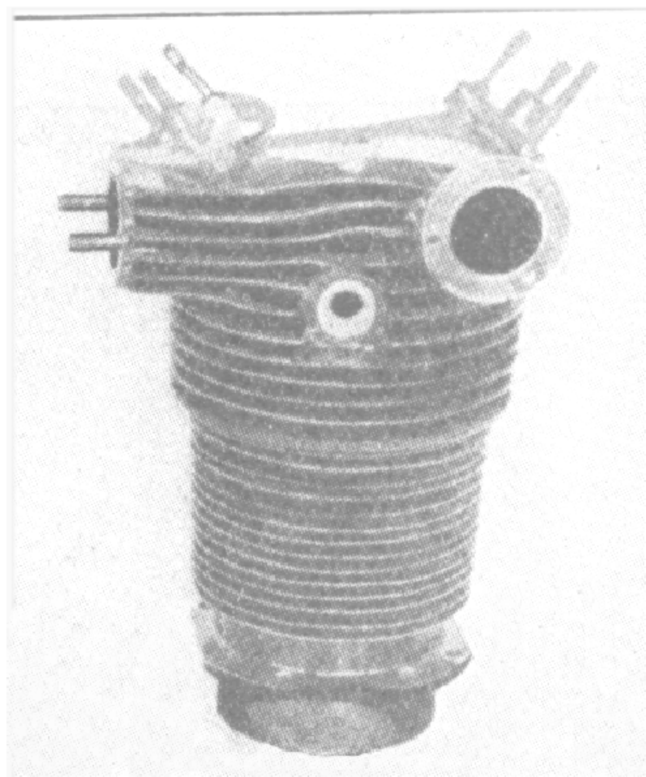


Figure 8. J-5 cylinder

Cylinder heads are another example of the progress of the casting art. Compare the Wright J-5 "Whirlwind" with the Pratt & Whitney R-2800. Each engine has cast cylinder heads, but the fins on the J-5 are much further apart and much less deep than those of the R-2800. Considerable experimentation was required to perfect these extremely complex castings, and much work was required to produce the pattern and the mold for each one. The result was an enormous increase in fin area and better cooling. Later heads were forged, with their fins cut by special automated machines. Not only were the forged heads about twice as strong as the best cast ones, but the fins could be deeper and closer together, resulting in higher powers and better cooling. Forged heads can be seen on the Wright R-3350.

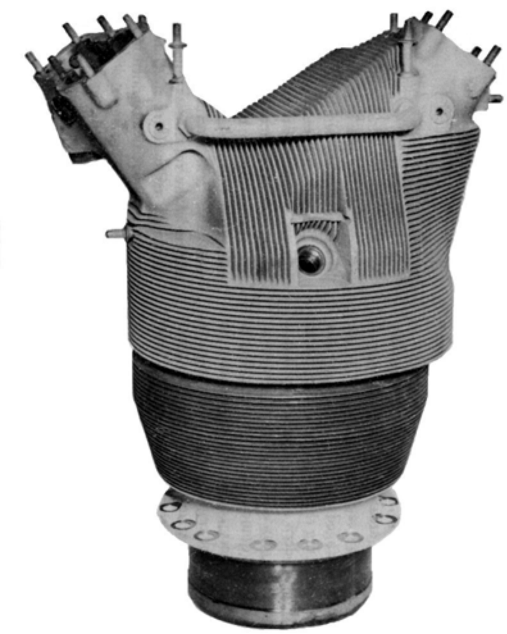


Figure 9. R-2800 cylinder

As Pratt & Whitney began to extract more and more power from their early engines, they began to have occasional master rod bearing failures in the lead-copper plain bearings originally used. A massive amount of effort was thrown into experiments with different bearing materials. Eventually, it was discovered that a silver bearing plated with lead and then indium had extremely good wear properties. In the 1950's, an airline returned one of these bearings to Pratt & Whitney for rework after it had run over 7,000 hours. Pratt & Whitney returned it saying there was no wear, approving it for continued service.

Finally, improvements in the materials and fabrication techniques for valves made significant improvements in the power and durability of engines. Most of this work was done first at the Royal Aircraft Factory at Farnborough, England and later at McCook Field in Dayton, Ohio. Experimentation with simple single-cylinder engines determined the best materials and geometry for valves, guides and seats. The sodium-cooled exhaust valve was also invented at McCook field. This valve featured a hollow stem partially filled with liquid sodium. As the valve opened and closed, the sodium sloshed about, moving heat away from the head to the stem of the valve. All Wright and Pratt & Whitney radial engines use this style of exhaust valve.

Cooling

No debate was more heated in engine design circles than the one over cooling. As with most heated debates, neither side in retrospect knew what it was talking about. The choices were liquid cooling, where, as in automobile engines, the cylinders are surrounded by a liquid coolant (usually water and anti-freeze) which removes excess heat from fuel combustion and is circulated to a radiator where it gives up this heat to the air. Air-cooled engines, like lawn mowers, have cooling fins on the cylinders, and give up their heat directly to the air. The subject is complex, and it took many years to sort it out completely (indeed, it may still not be sorted out). In the early days, air-cooling was so poorly understood that almost no one could make it work at all, and certainly not for any high-power applications. Liquid cooling at least allowed the production of four or five hundred horsepower engines. But these were unreliable engines. The Army, who in those days had the luxury of flight over land, preferred liquid cooled engines because of their lower frontal area. The Navy, on the other hand, discovered that fully twenty-five percent of engine failures were due to failure of the cooling system, and declared that "Liquid-cooled airplanes make about as much sense as air-cooled submarines!"

During the twenties, air cooling became much better understood, and high-power air-cooled engines flourished to such an extent that all work on liquid cooled engines ceased, and both the Navy and Army had to pay premiums to attract any interest among engine companies an liquid-cooled engines. The major improvements were made at McCook Field, and appear on all air-cooled engines since. Innovations included an aluminum cylinder head with the valves set at a very wide angle to allow plenty of airflow around the exhaust port. A steel cylinder liner with machined cooling fins was screwed and shrunk into this aluminum head, resulting in a gas-tight seal between the head and barrel. The exhaust valve was the sodium-cooled variety discussed above. Nearly all air-cooled engines have cylinders of this design (it first appeared on the Wright J-5 "Whirlwind").

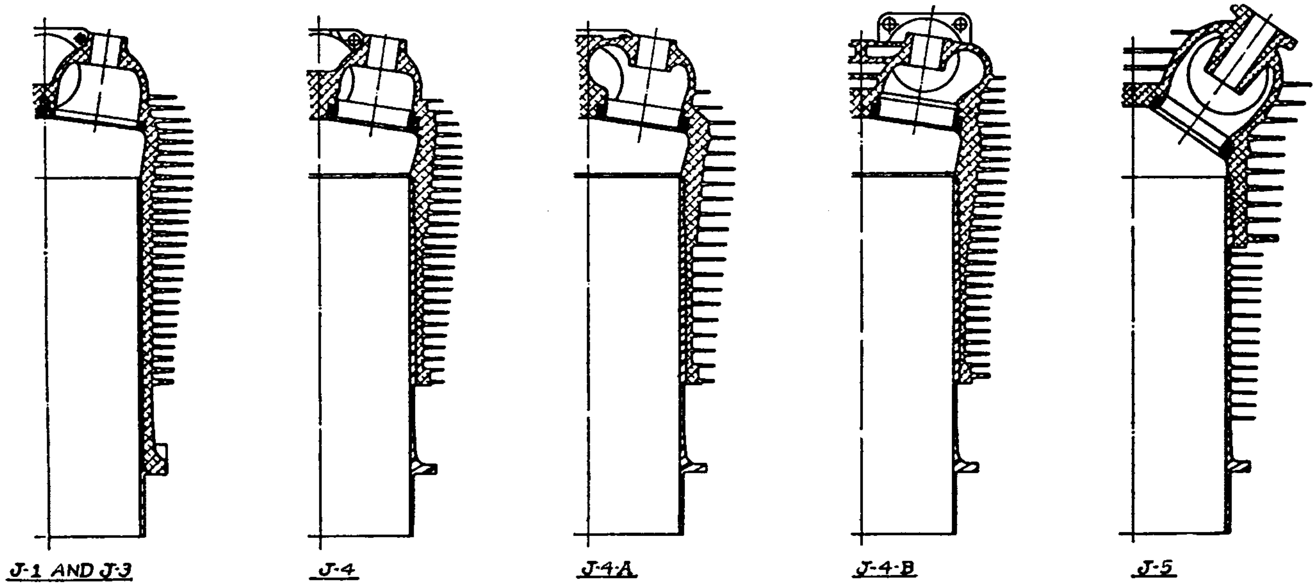


Figure 10. Wright J-5 Cylinder Development. Note improved heat rejection at exhaust port.

Induction

Induction is the process by which fuel is mixed with air and introduced into the cylinder. Engine power is a function of the pressure at which induction occurs. By forcing more of the fuel-air mixture into the engine at higher pressure, impressive additional power can be achieved. This process is called supercharging. Superchargers are pumps that increase the pressure of the fuel-air charge. In aircraft engines, these nearly always take the form of centrifugal compressors.

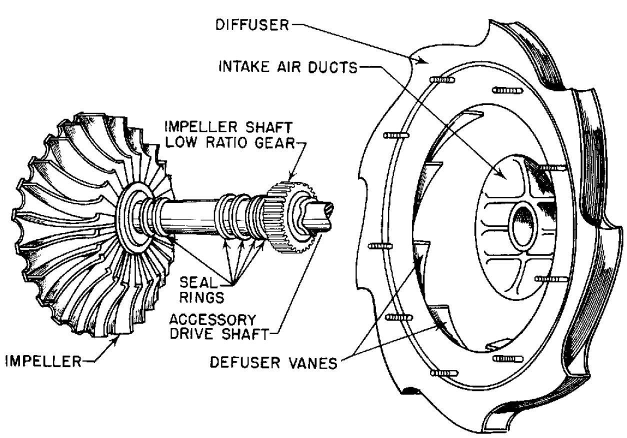


Figure 11. Supercharger impeller and diffuser

Improvements in superchargers greatly assisted the increased production of power, and also allowed the engine to produce sea-level power at considerably greater altitudes than non-supercharged engines. Early superchargers were just “rotary induction systems”, and served little purpose other than to assure equal distribution of fuel to all cylinders. As engine development progressed, superchargers became better and better compressors by providing higher pressure while consuming less power.

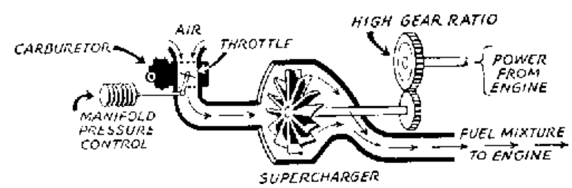


Figure 12. Single-stage supercharger

Supercharger design is a tricky business. Not only must the supercharger be efficient to avoid wasting engine power and excessively heating the intake charge, but it must also have a pressure rise and pumping volume that is carefully matched to the engine it is a part of. The first American production engine to use a supercharger was the Pratt & Whitney R-1340 “Wasp”. All early engines used superchargers from the same source - General Electric. By the 1930’s, it became clear to both Wright and Pratt & Whitney that the GE superchargers were very inefficient, and both companies established their own in-house supercharger design teams. These designs went on to set records for efficiency and pressure ratio.

As supercharger boost levels improved, the need arose to tailor supercharger output to the engine power and altitude. This was the reason for development of two-speed and two-stage superchargers. The Pratt & Whitney R-2800 in the F4U Corsair is an example of the two-stage supercharger. The huge casting behind the last row of cylinders is almost entirely a two-stage supercharger. Output air from the first stage is ducted to the second stage for further compression. An intercooler, which is a sort of air radiator to cool the compressed intake charge was often fitted to these highly-boosted engines.

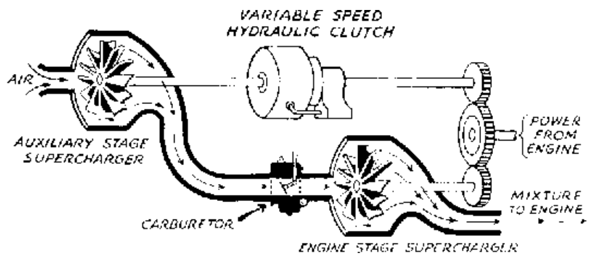


Figure 13. Two-stage supercharger

The huge induction system on big engines with high boost pressures full of explosive fuel/air mix can be blown apart by backfires resulting from improper operator technique. This is one of the difficulties with having the carburetor at the entrance to the induction system. A more acceptable solution is fuel injection, preferably directly into the cylinder. In this situation, the induction system is just pumping air, so designers do not have to worry about backfires, uneven mixture distribution, and carburetor ice.

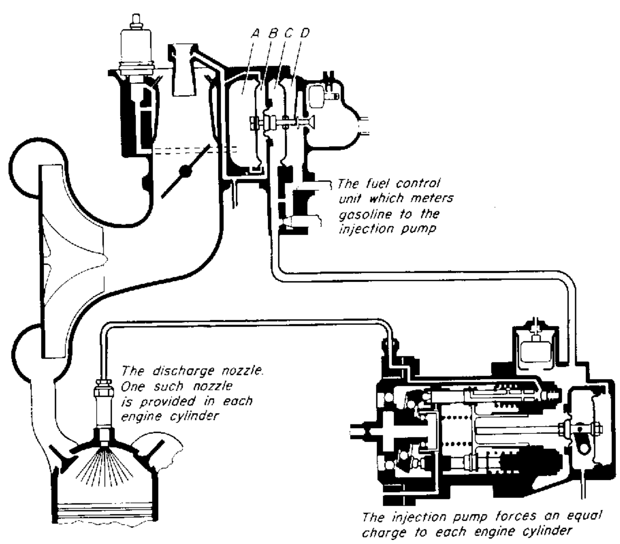


Figure 14. Direct fuel injection

Another type of supercharging that is very effective is turbo supercharging. In this application, engine exhaust velocity is used to drive a turbine which is connected to a centrifugal compressor which rams more air into the engine. The combined package is called a turbocharger. A valve called the waste gate controls turbine speed. The turbocharger has an advantage of not robbing as much horsepower from the engine as gear-driven superchargers do.

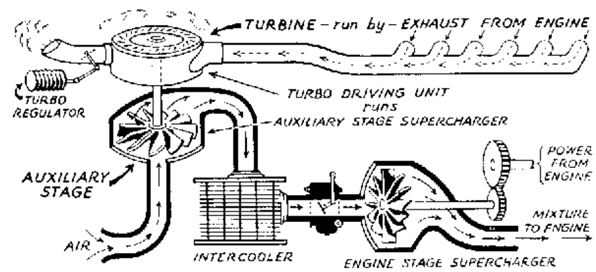


Figure 15. Turbo-supercharger with intercooler

General Electric built all of the turbochargers used in World War II. All high-altitude bombers (B-17, B-24, B-29) and many fighters (P-38, P-47) used turbochargers to maintain full engine power up to an altitude of eighteen to twenty thousand feet.

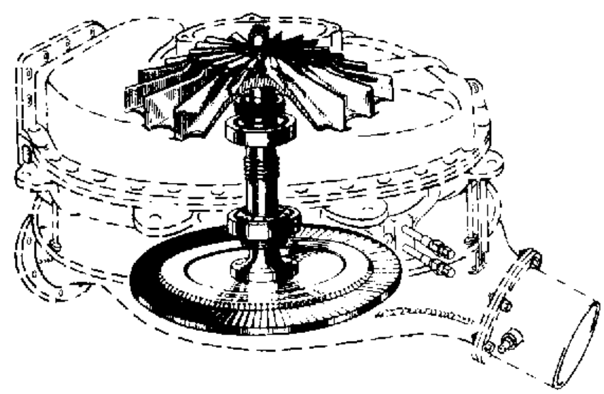


Figure 16. General Electric turbosupercharger

Near the end of World War II, someone got the idea to harness the wasted energy in engine exhaust by using the exhaust to drive a turbine that was coupled to the engine crankshaft. This process is called turbo-compounding. Although numerous engines had experimental test programs with turbo-compounding, only the Wright R-3350 Turbo Cyclone ever saw wide service. Referring to Figure 18, notice the three large pressure recovery turbines spaced equally around the aft side of the engine. Each of these was fed by the exhaust from six cylinders and contributed nearly 200 additional horsepower (600 total) to the engine output. Another advantage of turbo-compounding is the exceptionally good fuel consumption.

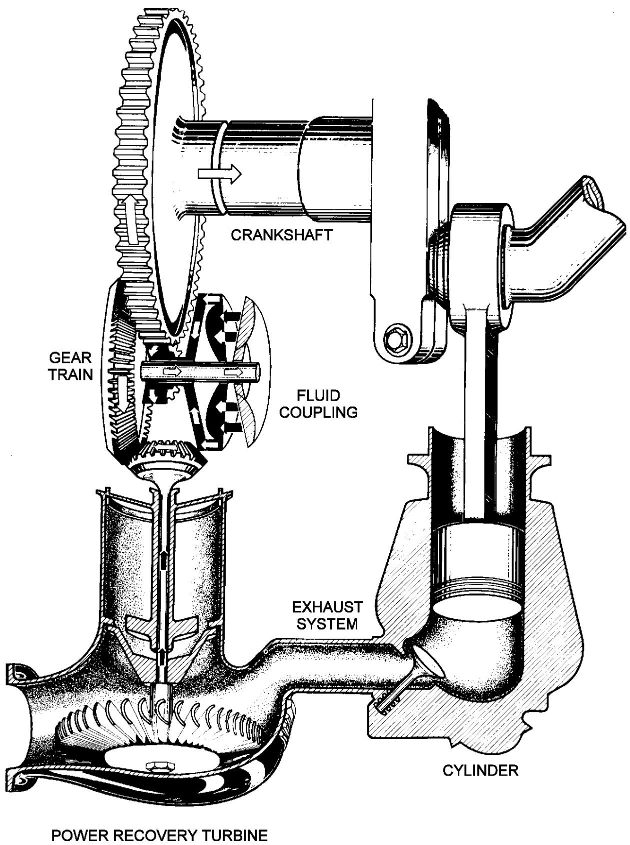


Figure 17. Turbo-compounding schematic

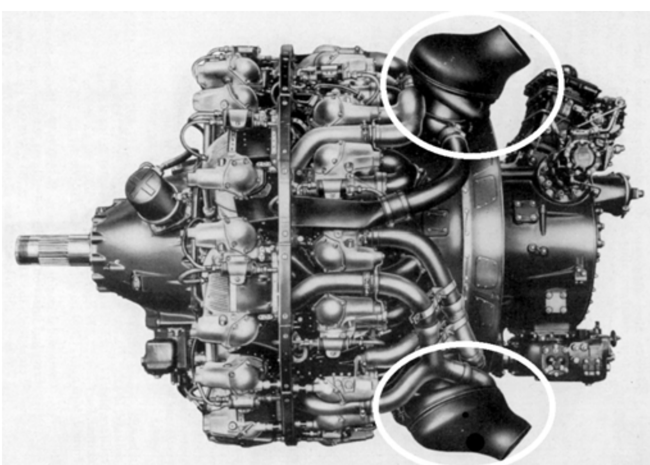


Figure 18. Wright Turbo-Compound 18 showing two of three power recovery turbines

Lubrication

Early engines were lubricated with vegetable oils usually castor oil. Castor oil was chosen because it had nearly constant viscosity (resistance to flow) across its temperature range, and because it coated the metal surface well so that the lubricating film was not easily scraped or washed away. It had the unfortunate characteristic of turning to a gel after being heated and then cooled. For this reason, it was and still is used only in "total loss" lubrication systems such as rotary engines, model airplane engines, and outboards.

The introduction of high-quality mineral oils allowed re-circulation of the oil (drastically reducing oil consumption) as well as the production of greater power by assuring that metal parts were separated by a thin film of oil and never came in contact with one another. To do this, the oil has to be able to resist mechanical pressure, heat, the tendency to oxidize, and the tendency to lose viscosity. Originally, only straight mineral oils were used. In the 1950's, additive packages were introduced to make the oil "Ashless-Dispersant" (AD). AD oils leave no residue when they burn away (hence the ashless) and are formulated to keep contaminants in suspension until the oil is changed. Nearly all oil in use today is the AD type. Eventually, synthetic oils with superior lubrication, viscosity, and stability will probably replace mineral oils.

Fuels

Of at least equal importance to all other areas of actual engine development is the development of fuels. During WWI, pilots noticed that gasoline refined from Romanian crude oil, ran better than that refined from California crude. After the war, an investigation of this phenomenon revealed that "bad" gasoline caused the engine to detonate. Detonation is a condition in which the fuel-air mixture in the cylinder burns explosively rather than smoothly. It was further discovered that pure iso-octane, a gasoline constituent of a certain molecular structure, was about the best that could be had. Hence, the Octane rating system was born. Early gasoline was between 25 and 50 octane. Combinations of poor cooling, high compression ratios (the ratio of cylinder volume at the top and bottom of the piston stroke), and/or excessive supercharging lead to detonation, often with disastrous results. In the late twenties it was learned that the addition of tetra-ethyl lead to gasoline drastically improved its octane rating, so much in fact that it was better than iso-octane. Fuels that test better than iso-octane are rated with Performance Numbers (PN) These improved fuels, often as high as 145 PN, allowed higher compression ratios and higher supercharger pressures which resulted in doubling or trebling of engine power. It is interesting to note that the Allison and Rolls-Royce engines used in WWII Allied fighters got about the same horsepower from around 1700 cubic inches that German engines got from 2600 cubic inches. This was almost entirely due to use of 115/145 PN aviation gasoline in Allied aviation engines verses the 80-90 octane German fuels.

Toward the middle of World War II, another technology came on the scene that further improved engine take-off horsepower ratings. This was Anti-Detonation Injection, or ADI. ADI was simply a pump that during extreme power conditions such as take-off, injected a mixture of water and alcohol into the induction system. The alcohol was primarily to prevent freezing of the water. ADI greatly improved detonation margin, but since it consumed large quantities of water (which is heavy), it was typically only used during take-off or for short times in combat.

Operation

The final area of improvement is that of actual operation of the engine. When the R-3350 entered service in World War II, it often did not run more than 100 hours before having to be overhauled. In airline service, it would sometimes last over 3,000 hours. It is true that the early R-3350s had design problems that were fixed as the engine matured, but another important factor was how the engine was operated. The early engines were run very hard and very hot, often overheated, flown by inexperienced crews, and maintained by poorly trained mechanics. In airline service, engines were treated very well, kept cool, flown and maintained by experienced and competent crew. They were also better instrumented and better data was kept which allowed correlation between operational practice and longevity.

One of the most useful instruments introduced during the war was the torquemeter. This device measured the amount of power actually being delivered to the propeller and allowed the crew to select power settings accurately and to lean the engine correctly to prevent overheating.

Conclusion

By 1950, aircraft piston engines had reached their pinnacle of development. They had become light, powerful, reliable, and fuel-efficient. But they had also reached their pinnacle of complexity and probably power. It is doubtful that anything larger than the R-4360 could have ever been cost-effective simply because of the number of precision parts and amount of maintenance required. Even the R-4360 was never popular in commercial service because it typically required many hours of maintenance for each flight hour, and sophisticated fault diagnosis equipment to boot. Cylinders larger than around 200 cubic inches or producing more than about 200 horsepower were not practical, and engines with more than about 28 cylinders were not practical. It follows that engines larger than six or seven thousand horsepower were also not practical. Around 1945, engineering effort at the major engine plants began to turn away from piston engines to engines with much greater potential for development - jets.

12-16-99