How Many Valves?

by Kevin Cameron

Even a cursory look at the history of the four-stroke internal combustion engine reveals that the number of poppet valves employed has varied over time and circumstance. The very clever engineer Frederick Lanchester used a single valve in the head of one of his early engines, with a two-position intake-exhaust diverter valve upstream from it. This allowed the intake flow to cool the valve after the exhaust cycle, as the engine was designed at a time when no heat resistant valve materials were available.

In our own era, Yamaha Motor Company have tested engines with up to seven valves (four intakes, three exhausts) and settled for a time upon five (three intake, two exhaust). Audi, Ferrari, and others have likewise had their innings with five valves. For racing and sports use, the former 5-valve advocates have now generally returned to four. In a well-publicized occurrence, Ferrari endurance-racing cars with 5-valve engines were unable to be restarted after pit stops because valve seat distortion robbed them of compression.

Yet we also know that the great American air-cooled radial engines of WW II and thereafter employed only two valves, while in-line engines of the same period usually (but not always) had four.

If we examine the history of the motor car, we find makers circa 1903 using a single exhaust and one or more atmospheric (self-acting) inlets—as many as six. There was also an "SOE" period (Suction Over Exhaust) in which a single atmospheric intake was mounted, stem-up, directly over the single stem-down exhaust, which was cam-operated. There followed a period in which side-valve construction was dominant (often with two inlets on one side of each piston, and two exhausts on the other), but then overhead valves began to be adopted 1905-1910. A great synthesis was achieved in 1912-13 when three experienced racing drivers (who in those days had intimate knowledge of machinery) and a Swiss draftsman combined what they believed to be the most useful features into a single design—the Peugeot L76 racing car. Its four-cylinder engine had four valves arranged in pent-roof fashion with a single central spark plug, the valves driven by a pair of overhead camshafts—one for the intake valves, the other for the exhausts.

This quickly became a new orthodoxy, affecting not only racing cars but aircraft engines as well. With few exceptions, the in-line water-cooled six-cylinder engines used by the Central Powers in WW I employed the four-valve central plug design pioneered by Peugeot.

It is essential to note that overhead camshaft operation had existed at least since 1905 and came into general use from about 1908 in advanced racing cars, often combined with four valves. How this came to be requires further explanation. Early racing car engines filled their cylinders poorly so that their combustion lacked the intensity that was later achieved. This allowed engines in that period to have nearly equal bore and stroke without causing trouble for the thin cast-iron pistons used by all makers. But as cylinder filling improved, piston temperature rose, bringing with it the dual problems of piston crown sagging and "irregular firing".

Quite a high temperature is required to produce such piston crown sagging—of the order of 1,200° F—certainly enough to produce pre-ignition, which is what the "irregular firing" was. Until the adoption of aluminum pistons, iron pistons in many cases featured conical dome supports. The base of the cone supported the central region of the piston dome, while the cone's apex bore against the top of the wristpin through a slot in the top of the connecting rod.

For the 1908 auto-racing season it was decided that cylinder bore diameter would be limited by rule, as this was, through valve area, the main determinant of power. This had the valuable effect of reducing piston temperature by bringing the hot piston crown center closer to the water-cooled cylinder wall. It also started a long-running tendency to make bores quite small. Even once aluminum pistons were adopted, with their greatly improved heat conductivity, the thermal and mechanical "tenderness" of pistons continued to be a good reason to make them as small as possible.

Yet even with smaller bores and cooler iron pistons the irregular firing persisted. How could this be? It turned out to sometimes result from complex combustion chamber shapes which permitted persistence of lurking hot combustion gas from one cycle to the next. The readiest remedy for this was to adopt the simplest of chamber shapes—those with overhead valves. FIAT were among the first to adopt four valves, all with their stems vertical and operated by a single overhead camshaft. It shortly became an article of faith that two valves per cylinder could support operation at 2,000 piston feet per minute, but four valves could take this to 2,500 feet per minute.

An additional reason to adopt four rather than two valves was the constant erosion, cracking, and breakage of exhaust valves. A feature of early motoring was the need for combustion chambers to be "de-coked" and valves re-seated every few weeks. A contemporary catalog of motorcycle engine failures at Britain's Brooklands raceway places valve and spring failure at the top. As with pistons, the smaller the valve, the shorter the heat path from the valve head's center to its principal source of cooling, the valve seat. In the "natural selection" of engines, this tended to give smaller valves significant adaptive value.

In the design of Kaiser War water-cooled aircraft engines intense concern for valve cooling may be seen, from the use of water jacket tubes to direct high-speed cooling water onto valve seatings to exposure of the OD of valve guides to direct cooling water contact. These measures are today termed "strategic cooling" and are regarded as rather sophisticated when applied to automobile engines. In fact they are 90 years old.

When paired exhaust valves are employed a rich garden of problems exists in the "exhaust bridge"—the region of the cylinder head between the two valve seatings. Here, the constant heatings-and-coolings generate stresses which eventually crack the head even if it is water-cooled and made of either cast iron or steel. For this reason it has been usual to locate the exhaust valves as far from each other as practicable.

The German WW I in-line engines, having iron pistons, were given fairly small bores in the interest of reliability. To enable adequate airflow with the resulting smallish bores (as imagined under the paradigm of that time) four valves were generally used. It is interesting to note that the Napier Lion, with aluminum pistons, was given a bore slightly larger than its stroke—but also four valves.

Engine Type	Bore X Stroke (mm)	Bore/Stroke Ratio	Piston Material
Basse-Selve 270-hp	155 X 200	0.775	iron
Austro-Daimler 200-hp	135 X 175	0.771	iron
Benz 230-hp	145 X 190	0.763	iron
Mercedes 180-hp	140 X 160	0.875	iron
Mercedes 260-hp	160 X 180	0.889	iron
Napier Lion 502-hp	139.69 X 130.17	1.073	aluminum

When GP auto racing ended with WW I, a trend toward smaller, higher revving engines had developed, displacing the 14-liter four-cylinder giants of an earlier time. Very quickly it emerged that four valves per cylinder were not necessary—provided that the two valves put in their place be set at an included angle large enough to permit adequate diameter. In the 1922 Fiat straight-eight this angle was a large 100°.

The next trend—arriving in 1925—was supercharging, which would increase the severity of life for exhaust valves in both racing car and aircraft engines.

Between the wars actual airflow measurement was carried out in both Britain and the USA, and it was discovered that a properly-designed single intake valve and port, flowing into a hemispherical chamber, could flow as much or more air than could two smaller valves in a pent-roof chamber. This counter-intuitive result arises from the fact that orifice coefficient can be more important than simple geometric flow cross-section. The improvement in single-valve orifice coefficient arises from the ease with which its outflow can be attached to the curved inner surface of the combustion chamber. This causes it to act as "half a diffuser", reducing the pinch effect of surrounding and higher-pressure air on the entering jet.

In the case of a four-valve's two inlets, the flat shape of the pent-roof head makes it difficult to attach the flow and this, plus interference between the two inflows and their closer proximity to the cylinder wall all work to reduce flow coefficient—and flow.

An early step in the development of the American high power air-cooled radial was the Wright R-1, which copied the apparent success of the British Bristol Jupiter. That four-valve engine employed the "poultice" bimetallic head construction, which consisted of a solid steel cap on each cylinder, mechanically held in tenuous thermal contact with a surrounding exterior finned head of aluminum.

Sam Heron, working for the US Army at McCook Field near Dayton, Ohio, expressed doubt that the R-1 would ever be satisfactory. He knew the rules for cylinder head design set forth in 1916 at the Royal Aircraft Factory by mentor Prof. Gibson. One of these was that "The more holes you put into the head, the more trouble there will be with warping and cracking". Heron now directed a McCook project to develop an improved air-cooled cylinder. The result—the J-type cylinder—pioneered the definitive configuration for the air-cooled radials of the 1930s and '40s—two large valves, their stems splayed apart sufficiently to permit cooling air access between, set into a hemispherical chamber with two spark plugs, in an all-aluminum head screwed onto a steel cylinder barrel. The US Army, after much difficulty with the R-1, decided to "stop fighting the details" and adopt Heron's cylinder construction. But before the R-1, now re-named "R-1454", could become successful, a far better two-valve engine pushed it off the stage—the P&W Wasp.

The more "shape" the cylinder head is given by coring it for multiple ports, the greater the opportunities for thermal stress to work at cracking it. Sam Heron's two-valve head was the closest practical approximation to a uniform, featureless block of aluminum of uniform cross section.

Meanwhile Bristol persisted with four valves in its Jupiter, in 1929 abandoning the bimetallic construction for an all-forged-aluminum head whose cooling fins were machined. Why go to such trouble? Because aluminum casting alloys with the hot strength necessary to retain hard valve seats could not at that time be soundly cast in Britain. The added strength of a forged head probably helped to make the exhaust bridge problem tolerable.

At McCook Field in the US, Heron assigned metallurgist E.H. Dix, Jr. to see what he could do to make the high-hot-strength aluminum "Y-Alloy" more castable. Previously, this remarkable material failed to fill mold details when poured too cool, and produced intolerable porosity if cast hotter. For this reason it was used in forged form. Dix succeeded, and the two-valve heads of Lindbergh's Wright J5 Whirlwind air-cooled radial of 1927 were (soundly) cast in this modified Y-Alloy. Closely-related alloys continue to be used to this day where hot strength is required.

Four valves continued in use in most of the in-line liquid-cooled V-engines, despite long-term durability issues. So often in engineering it is easier and more effective to keep going down the road chosen—even if it is less than optimum—than to back up some distance to begin a new route. When Chrysler designed its V-16 IV-2200, it looked superficially like a Merlin with four extra cylinders. Yet each cylinder had only two valves, located in a hemi chamber that looked a lot like those of successful American radials.

Part of the reasoning here was the knowledge that if two great big valves could be made acceptably durable in air-cooled engines, they could certainly be relied upon in liquid-cooled ones. The important changes enabling this were (1) development of heat- and lead-resistant valve materials and (2) internal cooling of the valves by means of partial filling with liquid sodium.

Two-valve air-cooled heads may have become acceptably reliable, but they were never reliable in absolute terms. Wright would have such chronic problems with exhaust valve seat displacement and ovalization from hot creep that they would eventually develop a sliding valve seat with self-aligning properties. Head cracking forced Wright through at least five re-designs of the heads used on the R-3350. In early versions, large pieces sometimes cracked completely free of the main casting.

This history supported a maverick view that <u>even two valves</u> were too many to put in the cylinder head. In the opinion of some, the logical next step was the single sleeve valve, whose porting and valving functions were in the cylinder wall where they did not expose long ports in major castings to the heat of exhaust gas. As engine pioneer Harry Ricardo has noted, about half the heat rejected to coolant in a four-stroke engine is picked up by the material around the exhaust valve seat and port. If at one stroke you could cut heat-to-coolant nearly in half, what would that save an aircraft engine in the form of cooling drag?

The liquid-cooled V engines were not themselves immune from such troubles. Merlin heads that I saw in Jack Roush's shop showed as many as 12 combustion chamber cracks per cylinder—but after unknown hours of operation.

Racing car and motorcycle engines continued with the two-valve orthodoxy of the 1930s until two developments conspired to give four valves new advantages.

First was Honda's 1959 adoption of four valves as a means of raising the safe rpm ceiling of its road racing engines. The famous squared/cubed law makes two smaller valves easier for cams and springs to control than is a single valve of equal flow area (The British racing consortium BRM had in its P25 four-cylinder GP engine attempted to use two very large valves per cylinder—and was rewarded with frequent breakage at high revs). MV-Agusta's famous transverse-four racing motorcycle engines had two valves—and could deliver only a 300-rpm valve train safety margin beyond peak power. Honda's new four-valve 250-fours increased this safety margin to 2000 or more rpm, requiring less "engine management" from riders.

Second was Keith Duckworth's realization that the supposed flow disadvantage of four valves could be overcome by sheer area. By making the bore of his 1967 Cosworth DFV Grand Prix V8 1.3 times its stroke, he had room for paired inlets big enough to flow all the air required.

Another advantage of four valves over two is in the rate at which each exposes flow area. Flow area equals total valve perimeter multiplied times valve lift, so for equal valve head area, two inlets expose flow area 1.41 times faster than can a single valve. This permits paired inlets to complete a given time-area event in less time, so total valve-open timing can be reduced. This increases powerband width because shorter timing reduces opportunity for mixture to be pumped back through intakes held open past bottom center. This alone has been decisive in selection of four valves for auto and motorcycle applications.

Since Duckworth's 1967 demonstration, four valves with single central spark plug have become nearly universal in auto and motorcycle engines, whether at the present 1:1 bore/stroke ratio forced upon autos by emissions requirements, at the 1.5:1 favored in sporting bike engines, or at the 2.25:1 found in pure racing engines.

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