# Valve Cooling: The Key to Record Breaking

**F. Starr**
***Newcomen Society***

Early stationary gas engines required the internal circulation of water within the valves themselves to hold down valve temperatures. Later on, despite the development of high temperature alloys, new cooling techniques were needed for aircraft engine valves; otherwise temperatures would have been in the 900°C range. Following work at the RAE, using water within sealed valves, Heron used mercury, molten salts and then sodium as internal coolants. Valves of this type were used for Lindberg's Transatlantic Flight and the Schneider Trophy Racers. And in 1938 the Japanese Kokenki monoplane used a novel type of air-cooled valve to help achieve a closed circuit distance record of 11658 km. But from 1930 onwards all aircraft engines were using sodium-cooled valves which were vital in the long distance record flight of a Lockheed Neptune in 1946. As well as highlighting advances in valve cooling technique, the paper also reviews the heat transfer aspects basing the analysis on NACA wartime reports and standard heat transfer correlations.

**Keywords:** IC Engine History, Valves, Valve Cooling, Heron. RAE,

## Introduction

All internal combustion engines require a continuous flow of water or air through or over the jacket and cylinder head. Cooling of this type prevents lubricants from decomposing and stops distortion of critical parts; if a car radiator bursts, the engine will grind to a stop within a few minutes. Valve cooling is different. In a sense it is optional. It is something that is only needed when the materials that are available are deficient in high temperature strength or lack resistance to corrosion by high temperatures gases. Temperatures are reduced using the circulation of a fluid within the valve. But valve cooling, even in its simplest form, adds complication to valve manufacture, even if it does not add much complexity to the engine.

In a standard make of automobile the valve reciprocates up to 50 times a second and is exposed to the searing heat of the exhaust gases. Figure 1 shows the variation in temperature over an exhaust valve in a car engine, where almost all makes use uncooled valves. Indeed, until the invention of the jet engine, the exhaust valve was subject to higher levels of stress and temperature than any other engineering component. Soon after the four-stroke cycle was developed, it was recognised that the only two materials that were then available for making valves,

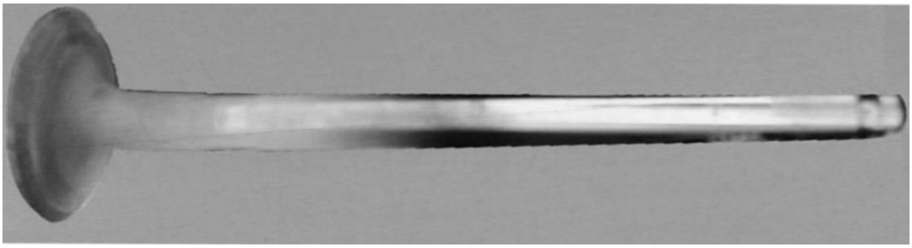

Figure 1. Valve temperatures indicated by how "red hot" the valve is at different points.

the common-or-garden steels and cast irons, had serious shortcomings. Neither has good strength at temperature and oxidation resistance is very poor. Hence despite the complexity, valve cooling was tried and used commercially for a period of about 15 years, until alloys with better high temperature strength and corrosion resistance were invented.

Valve cooling again became a critical factor when high specific power in aircraft piston engines, combined with reasonable reliability, became a commercial and military necessity. But today, with the demise of the "big" aircraft piston engine, the technique of valve cooling has virtually disappeared.

Despite the improvements in high temperature alloys and improved fuels, this paper argues that without the use of exhaust valves, which were cooled, aircraft engine development would have stagnated as early as 1930. The state of commercial and military aviation would have been quite different. Nevertheless, this is just an opinion. What cannot be denied is that valve cooling was vital in the engine used by Lindberg in his solo crossing of the Atlantic, in the engines used by the Schneider Trophy racers and in the engine used for the little-known long-distance record set up by the Japanese Kokenki aircraft in 1938.

Valve cooling came into being long before heat transfer was put on a scientific basis and even now it is extremely difficult to model. Valves are subject to a reciprocating action and high rates of acceleration and deceleration. Depending on the coolant and the cooling technique, these are enormously important in affecting heat transfer. The approach used in this paper is to tie the specific method of valve cooling with the materials and types of engines at the time they were constructed. It will be seen that as the methods of cooling and types of coolant changed, the heat transfer mechanisms also changed.

## Early History of Valves

The Lenoir Gas engine is regarded as the very first IC engine to have reached production status and is mentioned in other papers in this volume. It soon fell out of use. Its gas consumption was high and it seems to have been something of a maintenance nightmare. A major failing were the slide valves, which needed to be lubricated every 15 minutes.[1] The weight of the slide valve and its friction were other shortcomings.

Later pioneers soon dispensed with slide valves. The “Silent Otto” four-stroke of 1876 used a slide valve only for the inlet and facilitated ignition by a pilot flame. Presumably, based on the experience with his earlier engines, Otto had concluded that the temperatures were too great for a slide valve to be used to control the exhaust so a poppet valve was used instead. By 1888 Crossley Brothers, who had a licence from Otto, were using valves of the poppet type for both inlet and exhaust and to all intents and purposes the four-stroke cycle had reached its modern form.[2]

## Valve Cooling on Large Gas Engines

The first IC engines were limited to just a few horsepower, but after the development of gas producers whereby a low cost gaseous fuel could be generated in large volumes, power outputs reached over 600 hp per cylinder. As Dr Lawton has explained in his paper on large gas engines, the tendency on the Continent was to build large single cylinder machines, which, in consequence, needed big inlet and exhaust valves.[3]

Internal valve cooling was an absolutely vital development. Massive increases in engine size became possible, enabling records for power output to be continually made and broken. In machines of this type pre-ignition was likely, that is the gas-air mixture would tend to ignite prematurely through contact with hot surfaces, the most critical being that of the hot exhaust valve. Obviously, the bigger the valve is, the greater the risk. Water cooling of engine cylinders and cylinder heads was standard practice, so it was a small step to do the same for the exhaust valve.

Fairly typical of this class of engine is the 1200 hp tandem cylinder machine, built in 1907 by Maschinefabrik Augsberg and Maschinenbaugellschaft Nurnberg (today known as M.A.N.). It had a brake efficiency of 28.5%, a level that even steam turbines did not approach until the 1930s. Engine bore and stroke were 870 mm and 1100 mm and speed was 100 rpm. Specific output equated to 0.92 bhp/litre of cylinder capacity when the engine was running on coke oven gas. Other salient facts were the power per square metre of piston area, namely 760 $kW/m^2$, and the probable rate of heat release to the cylinder walls and water cooled piston of around 200 $kW/m^2$. The engine was double-acting, so it was essential to cool the piston, since it was heated from both sides.[4]

Figure 2 shows a drawing of the M.A.N. engine exhaust valve, in which the diameter of the crown was 280 mm. This was kept cool using a stream of water running down an internal tube within the valve stem, into the large hollow head of the valve. The return flow was in the annular space between the tube and the stem. No figures were given for the rate of flow of water, but it is possible to make an

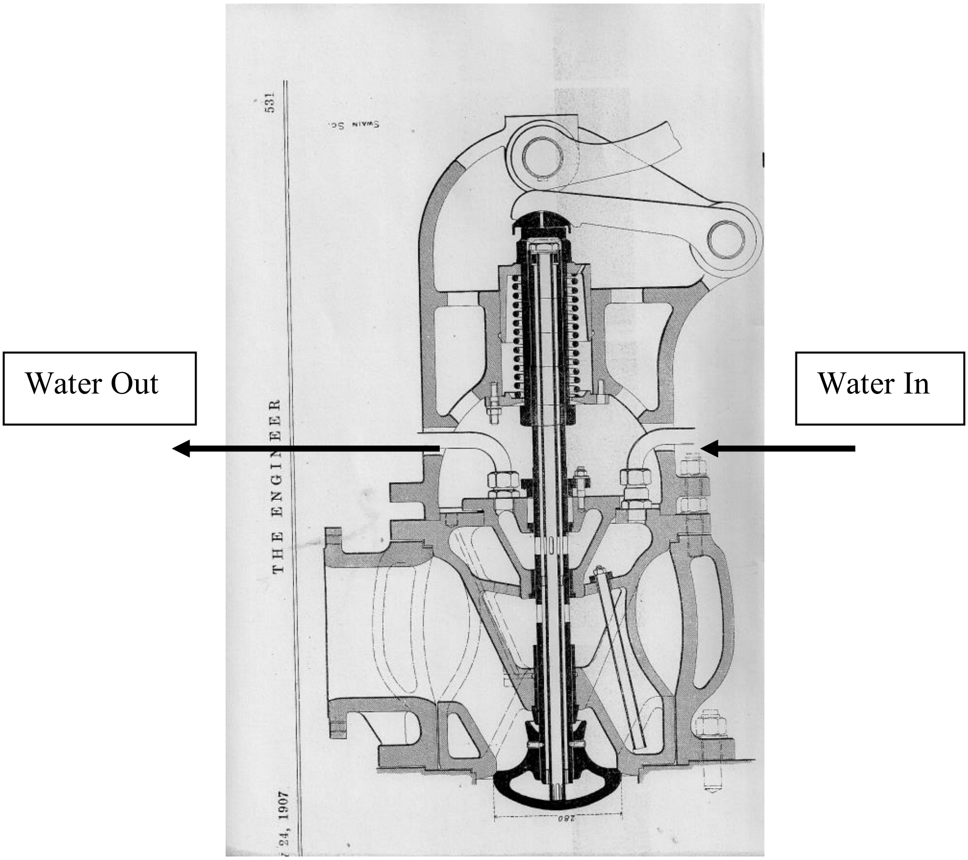


Figure 2. Cross Section of Water Cooled Valve in MAN Engine

estimate if we assume that the heat input to the valve was similar to that entering the cylinder walls. We also need to know the flow rate of coolant in gas engines of this type. Table 1 is helpful in this respect, which is based on data stated by Snell, who gives the cooling water flow in terms of gallons per horsepower hour.[5] Table 1 gives the inlet and outlet temperature of the cooling water and, as will be seen, the lower the inlet temperature the less water is required. Snell gave his data in Fahrenheit and in gallons per horsepower-hour; this is shown bracketed, together with approximate Centrigrade and kg/kWh equivalents.

It is arguable whether the rate of water flow in the valves would have been at the same rate as in the rest of the engine, but as the flow was taken from the passages in the cylinder head this seems a reasonable assumption. The water reaching the valve head would have been warmed up slightly by return flow up the annulus, so it is sensible to use the data pertaining to the 27°C (80°F) case in Table 1 in working out the required flow. It is also necessary to estimate the internal

Table 1. Water Flows for Cooling Large Gas Engines

| Inlet Temperature °C | kg/kWh | Outlet Temperature °C |
|---|---|---|
| 10° (50°F) | 39 (6.5 gals/hp.h) | 31°\|C |
| 15° (60°F) | 47 (7.75 gals/hp.h) | 34°C |
| 21° (70°F) | 59 (9.75 gals/hp.h) | 36°C |
| 27° (80°F) | 73 (12.0 gals/hp.h) | 39°C |

diameter of the tube, which using the valve crown diameter in Figure 2 can be estimated to be 26 mm. The calculation shows that the necessary flow rates are quite modest at 0.16 litre/s. This corresponds to a flow velocity of about 0.3m/s down the valve stem, or about 1ft/sec in Imperial units. Clearly there was scope for increasing the velocity and this would have avoided any tendency towards the depositing of "chalky scales". This was of concern to Snell and he recommended keeping the outlet temperature below 43°-54°C (110°-130°F). Although the flow velocities within the head of the valve are likely to have been quite modest, natural circulation at this point would have been enough to have given quite good rates of heat transfer. A 25°C temperature difference between the cast iron and the bulk water temperature would have given heat transfer rates in excess of 250 kW/m$^2$.[6] The thickness of the valve crown is about 25 mm. Hence, assuming the valve was a standard grey cast iron, whose conductivity is about 50W/mK, calculation indicates that the surface temperature would have been around 150°C, eliminating any risk of pre-ignition. The water supply to and from the valve was from passages within the cylinder head, which must have presented some sealing problems.

On a later M.A.N. submarine diesel of 1917, Figure 3, which also used an internal flow of water for exhaust valve cooling, the water was introduced into a central tube near the top of the valve stem.[7] After the cooling water returned from the valve crown, via the annular space, it was taken off close to the top. Crossley also appear to have used this technique in a 70 bhp semi diesel engine of 1913.[8]

In the M.A.N. engine "garden hose" quality rubber pipes were used to supply the water and, although the engine speed was fairly high at 450 rpm, the hoses only needed to be changed every three or four years. The engine ran for 8-10 hours a day from 1923 to 1945 and never experienced a failure because of the hoses. These valves, unlike the ones used on the 1200 hp stationary engine, were wrought with the crown being first screwed, and then welded, into place in the head of the valve.

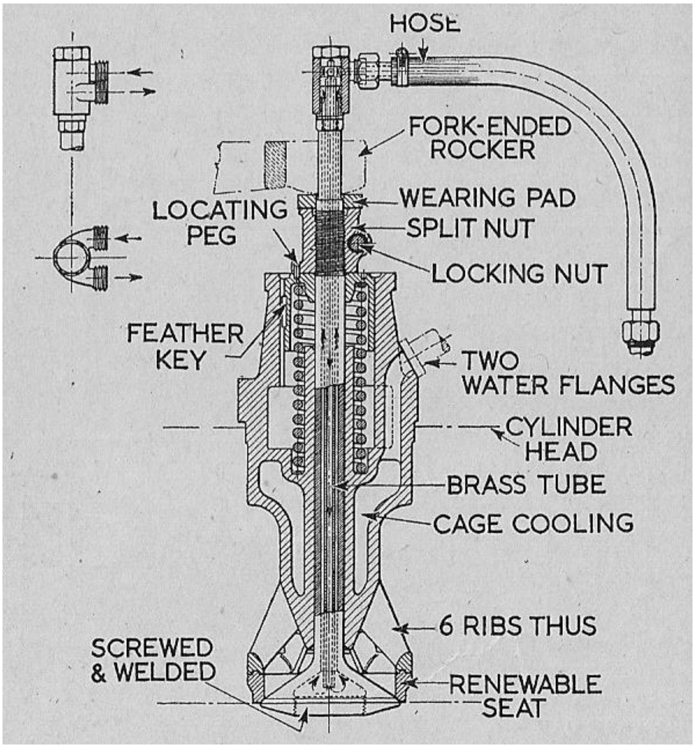

Figure 3. Water Cooled Valve in M.A.N. Submarine Engine.

As far as the author knows, water-cooled valves of this type are obsolete. In modern diesels, valve temperatures are sufficiently low so that valve cooling is not a vital consideration. In big stationary spark-ignition engines, there is a risk of pre-ignition from hot valves, even when valve alloys have adequate high temperature strength, so why are the valves not water-cooled?

One would guess that on modern engines, if the cooling water stopped it might not be long before the valve failed in a catastrophic manner, leading to destruction of the engine. But there could be a much more prosaic reason for dispensing with water-cooling. In less enlightened times, it was the practice to leave the valve mechanism open to the air. This helped with cooling and also allowed the operating staff to go round periodically, giving a squirt of oil to the tappets and rockers. The downside of having an open mechanism is that the hammering action of the tappets on the top of the valve stem caused any oil between the two to splash, giving an all-pervading oil mist throughout the engine house. In the old days the oil haze was "part of the job", but thankfully it has been minimised by enclosing the valve gear within a cover. Unfortunately the cover makes it difficult to bring in cooling pipes and the job of connecting up would be a fitter's nightmare.

## Experiments Using Evaporative Cooling

During the First World War, aircraft performance depended on the liquid-cooled inline and the air-cooled rotary. Liquid-cooled engines were intrinsically heavy and needed a large radiator which did not do much for speed or climb rate. The rotary engine in contrast was light and needed no additional radiator, the engine being cooled by rotation of the cylinders through the air. One does not get something for nothing; more than 10% of the engine power was expended in rotating the cylinders at the same rpm as the propeller. The gyroscopic forces created by the rotating cylinders could be a killer for the inexperienced pilot.

Reliability in aircraft engines was a real challenge. By the standards of the time, aircraft engines were highly rated and driven hard. An American, J.A. White, stated that, unlike the motors in automobiles, an aircraft engine used 75% of its horsepower most of the time. He went on to say

> A motor car engine generally runs up to a mileage of 25000 ….or completes 1000 hours of operation before overhauling is necessary. The aviation engine…..requires a complete overhaul in 50 flying hours.[9]

One reason for the high maintenance demands was that none of the valve alloys of the time had good resistance to high-temperature oxidation and corrosion. Stainless steels, which have reasonable resistance, had only just appeared. Not much was known about the strength of various types of steels at high temperatures. Engine manufacturers would try one alloy after another until a reasonably reliable valve was found.

In this situation, the Royal Aircraft Establishment (RAE) at Farnborough embarked on a major programme to assess valve alloys.[10] Professor Gibson and his team backed up the work with experiments to determine valve temperatures in liquid- and air- cooled engines. A key player in part of this work was Samuel Heron, whose character might be best exemplified by the fact that between 1914 and 1920 he had seven changes of employment!

Critical to the programme were techniques to determine valve temperatures; Figure 4 shows a cross section of a valve containing a thermocouple, this being designed (and probably constructed) by Heron. It is difficult to make out exactly how this special valve was put together, but it appears that the input and output leads of the thermocouple consisted, respectively, of a straight piece of Nichrome wire and a mild steel tube. Most of the cross section of the latter was cut away to produce a "C" shape. However, the bottom of the tube was left intact and the Nichrome wire was welded to it at this point. The tip of the thermocouple therefore appears to have consisted of a ring, which could be forced over a plug at the base of the valve stem. The hollow stem was then packed with refractory cement to prevent short-circuiting between the mild steel tube and the Nichrome wire.

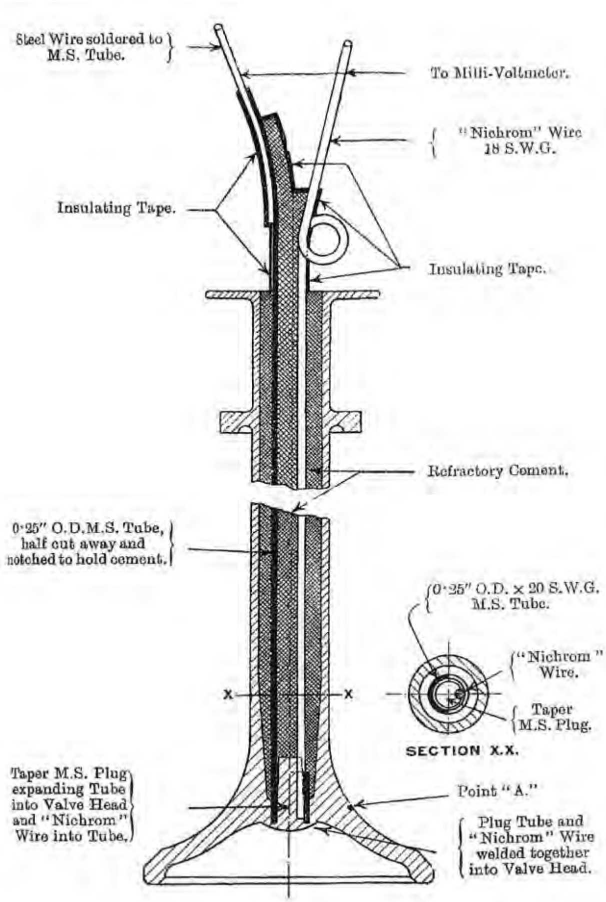


Figure 4. Valve with Thermocouple Designed by Heron.

Subsequently, Heron moved to the USA, where he found a milieu more suited to his temperament. To quote Lt General James H. Doolittle, Heron became "One of the greatest living authorities on the development of the piston engine".[11] Heron, however, was no simple aficionado of engineering history. He helped design the first successful air-cooled aircraft engines, he supported the development of high-octane fuels and as part of our story he invented sodium cooling of valves. Cowley of Thompson Products, which was one of the leading manufacturers of valves and is still in existence as TRW Inc, described sodium cooling as the single most important step in valve design, but we will deal with this development later.

To return to the subject of internal evaporative cooling, the RAE which, although a Government organisation, had the capability to design both aircraft and engines, began to look at the prospects for a good multi-cylinder air-cooled radial. It would have the high power-to-weight ratio of the rotary, but without the windage losses or the gyroscopic effects. Valve temperatures would be a challenge, however. Figure 5 shows that in a radial engine of the time, temperatures could be well in excess of 700°C.[12] In all essentials this graph would be applicable to any highly-rated, spark-ignition engine of today. Evaporative cooling must have appeared to be an answer.

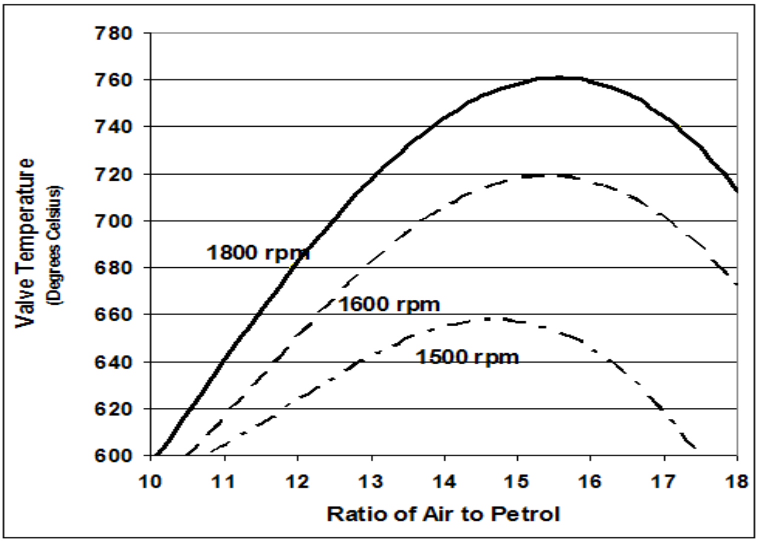


Figure 5. Variation in Valve Temperature with Engine Speed and air:fuel ratio.

The internal evaporative effect, in this context, is an arrangement where a liquid boils in the bottom of a pipe and condenses in the top. The condensed liquid then runs back down to the bottom, where it is re-evaporated. Since both boiling and condensation give high rates of heat transfer, internal evaporative cooling results in a very compact arrangement.

The Farnborough tests involved drilling out the stem of a valve, filling it about one third full of water and then welding the top shut. The top section of the valve stem was equipped with steel cooling fins, since the normal method of conducting heat from the stem into the cylinder head would have been quite inadequate (Figure 6). The heat had to be removed from the fins using a 60 mph (100 kph) air blast.

The Farnborough tests were extremely successful. Compared to a normal valve, the crown temperature dropped from well over 700°C to temperatures ranging from 260° to 310°C depending on the test conditions. In addition the cylinder head and piston temperatures also dropped and there was a small but

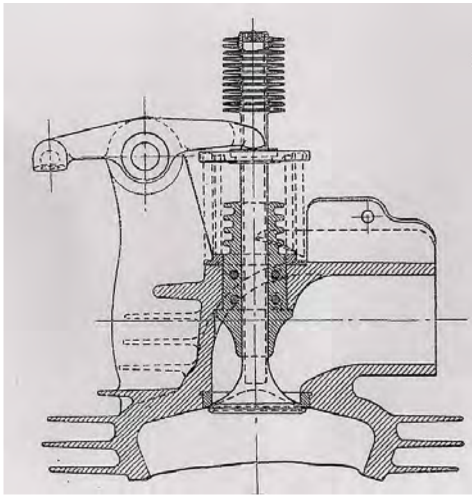

Figure 6. Cross Section of Valve and Cylinder Using Evaporation of water for Internal Cooling.

noticeable improvement in power output and fuel consumption. Professor Gibson did not state any heat transfer rates, but he did comment that the valve stem temperature was about 70°C below that of the crown. This suggests that the water temperature will have been somewhat in excess of 200°C, giving an internal pressure of around 30bar. In one "test to destruction" the cooling air to the fins was turned off. The result being that the hot part of the valve stem bulged. According to Gibson this would have equated to an internal pressure of over 4 tons per square inch or over 600bar pressure. This may be something of an exaggeration, based on faulty data about the strength of steels, but pressures could have been well in excess of the critical, in which all the water would have turned into steam.

Even under these circumstances, in which the evaporation/condensation mechanism ceased, the average density of the fluid within the valve would be quite high, being, by definition, about one third of that of water at room temperature. However, even the fairly modest differences in density between the hot and cold end of the valve stem would have been amplified by the high "g" forces associated with the reciprocating motion of the valve. Accordingly there would have been a reasonable amount of back-and-forth flow of steam, so it is not too surprising that under these conditions the valve head temperature, at 400°C, was still significantly below that of the uncooled valve.

Under normal conditions, water would exist in the valve and the main mechanism of heat transfer from the crown to the water would have involved some form of nucleate boiling. If the usual correlations for pool boiling (that is where there is no deliberate stirring or forced flow) are applied, very high rates of heat transfer are possible. For example a temperature difference of 40°C between the crown and the water would give a transfer rate of over 1300 kW/m$^2$.[13] During the

Second World War, as described later, NACA tests showed that the heat picked up by a water-cooled 3 inch (c.76 mm) valve in a Curtis Wright engine was up to 3.8 kW. The diameter of the valve used in the RAE tests was much smaller at 42 mm which would provide a heat input of a kilowatt. However, the bmep of the Curtis Wright engine was almost twice that in the RAE test, so it seems likely the heat input would have been about half a kilowatt.

Calculation shows that the corresponding heat transfer rate would be about 360 kW/m$^2$. In practice, since the water is being sloshed from one end of the stem to the other, even higher rates would be possible without "burn out" (to use the pool boiling term) occurring.

Obviously the heat abstracted from the valves has to be equal to the heat input. Judging from the drawings of the valve, the area of the stem in contact with finning is about 0.0013 m$^2$. It follows that that the condensation rate was about 380 kW/m$^2$. This figure needs to tie in with the temperature differences for condensation, in which the heat transfer rates are up to 4 kW/m$^2$K.[14]

Given the 70ºC temperature difference between the top and bottom of the valve, the temperature difference between the steam and the valve stem could not have been much more than 50ºC, giving a theoretical condensation rate of 200 kW/m$^2$. In fact the rate seems to have been very much higher. Presumably the high rates of acceleration and deceleration and violent changes in direction resulted in greatly enhanced dropwise condensation.

A further check can be made on the heat flows through the valve using the heat loss through the fins. Unfortunately the only "hard" information we have is that the fin diameter was 1.1 inches (2.48 cm), that the total area was 21.5in$^2$ (138.7cm$^2$) and that the fins were made of steel. Cooling air velocity was 60 mph (26.2 m/s). The drawing appears to show that the fins were machined from a solid cylinder and that the gap between the fins was wedge shaped; hence it is difficult to apply standard heat transfer correlations for fins. Instead the formula for forced circulation of air within tubes was applied, as shown below:[15]

$$h = \frac{0.2.k}{D}\left(\frac{VD}{\nu}\right)^{0.8}$$

Where:

h = heat transfer coefficient
k = thermal conductivity of gas
V = velocity
D = tube diameter
υ = kinematic viscosity

In calculations using this formula, tube diameters were set at what appeared to be at gap size of between 1.25 to 5 mm. These gave heat transfer coefficients around 0.2 kW/m$^2$K. Assuming that the temperature difference between the air and the finning was 150ºC and, using an area of 0. 138.7 m$^2$ for the finning, the heat transfer to the cooling air was 0.44 kW. This corresponds quite well to the estimated heat input to the valve of half a kilowatt.

Gibson mentioned that mercury had been tried as a coolant with disappointing results, even though the conductivity is seventeen times that of water. It supports the view that the mechanism of heat transfer, when using water, was by evaporation and condensation.

Although very promising results emerged from these tests, the internal evaporative concept was never used practically. An obvious disadvantage is that that, as the calculations show, it is much easier to get the heat from the valve crown and lower stem, than to get it out via the upper stem and cooling fins. These problems would have got worse as engine outputs increased. Gibson and his co-workers may have appreciated the problem since one of the test valves was equipped with aluminium fins.

In actual fact, valves were being overcooled, so that the heat flow into the heads and steam was unnecessarily high. The ideal was a fluid with a boiling point of about 200-250°C and which did not decompose or corrode at temperature. No such fluid exists.

## Metals, Salt, Sodium and Success

*Silchrome*

Internal valve cooling would not be sufficient on its own to ensure an acceptable valve life on engines in which the power output was high. The invention of stainless steels, as well a giving greatly improved the resistance to high temperature oxidation, also offered the prospect of good high temperature strength. During the 1920s, when these materials came into use, automotive engines could be built with good performance combined with acceptable reliability.

The first stainless steels to be used for exhaust valves were based on the alloys developed by Hadfield of Firth Vickers, which contained 12% chromium. These seem to have been tried by the British towards the end of WWI, but they were soon superseded by an American alloy “Silchrome” which was marketed by Thompson Products. Fuller details of the materials in use at the time are in the literature.[16]

Silchrome was cheaper to make than the British alloy, containing just 8% chromium. It also contained 3% silicon, which more than made up for the deficiency in chromium in giving good oxidation resistance. Silchrome swept through the American car industry and even today it is still used for the inlet valves of most car engines.

Silchrome was soon taken up by the manufactures of aircraft engines, but at best it was on the borderline of acceptability, limiting engine outputs. Here we have problem, although it is relatively easy to determine valve temperatures, there almost complete silence on the distribution of stresses in valves and what are acceptable levels for design purposes. This is understandable; valves are subject to high accelerations and when closed are held onto the valve seat by a strong valve spring. These particular stresses do not seem to be too significant; the main concern is the somewhat unquantifiable impact forces when the valve returns to the seat. Giles in a paper, written in 1965, seems more concerned about the "gas loading" on the underhead section of the valve crown.[17] He quotes very high levels of stress in some laboratory tests, in which valves with various crown shapes were subject to high gas pressures. However, he ends his account with the comment that the crown can always be thickened up to reduce stress levels. The underhead stresses quoted by Dowling et al of Ford Inc are in the 35-70 MPa range, but these probably applied to automobile engines.[18] It does however seem likely that these levels could also be applicable to unsupercharged aircraft engines of the late twenties and early thirties. Later on, when most aircraft engines were highly boosted, using supercharging or turbocharging, it is possible to surmise that the valve stresses were very much higher.

The base of the stem is critical, as being the point on the valve which can be hottest. It receives heat from the crown and also the high velocity combustion products when the exhaust valve opens. If the stem breaks the crown will fall into the combustion chamber leading to destruction of the engine. Figure 7 shows that a valve crown has broken off from the stem and has embedded itself in the piston. Less dramatically, the valve stem will stretch and lead to the valve losing contact with the valve seat. Valve burning will then result.

It arguable, of course, how applicable is the work of Giles and Dowling to engines built in the 1920s. What we do know from modern data is that providing valves made of Silchrome were well designed, so the stress levels were low, they should have given an acceptable performance in motorcars, where peak valve temperatures are around 650°C For aircraft engines it is another matter, since even in these early engines valve temperatures could easily reach well over 750°C on takeoff. It is easy to see from Table 2 why engines would be given 5 minute or 1 hour ratings. In practice valves stretch, as a result of high temperature creep, occurs before the stem actually breaks, and would be a main concern, requiring adjustment of the tappet clearances after just a few hours.

Table 2. Silchrome Life at 40 MPa Stress

| **Temperature** | **Life (hours)** |
|---|---|
| 650°C | 1000 |
| 700°C | 65 |
| 750°C | 5 |
| 800°C | 0.6 ( approx 40 minutes) |

Figure 7. Valve Crown has embedded itself in the Piston

These estimates of the life of Silchrome and other high temperatures alloys are either based upon modern data, or where alloys have gone out of production, as in the case of TPA, modern near equivalents have been used to estimate life.[19] Estimates of valve life at higher temperatures than design, were made using the Larson-Miller parametric equation which is:[20]

$$P = T\,(C + \log t)$$

P = Parameter which depends on the material and stress
T = Absolute Temperature
C = Constant, which is usually assumed to be 20
t = Time in hours

The merit of the Larson-Muller equation, is that once the time to failure is known for a particular stress and temperature, it is easy to calculate the failure time at different temperature

## Sodium Cooled Valves and the Lindberg Flight

For Lindberg's attempt to fly from New York to Paris, there could be no mid-Atlantic maintenance stop! In addition, for much of the early part of his flight, his engine, a modified Wright J-5 Whirlwind, would be running at high power, as it dragged the overladen "Spirit of St Louis" through the sky. It will be apparent that not even Silchrome valves could have got Lindberg across the Atlantic. A cooling fluid was needed, which could transfer a few hundred watts from the lower stem region up into the valve guides. Help was needed, which was provided by the ingenious Sam Heron.

The experiments at the RAE, which had involved Heron, had used mercury as an internal coolant. These trials were not successful. Moving to America, Heron restarted his experiments, using molten nitrate salts. These tests seem to have been partly successful and valves using this principle were used in the early Wright engines. One drawback is that nitrate salts begin to decompose at temperatures of around 600°C.

By 1925, Heron had moved on to using liquid sodium, which has much superior heat transfer properties as a valve coolant. In this situation the coolant is shunted from one end of the valve stem to the other, with the fluid being stationary for much of the time. This is in contrast to conventional heat transfer, where a fluid flows continuously through or over a tube. During the time that the sodium is stationary the main mechanism of heat transfer will be simple (i.e non-convective) thermal conduction from the valve walls into the coolant. For this reason the fluid should have a high thermal conductivity and a high heat capacity, or "volumetric specific heat. Table 3 shows that molten sodium has by far the highest thermal conductivity. Its volumetric specific heat is not as good as water, but other advantages are the extremely low density, which reduces the power required to drive the valve up and down.

Table 3. Thermal Properties of Valve Coolants [21]

| **Coolant** | **Melting Point °C** | **Boiling Point °C** | **Thermal Conductivity $W.m^{-1}.K^{-1}$** | **Volumetric Specific Heat KJ./l** | **Dynamic Viscosity Pa.s ( $x10^4$)** | **Density $kg.m^{-3}$** |
|---|---|---|---|---|---|---|
| **Water** | 0 | 100 | 0.6 | 4.184 | 10 | 1000 |
| **Nitrate Salts** | 220 | Decomp c.600°C | 0.55 | 4.894 | 17 | c.1800 |
| **Mercury** | -39 | 359 | 10.4 | 1.896 | 15 | 13600 |
| **Sodium** | 98 | 883 | 68 | 1.088 | 2.6 | 966 |

Although the quantity of sodium with in an exhaust valve stem is just a few millilitres, the movement up and down the valve stem can transport very large amounts of heat. If the temperature loss from in the sodium was about 10°C, in going from the bottom to the top of the valve stem, the transport of heat would have been about 300 watts, which is more than is needed to keep a Silchrome valve at acceptable temperatures. It is easy to see how, in the Whirlwind, the use of sodium cooling was a major benefit and also how Heron could describe the valves as running "black", not the usual "red", indicating that temperatures were below 550°C.

Salt could never have approached sodium as a coolant, its main drawback being the very poor thermal conductivity. This brings us to one of the mysteries of Lindberg's flight. According to Dyer, in his comprehensive history of Thompson Inc, its main rival, the Rich-Tool company, had been supplying salt cooled valves, (possibly made of tool steel rather than Silchrome) for the J5 Whirlwind. However concern was expressed about the survivability of these valves for long distance flights and Thompson's sodium cooled Silchrome were substituted on an "experimental basis". Following the success of the flight, a statement was put out by Rich-Tool claiming that salt valves were used. Figure 8 shows the quotation from the April 1928 edition of Popular Mechanics, reproduced as far as possible in the same style as the original.

The Thompson company were understandably annoyed about this turn of events and even to this day, the fiction that the valves used in Lindberg's Whirlwind were salt filled is still repeated. Out of this, however, came the decision by Thompson to sponsor the Thompson Trophy, for the highest speed round a 50 mile race of ten laps, at the annual air show at Cleveland, which of course led to another series of record breakers.[22]

**SALT IN PLANE MOTOR'S VALVES AIDS LINDY'S SUCCESS**

**Salted valves on Col. Charles Lindberg's plane, "The Spirit of St Louis", were one of the secrets of his success, according to engineers. The salt was inside the stems, which were bored out, filled and sealed in the process of manufacture. The advantage of this arrangement, according to the claims made for the units, was that the intense heat was relieved somewhat by being distributed through the salt to the cooler stem, which was about twice the thickness of the average automotive stem.**

Figure 8. Misleading Comment in Popular Mechanics about the Salt Cooled Valves.

One final question, to conclude this section in which it is hoped that this barrage of heat transfer data, has helped to support the view that sodium cooled Silchrome was the key to the Trans-Atlantic flight. Was Lindberg being a fool to rely on "experimental components". Certainly not! Even before starting off, Lindberg had already flown from San Diego to St Louis, with just one stop, and then from St Louis on to the Trans-Atlantic take-off point at Roosevelt Field, Long Island.

### The Schneider Trophy Racers and World Speed Record

The engine used in the Supermarine S6 and S6B was developed from the Rolls-Royce Buzzard, which was for its time an extremely powerful liquid cooled, 12 cylinder, V-12 , of 937 hp. The "R" modification was run at 1.21 bar (17.5 psi) boost pressure; at 3400 rpm the engine produced 2783 hp. Engine capacity was 36.7 litres, so the specific power was almost 57 kW/litre, about 5 times that of the Whirlwind. With the help of these seaplane racers Britain won the Schneider Trophy outright in 1931 and then went on win the world speed record, the first time a plane had done over 400 mph in level flight.

Sodium filled valves were mandatory and, in contrast to the American radials, Rolls-Royce opted for four small valves per cylinder, rather than two, i.e., two inlet valves and two exhaust valves. This combination helped reduce valve temperatures, as there were shorter heat paths into the cylinder head. Heat inputs, nevertheless, would be such that even sodium cooling would not bring temperatures down to safe levels. Better materials than Silchrome would be needed.

At this point another engine specialist, FR Banks enters the scene. Banks is usually associated with fuel development, having been the technical agent for the Ethyl Corporation, which was marketing tetraethyl lead (TEL) as an octane number improver. A major drawback of TEL is that it tends to corrode exhaust valves, especially those of the Silchrome type. Accordingly, it would seem that Banks had begun to take an interest in valve design and materials. Furthermore in the process of concocting fuels for the Schneider Trophy Contest he had got to know that valve "distortion" had been an issue 1929 version of the engine.

On one of his trips to the USA Banks got in touch with RS Jardine of Wilcox Rich and arranged for a trial batch of some sodium cooled valves to be manufactured. These were tested in the "R" engine, but because of the rules of the Schneider Trophy Race, Rolls had to get the valves made in the UK. Bristol however, had the licence from Wilcox-Rich, so Rolls had to acquire a sub-licence from Bristol.[23]

One type of distortion is stretching of the valve stem in the underhead region and this is where the form of sodium cooling adopted by Rolls-Royce would have been most useful, as only the stem region of the valve was hollow. Since the valve dimensions on the R engine are relatively small the heat flows along the stem could not have been more than 500 watts.

Reasonable estimates can also be made of the ability of the sodium to cope with this level of heat input. The "R" engine peaked at 3400 rpm, implying that the sodium was being shaken up and down the valve stem 28 times a second. For the sodium to transport the heat, it would have needed to experience a change in temperature, first of all picking heat up from the valve head region and then losing the heat in the valve guide. If the heat from the stem were entering the sodium over a 2cm length, if the internal diameter were 4mm and the temperature change in the sodium were 20°C, it is simple arithmetic to show that the heat transported on each "shake" of the valve was about 0.011 kJ. However since the valve is shaken 28 times a second the heat transported corresponds to just over 600 watts. Clearly this is just about enough to keep the valve crown and stem cool.

In terms of the valve design and materials, as noted above, about the only thing that can be said with any degree of certainty is that the valves were stem cooled. It seems highly unlikely that the exhaust valves in the "R" engine were of Silchrome. Even with good cooling, in an engine like the "R," its strength and corrosion resistance would have been deficient. The materials of choice would have been of the austenitic stainless steel type, containing about 10-15 % nickel as well as about 12-16% chromium. In America the alloy in use at that time was "CNS" which had a rather broad composition (see Table 4), but in Britain Kayser Ellingham of Sheffield were producing KE 965.

Table 4. Valve Materials of the Early 1930s [10]

| Alloy | Fe | Cr | Ni | Si | Mn | C | Other |
|---|---|---|---|---|---|---|---|
| **Silchrome** | Bal | 8.0 | - | 3.0 | | | None |
| **CNS** | Bal | 13-20 | 7.0-8.5 | 1.5-3.0 | 0.65max | 0.3-0.4 | W |
| **CNS** | Bal | 12.8 | 8.5 | 2.65 | 0.33 | 0.24 | None |
| **KE 965** | Bal | 14.0 | 14.7 | 0.9 | 0.8 | 0.41 | 2.1 W |

It will be noted that two sets of compositions are quoted for CNS. The top row is from a paper by Boegehold and Johnson at the "Symposium on the Effect of Temperature on Metals" in 1931. These seem to be data from the manufacturers. The second row appears to be the actual composition as determined by Handsforth, as stated in a paper on valve alloys in 1932. Handforth gives a much tighter range of compositions, as he gives data for two other CNS samples, all of which are quite similar to the second row.

Although this may seem an aside to the question of valve cooling, it seems reasonable to suppose that the valves first tested were of the CNS type. Later on, once the principle had been established, Rolls-Royce switched over to KE 965 for all of its subsequent range of engines.

## Long Distance Flights and the NACA Valve Test Programme

It would be an idle boast to point out that every piston engine which powered a speed record breaker, following the ultimate Schneider trophy winners, used sodium filled valves. But to meet the FAI requirements a speed record breaker must complete the attempt within one hour and the actual time at top speed will be just a few minutes. Hence, aircraft of this type added little to the reliability of flight as a commercial endeavour.

Much was done in the 1930s by the valve companies to improve valve performance in highly rated radial engines. Figure 9 shows the evolution of valves.[24] The stem of the valve on the top left, from the early 1920s, was drilled for lightness only, containing no coolant. The next three were salt-cooled. The four valves in the bottom row were all sodium cooled. The emphasis at that time was to reduce the costs of flying passengers across the USA. Military requirements were in the background.

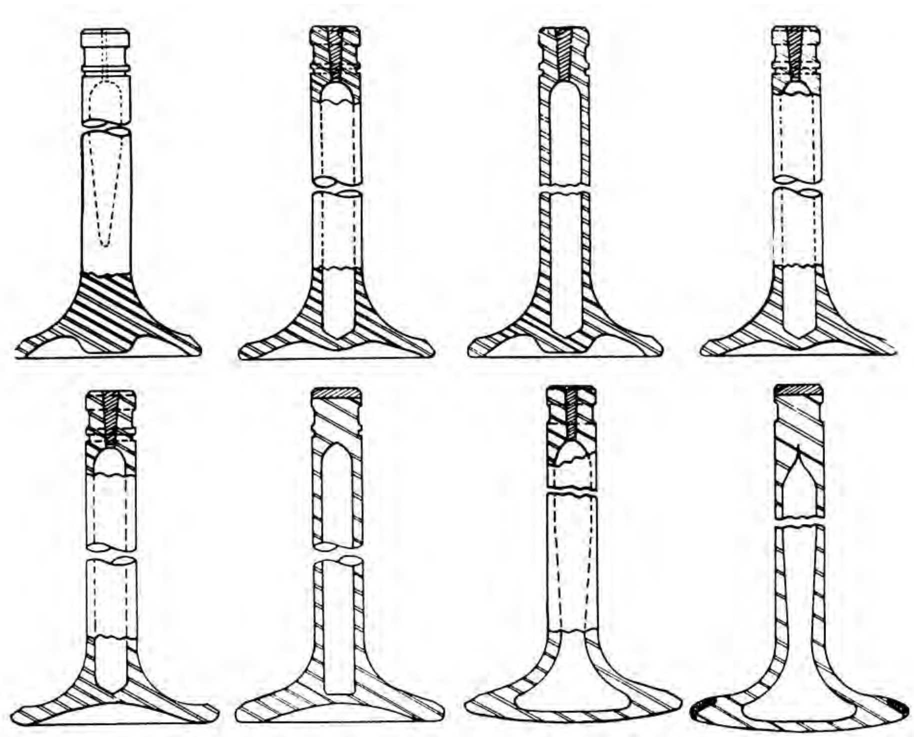

Figure 9. Progress with Valve Design for Aircraft Engines 1920 -1940.

During the wartime years, engines had to be made to work a lot harder. The success of this can be judged from how long heavily laden bombers and reconnaissance aircraft were expected to stay in the air. During the War patrol aircraft made the longest flights over the Atlantic and in the raids by the B29 from Okinawa against Japan. This required much development effort by the engine makers and by the backroom boys at NACA (National Advisory Committee for Aeronautics).

The culmination of this was the post war record-breaking flight by the Lockheed Neptune "Truculent Turkey". The PV2-1, to give it its US Navy designation, flew from Perth, Australia, to Columbus, Ohio, a distance of 18,089.3 kilometres (11,235.6 miles) in September 1946. The flight time of 55 hours 17 minutes is more significant than distance. For much of the flight engines would have been leaned back to maximise fuel economy, which results in high exhaust and valve temperatures.

The engines were Wright R-3350s, sometimes called the Duplex Cyclone, a two-row eighteen cylinder supercharged radial of 2200 hp. These had been developed from the earlier single row Cyclone. As might be anticipated, the engine was, to be diplomatic, "overdeveloped" and it would seem, judging from NACA research reports, that it had been subject to extensive testing to improve reliability and performance.[25] The work by valve manufactures, extending over a twenty year period, had culminated in the sodium cooled hollow head valve, which was absolutely vital to both Wright and Pratt and Whitney as manufacturers of big air cooled radial engines. All such engines used two valves per cylinder, which implied long heat flow paths and difficulties with valve cooling.

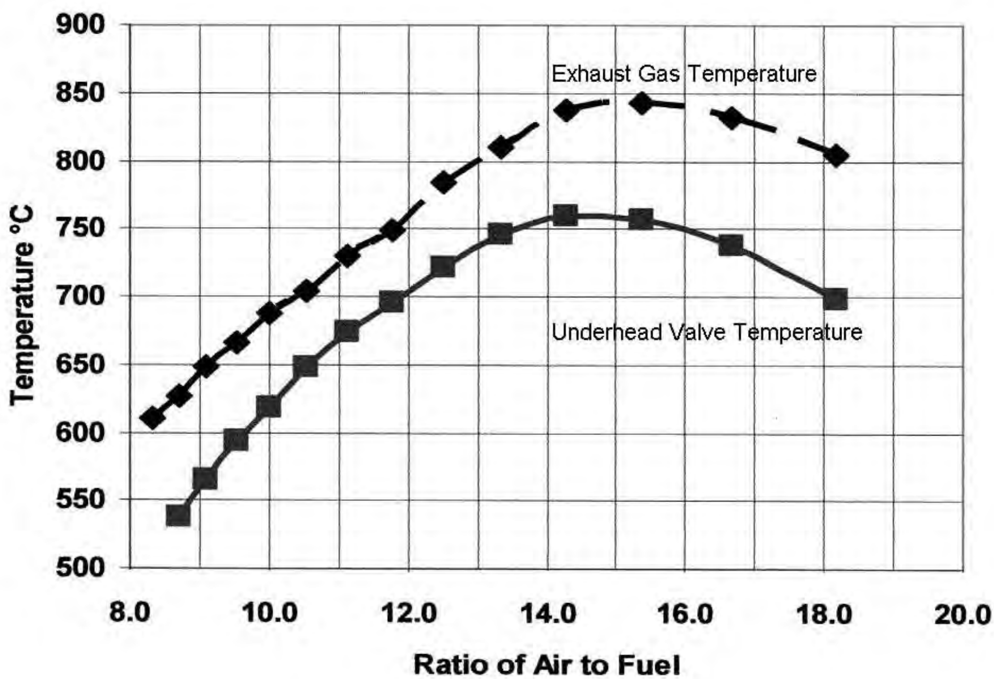


Figure 10. Variation in Exhaust Gas and Underhead Valve Temperatures with Air-Fuel Ratio, after Sanders et al.

These NACA research reports, based on a single cylinder test "engine" give some useful information about likely valve conditions and heat flows. Figure 10, replotted from one of these reports,[26] shows the variation in underhead temperature with the fuel/air ratio. As can be seen, valve temperatures are much higher when the mixture is at the stochiometric point or not too rich, corresponding to cruise power conditions.

Much of the heat input to the valves was coming from the in-cylinder combustion products. Zipkin and Sanders, in developing a model for the flow of heat through a valve, specifically discounted the input from the exhaust gases as they flowed over the underhead and stem region.[27] Later work by Rolls-Royce gives support to this claim. In contrast to the tulip-shaped valves on the Merlin engine, in which the crowns were concave, the valve crown on big American aircraft engines, had a convex shape, with the crown tending to protrude into the combustion chamber. Rolls-Royce tried out some valves of this type and found that they tended to run hot.

In developing their heat transfer model Zipkin and Sanders utilised the concept of an "effective combustion gas temperature", which could be as high as 1240°C (the actual gas temperature would have been 200-300°C lower). The relation between this temperature and the mixture ratio is shown in Figure 11.

Of more interest are the two lower curves in Figure 11, which show the valve temperature respectively with and without sodium cooling. These are measured values, not theoretical, and it will be seen that without sodium the valve temperature is basically that of the exhaust gas temperature. However the addition of about 10ml of sodium brought the valve temperature down to levels, which for this valve alloy, TPA, a Chinese copy of KE965, would have been just about acceptable.

The paper indicates that valve temperatures could be brought down to even lower levels, through some redesign. As Figure 12 shows, the original form of valve, on the left, had a restriction at the bottom of the valve stem (probably because of the manufacturing process). Temperatures dropped by over 50°C when this was eliminated, as with the valve on the right,. Further reductions were obtained by increasing the stem diameter which improved the heat flow from the stem into the valve guide

The importance of sodium cooling can be judged from Table 5 which shows the effect of temperature on the creep rupture life at a stress of 70 MPa. At 750°C a reasonable life can be obtained, but at 900ºC it is just a few hours. This, however, discounts the corrosive effect of lead deposits on valve alloys, coming from the use of tetraethyl lead in fuels. For alloys as TPA and KE 965, if valve burning and corrosion fatigue are to be avoided, temperatures need to be well under 700ºC.

The paper by Zipkin and Sanders does not state the actual heat input to the valves. Fortunately this can be estimated using data using a water-cooled valve,

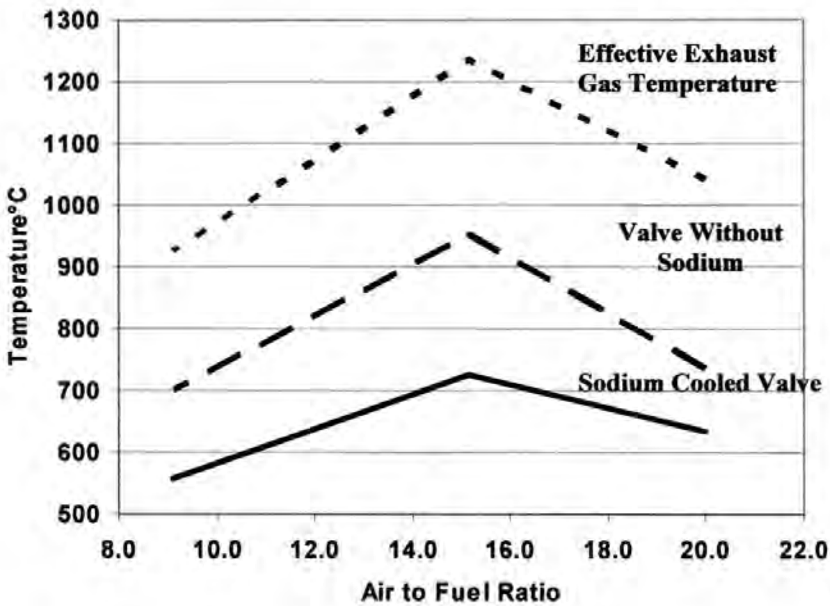


Figure 11. Variation in Valve and Effective Gas Temperatures with Air-Fuel Ratio after Zipkin and Sanders.

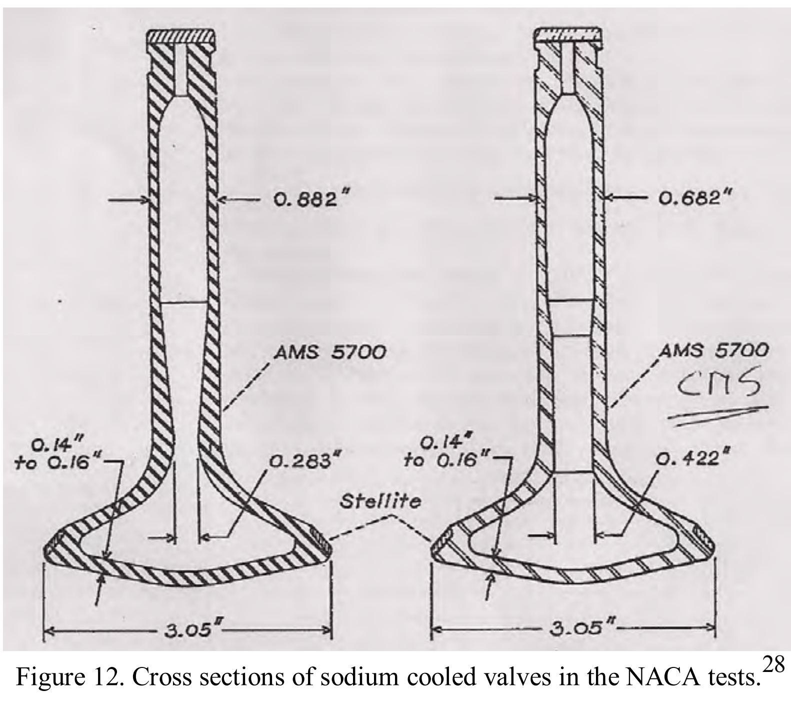


Figure 12. Cross sections of sodium cooled valves in the NACA tests.[28]

like those used on the M.A.N. submarine engine. In the NACA tests

Table 5. Estimated Life of TPA Valve Alloy at a stress of 70 MPa

| Temperature in Celsius | Life in Hours |
|---|---|
| 650º | 87000 |
| 700º | 40500 |
| 750º | 2500 |
| 800º | 200 |
| 850º | 20 |
| 900º | 3 |

peak heat input reached 214 BTU/hour or about 3.8 kW. Of course, since the valve surface temperature, using a water flow, could not have been much more than100ºC, the heat input to the valve would have been much higher than with sodium cooling. If we accept that the effective gas temperate was 1140ºC , this implies that the heat input to the sodium cooled valve, compared to the water cooled was 440/1040, or 0.423. Accordingly, the heat input to the sodium cooled valve was about 1.6 kW.

How difficult was it for the sodium to cope with that much heat? The valve dimensions suggest that the amount of sodium in the valve was about 8ml, just enough to fill the hollow crown of the valve. Calculation shows that a one degree Celsius increase in the temperature of the sodium is equivalent to a heat input of 0.0875 kJ. With this heat input for each jerk of the valve and for an engine speed of 2400 rpm corresponding to 36.7 jerks per second, the heat transferred per second is 1.57 kJ or 1.57 kW. It follows that a very small amount of sodium was able to make an amazing difference to valve temperatures.

Of course, the heat picked up by the sodium has to be transferred to the valve guides and from thence into the cooling fins and into the cooling air. The Wright Duplex Cyclone had problems in this respect, in its installation in the B29, since the engine was to closely cowled. And in the first versions of the engine, mixture distribution was very bad and, as Figures 10 and 11 show, weak mixtures could be very harmful. Sodium cooling could not solve all engine problems; a nickel based alloy, “Inconel M”, had eventually to be used.

Towards the end if the Second World War, the Duplex Cyclone switched to direct injection, close to the entrance of the cylinders, giving much better control of the air-fuel ratio and better fuel economy. It seems likely that these engines powered the Truculent Turkey. Still later the Duplex-Cyclone was developed as a turbo-compound. Apparently, the earlier versions suffered form overheating because of increased backpressures. Eventually these problems were sorted out and the engine became the mainstay of the last Trans Atlantic commercial transports.

And although this section is about distance records, it is worth pointing out that the World Speed Record for piston-engine aircraft is held by “Rare Bear” with a speed of 850 kph (528 mph). The engine in this much-modified Grumman Bearcat, is a highly boosted Wright R-3350, which puts out 4000 hp! But one would bet, not for long!

### Internally Air Cooled Valves: The Japanese Closed Circuit Distance Record

By their nature closed-circuit distance records are harder to make than the point-to-point variety. No advantage can be taken of following winds. On the other hand the flight can be extended until fuel begins to run short, or the engine shows signs of misbehaving. But closed-circuit records do not attract much interest; that set up by the Japanese Kokenki monoplane in 1938 has, until recently, dropped from view. The distance achieved was 11,651km or 7,239 miles.

The main reason for including the Kokenki is that the Japanese engineer and entrepreneur, Takashi Suzuki, has highlighted that the valves in the engine, a modified BMW-9C, V-12, built by Kawaski, utilised air cooled valves.[29] Suzuki states that the aim was to minimise valve temperatures when the engine was running at air fuel ratios of 13.5/1 during the take off and climb. As stated previously, this is a slightly rich condition close to the point where valve temperatures are high. However Suzuki also states that the air cooled exhaust valve prevented knocking and enabled the engine to run at safely at lean mixture ratios from 16/1 to 19/1. This gave a fuel consumption of 180gm per metric horsepower hour, or about 0.4 lb/hp.hr, a very creditable figure. The cooling air was provided by a Roots blower, which indicates that the air pressure to the valves cannot have been high.

Suzuki poses the question “Why were sodium cooled valves not used?”, since air is much less effective as a coolant. One possible reason was that the engine was licence-built from Germany, there being USA trade embargoes with Japan in the late thirties. A more technical reason may be found in the likely characteristics of the engine when cruising round the closed circuit.

The Kokenki was a highly streamlined high aspect ratio monoplane with a wing span 28 m (91 ft) and a loaded weight of 9,216 kg (20,317 lb). Cruising speed was 211 km/h (131 mph). Assuming a lift-to-drag ratio of 18/1, the required engine power could not have been much more than 500 hp, about three quarters of the declared rating of the engine’s 715 hp. Engine capacity was about 48 litres. Power output under these conditions was just over 10 hp/litre; a very modest figure.

Figure 13, showing the air cooled valve gives further clues to why air cooling was used, rather than sodium. The air enters the valve stem from the right from a pipe. The sides of valve stem at this point contain four slots which allow the air to enter the valve. As air passes down the stem, the stem is cooled to some extent of course, but calculations show that, even at high velocities, the likely rates of heat transfer are around 50 Watts. Unfortunately no dimensions are given, so these calculations are somewhat rudimentary, but Suzuki states that the airflow to each valve was 3.7 gm/sec which would correspond to about 10% of the combustion air flow.

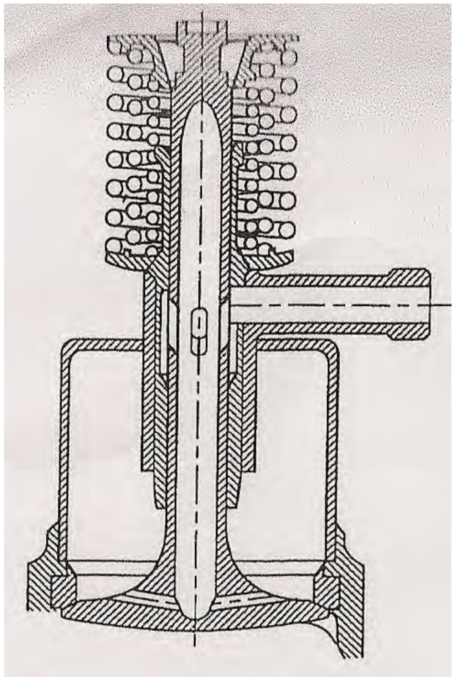

Figure 13. Air-cooled Valve.

A key feature of this cooling technique is that the cooling air exits the valve through four slots on the underhead side of the valve. The stream of air is directed towards the valve seat, reducing its temperature, and after this the cooling air will pass out of the valve chamber keeping the valve guide cool. Owing to the high rate of air flow, cooling air temperature remains quite low at all times. Accordingly, as the air flowed out through the valve chamber, it cooled the valve guides and in so doing allowed them to protrude into the valve chamber for a greater distance than would normally be acceptable. The greater length of valve guide would improve stem cooling.

It can be seen that in contrast to valves in which the stem is cooled by sodium, the air cooling will reduce valve temperatures in a variety of ways. But it was very much a "one off" and never seems to have been used on any other Japanese aircraft. Calculations suggest it could not be very effective on high output aeroengines, where valve heat transfer is very severe. The air cooling of valves is therefore another “good idea” which found itself parked up a technological cul-de-sac.

## Conclusions

Valve cooling developed without much theory to back it up. Heat flows in valves have always been difficult to model. Most of the work must have involved trial and error experimentation, in which valve temperatures could be ascertained from metallurgical changes in the valves, or by simply looking down the valve port with an optical pyrometer. This paper has endeavored to put some figures on the rates of heat transfer; at some point the author will publish the supporting calculations, as this paper is not a suitable vehicle for them. However the Appendix give a little more information on this subject.

Turning to other matters, any review of aeroengine development in the UK would have to say that our greatest loss was the move of Sam Heron to America in the early twenties. At the time when the Government-owned Royal Aircraft Establishment, was still allowed to do more than R&D, Heron was designing engines for them. Before that, as a mere machinist, he argued that valves should be tulip shaped, as tests had shown this to be the “natural form”. Subsequently every high powered liquid cooled aircraft engine used valves of this type. As was described, Heron was closely involved in the cooling of radial and rotary engines and had gone to the USA armed with the knowledge of what Gibson and his co-workers had done. Once there he formed a relationship with Curtiss-Wright, who were moving into aircooled radials. Heron believed, in contrast to Harry Ricardo, that fuel could always be improved; this work led to 100 plus octane fuels, so vital to the Allies in the Second World War. Heron kept abreast of materials technology. Indeed when he was challenged about his suggestion about using Vitallium turbine blades in jet engines, he removed his Vitallium teeth. In this way he convinced the engineers that Vitallium blades could be cast with high precision!

It is worth considering how aviation technology might have developed without the use of sodium cooling. Even with the best that materials technology could offer, engine outputs would have been limited to power to weight ratios of less than 0.3 hp/lb. It is also difficult to see how engines could have taken advantage of high octane fuels, as the use of these went hand-in hand with increased engine output and very high valve temperatures. Even intermediate range commercial flying would have been limited and it seems probable that fighter speeds would have been stuck below 300 mph.

Some would suggest that there were alternatives to the poppet valve. Two stroke piston engines could have been a possible option. High fuel consumption was an obvious drawback. And surely, if the two stroke engine had been a possibility, one of the aero engine builders would have offered it in the pre-war era? The other options, the diesel and the sleeve valve engine can similarly be dismissed. Work on these forms of the IC engine did not begin until there was a sizeable market for aero engines. Jumo, in Germany did make a success of the diesel, although limited to just a few aircraft types. The sleeve valve engine was pushed through by the efforts of Sir Roy Fedden, but it can be argued that this came about because of the bad experience Fedden had with valves in the early part of his design career. The eventual success with the Bristol Mercury seems to have cost Fedden his career with the company. If valve technology had stood still, the sleeve valve might have had more of a chance, but it didn't.

Internal valve cooling has gone the same way as the aircraft diesel and the sleeve valve, apart from niche markets. In the author's view, despite the complexity, the water cooled valve could make a comeback. Sodium cooling is still used in medium output aircooled aircraft engines, but this is under pressure from the small turbo prop and may be becoming another part of engineering history.

## APPENDIX: Valve Temperatures and Heat Flows in Automotive and Aircraft Engines

A completely rigorous analysis of the efficacy of various methods of cooling valves should start with an estimate of valve temperatures in the uncooled condition and with the amount of heat entering a valve. Yet despite their obvious importance, there is very little in the literature on these subjects. This not surprising, the complexity of valve heat transfer is daunting. The exhaust valve is closed during three strokes out of four, with engine pressures and temperatures changing radically during each of these "closed" strokes. During the exhaust stroke the valve opens and is subject to the flow of hot gas at near sonic speed. Finally the heat paths from the valve into the cylinder head, via the valve seat and valve guides are difficult to model, since oxide scales and oil films of indeterminate thickness disrupt the contact with the adjacent parts.

The only recent writer who has attempted to tackle this subject, without recourse to computational fluid dynamics, is Lumley, who makes the important point that unlike the other components in the engine cylinder, the piston, walls and cylinder head, the exhaust valve is so hot that only during part of the engine cycle is the valve being heated.[30] It loses heat the rest of the time.

Although Lumley appears to make a successful attempt to predict valve temperatures, in the view of this writer, his thinking is flawed, principally through his reliance on average heat transfer rates. Lumley estimates these using a correlation developed by Taylor in which the <u>average</u> heat transfer coefficient is related to a Reynolds-type turbulence number within the cylinder. Having obtained this value, Lumley, uses an estimated valve temperature, plus an estimated exhaust gas temperature to obtain a more accurate assessment of the valve temperature. How much validity can be placed on what is a series of conjectures and estimates is arguable

However, in our case where we are attempting to assess various methods of valve cooling, some of Lumley's thinking is very helpful. He points out that once an engine is up and running, despite the wide variations in heat flows during each four strokes of the engine, valve temperatures stabilise in the 600-750ºC region and can be regarded as constant. In addition, Lumley suggests that in an uncooled valve, of the heat flowing through the valve, that going into the stem and then into the valve guides, comes from the area corresponding to 0.65 of the valve diameter, underneath the valve stem. The remainder goes out through the valve faces.

The amount of heat entering a typical aircraft valve is of the order of a few hundred watts. Accordingly, the heat going into the stem and then into the guides will be at least 100 watts. With a big valve as used in the later American aircooled radials it could be as high as 300 watts. Furthermore, the temperature of the stem entering the valve guide cannot be much more than 400ºC, otherwise the guide will become overheated. Similarly, also because of material limitations, valve crown and stem temperatures rarely exceed 750°C. Hence the temperature difference between the bottom of the stem and the guide can never be much more than 350°C and it is the temperature differential which drives the heat transfer.

If we apply a temperature difference of 350°C to the type of big valve used in American piston engines, where the stem diameter is 1.7cm and the distance from the bottom of the stem to the guide is about 3.9 cm, the rate of heat transfer along the stem will be 45 watts. Even this figure is high. Even uncooled valves are hollow, so the amount of metal for conducting heat is reduced, bringing down the rate of heat transferred to less than 30 watts. The principal reason for the poor rate of heat transfer is the need to make the hot section of the valve of austenitic stainless steel, which at 21 watts/m.K has a relatively poor thermal conductivity. It is not surprising that the early valve manufacturers tried using an insert of copper, whose conductivity is 15 times higher than stainless as a “fill” for the hollow stem. This quite sensible idea was thwarted by differences in thermal expansion, leading to the copper insert working loose from the stainless. More reliable means of improving heat transfer were needed.

## References

1. D. Clerk, *The Gas and Oil Engine* (Wiley and Sons, 1907), pp. 118 –129.
2. J.L. Cummins Jr., *Internal Fire* (Soc. Automotive Engineers, 1989), pp. 179-180.
3. B. Lawton, ‘A Short History of Early Gas Engines’, *Int. J. History of Science and Technology*, 81/1 (2011), pp. 79-107.
4. Anon, ‘1200 Horse-Power Gas Engine’, *The Engineer*, 24 May 1907, pp. 530-4.
5. J.C. Snell, *Power House Design* (Longmans, 1921), p. 299.
6. H. Heiler, *Advanced Engine Technology* (Edward Arnold, 1995), p. 720, fig. 14.2.
7. T.D. Walshaw, *Diesel Engine Design* (Newnes, 1921), pp. 273-4.
8. Anon, ‘The Royal Agricultural Show’, *The Engineer*, 11 July 1913, pp. 37-40,
9. J.H. White, *Practical Aviation* (Wireless Press, 1918), p. 63.
10. F. Starr, ‘Internal Combustion Engine Exhaust Valves 1860-1930 and 1930-1980 Parts 1, 2’ *Int. J. History of Science and Technology* forth-coming.

11. S.D. Heron, *A History of the Aircraft Piston Engine - A Brief Outline* (Ethyl Corporation, 1961).
12. A.H. Gibson and H. Wright Baker, 'Exhaust-Valve and Cylinder-Head Temperatures in High-Speed Internal Petrol Engines' *Trans. Inst. Mech. E.* 105 (1923), pp 1045-1119.
13. Heiler.
14. 'Overall Heat Transfer Coefficient', www.EngineeringToolBox.com
15. H.M. Spiers, *Technical Data of Fuels*, 6th Edition (The British National Committee, World Power Conference, 1961), section on Forced Convection, pp. 70-4.
16. Starr.
17. W.S. Giles, *Fundamentals of Valve Design and Materials Selection* (SAE Paper 66071, 1966), pp. 1-20.
18. W.E. Dowling Jr,, J.E. Allison, L.R. Swank and A.M. Sherman, *TiAl Based Alloys for Exhaust Valve Applications* (SAE Paper 930620, 1993), p. 32; *TRW Handbook,* (TRW Automotive, 1993), Section 1.5 Valve Materials.
19. L. Taylor, *Metals Handbook- Selection of Materials for Engine Valves* (American Soc. Testing Materials, 1961), pp. 626-634.
20. L. Taylor, *Metals Handbook- Wrought Heat-Resisting Alloys-Extrapolation of data* (American Soc. Testing Materials, 1961), pp. 471-3.
21. S.M. Sohal, S.A. Ebner, P. Saberwall and P. Sharpe, *Engineering Database of Liquid Salt Thermophysical Properties* (Idaho National Laboratory, 2010); C. Sharpe, *Kempes Mechanical Engineer Handbook* A6/8 (Benn, 1992), table 8.
22. D. Dyer, *TRW-Pioneering Technology and Innovation since 1900* (Harvard Business Press 1998), pp. 53-7.
23. F.R. Banks, *I Kept No Diary* (Airlife, 1983), pp. 90-1.
24. A.T. Colwell, *Modern Aircraft Valves* (SAE Transactions, 1940), pp. 147-165.
25 J.C. Sanders, H.D. Wilstead and B.A. Mulcahy, *Operating Temperatures of a Sodium Cooled Valve as Measured by a Thermocouple* (NACA Advanced Restricted Report 3LO6, 1943); J.M. Jagger and F.O. Black Jnr., *A Cooling Correlation Equation for a Double Row Radial Engine based on the Temperature of the Exhaust Valve Seat* (NACA Memorandum Report E5D30a, 1945); M. Munger, E.D. Wilstead and B.A. Mulcahy, *The Effect of Valve Cooling Upon Maximum Permissible Engine Output as Limited by Knock* (NACA TN 861, 1942); M.A. Zipkin and J.C. Sanders, *Correlation of Exhaust-Valve Temperatures with Engine Operating Conditions and Valve Design in an Air-Cooled Cylinder* (NACA Report 813, 1945).
26. Sanders, Wilstead and Mulcahy.
27. Zipkin.
28. Ibid.
29. T. Suzuki, *The Romance of Engines – Voyager and Kokenki*, (SAE, 1997), chapter 35.
30. L.L. Lumley, *Engines, an Introduction - Engine Cooling* (Cambridge, 199X), pp. 95-117.

## Notes on Contributor

**Dr Fred Starr** is a metallurgist who has specialised in gas manufacture and electrical power generation. He is greatly interested in technical developments in the twentieth century and has been secretary to the organising committee of this conference and the main contact with authors. This has complimented his other main interest in the history of aircraft design.
Email: starrfred@yahoo.com