Ricardo Research and Development 1945-1985

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The paper covers the major internally funded and sponsored work carried out by Ricardo during this period. While it is not possible in a review paper, covering such a wide range of topics, to give detailed results; highlights of the results, details of novel experimental equipment and references to the published programmes are given.

Immediately after the war the Company continued with Government sponsored studies into very high power aircraft piston engines, although these programmes were run down as it became clear that the gas turbine was the engine for the future.

Combustion in the spark ignition engine continued as a major area of interest. High-speed sampling combined with gas analysis was used for detailed studies into the mechanisms involved in detonation and pre-ignition. This included the mechanism by which tetraethyl lead inhibited detonation. The effects on engine durability, of both very high and very low levels of tetraethyl lead concentrations in petrol were studied.

High-speed photography was employed to study both the fuel air mixing processes in diesel engines and actual combustion itself, over a wide range of combustion chamber types. Improvements in the Comet system were obtained as a result of these tests.

The extensive employment of turbocharging in diesel engines, from the 1950s onwards, substantially increased both the thermal and mechanical loading on engine components. Major programmes were carried out to obtain data to enable the designer to predict the temperature distribution and hence the thermal stress levels in cylinder liners, cylinder heads and pistons. These programmes covered the distribution of local heat fluxes and the coolant side heat transfer conditions in running engines on both static and dynamic rigs. Indirect and direct injection combustion systems were included in the programmes with a range of cylinder bores from 120mm to 670mm.

Major programmes were carried out into the reduction of exhaust emissions in both petrol and diesel engines. A novel catalytic engine employed catalyst gauzes in the combustion chamber of an engine with petrol injection in an attempt to widen the inflammability range of the mixture strength, without giving rise to excessive exhaust hydrocarbons.

Other programmes covered included engine noise reduction, the operation of diesel engines on residual fuels, the use of exotic engine operating cycles for submarines and torpedoes, and alternative engines for passenger cars - steam and Stirling cycles. Mention is also made of the development of extensive computer programs for engine cycle analysis and component stressing.

KEYWORDS: Ricardo, Diesel, Petrol, Combustion, Design

The Wartime Move to Oxford

In 1940, the Ricardo research organisation was evacuated to Oxford. The staff were working on important aircraft propulsion projects and the Government felt that at Shoreham they were too vulnerable to attack from enemy aircraft. While at Oxford, Ricardo made an important contribution to the Whittle gas turbine programme by developing the altitude fuel control system and the engine governor and then by manufacturing the actual components used in the engines.

Aircraft Propulsion

The Company returned to Shoreham in 1945. Advanced aircraft propulsion had been an important part of its work for about fifteen to twenty years. From the early thirties, Ricardo had had discussions with Rolls-Royce concerning the future development of high power engines for aicraft and in particular, the potential advantages offered by the two-stroke engine. Following these discussions, and under a contract from the Air Ministry, Ricardo had from before the war been involved in the manufacture and testing of single-cylinder, two-stoke, petrol injection type, sleeve valve engines. As a result of the success of this work, Rolls-Royce constructed prototype multi-cylinder engines. This engine was named the Crecy. With the rapid development of the gas turbine however, Rolls-Royce decided that they would not proceed with the development.

Despite the abandonment of the Crecy Engine by Rolls-Royce, Ricardo decided to reinstall the single-cylinder E65 engine (Figure 1), on which the early development had taken place, to establish the maximum power which it would have been possible to reach.

Short duration tests were successfully carried out at 354psi BMEP at 4000 RPM, and it appeared that still higher powers would have been achieved had fuel injection pumps of higher capacity been available. The Crecy engine in its developed form would have been able to produce some 5000 bhp for a gross weight of about 2000lbs and with little more frontal area than that of a Merlin or Griffon engine.

Compound Engines

During the 1930s and 1940s, work was carried out on compound engine projects, combining a boosted piston engine as a gas generator with a turbine expander. Early work had shown that the onset of detonation prevented the use of spark

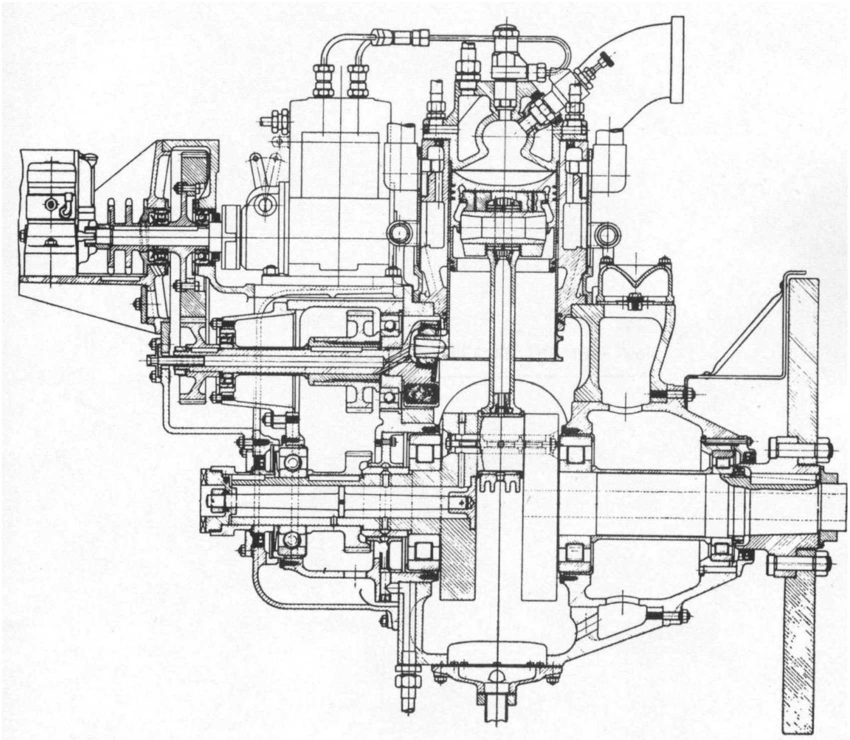


Figure 1. Longitudinal section of E65 engine.

ignition and a comparison of two- and four-cycle diesels demonstrated that two-cycle was superior to four-cycle in terms of power output and specific weight.

Two alternative simple ported, single-cylinder, units together with a sleeve valve engine were constructed and run at Oxford. This work continued at Shoreham until 1952. This work formed the basis of Napier Nomad prototype aircraft engines that were ultimately built, developed and flight tested with results that agreed closely with Ricardo predictions. As with the Crecy engine, however, gas turbine developments overtook these programmes.

Combustion in the Spark Ignition Engine

This subject had of course always been an interest of Sir Harry Ricardo. He had identified the difference between detonation and pre-ignition and had produced an early fuel rating scale for detonation. His invention of the Turbulent Head for spark ignition engines had not only been important in establishing the reputation of the Company but had also been an important source of income in the 1920s and early 1930s.

Detonation and pre-ignition are the two most important abnormal combustion phenomena in the petrol engine. Detonation or knock is due to rapid combustion of the last part of the mixture, following initiation of the flame by the spark, whereas pre-ignition is auto-ignition of the whole charge by a hot body, independent of the spark. Sir Harry's classic study for the Shell Company in 1918-1920 showed that in the spark ignition engine there is a uniquely close link between fuel quality and engine performance, The efficiency of the engine is directly related to the compression ratio employed, the limit to the compression ratio used being set by the onset of knock which in turn is influenced by the oxidation resistance (usually expressed as the Octane Number) of the fuel. The higher the compression ratio of the engine, the higher is the power output and the lower the specific fuel consumption.

Following this discovery, most of the practical answers to the matching of engine fuel requirements and fuel quality in the interwar years had been obtained empirically. The basic rules of good combustion chamber design were established. The effect of such operating conditions as: mixture strength, ignition timing, engine speed and temperature on knock were known. The effects of such anti-knock additives as tetra ethyl lead were also well established.

Despite the accumulation of this vast amount of empirical information however, by the early 1940s little more knowledge of the fundamentals of knock had been added. At this time, the Shell Company placed a research contract with Ricardo to pursue more fundamental studies. Empirical methods of measurement were being exhausted and it was hoped that a fresh attack on the problem at a fundamental level would be more fruitful.

One characteristic of knock, which facilitates its study, is that it always appears in the same part of the combustion chamber i.e. that which is most remote from the spark plug. It was decided to develop a high speed sampling valve and to analyse gas samples to follow the chemical processes occurring in the end gases, prior to and during the knocking process.

A sampling valve (Figure 2) was constructed using parts of an American Atlas electromagnetic fuel injector and very extensive studies were carried out over a period of some years. These studies were initially sponsored by Shell but later by the Associated Ethyl / Octel Companies.

By varying the timing of the opening of the sampling valve as referred to the crank angle, it was possible to follow the progress of the chemical reactions. Preliminary analytical work established that of all the stable intermediate products of reaction formed in the end gas prior to knock, organic peroxides and hydrogen peroxides were the only ones that had a strong pro-knock effect. Formaldehyde was the only intermediate product having an anti-knock effect. Figure 3 demonstrates the success of the sampling techniques, showing typical curves of peroxide and aldehyde concentrations plotted against crank angle at various compression ratios and with and without the addition of a knock suppressant.

The studies showed that knock was a two-stage process with an initial cool flame passing through the end gas with a slight rise in temperature, followed by a

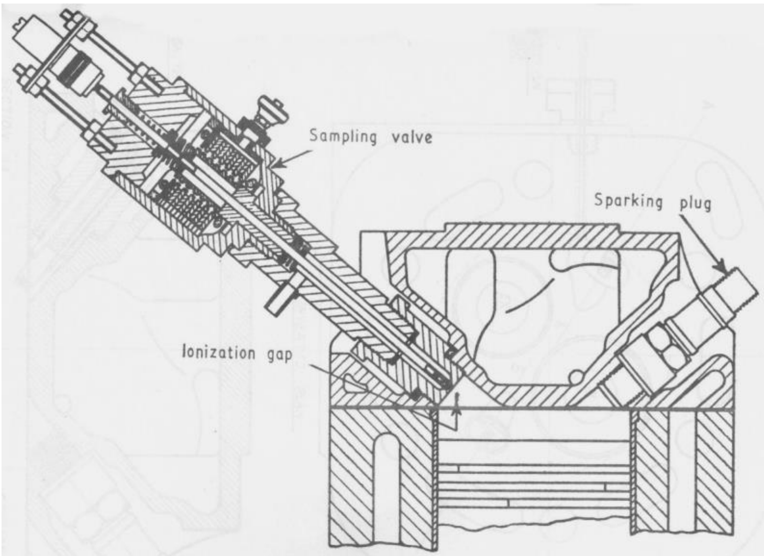


Figure 2. Sampling valve sited in cylinder head of Ricardo E6 engine.

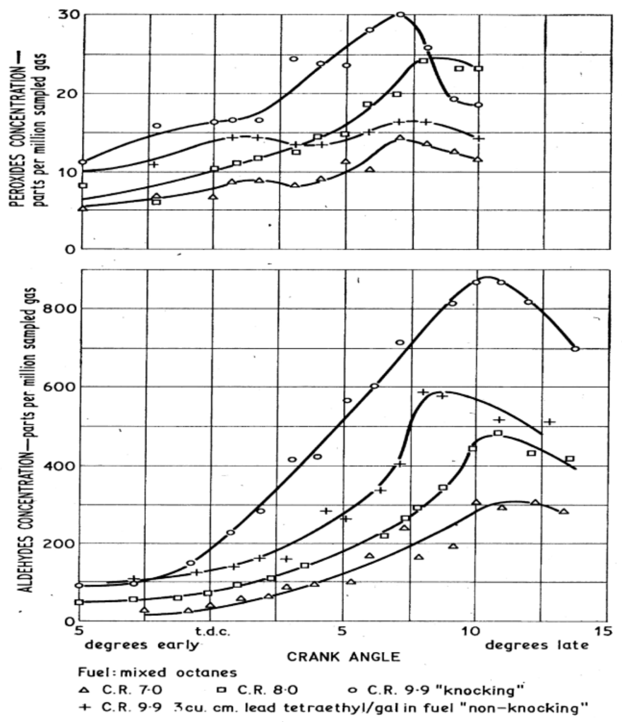


Figure 3. Peroxide and aldehyde concentrations in gases sampled at various crank angles.

hot flame. The point of inflexion in the concentrations of aldehydes and peroxides in the figure results from this change from a cool flame to a hot flame.

A study of the mechanism of knock suppression with tetraethyl lead indicated that the active agent is lead oxide formed by the breakdown of the tetraethyl lead during the cool flame process.

In a review paper of this type, it is not possible to give a detailed analysis of the results of such an extensive series of tests, carried out over a period of years. For this, the reader must be referred to the extensive reference list at the end of the paper.[1]

Pre-ignition, the initiation of combustion prior to the spark, can have a serious effect on engine life as shown for example in Figure 4. With ignition occurring well before top dead centre, very high gas temperatures occur. Furthermore the process is progressive. As component temperatures increase, ignition occurs earlier and earlier, with resulting higher and higher gas temperatures. Piston failures for example can occur very rapidly as can burning of the exhaust valve head and seat.

Figure 4. Automotive piston with hole through the centre of the crown.

Before the abolition of tetraethyl lead in fuels, one cause of hot spots leading to pre-ignition could be lead deposits in the combustion chamber. The method, which Ricardo employed to compare the tendencies of fuels to pre-ignite, was to measure the electrical energy required to heat an electrically heated hot spot in the combustion chamber. Downs gives more details of the results but one interesting discovery was that there was no simple relationship between the knock and pre-ignition ratings of various fuels as may be seen from Figure 5.[2]

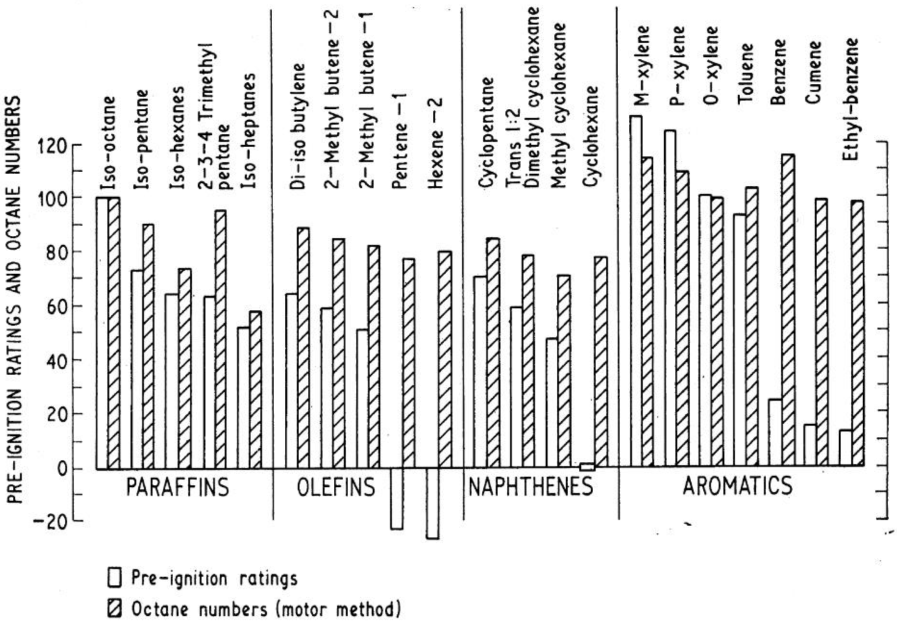


Figure 5. Pre-ignition ratings and knock ratings of pure hydrocarbons.

Ricardo carried out several programmes exploring the effects of both the presence of high concentrations of tetraethyl lead and the effects of its absence in petrol. The first programme resulted from the decision by the British Army to look into the use of multi-fuel engines which could burn any fuel which might be available at time of war.

The high concentration level was 3.6ml./Imperial gallon, which concentration had also been employed in some earlier studies concerning the distribution of lead between cylinders in multi-cylinder engines. Such high levels can lead to excessive deposit formation and this was the reason for the programme.

An early study was aimed at ensuring that small industrial units of say 1-10 hp can operate on such a fuel for 1000 hours without failure. In vehicle engines, constantly fluctuating speed and load conditions give temperature variations that encourage the regular flaking off of combustion chamber deposits before they reach serious proportions. These conditions are not obtained with small industrial engines which may operate for long periods at constant speed and load. Also, in a single-cylinder engine, one small piece of deposit trapped between the valve and its seat may cause the engine to stop, whereas in a multi-cylinder engine, the engine would continue to run on the other cylinders, resulting in severe burning of the exhaust valve and in some cases also of its seat, in the affected cylinder. As a result, serious burning failures which at that time were common on road vehicle engines were rarely experienced in single-cylinder engines.

The major problem encountered in these tests was sticking of the stems of the exhaust valves in their guides. It was found to be important that the valve guides did not project into the exhaust. Counter boring of the guide for a length of the lift for water-cooled engines and twice the lift for air-cooled engines was found to be advantageous.[3]

The British Army was also interested in the selection of a possible additive which could be added to petrol to enable it to be used as a fuel in diesel engines. A number of possible alternatives were explored. The addition of 5% lubricating oil appeared to be the most attractive possibility.

During the early 1960s, as a result of concern with the smog problem in California and the consequent need to reduce nitrogen oxides, carbon monoxide and hydrocarbons concentrations in engine exhausts, attention became focussed on the use of noble metal catalysts as an exhaust after treatment. Such catalysts are poisoned by the presence of lead compounds and hence there was a need to eliminate lead from petrol. This predated the campaigns to eliminate lead due to its harmful medical effects on the human body.

When it appeared likely the lead would be removed from all petrol, work was carried out to investigate effects that would result from this. The principle effect encountered was exhaust valve seat recession, which could happen at an alarming rate due to the absence of the lubricating effect of lead deposits. Hardened seats were a positive solution.

Combustion in the Diesel Engine and Combustion Chamber Design

Early in the 1930s, Sir Harry decided that in view of the development state of fuel injection equipment at that time, indirect injection was the most promising form of combustion system for transport engines, which needed to be operated over a wide speed range, as compared with those employed for power generation. Following this decision, the Comet series of swirl chamber combustion chambers were developed. The first passenger car diesel engine to go into production, the Citroen employed a Comet combustion chamber and further Comet development continued into the 1950s, culminating in the Mark 5b. The development of Comet combustion systems over the years may be seen in Figure 6.

While indirect systems such as the Comet offer substantial advantages in terms of noise, power output and a wide speed range capability, cold starting can be a problem. The introduction of heater plugs into the combustion chamber is a solution but at the expense of a 30 second wait while the plug warms up. Jointly with CAV, Ricardo developed the Pintaux nozzle. At cranking speeds, the needle only lifts a small amount and the fuel spray is directed into the hottest air, i.e. the

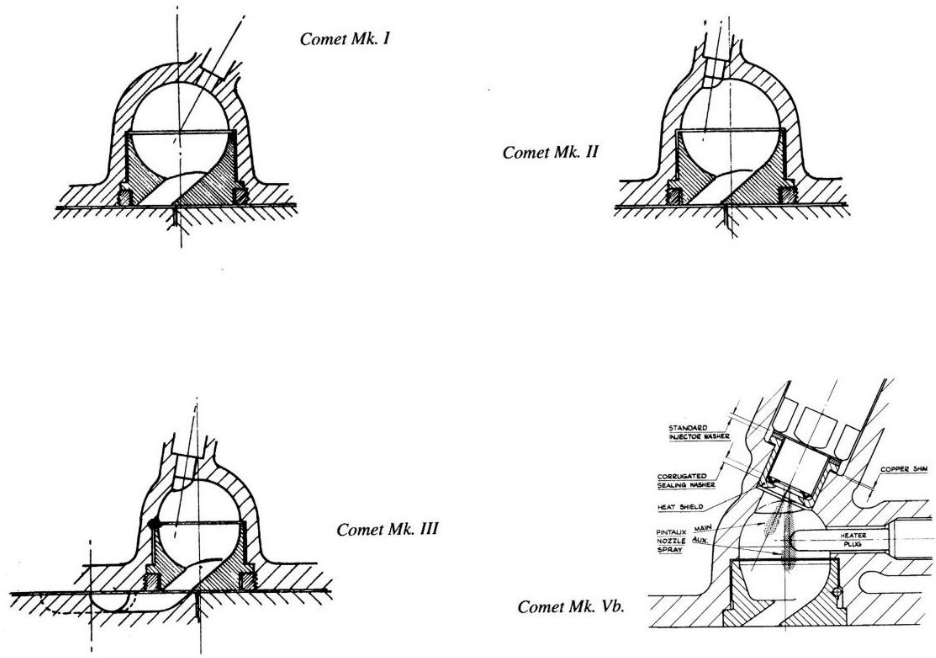


Figure 6. Development of Ricardo Comet combustion systems.

stream of air entering the pre-chamber. This results in substantially improved cold starting; Figure 7 shows a Pintaux nozzle. Since the war the Comet combustion system has been applied to light-duty engines for many different manufacturers throughout the World and many millions of engines have been manufactured and gone into service.

The early development of the Comet was carried out empirically but as time went by there was a desire for an approach which took into account a better understanding of air motion in the combustion chamber and of the fuel/ air mixing process. There was a similar desire to better understand the mixing and combustion processes in direct-injection engines. It was decided to attempt to employ high-speed photography for this purpose. This followed work that had been carried out by the NACA and others in the United States in studying knock in petrol engines.

The camera employed was a Western Electric Fastax 8mm. high-speed camera. A hundred foot spool of film is used. Film breakage limits the speed to 8000 frames a second. It was possible however to increase the film speed to 16000 frames a second by starting the camera run at normal voltage and by then increasing the voltage during the run. This limited the initial acceleration loads on

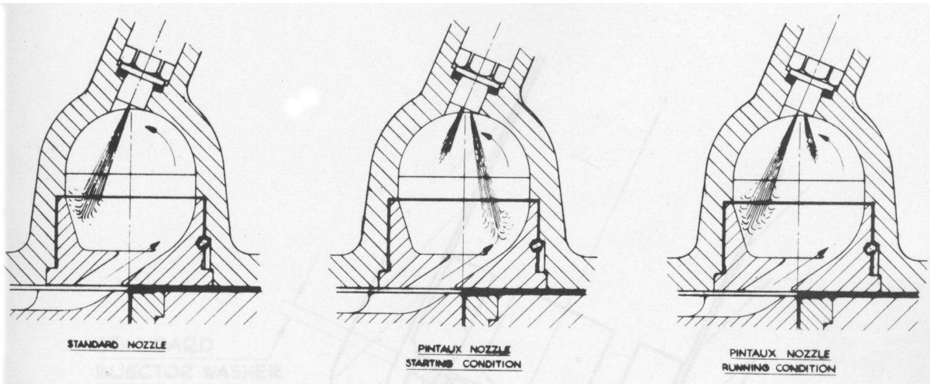


Figure 7. Pintaux nozzle for Comet combustion systems.

the film material. Photographs were taken through Perspex windows which material proved adequate for very short runs, although some re-polishing of the Perspex might be required between runs. Photographs were taken over a wide range of engine operating conditions and with a range of combustion chamber types and with different geometries. A typical photograph is shown in Figure 8.

The use of combustion photography did not result in any dramatic improvement in combustion chamber design and indeed was unlikely to do so, but as so many variables had been studied empirically over the years, we found out why many geometries did not work and the final form of the Comet series, the 5b, resulted from a study of combustion photographs.

A steady state blowing rig fitted with a vane type anemometer was employed for swirl measurement in direct injection engines. Later, the use of Laser Doppler Anemometry enabled turbulence to be measured as well. This technique was also employed in motored engines, fitted with windows.

The Use of Residual Fuels in Marine Diesel Engines

In the early 1950s there was an interest in the burning of residual fuels in large, low speed, diesel engines since they were very much cheaper than distillates. Such heavy fuels have to be heated for pumping in order to reduce the viscosity of the fuel. It was also necessary to centrifuge the fuel to remove water and inorganic rubbish which might be contained in it. Such fuels tend to have very high levels of sulphur and of vanadium salts. During combustion, the sulphur gives sulphur oxides and, as temperatures fall, these combine with the water from combustion to give acidic sulphuric acid. The Vanadium salts tend to give very hard deposits. These two contaminants can give very high levels of cylinder liner and piston ring wear which leads to unacceptable engine life.

In 1954, Ricardo was contracted by the British Ship Research Association

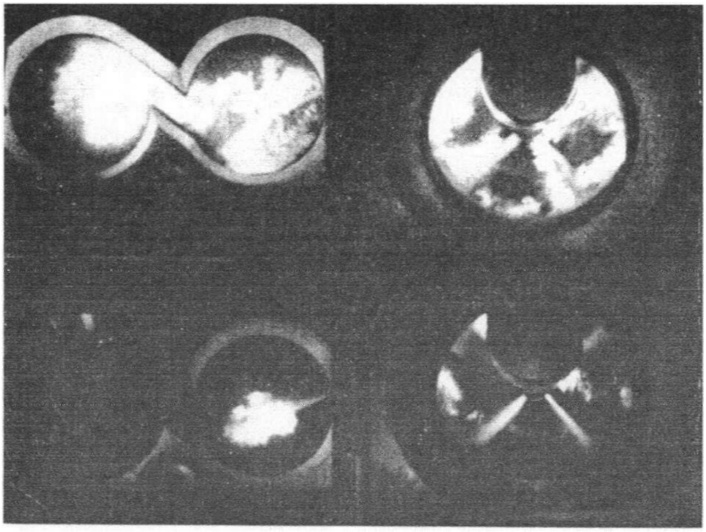


Figure 8. Typical combustion photographs.

to carry out a study aimed at identifying the causes of these engine problems when operating on such fuels and at finding a solution. Two Crossley HH9 single cylinder engines of 248mm bore and 406mm stroke were installed for this project.

The tests involved the collection of the sludge from the mouth of the cylinder liner into a simple circular trough around the exposed outer end of the liner and the sludge was drained away into collecting bottles. A 1500 second residual fuel was employed for all the tests.

Wear was principally assessed from the iron content of the sludge but the cylinder liners and piston rings were also measured for wear. Many operating conditions were studied but the main result of the findings was that wear was strongly affected by the coolant temperature and wear improved up to the limit of 95 ºC, which was the highest employed.

The Thermal Loading of Engines

From the early 1950s onward there were dramatic increases in the output of diesel engines, consequent upon the increasing use of turbocharging. As a result of this the engine thermal and mechanical loadings were increased substantially. While the increases in the mechanical loading of components due to increases in cylinder pressure could be easily calculated and redesign carried out, there was less knowledge as to the increases in thermal loading which would result from this up-rating.

Because of its concerns as to the likely effects on the durability of propulsion and auxiliary engines, the British Admiralty placed a contract with Ricardo to carry out a detailed experimental study into the effects of load and speed on the local heat fluxes and temperature distribution in pistons, cylinder liners and cylinder heads of several different diesel engines including a Foden two-stroke, through-scavenged, exhaust-valve-in-head engine. Substantial up-ratings were also occurring in marine diesel engines and the British Ship Research Association placed a similar contract regarding large marine engines.

Subsequently, Ricardo extended the studies, as part of their own research programmes, to examine Comet IDI engines, which were coming into use in large numbers in light-duty applications and where solutions were required to solve cylinder head and piston crown cracking problems arising in service and also to measure heat flows in petrol engines. Ultimately, the direct injection engine programmes were extended to include studies at very high ratings using the Ricardo Atlas single cylinder research engine.

The programmes extended over some twenty years or so and since the results are still relevant today to the design of thermally loaded engine components, it is thought appropriate to go into some detail into the techniques employed and to outline the results obtained.

Since we required to measure not only the metal temperatures at the gas face of the component but also to establish the temperature gradients in order to be able to calculate the local heat fluxes, traversing thermocouples were fitted to cylinder heads and cylinder liners. These thermocouples had been developed by Ricardo for earlier work for the Air Ministry. As can be seen from Figure 9 a small flat-bottomed hole is drilled through the metal from the coolant side leaving only a thin skin of metal at the gas face. A guard tube which seals against a neoprene washer prevents coolant entering the test hole and a fine-fitting thermocouple button can be moved backwards and forwards by means of a micrometer head. Comparative tests with fixed thermocouples had established that the traversing thermocouples gave results that agreed closely with those of fixed ones.

As an example of the studies carried out, the following covers the tests on a Ricardo E19 four-valve, direct-injection diesel engine of 127mm bore and 138mm stroke operating over a range of up to 21 bar BMEP.[4]

While access to the deck of the cylinder head can be restricted, four traversing thermocouples were fitted, at a range of radii from the centre of the head, including the critical areas of the valve bridges between the exhaust valves and between the inlet and exhaust valves, where thermal cracks can occur. Access to the cylinder liner is of course much easier and six thermocouples were fitted down the cylinder liner. The arrangement is shown in Figure 10.

The measurement of piston temperatures poses more of a problem. Two methods have been employed. The first uses fixed thermocouples, the leads from which were attached to glass insulated contacts attached to the piston skirts. At about bottom dead centre, these make contact with beryllium copper leaf springs from which the temperatures may be measured. At Ricardo’s we have also used

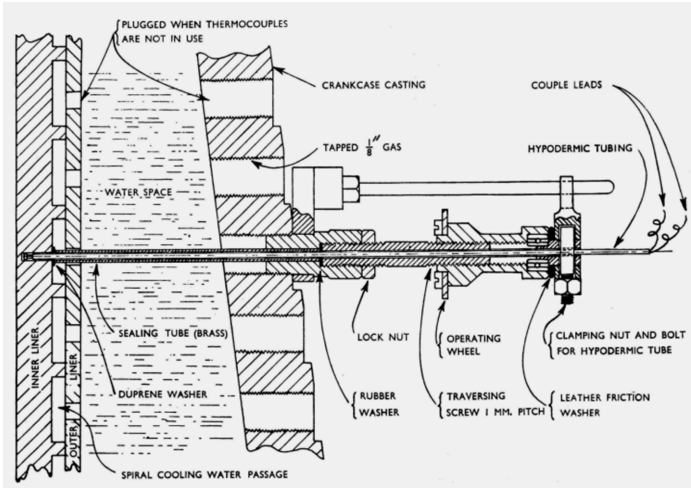


Figure 9. Traversing thermocouple.

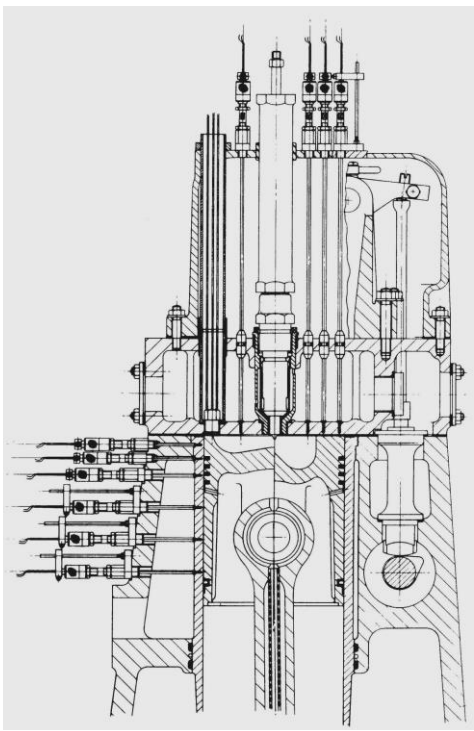


Figure 10. Arrangement of upper half of E19 engine showing thermocouple positions.

eutectic plugs which melt at fixed known temperatures. Holes are drilled into the piston crowns from the gas side and the plugs are driven into these holes until they are just flush. They are located in groups of three with slightly differing melting points. The plug whose surface can be seen to have just changed its appearance by incipient melting indicates the correct temperature. We have also used Shell Tem Plugs for temperature measurement. These were metal plugs whose hardness changed with temperature. Plugs were fitted to engine components, the engine operated under fixed conditions for a specified time and the plugs were then removed and returned to Shell for hardness measurement.

Similar hardness recovery techniques can also be employed for obtaining complete temperature maps for exhaust valves and for aluminium pistons by measuring the change in hardness of the parent material. Obtaining the temperature plots at the conclusion of the tests, however, involves destroying the component by sectioning and of course, as is the case with Tem Plugs and eutectic plugs, results are obtained for only one operating condition.

Similar detailed temperature and heat flux measurements were also carried out on an E 16 Ricardo Comet indirect injection engine of 4¾" bore with six traversing thermocouples in the cylinder head and three in the thermally insulated hot plug.[5]

The marine engine tests were carried out at the Sunderland engine works of Messrs Doxford on a single cylinder version of their "P" opposed piston engine, with a bore of 670mm and a combined stroke of 2100mm.[6] In the case of this engine of course, the "centre" section of the liner, i.e. that between the inner swept paths of the pistons, comprises the combustion chamber. Nineteen traversing thermocouples were fitted along the length of the combustion chamber and the liners and fifty three fixed thermocouples with intermittent contacts to each piston.

In order to make the maximum use of the piston temperature measurements, an electrolytic analogue of the piston was constructed. This took the form of a hollow, wedge-shape, half-section of the piston, the body of which was filled with tap water as an electrolyte. The measured surface temperatures, as measured by the thermocouples, were represented by voltages applied to the boundaries of the tank, through copper electrodes. The internal temperatures of the piston were then measured by reading the analogous voltages within the electrolyte.

While the reader must be referred to the published papers for detailed results, the amplitudes of the heat fluxes measured and their distribution vary widely between different combustion chamber types. In general however it was found that for each engine, the heat flux varied with fuel flow by an index of the order of 0.75 -0.8 of the fuel flow per unit of piston area.

Using the results of the tests and the flux distribution map appropriate to the chosen combustion chamber type, it is possible to predict the heat flux distribution for an individual component under any load condition. To obtain the actual temperatures however, it is necessary to know the heat transfer conditions on the coolant side. For the cylinder head and liner this is normally water either with or without a chemical additive. For the piston, it could be an oil jet, an internal chamber containing an oil feed or, in the case of some marine engines, water.

Water Side Heat Transfer

In the critical areas of a cylinder, where the heat flows are high, heat transfer is by nucleate boiling where, although the bulk temperature of the water is below boiling point, steam bubbles are formed at the metal / water interface. Heat transfer involves therefore the latent heat of the liquid and very high rates of heat transfer can occur without the very high temperature steps which would be necessary for forced convection heat transfer.

The literature contains large amounts of data concerning such nucleate boiling but unfortunately this data applies to chemically pure water and chemically clean surfaces. There can be no piece of heat transfer equipment where the fluids and the surfaces depart further from these ideals. In the engine, the metal surfaces are as cast and in the case of cast iron may have casting sand adhering to the surface; the water may well be untreated, with appreciable quantities of hardness and oil may be present due to gasket leaks, although hopefully not!

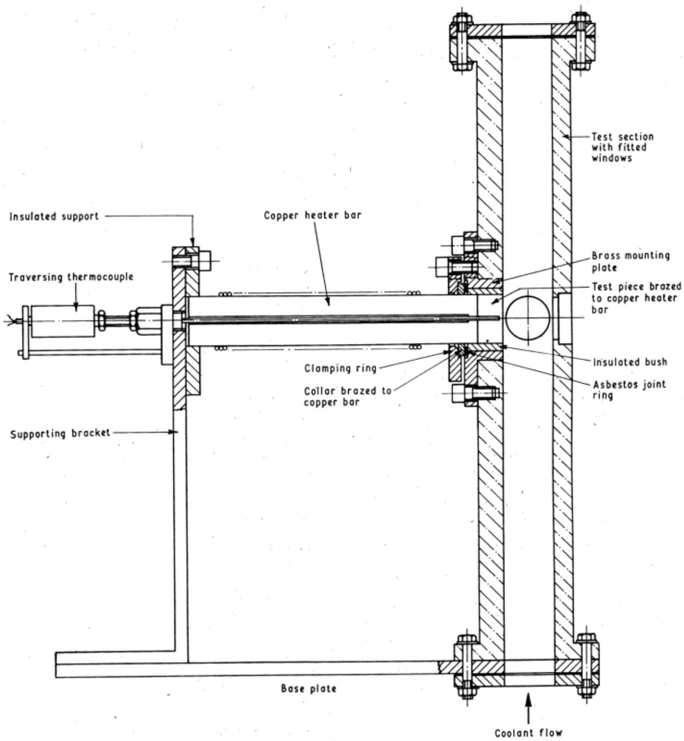


Figure 11. Dynamic metal coolant heat flow rig.

Ricardo therefore carried out a further series of programmes, investigating the heat transfer between water, with or without a range of additives and contaminants, and cast iron and cast steel with surfaces as cast, and also with machined surfaces. Two rigs were employed, one with a pumped coolant flow, the other a pool boiling rig with the specimen heated by gas. For the dynamic rig the specimens were heated electrically by being brazed to a copper heating bar wound with a heating element, the specimen being fitted with a traversing thermocouple. In the pool-boiling rig, with gas heating, which was used for durability testing, temperatures and hence heat flows were measured by the use of fixed micro thermocouples. These rigs are shown in Figures 11 and 12.

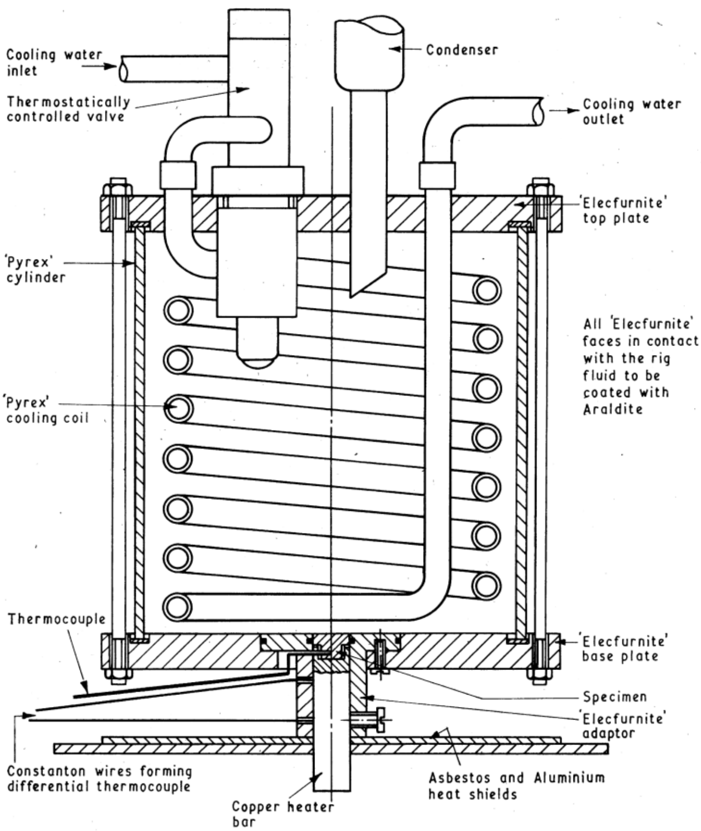
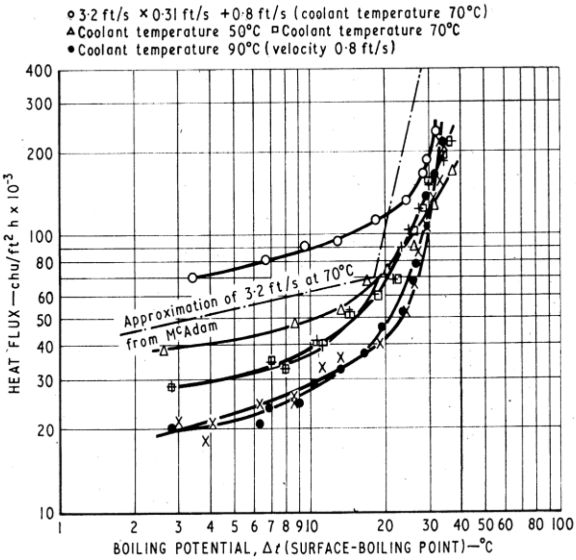


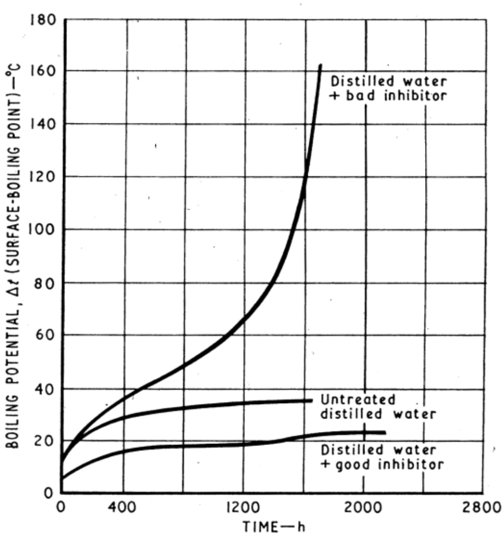
Figure 12. Pool boiling heat flow rig.

Some typical results are shown in the following figures. Figure 13, with a copper surface, shows the rapid increase in rates of heat transfer as nucleate boiling commences, while Figure 14 shows that an inappropriate additive can have a very serious effect on heat transfer. Among the results, one interesting effect was that with some as cast iron surfaces, the heat transfer under pool boiling conditions was poor, due to a "thermal barrier".[7] From observations of the surface under boiling



Coolant: distilled water, copper specimen.

Figure 13. Heat flow curves at various velocities and bulk coolant temperatures.



Heat flow ≃ 90 000 Chu/ft² h, coolant temperature ≃ 70°C.

Figure 14. The effect on heat transfer of adding corrosive inhibitors to a coolant of distilled water.

conditions, this seemed to be related to the size of the graphite cells in the iron influencing the size of the steam bubbles.

Piston Cooling

Pistons may be cooled by an under-crown jet; by splash from the bearing lubricating oil feeds or by more organised cooling. In a cocktail-shaker-cooled piston the under-crown cooling cavity is fed with oil, but the oil outlet is at a point where the cavity runs partly full at all times. Alternatively, there can be a solid flow system where the cooling chamber is full at all times.

Ricardo carried out a wide range of tests with all these alternatives on the reciprocating rig shown in Figure 15. The piston was electrically heated, fed by brush gear, a swinging beam carried the thermocouple leads and articulated pipes were employed to feed coolant into and out of the rig. [8]

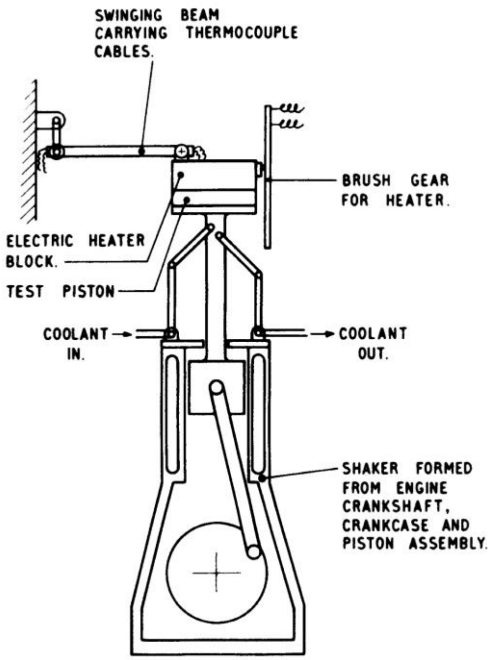


Figure 15. Schematic arrangement of piston cooling rig.

Calculation of Thermal Stress

The uses of the heat flux and coolant side heat transfer data obtained from these very extensive series of tests contributed greatly to the design of improved engine components for operation over a range of ratings. They provided boundary conditions for finite element calculations and are I believe still employed although, in some cases, they have been superseded by alternative computer based methods.

Diesel Engine Noise

Analysis of engine noise and the development of engines with a reduced noise signature became a subject of study in the early 1960s. An anechoic cell was built in which engines of up to 400bhp could be operated over their full range of loads and speeds. The cell had a loose floor, which could be removed, in order that the cell could be operated under semi anechoic or fully anechoic conditions. Extensive test were carried out covering a wide range of modifications to engine structures such as isolated sumps and valve covers, a ladder frame section to carry, and hence to strengthen, the main bearing caps and noise shields surrounding the engine.

A novel technique was developed for investigating the mechanism by which combustion noise is transmitted through the engine, before finally being emitted as vibrations and hence as an audible noise.[9] The basic idea was to separate combustion from mechanical noise by producing the cylinder pressure rises, which would occur in a firing engine, in a static engine. The explosions were produced by sparking off mixtures of propane, air and oxygen in the combustion chamber of the engine by means of a special combustion device. Two such mechanisms were produced. The first, which was only applicable to a single cylinder engine, involved the insertion of a sandwich plate between the cylinder block and the cylinder head as shown in Figure 16. The second, which could be used in a multi-cylinder engine, took the form of a dummy fuel injector as shown in Figure 17. This contained the valve, spark plug and a pre-chamber and replaced the fuel injector of the cylinder under study.

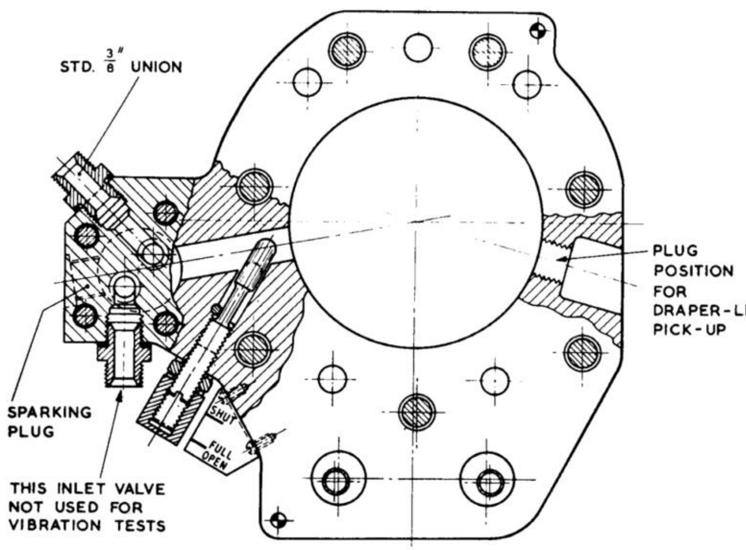


Figure 16. Single cylinder Banger rig.

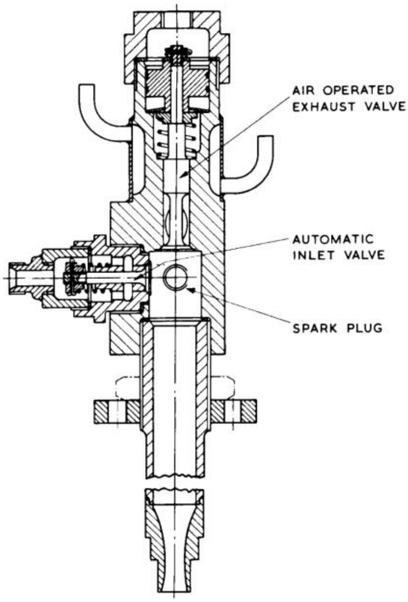


Figure 17. Universal combustion system for static noise tests.

Tests were carried out covering a range of rates of cylinder pressure rise. It was interesting that all the high vibration levels were associated with flexing of the crankshaft system. Very large reductions in level were obtained by fitting a very stiff dummy connecting rod / crankshaft. On a single cylinder engine where the flywheel inertia is relatively large, energy is stored up in the flywheel and fed back into the system after the pulse has died away.

Rubber Model Tests for Mechanical Stress Determination

Before sophisticated finite element methods were available for the calculation of stress levels in engine components of complex shape, such as cylinder heads, crankshafts, cast crankcases, connecting rods and pistons, reliable methods of stress analysis were not available and it was desirable to find a technique for predicting these stresses before prototype components were procured.

Ricardo carried out extensive testing employing silicone rubber models. While rubber models had been employed by others for qualitative testing, Ricardo developed a zero stiffness strain gauge which enabled quantitative results to be obtained. The strain gauge takes the form of two parts. Both parts are mounted in the rubber by means of pins. One pin carries the core of a small inductive transducer and the other carries a ferrite core.

At an early stage in the testing of a component, a brittle lacquer technique test may be carried out using cellulose enamel for the lacquer. This will indicate high stress levels where the strain gages are then located. Figure 18 shows the arrangement of a gauge. Loading may be by means of a proof ring or by a system of pulleys and weights. A typical layout for the testing of a crankcase diaphragm is shown in Figure 19 and further details of the technique are in the literature.[10]

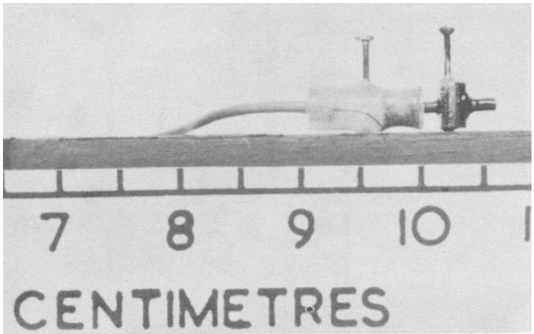


Figure 18. Zero stiffness strain gauge.

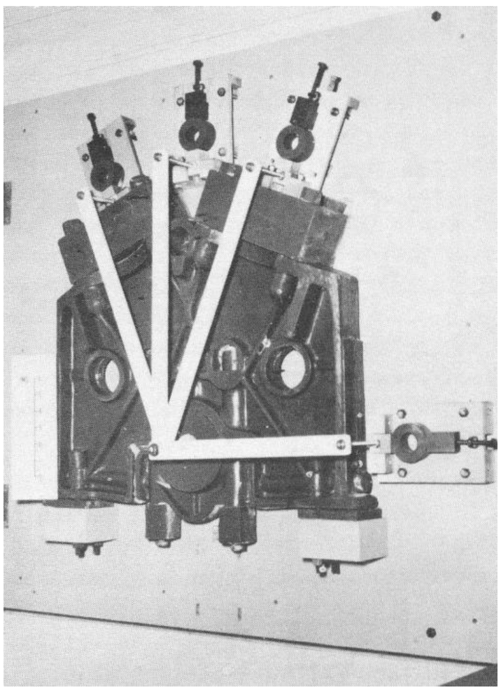


Figure 19. Arrangement of model crankcase diaphragm showing loading frame.

Submarine and Torpedo Propulsion

While being very much outside the normal run of experimental work for most organisations working in the piston engine field, some mention of the work which Ricardo carried out for the British Admiralty in the 1950s may well be of interest!

Before the introduction of nuclear power for submarines there was a desire to increase the underwater range of submarines by employing the use of "recycle" type diesel engines. During such operation, the oxidant for combustion is provided from either bottled oxygen or by the decomposition of High Test Peroxide (HTP). The carbon dioxide from combustion is voided but is soluble in seawater and can give no visible trace while the un-burnt oxygen and steam, together with some of the CO_2 as a dilutent are recycled to mix with the oxygen from store to form the induction gas.

Ricardo carried out a range of tests with varying concentrations of inlet gas constituents on single cylinder engines while the Admiralty worked with multi-cylinder engines. In spite of the solubility of CO_2 in sea water it was desirable to develop a scrubber which would separate oxygen from the voided gas in order to increase the range and to avoid the visible trace which would result from voiding insoluble oxygen.

We carried out tests both with a seawater scrubber which could be carried inside a housing outside the pressure hull and also with a chemical scrubber. This latter took the form of a rotating Piazza scrubber together with a small chemical plant to regenerate the absorbent. In due course the arrival of nuclear power rendered this work obsolete although we did return to recycle engines as a power plant for small commercial submarines that might be employed on off-shore installations. A complete sixty horsepower plant was designed and built and demonstrated in Shoreham Harbour.

Torpedo propulsion led to a more exciting project! To extend torpedo range and power an "inverted" cycle piston engine was conceived (Figure 20).[11] A small amount of HTP was decomposed by a catalyst and a proportion of the kerosene fuel was burnt in the resulting oxygen-rich gas. This hot gas was used to vaporize the remainder of the kerosene. The vaporised fuel was used to scavenge the exhaust gases from the cylinder and after compression of the mixture, the main HTP charge was injected into the cylinder, whereupon ignition occurred. Complications occurred if HTP came into contact with lubricating oil, as for example in the piston ring grooves. The resulting explosion was sufficient to completely shatter the piston. When looking for a high pressure pump for the HTP, it was found that a homogenising pump, designed for use on milk, was quite satisfactory at pressures up to 3000 psi: there must be no oil contamination in milk!

As an alternative method of using HTP, we developed and ran a Brayton cycle engine using decomposed HTP at 600psi. A two-cycle, single-cylinder, poppet-valve engine of 108mm bore and 152mm stroke was employed (Figure 21). To avoid the use of excessively high valve spring loadings, pressure balanced Nimonic valves were fitted. The inlet temperature could be boosted beyond the decomposition temperature of HTP by injecting pilot fuel into a combustion chamber fitted into the inlet system. Main fuel could also be injected into the charge during inlet via a fuel injector fitted into the cylinder head.[12]

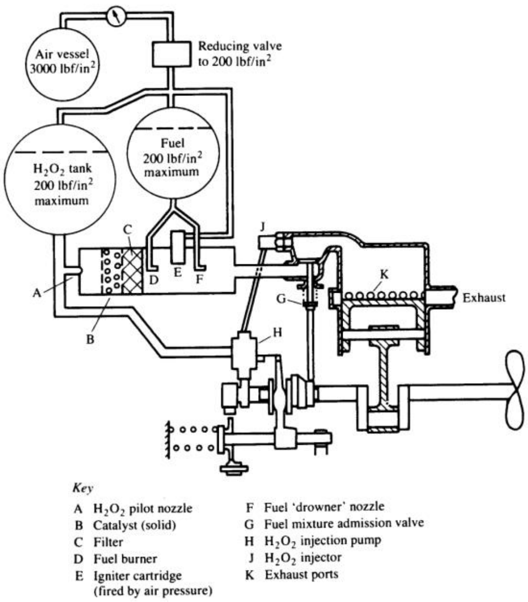


Figure 20. “Inverted” cycle piston engine.

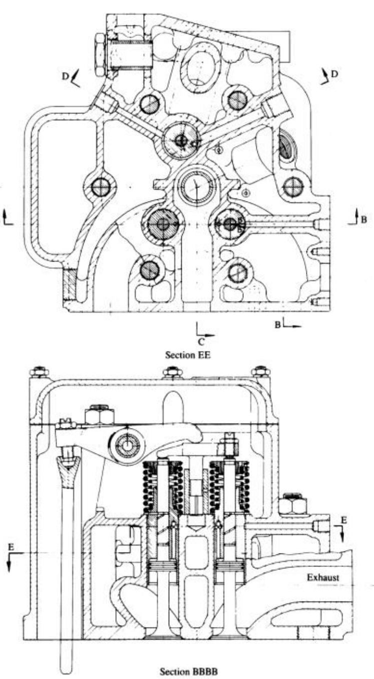


Figure 21. Cylinder head and valve gear for reciprocating Brayton Cycle engine.

Alternative Engines

Steam Engines

In the early 1970s the United States Environmental Protection Agency wished to investigate the use of a steam engine for the propulsion of a passenger car in the belief that the use of external combustion would give very low exhaust emission levels. They placed a contract with Steam Engine Systems of Boston with Ricardo as sub contractor, to design and construct a car. The Ricardo company was responsible for the design and procurement of the expander (the steam engine). The four-cylinder engine had a Caprotti valve gear with two poppet valves in series and a phase change mechanism between the two camshafts operating the valves. This gave variable cut off for load control, essential for efficiency. While the prototype did achieve low exhaust emission levels, the large rises in fuel prices in 1973, together with the growing American concern about their dependency on imported fuels, emphasised the importance of fuel economy, where the steam engine had no hope of competing. The project did not continue therefore to the point where the problems of winter operation would have had to be faced! Figure 22 shows a section of the engine.

Stirling Engines

Ricardo also played a major part in the development of a Stirling engine for United Stirling of Sweden. Here again Ricardo designed and built the mechanical section (Figure 23), while United Stirling produced the combustion chamber and the heat exchange elements. Prototypes were produced and tested and Ricardo then proceeded to produce a batch of, I believe, of the order of forty pre-production models. Ultimately however the engine did not go into production.

Gas Turbines

While the required capital investment required meant that Ricardo did not, after the war, pursue the possibility of working on large gas turbines, several limited programmes were carried out. The first, for Shell, involved the burning of heavy fuels in a gas turbine combustion chamber. Further studies included the distribution of airflow in the chamber, and the comparison of alternative burner designs.

An interesting programme for the British Government Department of Industrial Gas Turbines (DIGT), involved the testing of small inward flow, radial gas turbine rotors covering a wide range of design parameters such as entry width and number of blades. The rotor diameter was 127mm, and a high speed dynamometer capable of operation at up to 80,000 rpm, was developed by Heenan and Froude for the programme. This dynamometer took the form of a sleeve bearing with variable overlap. Tests were carried out both under steady flow conditions to study gas turbine operation and also under pulsed conditions, employing a rotating shutter, to simulate turbocharger operation.

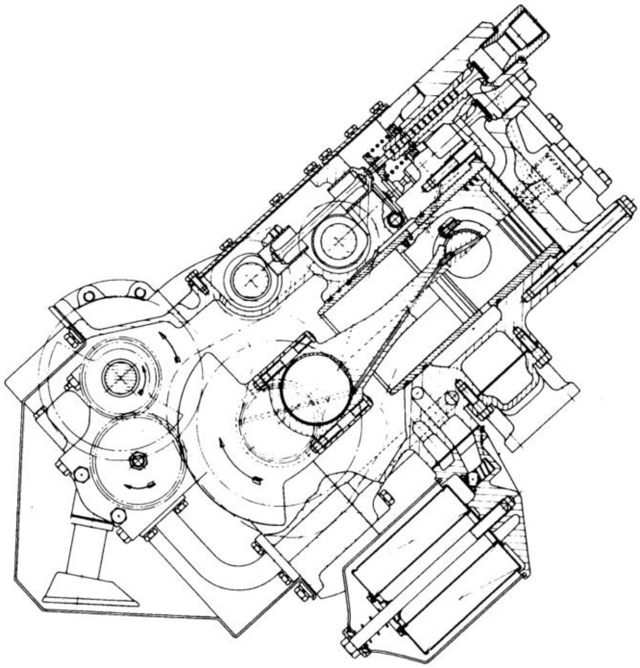


Figure 22. 130 bhp passenger car steam engine.

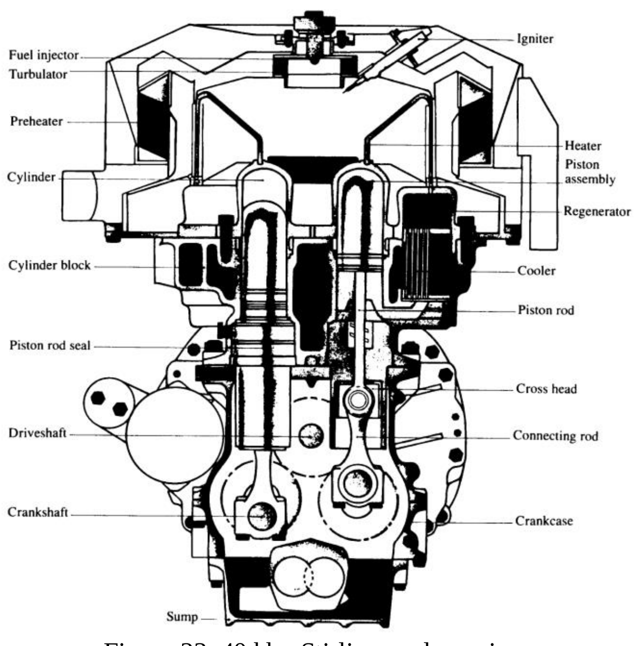


Figure 23. 40 bhp Stirling cycle engine.

Catalytic Engine

Sir Harry had always been interested in the use of charge stratification in spark ignition engines in an attempt to reduce or indeed eliminate the losses inherent in throttled operation. It had proved impossible to achieve satisfactory operation over a wide range of load and speed. In an attempt to widen the inflammability range of the air-fuel mixture and hence to operate over a load range without the use of charge throttling, some experiments were carried out by Ricardo on what was termed the Catalytic Engine. The petrol was injected late in the cycle and a catalyst mesh was fitted across the combustion chamber to initiate and help to give complete combustion. Test were carried out with a mesh fitted both across the top of the piston bowl in an open chamber engine (Figure 24) and across the centre of the pre-chamber of a Comet engine (Figure 25). With the open chamber engine, although the engine was surprisingly quiet, the power was limited to an unacceptably low level by the onset of smoke in the exhaust. This was thought to be due to a severe reduction in air swirl levels caused by the catalyst mesh, a theory which was subsequently confirmed by combustion photography. In the pre-chamber engine, the hoped for improvement in exhaust hydrocarbons was achieved, but the fuel economy was worsened to an unacceptable level at high

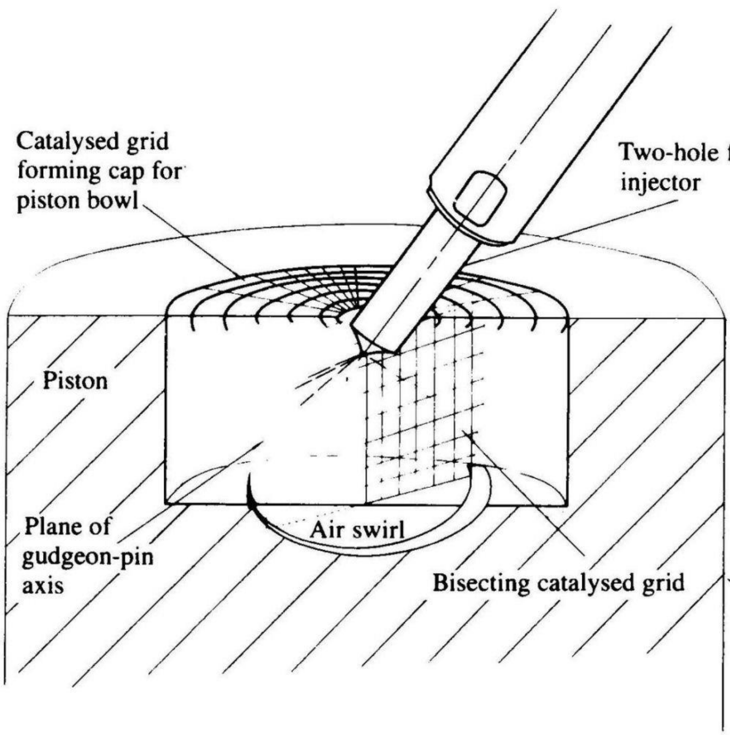


Figure 24. Direct injection catalytic engine.

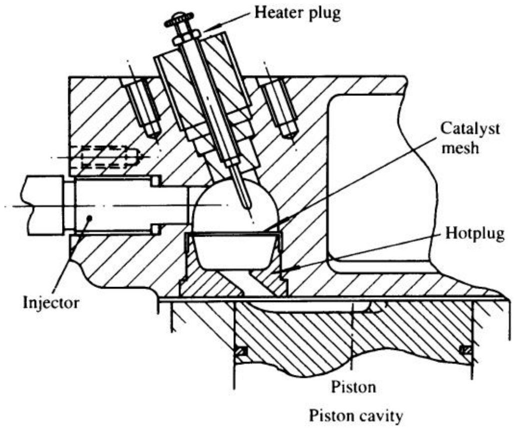


Figure 25. Comet, swirl chamber, catalytic engine.

loads. It may also have been due in part to the effects of the mesh on the airflow in the chamber. Smoke levels would also have presented a problem. Only limited testing was carried out. More details as to the testing may be found in the literature.[13]

Design Techniques

This paper has not attempted to cover the substantial efforts that Ricardo had invested in the development of improved computer design techniques during the period under review. Finite element analysis, both static and dynamic, computational fluid dynamics, boundary element analysis, advanced cycle analysis, improved data handling techniques and many other areas have been the subject of considerable development and in-house programs which have been developed are also now licensed for use outside the Company.

Miscellaneous Projects

In the early 1950s, two small, spark ignition, sleeve valve engines were designed and prototypes were built for use by the Signals Branch of the British Army. The larger engine had four cylinders and gave a power output of 2¼ kVA. The smaller engine was intended as a backpack engine with a single cylinder. Neither engine went into production, possibly due to the replacement of high current demand thermionic valves by transistors.

A small 2½ hp, steam power plant was developed for use in the third world. The National Research and Development Corporation sponsored the project. The novel boiler comprised a hollow, externally finned aluminium water drum and the simple firebox was designed to burn a very wide range of fuels ranging from straw to coal. With the wide availability of petroleum fuels however, there proved to be no market for the engine.

Non-engine projects included two compressors. A multi-cylinder axial machine with a wobble plate drive proved to be very quiet in operation. Messrs Wellworthy made some numbers of these as their relatively quiet operation made them very popular for use in bulk tankers that were offloading flour to bakeries in the middle of the night.

Another compressor was a two-stage, two-cylinder, high-speed machine running at up to 3000 rpm. This employed air cushioned poppet valves and was intended for use in portable air compressor plants providing air for use by pneumatic tools.

As an attempt at diversification, and as an extension of the work on gas turbine combustors, the Company also developed an oil burner for domestic oil-fired boilers.

Another diversification project was an egg-cleaning machine! It was believed that water washing affected the life of eggs. The Ricardo machine employed a rotating helical spiral to transport the eggs through a chamber in which they were grit-blasted. While relatively successful, the machine did not win the competition for which it was designed and did not go into production.

Acknowledgements

The author has mined deeply into a number of publications which both he and his former colleagues have written over the years. He would like to acknowledge the part which many of them played when the original work was carried out. While this paper is the sole work of the author and he must apologise for any errors of fact or for any omissions, he is most grateful for the assistance which he has received from Roland Christopher and his colleagues in the Information Services Department at Ricardo for their help in turning this manuscript into a form for publication.

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Notes on Contributor

Cecil French was educated at Newport (Essex) School and Kings College, London. He followed his B.Sc. Eng Degree by completing a Master's degree for a thesis entitled "Photometric Methods of Particle Size Analysis". After a graduate apprenticeship at Lucas CAV he was awarded a Marshall Aid Scholarship to the United States. He carried out graduate studies at Columbia University, New York, and then proceeded to MIT where he worked on an industrially sponsored project, studying combustion in the spark ignition engine, employing combustion photography. After three months studying production methods at the Waterloo, Iowa, Tractor Works of John Deere, (at that time the largest tractor factory in the world), he returned to England and joined Ricardo.

After a period as a research engineer, he gradually became responsible for, initially, the Admiralty Department and then also the Diesel Research Department and finally all Ricardo Research. Appointed a Director in 1969, he later became Vice Chairman.

Cecil French was awarded the degree of Doctor of Science (Engineering) by London University in 1987 for his published work. He is a Past President of the Institution of Mechanical Engineers, of the Diesel Engineers and Users Association (as it then was) and of the International Council for Combustion Engines. He is a Fellow of the Royal Academy of Engineering. He is an Honorary Doctor of Engineering of Brighton University.

Retiring in 1991, he is active in his local Rotary Club, has been a Governor of a local Primary School for many years and is a volunteer custodian of the local museum in Shoreham. He can be reached on 01273 452050 or by email on CFr6185471@aol.com.