C) Evaluation of Diesel Fuels

In Germany, the four usual methods of measuring ignition delay were [13] :-

(a) Pressure measurement, which could be made anywhere in the combustion chamber provided it was of a uniform shape.

(b) Ionisation measurement, which only referred to one local spot.

(c) Heat emission from the combustion chamber.

(d) High speed photography.

The latter two depended on the shape and position of the window, and their sensitivity was affected by soot deposits.

An instrument was developed [74] for the measurement of ignition delay, which utilised an inertia indicator to determine the start of ignition. A contact fitted on the nozzle holder, and operated by an elongated nozzle pin, closed a circuit when fuel injection commenced. When ignition occurred the pressure rise was so rapid that the rate of change of deflection of a diaphragm in the wall of the combustion chamber caused the contact in the interior of a light metal tube to be opened. This broke the circuit. A photo-cell could be used in place of the inertia indicator if so desired.

An attempt was made to develop a universal engine for both cetane number and octane number determination. An F.K.F.S. engine with fuel injection was used. The compression ratio was kept constant and the delay period before self ignition was determined using a photo-electric cell. It was claimed that ratings obtained by this method agreed very well for the entire cetane range, and even up to approximately 50 units on the octane number scale. Above this figure the method could not be used successfully. Using mixtures of reference benzene and gasoline, Ernst [13] found the ignition delay octane numbers to be approximately 1 - 2 units higher than those obtained in an I.G. engine under C.F.R. Research Method Conditions.

In 1942 the special Committee of the D.V.M. for the Standardisation of Engine Tests on Diesel Fuels recommended [94] :-

(i) Ignition delay process should be standardised as the basis for cetane number determination.

(ii) Ignition delay should be constant throughout tests.

(iii) Engines used should be the H.W.A. and I.G. Test Diesel.

(iv) The ignition delay should be kept constant either by throttling or altering the compression.

(v) The measuring instruments used should be the inertia indicator (Rhenania-Ossag), the piezo-quartz indicator or the F.K.F.S. photo-cell indicator.

The most common test procedure used the I.G. Test engine[99]. The method was similar to the C.F.R. diesel method, except that an ignition delay period of 18° was used. Another method in which the delay period was kept constant, was that of the H.W.A. In this method the inlet air was throttled back to the limiting ignition and the resulting suction in the inlet tube was taken as a measure of the ignitability. It was claimed[94] that this throttling method corresponded better with cold starting behaviour than did the other test methods.

In contrast to these methods which employed a constant ignition delay, the D.V.L., with its test-bench diesel, measured the duration of the ignition delay whilst keeping the compression ratio constant.

A correlation between the cetene number of a fuel and its specific gravity, aniline point, bromine number and pour point was drawn up in graphical form by the H.W.A.[108]

D) Ignition Accelerators

Heinze, Marder and Veidt [24] determined the effect of the addition of a large number of compounds to various brown coal tar and anthracite tar distillates. The compounds tested included:- ethyl nitrate, amyl nitrate, amyl nitrite, ethylene chlorohydrin nitrate, tetralin peroxide, benzoyl peroxide, nitroso n-methyl urethane, diethyl tetrasulphide, diethyldioxime, copper stearate, butyl bromide, p-nitroso dimethyl aniline, chlorodinitrobenzene, trinitrotoluol, benzoyl acetone, cyclohexanone oxime, dipentene and terpin. The last seven compounds had no effect on the ignition behaviour, whilst of the others, the nitrates and nitrite were the most effective, the rise in cetane number of the fuels being approximately proportional to their concentration. With nitroso n-methyl urethane, ethylene chlorohydrin nitrate and diethyltetrasulphide, however, the improvement per cent of additive decreased as the additive concentration increased.

The effect of the additives on a number of other fuel properties was also determined. Except for tetralin peroxide, an addition of less than 0.5 % of additive always brought the Conradson Carbon value of the fuels well in excess of the British and U.S.A. specification of 0.2%. All the additives tested increased the corrosion effect on zinc, but only with tetralin peroxide and amyl nitrite was the corrosion considered excessive. All the additives were completely stable in storage even after one year.

E) Cold Starting and the Use of Additives

Whereas in Britain and U.S.A. additives have mainly been used to raise the cetane number of a fuel for normal running, in Germany the emphasis in research has been centred on their use for improving cold starting behaviour.

The effect on the starting behaviour of diesel fuels by the injection of special starting fuels into the air intake manifold of the engine was studied by Leib [36]. He used mainly ethers and similar compounds for these starting fuels.

The minimum compression ratios required

for the ignition of these fuels, without injection of the main fuel, were first determined. An I.G. engine was used in a room which could be cooled to -25°C. The lower the room temperature the higher was the compression ratio necessary for ignition. In general, decrease in vapour pressure of these starting fuels resulted in a higher compression ratio being required for ignition. An exception was ethyl iso-propyl ether, which, despite its lower vapour pressure, (and also lower cetane number), required considerably less compression than di-ethyl ether. No unexpected effect resulted from a mixture of starting fuels. With the two lowest boiling fuels tested - diethyl ether and ethyl iso-propyl ether - the engine would only start within a certain compression ratio range. Above an upper compression limit, spontaneous combustion in the cylinder resulted in all the fuel being burnt before the end of the compression stroke. With the higher boiling starting fuels this phenomenon was only observed at fairly high temperatures and compression ratios of nineteen to twenty.

Tests in which diesel fuel was injected into the cylinder and starting fuel into the induction line, showed that for easy starting fuels with high cetane number and high vapour pressure are needed. As with ethyl iso-propyl ether, however, the inner structure of the fuel is also a factor. For practical use with induction line injection the following order of starting fuels was given: ethyl iso-propyl ether, diethyl ether, di-iso-propyl ether and di n-propyl ether.

A series of investigations concerned with the improvement of starting behaviour was made at the Technische Hochschule, Stuttgart. All the tests were made on an F.K.F.S. engine. Additives were either admixed with the fuel, introduced into the intake air, or directly injected into the cylinder separately from the main fuel.

Demmer [7] judged starting behaviour by motoring the engine under fixed conditions and determining the minimum compression ratio needed to keep the engine running by itself. Direct addition of ethyl nitrate to a commercial diesel fuel gave an improvement of 1/2 compression ratio. The improvement with Fischer Tropsch

RCH oil was much less, and at high additive concentration the performance even deteriorated. The cetane number for both fuels increased with the concentration of ethyl nitrate. Admixture of carbon disulphide, although slightly improving the starting behaviour of commercial oil, had an adverse effect on the RCH diesel fuel. Carbon disulphide vapour, however, effectively improved the starting behaviour. The cetane number of the commercial diesel fuel decreased with carbon disulphide addition, but that of the RCH fuel increased slightly. Acetaldehyde had little effect when added directly to the fuels, but vapour addition improved the critical compression ratios by 2 or 3. The cetane number dropped appreciably on addition of acetaldehyde to the commercial fuel, but the RCH fuel showed the reverse effect. It was concluded that the raising of the cetane number of a fuel by the use of additives is not indicative of an improvement in the starting behaviour of the fuel. This agreed with the experience [37] that the cetane number measured in an engine, even by the H.W.A. method, is no criterion of the starting behaviour of a fuel, at least at temperatures below 0°C. In this connection it was suggested[37] that possibly a useful characteristic of starting behaviour might be obtained by considering cetane number, boiling range and viscosity.

Similar experiments were made by Schutze [66], but he added fuel admixed with additive to the intake air as well as simultaneously injecting it in the normal way. When using the highly paraffinic RCH fuel the engine could run for a time under its own power without any flames appearing in the cylinder. This indicated strong preflame reactions. The gradual heating of the engine eventually resulted in flames appearing, accompanied by considerable knock and an acceleration of the engine. Naphthenes and aromatics did not show this phenomenon. Experiments with varying inlet air temperatures showed that the critical compression ratio when using RCH fuel containing 5 % ethyl nitrate rose sharply as the temperature fell below 50°C. This was attributed to the ethyl nitrate being sucked into the cylinder in the liquid state, the drops of ethyl nitrate being surrounded by a cool zone.

With normal quality fuels the effect of the heat lost by evaporation of the droplets would be far outweighed by the increased ignitability caused by the ethyl nitrate. With the highly ignitable RCH oil, however, ignition would be hindered. From engine tests the ignition temperatures of cyclohexane and cyclohexane containing 5 % of ethyl nitrate were calculated using the equation

$$T_e = T_a \varepsilon^{\kappa-1} \qquad \text{..................(20)}$$

These calculated values were compared with tests made in the Jentsch ignition tester. It was concluded that provided fuel does not enter the engine cylinder in the liquid state the ignition point gives a suitable guide to starting behaviour.

From engine experiments in which the main fuel was not injected, Staats [73] found, that ether added to the intake air from a carburettor required a smaller compression ratio for ignition than did ethyl nitrate in the vapour phase. Ether, when added in the vapour phase, however, required an even lower compression ratio.

In actual engine operation, the starting behaviour, when ethyl nitrate was used in the vapour phase as an ignition accelerator, was not dependent on the ignitability of the main fuel. In contrast, the effect of the different ignitabilities of the individual fuels was slightly noticeable when using ether vapour. It was found that there was an optimum ether vapour quantity; introduction of too much ether vapour so cooled the combustion chamber that, presumably, the prereactions between the ether and the air were retarded.

Cold room tests at temperatures down to -40°C showed that at such low temperatures ether was the only substance that would assist starting. Ethyl nitrate was only effective for temperatures down to 0°C.

A somewhat different attempt to improve the starting behaviour of an engine was made by Gerschler [23]. During starting he passed the products from the exhaust port back into the intake port. A very slight improvement resulted, but constructional difficulties prevented the practical use of the system. The work, however, furthered the development of the recycle engine.

F) Fuels and their Properties

The diesel fuels used in Germany were of the normal petroleum type. The Ruhr-Chemie, A.G. also produced a Fischer-Tropsch fuel which was usually used for blending purposes. They also produced a reference diesel oil (RCH reference), with a cetane number greater than 70 [103]. Increasing shortage of supplies, however, brought about the use of some alternative fuels.

At first, an attempt was made to operate diesel engines with liquefied gas, such as a propane-butane mixture. Bubble formation in the fuel lines was a problem, but it was found [11] that this could be avoided by maintaining the entire fuel system at a pressure of twelve atmospheres. The chief difficulty inherent in the use of liquid gas in the engine was its great compressibility compared with normal gas oil. A much larger injection nozzle was required, and the pump timing had to be advanced about 20°. Under such conditions the ignition delay was about 14° - 18°. A larger injection pump was necessary because, in spite of the pressurised fuel system, the pump sump never completely filled with liquid. The size of the anti-dribble valve in the outlet port of the pump was also increased to prevent lengthening of the injection period. Other difficulties arose in the form of leakages in the fuel system, and lack of lubrication of the injection nozzle valve and injection pump plunger.

Further development in the use of liquid gas was stopped by the introduction of the more conventional, wood fired gas generators. It was claimed [101] that when using the gas from such generators, petrol engines developed 70 - 75 % of their normal power output, and diesel engines about 80 %. Compression ratios of 9 : 1 to 11 : 1 were used.

As early as 1940 information was given [32] on running automotive diesel engines on gasoline and other fuels, without alteration to the engine, in the event of a temporary failure in the supplies of normal diesel fuel. Benzene, alcohols and other high octane fuels were unsuitable, but all commercial petrols, even if they contained lead or alcohol, could be used directly in the engine. In an emergency, middle distillates, lamp oil, etc., could also be used. When using gasoline that was not blended with at least 25 % of gas oil, the addition of 5 - 10 % of engine lubricating oil was advised in order to lubricate the fuel pump and nozzle. The use of gasoline in warm weather also necessitated cooling of the injection pump to prevent vapour formation. The low density and, in general, poorer ignitability of the alternative light fuels caused the engine output to be lowered by 10 - 15 %. Starting was also very difficult, and higher idling speeds had to be employed.

A comprehensive investigation was made by Penzig [51] on the use of nitroparaffins as fuels. In his report he tabulated the properties, and presented other data in respect of nitromethane, nitro-ethane, nitropropane, nitrobutane, and nitrobenzene. Approximately 25 % more energy was obtained from a given amount of air when using nitropropane than when using n-heptane. When burning heptane in air to which nitrous oxide had been added in such proportion as to give 3 mols N_2O/mol C_7H_{16}, however, almost the same energy was obtained, as with nitropropane and normal air. This increased energy liberation was not solely due to the extra oxygen content of the air. Thus when ordinary air was brought up to the same oxygen content by the addition of free oxygen, the energy liberation, although better than with normal air, was not so great as with the nitrous oxide containing air.

In a reference to the work on glow ignition[88], it was stressed that nitroparaffins are readily ignited at hot surfaces, even though they are difficult to spark ignite. Glow ignition temperatures were obtained by passing the fuel vapours over an electrically heated coil. It was suggested that the nitroparaffins might be used as fuels for high altitude flying, and thus eliminate the necessity for the conventional spark ignition system.

The glow ignition properties of the nitroparaffins were also shown by their cetane ratings. With direct injection the technical product S-3 (a mixture of 1 and 2 nitropropane) had a cetane number of only fifteen. In a prechamber engine, where the fuel contacted the chamber walls to a greater extent, it had a cetane number of forty five.

The admixture of nitropropane (in the form of S 3), with a number of gasolines gave surprising results. The fuel S 3 had an octane number of 72, but when mixed with certain gasolines it gave rise to mixtures with octane numbers lower than those of either component. The minima occurred with mixtures containing approximately 30 % of S 3. With other gasolines no such phenomenon was observed. Nitro-ethane and nitrobutane behaved similarly to nitropropane. The octane number of nitrobenzene could not be determined because of glow ignition, but experiments were made in which it was mixed with gasoline VT 702. Up to 50 % nitrobenzene addition the octane number of the fuel was only slightly changed, but further increase in the nitrobenzene content, however, resulted in a considerable improvement in the octane rating.

Experiments were made using a number of diesel fuels. Corresponding to their effect on the octane numbers of gasolines, the nitroparaffins gave mixtures with cetane numbers greater than those of either component. The maxima, however, were not so pronounced as the minima in the octane number curves, although the improvement was greater the higher the cetane number of the original fuel.

On recycle diesel operation, use of nitropropane as a fuel was estimated to be able to give a saving on the total weight of fuel and storage equipment of 16 %. Its use in submarine operation would, however, be limited because of the bubbles that would arise from the evolved nitrogen.

Table 4 of the appendix is a compilation from the literature [36, 51, 89, 90] of cetane ratings of various compounds.

Finally, Tables 8 and 9 show the general German specifications for diesel fuels used in aero, automotive, and marine work.