E.) Fuels and their Properties.

The use of hydrogen as a special fuel was considered [48] both from theoretical aspects and from the results obtained using a single cylinder, external ignition side valve, stationary engine. The engine was operated under pressure charge because of the high output attainable by this method. Even with high compression end pressures the combustion in the engine tended to be irregular, especially with very lean mixtures. Except for greater combustion speeds, however, the behaviour of the hydrogen motor did not deviate from that of other gas motors. In contrast to results obtained in bomb tests, flame speeds in the hydrogen motor were not greatly in excess of those of liquid fuels. Ignition limits were found to be similar to those observed in bomb tests. Self ignition was never observed, and the combustion, over a wide range of mixture strength was found insensitive to ignition adjustment. Output was limited by knock, and the highest output was obtained with mixtures 20 % richer than stoichiometric. Comparing the results with other engine methods, the output of the hydrogen motor was seen to be in the range of the diesel engine. Where container weight is not important, as in locomotive traction or stationary engines, it was considered that hydrogen would be a suitable fuel. In respect to thermal properties and economy, hydrogen could be rated equally with ordinary fuels.

The problems involved in knock testing of gaseous motor fuels were discussed by Ruess [93]. He gave values for the octane numbers of various gases as shown in Table 1 of the appendix.

As regards liquid fuels, the knock behaviour of a large number of alkyl benzols was reported by the I.G. Farben, Ludwigshafen [85]. In Tables 2A and 2B of the appendix are presented the motor octane numbers of these compounds (diluted with Eichbenzin I.G. 10 in the proportion 50 : 50 Vol % and with the addition of 0.15 Vol % T.E.L.) and their superchargeability, as determined in the BMW 132 cylinder by the D.V.L. simplified procedure. These results were summarised as follows :-

1) Of the alkyl benzols treated with a sulphuric acid catalyst the iso compounds show a better knock behaviour than the normal compounds, but the contrary is true in treatment with an aluminium chloride.catalyst.

2) In the series mono- di- tri and tetra-ethyl benzol the diethyl benzol shows the most favourable knock behaviour. In the propyl substitution the highest knock resistance is shown by tripropyl benzol i.e. superchargeability increases from mono over di to tripropyl benzol, but is much smaller with tetrapropyl benzol.

3) With the exception of ethyl and propyl benzol, the knock behaviour in alkyl benzols deteriorates with increasing carbon atom number and boiling temperature.

It should be emphasised that these results do not refer to pure compounds, (see boiling range) and should, therefore, be considered with caution.

The above results do not appear to be in accord with the statement by Philippovich [54] that in the cases examined, supercharging could be increased as the number and length of side-chains of the benzene nucleus increased; and that of two highly aromatic fuels, the one containing aromatic compounds of higher boiling point could be used for greater supercharging.

Data on hydrocarbons and other compounds used as fuels and fuel components were given in another report from I.G. [89] This data was presented in the form of tables according to substance clases and not chemical structure. From these tables and other sources [36,51,53,90] were obtained the octane numbers of the large number of compounds given in Table 3 of the appendix.

Three grades of aviation gasoline were used by the Germans;- A3 for training purposes, B4 for normal operational use, and C3 for aircraft having high duty engines. The specifications for these fuels, as given in BIOS Report No. 119, are reproduced in Tables 5 and 6 of the appendix. As with all the other fuel specifications given, these show a relaxation in some of the requirements compared with the specifications laid down earlier in the war. It should be noted, however, that the octane number requirements were never relaxed.

For completeness, the specification for gas turbine fuel J-2 is also reproduced - Table 10. It has been reported [95] that kerosine complying with this specification was only accepted as a gas turbine fuel because of the shortage of gasoline.

In Table 7 is shown the specification for motor gasoline used in military vehicles.

3. COMBUSTION IN DIESEL ENGINES.

The diesel engine was used for general automotive and marine (mainly submarine) propulsion, and only to a small extent for aviation purposes. Work on diesel fuels was directed mainly to an improvement of their starting qualities, and to the development of alternative fuels as supply of the normal fuels diminished.

A) General Theory and Practice.

The efficiency of an engine in relation to the ideal engine was discussed by List [41]. Idealised curves for the combustion laws needed for the different types of diesel engine cycle were given, taking into account variation in compression ratio, limiting maximum pressure and limiting maximum pressure rise. For a constant maximum pressure, the mean pressure of the cycle was shown to depend strongly on the combustion law. The considerations showed that for greater efficiency a better control of combustion must be attained, so as to give diagrams with a small pressure rise in relation to the compression end pressure. Bearings must also be improved to permit the use of higher maximum cylinder pressures

Tests were made in a single cylinder engine using direct injection, prechamber, turbulence chamber and air storage chamber. The combustion law for each process was determined by accurate engine indication and careful fuel and air consumption measurements. It was shown that high initial combustion speeds which decreased during the course of combustion were not desirable; also, further knowledge of the processes occurring between injection and ignition were required to allow for adequate control during this part of the cycle - combustion after ignition already being well controllable.

Combustion chamber design, in contrast to that in Britain, tended towards the use of air storage chambers. Several engine and bomb investigations of the combustion process have been made using this type of chamber.

Petersen [52], using a double air storage chamber fitted to a bomb, studied flame movement (with air movement) by high speed photography. He found that slightly late injection of fuel, equivalent to half load, resulted in the greater part of the fuel remaining in the main chamber near the first throttle point, although a small proportion reached the first storage chamber where ignition occurred. The flame raced along the fuel layers before the first throttle point, throwing it in the direction of the injection nozzle. From there, combustion spread laterally and filled the main chamber. It was found that there were two main courses of combustion. When injection took place after the maximum inflowing air speed, the second storage chamber took little part in the combustion, since the bulk of the fuel remained in the main chamber. When the fuel was injected earlier, however, the strong air stream carried it into the second storage chamber, and then the main chamber played only a small part in the combustion since little fuel was brought back into it. In this latter case soot formation occurred in the second storage chamber. Between these two injection extremes, there was a favourable range, dependent upon the fuel quality. It was found that the injection nozzle needed to be no wider than that necessary to bring the fuel into contact with an adequate supply of air. Increase of the angle of spray caused a drop in combustion speed, because the effect of each burning fuel droplet on its surrounding droplets became less the greater the distance between them.

In engine experiments, the combustion course was followed by the use of ionisation methods to determine flame travel, and by pressure pick-ups. The latter were usually of the piezo-electric type, which the Germans favoured rather than the capacity type.

Tests were made by Dreyhaupt [8] on an engine with a Lanova air-cell combustion chamber. With this engine at full load, ignition occurred only after the complete fuel charge was injected, and a smooth pressure rise occurred in the main chamber, thus eliminating "diesel knock". The fuel spray angle was fairly critical on this engine, and alteration from 6° to either 4° or 8° was detrimental to the combustion.

Experiments were also made [64] on a Deutz prechamber engine, gas samples being taken from the points at which pressure and flame ionisation measurements were made. Although there should have been ample air available in the prechamber, combustion was actually found to occur under a great air deficiency. This led to soot formation in the prechamber at the commencement of combustion. The flame spread very quickly into the main chamber because of the high pressure developed in the prechamber. This engine was very insensitive to the ignition quality of the fuel and gave an almost constant delay period under all conditions.

B) Modifications in Engine Design and Operation.

An important development was the introduction of the recycle diesel engine for underwater submarine operations. Its ultimate aim was to enable the engine to be operated either entirely on oxygen supplied from high pressure cylinders, or under "Schnorkel" conditions in which a limited supply of air was drawn through a pipe from the ocean surface. A twenty cylinder Krupp Germaniawerft engine was run on this principle[102]. Its superchargers were removed to reduce excessive exhaust temperatures, and an inlet temperature of approximately 100°C was used. Exhaust back pressures reached 20 p.s.i., and intake suction 1.4 p.s.i.

In German aero engines, considerable difficulty was experienced by failure of the spark ignition system at high altitudes. Trouble with the ignition also arose because of excessive plug fouling with high octane, lead containing fuels. An attempt was made to overcome these difficulties by the use of a low tension ignition system operating at about four hundred volts [97]. Later, however, investigations centred on the use of the "Ring" process. This process had the additional advantage that it made feasible the use of high boiling point safety fuels. The work on the "Ring" process has been summarised by O'Farrel in BIOS Report No. 1609, which also contains an extensive bibliography on the subject.

In the "Ring" process, ignition was produced by spraying a liquid into the combustion chamber, at the appropriate moment in the compression stroke. This liquid spontaneously ignited at the cylinder temperature, thus igniting the main fuel charge. Diglycol diethyl ether and 1,4 butandiol diethyl ether were found particularly suitable as ignition fuels. The former, which had a cetane number of 188, was manufactured in quantity and was also used as a diesel starting fuel. The mechanism of the self ignition of this fuel was thought to be a rapid disintegration of the molecule under the action of heat. This reaction, being exothermic, produced a rapid temperature rise causing the products of the decomposition to ignite.

Operation of the "Ring" process could be made at a compression ratio of 7 : 1, but in practice, a ratio of 8 : 1 was normally used. For weak mixture operation the optimum ignition fuel (R-fuel) quantity increased slightly, whilst with overrich mixtures the performance deteriorated because of longer ignition delays. In practice, the timing of the R-fluid injection was not too critical, and was usually kept constant.

Cylinder head temperatures were considerably lower with R-fluid injection than with spark ignition, although no appreciable difference in exhaust temperature was observed. If the operating temperature was too low, ignition difficulties arose. In this respect a great improvement was obtained when the R-fluid was injected on to the hot exhaust valve. This increased the fuel consumption, which, however, was still an improvement on that obtained using spark ignition.

Compared with the spark ignition process, the maximum power output, when using R-fuel, was approximately the same at rich mixtures, but was considerably improved at weak mixtures. Although at high compression ratios knock was considerably reduced because of the multipoint ignition of the mixture by the R-fluid, at the compression ratios normally used there was little improvement over the usual method of engine operation.

With the "Ring" process, starting was difficult, and sometimes necessitated an auxiliary spark ignition system. The other disadvantages were the cost of the injection equipment, even when using "pumpless" injection [109] of the R-fluid, and the necessity for careful coolant control.

Preliminary experiments were made [14] to investigate the possibility of self ignition operation of mixture compression engines. Such a process would reduce the outlay on accessories in high speed multi-cylinder engines of small capacity, and might make possible the utilisation of low boiling, low anti-knock fuels.

The experiments were made in a single cylinder, air cooled, spark ignition engine of 200 cc. capacity and in a 700 cc. water-cooled, single cylinder diesel engine. A fuel blend of 60 % of low boiling, primary gasoline of octane number 50, and 40 % of RCH diesel fuel of octane number -80 was found to give the most favourable conditions for self ignition operation. At first, however, knock-free operation was not attained.

The knock could not be suppressed by additives, without adversely affecting the ignitability. Attempts to suppress the knock by altering the combustion chamber design were also ineffective. It was found, however, that for very rich and very weak mixtures (air:fuel weight ratios of 8 - 10 and 25 - 28 respectively) knock-free self ignition could be obtained. This phenomenon was attributed to a reduction in the combustion velocity, Indicator diagrams showed that the pressure rise occurred fairly smoothly, a few degrees after T.D.C. The flame in the knock-free region was a faint blue, in contrast to the bright white flame appearing with knock.

Starting from cold required the use of additives, preheating or a glow plug. Power and consumption in the knock-free lean region corresponded approximately to those of the automotive diesel engine.

It was concluded, however, that for practical self ignition operation, the lean mixture knock-free region had first to be extended. Also the development of a precise instrument for control of the air:fuel ratio was essential.

Other modifications made have mainly been in details. Thus M.A.N., on their two-stroke double acting engine injected lubricating oil through a nozzle on to the cylinder walls. This was all consumed, and it was claimed [96] that both wear and fuel consumption were greatly reduced. Junkers [96], in their opposed piston aero diesel engine, had pistons made in three sections, the one being a steel crown that ran at 1300°F. Four through bolts, with heavy springs to take up expansion, held it together. Klöckner-Humboldt-Deutz [102] were developing a 16 cylinder diesel aero engine. In this, open combustion chambers were used, with six or eight hole fuel injection nozzles. The fuel injection time at 2000 r.p.m. was shortened from 50° to 30°. To prevent ring sticking the top piston ring, (a composite type) had its upper half made in two separate segments.