

The Ring Process

OUTLINE

The development of the ring process showed that it was advisable to re-edit it and complete report number 394 published in August 1939. A comprehensive description of the results to date must be left until later, when the results of all the agencies participating in the development will be considered. For the time being the enclosed list of all published reports (Enc. 3) gives an idea of the present state. The development has now reached a definite point: in May, 1942, BMW carried out at Spandau the first test flights with an engine operating on the ring process.

The report describes first the fundamental features of the ring process, in which a gasoline mixture is ignited by diesel combustion. Since this diesel ignition must take place at low compression ratios, the necessity has therefore arisen of developing new exceptionally ignitable fuels, the characteristics of which are described: they are called R-fuels. From the mechanical standpoint the measurement and injection of the small R-fuel quantities as well as the nozzle design are important. A considerable advantage of the ring process is that it eliminates high tension ignition, which renders the radio communications of the aircraft much more difficult - moreover there is the advantage of the wide control range, because very lean mixtures can be ignited. The ring process resulted from the attempt to ignite reliably with air the mainly imperfect mixtures of high boiling point safety fuels. These tests form a working field in themselves and they will not therefore be dealt with here. In the meantime the Diesel gas process has found extensive application in the operation of Diesel engine lorries, utilising fixed gas or producer gas. It appeared therefore convenient briefly to deal with this accessory working system in an appendix. The ring process and the diesel gas process go back to Diesel himself, who in a patent set down the fundamental data of this working process. The idea of operating gasoline engines working on liquid fuel by injection ignition was mentioned in 1938 by Eisenlohr. Independently of this, a solution was found at the Technical Experiments Station by operating a diesel process at low compression ratios. A further appendix deals with the question of priority.

INTRODUCTION

At present both gasoline and diesel engines are used in aviation. If we seek the differentiating features of these two types, we find that this is not at all a simple question to answer. The compression ratio is not characteristic: there are gasoline engines with very high compression ratios and diesel engine designers strive to achieve the lowest possible figures. In both engines the mixture is obtained with the injection of the fuel: not even the moment of this injection is a characteristic, as for instance the Hesselman engine (a special gasoline engine design) injects the fuel almost as late as the diesel engine. The diesel engine combustion too is mainly a constant volume one as in the gasoline engine, so that the only decisive feature left is the ignition system. The two engines are so closely related, that it is exactly the ignition system that offers the possibility of developing a new working process combining the features of the two types. This has however produced new views on the relationship between fuel and engine which, as far as they are known to-day, will be described below.

The main differentiating feature of the new working process will be more easily recognized if we give a brief outline of the gasoline and diesel processes and their main properties.

A) Comparison of gasoline and diesel processes

1) Gasoline process

The main features of the gasoline process which have been maintained since its inception are its dependence on the ignition limits of the fuel-air mixture and the source of ignition in the shape of an electric spark.

It is well known that the dependence on ignition limits results in the fact that the engine output can be adjusted only to a very limited extent by acting on the fuel (Fig. 1, 906). The conventional expedients allow the combustion of mixtures up to a 30% air excess, whereby the output can likewise be reduced by about 50%. On the main engine it is absolutely impossible to adjust the mixture to this extent, because the various cylinders are not uniformly fed.

The quality adjustment must therefore be completed by a quantity adjustment, i.e. by throttling, Fig. 2 (907). The drawback of this process consists first of all in the fact that a loss area appears in the diagram, moreover the ratio of residual gases to fresh gas increases and finally the combustion is less complete, as shown by the CO content of exhaust gases at low load. At part load the gasoline engine works with low efficiency. On the other hand at full load the efficiency is good and the output is also high, as the cylinder capacity can be completely utilized. The time the fuel spends in the cylinder during inlet and compression strokes, and consequently the quality of the carburation, are such that even mixtures without excess air can burn completely.

If we now turn to the ignition, we note first of all that a point source of ignition is not convenient, because its action depends on the composition of the mixture in the neighbourhood of the spark gap. This is shown clearly by the fact that the engine does not stop suddenly when the excess air increases. Isolated ignitions still occur when richer mixture happens to be present in the vicinity of the ignition spark. The typical variations of the otto cycle diagram Fig. 3 (908) show that in the gasoline engine the carburation cannot be expected to be always uniform.

The non-uniformity of the carburation is particularly high when using high boiling point fuels, which can be introduced in the cylinder only during the compression stroke to avoid condensation during the inlet stroke (Hesselman). The incomplete carburation due to the short length of time compels the Hesselman engine to use sparking plugs with protruding electrodes. Experience shows that on the wall of the combustion chamber the mixing is particularly unsatisfactory. It is quite clear that such sparking plugs are unsuited to high loads.

As regards the efficiency of electrical ignition, it is known that the electrodes are seriously affected by the residues of the anti-knock additive. Sparking plugs should therefore be considered as accessories rather than structural elements, which in fact they should be just as injection nozzles are.

The development of special anti-knock fuels, produced by the hydrogenation process, has led to the endeavour to apply to these fuels not only higher boost but also higher compression ratios, e.g. 8:1. The result should be to improve both the output and the economy. The resulting higher temperatures and pressures cause a further strain on the sparking plug, due to the need for higher voltages. This adds further to the difficulties already apparent in altitude flying at usual compression ratios, when the ignition current tends to make its way outside the sparking plug instead of jumping over to the electrodes inside the cylinder. If we add that the whole high-tension ignition system must be very carefully screened to avoid disturbances to the radio communication, the desire to operate the ignition by a different system appears fully justified.

2) Diesel Process

The outstanding advantage of the diesel engine is a certain independence of the air excess; even the smallest fuel quantity injected will burn completely provided the air temperature is sufficiently high. Merely to produce this temperature the compression must be boosted to about 14:1 - 18:1. From the point of view of the thermal efficiency this pays, as in this range also efficiency still increases, Fig. 4 (895). Practically, however, the result is that at the prevailing high pressures the mechanical efficiency drops: thus any advantage disappears. It can be proved, fig. 5 (922) that as the compression ratio falls off, the power of a diesel engine does not drop but it even rises. The illustration shows the output of a direct injection diesel engine working on gas oil rises considerably by reducing the compression from 17:1 to 11:1. This advantage has no practical application, because the ignition lag at this low compression ratio becomes so great that starting is no longer possible. Moreover the run of the engine is very jerky. The disadvantages of high compression originated the endeavour to develop low compression diesel engines. The tests on other fuels also included in the illustration will be dealt with again later. The ignition process itself can be roughly described as follows: after the fuel is injected into the air heated to 500/600°C, it is atomised and vapourised, which process involves at first a certain heat absorption. In the course of this transformation in which the air oxygen participates only in part, cracking occurs as well as oxidation on the surface of the jet. This oxidation increases during the conversion and finally visible combustion appears, whereupon the pressure rises, fig. 6 (909). The size of this ignition lag depends on the fuel quality: it is known that paraffin compounds have a good ignitability and aromatic compounds a bad one.

As already mentioned, the ignition is independent of the fuel-air ratio; somewhere at the jet surface the mixture most suitable for combustion is always present. It is therefore possible to control the output from idling to maximum by controlling the fuel. The diesel engine, however, cannot be operated with the stoichiometric fuel-air ratio, although this would mean the complete utilisation of the cylinder capacity. An air excess of 20% at least is always required; otherwise the short ignition lag is insufficient to combine each fuel particle with the corresponding oxygen quantity. The diesel engine is therefore inferior by about 20% to the gasoline engine, as regards the attainable maximum output, fig. 7 (910). Conversely, at low loads the diesel engine working with high air excess is economically superior to the throttle controlled gasoline engine.

B. The Ring Process

1. General

Apparently it is possible to combine the two types of engine by using a carburation and compression as in the gasoline engine, followed by an ignition of the diesel combustion type. This working system has the code name "ring process" if applied to low compression engines; the highly inflammable diesel fuel required is called "ring fuel". As in the diesel engine, this process allows operation by mixture control only, ^{to be used} because the diesel combustion develops sufficient heat to burn even very lean gasoline mixtures. This offers the particular advantage that at part load the efficiency is considerably improved, owing to the absence of throttle losses. This applies, however, only to freely aspirating engines. In supercharged engines, keeping the blower always at full load would cause a waste of power. A variable boost pressure control is therefore more economical. The conventional carburation process produces a uniform distribution of the fuel in the air and no excess oxygen is required as in the diesel engine. The same output can therefore be achieved as in the gasoline engine. The countless ignition cores of the diesel fuel take the place of the one or two ignition sparks and an injection pump with nozzle replaces ignition magnets and plugs. When idling the engine runs exclusively on the diesel principle.

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In the discussion on the diesel process it was shown that it is convenient to operate at very low compression ratios. The diesel engine however, fig. 8 (820) shows that the ignition lag is very strongly dependent on the compression ratio. This applies particularly to the low compression region, where, with ordinary gas oil, the ignition lag grows so steeply that it makes operation impossible. The ring process must be operated with the lowest possible compression ratios, both to avoid high pressure peaks and because too great a demand should not be made on the antiknock value of gasoline. For the ring process development on 8:1 compression ratio was adopted at first. This ratio can easily be used in available engines and fuels could be found that ignite at the corresponding compression temperatures.

This process creates numerous and interesting problems for development and research. First of all, it is necessary to procure a very highly ignitable diesel fuel, and its chemical as well as physical properties must be investigated. This R-fuel must meet all other specifications, such as corrosion, freezing point and viscosity. From the operational standpoint it is required that the ignition take place even at comparatively low pressures and temperatures. It is also necessary to investigate how the ignitability is affected by the presence of different gasoline types. Finally the questions of transformation velocity of these fuels, are also very important; the pressure increases, the maximum pressure peak as well as the temperature depend on it.

Thorough investigation must be carried out to find in which way R-fuel should be injected in the gasoline charge. Jet shape and position must also be thoroughly studied, the R-fuel quantity required in different conditions, as well as the instant at which the injection must take place.

Very extensive work is necessary to assess the R-process as compared to the gasoline cycle. These comparisons are necessary at operating conditions between idling and full load and between operation with free aspirating engines and super-charged ones, such as used in aviation. The problem of starting is an extremely difficult one because this must be possible at compression rates considerably lower than in diesel engines, in much more unfavourable circumstances than in conventional automotive engines. The question is particularly difficult to solve even in the automotive diesel the problem can hardly be considered solved.

The investigations must also deal with the question of the flame propagation rate as well as of how the ignition occurs at all in the ring process. The explanation of these details is highly significant for the investigation of knock behaviour.

The ring process was specially suited to the use of high boiling point fuels, because instead of one point ignition source, there are several ignition foci, apparently distributed over the whole combustion chamber. Safety fuels which cannot be ignited by the usual incendiary shells are viscous and high boiling point materials. The exceptional difficulties encountered in their use are mainly due to oiling of the sparking plugs. According to recent results it appears that the ring process is likely to facilitate the use of safety fuels in gasoline engines.

2 Details of the ring process

a) Chemical and physical properties of R-fuels

The particular feature of the ring process consists in the fact that at low compression rates combustion occurs on the diesel pattern. As shown in fig. 4 (895), at 8:1 compression ratio the terminal temperatures are about 200°C lower than at the usual diesel compression rates. Diesel engines require 40/50 Cetane No. fuels; it is therefore instructive that in the ring process the ignitability must far exceed 100 Cetane No. to achieve sure ignition.

The development of highly ignitable R-fuels presents a new problem, the solution of which was attempted in two ways:-

- 1) Development of additives, to counteract as far as possible the antiknock ingredients, such as lead tetraethyl. These additives, mixed in small quantities with diesel fuel, should considerably increase its ignitability.
- 2) Development of un-mixed fuels, having a much higher ignitability than ordinary diesel fuels thanks to their chemical structure.

1) Additives, general

On the basis of recent research, the combustion of injected diesel fuel and the action of ignition accelerating agents can be depicted as follows: when diesel fuel is injected into air, highly heated, several reactions take place during the ignition lag, i.e. in the interval between injection and burning; their velocity can be expressed by the following equation by Semakoff

$$v = A(e^{gt} - 1)$$

The velocity "v" is therefore an exponential function of the time "t". The other constants depend on molecular structure, pressure, and temperature.

Fig. 9 (894) shows the example of two fuels, one of which "A" is more easily ignitable than "B", the latter requiring a longer distribution time. The reaction velocity grows slowly at first, then rapidly and eventually at v_2 combustion is achieved. The intervening period of time is called ignition lag. Apparently this can be effectively shortened if it is possible to accelerate the slow reaction process. The addition of high dissociation velocity fuels achieves this purpose, as they influence considerably the reaction. The velocity increases very rapidly as long as these additives last, reaching a terminal reaction velocity "v₂". Beyond that the velocity conforms with the properties of the fuel. Because curves "A" and "B" diverge more in their first section than in the last, it is significant that the additive has a stronger action on the worse fuel "B" than on "A" and that an increase in the additive affects "B" more strongly than "A". This notion is confirmed by observation.

The list of ignitable raw oils is topped by fuels of the paraffin series; their ignitability is a function of their molecular weight. The latter governs their melting point too, which restricts their practical use. Cetane is the best known of normal paraffins, although it is not produced in large quantities.

	Cetane	Cetene	RCH oil
Formula	$C_{16}H_{34}$	$C_{16}H_{32}$	-
Sp Gr @ 20°C	0.775	0.785	0.762
Boiling point °C	282-297	280-295	200-315
Aniline point °C	94.2	73.2	86.6
Flash point °C	136	129	70
Fire point °C	161	156	102
Calorific value kcal/kg	10,400	10,400	10,400
Ignition point (O ₂) °C	230	238	240
Crystallisation start °C	+16	-2.5	-13
Freezing point °C			-16
Viscosity @ 20° cSt	4.5	4.1	2.5
50° cSt	2.4		1.4
Cetane No	100	87	90

The most easily obtainable raw oils were the products of CO hydrogenation (Fischer-Tropsch process). The data of one of them are shown in the above table.

Two ignition accelerating agents have been known for a long time:

- α) Nitro compounds
- β) Peroxides

Such additives are covered by various patents: the most comprehensive is possibly the English patent No. 294129 dated 14.4.1927. It mentions the advantages of shortening the ignition lag of diesel fuels, both to allow the use of lower compression and to avoid difficulties at high speed. Generally it is recommended to employ additives which lower the ignition temperature of the diesel fuel. Beside nitrates, nitro compounds and peroxides, iodine, chlorine, mercury and selenium compounds are mentioned, as well as acetylene compounds such as copper acetylide.

α) Nitro compounds

Below is a list of the main compounds often referred to in technical literature as ignition accelerators:

Name	Formula	Specific Gravity	Boiling point °C	Melting point °C	Oxygen %
Amylnitrate	<chem>C5H11ONO</chem>	0.782	99	-	27
Amylnitrate	<chem>C5H11ONO2</chem>	0.998	148	-	36
Nitromethane	<chem>CH3NO2</chem>	1.13	102	-29	53
Tetranitromethane	<chem>C(NO2)4</chem>	1.65	126	+13	65
Nitroethane	<chem>C2H5NO2</chem>	1.05	114	-	43
Nitroethylene	<chem>CH2CHNO2</chem>	1.07	99	-	44
Ethyl nitrate	<chem>C2H5ONO2</chem>	1.11	98	-112	53

Nitrates and nitrites are most easily obtained. Amylnitrate is preferable owing to its high boiling point. Tests have shown that it is as effective as ethyl nitrate, which proves that both the oxygen content and the molecular structure are determining factors. Other compounds are mentioned both as additives to diesel fuels and rocket fuels, but their manufacture is difficult.

Nitrates and nitrites are impractical not only because of their chemical instability but also owing to their vapours being highly poisonous. It is further known that the ignitability of aromatic fuels, such as coal dust or coal tar oil, can be increased by NO2 additions. The drawback is that oils treated in this way form oxygen containing substances of a resinous nature which cause troubles in the injection nozzles. This drawback does not occur when pure fuels are nitrated. Thus a practical R-fuel could be produced by the nitration of cetane: its ignitability corresponded to that of cetane with a 8% addition of amylnitrate.

Like many nitro substances, this nitro cetane also had corrosive properties.

β) Peroxides

Very little data are available on the structure of the peroxides known as ignition accelerators. The physical characteristics are known only for rather ineffective substances: the active representatives of this group are very difficult to handle owing to their being highly explosive. Their application to the improvement of diesel fuels has been often described. So far they have attained no practical significance.

The great disadvantage of peroxides is that they are dangerous because they are explosive. Moreover they are unstable and when mixed with hydrocarbons they develop acids which corrode metals heavily. It was also found that they transfer their oxygen directly to metals and thus damage them. Many peroxides are solid substances and only slightly soluble in hydrocarbons, such as the acetone peroxide proposed by Broeze. As a result there is the danger of precipitation when cooling, which can cause explosions. A peroxide (methyl-ethyl-ketone peroxide) was found (by Dr. Andronov of Amm. Lab. Oppau) presenting the advantage of being liquid and unrestrictedly soluble in hydrocarbons. It has a long life and it was even found that the ignitability of RCH diesel fuel with Dibutin addition increased in the course of months. Of course it is not possible to use "Dibutin" as an additive to commercial diesel fuel because reactions with the unsaturated elements would occur. In its pure form Dibutin can only be handled with particular care. Mixtures with diesel fuel in equal parts are, however, entirely harmless. In the course of tests, a 10% addition was found sufficient. A fuel composed of 10% Dibutin in RCH diesel fuel was called R-110 and it was widely used in the first tests. As shown in fig. 10 (917) in the ring process the ignition lag was considerably reduced by doubling this addition. Output however was hardly affected. The additive alters the properties of the diesel oil only as regards the cetane number, which is increased from 90 to about 200.

2) Homogeneous R-fuels

The tests on the fuels discussed in the preceding chapter can be regarded as concluded, since it was possible to find homogeneous fuels having a considerably higher ignitability than hydrocarbons of the paraffin series. A systematic series of tests covered a large number of fuels and the choice fell on diethyl-diglycol-ether $C_2H_5-O-C_2H_4-O-C_2H_4-O-C_2H_5$ it was called R-300. This research work took into account not only the operational properties, but also the possibility of large scale production.

The properties of R-300 are:-

Specific gravity	0.91 kg/lt.
Boiling point	180°C
Crystallisation start	-45°C
Viscosity -30°C	5.94 cSt.
+20	1.50 "
+50	0.93 "
+99	0.52 "
Calorific value	6.880 Kcal/kg
Air consumption	9.3 Kg/kg
Steam pressure 80°	0.02 atm
100	0.05 "
150	0.35 "
Refraction	1.412
Flash point	780
Cetane No.	190
Oxygen content	22%

This is therefore a rather high boiling point fuel, its viscosity lying between that of gasoline and diesel fuel. It can be used with the usual nozzle system. Its cold stability to -45°C constitutes a considerable advance on R-110 (10% Dibutin in RCH diesel fuel), which at -12°C gave wax crystals. R-300 is satisfactory as regards corrosion (with the possible exception of elektron).

b) Operational behaviour of R-fuels

Ignitability is the main determining factor for the use of R-fuels: the starting of the cold engine depends on it, as well as the ignition lag, i.e. the time during which the R-fuel gets undesirably mixed with the main fuel.

1) Ignitability fuel sensitivity

The I.C. test diesel engine, fitted for measuring the cetane number between 0 and 100 can also be used for the determination of higher ignitability values. This is done by the ignition lag method, in which the ignition lag is kept at a fixed level by varying the compression. The compression then gives a measure of the ignitability. For very highly ignitable fuels, other representative substances must be used instead of the usual calibration fuels, methyl naphthalene and cetane. Two mixtures were used, one 80% cetane and 20% methyl naphthalene and the other RCH fuel plus 50% Dibutyl, rated at a cetane number of 245. This was obtained by determining the cetane no. of pure dibutyl in different mixtures at 600. Recently a pure fuel was used for the upper limit, which had been likewise rated at a cetane number of 196. With this method the ignitability of R-300 was determined at about 190, thus attaining an advance on the earlier R-110, rated at 155. The higher ignitability offers the main advantages of an easier start when the engine is cold and of allowing operation on low temperature with intake air. It is true that the ignition lag decreases as the ignitability rises; this, however, becomes manifest only when the combustion and consequently the pressure rise always start at the dead centre. When adjusting to optimum output the maximum pressure must be reached at about 170° A.T.C., with the result that the injection advance angle does not vary as a function of the cetane number. This agrees with experiences on diesel engines, e.g. in practical experiments the optimum injection timing was found to be but little affected by the cetane number. It appeared further that highly ignitable fuels must be injected earlier to balance the effect of the slower combustion.

During the ignition delay period the ignitability of the injected R-fuel is reduced by mixing with gasoline. The necessary injection advance angle depends therefore on the type of gasoline used. In fact the ignition lag increases as soon as lead tetraethyl is added to the gasoline. The results tabulated in fig. 11 [old] are rather surprising. It appears that the ignition lag is actually greater for iso-octane than for benzene, although the opposite might be expected considering the higher antiknock value of benzene. As already mentioned the effect of lead tetraethyl is clearly visible, though it is very slight and not in proportion to the rise of antiknock value which these additives produce in gasoline. On the other hand various R-fuels affect differently the same fuel. Following are the results of adding 25% aviation spirit B4 to various R-fuels.

	undiluted	mixed with 25% B4	cetane number drop
R 110 C. No.	147	C. No. 116	31
R 200 "	136	" " 147	41
R 300 "	134	" " 152	32

It appears therefore that R-110 and R-300 react in the same way, whereas the effect on the ignitability of R-200 is greater.

2) Injection timing

The combustion of R-fuels is of the diesel type. It is therefore instructive that the rules governing diesel engines also apply here. Thus, for instance, the ignition lag increases with fall in compression ratio and boost air temperature.

These tests had the purpose of determining as quickly as possible the principles governing the practical application of this new process to aero-engines: the R-fuel was injected at the timing most suitable for best power output. For this purpose the injection advance angle was measured, i.e. the angular interval between injection start and dead centre measured in crank angle degrees. Usually this angle is greater than the ignition lag measured between start of injection and the start of combustion; optimum output can be achieved as in the

. 9 .

gasoline engine by initiating the combustion before top dead centre.

The injection advance angle falls with increase in compression ratio, fig. 12 (1001). The gasoline engine ignition timing also points to the combustion velocity increasing as the compression ratio is increased. As shown by the gasoline engine curve, the working pressure also varies with the compression ratio. In the R process the working pressure falls more steeply since the combustion becomes incomplete. The injection advance angle must be increased at first and at very low compression ratios the optimum is again achieved with a rather smaller angle. Apparently this depends on the fact that to produce ignition at low compression ratios the injection must be effected near the dead centre, i.e. close to the maximum compression temperature. A very important practical question is presented by the observation that the injection timing depends on boost air temperature, due to the latter being considerably lower at high altitudes than near the ground, fig 13 (1002) shows that the injection advance angle varies but little with reduction at the same time of the temperature of boost air and coolant. Eventually the engine fails, at temperatures varying inversely with the ignitability of the R-fuel used. Later on, various other operating conditions are dealt with at which the optimum injection timing was determined. Summing up, we can say that in the region of usual operating conditions the injection timing varies but little, so that except for starting, operation is possible at constant injection advance angle.

3) R-fuel quantity and jet shape

Fig 10 (917) showed that the R-fuel quantity hardly affects the engine power even when air excess is used. This means that R-fuel itself burns without considerable power output. This surprising fact must be clarified by further experiments. Should the R-fuel quantity be reduced below a certain limit, at first the ignition lag increases and finally the engine fails. This is due not only to the fact that a minimum of energy must be expended to produce the temperature required, but also that it becomes mechanically difficult to meter regularly and in a good jet form such small quantities (5 to 10 cu. mm.). The addition of antiknock fuel reduces the ignitability of the R-fuel. This proves that the higher the ignitability, the smaller the R-fuel quantity required for the ignition.

The minimum R-fuel quantity sufficient for the ignition is by no means the most convenient for the combustion process; especially at part load, more is needed to achieve complete combustion. Apparently this is due to the effect of the penetration of the jet, which depends on the quantity.

Fig 14 (1054) shows that, with a rich fuel-air mixture, the minimum R-fuel quantity needed for the ignition is also the optimum one for the overall consumption. Tests have proved that this quantity can be doubled without affecting the economy. Considerably more R-fuel must be added to lean mixtures than required for the ignition, otherwise the combustion is incomplete. Here, too, there is a certain latitude for the R-fuel quantity, which is most convenient for control purposes. With very lean mixtures the R-engine runs almost as a diesel engine, the minimum R-fuel quantity therefore being the optimum one from the consumption angle. It was found that at very low part loads, about 1/10 load, such as are anyway never used in flying operations, it is convenient to switch off the fuel and to obtain the whole output with R-fuel only.

The injection advance angle is always greater in the case of lean mixtures than in rich ones. It could be expected that the ignitability would be more affected when the injection takes place into a rich gasoline mixture than into a lean one. Rich mixtures however present a much shorter combustion time, which results in a smaller injection advance angle.

Experiments have shown that generally 10 to 20 cu. mm. are sufficient for the practical load range of aero-engines and that greater quantities are needed only for very low loads, and for starting. The R-fuel injection pumps will therefore probably be designed for two delivery rates.

Contrary to expectations the available pump types (e.g. Bosch PE 1b pump with 6 mm. plunger) are quite satisfactory. It has never been necessary to bother about particularly small dead spaces. In these tests the variation of the combustion pressure typical of gasoline engines was evaluated by statistical methods. The average deflection from the mean value was an indication of steadiness of running, thus giving a new evaluation standard for the quality of the ignition. This proved that at full load the spark ignition engine is steadier than with R-operation, whereas at cruising power engine running is considerably steadier when the R-process is used, fig. 15 (929). This new standard will undoubtedly be very useful in future experiments on R-fuel injection.

The R-engine differs from the diesel engine in that the ignitable fuel is not injected into pure air but in a fuel-air mixture. It is instructive that the ideal of multi-spark ignition would be attained if it were feasible to deliver diesel fuel where oxygen molecules have not yet been replaced by light fuel. This is opposed by the impossibility to distribute small fuel quantities over the whole combustion chamber. The solution of this problem would be equivalent to the discovery of the maximum performance diesel engine.

It is more likely that only some droplets of ignition fuel find the necessary oxygen and the rest burns incompletely. The ignition fuel quantity must therefore be as small as possible. The jet however must always penetrate the gasoline mixture very deeply to increase the probability of association with oxygen.

The ignition fuel quantity necessary to inflame a gasoline mixture and the corresponding ignition lag depend therefore also on the type of nozzle used. On this subject also experiments still proceed; it has however been repeatedly proved that fine atomising is not advantageous. Simple singlehole nozzles have given good results. There are two reasons for this - on the one hand it is unavoidable that gasoline and diesel fuel get mixed to a certain extent, and the more so the more finely distributed is the diesel fuel. In the case of a solid jet of fuel, on the other hand, the proportion of gasoline will be relatively small. A further reason is that finely distributed ignition fuel droplets, however immediately to the gasoline mixture the heat produced during their reaction, whilst in the case of a solid stream the heat is confined. With starting, when the R-fuel injection occurs into fresh air according to the diesel process, a very fine distribution is desirable. Future nozzle development must aim at combining these two opposite requirements. In the course of the experiments it appeared advisable to observe the jet at various stages of its formation. An apparatus was therefore produced which allowed the jet to be ignited by the sparks of large induction. This instrument was controlled on the low tension side by a specially designed mercury contact breaker. By turning the breaker casing, the instant of discharge could be adjusted to any stage of the jet formation. The duration of the spark was so short, that the droplets appeared undistorted in the photograph; fig. 16 (1000) shows the jet of a closed nozzle of 0.3 mm. bore and the conical jet of a pintle nozzle with an angle of 60° . Experiments in a pressure chamber are contemplated for a thorough investigation of the penetration. As above mentioned the best results have been obtained with single-hole nozzles giving a rather narrow jet. Fig. 17 (995) shows that the conical jet has a much higher consumption than the straight jet. A nozzle producing a wide spray gave very bad results, although it seemed very suitable to cover the whole combustion chamber. It can generally be said that the nozzle bore has very little importance. It should be about 0.3 to 0.4 mm. In Bosch type closed nozzles a small quantity of fuel always leaks out at the lapped nozzle stem, though it is not considerable compared to the total quantity. In the R-process, however, the

R-fuel quantities are so small that the leakage represents a considerable proportion of the total. It is therefore very difficult to fit multi-cylinder engines with nozzles having about the same leakage. So-called semi-open nozzles are therefore preferable for R-fuel, as they have a non-return valve before the nozzle opening and give no leakage.

A pre-combustion chamber was used to obtain a special shape of ignition jet. In these tests the nozzle was not fitted immediately in the combustion chamber wall, but an air-cooled chamber of about 5 cu. cm. capacity was interposed. The R-fuel ignited itself in this chamber, and the cylinder charge was inflamed by the fine pointed flame issuing from the pre-combustion chamber. These tests showed that the R-fuel quantity could be very small, and the operation was thoroughly satisfactory. It is necessary to follow up this possibility because an R-engine fitted with pre-combustion chamber can operate at considerably lower boost air temperatures than a direct injection type. At the beginning of 1940 attempts were made to apply Prosper L'Orange's pressureless injection to the ring process. The results so far available of tests carried out by Hirth show that this method has possibilities: it is therefore possible that the injection pump for R-fuel may be dispensed with.

c) Performance and consumption in spark-ignition engines

The maximum performance is the same in both systems. Here, too, the necessary mixture is stoichiometric proportion, owing to the non-uniformity of the mixture formation, contains always so much oxygen that the ignition can take place. In the case of richer mixtures the performance is rather lower than in the spark-ignition process.

The combustion peak pressures of the R-process were compared with those of the Otto cycle in the course of numerous experiments. At the same compression ratio and maximum power output, lower peak pressures were obtained in the Ring process. In another series of tests the injection timing and the ignition timing were varied at constant fuel-air ratio. The result was that in the spark-ignition engine the peak pressure rises steadily as the ignition advance is increased, even when the output falls off again. On the other hand in the Ring process the peak-pressure decreases as the output drops, when the injection advance exceeds a certain limit.

At very rich mixtures the performance on the R process decreases more rapidly than in the Otto process. This is not due to the fact that failures occur owing to oxygen shortage, because the diagrams do not fluctuate more than at full load, fig. 18 (1091). The investigations still proceeding tend to explain why the pressure rise occurs long after top dead centre and cannot be more favourably adjusted by displacing the injection timing. The cause seems to be that on one hand the evaporation heat of the large quantity of fuel keeps down the compression temperature; on the other hand undoubtedly a great deal of R-fuel is used up or its ignitability is more strongly depreciated than at weaker mixtures. At higher boost pressures this phenomenon is less marked. At very high boost pressures an increase in output can even be observed in the ring process, fig. 20 (1094).

In the part load region the consumption was considerably lower than in the Otto cycle. This is due to the fact that in the R-process there are no throttle losses and that moreover a considerable air excess gives a higher efficiency. Fig. 19 (994) shows a normally aspirated engine with a 15% lower consumption at half load. The consumption reduction is most marked at boost pressures up to about 1.4 atm. Fig. 20 (1094), i.e. in the normal operating range. At higher boost pressures the consumption drops for causes as yet not fully explained.

It might be expected that the same occurs at very low powers. In fact, however, it is found that consumption is the same at about $\frac{1}{4}$ load. This load is obtained in the ring process with about 1.6 air excess, with the result that the

combustion rate drops considerably. This necessitates increase of R-fuel quantity. Fig.21 (1016) shows that it is quite possible to cover the whole range with a low fixed R-fuel quantity, but that at part load operation the consumption rises. The increase of R-fuel quantity producing with certainty the ignition of very lean mixtures lowers considerably the consumption. Loads below 50% are rarely used in flying, but only at the start and end of a flight. No complete combustion is possible, even with large R-fuel quantities, at very low outputs, close to idling. It is better to eliminate gasoline completely as shown in Fig.22 (1017). In this test, load and speed were varied simultaneously, to reproduce the behaviour of an aero-engine. The course of the b.m.e.p. curve is therefore arbitrarily chosen. For the above mentioned reasons the R-fuel quantity had to be increased as speed and load were reduced; at 1,200 r.p.m. this adjustment appears quite clearly necessary. Below 1,000 r.p.m. the air excess is about 2.5. The consumption here could be considerably lowered by leaving out the gasoline which burns only incompletely or not at all. A corresponding increase of R-fuel quantity was found necessary, as well as a considerable reduction of the injection advance angle. It is shown later that R-fuel only must be used for starting up; the control can therefore be easily effected by switching off completely the fuel below a certain quantity. The fuel nozzle is then no longer cooled by the fuel, but it was shown that the nozzle does not become overheated. Below 1,000 r.p.m. the exhaust gas had a temperature of slightly over 1000°.

d) Knock behaviour of fuels in the R-process

In the R-process the ignition is produced by the R-fuel which is distributed in droplets over the whole combustion chamber. It may therefore be expected that the combustion starts simultaneously in numerous points; this excludes the formation of detonating mixture residues.

The first experiments seemed to confirm this. In this first test the injection was timed so as to produce the pressure rise at T.D.C. The comparative spark-ignition test was operated with a constant ignition 30° B.T.C. These conditions showed an increased knock resistance, which was particularly marked with aromatic fuels. A more thorough investigation in comparable conditions showed that knocking occurs in equal measure with both methods. This must be due in the first place to the mixture of R-fuel with fuel occurring during the ignition lag. This results in a reduction of the anti-knock value, which apparently, just balances the advantage offered by the multiplicity of ignition points. It may be that in the R-process the knocking proceeds quite differently from the normal gasoline engine, where it is due to the sudden ignition of a residual gas mixture. In the R-process ignition centres are available over the whole combustion chamber, so that it is not impossible that knocking might be produced by the sudden ignition of the whole mixture. Comparative tests are contemplated on the combustion process of diesel, spark ignition and R-engines. In the choice of R-fuel nozzles special requirements are presented by the starting operation. All experiments have shown that a certain depth of penetration is necessary to ignite with certainty the gasoline mixture; this can only be achieved with a solid fuel jet. A small nozzle bore is essential to obtain this depth with small fuel quantities. For starting, however, a large orifice is necessary rapidly to deliver to the cylinder large R-fuel quantities, whilst fine atomization is desirable to allow an intimate mixture with the air. The problem is therefore to produce a nozzle delivering a solid jet with small quantities and a dispersed one with large quantities. Low temperature starting presents a problem which is more difficult to solve than in the diesel engine owing to the low compression ratio. The low starting speed and the large clearance of cold pistons as well as the large valve overlap, produce additional difficulties.

As in many stages of the engine development, the work on the Ring process for the development of a suitable starting method has led to subjects which present an interest outside the R-process. Until we discover a fuel that is harmless outside the engine and ignites itself immediately when injected even at low temperatures, it is necessary to apply special sources of heat. The simplest solution seems to be to warm up the intake air.

From this angle the development of small internal combustion engines to start big aero engines is particularly important. These small two-stroke engines such as are produced by Hirth, deliver during the starting process waste heat from the cooling air and the exhaust gases. These heat sources can be used to warm up the intake air of the main engine. As these starters can turn over the main engine for a long time, it is possible to scavenge the cylinders with warm air. This development mainly based on the careful study of the waste heat, has proved very useful also for present day gasoline engines.

In the flight tests carried out in May 1942, by BMW Gnadau, one sparking plug was fitted in each cylinder and fed by simple coil ignition. This ignition is required only at the start, thus eliminating the complicated and heavy screening system otherwise necessary for the protection of radio communications.

THE DIESEL GAS PROCESS

After experiments had been started on the R-process, publications appeared dealing with the conversion of diesel engines to fuel gas. All these works were directed to finding an alternative in case diesel fuel supplies deteriorated through war developments.

The work was based on a diesel engine, which operated in the normal manner at idling and low loads, while, at higher loads a mixture of gas and air was used. A compromise had always to be reached, since the compression ratio was restricted by the anti-knock value of the fuel. On the other hand, however, the compression ratio had to be high enough to assure the ignition of the injected diesel oil, especially for starting a cold engine. In spite of certain defects, particularly apparent in the use of fuel gas, this process was better than the conversion of diesel engines to gasoline engines.

As opposed to this makeshift conversion of diesel engines, the R-process was developed from the gasoline engine. The low compression ratio of these engines required a new exceedingly ignitable diesel fuel, the R-fuel, to produce diesel combustion. The R process was developed not only because a substitute for sparking plugs was absolutely necessary, especially to use safety fuels, but also in the knowledge that this would offer a working system for gasoline engines presenting new and improved properties.

The idea to replace gas oil at least partly by gas as a wartime emergency was not restricted to Germany. In the first half of 1939 a series of articles appeared in the English magazine "Oil Power", and a report on "A new type of gas engine" in the "Geo Times" of July, 1939. This was a reciprocating engine, working both as a conventional diesel engine and as a gas diesel. The fuel contemplated was house-hold gas. The diesel oil producing the ignition, whilst the output is controlled by the gas. The appearance of these articles abroad showed how these problems were very much to the fore. They were then considered as an incentive to develop the R-process as fast as possible, at least to achieve an initial advantage.

Very early the Reichs Ministry of Transport and the War Office set the task to adapt lorry diesel engines for the use of other fuels. It was thought at first to convert them to gasoline, involving a compression decrease and the provision of carburettor and ignition system. Fuel gas and producer gas were considered, as well as methyl alcohol, which, in contrast to gasoline, cannot be directly used, as a substitute for diesel fuel. It was assumed then that nitrogen industries idle during the war would be available for the production of methanol, this, however, did not materialise. All questions were studied so thoroughly from the operational standpoint that a trial run was carried out in October 1936 with home-produced fuels. As part of this work a 5.3 ton Daimler-Benz lorry operated successfully with engine having been adapted to work on straight methanol.

The conversion of diesel engines to gasoline operation presented the drawback

that costly equipment such as carburettor and ignition system, had to be produced and kept in readiness for an emergency. The application of gaseous fuels to diesel engines constitutes in itself an improvement on this. The R process was originally called the Otto-Diesel process. At the beginning of 1940, report No. 1022 on "operation of diesel engines with gaseous fuel on a mixed Otto-Diesel process" was issued by the scientific-technical section of the Benzole Association in Bochum. These experiments were started in 1939. This however could cause confusion; moreover it did not seem convenient to publicize the fact that the aero-engine industry was concerned with such activities. A code name was suggested. The expression chosen was one which caused no confusion in the aero engine industry and still did not sound strange: it was "Ring Process". Similarly Z fuels (for Zündstoffe) were called "R-fuels".

The war has produced many applications of the diesel gas process suggested by Diesel. Sufficiently knock-resisting fuel gas was not available, with the result that in 1941 it was necessary to go over to the use of producer gas on a larger scale. The drawback opposed to the advantage of a high antiknock value is that bulky gas producer plants were required. This leads to the question whether it is preferable to mount numerous small chemical factories on vehicles or to use the same quantities of steel for the construction of hydrogenation plants. The urgency of producing the fuel decided the issue, because automotive gas producers can be turned out more rapidly than hydrogenation plants.

The development of producers suited for low ash content coal was accelerated in 1942. However the use of the diesel gas process has passed its peak, because fuel oil is so scarce that it is no longer available as ignition fuel. It is again necessary to consider the conversion of diesel engines to gasoline operation and to restrict to a minimum the new production of diesel engines. For this state of affairs the motor industry was largely responsible; in its attempt to present the automotive diesel engine as particularly convenient, it fought all price increases of diesel fuels that would have been necessary as a basis for the diesel fuel production by hydrogenation. Many publications have appeared on the diesel gas process. In April 1940 Mehler published in the A.T.Z. experiments carried out on a stationary Krupp engine at a compression ratio of 1.44 working on fuel gas, illuminating gas and butane. It was immediately clear that at such a high compression ratio, satisfactory operation on butane or fuel gas was impossible. This seemed inexplicable at the time because it was thought to be connected with the different thermal efficiencies. Many practical questions were then unexplained, e.g. it was believed that in the diesel gas process throttling should be applied at part load, similarly to the gasoline operation. The Technical Experimental Station also worked in 1939 on the conversion of diesel engines to fuel gas, and the fundamental principles of the R process proved very useful (ATZ 194, p. 188). The compression was reduced to 1.14 in engines with pre-combustion chamber, as otherwise the antiknock value of the fuel gas was too low. The following measures were found suitable for the conversion of diesel vehicles. The injection pump is set at idling rate. The greater rate necessary for starting can be obtained by pulling a knob which may alternatively be pushed to cut off the fuel feed and stop the engine. The fuel gas was expanded through the usual reducing valves and fed to the intake manifold at low pressure. The control was effected by a small valve actuated by a pedal. The diesel fuel consumption on long runs is 15 to 30% of the nominal diesel engine consumption. In town service this rate rises to 30% with the result that here too considerable quantities of diesel fuel can be replaced by fuel gas. The total consumption of the engine and its performance are about the same as in the diesel engine.

In connection with the operation of automotive engines with producer gas it can generally be said that it is possible to achieve approximately the same output as in diesel operation. The extra performance, which a gasoline engine should obtain owing to the lower air excess is lost, as the calorific value of the mixture is lower when gas is used. This is particularly apparent when producer gas is used, the calorific value of the mixture being about one third lower than with gasoline. Fuel gas mixture has a comparatively high calorific value, but the compression ratio used must be lower.

Most suited to the conversion are direct injection engines; precombustion chambers must either be completely removed or their orifices considerably enlarged. It is convenient to fill in jet chambers, to eliminate the rapid gas transfer which would produce excessive heating.

Precursors of the ring process

The DRP granted on 27.1.1928 to the firms Maschinenfabrik Augsburg, Nürnberg and F. Krupp, a patent with the following specification.

Ignition and combustion process for combustion engines, characterised by the fact that the compression temperatures of the mixture does not reach its own ignition temperature, but reaches or exceeds the ignition temperature of another more highly ignitable fuel or mixture, with the result that the injection of the latter fuel starts the combustion of the mixture, the combustion of the ignition fuel being controlled by the engine timing.

The actual inventor is Rudolf Diesel, then in charge of the Experimental plant at Augsburg. It is further known that, during the development of his engine Diesel had thought very early of running it simultaneously on two fuels whilst he originally contemplated spraying the gas in the cylinder shortly before injecting the ignition fuel; he also considered mixing the gas with the intake air.

This diesel gas operation however produced no economic advantages and consequently the process was given little consideration in the following period. In 1926 the Hückner Humboldt Deutz A.G. took up again the process but again no economic stimulus materialised.

Diesel's patent is undoubtedly based on the notion of ignition by injected fuel in an engine working on gas. This system is used to-day in automotive engines fed by fuel or producer gas. Without knowing Diesel's patent, Gen. Eisenhoer of the German Air Ministry again took up the idea in 1938; he intended to ignite a fuel-air mixture such as used in gasoline engines, by the injection of a burning liquid. The I.G. was also encouraged to carry out tests on the subject. Unfortunately there is no record of this, but the fact should not in the least be doubted that the German Air Ministry first had the idea.

Independently of all this, the idea occurred again and was developed in the course of work on safety fuels. These tests proved that the ignition spark does not guarantee the ignition of the mixture safety fuel-air which gave rise to the thought that combustion on the lines of the diesel process might be used. To apply this process to conventional gasoline engines, it was necessary to find a special highly ignitable diesel fuel; after long development work R 300 was obtained and is now produced on a large scale.

Report No. 372 of 10.2.1939 dealt with the state of the experiments on safety fuels in aero engines. The fundamental features of the ring process were also described. As it did not seem convenient to make these notions accessible to other parties before the tests were concluded, the report was published in abridged form and classified as No. 372a. The doubtful section in report No. 372 reads as follows: "In the development of present day gasoline engines, special attention must be dedicated to the ignition. It is known that one ignition spark is insufficient to ignite the charge of an aero engine cylinder. A considerable gain in performance is therefore obtained by using two sparking plugs. Efforts should be made to achieve multi-spark ignition. Most hopeful is the injection of fuels with a low self-ignition point, such as amyl nitrate, peroxide, phosphorous, metal alkyls.

The engine worked as at present by injecting gasoline into the air during the inlet stroke. Shortly before the end of compression an ignition fuel is injected through the same nozzle or another one. The specifications of such a

fuel are as follows:

- 1) Flash point, which is the same or higher than that of the fuel used
- 2) Ignitability when injected in the compression space. Pressure about 10 - 20 atm., 250 - 400°C
- 3) Low residue formation, solubility in hydrocarbons, non-poisonous, etc
- 4)

The advantage of such a fuel would be -

- 1) Probably a very considerable influence on the knock behaviour, because controlled pressure waves are avoided
- 2) Power increase.
- 3) Economic advantages. Up to now the misfiring limit was reached very early when working on lean mixtures. The engine missed when the composition of the mixture near the sparking plug happened to be below the ignition limit. A liquid that burns during its atomization would ignite even very lean mixtures.
- 4) Assured ignition of different mixtures, as for instance in the case of high boiling point and viscous fuels. The fuel must be injected as late as possible to avoid deposits on the cylinder walls. This however reduces the time available for the mixture formation which, in turn, affects the uniformity. This is the reason why electrodes protruding into the combustion chamber and an ignition spark of long duration are used in the Hesselman engine. The working principle of the injection-ignition engine can be described as that of a diesel engine working at low compression, employing the use of a highly ignitable fuel (E = 1.8 about 100 cetane). The engine compresses, however, not pure air, but a fuel air mixture. Experiments are in progress.

This survey shows that the fundamental idea, i.e. the ignition by means of a highly ignitable fuel of a mixture that would not be ignited by the compression heat, had already been clearly grasped by Diesel. This idea had not been forgotten, as it is shown by Deutz's tests of 1926 and the application to automotive engines since 1939.

As a result of the need to replace the unreliable sparking plugs of gasoline engines, it was planned in 1938 to inflame the compressed mixture by injection ignition. Whether the idea was to use the self-ignition of the fuel on the lines of the diesel process, or a fuel that burnt on atomizing, is less important than the idea thus to ignite fuel air mixtures. So far the research work had followed Diesel and considered gas only.

The last development resulted from the notion that the solution depended on the realisation of a Diesel process to be operated in conditions so far wholly unusual for a Diesel engine. The problem was solved starting from the fuel, and developing a Diesel fuel which ignited at the low compression temperature corresponding to the low compression ratio of gasoline engines.