B.I.O.S. No. U.5

F.D. 2872/46
Item 7

Lilienthal-Gesellschaft für Luftfahrtforschung,
Report No. 158, pps. 49 - 59
28, 29 January, 1943.
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The "Ring" process

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There is so much talk to-day of novel methods of propulsion that one would suppose that the good old piston engine had done its job, and was hardly worth talking about any more. This is far from the truth, however, and one is repeatedly astonished at the way in which possibilities of further development reveal themselves. A proof of this is provided by the new "Ring" process.

We still distinguish to-day two methods of engine operation, the Otto and the Diesel process. With every development this distinction becomes less. The Otto and the Diesel engine are approaching a common compression ratio. In the Otto engine the fuel is no longer mixed with air in the carburettor, but is injected into the cylinder in a way which closely resembles that in use in the Diesel engine. At the same time we have the possibility of altering the injection timing at will. In the Hesselman engine, injection has moved right up to the end of the compression stroke, so that this engine might be considered as a Diesel engine with auxiliary ignition. The Diesel engine can run on gasoline, and the Otto engine can use safety fuels with high boiling points.

The one distinction remaining is that the Diesel engine ignites the fuel itself, while the Otto engine requires the aid of a sparking plug. This distinction has been bridged by a third process, which is really not a third process at all, but a cross between the Otto and Diesel processes.

A number of people have invented such combinations. The first was Diesel himself. In a patent of 1898 he stated quite clearly, that a mixture of fuel and air should be compressed to a point at which it does not itself ignite, but that the limit compression should be so high that a second fuel injected near dead centre will ignite itself and the mixture with it. The process was never applied, because the use that was intended to be made of gas was not then an economic proposition. In 1939 Eisenlohr had considered the possibility of igniting gasoline by means of a burning liquid, and in 1939 two-fuel processes were invented in several quarters, apparently simultaneously. To give one instance, the method was invented for operating automotive diesel engines on gaseous fuels, and again by us, since our work on safety fuels led us to seek a more powerful means of ignition than sparking.

(1) Report by Technical Test Station Oppau of I.G. Farbenindustrie.

The process which we have developed, and which goes by the name of the "Ring process", is different from that invented by Diesel and his successors. The latter started off with a Diesel engine, and instead of air wished to supply it with a mixture of fuel and air. In our present state of knowledge, this makes certain demands on the knock rating of gasolines. The "Ring" process, on the other hand, is based on the Otto cycle, and requires a fuel which ignites easily.

A fuel such as would allow an Otto engine to run as a Diesel engine without any appreciable increase in compression was not known at that time. It appeared in the substance known as R 300, which forms the basis for the "Ring" process.

Diesel oils are easier to ignite the more paraffins they contain and the longer the paraffinic molecules. Paraffins with up to 4 C-atoms are still not very easy to ignite, as is proved by the good knock-rating of the gases from Methane to Butane, which of course are used as fuels for gasoline engines. The paraffins from hexane onwards are suitable for Diesel fuels. The most easily ignited is Cetane with 16 C-atoms (figure 1), but this exhausts the possibilities of the paraffin series for our purpose. It is possible that larger molecules will disintegrate even more easily, but these are of no interest on account of their setting point, as this is already +16° for cetane.

(Fig. 1 - Ignitability of straight chain paraffins)

It will be common knowledge that we have in the nitrates, nitrites and peroxides so-called ignition accelerators, which, like a detonator, increase the rate of reaction of a Diesel fuel. But they unfortunately only increase the speed, as they themselves only come into operation at certain temperatures. We used these substances at first as a stop gap, but were glad to dispense with them, as they proved very tricky, though less when in a finished blend than when they were being prepared.

A happy solution was found among the ethers. The best known of these is ethyl ether, which is a common starting aid in gasoline engines because of its volatility, and in Diesel engines because of its easy ignition. It now appears that the ethers with higher boiling points also have good ignition properties. A characteristic of ethers is that they contain oxygen in the molecule, which should be a straight chain if possible. The ease of ignition of ether does not, however, arise from the fact that it carries some of its combustion oxygen, for ease of ignition does not depend on oxygen content. But probably ethers have the property of forming compounds specially rich in oxygen when they decompose; that is, they form peroxides.

(Fig. 2 - Viscosity of ignition material R 300
The viscosity of R 300 lies between that of gas oil and of gasoline)

(Fig. 3 - The properties of R 300
The properties of R 300 are compared with those of other known fuels)

We selected from the ethers with high boiling points one which was not only distinguished by its properties, but could also be produced technically. This substance became known as R 300. Figure 3 shows some of the properties of R 300. According to these, R 300 is a fairly heavy liquid with a high boiling point, which, thanks to its high cetane number, may be described as an easily ignited Diesel oil. Its calorific value on a weight basis is 66%, and on a volume basis 80% that of gasoline. The small requirement of air means that the calorific value of the mixture is somewhat higher than that of gasoline. Therefore R 300 can be used as a starter fuel for Diesel engines. It is then called KS II.

If now the R-fuel is injected into a compressed gasoline-air mixture, the particles begin to react with the oxygen present. Although heat may be absorbed to begin with, this is followed quickly by generation of heat, and soon the reaction has reached such a speed, that burning occurs, and the whole mixture is ignited. Whereas in gasoline combustion only begins with the igniting spark, we may assume that in the "Ring" process combustion will occur almost simultaneously at several points, and that it will occur at those points at which the R-fuel has a preponderance over gasoline, and where the temperatures are highest.

The ignitability of R-fuel is due to the fact that reaction commences at comparatively low temperatures. This well known fact is well demonstrated by the tests which were carried out by LFA Brunswick. In these a gasoline engine, actually a CFR engine, was driven externally without ignition, and first of all the temperature of the exhaust air was determined. When fuel was added to the intake air, there was a rise in the exhaust temperature, and this was higher, the greater the reaction during compression.

(Fig. 4 - Pre reaction of R 300
When a mixture of fuel and air was compressed, a much higher rise in temperature was observed with R 300, which is susceptible to reaction, than with an easily ignitable gasoline)

Figure 4 shows the relationship between excess air ratio and the rise in temperature of an ignitable gasoline of cetane number 42 which is highly susceptible to knocking, which gives a maximum rise in temperature of 40°. Under the same conditions R 300 underwent self ignition, which was only reduced when the compression ratio fell to 13.5 and the temperature of the mixture to 60°. Nevertheless, the pre-reactions observable in the increased temperature are much more pronounced than with gasoline.

Another estimate of the ignitability of R 300 is given by the Cetane number determination on the I.G. test Diesel, in which the ignition delay is adjusted to a value of 18° by alteration of the compression ratio. This is about 1:14 for gas oil and 1:7 for R 300. An investigation of the ignition delay in relation to pressure and temperature was carried out in the machine laboratory of the Technical High School Dresden on the Holfelder compression bomb (Fig. 5).

(Fig. 5 - Ignition Delay of R 300 and gas oil
In the investigations in the Holfelder compression bomb
with R 300 there were very small ignition delays
which were little affected by pressure).

It appeared from these experiments that ignition delay is much less than with a gas oil having a cetane number of 65. It was further established that the ignition delay of R 300 is very little influenced by pressure. Also, as temperature increases the ignition delay appears to decrease uniformly, whereas with gas oil the effect of temperature continually decreases.

A jet of this quick-reacting R-fuel therefore takes the place of the ignition spark which brings about combustion in the Otto process. But this is one of the great advantages of the "Ring" process. It is well known that, as engines develop, electrical ignition is becoming more difficult. The necessity for providing a screening is a nuisance, but a real disadvantage is the fact that at high altitudes the sparking plugs mis fire owing to sparking-over externally. Other faults became apparent in the sparking plugs themselves, where the efficiency of the insulators is impaired by deposits from tetra-ethyl lead. Then again the electrodes are attacked. The result is that the sparking plugs are not a component of the engine, but a consumable part. There is little prospect of finding an additive other than tetra-ethyl lead, so that it is to be considered a s a step forward if, instead of a sensitive sparking plug, we have a jet of liquid controlled by a reliable nozzle.

The limiting factor in the use of tetra-ethyl lead as an additive is the damage which large quantities of it cause to valves and plugs. We may assume that for the future plated valves will be used, therefore the weakest point is the sparking plug. If this weakness can be corrected, there is the possibility of going ahead with the use of larger concentrations of additive, and of arriving in this way at high performance fuels (Fig. 6). Of course the greatest care must be taken that this increased use of additives does not cause trouble in other directions: it will not affect the R-fuel jet at all.

(Fig. 6 - Increase in knock-rating through increased use of lead additive
Increasing the additive used above the 0.12% at present customary resulted in increased knock-rating, which appears of value in the "Ring" process, if the valves are adquately protected)

(Fig. 7 - Comparison of Otto- and Ring-processes
In both processes the attainable maximum is practically the same. The fuel supply of the "Ring" engine is controlled from full load to idling)

It is now necessary to determine whether the new type of ignition is subject to deviations in power and consumption. There is no reason to suppose that this is so, for the power is determined by the energy content of the charge, and in both cases this can be made to ignite completely. Admittedly, R 300 has a low calorific value, which however is cancelled out by its low consumption of air. Thus, R-fuel does not reduce the energy content of the charge.

Therefore we also find that the maximum attainable performance is the same in both processes (Fig. 7). But we can also perceive another advantage of the Ring process, which may be considered as an heirloom of the Diesel process: the fuel supply of the R-engine can be controlled from full load to idling. With the Otto process it is possible under specially favourable conditions to use a 30% air excess. But owing to unavoidable inequalities in supply to individual cylinders, an air excess of only a little more than 10% is permissible. In the Ring process, however, even the leanest mixtures are ignitable. The reason is the high energy content of an R-fuel jet, which is about 70 kcal compared to 10^{-6} kcal of an ignition spark. With very weak mixtures it is necessary to raise the volume of R-fuel somewhat, as weak mixtures require a more powerful aid to ignition. The volume of R-fuel must then also be raised, because when idling all the friction horsepower is provided by the R-fuel.

Apart from the question of control, it is a decided advantage of the "Ring" process that it can ignite mixtures however weak. With spark-ignition engines great care is required to achieve a good distribution of the mixture when injecting the fuel into the cylinder, as otherwise, whatever the engine speed or other operating condition the mixture near the sparking plugs will be either too rich or too weak. The result is poor combustion, or even missing. It is significant that the "Ring" process is not nearly so sensitive, as it depends less on the composition of the mixture, and the jet penetrates sufficiently to find a mixture suitable for ignition.

Because of the sensitivity of the mixture, the peak-pressures in a spark-ignition engine fluctuate very greatly even under normal conditions, so that only by taking the average is it possible to form a picture of the combustion process. In the Ring process these deviations are not eliminated, but are considerably reduced, as will be demonstrated later.

Taking a fuel with adequate vaporisation, the formation of the mixture will be better the longer the time which is available for fuel and air to mix. Therefore in the spark-ignition engine the fuel is introduced at the beginning of the suction stroke. If the time is now reduced by postponing the moment of injection, there is a loss of power through incomplete combustion, as shown in Fig. 8. In the spark-ignition engine, in this case a

BMW 132 N, the power falls if the beginning of injection is later than 120°. On the other hand, in the Ring process the engine can make do with about half this time in which to form the mixture, i.e., injection can take place to a large extent during the compression stroke. Thus the "Ring" engine can work on incomplete mixtures, or intentionally stratified charges.

Fig. 7 shows that with rich mixtures, corresponding to take-off, power falls more quickly with the "Ring" process than with the Otto process. This is evidently because the R-fuel comes into contact with fuel everywhere, mixes with it, and so loses its effectiveness: also the compression temperature is less because of the large volume of fuel which is vaporising.

(Fig. 8 - Influence of the beginning of injection in the Otto and Ring processes
In contrast to the Otto engine the "Ring" engine is considerably less sensitive to incomplete mixtures, caused by late fuel injection)

Illustration 9 shows that this increases ignition delay, so that maximum pressure is not reached until after dead centre. If we were to inject sooner, ignition delay would be even greater, and so this condition would not be remedied, but made worse. Improvement only occurs if the charge is deliberately made heterogeneous: for instance, by delaying injection (Fig. 10). As a substitute for this practice, which is only usable to a limited extent, it is better to have a stratified charge.

The reduced power with the Ring process at rich mixtures is seen to occur mainly at low boosts. At higher boost pressures the uniformity of the mixture falls off, evidently owing to the diminished penetration of the fuel, and also the compression temperature rises because of the increased load so that at high boost the "Ring" process is superior to the Otto process even for take-off power.

(Fig. 9 - Pressure diagram with a rich mixture
Although R-fuel is injected early, combustion begins too late.

(Fig. 10 - Power at rich mixture
The inferior power of the R-engine at rich mixtures can be influenced by altering the formation of the mixture)

(Fig. 12 - Comparison between Otto- and Ring-process with super charging
At higher boost pressures the Ring process is equal or superior to the Otto process even at rich mixtures)

The question of non-uniform charging has acquired great interest today, as there are possibilities here of improving the detonation performance of an engine, and so avoiding as far as possible having recourse to expensive fuels. It would be desirable, therefore, to try out the Ring process in tests with stratified charge.

Before going into details, we will consider the Knocking behaviour of the Otto and the "Ring" engines quite apart from the quality of the mixture.

Knocking is caused by the fact that the unburnt part of the fuel reacts so quickly with the oxygen of the air that ignition occurs before the flame front initiated by the spark has reached this part of the mixture. The knocking is more violent the greater and more uniform this part of the mixture is: its independent reaction is affected by the pressure of the burnt mixture as well as by temperature. It is therefore to be expected that the tendency of engines to knock can be reduced if several sparking plugs are arranged so as to cause such speedy ignition of the charge that self ignition occurs only to a limited extent, or not at all.

From this we may expect that the Ring process will demand knock-resistance in a fuel, insofar as the particles distributed in the combustion chamber ignite the charge simultaneously at many points. Tests have now shown that an improvement in knocking behaviour may be expected, even if at present this is not as much as expected.

Thus for example, if a normally aspirated engine was run on several different fuel:air mixtures, with adjustment of ignition advance, or injection advance to give maximum power or the knocking limit, then at 1 : 8 (Fig. 12) the behaviour was the same in both processes. At higher compression ratios knocking occurred earlier in the Otto process: this was overcome by adjusting the ignition, which resulted in a reduction in power. This phenomenon, which requires closer investigation, appears to indicate that at a lower compression ratio the advantage of multiple ignition disappears owing to the deterioration of the Otto mixture through contamination by R-fuel. We may suppose that at higher compression ratios this deterioration will be less, corresponding to the reduction in ignition delay.

(Fig. 12 - Highest power with Otto and Ring processes at different compression ratios
The lower tendency to knocking of the Ring process becomes more pronounced the higher the compression ratio)

For final clarification of the detonation process, it will be necessary to investigate closely the course of combustion. It is quite possible that in the Ring process, in addition to the form of knocking with which we are familiar, we may have space explosions (raumexplosionen).

A further comparison between the Otto and the Ring process was obtained by plotting knock limit curves with various fuels. For the spark-ignition engine an ignition advance of 38° before top dead centre was chosen, being that usually laid down for such tests. For the "Ring" engine the beginning of the injection of R-fuel was fixed at 80° before top dead centre. Incidentally the position of the knock limit curve was only slightly influenced by the injection advance. Fig. 13 shows the curves for several typical fuels. There is no pronounced difference here between the Otto and Ring processes, except that with B4 and C1 at rich mixtures a great increase in knock rating was observed.

(Fig. 13 - Knock limit curves for the Otto and Ring processes Under the given conditions, the b.m.e.p. values are about equal)

It is a known fact that by stratifying the charge it is possible to reach a condition where the last part of the mixture to burn has either a very high or very low proportion of air, so that the spontaneous reaction is inhibited. Another possibility consists in altering the time during which the mixture remains in the cylinder. Two phenomena are important here. If the fuel is injected at the beginning of the induction stroke, then it has sufficient time to form a suitable mixture during the suction and compression strokes. Simultaneously it begins to react with the oxygen in the air, so that its knock rating will be reduced for example by the formation of peroxides. This latter phenomenon chiefly occurs under the influence of the high temperatures during the compression stroke.

If the injection of gasoline is delayed from the beginning of the suction stroke until its end, the only essential difference will be that the formation of the mixture will not be so good, and the knocking tendency will thus be reduced. This may possibly be due to the fact that the whole of the charge, and thus the last part of the mixture to burn, is not uniform in character, so that in larger volumes it has no tendency to spontaneous ignition. But it is also extremely likely that the coarser distribution of the fuel makes the reactions during the compression stroke more difficult, and so reduces the tendency to knocking.

If the injection timing is made later in the compression stroke, then the time available for pre-reaction is curtailed, and, as the tests are on the test stand with Hesselman engines , showed a pronounced improvement in the knocking tendency is achieved.

We have seen (Fig. 8) that the Ring engine is particularly well adapted to operating on charges which, owing to their short stay in the cylinder, have a certain lack of uniformity. Fig. 14 shows the way in which the knock limit curves can be changed by altering the injection timing of the gasoline fuel.

In both the Otto and the Ring process the knock limit curve is so altered that the lowest point is raised the most. The curves become flatter, especially for the reason that the knock rating falls somewhat in the rich region. This is possibly connected with phenomena which Frank found occuring in a DB 6001 at various valve overlaps.

(Fig. 14 - Influence of beginning of injection on the knocking tendency
By injecting fuel later, it is possible, especially in the Ring process, to achieve an improvement in knock behaviour)

According to Callender, reactions on the droplets, especially with fuels poor in aromatics, lead to the formation of peroxides. As the quality of the mixture is undoubtedly reduced through retarding the injection, the fall in knock rating with rich mixtures could be explained by the presence of droplets, and thus of peroxides. The reduction in knock rating obersed in gasoline engines at weak mixtures requires further investigation.

The illustration makes it clear that the raising of the minimum boost point is specially pronounced in the "Ring" process, and that late injection is possibleup to a point at which the spark-ignition engine would fail. Admittedly consumption deterioirates as a consequence of this.

The curtailment of the time spent in the cylinder by the mixture was merely instanced because it is a particularly convenient example. Much better results can be obtained by the use of carefully stratified charges, by the DVL process. By using a two-jet nozzle BMW have already succeeded in displacing the knock region beyond the range of maximum power. Good results were also obtained by slight alteration in injection timing.

In considering combustion processes, peak pressures should not be left out of account, as maximum pressures are an important consideration in determining the dimension of a power unit. The peak pressures will be higher the more closely combustion resembles constant volume combustion. The Otto and "Ring" diagrams are distinguished by the fact that with the Otto, combustion begins ~~directly~~ the spark occurs, and is much less violent to begin with than in the "Ring" process, where combustion does not begin until at or shortly after top dead centre (Fig. 15).

(Fig. 15 - Course of combustion in Otto and Ring processes
In contrast to the Ring process, combustion in the Otto process begins before top dead centre)

(Fig. 16 - Indicator diagram for the Otto and Ring processes
Earlier combustion and more rapid fall in pressure in the expansion stroke result in losses in the Otto process compared with the Ring process)

Peak pressure should in both cases be about 10 - 20° after top dead centre, so that there is no doubt that greater pressure accelerations occur in the Ring process. But as things turned out higher peak pressures did ~~not~~ occur, as the volume in which combustion takes place is about the same in both cases. The fact that in the Otto process between ignition and dead centre the volume is at first diminished, that is, that burning mixture is compressed, leads to a loss which does not occur in the Ring process (Fig. 16). Two diagrams are shown here with almost equal peak pressures. In addition to the slight loss in the compression stroke, there is a noticeable deviation in the expansion stroke. The Ring diagram is throughout somewhat higher, thus gaining by comparison with the Otto cycle. Therefore for equal powers the peak pressure would actually be smaller in the Ring process. The diagrams have been selected as typical examples from a large number of tests, so that they are not haphazard. The scattering to which the Otto and even the Ring diagrams are subject makes it very difficult to give an exact picture of conditions, and it would be desirable to make thorough investigations so that this question might be cleared up.

(Fig. 17 - Peak pressures in Otto and "Ring" processes
Peak pressures rise with ignition advance in the Otto process: in the Ring process they follow the b.m.e.p.)

We have also studied peak pressures as regards their dependence on ignition advance or on injection advance, and have arrived at the conclusions presented in Fig. 17. The best power was the same in both cases, which is quite understandable, as in each case an excess air ratio of 0,92 was used. In the Ring process a volume of 22 mm^3 of R-fuel per cycle was included. The limits within which the peak pressures fluctuate are shown. This scattering relative to the maximum pressure is 18% in the Ring process and 25% in the Otto.

In the "Ring" process maximum pressure is more or less related to b.m.e.p. If the b.m.e.p. falls through excessively early injection, peak pressure falls with it. In the Otto process, on the other hand, peak pressure rises continuously, since combustion commences with ignition, and the mixture, which is already burning during compression may be completely burnt by the time dead centre is reached.

In the "Ring" process the pressure always rises at about top dead centre. R-fuel, if injected toosoon, does not meet the temperature necessary for combustion, so that ignition delay increases. At the same time ignition is hampered because during the prolonged ignition delay R-fuel mixes with gasoline If injection takes place too close to dead centre, ignition occurs too late, and peak pressure falls as combustion is too late in the expansion stroke. But BMW observed a different behaviour with super-charging, and this requires clarification. The most favourable point for beginning combustion therefore is selected automatically, and this explains why b.m.e.p. is independent within wide limits of the injection advance (Fig. 18). This phenomenon is a valuable aid to control, and explains why pumpless, uncontrolled injection as developed by Hirth, which will be discussed later, is not only possible, but moreover gives useful results.

(Fig. 18 - Influence of ignition advance or injection advance on the course of combustion
In the "Ring" process the useful pressure is independent within wide limits of the degree of injection advance)

(Fig. 19 - Comparison between cylinder-head temperatures in the Otto and Ring Processes
Under comparable conditions the temperatures in the Ring process are well below those of the Otto process)

(Fig. 20 - Comparison between heats to coolant in the Otto and the Ring processes
The coolant heat is considerably greater in the Otto engine than in the "Ring engine)

As already mentioned, we found that during the expansion stroke the reduction in pressure was slower in the "Ring" process than in the "Otto" process. This led us to the conclusion that after-burning took place, that is, that there were greater heat losses in the exhaust and the coolant. But the coolant heat is not greater, but actually considerably less than in the Otto process. This fact was first established by BMW in tests on air-cooled cylinders. Under equal power and cooling conditions the mean cylinder head temperature was 40° lower than with the Otto process.

Using a small cylinder of 1 l capacity, Hirth observed the same phenomenon, but not to such a pronounced degree. (Fig. 19). Finally we have measurements of a liquid-cooled cylinder (Fig. 20), in which the power loss through cooling was 25% less than in the Otto process. The missing heat can only be in the exhaust gases. When this could sometimes not be shown at all by temperature measurements, at other times only partly, it may have been because the temperature measurements were not above suspicion. We suspect that one source of error was the fact that in the different processes radiation varies.

Tests are being carried out on these lines. It must also be remembered that the measurement of coolant heat is subject to errors, so that the transfer of heat from coolant into the exhaust gases is not 25%, but probably less. We will make further attempts to explain this interesting phenomenon.

So far we have merely stated that in the "Ring" process ignition is brought about by injecting a substance which easily ignites. We had expected to encounter serious difficulties in this injection process, but everything went off much better than we expected. Whereas we had supposed that it would be necessary to develop special pumps it appeared that ordinary Diesel injector pumps with a small plunger of 6 mm. diameter were quite capable of controlling efficiently small volumes of 10 to 20 mm.^{3}; it was not even necessary to pay special attention to small dead spaces or the dimensions and pressures of the fuel line. Even at higher speeds the metering of small volumes presented no difficulties, as was established by Hirth in tests at 3800 r.p.m. (Fig. 21). However, at speeds above 2200 r.p.m., injection must be advanced. The volume of R-fuel was increased slightly with the speed. Up to 2500 r.p.m. our experiments showed that there appeared to be a possibility of reducing it somewhat.

(Fig. 21 - Influence of speed on maximum power
Small volumes of R-fuel can be injected efficiently even at high speed)

(Fig. 22 - Influence of the form of the R-fuel jet on power and consumption
Fine-atomizing nozzles are unsuitable for the injection of R-fuel)

In main engine tests, we continued to use the available large fuel pumps, by inserting small pump elements. Later it will become possible to use special pumps of smaller dimensions. Prolonged tests over 2000 hours at BMW have shown that R-fuel does not increase wear and tear, and this confirms our own experience.

Nor did the nozzles cause any material difficulties. So-called open nozzles with non-return valves proved just as good as closed Bosch nozzles. Many tests were carried out to determine the form of the jet. The best type proved to be a jet which is not too fine, such as a single hole nozzle or pintle nozzle. But pintle nozzles are unsuitable for wide angles, such as are required for injecting gasoline: fan nozzles evidently atomize the small volume of R-fuel too thoroughly, and have too little depth of penetration (Fig. 22). This depth of penetration is obviously important. Tests (Fig. 23) showed that with a pintle nozzle with an angle of 40° the power achieved was very low at 20 mm^3, and that only at 35 mm^3 was the same effect achieved as with a single hole nozzle of 0.3 mm. diameter. In general the best results were obtained with single hole nozzles with an aperture of 0.3 to 0.4 mm., or pintle nozzles with an angle of 0°. The volumes are 15 to 20 mm^3 in 3 litre cylinders: in smaller cylinders 10 to 15 mm^3 are sufficient. But the volume must in any case be somewhat greater than required by considerations of misfiring.

(Fig. 23 - Fuel curves with various R-fuel nozzles
With large aperture nozzles, e.g., pintle nozzles, larger volumes of R-fuel are required, in order to attain the necessary penetrating power.

The selection of definite types of nozzle was based entirely on observation of their long-term behaviour. The open nozzle sprays less exactly, so that drops of R-fuel cause coking in the bore of the nozzle. Therefore the closed nozzle, as used by Bosch for the injection of gasoline, is to be preferred. It has however the disadvantage of being rather large, of requiring a special spill line, and of being subject to fluctuations in the

the volume of spill. These faults make it desirable to use the new so-called dripless Bosch nozzles, which are only half the weight of ordinary gasoline nozzles.

The arrangement of the R-fuel nozzle, that is, the position of the R-fuel jet in the combustion chamber, presented no difficulties. Every arrangement gave satisfactory results. It is important to put the nozzle in at a well cooled point, although there is no fear that vapour bubbles will form, or that the nozzle will become overheated.

But if such a position is chosen the result will be that the jet of R-fuel will be directed against hot parts of the combustion chamber, especially in air cooled cylinders. According to tests made by BMW it is specially advantageous to direct the jet against the hot exhaust valve. In this way the power in the rich mixture region is so much improved that within useful limits up to : 0.6, the power may be said to be equal to that of the Otto process (Fig. 24).

(Fig. 24 - Improvement in take-off power due to spraying the R-fuel on to the exhaust valve
With a rich mixture a gain in power was observed with the better method of delivery of the R-fuel)

At the same time, of course, we also observed that power and consumption deteriorated with an excess of air, and that there was an undesired approximation to the Otto process. We think that apart from the exploitation of an accidental stratification of the charge, these phenomena are due to an improvement in the supply of the R-fuel, that is, to the effect of the large volume of R-fuel in reducing the compression temperature. With a weak mixture the difference in penetration between R-fuel against the exhaust valve and the unimpeded jet was disadvantageous.

As already mentioned, other aids can be applied to increase starting power. The pronounced effect obtained from spraying R-fuel on to the exhaust valve occurs at lower boost air and cylinder-wall temperatures than are possible when the machine is lightly loaded. We can then draw mixture loops with practically equal minimum consumptions, and the gain in charge weight which is brought about by lower boost air temperature appears as a gain in power (Fig. 25). By way of comparison, tests on a liquid cooled cylinder, with a nozzle which sprays straight ahead, are shown.

The influence of lower temperatures also has an important bearing on the starting of a cold engine. The "Ring" engine is started on R-fuel only, and the rate at which gasoline can be introduced depends on the heat condition of the engine. But in this way a cold "Ring" engine can only be started at temperatures above 20°. In main engine tests at DB and BMW, low temperature starts were achieved at temperatures below 0°: but these appear to be exceptions.

The conditions at starting are very unfavourable for an engine operating on the Diesel cycle. In addition to the low speed of the ordinary starter, the large clearance of the cold piston makes it difficult to achieve an adequate compression pressure. The piston clearances are particularly large in a cold engine with air-cooled cylinders.

(Fig. 25 - Ring process at low boost air temperatures
If the jet of R-fuel is directed against the exhaust valve, we can use low boost air temperatures, with unchanged consumption and higher power)

Also, the valve clearance of an air-cooled cylinder at low temperatures is very small, and consequently the intake valve closes very late. This is the reason why tests by Hirth have shown that the compression pressure is very low at the normal starting speed of 50 r.p.m. The charge air must be preheated, but this heating again cannot be exploited, as the cold engine breathes badly, and the heat is dissipated on its way through the blower to the cylinder. These familiar difficulties are particularly pronounced in the Ring process.

According to these experiments, the best thing would be to use an auxiliary sparking plug without screening, and BMW (Spandau) have been successful in this. The engine is then started at low temperatures as an Otto engine with the aids available for the purpose, such as light gasoline or acetylene. A special case of the ignition of R-fuel is in the use of a pre-combustion chamber. An advantage of the pre-combustion chamber is that, as in the Diesel engine, the temperature necessary for combustion need only obtain in the chamber, and combustion is thus largely independent of the temperatures in the combustion chamber. It is further to be expected that before ignition the R-fuel will hardly mix with the fuel in the combustion chamber, and that the flame jet issuing from the pre-combustion chamber will cause thorough ignition simultaneously at many points.

While some tests with pre-ignition chambers have been made by Daimler-Benz and ourselves, the tests made by Hirth are of special interest, since, acting on a proposal made by Prosper L'Orange, a pumpless injection system was evolved: Bentele will report on this in the near future.

Further investigation is required into pre-combustion chambers, as the concentration of the R-fuel in the pre-combustion chamber and the ignition of the mixture in the main combustion chamber by the flame jet lead one to expect that the knock behaviour will be affected.

I shall only deal briefly with the question of regulation, firstly, because everything of importance has been said, secondly, because Peter will deal with this on the basis of his experience with a BMW main engine.

The mixture regulator can be given more adjustment on the weak mixture side, without worrying about weak firing cylinders, as in the Otto engine.

The regulation of R-fuel related to volume and injection advance angle - volume control can be dispensed with, if an auxiliary sparking plug is provided for starting and for idling. The pump can then be set permanently at 15 to 20 mm.^{3} while otherwise there would have to be a second stage with 50 to 100 mm^3. Under the same simplified conditions the injection advance angle can remain constant. No special adjustment for speed is necessary, except insofar as this can be done by a special arrangement of the pump parts and non-return valve. With spraying of the R-fuel against the exhaust valve, or with a pre-combustion chamber, existing engine cooling installations are adequate. But it would be very desirable in the "Ring" process, as in the Otto process, to be able to regulate the coolant temperature.

To sum up, we may say that the real advantage of the "Ring" process is that it dispenses with the customary screenёd ignition installation, which is sensitive to altitude. The lack of sensitivity of the engine to lead deposits, and its ability to run on eak mixtures, are also important qualities. It is established that the coolant heat for the R-engine is considerably less than those for the spark-ignition engines, although the reasons for this are not clear. Finally, the Ring process appears to have better detonation performance than the Otto process. The "Ring" process thus combines a number of novel qualities, which make its further development desirable.

29.1.46