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 O. Holfelder

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The expression "safety fuel" has never yet been clearly defined. If I am to produce a comprehensive report on the efforts made to adopt safety fuels for use in engines, I must first attempt to define this term more exactly.

The "safety" of a fuel refers principally to its resistance to burning. A fire in the fuel supply of an aircraft can come about for several reasons, such as ignition on hot exhaust pipes, short circuit sparks, impact on crashing, or through shooting up by any of the various types of incendiary and explosive ammunition. The less the tendency of a fuel to burn in the face of these means of ignition, the higher its rating as a safety fuel. The higher boiling point of the gas oil of our Diesel engines, is already a good safeguard catching fire on crashing. With gasoline attempts were made, above all in America, to obtain a "Safety fuel" with equally good protection against fire on crashing by separating the low boiling components and by treatment with gelatine. A similar fuel was developed in Germany in the St la of I.G. Thickened

gasoline, formed by the addition of acid aluminium salts, was tried also. Of course the starting behaviour of these fuels, with their higher boiling points, is unsatisfactory, especially in winter, and protection against fire is limited. None of these fuels provides adequate safety against shooting up. As the initial ignition effect on shooting up is considerably heightened by the detonation of the bullets, which cause pronounced atomisation, and by the impact with the fuel in the container, a real safety fuel should have, in addition to a high boiling point and high flame point, as great a viscosity as possible. I.G.'s work on the synthesis of high grade spark ignition aero-engine fuels led to the development about 1930 of such a highly viscous fuel through polymerisation of Isobutylene C_4H_8 . This was given the code name TZ 900. Viscosity can be graded according to the degree of polymerisation, and can be expressed in °E at 100°C fuel temperature by appending an index number to the number 900: thus TZ 900/5.0 indicates a viscosity of 5°E at 100°C. This viscosity was fixed as the lowest limit from the point of view of safety in aircraft fuel tanks, as the result of extensive firing tests, about which my colleague W. Schmützler will make a separate report. From the point of view of delivery from the tank to the engine, however, it is probably that this viscosity represents the highest controllable limit. It should be stated for the sake of comparison that our lubricants have about 3,0°E at 100°C.

The more fuels satisfy safety requirements, which are now ever more exacting as weapons continue to develop, the harder it becomes to bring about their efficient consumption in the engine. Since the idea of using fuels with high boiling points in a carburettor could be dismissed, at the time of the re-building of the German Air Force the Technical Department, with special consideration to the possible use of safety fuel, at the instigation of H. Sechse, specially recommended fuel injection. But even with direct injection the problem of forming mixtures with TZ fuels is fraught with difficulty. While spark ignition of undecomposed TZ fuel has produced completely unsatisfactory results, the "Ring" process developed for I.G. by Penzig partially overcame, by ignition with R-fuel, the ignition troubles so familiar in fuels with high boiling points. Through the use of R-fuel, therefore, the work on safety fuels, in particular TZ fuels, comes within the scope of the present session on two-fuel operation of aircraft engines.

Despite several years of intensive work by the Technical Test Station of I.G. in Opau, my own institute in Gatow and at times the machinery-laboratory of TH Dresden, as well as industrial development by BMW, Junkers, and Daimler-Benz, only partial solutions have been found. These nevertheless serve to indicate more clearly the technical requirements for using TZ fuels in aero-engines. An attempt follows to draw a comprehensive picture from the numerous reports available, and from the latest results of our tests.

A. Preparation of TZ fuels

Table 1 shows the physical and chemical properties of TZ fuels.

While the calorific value and specific gravity are within the normal range, flame point and viscosity are considerably higher. One observes the dependence to a certain extent of flash point and fire point on viscosity. The theoretical products of thermal decomposition are set out below.

Fig. 1 shows the viscosity temperature curves of TZ fuels according to Ubbelohde compared with some other substances, such as lubricating oils, gas oil, Diesel safety fuel TZ 100, and coal tar oil.

In tests by the I.G. before the war up to 1937, on automotive engines, one arrangement was to deliver the fuel into large pre-heaters lined with catalysts, where it was decomposed to a great extent at about 550°C, and passed as gas via a gas regulator to the otherwise normal engine. While power and consumption were satisfactory, and the degree of control was adequate for motor-car engines, the decomposer proved to be disproportionately large, the tendency to coking was too great, and the life of the catalysts too short.

(Fig. 1 - Viscosity-Temperature curves)

Short tests by I.G. on TZ 900/1.7 in an indirect injection automotive Diesel engine showed that at a temperature of 1000°C the performance was almost as good as with gas oil, despite the high knock-rating of the undecomposed TZ fuel. This observation leads to the conclusion that with the partial decomposition of the higher polymers components which are easily ignitable and therefore liable to knock are formed. We shall have to refer to this phenomenon later on.

Bearing in mind the control requirements, it appeared that a large volume of decomposition equipment would be unsuitable for a spark-ignition aero engine. So our first tests were directed only towards the thermal preparation of TZ fuel with a view to improvement of the mechanism of mixture formation. Comprehensive tests led to the establishment of the conditions required of the fuel on the one hand, and of the nozzle and the whole injection system on the other, for achieving good mixture formation.

Table I - TZ 900 data

			Fuel type			
			TZ 900/2	TZ/ 900/5	Gas oil	B4
Specific weight at 20°C	Y	Kg/cm ³	086	086	084	075
Molecular weight	M	-	400	550	170	102
Calorific value	Hn	Kcal/Kg	10300	10300	10090	10450
Flame point	-	°C	175	190	73	under- 15
Fire point	-	°C	190	210	85	" - 15
Boiling Point (beginning of decomposition)	-	°C	300	320	130	42
Viscosity at 20°C	-	°E	85	275	13	1
" " 50°C	-	°E	14	55	1.0	-
" " 100°C	-	°E	2.0	5.0	-	-
Heat of decomposition	-	Kcal/Kg	300	300	-	-
Vapour pressure Reid	-	Kg/cm ²	0	0	0.1	0.5
Cetane number	CaZ	-	12	12	50	17
Octane number	OZ	-	95	95	20	87

Theoretical products of decomposition of 1 Kg TZ

Isobutylene C₄H₈ 430 1 Hn : 10850 Kcal/Kg Sp : -6°C
 or Di-Isobutylene C₈H₁₆ 215 1 Hn : 10470 Kcal/Kg Sp : 102°C
 or Tri-Isobutylene C₁₂H₂₄ 107 1 Hn : 10410 Kcal/Kg Sp : 180°C

(Fig. 2 - Atomizing properties of pre-heated TZ fuel)

Owing to its high viscosity, cold TZ fuel when atomised does not disperse sufficiently. Fig. 2 demonstrates this fact. Therefore pre-heating appeared indispensable until a viscosity equal to that of gas oil was reached. Even at higher temperatures, which to all appearances should have produced perfect mixing on direct injection, it was impossible either by spark or R-fuel ignition to run the engine satisfactorily. The reason is the fact that the boiling point is high, being above 250°C so that the atomised fuel, being hotter than the air in the cylinder, condenses on the walls, and in the form of soot, and some coke and lubricating oil dilution, is lost to the combustion process. Injection of the main fuel supply at the end of the compression stroke is not effective since there is then insufficient time for evaporation and formation of the mixture.

These tests thus led us of necessity to impart to the fuel, by pre-heating, temperature above the lower limit of boiling, that is, above 300°C . One cannot exactly speak of a boiling range for TZ 900, rather one should speak of a range of decomposition, as the substance decomposes directly at high temperatures in practice without a boiling curve. The need for high pre-heating of viscous substance in the injection system created a series of new problems, which are difficult to discuss separately because they are so inter-connected with each other.

I will name here only the principal ones:-

1. How to deliver viscous fuels to the injection pump and injection system.
2. Type and place of pre-heating, construction of the pre-heater.
3. Form of nozzle for spraying highly heated, decomposing fuels.
4. Composition of the decomposition products of the heated fuel.
5. Correlating place of injection and time spent in cylinder in connection with ignition of R-fuel.
6. Finding optimum pressure conditions, knock limit, and performance to determine the nature of the regulation of pre-heating and injection.

My colleagues Todt, Herbrich and Matthes have cleared up some of these problems by extensive tests, so that I can here give a summary of all the results obtained so far.

1. Delivering viscous fuels from tank to cylinder.

Despite its great viscosity, cold TZ fuel could be fed in and delivered at 20°C by normal Bosch injection pumps. This was due to its low vapour pressure. It was necessary to adjust the initial pressure in the suction chamber to at least 1.5 atü. Through its own friction the pump sets up a working temperature of about 70°C , and so reduces viscosity.

The high viscosity also raises the problem of delivering the fuel from the tank to the injection pump. Whereas the high vapour pressure of gasoline does not permit any suction pressure,

and we therefore use centrifugal-type tank pumps, TZ operation demands, especially at high altitudes and in winter, a displacement-type tank pump, e.g. a slow-running screw or screw-piston pump, even though its vapour pressure may in practice be neglected. In conjunction with this, we require pipe lines of three times the section required for gasoline, e.g. 40 mm. internal diameter instead of 25 mm. In this way speed and resistance to flow are reduced. As long as it is possible to run these pumps off the engine, it would be desirable that the pumps work inefficiently so as simultaneously to pre-heat the TZ fuel through turbulence energy. The firm of Bosch has developed such a device, coupled with the injection pump, in motor-vehicle tests on TZ fuel.

It should be mentioned here that as far as physical structure is concerned TZ fuel is an excellent lubricant, free from deposit formation. We may therefore hope in the future to have a combined lubricant and fuel. Then the volume required as a fuel at any time could be drawn from the lubricant circulation after the scavenger pump at a temperature of about 150°C. But this only accentuates the problem of filtering and de-aerating the oil in order to ensure the efficient working of the injection pump. As TZ fuel, when used as a fuel, decomposes on reaching a certain temperature, and so loses its lubricating properties, the limit of loading for TZ as a lubricant will presumably be a little below the value for present day lubricants. After extensive initial tests by I.G. on a BMW 132 oil-testing engine, it was decided to widen the basis of experience by tests on other engine types, and on main engines.

A certain amount of pre-heating before the pump naturally facilitates injection and prevents pump peak pressures from becoming too high. Eccentric cams are used as far as possible instead of steep cams for reducing peak pressures, especially if the injection pipes are long, as shown by the measurements in Fig. 3.

Whenever it is still at all possible at high pre-heating temperatures to control the injection by means of the pump plunger, it is necessary to use closed nozzles and to maintain a residual pressure in the line at least equal to the saturated vapour pressure for the highest occurring temperature. If the fuel disintegrates, it is only possible to maintain control for as long as there are components present at the residual pressure selected, which have higher boiling points, so that they can dissolve the products of decomposition. The figures for water up to the critical pressure were included, in addition to those for safety fuel. Fig. 4 shows the results of tests to determine the effect of residual pressure.

Vibrations in the long injection pipes required for the pre-heaters did not have a disturbing effect, as the viscosity of the fuel damped such vibrations.

(Fig. 3 - Delivery pressure pump of TZ 900/2.0 at 20°C measured at the pump end of an open pressure pipe 2500 mm. long)

(Fig. 4 - Determining the best pressure for TZ delivery)

2. Arrangement and form of the pre-heater.

The only possible heat source for pre-heating of the fuel in an aero engine is the exhaust gas energy, as, especially for complete decomposition it is a question of really large heat quantity, equal to about 5% of the calorific value of the fuel.

On account of the inadequate control of the system, the pre-heater cannot be fitted before the injection pump, unless pre-heating is carried to the point at which extensive decomposition occurs, and the decomposition products are then cooled down to room temperature again. In spite of an initial pressure of 4 atm, the pump fails at a fuel temperature of 200 °C through evaporation in the suction chamber.

The best place for the pre-heating is therefore between the injection pump and the nozzle. It then follows that the total volume has to be distributed between the individual cylinders, and that the pre-heater must be built into the exhaust pipe, with due consideration for back pressure and cabin heating. In this way the pipes carrying prepared fuel and therefore dangerous in regard to enemy action, can be reduced to a minimum and the quantities involved become insignificant.

The dimensions of the pre-heaters are connected with the problem of heat transfer. At first, there were insufficient data on the subject. Heat transfer depends on the pattern of the injection, with the fuel stationary in the pipe for longish periods between the short delivery strokes. It also depends on exhaust gas temperature, on speed of flow, on the physical properties of the fuel being heated, its viscosity in particular, and finally very much on the diameter of the pipe, which determines the speed of flow. Fig. 5 shows calculations from the results to determine the length of piping required: the heat output in each case was 1250 Kcal/hour, sufficient for a 2-litre cylinder operating at 8 at. m.e.p. and 2600 revs/minute. The basis was a TZ end temperature of 300°C and normal cylindrical injection pipes without indirect heating surfaces. We are aware that at these TZ temperatures small diameters are superior, mainly on account of the earlier change to turbulent flow.

The engine tests, which have yet to be discussed, pointed to the desirability of increasing the fuel temperature to 450°C and finally even decomposing it completely at 600°C. In order to exploit to the full the heat drop in short pre-heaters at an end temperature of 450°C, we successfully introduced indirect heating surfaces on the gas side. A similar attempt on the fuel side, which is even less favourable to heat transfer, raised the flow resistance excessively.

(Fig. 5 - Calculated temperatures in pre-heaters at constant heat input)

(Fig. 6 - Structure of various pre-heaters which were investigated).

Fig. 6 shows various forms of pre-heater used and developed by ourselves, with their working data. Those in the form of square-section screw threads are hard soldered after being copper plated. They were produced in co-operation with R. von Linde, Munich. While these pre-heaters are only intended for end temperatures of 450°C, those intended for decomposition must of course be larger by at least 80%, with a view to the introduction of a heat of decomposition of 300 Kcal/Kg. But a pre-heater of even this size could be accommodated in the exhaust pipes, or in the exhaust manifold in the case of exhaust gas turbine operation. I will now discuss the question of temperature regulation in connection with the engine tests.

The question of the coking tendency of tube pre-heaters has still to be cleared up. While at temperatures up to 475°C

none of the pre-heaters coked up during operation, despite many endurance runs, at 600°C and above they often became quite suddenly choked up by a thick layer of coke and were thus rendered unserviceable. As a hydraulically controlled nozzle, which has still to be discussed, makes it possible, in contrast to the normal closed nozzle working on liquids to go over to a unit which works on vapour or gas, then with the additional heat transfer coking can occur in the pre-heater. In the same way dirt in the pressure pipes can promote coking by catalytic action. The coking tendency became less pronounced after we had cleaned the pre-heaters before use by etching on the inside, followed by Bonderising. There is no doubt that coking is also influenced by the difference in temperature between tube walls and fuel, and by the time spent in the pre-heater. Whereas for partial decomposition at 450°C high wall temperatures, that is, large indirect heating surfaces, are an advantage in the construction of short pre-heaters, for complete decomposition the wall temperatures must be kept lower, in order to avoid coking. Thus large indirect heating surfaces on the exhaust gas side are not recommended.

3. Shape of the nozzle for injecting highly decomposing fuels.

To obtain data for the important problem of the nozzle shape required for injecting highly heated or even decomposing fuels, thorough investigations were made, involving spark photography of the jets. Fig. 7 shows photographs of the jets at different phases of the injection process, and above all with the substance at different temperatures. Although with the substance at the same viscosity as gas oil the atomisation was the same, after atomising TZ the particles are not further reduced in size, as the low vapour pressure and the absence of a temperature difference between the air and the fuel means that there is no more vaporisation. Pre-heating had therefore to be raised above the lower boiling limit, so as to bring about the dispersion of the jet from within. It was shown here that the form of the jet depended on the shape of the nozzle, and also very much on the fuel temperature. Fig. 8 shows this plainly; it also shows a dependence on the injection pressure. The conical nozzles also proved very efficient when working on TZ. If the fuel is heated to above the lower boiling limit, then as a consequence of the vaporising of a part of the liquid issuing from the nozzle, a thermal dispersion of the jet augments the mechanical dispersion. We studied pictures of the jets of homogeneous liquids such as water and propane heated above boiling point, in order to elucidate the thermal dispersion of the jet. As temperature rises, the form of the jet and its range become more independent of the shape of the nozzle, and are only dependent on the thermal conditions of the injected liquid.

(Fig. 7 - TZ atomised with medium pre-heating
high injection pressure, and wide cone angle)

The possibility remains, however, of influencing the form of the jet by varying the angle of the nozzle pintle and the swirl.

The high fuel temperatures naturally make great demands on the functioning of the spring-loaded, closed nozzle. The need for maintaining control calls for nozzle opening pressures of about 200 at. and for strong springs. In non-spill nozzles these lie in the path of the fuel, and so at temperatures above 400°C their spring constant decreases, and the nozzles inject erratically

owing to evaporation of the fuel. To remedy this condition, and to eliminate the long injection delay caused by the long heating pipes, we developed a hydraulic nozzle controlled by cold TZ fuel. According to a short report by Zinner, he used a specially controlled nozzle in his TZ tests for Junkers in 1939. Fig. 9 shows the slow system and method of construction of our hydraulic nozzle.

(Fig. 8 - Dependence of form of the jet on injection pressure, temperature, and shape of nozzle)

The length of pipe between the pump and the nozzle is no greater here than in normal engines. The passage of the substance through the nozzle is also shown in the diagram; special importance attaches to the closing of the control cross-sections U_1 and U_2 . The closing surface for U_1 must always be smaller than that for U_2 , as otherwise the nozzle needle will open; as soon as the first wave of delivery pressure reaches the valve, whereas this pressure wave only reached the outlet of the nozzle after passing through the pre-heater. The best sizes, having regard to tightness, are 0.4 mm. for U_1 and 0.5 mm. for U_2 .

If pre-heating is increased until partial decomposition occurs, and is not followed by cooling, care must be taken that leakage losses at U_1 between two injections do not cause the nozzle to re-open involuntarily through the increase heater pressure caused by the heat transfer. This is done in a practical manner by emptying the pipe between the pump and the nozzle completely after each injection. This is in contrast to what is required in medium pre-heating. The tightness of U_1 can be still further improved by means of a non-return valve R in the pipe leading to the pre-heater. Fig. 10 shows the time intervals for nozzle opening at different closing areas. The incidence of the pressure wave, illustrating the lag caused by the long pipe of the pre-heater, is also shown. The unloading of the part of the injection pipe carrying the cold fuel can be ensured by means of a specially constructed non-return valve, so that the characteristic curve of the pump remains constant; the right side of the picture shows how this valve is constructed. The firm of Bosch were kind enough to give us every assistance in constructing these valves according to our design, so that it has since become possible to produce hydraulically controlled nozzles which work safely at fuel temperatures up to 600°C.

If heating is carried to the point where TZ is completely decomposed, there is no longer any reason to deliver the substance, which has been reconverted into isobutylene, to the engine in this hot condition. If the decomposition products are cooled down again after the pre-heater, now working as a decomposer, this simplifies tremendously the operation of the hydraulic nozzle, and does away with the necessity of removing the pressure from the pipe. In this cooling process there is no need for a special cooler to act as a heat exchanger, as there is no need to cool down to the point where the decomposition products are completely liquefied. It is probably sufficient if the pipe between the pre-heater and the nozzle is provided with cooling fins, and if it is exposed to the stream of cooling air. This cooling also reduces the specific volume of the decomposition products to such a point that it is possible to operate with the same nozzle cross-sections as for liquid fuels, and with moderate injection pressures.

4. Composition of the decomposition products of the heated fuel.

Before reviewing the engine tests with safety fuels, let

us consider for a moment the composition of the decomposition products of the heated fuel. The TZ volume was heated in a special pre-heating test installation to a constant temperature in each case and delivered through the normal Bosch pump. After being ejected from the nozzle it was collected, condensed by cooling, and the gaseous components were liquefied by low-temperature cooling.

(Fig. 10 - Time intervals of the hydraulic nozzle, and the unloading valve)

(Fig. 11 - Thermal decomposition of TZ 900/5)

Fig. 11 shows the effect of temperature on the recovered decomposition products. After studying this, one realises that even at pre-heating temperatures of 400°C and 450°C the consumption figures recorded in the engine were unsatisfactory, as at this temperature only 20% of the TZ fuel is converted. Whereas decomposition, when it reaches the stage of liberating isobutylene, has then produced a gas which has a good knock-rating, tests on knock-rating engine of the I.G. showed that the low and high boiling components had a motor method octane number of 79. They are thus the cause of the poor knock-behaviour of TZ fuel prepared by partial decomposition. The easily boiling components consist of a multiplicity of higher olefines, also small volumes of di- and tri-isobutylene. The high boiling components consist of higher olefines and higher polymers of isobutylene. The residue has roughly the same properties as the original product TZ 900. The components with boiling points up to +20°C were gaseous. Their volumetric composition is shown in Fig. 12. Boiling curves of the proportions distilled at three different pre-heater end temperatures are shown in Fig. 13.

(Fig. 12 - Thermal decomposition of TZ 900/5)

(Fig. 13 - Boiling curves of TZ decomposition products)

The composition of the products of decomposition so obtained must depend, apart from the maximum temperature in the pre-heater, very much on the time spent there. Thus for example, if the other factors remain unchanged in the test installation and the volume per stroke is reduced to 20% of that delivered in Fig. 12, then at 585°C the gaseous fraction is already raised from 40% to 58% through the increased time spent by the fuel in the pre-heater. Now that the hydraulic nozzle has been produced one need have no hesitation about exploiting this phenomenon by increasing pre-heating to a certain extent.

We have not yet made an exact analysis of the decomposition products.

B. Engine operation on TZ fuel with R-fuel ignition.

The methods of delivery of viscous safety fuels have occupied the greater part of this report, representing as they do the most difficult problem in the adaption of highly viscous fuels. Naturally the physical and engine tests which our work involved were carried forward always in conjunction with each other. The large number⁴⁾ of more or less unsatisfactory engine tests made

4) See LKA Report No.6 on TZ engine tests, 1.7.1941.

in the beginning, when the TZ fuel was pre-heated up to the lower boiling limit, need not be discussed here. But we will report on some tests made at pre-heating temperatures of about 450°C, and on the latest work done, which involved the most extensive possible decomposition of TZ. The earlier test engines were 1-litre Fiat DVL single-cylinders, while we now use 2-litre Jumo 222 single-cylinders and 3-litre BMW 801 single-cylinders, both with a DVL crankcase.

1. Engine tests with a fuel temperature of 450°C after the pre-heater (hot injection)

As in the "Ring" process, so also in the TZ process, if working on R-fuel ignition, it is necessary to use a higher compression. After investigating the ranges between ϵ : 6.5 and 9.5, we selected a standard compression of 7.5 for this series of tests, although higher compression gave better consumption, because of the knocking tendency of heated TZ fuel. The starting behaviour is already a problem with R-fuel at chamber temperatures below 450°C. Indeed, R-fuel starting, like Diesel engine starting, requires a higher speed to ensure adequate compression temperature. Intensive development is required here. Starting with R-fuel is an advantage in TZ operation, as during the first two or three minutes of the run-in the TZ fuel in the pre-heater is heated to such a point that it can be used by the engine immediately.

If it should prove possible to work economically on completely decomposed TZ by means of sparking plugs, starting would require an auxiliary starting carburettor supplied with gasoline, or injection before the blower, thus making it possible to start by means of a special fuel even at low external temperatures. But it might be impossible to supply the TZ fuel pipe with gasoline because of the inserted pre-heaters, while the transfer from gasoline to TZ fuel could hardly be made without causing difficulties.

It was established that at pre-heating temperatures to 450°C the easily knocking liquid decomposition products which then appear in large proportions lower the knock limit to an undesirable degree.

On the other hand, it is probable that it is these components which, as already mentioned, make Diesel operation possible at all. Fig. 14 shows two power curves for a Jumo 222 single-cylinder engine at compression ratios of 7.5 and 8.0.

(Fig. 14 - Jumo 222E operating on TZ and R.
Influence of compression ratio)

At the selected boost pressure of 1.26 ats., the knocking limit was already reached at 10 at. b.m.e.p., and only 20°C suction air temperature. At ϵ : 7.5, using the same arrangement without boost, a b.m.e.p. of about 7.5 was obtained at a total heat consumption of 2750 Kcal/BHP.hr. With B4 and spark ignition, and the other conditions unchanged, the engine produced 9.5 at. b.m.e.p. with normal aspiration. Since at 450°C there is still practically 80% of undecomposed TZ fuel, fuel consumption is excessive, and points to heavy condensation losses.

It should be added here that in our single-cylinder tests on lubricating oil consumption and suitability of oils for TZ operation we nearly always observed as a result of condensed fuel an increased volume of oil, but never a reduction in the supply, although there were external sources of oil loss. There was no

evidence of dilution of lubricating oil from its viscosity, nor was the circulation of lubricating oil impaired, and the piston rings did not stick. This is certainly explained by the good lubricating properties of TZ fuel as already mentioned. The faulty combustion was evident from the smoky exhaust.

(Fig. 15 - Jumo 222 single-cylinder engine operating on TZ and R. Influence of compression ratio and R-fuel volume on power)

Fig. 15 reveals the pronounced dependence of the knock limit curves on intake air temperature, at a constant boost pressure of 1.26 ats. The fall in useful m.e.p. is particularly striking at ξ : 8.0. The m.e.p. values at 450°C fuel temperature are indeed very low, considering the minimum air temperatures of 80 to 90° which are usual today.

In our work on TZ 900 we also examined the question of whether combustion, and hence power and consumption, can be improved by increasing the proportion of R-fuel. The right side of figure 15 shows that an increase in the proportion by weight of R-fuel from 10 to 13% hardly raised the m.e.p. and only improved the economy by an insignificant amount. The main tests were therefore conducted throughout with about 10% weight of R-fuel. As with gasoline, TZ operation was still possible with 5% weight of R-fuel but only with a sharp fall in m.e.p.

Fig. 16 shows the dependence of temperature on consumption again for ξ : 7.5, and it is interesting to see here that the higher air temperatures considerably aid the mixing of the TZ fuel, which is at 450°C, with the air. Thus, consumption is almost constant along the knock limit curve, in contrast to the values for the mixture loops at 20°C.

(Fig. 16 - Jumo 222 single-cylinder with TZ-R-operation
Effect of air temperature on power and consumption)

To counteract knocking at medium pre-heater temperatures we have tried a great many expedients. Leading the heated TZ fuel was of no avail, as the anti-knocking effect of tetra-ethyl lead is almost completely lost owing to the high degree of pre-heating. Leading the R-fuel to the extent of 10%, equal to leading the entire fuel 1%, produced an anti-knocking effect, it is true, but, as might be expected, reduced the ignitability of R-fuel out of all proportion. Therefore, it is mainly through the treatment of the main fuel during supply that the knocking behaviour is influenced, as described in the work on the complete decomposition of TZ to isobutylene.

Also, further co-operation with chemists is urgently required to raise the knock rating of safety fuels.

2. Engine tests with TZ fuel in an advanced stage of decomposition, with accompanying cooling of the fuel.

After successfully bringing about extensive decomposition of TZ at about 600°C in the pre-heater without constant danger of coking, new engine tests were made with the same equipment on a BMW 801 single-cylinder. The experimental set-up shown diagrammatically in Fig. 17 differs from the preceding one only in that it has after the pre-heater an extension which is exposed to the cooling air stream and acts as a cooler. For the rest, we used the hydraulic nozzle as before, so that only two pumps were

necessary for the Ring process, and the additional parts consisted of the decomposer and cooler.

The picture also shows the figures for m.e.p. and related data. These results are within the normal range of pure gasoline injection engines. The tests are not yet completed as regards the question of the optimum size of the pre-heater for complete decomposition. Even though the knocking tendency diminished considerably when there was a greater degree of decomposition, it was still too high, and at $\xi : 7.5$ it still does not allow operation up to take-off power. Also, with relatively small pre-heaters of about 4 m. pipe length the engine is still too unstable, and not flexible enough.

(Fig. 17 - Consumption and temperatures in R-TZ operation - extensive decomposition of TZ)

Coking did not occur in the pre-heater even after several hours in operation, but now coking could be observed at times in the cooler, for which there is no proper explanation.

The tests show at any rate that given extensive decomposition of TZ a way can be found of operating an engine on viscous safety fuels.

3. Directions as to control.

The foregoing matter contained several references to the question of control. It should be mentioned here that two volume ranges and two injection timing ranges are required for the R-fuel injection pump. The start requires 60-80 mm³ per stroke with injection beginning at 35° crank angle before top dead centre, and, throughout the remainder of the operating range 14/20 mm³ per stroke, with injection beginning 100° crank angle before top dead centre. The TZ pump, on the other hand, would be laid out normally like any other injection pump, with volume according to the attainable power and the consumption, and with injection timed for 270° to 360° before top dead centre for partial decomposition. ~~For complete decomposition the injection timing would be~~ practically constant at 200° crank angle before top dead centre, which would probably be adequate in view of the improved fuel supply, less time being required for mixing.

The problem of finding a control principle for the pre-heater or decomposer is a matter of some difficulty. We have seen that good knocking properties are achieved only through extensive decomposition, but that on complete decomposition a slight increase in heat leads to coking of the decomposer. Therefore the permissible temperature variation in the exhaust decomposer is so small that it will be impossible to manage without some control arrangement. This raises the question whether the advantage conferred by R-fuel of operating on a greater excess of air can be exploited at part load.

Whether complete decomposition will make it possible to operate entirely with sparking plugs is a question which be settled by further engine tests, in conjunction with the question of ignition at high altitudes.

C. Coal tar middle oils in the spark ignition engine.

The use of highly viscous safety fuels involves considerable modification and in the present state of development prolonged tests will be necessary. At the request of the German

Air Ministry, preliminary tests were made to determine whether, though complete immunity from shooting up were dispensed with, the use of thin liquid fuels with high boiling points would permit progress in the immunisation from fire of spark ignition engines.

In these tests we used an unrefined coal tar middle oil, such as is formed in the liquid phase stage of hydrogenation. As attempts to use coal tar oil in a normal Diesel engine have failed so far, we expected to encounter great difficulties in the spark ignition engine. The method of supply for the fuel again used an exhaust gas heated pre-heater, which could operate at oil temperatures up to 500°C without coking.

Thanks to the excellent anti-knock properties of coal tar oil, we were able to achieve knock-free m.e.p.'s of 10 at. at 80°C boost air temperature and a boost pressure $p_1 = 860$ mm HG, using an unmodified BMW 801 operating with spark ignition, consumption being admittedly very bad at 260 g/Bhp.hr. Even if this figure is converted, for fuel of 10,000 calorific value, to 235 g/Bhp.hr., one observes a considerable condensation loss of unvaporised fuel, resulting in dilution of the lubricating oil and after about 6 hours running, excessive fouling of the piston rings, and ring sticking. Consumption was rather more satisfactory on R-fuel ignition, and the m.e.p.'s attained were somewhat better, but ring sticking still occurred after a short while. A centrally placed nozzle and a dished piston crown would counteract the fuel condensation, but are probably out of the question in aero-engines, because of the need they would create for developing new types, merely to incorporate a "half" safety measure.

These tentative tests should be continued with one of the coal tar middle oils, from which resin and coke-forming phenols have been separated. Still more attention should be given here to the question of fuel vaporisation in the cylinder, because of the dilution of the lubricating oil which is so bad a characteristic of tar oils. As the tests are by no means concluded yet, they have only been mentioned very briefly in this report.

Summary.

I have tried in this report to give a survey of the problems involved in the use of safety fuels which it is the task of development work to solve, and of the way in which we have gone about this task. We agree with the authority on fuel questions of the German Air Ministry, Herr Mücklich, that we have not succeeded to the extent of being able to supply the motor industry with tangible data for application to distinct engine types. Nevertheless, we believed the time had come to inform a large circle of experts of the results of this work, and throw them open to discussion, so as to create understanding of the engine modifications necessary if safety fuels are to be introduced. The work done shows that the accessories required would not make excessive demands on weight and space, certainly much less than is required for adequate armouring of aircraft fuel tanks.

The advantage offered by safety fuels to military and civil flying is so great as to warrant further intensive development work.

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