THE CORRELATION OF FUEL RESEARCH & SUPPLY PROBLEMS. (Extract)

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1. INTRODUCTION.

Fuel research and fuel supply are closely linked, especially in the realm of aviation, above all of military aviation.

These two branches, civil and military flying, have almost the same material requirements as regards fuel, but differ markedly in the accompanying supply requirements.

This paper is an attempt to give a picture of conditions in the supply of light fuels especially for high performance engines of current construction.

Fuels for Diesel and jet propulsion or safety fuels make the picture more confused, without, however, altering it fundamentally. The present situation is naturally taken into account, but the views given apply generally. For the most part they already enter into planning.

Home production and uniformity are, together with aeroplanes of the highest performance, the most important demands of military aviation. These requirements cannot all be fulfilled without contradiction, so that certain compromises become necessary. In Germany, through the Air Ministry and Industry (especially the I.G. Farbenindustrie) working together with the German Research Institute for Aviation much has been done already towards the fulfilment of both requirements.

The following paper deals in detail with this work.

Increase in both availability and uniformity affect the high performance fuels considerably more than fuels of the 87 Octane No. Class, so that developments will be discussed with special reference to the former class.

2. REQUISITES OF AN AVIATION FUEL.

The most important requisites of fuels have often been discussed, but are collected here for reference.

(a) Physical.

Freedom from vapour formation.
No oil dilution.
Good stability in the cold (anti-freeze properties)

(b) Chemical.

High performance.
Good stability in storage (oxidation stability)
Low deposit formation.
Freedom from corrosive properties.

(c) Physical and chemical.

Low fire-risk.

The fulfilment of these requisites can result from the fuel side, as well as from the utilisation side.

3. FULFILMENT OF REQUIREMENTS BY THE PRODUCTION SIDE.

(a) Physical Properties.

Vapour formation and oil dilution are consequences of bad boiling behaviour, according to whether too much low or high boiling components are present in the fuel. Correct cutting of the benzine fraction gives a fault free product; an admixture of suitable fuels will also improve boiling behaviour. Simple distillation or blending installations can be used for this. Dissolved gases can also cause trouble under certain circumstances. Remedies for this must come from the design side. Stability to cold in the case of pure hydrocarbons, is only a question of pure benzol content and water content. By diminishing the benzol content and drying the fuel the required stability to cold can be attained. Mixtures with alcohol and other water-soluble components must be made anti-freezing by the selection of suitable blending proportions, by dehydration and the use of stabilisers. Additions, such as are used with lubricating oils to lower their pour point, are useless here.

(b) Chemical Properties.

In the no-knock range the ultimate performance is materially controlled by the intake temperature which in turn depends on the heat of vapourisation. However, this value is so nearly the same for different hydrocarbons, that it does not play a great part. Alcohols have a higher heat of vapourisation, so that they give a performance 4-5% higher than that of hydrocarbons.

When the performance is limited by the commencement of knocking this tendency, which is determined by the chemical structure of the fuel, is its most important characteristic, all the more so as almost all engines aim at the highest performance. Table 1 reviews the properties of typical examples of high anti-knock fuels. It must be remarked in this connection, that at the present time although anti-knock values are still estimated in part by the Octane number, frequently other methods are used, e.g. the rich-mixture test introduced into Germany by the DVL. For this test the RLM provided the BMW 132 one-cylinder engine.

TABLE 1.

ANALYTICAL DATA OF HIGH ANTI-KNOCK FUELS.

Compound	S.G. 20°C	M.Pt. °C.	B.Pt. °C.	Mol. wt.	% H	Cal. Value kcals/kg. Upper	Cal. Value kcals/kg. Lower	Cal. Val. kcals/Lt. Lower	Blending Octane No.	Octane No. Motor Method.
Isopentane (2-Methyl-butane)	0.620	- 24	28	72.15	16.6	11546	10650	6603	90[1])	R 94[3])
Neohexane (2,2,-Dimethylbutane)	0.649	-100.1	50	86.17	16.3	11480	10600	6879	105[1])	R 101[3])
Triptan (2,2,3-Trimethylbutane)	0.686	- 25	81	100.20	16.0	11414	10550	7237	125[1])	101
Isooctane (2,2,4-Trimethylpentane)	0.692	-107.4	99.2	114.23	15.8	11353	10500	7266	100[1])	100
Isododecane (2,2,4,6-Pentamethyl-heptane)	0.737	-	193	170.33	15.3	11326	10500	7739	93[1])	-
Benzol	0.879	+ 6	80.4	78.05	7.7	10046	9630	8465	98[1])	115
Toluol	0.867	- 95	110.3	92.06	8.8	10225	9750	8453	99[1])	109
o-Xylol	0.881	- 27	144	106.08	9.5	10338	9825	8656	95[1])	102[4]) (o-, m-, p-Xylol)
m-Xylol	0.864	- 54	139	106.08	9.5	10263	9750	8424	100[1])	
p-Xylol	0.861	+ 15	138	106.08	9.5	10295	9780	8421	101[1])	
1,4 Diethylbenzene	0.865	- 35	183	134.1	10.5	10425	9858	8527	116[1])	116
1,4-Ethyl-isopropyl-benzene	0.858	- 20	197	148.2	10.8	10528	9945	8533	120[1])	-
Isopropylalcohol	0.785	- 89.5	82	60.06	13.3	7902	7182	5638	-	-
Isopropylether	0.724	- 87	67	102.11	13.8	9390	8664	6273	-	105
Isopropylketone	0.805	-	124	114.11	12.4	8405	9172[2])	7383	-	-
Isobutylketone	0.833	-	182	142.14	12.8	-	-	-	-	-

(1) 50% blend with Benzine of Octane No.42.
(2) At constant pressure.
(3) R = Research Method
(4) Xylol generally (Xylol allgemein.

Possible means of production of high anti-knock rating fuels of the 100 Octane No. class are shown in diagram 1.

The raw materials are gas (natural, cracked, or synthetic), crude-oil (or tar) and coal (lignite and anthracite).

Starting from these, natural products of the desired properties can be separated by simple condensation and fractionation or new material built up by molecular transformations. The great difference between these two procedures is that simple methods yield only products whose quantity and quality depend on the nature of the crude. When the natural qualities are insufficient, as in crudes from Iraq, Iran, Grosny and Pennsylvania such crude oils are useless for aviation without plant for the necessary reforming. Simple separation methods are insufficient to satisfy the great demand for aviation fuels. In addition the quality of fuels so obtained is usually far below that of reformed or synthetic fuels.

By separation (isopentane), isomerisation, polymerisation and condensation gas can be turned into suitable isoparaffins. Crude oil can yield usable products by simple distillation, catalytic cracking (isoparaffins) or thermal cracking (aromatics); moreover, motor spirit is formed. Lignite and anthracite can yield benzine either by the Fischer-Tropsch or by the I.G. methods. While the former gives benzine with pronounced knocking tendencies, hydrogenation of lignite or steam coal according to the second procedure gives aviation spirit straight away.

To produce fuels of high anti-knock rating all unsatisfactory properties must be modified by catalytic aromatisation, dehydrogenation and isomerisation and in certain cases, also extraction. Details of these processes cannot be given here, but it may be indicated that isoparaffins are prepared mainly from gases and aromatics from benzines. All these processes render necessary extensive and specialised plant. Among fuels from other sources, suitable for use in blending may be included motor spirit.

Benzine distilled from lignite and shale is small in quantity and because of high sulphur content and a high degree of unsaturation needs extensive treatment. Alcohol may be derived from potatoes etc., or from coal, but is of little importance. Isopropyl either is prepared from gas (natural or cracked) or indirectly from coal, but also plays no part. All aviation fuels contain tetraethyl lead in quantities varying between 0.07 and 0.12% by volume and in certain circumstances up to 0.18% by volume. Isoparaffins and aromatics at present are the extremes of sensitivity to rich mixture and temperature conditions in high performance fuels. Diagram 2 shows that the aromatic C_3 (German) is superior to the isoparaffinic C_8 (foreign) in the rich mixture range, but on weakening falls strongly in performance. This fuel (C3) contains only about 50% of aromatics. With pure aromatics, the curve would become steeper but at * λ = 1.05 would more nearly approach or even surpass that of pure iso-octane, the typical isoparaffin representative. The limiting performance is controlled nowadays by the engine, not by the fuel. * λ = excess air fraction.

The knock rating of a lower grade fuel cannot be improved without blending except by a complete reforming such as already discussed. Either suitable fractions can be taken (diagram 3) or an appropriate procedure used to turn the fuel into one of an isoparaffinic or aromatic nature.

Again, in addition to this, increase in lead content and blending with a higher knock-rating fuel can be used to reach the desired quality. There are limits to both these possibilities. Examples of the action of lead and of blending with higher performance fuels are given in diagrams 4 - 6.

Consumption is, when knock ratings are equal, a function of the calorific value which in turn depends on chemical structure (hydrogen content). The only way to increase the kg. calorific value is a change over to the use of gas (methane, hydrogen) but this entails a grave fire-risk. Since the injection pumps work by volume and not by weight and there is little available room in a 'plane, the cal. value/litre also plays an important part. Aromatics have the most favourable litre cal. value, e.g. toluol 8450 WE/l against iso-octane 7260 WE/l.

As regards stability in storage (stability towards oxidation) pure fuels behave quite differently according to their content of small quantities of substances favouring oxidation or inhibiting it. Of the pure hydrocarbons only olefins, especially di-olefins are unstable. Correspondingly, the saturated and carefully refined aviation spirits of natural or synthetic origin, are stable with or without lead. Aromatic fuels, like motor benzol and synthetic benzine show, up to the present, greater tendencies towards storage changes. Future developments will probably bring improvements here. Two typical examples of the 'ageing' of a paraffinic and an aromatic benzine are given in table 2. It is seen that the aromatic, leaded benzine shows a high increase in gum content and lead decomposition although stable when unleaded, while the paraffinic benzine remains stable even when leaded.

TABLE 2.

OXIDATION STABILITY OF AROMATIC & PARAFFINIC BENZINE (Leaded & Unleaded)

FUEL.	T.E. Lead Content Vol.%	Ageing time hr.	Gum Content DVL	Gum Content Conv.	Total decomposed T.E. Lead %	Induction period mins.
Synthetic Aromatic	0	-	-	0	-	-
		4	-	1	-	>240
		-	-	1	-	-
		4	7	30	35.0	225
Paraffinic (Natural Benzine)	0	-	-	2	-	-
		4	-	2	-	>240
	0.1205	-	-	2	-	-
		4	2	2	3.7	>240

The process is very complicated. Atmospheric oxygen probably attacks the fuel first and then acts on the lead. The oxidised lead speeds up the fuel oxidation. As experiments by the DVL have shown, suitable additives bind the lead compounds into complexes and greatly reduce the general ageing. Examples of such are acids, amines, phenols and other complex-forming substances. They act differently with different fuels. Even with the same fuel their action varies according as the fuel is fresh or already aged. The quantities necessary are very small (0.01 to 0.001%).

The blending of incompatible additives can produce a fuel worse than every individual component. Table 3 shows results obtained by the use of suitable inhibitors (DVL experiments). A more exact knowledge of the course of the reaction would be very valuable.

TABLE 3.

INCREASED OXIDATION STABILITY OF LEADED FUELS USING INHIBITORS.

Fuel	Content of T.E. Lead Vol. %.	Inhibitor	After 4 hrs. Induction in Bomb @ 100°C. Gum Content mg./100. DVL Method	Conv. Method	Total Decomp. LTE %.
1	0.1190	-	19.2	47.4	52.9
1	0.1190	0.0040 Vol.% Inhibitor 1.	2.3	8.3	12.4
1	0.1170	0.0055 Vol.% Inhibitor 2.	2.7	7.2	11.7
2	0.1180	-	-	-	82.3
2	0.1180	0.001 Wt. % Inhibitor 3	-	-	2.10
2	0.1180	0.002 Vol. % Inhibitor 4	-	-	2.55

Deposit formation acts first to cause piston ring sticking and contamination of the lubricating oil with carbon and asphaltic compounds. Disturbance of the oil circulation and further ring sticking may result. More thorough refining can decrease deposit formation by the removal of certain harmful constituents. Other methods are not so far available in production. Aromatics show a greater tendency to deposit formation than isoparaffins.

Corrosion of the vabes is caused by too high a working temperature and excess lead content.

The use of high knock rating fuels with less lead as well as limitation of aromatic contents are the remedies. More data on the demands made by fuels on the heat-resistivity of the engine materials used are required.

(c) Physical Chemical Properties.

Fire-risk is diminished by increasing the flash point (higher boiling point) and the use of compounds with little tendency to self-ignition as well as narrow limits of inflammability. In current practice the difference between individual fuels is small, however the self-ignition temperature of the aromatics is well above that of other benzines. Much cannot be expected here from the production side.

4. ATTAINMENT OF THE REQUISITE CONDITIONS IN PRACTICE.

(a) Physical Behaviour.

Vapour locking can generally be avoided by lowering the temperature or raising the pressure.

Lift pump suction pressure, carburettor jet pressure and tank pressure must be regulated so as not to exceed vapour pressure (sic.). The same holds for the temperature; in certain circumstances the fuel must be pre-cooled. Kinks in tubing, leading to air-pockets, must be avoided. Air separators should be used.

Lub.Oil Contamination must be prevented by using the weakest mixture possible, by avoiding or limiting starting from the cold and keeping the oil temperature as high as possible. Better 'sealing' of the piston rings can help, when the piston lubrication is not impaired thereby.

Insufficient stability to cold results when remaining above the critical temperature; a correct filter-conséruction (prevention of stoppage by water and snow) is also helpful.

(b) Chemical Properties.

With a low knock-rating fuel the performance of a better fuel can only be reached in rare cases. Enriching the mixture or retarding ignition are the corresponding measures to be taken. With engines having an adjustable injection pump this is difficult enough. It is practically impossible where it is set for a certain fuel. In this case a dual fuel system is a possibility (aniline alcohol, 80% alchol, 0.12% lead). It renders practical the use of unsuitable fuels, but can be dispensed with when other fuels are available

Much can be attained by the use of other methods, e.g. the divided injection of F.A.F. Schmidt or the R - process of I.G. (Penzig). Whether differences in fuel are unimportant here is not yet certain.

Consumption is substantially a function of the cal. value, but can be reduced by considerate use. With a better knock-rating, for example the compression can be increased or the mixture weakened.

Oxidation Stability is increased by low temperature, exclusion of air and absence of oxidation catalysts. Cool storage, good air and water exclusion, suitable container materials and the avoidance of frequent transference favour stability.

Deposit Formation by fuels is generally reduced by using a weak mixture. Whether running at a higher or lower temperature gives a reduction depends very much on the individual case in question.

Valve corrosion can be countered above all by keeping the cylinder temperature low and also by either running as little as possible at full load, or using a rich mixture. From the constructional viewpoint, good valve cooling, especially good heat transference along the valve-stem is necessary.

(c) Physical Chemical Properties.

Fire risk is avoided by excluding the formation of exposive mixtures (Watch pressure and temperature in the tank!) and preventing leakage losses. Other precautions are, use of inert gases for de-aerating, exclusion of ignition danger from electric leads and exhaust-pipe, the use of protected and detachable tanks as well as quick acting safety valves.

5. NECESSITIES OF SUPPLY & THEIR INFLUENCE ON FLYING & FUEL RESEARCH.

(a) Present Position (supply needs of aviation).

As already mentioned the demands of military and civil aviation are materially similar, but there are additional factors showing a great divergence. This is best seen when the two are put side by side:

TABLE 4.

SUPPLY NEEDS OF CIVIL & MILITARY AVIATION.

Requirement	Civil Aviation	Military Aviation
Availability		
(a) Quantity	comparatively small	large
(b) Source	unimportant	home
Uniformity	individual, according to airline, air-port, engines.	over the whole range.
Price	as low as possible.	unimportant (as long as availability not affected).
Performance	most economical.	Best performance
Use.	In different climates, with a general attempt to find fuels suitable for any climate.	Universally suitable fuels. Special fuels only in case of necessity.

Civil aviation is more elastic in its demands and adapts itself more to given circumstances. On the contrary military aviation makes imperative demands with which supply must fall in. Its demands are not always reconcilable . Availability, uniformity and usefulness under all working conditions as well as uniformity and the best performance with all types of aeroplane can only be united in special circumstances, for the emphasis on performance means that for the whole range of military aviation fuels with the highest cal. value and knock rating must be delivered, i.e. isoparaffinic fuels.

(b) Availability of Fuels.

Import from abroad may be possible as well as the use of captured fuel. This is not risky with 87 Octane No. fuels, but high performance fuels are another matter.

With a sufficient number of production centres, the fuel most easily prepared may well be used, even when very different from that of other countries.

De-centralisation of plants is advantageous as regards transport. Imported fuels should be usable with as little alteration as possible. If very different from home-made fuels this may be difficult or impossible. The same holds for captured fuels.

For the consideration of these questions, it is important to know the permissible straying of quality in imported or captured fuels in relation to engine performance, or better, what magnitude it can reach in extreme cases. Then in practice, full engine performance must be aimed at with fuels whose properties stray within this range.

These considerations are naturally superflous when home production can be relied upon completely.

(c) Uniformity of Fuels.

France and England have each one fuel of the Octane No. 87 Class (85 & 87.O.No. respectively). England has also one for 100 O.No. fuel. In the U.S.A. there were 6 somewhat different fuels in the Army & Navy Air forces. The position in Russia is especially interesting. The 1940 supply specifications call for 6 different octane numbers and boiling ranges, varying according to origin. Thus a country well supplied by nature remains bound to the natural qualities of the crude oil, perhaps because of lack of industrial preparedness.

In Germany there are only the 87 and 100 classes; uniformity has been very largely realised. The knock boundary curve of various high performance fuels is shown in diagram 2, as measured by the DVL in the BMW 132 single cylinder engine. As development and supply rest on this test its dependability and general applicability must frequently be checked. This test is not simple, but exact control gives very usable values, as diagram 7 shows. In considering the straying of results, one must remember that multi-cylinder engines even of the same type would show still more straying if carefully supervised single cylinder engines do not give identical results. Working data on full-size engines is urgently needed. For if on one hand the variation in fuels is greatly cut down perhaps even a standard fuel aimed at, it must be known on the other hand how engines of the same construction vary. But the test should be applied to all aviation engines, not to just one.

That this really obvious need has not long since been attended to, is explained by the difficulties of investigation using a full size engine. With single cylinder engines of differing makes the DVl obtained rather unsatisfactory results with four typical 87 Oct. No. fuels (diagrams 8a & b). The order of evaluation given by the different engines is very different. The fuels were of very different composition; what the differences are considered from the angle of differences occurring in practice, and how 100 Octane No. fuels behave is at present being investigated by the D.V.L.

A real standard fuel must be usable in all climatic conditions; the test conditions must take this into consideration also. When investigation shows a deviation in the engine behaviour, then it must be modified if it is to use the standard fuel. Otherwise, a suitable fuel must be supplied.

6. RESEARCH AND ECONOMICS.

Civil aviation of the future will buy the cheapest suitable fuel available unless a State Control is imposed. The cheapest energy is that stored in coal and crude oil, supplies of which are so great that so far little thought has been given to other sources. All the same, estimates have been made according to which increased alcohol production from vegetable products may be reckoned to bring the price down to 8-9 Pf./Kg. so that alcohol from this source could play some part as a motor-fuel. For use as an aviation fuel the extensive chemical treatment necessary would make it dearer than mineral oil products, perhaps even dearer than synthetic fuels from coal. Fuels from coal are dearer than those from mineral oil because of costlier processing. However, this difference in cost must be reduced as far as possible. When the costs of production of aromatics and iso-paraffins from coal are compared, the advantage lies with the aromatics. More exact data for the production costs of the various processes will probably only be available in the future. With the spreading of air transport, uniformity plays a more important role even in civil aviation.

7. CONCLUSIONS.

(a) Necessity of Planning Control.

Work in the field of Otto fuels has shown that fuel production and use are closely inter related, so that alterations in one necessitate corresponding alterations in the other. Since both fields are very large and thus have a great inner inertia, every change round is difficult. To avoid this, changes must be planned far ahead and this applies generally, not only to Otto-Fuels. The following points are important:-

i. Sensitivity of the manufacturing process and the plant to changes in fuel properties.

ii. Determination of the sources of supply which are to be considered.

iii. Decision as to whether a standard fuel, several standard fuels or fuels of different properties are to be used.

(b) Fuel Production.

Production depends especially on the engine performance of the fuel. Maintenance of the minimum permissible quality is the most important factor at the moment. In the future a price reduction of iso-paraffinic fuels may be possible, also the development of suitable compounds for a dual fuel system. The production of oxidation stable aromatics should be further developed. Inhibitors should be added immediately after manufacture. Lead content should be decreased by improvement in the knock-rating of fuels.

(c) USE.

Engines should preferably be suitable for given fuels (standard fuels) but the possibility of using varying fuels should be examined. Variation in full scale engines of the same type should be investigated. The behaviour of fuels under extremes of climate should also be examined. The possibility of a duel fuel system should be gone into in certain circumstances. Engines running on pure aromatics should be developed. Insensitive fuels should be aimed at.

(d) RESEARCH.

The chemistry of oxidation-stability should be investigated so that a scientific basis for the preparation of stable fuels can be established. Knocking behaviour should be the object of further research in the laboratory (delayed ignition measurements) so that light may be thrown on the physical characteristics of the engine from constructional as well as operational points of view. Heat transference and its dependence on valve overlap (Ventilüberschneidung), super-charging, inlet air temperature, volumetric efficiency and significance of residual gases should be examined. Agreement of laboratory and engine characteristics of fuels is desirable. In this connection the general validity of the rich mixture test must be further examined and an attempt made to improve it. The permissible variation in fuels must be firmly laid down. Fuel deposits in the engine must be further investigated in order to reduce them in quantity. The action of different fuels on the materials of construction is also a matter for research.