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## THE THERMAL STABILITY OF AVIATION FUEL

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### ABSTRACT

The propensity of aviation turbine fuels to produce deposits in the oil-cooler and filter sections of aircraft fuel systems has been examined using a rig that simulates the fuel system of an aircraft and which employs realistic flow rates. All the fuels examined were found to be thermally stable up to temperatures in excess of those currently attained in engine oil coolers. Comparison with results obtained with the JFTOT indicates that this is not suited for use as a research tool.

### INTRODUCTION

The high temperatures encountered by aviation turbine fuel in an aircraft's fuel system stimulate oxidation reactions that lead to the formation of insoluble material. This material can deleteriously affect the performance of the system in a number of different ways. It may:

- (i) lacquer heat exchangers and reduce their efficiency.
- (ii) lacquer fuel control valves and cause them to stick.
- (iii) block fine filters.
- (iv) form a thick, carbonaceous layer on the inside of the injector feed arms; pieces of this deposit may subsequently flake off and block the injectors.

To date, problems of this sort have been experienced to only a limited extent; the difficulties that have occurred have usually been due to poor hardware design (1) or the use of fuel contaminated with instability-promoting materials such as copper (2). Problems due to fuel contamination have largely been obviated by the application of quality control procedures at refineries.

In order to improve their efficiency, however, future gas turbines will operate at higher pressures and temperatures than do the engines currently in service; as a result turbine fuels will be subjected to greater thermal stresses. This could lead to operational difficulties as has been demonstrated by

studies aimed at defining fuel requirements for commercial supersonic aircraft (3,4).

The main purpose of this paper is to describe the results of tests that are being conducted by Shell Research Limited to study the lacquering of heat exchangers and the blocking of fine filters. This work forms a part of a broader program of R&D whose main objectives are to determine under what conditions turbine fuels undergo unacceptable thermal degradation and to identify means of improving fuel performance. The tests are being conducted on a relatively large-scale rig that enables fuels to be studied under realistic conditions because, as demonstrated later in the paper, small-scale rigs may not provide an accurate prediction of how fuels will behave in practice.

The results from preliminary studies with an approved metal-deactivating additive are also described. The use of metal deactivators, or of other additives, to arrest the fuel oxidation process could afford a means of improving fuel performance and, therefore, of avoiding future operational difficulties.

### DESCRIPTION OF THE TEST RIG AND EXPERIMENTAL PROCEDURE

Only a short description of the test rig will be given here; reference 5 provides a more detailed account. Originally, the rig was built to investigate how turbine fuels would perform in the fuel system of the Concorde; it is now used, however, in a broader role to study fuel performance in advanced aircraft in general. As Figure 1 shows, the rig incorporates three fuel-heating stages comprising a 20 litre glass vessel, a preheater and the test heat exchanger. These simulate respectively: the wing tank of a supersonic aircraft, in which the fuel is subjected to aerodynamic heating, or the fuel tank of a military aircraft that has some form of recirculating fuel system; the hydraulic oil, cabin air cooler etc.; and, finally, the engine oil cooler. In practice fuel attains a higher temperature in the oil cooler which, therefore, is more likely to be affected by any thermal degradation that might occur. Thus, in the tests precise measurements to assess the effects of fuel degradation are limited to the test heat exchanger.

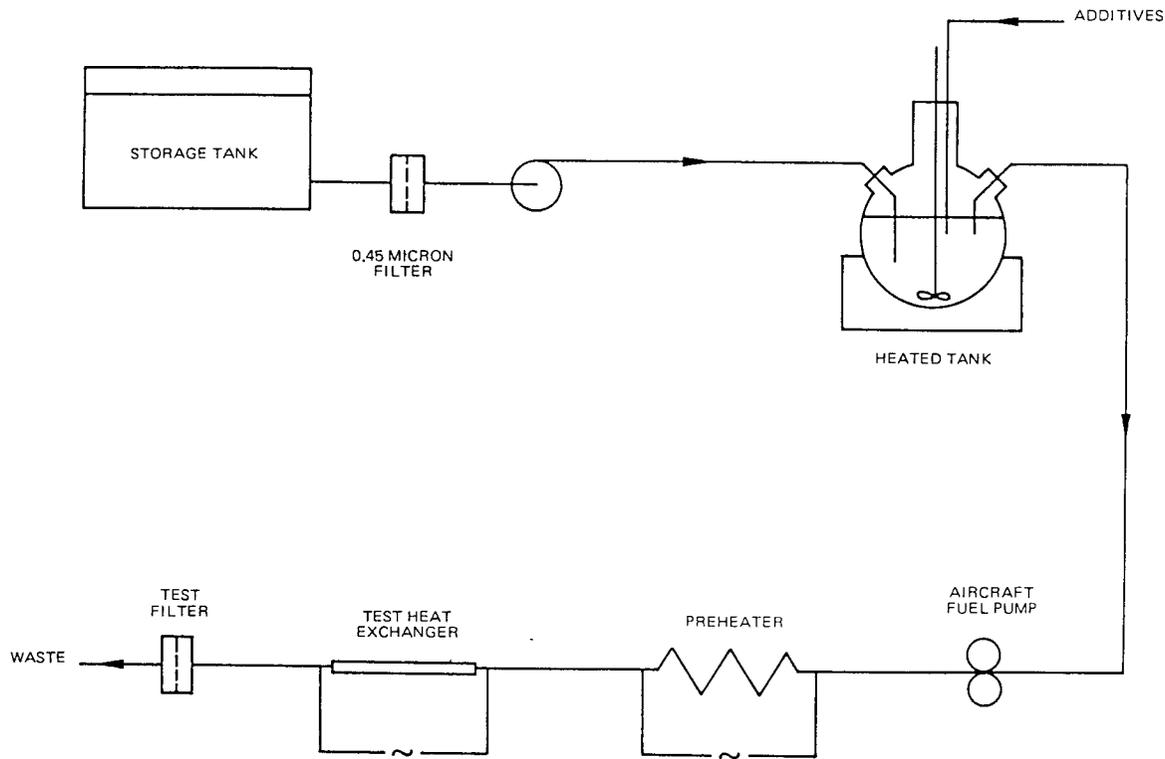


FIG. 1 — Simplified drawing of Single-Tube-Heat-Transfer-Rig

Heat exchangers comprising bundles of dimpled tubes are widely used as aircraft oil coolers. With this arrangement hot oil passing over the tubes is cooled by fuel flowing through them. To achieve test conditions similar to those existing in practice a single dimpled tube is utilised as the test heat exchanger (hence the name given to the rig: the Single-Tube-Heat-Transfer-Rig [STHTR]). The tube is made from stainless steel, has a length of 241 mm, an internal diameter of 2.78 mm and a wall thickness of 0.18 mm; fuel is pumped through it at a realistic rate. As the object of the work is to study deposition on the fuel side of the heat exchanger, heat is applied to the tube by passing an electric current through its walls rather than by immersing it in hot oil; this enables the rig to be operated in a more controlled manner.

A longer length of plain tubing is utilised as the preheater; this is also heated electrically. The test conditions are such that the maximum surface temperature in the preheater is lower than in the test heat exchanger.

Tests are usually conducted at a fuel flow rate of 3.78 g/s; at this rate the fuel resides in the heated vessel for about an hour. After leaving the vessel the fuel is pressurised to 250 psi by means of an aircraft fuel pump which prevents it from boiling when it passes through the heat exchangers. Finally, the hot fuel flows through a woven stainless steel filter, similar in construction to filters used in practice, before

being cooled and collected in a waste tank. The filter is automatically bypassed if the pressure drop across it reaches 12.5 psi during the course of a test.

To define the performance limits of a fuel the rig is operated at several different test conditions. These are listed in Table 1. Condition 2 was originally intended to simulate the operating conditions on the Concorde although more recent estimates of Concorde fuel system temperatures indicate that the temperature of the fuel at the outlet of the oil coolers will not exceed 140-150°C (3). At each condition the current supplied to the test heat exchanger is adjusted to maintain a constant fuel outlet temperature; thus, where lacquering of the tube is occurring the current supplied has to be gradually increased. The degree of lacquering is assessed via the rate of change of the tube's heat transfer coefficient,  $h$ , which is calculated periodically by means of the following formula:

$$h = \frac{MC_p (T_2 - T_1)}{A \Delta T_m}$$

$M$  = fuel mass flow rate  
 $C_p$  = specific heat of fuel  
 $A$  = area of tube's surface

$\Delta T_m$  is the mean temperature difference across the tube and is given by:

$$\Delta T_m = \frac{(T_3 - T_1) + (T_4 - T_2)}{2}$$

where  $T_1$  = fuel inlet temperature  
 $T_2$  = fuel outlet temperature

$T_3$  = inlet end tube wall temperature

$T_4$  = outlet end tube wall temperature

The rig is usually run for 24 hours at each test condition which enables changes in the tube's heat transfer coefficient of about -0.05% per hour to be resolved.

Table 1

STHTR test conditions

Fuel flow rate: 3.78 g/s

Condition no.	Fuel temp. in heated tank, °C	Fuel temp. at preheater outlet, °C	Fuel temp. at test heat exchanger outlet, °C	Typical Reynolds No. of flow in test heat exchanger
1	70	130	150.0	4560
2	85	149	171.5	5230
3	95	165	190.0	5750
4	105	180	207.5	6250
5	115	195	225.0	7210

RESULTS AND DISCUSSION

During the last 5 years studies have been conducted on 16 different samples of turbine fuel produced by refineries in the UK utilising a range of crude oil feedstocks and treatment processes. Figure 2 summarises the results obtained from tests on one of these fuels; the results obtained with the other fuels had the same general features. The figure shows how the rate of change of the test heat exchanger's heat transfer coefficient, as determined from a 24 hour test, varied with the temperature of the fuel at its outlet. The apparent changes in heat transfer coefficient at the two lower conditions fall within the limits imposed by experimental error and, therefore, are not significant. A deterioration is resolvable, however, at the third test condition; thus, the operational limit or breakpoint of the fuel in question was between 190 and 207.5°C. Once the temperature of the fuel was raised above its breakpoint the heat transfer coefficient deteriorated rapidly; similar observations have been reported by other investigators of this phenomenon (6,7).

The results from the tests conducted on the other samples of fuel are summarised in Figure 3; this shows the number of samples having breakpoints in a particular range. The highest temperature currently attained by turbine fuels in the engine oil coolers of both civil and military aircraft is about 150°C. As

can be seen from Figure 3, the breakpoints of the fuels examined all exceeded this value thus indicating that, at the present time, fuels are able to withstand the thermal stresses to which they are exposed in engine oil coolers; operational experience is consistent with this deduction.

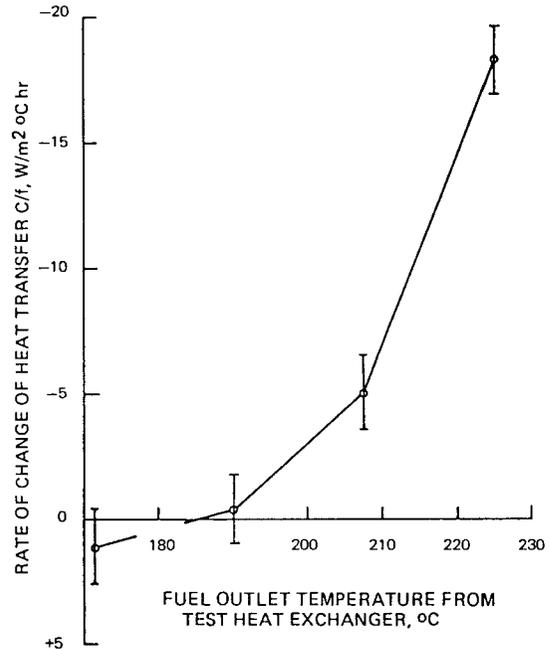


FIG. 2 - Influence of fuel temperature on deposition rate

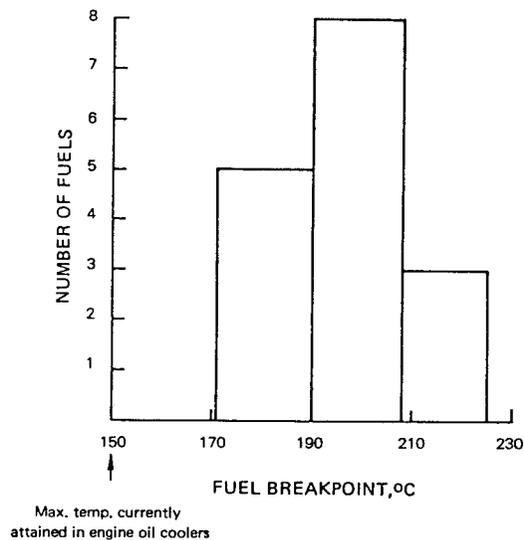


FIG. 3 - Summary of results from tests in STHTR

Looking to the future, however, it will be apparent that some of the fuels examined started to deposit lacquers under conditions only marginally more severe than those currently encountered; the use of such fuels in more advanced engines could lead to operational difficulties. As pointed out earlier, one way of avoiding difficulties could be to improve fuel performance by means of stability-improving additives. Aviation fuel specifications permit the use of a metal-deactivating additive for this purpose (8). This additive functions by chelating metals, such as copper, that catalyse fuel oxidation reactions (9,10). These metals may be carried over from the parent crude oil in the form of salts, picked up by the fuel during processing or handling, or leached out of aircraft fuel system components (11).

The ability of metal deactivator to reduce a fuel's propensity to lacquer heat exchangers was studied using three different fuels (Table 2 lists relevant inspection data). Each was doped with 0.3 ppm of active additive material which, according to the manufacturers, is sufficient to chelate 50 ppb of copper; the fuels examined all contained less than 20 ppb of this metal. The results from the tests are compared in Figure 4 with those obtained with the base fuels. It will be apparent that the additive had a variable effect: in the copper sweetened fuel it produced an immediate and significant improvement; in Mercox fuel A it had a beneficial effect at a higher temperature; but in Mercox fuel B it did not produce any measurable improvement.

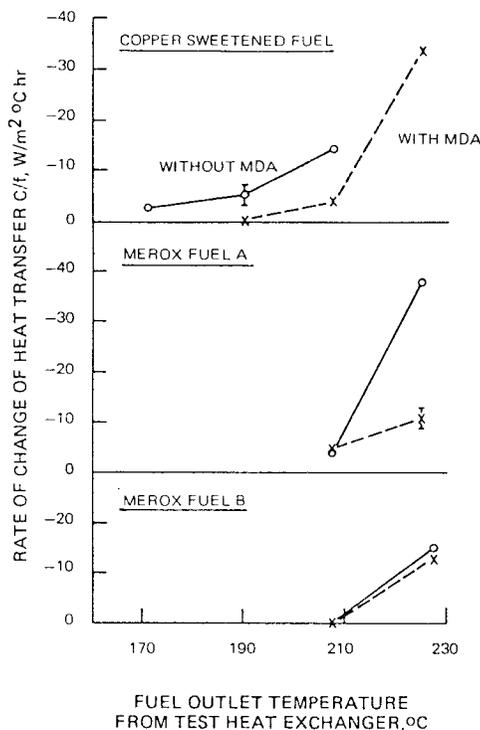


FIG. 4 - Influence of MDA on fuel performance in STHTR

Other investigations have also shown metal deactivator to have a variable effect (4). The cause of this is not known: it could be that in some fuels the metals present do not exert any significant catalytic influence; alternatively, some fuels might have components that prevent the metal deactivator from chelating the metals present. Further work needs to be performed to determine the cause of the observed variations.

Table 2

Inspection properties of fuels used for metal deactivator tests

		Copper sweetened fuel	Mercox Fuel A	Mercox Fuel B
Total acidity,	mg KOH	0.0015	0.003	<0.001
Aromatics,	%v	19.5	18.5	17.0
Olefins,	%v	0.8	<0.5	<0.5
Naphthalenes,	%v	2.35	2.35	2.38
Total sulphur,	%m	0.11	0.085	0.09
Mercaptan sulphur,	%m	0.0001	0.0003	0.0002
Flash point,	°C	53.3	43.5	43.0
Freezing point,	°C	-50.0	-49.5	-49.0
Viscosity at -20°C,	cSt	4.51	3.9	4.08
Smoke point,	mm	26	23	23
Density,	kg/l	0.8035	0.8035	0.7980
Existent gum,	mg/100 ml	1.3	<1.0	<1.0

Finally, in some of the tests described above the filter positioned downstream of the test heat exchanger did become blocked. This only occurred, however, when the fuels in question were stressed beyond their breakpoints with respect to the lacquering of the heat exchanger. Of the two components, therefore, the heat exchanger appears to be the more sensitive to the effects of fuel thermal degradation.

#### COMPARISON WITH THE JFTOT

Aviation fuel specifications stipulate that the thermal stability of turbine fuel must exceed a certain value when assessed on an instrument called the Jet-Fuel-Thermal-Oxidation-Tester (JFTOT), which is described in detail in reference 12. Briefly, aerated fuel, initially at ambient temperature, is passed at a rate of 0.05 ml/s over a heated aluminium tube and through a 17 µm filter. The stability of the fuel is determined by its propensity to lacquer the tube and to block the filter. Fuel specifications require that, when the maximum temperature on the tube is maintained at 260°C, the colour of the lacquer produced must not be darker than a specified limit and the pressure drop

developed across the filter during the 2.5 hour test must not exceed 25 mm Hg. The colour of the lacquer is assessed via a simple visual comparison with a standard colour chart.

In addition to being used as a quality control instrument, the purpose for which it was principally designed, the JFTOT is also used as a research tool to compare the stabilities of different fuels, study the effects of additives etc. In this role the JFTOT is successively operated at several different temperatures in order to determine the breakpoint of a fuel, this being the maximum tube temperature at which the lacquer produced and the pressure drop developed remain within their respective specified limits.

The JFTOT is, by design, an accelerated test. Compression of the test time is achieved at the expense of realism, mainly in respect of the fuel flow rate: in the JFTOT the flow is laminar and the fuel takes 13s to pass over the heated tube; in an aircraft's fuel system the flow is turbulent and the fuel takes less than 1s to pass through the hottest sections of the system. To investigate how accurately the JFTOT predicts fuel behaviour in practice, JFTOT breakpoints were determined for the 16 fuels used for the studies described in the previous section. The results are compared in Figure 5 with those obtained on the STHTR; a linear regression has been fitted to the data. It will be evident that the correlation between the JFTOT breakpoints and those obtained using the more realistic STHTR is very poor and that the two rigs rank fuels in a different order. Also, three fuels that failed to meet specification requirements performed satisfactorily in the STHTR (it should be noted that these fuels were not released by the refinery in question but were reprocessed).

These inconsistencies can be attributed to the principal differences between the two rigs which, in addition to that of fuel flow rate, are as follows:

- (i) The standard JFTOT does not incorporate a tank-heating stage; variants are available with such a facility but are not used for specification purposes.
- (ii) In general, the surface temperature required to obtain a visible lacquer on a JFTOT tube is significantly higher than is needed to obtain sufficient deposit on the STHTR's test heat exchanger to produce a measurable drop in its heat transfer coefficient.
- (iii) JFTOT tubes are rated visually; the deposit formed on the STHTR's test heat exchanger is rated quantitatively, however, via its effect on the element's heat transfer coefficient.

The findings reported here do not necessarily call into question the JFTOT's role as a go/no go quality control instrument. It must be remembered that fuels encounter higher temperatures downstream of engine oil coolers, although flow conditions will generally be turbulent. Also, none of the fuels examined performed badly in the more realistic STHTR and thus there is no evidence to suggest that the JFTOT could fail to identify a thermally unstable fuel. The findings do indicate, however, that, in its present form, the JFTOT is not suitable for research purposes and demonstrate that there is a need to conduct tests on larger rigs that provide realistic test conditions.

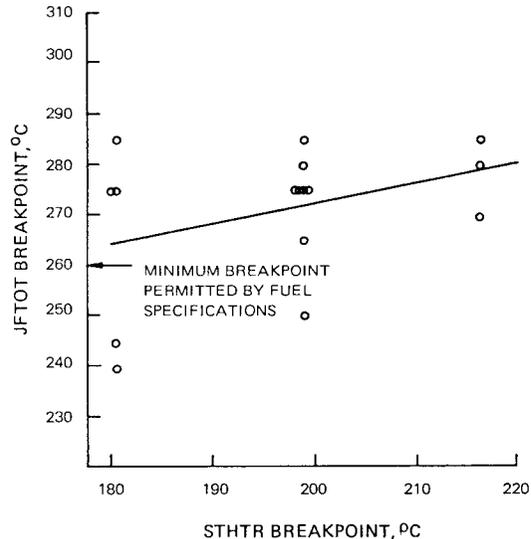


FIG. 5 - Comparison of results obtained on JFTOT and STHTR

#### CONCLUSIONS

1. Empirical and operational evidence indicates that, at the present time, aviation fuels are able to withstand the thermal stresses to which they are subjected in gas turbine oil coolers. However, there is only a relatively small margin between current operational limits and the lower limits of fuel stability.
2. The thermal stabilities of some turbine fuels can be improved significantly by the addition of metal deactivator.
3. There is strong evidence to suggest that the JFTOT is not suited for use as a research tool.

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