ABSTRACT

A test unit has been developed by Rolls-Royce for the U.S. Navy to evaluate fuel thermal deposition typically found in various aircraft engine components. Although the current Jet Fuel Thermal Oxidation Tester (JFTOT) provides a qualitative thermal stability evaluation, it may not be able to predict in service problems. Conditioning and testing of the fuel under realistic conditions is crucial if one is to accurately predict deposit formations. Engine fuel deposit evaluations and evidence from unpublished Rolls-Royce laboratory rig tests were used to help design a test unit that would address fuel stability problems in current or future aircraft. The Aviation Fuel Thermal Stability (AFTS) test unit embodies test modules that were selected with extensive fuel systems experience to enable the evaluation of thermal deposition in various fuel components using properly conditioned fuel. The test modules are controlled and results are recorded by a computer. This paper includes a review of the AFTS test unit design and preliminary test results thereof.

BACKGROUND

Kerosene grade gas turbine fuels are subject to thermal stress in the flow path between the aircraft fuel tanks and the combustion chamber. Advances in aircraft technology continue to increase the heat loads, and therefore the thermal stress, placed on the fuel. The additional heat loads increase the potential for fuel to undergo thermal oxidation deposition. This deposition can adversely affect the performance and durability of the aircraft in a number of areas. Insoluble deposits can block fine mesh screens or filters such as those found in fuel management units or nozzles. Gums or lacquers can form on and cause stiction of lightly loaded, close tolerance, sliding components. Carbonaceous deposits can form on fuel injectors and cause degraded atomization, flow rate and fuel distribution characteristics.

The U.S. Navy has particular concern about the potential for thermal degradation in its aircraft due to the nature of its shipboard aviation fuel distribution system. The shipboard distribution system is made up predominately of copper-nickel piping. Surveys have shown that concentrations of up to 800 ppb of copper have been found in aviation fuel aboard ship. Previous work has shown copper in concentrations above 50 ppb can be extremely deleterious to a fuel's thermal oxidation stability.

Current specification testing of a fuel's thermal oxidation stability is performed using the Jet Fuel Thermal Oxidation Tester (JFTOT). Although the JFTOT has been a satisfactory go-to-go quality control test, its capabilities as a quantitative research tool are extremely limited. Oxidation stability in the JFTOT is rated according to the visual appearance of the deposits that form on a heated tube as well as the pressure drop across a 17 micron filter. In order to quantify the effect of fuel thermal stability and aircraft operating parameters on hardware
performance and durability, a wide variety of rig, component and engine tests have been conducted. However, these tests usually have limited flexibility and require an extensive amount of fuel, manpower, and cost to conduct.

Internal, unpublished research conducted by Rolls-Royce, as well as other published data (Hazlett, 1991; Kirklin & David, 1992; Goodyear & Vere, 1985), show that fuel type, bulk fuel temperature, fuel residence time, metal wall temperature, recirculation paths, degree of initial filtration, fuel wetted metallurgy, surface roughness, and fluid flow characteristics all affect the degree of fuel thermal degradation and ultimate deposition. These deposits manifest themselves according to fuel conditioning, component characteristics, and fluid dynamics. The AFTS test unit strives to enable the test operator to simulate most of these conditions as they may be encountered in the aircraft/engine environment. Test specimens may then be evaluated for the amount of deposits formed from the system operating conditions, or the fuel may simply be evaluated for its quality by gauging the various deposits formed on all the test specimens.

**SYSTEM DESCRIPTION**

The AFTS test unit comprises test modules representing critical aircraft fuel components that have been found to develop in-service deposits. The fuel has been conditioned prior to each of these test modules to represent typical aircraft fuel system operating conditions.

**Typical Aircraft Fuel System**

Three major thermal regimes have been identified in aircraft, as shown in figure 1, that are known to contribute to fuel deposits: low (ambient-350K), intermediate (350-450K), and high temperature (470-570K).

![Figure 1. Aircraft Fuel System Components](image)

**Low temperature regime.** This area is characterized as that leading from the fuel tanks up to the engine high pressure (HP) pump and is operated at low pressure. The types of deposits in this section generally tend to be particulate. Deposit precursors can also form in this regime that results in further deposition downstream. The rates of build up are highly dependent on temperature, flow regime (residence time), and fuel type/composition including dissolved gases, water, etc.

**Intermediate temperature regime.** This regime usually is found within the aircraft engine after the HP pump and engine oil cooler but before the fuel nozzles. Deposits in this section tend to be gums, fuel borne and surface particulate. The rates of deposit are again influenced by the fuel temperature, flow regime, and fuel type. Fuel wetted component material composition becomes important in this section.

**High Temperature Regime.** This section is generally isolated to the fuel distribution system and/or fuel nozzles. It is characterized by the hot walls found within these parts. Deposits tend to be carbonaceous in nature and are fuel borne as well as surface deposited. The rates of deposit are influenced by the fuel temperature, flow regime, fuel type, component surface material, surface roughness, fluid dynamics, and most importantly, surface temperature and previous thermal stressing.

**AFTS Test Unit Fuel System**

Within the three thermal regimes, various test modules (figure 2) are included to represent aircraft components that have been shown to exhibit or affect deposition problems: conditioning (fuel delivery) filter, LP fibrous filters, HP filter screens, lightly loaded FMU sliding control valves, and fuel nozzle or injector passages.

![Figure 2. AFTS Major Components](image)

In designing the support system that drives the test modules, care was used in selecting equipment that had similar metallurgy to engine components. Haphazard use of parts with unknown material composition may lead to false indications of deposits in the test specimens.

Enough flexibility has been built into the unit to cater for simulation of present day, or future, aircraft fuel system conditions. Table 1 shows the system operating range along with the present specifications of the test modules. The test unit may be run in a single flow pass mode that is the most common testing method, partial recirculation to simulate spill from the aircraft HP fuel pump, or full recirculation for leak checking and maintenance. Further detail of the major components is presented.
Table 1. AFTS test unit operating parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Flow</td>
<td>5.7-22.7 LPH (9.5 normal)</td>
</tr>
<tr>
<td>Flow Path</td>
<td>Single Pass, Recirculation, Partial Recirculation</td>
</tr>
<tr>
<td>LP Pressure</td>
<td>138 to 690 kPa</td>
</tr>
<tr>
<td>LP Temperature</td>
<td>Ambient to 370 K</td>
</tr>
<tr>
<td>HP Pressure</td>
<td>690 to 9660 kPa</td>
</tr>
<tr>
<td>HP Temperature</td>
<td>Ambient to 500 K</td>
</tr>
<tr>
<td>LP Filter Module</td>
<td>Scaled 10 µm, resin-impregnated, LP aircraft filter</td>
</tr>
<tr>
<td>HP Filter Module</td>
<td>Scaled 70 µm, 304 stainless steel, HP aircraft filter</td>
</tr>
<tr>
<td>Stiction Module</td>
<td>Similar to aircraft spool valve</td>
</tr>
<tr>
<td>Nozzle Module</td>
<td>Instrumented, reusable, scaled EDM 316 stainless steel tube</td>
</tr>
</tbody>
</table>

Inlet Filter. Rolls-Royce tests have shown that the degree of initial filtration can have an impact on deposit formation. The inlet filter can condition the fuel prior to reaching the fuel heating section and test specimens. A 10 µm aircraft filter is used to simulate an airframe filter (if installed) or ground service vehicle filter. The inlet filter also serves to remove any debris that may be generated by the LP fuel pump. As this filter operates at ambient temperatures, no thermal related deposits are expected to be found, but instead serves to condition the fuel prior to thermal testing.

LP Filter Module. To address the possible blockage problem of aircraft engine LP filters from fuel additives, and locate low temperature fuel-borne particulate, this module characterizes the powerplant main LP filter that operates in the low temperature regime (ambient - 350 K). A 10 µm aircraft LP filter is modified (figure 3) to closely reflect the conditions and deposit characteristics found in service. Table 2 shows typical turbine engine filtration ratings.

![Exposed Surface Area](image_url)  
Figure 3. Modified LP Filter

Most filters are sized for a specific dirt holding capacity. However, a rule of thumb is to provide .85 to 1.70 cm² of filter area per 1 LPH fuel flow. Since it is important to keep a pleated configuration on the test filter to mimic the same type and location of aircraft fuel deposits, the excess filter area is blocked with an epoxy material similar to that used on production filters.

Stiction Module. To simulate the problems of hysteresis or sticking in close tolerance (down to .00254 mm) spool valves within the engine FMU, a 35 kPa hydraulic differential pressure sensing spool valve is used. Very small fuel deposit accumulations can be measured by this module.

Actual fuel dynamic similitude with engine components was difficult to achieve in this module due to availability of valve sizes, however, metallurgy is sufficiently similar. A survey of fuel management manufacturers showed the most common types of materials used in manufacture to be 440C stainless steel, 6061-T6 aluminum, and 5144C steels. The test valve uses 12L14.

The valve operates for approximately 12 hours, full open, while deposits are being formed on the valve barrel wall. The valve then slowly closes over a 30 second interval by re-routing the fuel flow around the valve. This causes an internal spring to push the spool down into the closed position, trapping fuel deposits between the spool and the barrel wall. Fuel is then again gradually routed back through the valve, pushing the spool back into its full open position. By simultaneously measuring the differential pressure across, and the flow through the valve one is able to record a qualitative measure of the degree of stiction by noting the hysteresis of the valve. Figure 4 illustrates the stiction module operating characteristics through one cycle.

Table 2. Sample of Aircraft Filtration Ratings  
(Straus, 1991)

<table>
<thead>
<tr>
<th>Engine</th>
<th>Component</th>
<th>Material</th>
<th>Rating (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>main filter</td>
<td>cellulose/cotton in phenolic resin steel</td>
<td>40 (80 abs)</td>
</tr>
<tr>
<td></td>
<td>servo screens</td>
<td></td>
<td>40 (nom)</td>
</tr>
<tr>
<td>B</td>
<td>main filter</td>
<td>polyester/fiber glass steel</td>
<td>40 (80 abs)</td>
</tr>
<tr>
<td></td>
<td>servo screens</td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>C</td>
<td>main filter</td>
<td>fiberglass</td>
<td>10 (35 abs)</td>
</tr>
<tr>
<td></td>
<td>servo screens</td>
<td>steel</td>
<td>100 to 300</td>
</tr>
<tr>
<td></td>
<td>nozzle screens</td>
<td>stainless steel</td>
<td>40 to 400</td>
</tr>
<tr>
<td>D</td>
<td>low press. filter</td>
<td>paper</td>
<td>10 (40 abs)</td>
</tr>
<tr>
<td></td>
<td>high press filter</td>
<td>steel wire</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td>servo screens</td>
<td>stainless steel wire</td>
<td>40 to 100</td>
</tr>
<tr>
<td>E</td>
<td>engine filter</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>servo screens</td>
<td>steel</td>
<td></td>
</tr>
</tbody>
</table>
Figure 4. Stiction Module Operation

**HP Filter Module.** Aircraft intermediate temperature fuel screens and HP filters have been found to develop deposits by catching fuel-borne particulate as well as generating surface deposits. This module can simulate either and currently uses a 70 µm, 304 stainless steel woven mesh screen as is shown in Figure 5. The screen is sized to simulate a small last chance filter and allows for 51.5 m/min. fuel velocity in the mesh open area. These filters are prepared and weighed prior to the test and re-weighed after the test. Discrete test data is gathered from deposit weight while real-time data is obtained from recording the differential pressure across the filter.

Figure 5. HP Filter Screen

**Heated Nozzle Module.** Engine fuel nozzles are especially susceptible to internal passage wall deposits and fuel-borne particulate blockage due to the hot environment the nozzle operates in.

The heated nozzle module can simulate hot parts of the fuel system, such as fuel nozzle feed arms, that operate with high metal wall temperatures, turbulent flow, rough walls, and high inlet bulk fuel temperatures, all of which contribute to increased deposition. The nozzle module also represents factors that act to decrease deposition, such as high wall shear stresses, low fuel residence time, and 316 stainless steel metal construction (one of the lowest deposition steels).

If one is to predict engine deposit rates, it is also important to re-create the same heating mechanism as found in aircraft engines. Some laboratory testing methods suggest using a heated tube while holding a constant wall temperature throughout the duration of the test (Chen and Lefebvre, 1992). However, in a turbine engine, the fuel nozzle wall temperature is not constant but varies in direct proportion to the amount of fuel deposition. A constant heat flux is available to the fuel nozzle walls by the hot compressor discharge air flowing around the outside of the nozzle as shown in figure 6. Cooler fuel flowing through the inside of the nozzle carries away some of this heat, lowering the nozzle wall temperature from its surroundings. As carbon deposits gather on the nozzle wall, an insulation is formed and the wall temperature rises to approach that of the compressor discharge air.

Figure 6. Engine and AFTS Nozzle Heating
Actual engine and fuel nozzle test data, along with laboratory test results and CFD modeling, were used to design the nozzle tube test section to closely match typical aircraft internal nozzle thermal and fluid dynamics. The tube test section can simulate a Rolls-Royce RB211-535 fuel nozzle feed arm. However, during testing, increased wall temperatures are normally used to ensure sufficient deposit accumulations in a reasonable amount of time. The nozzle tube consists of three sections, a middle heated test section and two end attaching pieces as shown in figure 7. The center tube test section was EDM manufactured from 316 stainless steel to match surface finish and metallurgy.

**Figure 7. Heated Nozzle Tube Assembly**

The AFTS test unit uses an HP system pressure sufficiently high to assure the fuel is kept above its vapor pressure to avoid two phase flow. A constant available heater power is used to drive the nozzle module. As a test commences, a rise in the tube wall temperature is observed over time that indicates deposition is taking place. A good correlation has been shown by Rolls-Royce, Goodman and Bradley©, and AFTS test results, between this rise in wall temperature and the total amount of carbon deposits (figure 8). This approach enables the continuous measurement of carbon build up throughout the duration of the test and provides a temporal record of results. After testing, the entire tube is subjected to carbon burn-off analysis to verify the temperature rise Vs. carbon deposit test results.

**Hot and Cold Exit Filter Modules.** Two filters were included downstream of the heated nozzle - one aft of the nozzle (hot exit filter) and another after the water cooled heat exchanger (cold exit filter). Although there is no aircraft equivalent of the cold exit filter, the hot exit filter may be used to evaluate the blockage potential of small nozzle exit slot passages. An analysis can also be made of the cooling effect on fuel during low heat stress tests. In addition, the filters also serve to protect the unit's flow metering valve. Both filters use a stock housing with a 830 mm² area element. A new 60 µm sintered 316 stainless steel element is carefully prepared and weighed before and after each test.

**Figure 8. Temperature Rise Vs. Deposition Thickness**

Test Unit Assembly
The test unit is comprised of a cabinet containing all the mechanical test modules (figure 9) and another two cabinets containing the control/data acquisition computer along with the supporting relay and electronic hardware (figure 10). The mechanical cabinet is located inside a test cell while the computer and relay cabinets are located in a control room.

**Figure 9. AFTS mechanical cabinet**

The computer controls all of the mechanical systems and records test data to disk as well as displaying real-time results. Testing may be conducted in a semiautomatic-automatic mode by issuing commands from a keyboard, or the test sequence may be fully automated. System parameters are monitored for unsafe conditions, and if found, the test will be automatically aborted with a controlled shutdown.

1 Extrapolated from Goodman and Bradley (1970).
PRELIMINARY RESULTS
Prior to installation at the Navy facility in Trenton, NJ, the test unit was shipped to the Rolls-Royce laboratories in Derby England for component functional checks, integrated system testing, and validation of test data.

A sequence of tests were conducted to evaluate the sensitivity of the test unit as well as to determine its ability to discriminate between fuels of differing thermal stability. The tests were run in a single flow pass mode (no recirculation), fixed low temperature (300K), low pressure (483 kPa). LP system condition with a varied high temperature (433-455K), fixed high pressure (4831 kPa) HP system condition. The nozzle was run at numerous constant available power settings. Jet-A1 was used as the baseline fuel for all temperature comparison tests. These conditions encompass the upper temperature regimes of many actual engine fuel systems.

LP Filter
The LP filter showed no signs of thermal related deposits because the LP system was operated at a low temperature (300K) with relatively short test periods (25 hours).

Stiction Module
The most significant result obtained for the stiction module was from a low stability fuel (JFTOT breakpoint of 493K) that was operated at a bulk fuel temperature of 433K. Significant hysteresis was observed in as little as 14 hours as shown in figure 11. Tests conducted with higher stability fuels (538K breakpoint) at the same temperature showed little indication of deposits after more than 50 hours.

Figure 10. AFTS computer and relay cabinets

Normal Operation
\[ \text{dP} \]
Flow

Evidence of Hysteresis
\[ \text{dP} \]
Flow

Scales:
Press: 0-4 PSID
Flow: 0-3 GPH

Figure 11. Stiction module result comparison between low and high stability fuels.

HP Filter
The HP filter was operated with three different bulk fuel temperatures; 433, 444, and 455K. As the fuel-borne, thermal related, carbonaceous deposits build on the filter screen, the differential pressure across the filter increases. A relief valve opens at approximately 25 kPa to by-pass the filter and allow continued testing. Figure 12 illustrates the filter blockage over time for the three differing bulk fuel temperatures using Jet-A1 fuel with a JFTOT breakpoint of 538K.

A sharp increase in deposits was seen for small increases in bulk fuel temperatures. At 455K, the test was terminated early due to rapid filter blockage. Most integrated testing was conducted with bulk fuel temperatures of 433K to allow sufficient time for other fuel components to gather deposits before the HP filter became blocked. The slow heating rate of the fuel at .58 Kelvin per second results in a long residence time that increases the deposit rate. Faster, and more realistic, heating rates are to be evaluated in the future.
Heated Nozzle Module

The nozzle module is able to gather real-time data of carbonaceous wall deposits. Figure 13 shows the results of two tests with differing initial nozzle wall temperatures. A deposit hold-off period is observed initially, as shown in other Rolls-Royce tests, after which the deposit rate increases. The increase in wall temperature, while at a constant heating power, is due to the insulating qualities of the carbon deposit. Both the initial and final wall temperatures were driven to higher levels than might be found in current aircraft nozzles to ensure sufficient carbon accumulations within the test period.

At the end of each test, the nozzle tube was removed and subjected to a carbon burn-off test to verify the results of the tube temperature rise. Figure 14 illustrates the deposit build up for various heater power (initial inner wall temperature) settings using two different inlet fuel temperatures. The trends seem to indicate a higher level of wall deposits with increasing fuel inlet temperatures and increasing initial wall temperatures.

The AFTS test unit was designed to mimic turbine engine fuel conditions, and as such, provides an opportunity to compare nozzle deposit data with previous work done on heated tubes. Data from Figure 14 is superimposed on test results presented by TeVelde and Glickstein (1983) at United Technologies Research Center (UTRC) and is shown in Figure 15. Although the UTRC tests utilized an 8 foot long, resistance heated stainless steel tube, with ambient JP-5 fuel inlet temperatures, the AFTS test data appears to follow the UTRC data trend. The decrease in deposit rate above 650 K as shown by the UTRC data is believed to be caused from fuel entrained oxygen depletion and a change in the deposit mechanism from autoxidation to pyrolysis.
Hot and Cold Exit Filter Modules

Initial tests show that the nozzle inlet bulk fuel temperature as well as the nozzle power have an impact on deposits arrested by the hot and cold exit filters. Figure 16 shows that increasing bulk fuel temperature results in increased deposits. Increasing the nozzle power (initial wall temperature) has the same effect. The hot exit filter always developed more deposits than the cold exit filter.

![Graph showing blockage over time for two differing pre-stressed fuels](image1)

Figure 16. Hot and cold exit filter blockage over time for two differing pre-stressed fuels

Interestingly enough, an Air-Force test rig using a similar test setup showed decreasing deposits with increasing bulk fuel temperature. In addition, the cold exit filter developed more deposits than the hot at comparable bulk fuel temperatures and test duration to the AFTS unit. Figure 17 shows the comparison between that data (Heneghan, et al., 1993) and those of the AFTS test unit. Variables that may contribute to this discrepancy are: the use of 2 micron filters Vs. 60 micron in the AFTS unit, and a much faster bulk fuel heating rate as well as a much lower filter velocity than the AFTS unit. The effect of these variable merits further testing.

![Bar chart showing deposits](image2)

Figure 17. Comparison of AFTS hot and cold exit filter results with that of Heneghan, et al. (1993)

CONCLUSION

A test unit was developed that showed its ability to quantify fuel thermal stability in those areas typically found in aviation turbine engines sensitive to deposition. The fuel is conditioned to represent realistic conditions while the test specimens closely reflect the dynamic, thermal, and material properties of actual aircraft fuel system components. Real-time data is obtained that provides good discrimination of changing test conditions and fuel quality. The AFTS test unit is now a viable test vehicle for investigating the causes and results of thermal degradation of aviation fuels.

ACKNOWLEDGMENT

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REFERENCES