EXTENDED DURATION THERMAL STABILITY TEST OF IMPROVED THERMAL STABILITY JET FUELS

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ABSTRACT

A single-pass, dual heat exchanger system called the Extended Duration Thermal Stability Test (EDTST) system was developed for evaluating jet fuel thermal stability. Various JP-8 fuels and thermal stability additives have been evaluated in the system. The test results indicate that additives can substantially improve the thermal stability of conventional jet fuels. Relationships of bulk and wetted wall temperatures on coking deposits that form in heated tubes have also been evaluated.

To date, tests conducted with EDTST have verified that additives can improve the thermal stability of JP-8 fuels. The goal of operating at wetted wall temperatures of 260°C (500°F) has been achieved. The goal for bulk fuel temperatures of 218°C (425°F) with no deposits has not been achieved. Additional additive candidates are to be evaluated in the EDTST system to identify additives that meet both the wetted wall and bulk fuel temperature goals of this program. However, if the bulk temperature goal cannot be totally achieved, the JP-8 fuel specification will most probably be changed to take advantage of the wetted wall temperature improvement already demonstrated by a JP-8+100 additive candidate.

INTRODUCTION

Advanced fighters that will be produced late in this decade will require increased cooling resources. Fuel will be subjected to higher temperatures, higher heat fluxes, and multiple heating and cooling cycles due to increased heat loads imposed by the aircraft and engine systems. Integrated aircraft thermal management is becoming a significant driver in the balance between providing sufficient cooling resources to maintain component integrity and life and maintaining aircraft performance capabilities. Fuel is the primary heat sink for aircraft thermal management. Most current fighter aircraft recirculate the fuel from the airframe heat loads to maintain proper aircraft cooling and to maintain the aircraft/engine interface temperature between 88°C (190°F) and 93°C (200°F). The fuel is cooled before it is returned to the main fuel tanks to prevent the bulk fuel from exceeding 66°C (150°F). The fuel is cooled via either ram air or natural convective/conductive cooling available in the metal wing tanks (Figure 1).

![Figure 1. Current Fighter Aircraft Thermal Management System.](image-url)
The burn fuel flow for the engines now being developed will be too low during most of the flight mission to satisfy the increased system heat loads. To provide the required fuel cooling flow, fuel will be bypassed from the engine back to the aircraft fuel tanks by way of a ram air/fuel cooler (Figure 2). From a thermal management standpoint, it is desirable for the aircraft and engine fuel systems to operate at higher temperatures. This eliminates or reduces the size of the ram air/fuel heat exchanger by reducing the required bypassed fuel flow and increasing the effectiveness of the heat exchanger. Bypassed flow with current fuels at low engine power settings can exceed 2.5 times the flow required to provide the engine thrust. In addition, it is anticipated that aircraft using current fuel such as JP-8 will require increased fuel system maintenance to replace fouled engine components. The improved thermal stability fuel (JP-8+100) is being developed to provide the additional heat sink capability and to eliminate the fuel fouling of fuel system components.

Figure 2. Advanced Fighter Aircraft Thermal Management System

Looking toward the beginning of the next century, the Integrated High Performance Engine Technology (IHPTET) program is developing technology that will potentially double the turbopropulsion capability of current engines. To achieve these goals, fuels will be stressed to considerably higher temperatures than present aircraft applications. New lubricants being developed under the IHPTET program will operate at temperatures of 316°C (600°F) for the next generation engines and 385°C (725°F) for the following generation. Present-day lubricants are limited to temperatures of 176°C (350°F). Future fuels must have a similar temperature capability increase to avoid fouling problems in the fuel/lube oil coolers. In addition, studies have shown (Harrison, 1990) that the wetted wall temperature in mainburner nozzles will be in the range of 260°C (500°F) to 300°C (572°F) compared to the maximum allowed wetted wall temperature of 205°C (400°F) for use with current fuel such as JP-8.

Temperature limits for engine fuel systems using conventional JP fuels were basically established by field experience. There are many tests, such as Jet Fuel Thermal Oxidation Test (JFTOT) for evaluating thermal stability of fuels. However, these tests do not provide data appropriate for system design considerations. These tests are normally conducted at high temperatures and for short durations to accelerate the test and at low flow rates to conserve the amount of fuel required for the test. These tests emphasize the fuel’s tendency to make deposits at higher temperatures. For example, the minimum acceptable temperature for JP-8 fuel in the JFTOT is 260°C (500°F); whereas the general temperature limits that are used for engine design are 163°C (325°F) for bulk fuel and 205°C (400°F) for wetted walls in engine fuel injector nozzles. The Extended Duration Thermal Stability Test (EDTST) system was directed toward establishing fuel thermal degradation criteria that can be used for aircraft system designers. This criteria is also required to evaluate the improved thermal stability fuel candidates.

**JP-8+100 FUEL DEVELOPMENT**

The United States Air Force embarked on a program in 1989 to improve the thermal stability of JP-8 fuel (Harrison, 1990). Two approaches were initially explored. The first approach was to develop a new refinery specification for a more thermally stable JP-8 fuel. This approach was discarded early because a new fuel would be costly to obtain and would offer logistic penalties contrary to a single fuel for the battlefield. The second and preferred approach was to develop a thermal-stability-improving additive package that could be added to the JP-8 kerosene base fuel and increase its thermal stability by 56°C (100°F). Currently, the improved fuel is referred to as JP-8+100; however, when development is complete, it is anticipated that the additive package will be listed in a Qualified Products List (QPL) for use in the JP-8 specification, MIL-T-83133. The cost goal for the additive is $0.001 per gallon of fuel.

Current research indicates that the additive package will contain four main ingredients: antioxidants, metal deactivators, detergents, and dispersants. The Air Force contacted major additive manufacturers and oil companies to provide thermal-stability-improving additives for evaluation. To date, more than 300 additives have been screened and several show promise for meeting the thermal stability goals. A number of test devices have been developed or modified for screening additives (Harrison et al., 1993). The EDTST system is a primary test system for evaluating the most promising additives identified by the screening test.

**EDTST SYSTEM**

As discussed in the introduction, the EDTST system was established to provide fuel thermal stability information for
designers. This system was established by modifying an existing facility that was originally a "hydrotreater" for processing fuels. A schematic of the EDTST system is shown in Figure 3. The system consists of a 60-gallon feed tank, an electrical motor-driven gear pump, two clam shell furnace heaters, and a scrap tank. Normally, fuel makes only one pass through the system. The first furnace heater (preheater) in the system is used to establish the desired fuel bulk temperature of fuel flowing into the second heater. The fuel bulk temperature is representative of the fuel temperatures that are experienced due to aircraft and engine heat loads. Temperature is established in the second furnace heater (main heater) to represent the wetted wall temperatures associated with engine injection nozzles. Bulk fuel and wetted wall temperatures have been emphasized because they are used to define limits for engine fuel systems design. The present bulk fuel temperature limit for engine control systems is 163°C (325°F). Engine fuel injectors are normally limited to wetted wall temperatures of 204°C (400°F) to avoid coking problems with conventional JP-type fuels. The desired capability for JP-8+ 100 fuel is to provide fuels that are thermally stable at bulk temperatures of 218°C (425°F) and wetted wall temperatures of 260°C (500°F). Another capability desired is the ability to recirculate the fuel at bulk fuel temperatures up to 218°C (425°F).

TEST PROCEDURES
During tests, the temperature of the heating zones of the preheater are increased to establish the desired bulk outlet temperature. Similarly, the temperature of the heating zones of the main heater are established to provide the desired wetted wall temperature as measured on the tube outer wall. The middle heating zone is set at the highest temperature to ensure that the desired wetted wall temperature occurs in this zone. A typical temperature profile for the main heater tube is shown in Figure 5. A flow rate of 1 gallon per hour (gph) and a duration of 96 hours have been used for most tests. At the 1 gph flow rate, the residence time from the inlet of the preheater to the outlet of the main heater is 50 seconds. Similarly, the residence time from the inlet to the outlet of the main heater is 1.6 seconds. The Reynolds number in the heater tube is approximately 2,500 at the 1 gph flow rate. These residence times are representative of those in aircraft and engine fuel systems. The EDTST system is computer controlled and can run unattended for long periods of time.

Both furnaces have two sets of thermocouples, attached to the outside of the thick-walled furnace tube in the center of each heater element zone, to control temperature. One set of thermocouples is used to control the heat input from the clam shell heaters; the other set is used with a safety shutoff control system.

A brief overview of the tests discussed in this paper appears in Table 1. This table includes the following effects: Bulk, Wetted Wall, Additives, and Recirculation.
### Table 1. Overview of Tests

<table>
<thead>
<tr>
<th>Wetted Wall Temperatures</th>
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<tbody>
<tr>
<td>232°C (450°F)</td>
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</table>

#### Bulk Effects

<table>
<thead>
<tr>
<th>Pos</th>
<th>Bulk Fuel Temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>POSF-2926 (JP-8)</td>
<td>122°C (250°F), 149°C (300°F), 177°C (350°F), 190°C (375°F)</td>
</tr>
</tbody>
</table>

#### Wetted Wall Effects

<table>
<thead>
<tr>
<th>Pos</th>
<th>Bulk Fuel Temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>POSF-2926 (JP-8)</td>
<td>149°C (300°F)</td>
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</tbody>
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#### Additive Evaluation

<table>
<thead>
<tr>
<th>Pos</th>
<th>Bulk Fuel Temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>POSF-2926 (JP-8) + Additive #1</td>
<td>177°C (350°F)</td>
</tr>
<tr>
<td>POSF-2980 (JP-8) + Additive #1</td>
<td>177°C (350°F)</td>
</tr>
<tr>
<td>POSF-2827 (JP-8) + Additive #1</td>
<td>177°C (350°F)</td>
</tr>
</tbody>
</table>

#### Recirculation Effects

<table>
<thead>
<tr>
<th>Pos</th>
<th>Bulk Fuel Temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>POSF-2980 (JP-8) + Additive #1</td>
<td>177°C (350°F)</td>
</tr>
</tbody>
</table>

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**RESULTS and DISCUSSION**

**Bulk and Wetted Wall Effects:** When EDTST testing was initiated, some basic sensitivity tests were conducted to provide fuel thermal stability information for fuel system designers and to provide baseline data for the evaluation of the JP-8+100 additives. Specific tests were conducted to determine the effects of wetted wall versus bulk fuel temperatures on carbon deposits. A series of tests were conducted with the POSF-2926 fuel at a wetted wall temperature of 260°C (500°F) and bulk inlet temperatures of 122°C (250°F), 149°C (300°F), 177°C (350°F), and 190°C (375°F). These tests were each conducted for 72 hours at a flow rate of 1 gph. A comparison of the carbon deposits for these tests is shown in Figure 6. The heater segment numbers correspond to 5.1-cm segments into which the tubes are cut for carbon analysis. Segments 13 and 14 are in the middle zone where the maximum wetted wall temperature occurs. Total carbon is measured by burning off the carbon from the tubes in a LECO Carbon Analyzer. The maximum segment deposit was about the same mass per unit area for all the bulk temperatures tested. This finding indicated that the wetted wall temperature was the predominate factor for deposit formations. There were higher deposits in the tube upstream and downstream of the high temperature zone at the higher bulk temperature conditions. These deposits indicate fuel degradation is being initiated by the high bulk fuel temperatures and deposits are formed throughout the tube. Other tests were conducted at a wetted wall temperature of 288°C (550°F) with bulk temperatures of 149°C (300°F) and 176°C (350°F). A comparison of the carbon deposits of these tests is shown in Figure 7. In addition to the deposits that form due to the wetted wall temperature, degradation particles form in the bulk at the higher bulk temperatures and also deposit on the walls. Based on data from another system (Phoenix test rig), these

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1 Each fuel sample acquired by the Air Force has been assigned a four digit number (e.g., POSF-xxxx). These Air-Force assigned numbers are used for identification.
Additive Evaluation: Test duration was increased to 96 hours for the evaluation of the JP-8+100 additive candidates to insure sufficient induction time for deposits to form on the tube. Tests were run with a variety of fuels to insure that the additive was effective in fuels from different base stocks and processing methods. Three Jet-A fuels were primarily used to evaluate the JP-8+100 additive: POSF-2926, POSF-2980, and POSF-2827. Tests were also conducted with a JP-8 fuel, which was established as a baseline fuel for the JP-8+100 overall program. Since JP-8 is the primary fuel for this overall program, the Jet-A fuels were often doped with the standard additive package (corrosion inhibitor, anti-icing additive, and anti-static additive) to make them JP-8 types. Evaluation of the JP-8+100 additives has been accomplished by running repetitive tests with and without the standard JP-8 additive in the Jet-A fuel. Tests were first conducted with the POSF-2926 fuel with and without JP-8+100 additive #1 at a wetted wall temperature of 260°C (500°F) and a bulk inlet temperature of 177°C (350°F). JP-8 additive #1 consists of 100 mg/L of a proprietary dispersant (Betz 8Q405) and 25 mg/L of butylated hydroxy toluene (BHT) antioxidant. A comparison of carbon deposits for these tests is shown in Figure 9. There were essentially no deposits with the JP-8+100 additive candidate added to this fuel for these temperature conditions. This same fuel and additive candidate was then tested at a wetted wall temperature of 288°C (550°F) and the same bulk inlet temperature of 177°C (350°F) to determine the temperature improvement the additive provides for this fuel. A comparison of the carbon deposits for this test and the previous two tests is shown in Figure 10. Based on these results, the additive provides approximately a 28°C (50°F) wetted wall temperature improvement for this fuel. This however is only a 28°C (50°F) increase with respect to the increased wetted wall temperature goal of 56°C (100°F).

Similar tests were conducted on POSF-2980 (JP-8) with and without JP-8+100 additive #1 at the same conditions as run with POSF-2926. A comparison of carbon deposits for these tests with POSF-2980 is shown in Figure 11. The deposits were...
approximately 50 percent higher with this fuel as compared with POSF-2926 and indicated that the JP-8+100 additive provided about the same wetted wall temperature improvement.

Tests were then conducted on POSF-2827 (JP-8) with and without JP-8+100 additive #1 at the same wetted wall temperatures and bulk inlet temperatures as used for the other two fuels. A comparison of carbon deposits for these tests is shown in Figure 12. The results of these tests indicate that the deposits from this fuel were similar to POSF-2980. The deposits with the JP-8+100 additive were higher than with the other two fuels. However, this deposit quantity is considered to be acceptable for meeting the JP-8+100 goals. The maximum thickness of the deposit, after 96 hours, is estimated to be 0.0002 inch. If this rate is assumed constant, it would take 5,000 hours at these conditions to obtain a 0.010 inch deposit.

Tests were also conducted on JPTS fuel at a wetted wall temperature of 288°C (550°F) with bulk inlet temperatures of 177°C (350°F) and 218°C (425°F). A comparison of the results of these tests is shown in Figure 13. This figure shows that the fuel formed significant deposits at 288°C (550°F) wetted wall temperatures at the higher bulk inlet temperature 218°C (425°F) but did not have any deposits at the same wetted wall temperature at the lower bulk inlet 177°C (350°F) condition. A comparison of the tube deposits in the preheater for these is shown in Figure 14. This figure indicates that the fuel formed deposits in the preheater at the 218°C (425°F) bulk inlet temperature. Deposits in the preheater are not acceptable since this would relate to potential fouling of control valves and heat exchangers. Therefore, the allowable bulk temperature of 218°C (425°F) for engine fuel system design, desired by this overall program, could not be met by the JPTS fuel tested.

POSF-2980 (JP-8) with JP-8+100 additive #1 was also tested at a 288°C (550°F) wetted wall temperature and bulk inlet temperatures of 177°C (350°F) and 218°C (425°F). A comparison of the carbon deposits from both the preheater and heater for these tests is shown in Figure 15. Similar to JPTS, this fuel also formed deposits in the preheater at the 218°C (425°F) bulk inlet temperature. This fuel had higher heater deposits at the lower bulk inlet temperature condition. These
Recirculation Effects: Tests were also conducted to determine the effects of recirculating high temperature fuels from the engine back to the aircraft fuel tanks. These tests were conducted by circulating the fuel through the system with the preheater providing the desired bypass temperature. The heater was heated slightly to avoid deposits due to cooling. After the heater, the fuel was cooled in a water-cooled heat exchanger, then collected in a fuel drum. After approximately 100 gallons of fuel were stressed through the preheater, the fuel was transferred back to an empty feed tank. A normal test was then conducted at this desired wetted wall/bulk inlet temperature. A series of tests were conducted at a recirculation temperature of 177°C (350°F) and a wetted wall temperature of 288°C (550°F). POSF-2980 (JP-8) fuel with and without JP-8+100 additives #2 and #3 were specifically tested. JP-8+100 additive #2 consists of 300 mg/L of a proprietary dispersant (Mobil MCP-147b), 25 mg/L of BHT, and 10 mg/L of a metal deactivator additive (MDA). JP-8+100 additive #3 is additive #1 with 10 mg/L of MDA added. JPTS fuel was also tested at the same recirculation temperature and a wetted wall temperature of 288°C (550°F). The heater deposits for these tests are shown in Figures 16 and 17. There were no significant deposits in the heater or preheater tubes for these tests, except for the POSF-2980 (JP-8) fuel without the JP-8+100 additives. The heater deposit with the POSF-2980 (JP-8) increased 15 times due to the recirculation. A preheater deposit that reached a peak of more than 100 pg/m² was also experienced with this fuel as shown in Figure 18. There were no significant preheater deposits experienced with JPTS or the JP-8+100 additives. Recirculation tests were conducted with POSF-2980 (JP-8) fuel and JP-8+100 additive #3 to determine what the allowable recirculation temperature is for this additive candidate. These tests were conducted with a heater wetted wall temperature of 260°C (500°F) and recirculation temperatures of 177°C (350°F) and 204°C (400°F). A comparison of the preheater and heater deposits for these tests is shown in Figure 19. Based on these results, this additive candidate provides a capability for recirculation at bulk temperatures only up to 177°C (350°F) in lieu of the 218°C (425°F) desired temperature. Other additive candidates and increased concentrations of the promising additives are to be evaluated to determine their potential to provide the desired capability.

SUMMARY

The development of an improved JP-8 fuel (JP-8+100) offers a significant payoff to the Air Force. The trends towards higher heat loads and their associated increase in fuel system temperatures are the main stimulus for this new fuel development. In addition to the higher thermal stability fuel, a need was also identified for improved test apparatus and/or test
techniques to evaluate the fuel. To date, tests conducted in the EDTST have verified that additives can improve the thermal stability of JP-8 fuels. The goal for operating at wetted wall temperatures of 260°C (500°F) has been achieved. The goal for bulk fuel temperatures of 218°C (425°F) with no deposits has not been achieved. Additional additive candidates are to be evaluated in the EDTST system to identify additives that meet both the wetted wall and bulk fuel temperature goals of this program. However, if the bulk temperature goal cannot be totally achieved, the JP-8 fuel specification will most probably be changed to take advantage of the wetted wall temperature improvement already demonstrated by a JP-8+100 additive candidate.

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