AFRL-RQ-WP-TR-2013-0069

EVALUATION OF NEXT GENERATION THERMAL STABILITY-IMPROVING ADDITIVES FOR JP-8

Phase I – Thermal Stability Impact Characterization

Robert W. Morris, Jr.

Fuels and Energy Branch
Turbine Engine Division

APRIL 2012
Interim Report

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
April 2012	Interim	01 January 2005 – 07 January 2011

4. TITLE AND SUBTITLE
EVALUATION OF NEXT GENERATION THERMAL STABILITY-IMPROVING ADDITIVES FOR JP-8
Phase I – Thermal Stability Impact Characterization

5a. CONTRACT NUMBER In-house
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER 62203F

6. AUTHOR(S)
Robert W. Morris, Jr.

5d. PROJECT NUMBER 5330
5e. TASK NUMBER N/A
5f. WORK UNIT NUMBER Q0N9

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Fuels and Energy Branch (AFRL/RQTF)
Turbine Engine Division
Air Force Research Laboratory, Aerospace Systems Directorate
Wright-Patterson Air Force Base, OH 45433-7542
Air Force Materiel Command, United States Air Force

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-RQ-WP-TR-2013-0069

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Aerospace Systems Directorate
Wright-Patterson Air Force Base, OH 45433-7542
Air Force Materiel Command
United States Air Force

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/RQTF

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RQ-WP-TR-2013-0069

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
PA Case Number: 88ABW-2012-1925; Clearance Date: 05 Apr 2012. This report contains color.

14. ABSTRACT
This report describes the thermal stability testing and evaluation of four additives that were down-selected from several candidates from several additive manufactures - each of which give thermal stability improvements at least as good as the currently approved and qualified additive, Spec-Aid 8Q462. The report also describes the testing of an additional 5th additive received late in the program.

In summary, the four new additives were determined to have the same or better thermal stability performance in JP-8 fuel as the currently approved additive, Spec-Aid 8Q462. These additives along with Spec-Aid 8Q462 are recommended for further evaluation in the Phase II Fit-For-Purpose and Specification Compliance Testing.

15. SUBJECT TERMS
JP-8+100, Fuel additive, thermal stability, Spec-Aid 8Q462

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
a. REPORT	b. ABSTRACT	c. THIS PAGE			Robert W. Morris, Jr.
Unclassified	Unclassified	Unclassified	SAR	72	19b. TELEPHONE NUMBER *(Include Area Code)* N/A

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FOREWORD

In the mid-1990s the US Air Force and the Air National Guard began using JP-8 containing a thermal stability-improving additive, Spec-Aid 8Q462, in truck-refueled aircraft. Manufactured by GE Betz (formerly Betz Chemical and Betz Dearborn), this additive was selected from hundreds of additives tested during a 5-year evaluation period by AFRL/PRTG (now AFRL/RZPF) and The University of Dayton Research Institute (UDRI). Fuel containing this additive was designated JP-8+100 – signifying the improvement in fuel thermal stability by up to 100 °F.

After nearly a decade in the field, the Defense Energy Support Center (DESC) sought assistance from the Fuels Branch (now Fuels and Energy Branch) at AFRL to develop and evaluate a 'Next Generation' JP-8+100 additive that could be fielded as a drop-in alternative to the currently used Spec-Aid 8Q462. In response to the DESC request, AFRL proposed a multi-phase program to develop, evaluate and approve one or more additives meeting the goals of the program. In Phase I, additive manufactures were solicited for candidates for evaluation. Candidate additives were screened for their impact on fuel thermal stability using an array of bench and rig-scale test devices. Those candidate additives that were found to provide thermal stability-enhancing performance equivalent to or better than the existing Spec-Aid 8Q462 additive were evaluated in a Phase II program where additives would be studied to determine their impact on fuel properties and characteristics. The goal of this broader-scope program would be to approve qualifying additives as drop-in alternatives to Spec-Aid 8Q462.

This report describes the thermal stability testing and evaluation of four additives that were down-selected from several candidates from several additive manufactures each of which give thermal stability improvements at least as good as the currently approved and qualified additive, Spec-Aid 8Q462.

ACKNOWLEDGEMENTS

This work was co-funded by AFRL/RZPF (Formerly AFRL/PRTG) and the Defense Energy Support Center (DESC). All of the work was done at laboratory facilities provided by AFRL/RZPF at Wright-Patterson Air Force Base, Ohio with technical and engineering support provided by AFRL and the University of Dayton Research Institute (UDRI) under Cooperative Agreement Grant Number F33615-03-2-2347. The author wishes to acknowledge the significant contribution to this program from the following individuals from UDRI:

- Dr. Steve Zabarnick for his ground-breaking work and expertise in the Quartz Crystal Microbalance apparatus and his expertise in the general field of fuel thermal stability and fuel deposition chemistry.
- Mr. Gordon Dieterle for his engineering support and operation of the Extended Duration Thermal Stability Test (EDTST).The authors also gratefully acknowledge Mr. Dieterle for his expertise in analyzing EDTST data.
- Mr. James Shardo for his engineering and technical support in the day-to-day operation and maintenance of the Advanced Reduced Scale Fuel System Simulator (ARSFSS) and for his effort in extracting test operation data for analysis.
- Mr. Kenneth E. (Ed) Binns for his vast experience in real-world fuel systems and for his bringing that experience to both the EDTST and the ARSFSS.
- Ms. Lori Balster for her work with the Isothermal Corrosion Oxidation Tester (ICOT). Many thanks to Lori for her effort and for providing timely data to this program.
- Mr. Dennis Davis for his engineering and technical support in the operation of the Extended Duration Thermal Stability Test (EDTST) for this program.
- Mr. Zachary West for his expertise in operation of the QCM. Many thanks to Zach for providing the authors with data analysis plots showing additive relationships.
- Many, many others … for their support and expertise brought to this program over the course of its execution.

LIST OF ACRONYMS AND ABBREVIATIONS

ACRONYM	DESCRIPTION
AO	Antioxidant
ARSFSS	Advanced Reduced Scale Fuel System Simulator
ASTM	American Society for Testing and Materials
BFA	Burner Feed Arm
CI/LI	Corrosion Inhibitor/Lubricity Improver
CRADA	Cooperative Research and Development Agreement
DESC	Defense Energy Supply Center
DiEGME	DiEthylene Glycol Monomethyl Ether
DLA	Defense Logistics Agency
EDTST	Extended Duration Thermal Stability Test
EHSV	Electro-Hydraulic Servo Valve
FCOC	Fuel-Cooled Oil Cooler
FCV	Flow Control Valve
FDV	Flow Divider Valve
FSII	Fuel System Icing Inhibitor
GDTC	Generic Durability Test Cycle
HLPS	Hot Liquid Process System
ICOT	Isothermal Corrosion Oxidation Tester
MDA	Metal Deactivator Additive
OEM	Original Equipment Manufacturer
PPH	Pounds (mass) Per Hour
PSID	Pounds Per Square Inch, Differential
QCM	Quartz Crystal Microbalance
QPL	Qualified Products List
RTB	Return To Bulk
SDA	Static Dissipater Additive
SV	Servo Valve
TO	Technical Order
UDRI	University Of Dayton Research Institute
WPAFB	Wright-Patterson Air Force Base

1. Executive Summary

In the mid-1990s the US Air Force and the Air National Guard began using JP-8 containing a thermal stability improving additive, Spec-Aid 8Q462, in truck-refueled aircraft. This additive, manufactured by GE Betz (formerly Betz Chemical and Betz Dearborn) was selected from hundreds of additives tested during a 5-year evaluation period by AFRL/PRTG (now AFRL/RZPF) and The University of Dayton Research Institute (UDRI). Fuel containing this additive was designated 'JP-8+100' – signifying the improvement in fuel thermal stability by up to 100 °F.

After nearly a decade in the field, the Defense Energy Support Center (DESC) sought assistance from AFRL's Fuels Branch (now Fuels and Energy Branch) at AFRL to develop and evaluate a 'Next Generation' JP-8+100 additive that could be fielded as a drop-in alternative to the currently used Spec-Aid 8Q462. In response to the DESC request, AFRL proposed a multi-phase program to develop, evaluate and approve one or more additives meeting the goals of the program. In Phase I, additive manufactures would be solicited for candidates for evaluation. Candidate additives would be screened for their impact on fuel thermal stability using an array of bench and rig-scale test devices. If any of the candidate additives were found to provide thermal stability-enhancing performance equivalent to or better than the existing Spec-Aid 8Q462 additive, a Phase II program would be initiated to perform a broader-scoped evaluation of the additive to determine the additive's impact on fuel properties and characteristics. The goal of this broader-scope program would be to approve qualifying additives as drop-in alternatives to Spec-Aid 8Q462.

This report describes the results of testing and evaluation of candidate additives that give thermal stability improvements at least as good as the currently approved and qualified additive, Spec-Aid 8Q462.

In summary, the following additive candidates were determined to have the same or better thermal stability performance in JP-8 fuel as the currently approved additive, Spec-Aid 8Q462.

- BP/Lubrizol OS 169558F, designated in this study as additive P39
- Nalco VX-7603, designated in this study as additive P44
- Infineum/ExxonMobil NB31011-33 (as of the publication of this document, Infineum has adopted the commercial designation of 'AV100'), designated in this study as additive P47
- BASF Kerocom 69781, designated in this study as additive P50 (as of the publication of this document, BASF has adopted the commercial designation of 'Kerojet® 100' for this additive)

These additives along with Spec-Aid 8Q462 (designated in this study as additive P41) are recommended for further evaluation in the Phase II Fit-For-Purpose and Specification Compliance Testing.

2. Background

In addition to providing the propulsion energy for flight, military turbine engine aviation fuel (JP-8, MIL-DTL-83133F) is also used as the primary heat sink in current and advanced military aircraft to provide necessary cooling of critical systems. The heat that is added to the fuel by these various cooling processes can cause bulk fuel temperatures to become significantly elevated – often in excess of 300-325°F in some areas of the fuel system. In addition, this same fuel can be exposed to fuel wetted-wall surface temperatures in excess of 500 °F. When any hydrocarbon-based fuel is exposed to these kinds of temperatures, thermal oxidation begins to take place as the oxygen which is dissolved in the fuel begins to react with fuel components.[1] These thermal oxidation reactions lead to the formation of gums, varnishes and hard carbon deposits in various parts of the fuel system and are commonly referred to as 'coke' or 'fouling'. Depending upon the temperature regime to which the fuel is exposed, the fuel can exhibit different deposition characteristics. In the 550 °F and below range, deposition is mainly characterized as 'oxidative' - where deposition is formed through a series of reactions involving free-radicals, peroxides and oxygen dissolved in the fuel. At temperatures of 900 °F and higher, deposition is characterized as 'pyrolytic' - where the fundamental reactions involve the breaking of molecular hydrocarbon chains instead of undergoing the reactions characteristic of oxidative deposition (See Figure 1). Regardless of the temperature range and method of formation, these deposits represent a significant detriment to the performance of aircraft engines and flight systems. Aircraft engine and airframe maintainers are forced to perform periodic maintenance actions on many fuel system and engine hot section components as a result of this coke.

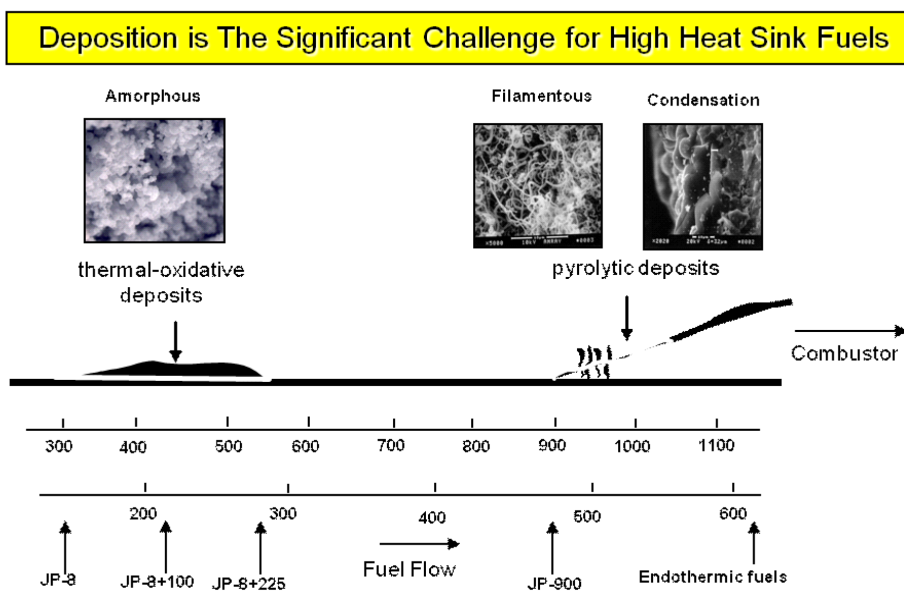

Figure 1. Deposition Characteristics by Temperature Regime

Coke present in an aircraft system, particularly the engine, lowers the on-wing time of engines and can result in significant damage to engine hot section components if not properly maintained. Even with proper scheduled maintenance, the presence of coke in any part of the aircraft or engine system always has a deleterious effect upon performance, reliability, maintainability and longevity. Ultimately, the net result of coking and the effort required to remove it from aircraft systems is increased maintenance costs. Each time an engine is removed from an aircraft for maintenance, a fixed minimum cost is incurred. Depending on the type of engine involved, the type of maintenance required and the location of coke in the

1 *Ervin J.S., Williams, T.F., Henegan, S.P. and Zabarnick, S., "The Effects of Dissolved Oxygen Concentration, Fractional Oxygen Consumption and Additives on JP-8 Thermal Stability" Accepted for Presentation at ASME International Gas Turbine Institute, Birmingham, England, 1996*

engine, hundreds of thousands of dollars may be expended to return an engine to service.

As current aircraft are updated with new and improved capabilities and as next-generation aircraft are developed and deployed, the cooling requirement which the fuel is expected to supply is rapidly increasing[2] (See Figure 2). Since fuel is used as a coolant medium for aircraft systems, and the amount of cooling available is dependent upon the fuel flow rates within the aircraft system, this problem is compounded by reduction in fuel consumption rates of newer aircraft versus legacy, currently fielded systems. The heat sink or cooling capacity provided by the fuel is directly related to the fuel flow rates through the system.

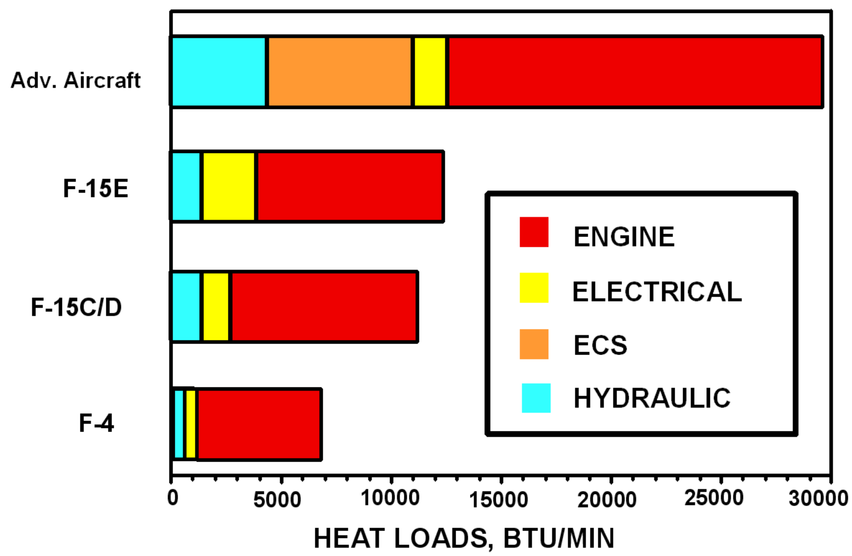

Figure 2. Engine Thermal Heat Loads - Legacy and Future Aircraft Systems

So, at the same time that the heat dissipation requirements are increasing, the reduction of fuel consumption rates means that there is less fuel flowing in the system that can be used to absorb this heat – resulting in higher fuel/fuel system component temperatures. This is a vicious cycle. Higher fuel and fuel system component temperatures lead to more coking -- and more coking leads to higher fuel system temperatures, reduced thermal management system performance and therefore higher fuel temperatures which leads to … etc.

In 1990, AFRL/PRTG (now AFRL/RZPF) formed a multi-organizational working group representing Government, Academia and Industry to develop a high thermal stability fuel (JP-8+100) with a goal of providing a 100 °F increase in fuel thermal stability and therefore a resultant 50% improvement in the heat sink capability over conventional JP-8. Although hundreds of additives were evaluated during this program, only one additive, GE Betz Spec-Aid 8Q462, was ultimately successful in qualifying for use as a thermal stability enhancing additive[3]. The fuel resulting from the addition of this approved additive at 256 mg/L is designated as JP-8+100. This additized fuel was first fielded in 1994 with the Oregon Air National Guard located at Klamath Falls, Oregon. Since that time, no other additive has been approved for use as a +100 additive.

In the last decade that the currently approved additive has been used in the field, Users have been consistently reluctant to use the approved +100 additive. While it has been conclusively shown in study

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2 Harrison, W.E. III, "Aircraft Thermal Management: Report of the Joint WRDC/ASD Aircraft Thermal Management Working Group", WRDC-TR-90-2021, 1990

3 Anderson, S.D., Harrison, W.E.III, Edwards, J.T., Morris, R.W.Jr., Shouse, D.T., "Development of Thermal Stability Additive Packages for JP-8", Paper for 5th International Conference on Stability and Handling of Liquid Fuels, Rotterdam, the Netherlands, October 1994 after study that there are measurable benefits to using the additive in terms of aircraft/engine maintenance and operation, there has always been a concern that since the GE Betz additive contains a detergent dispersant as a part of the active formulation, this detergent dispersant might decrease the water separation effectiveness of filter coalescers. While there was no technical data to support this concern, neither was there data to refute it. This lack of data has led to the fear of a particular behavior as the driving factor for constraints on logistics related to aircraft defuels and fuel RTB's (Return to Bulk). Because of this, some Users have been less than enthusiastic in their embrace of this new additive technology. In the ensuing decade and a half since the introduction of Spec-Aid 8Q462, this data gap has been closed and it has now been shown that Spec-Aid 8Q462 has no worse an impact on filter coalescer performance when compared to non-additized Jet A than standard JP-8[4]. During the program described in this technical report, RZPF has accomplished preliminary testing on selected additive supplied by several additive manufacturers (OEMs). Some candidate additives not only improve thermal stability equivalent to or better than Spec-Aid 8Q462, they even claim improved water separation performance. If these claims can be substantiated, then these new candidate additives may offer substantial potential for offering improved thermal stability performance without some of the logistical penalties of the currently approved additive. Additionally, at a time when there is consideration being given to making Jet A the Air Force standard fuel and then additizing at User location to meet operational and weapon system needs, it will be vitally important that potential additive negative effects and the additization process be as transparent to User operations as possible. If a +100 additive can be found that does not have the water separation concerns of the current +100 additive, it becomes infinitely more feasible to accomplish additive injection at the Using location without concern that the additive will adversely affect filter/coalescer function and performance.

From a logistical cost perspective, the availability of only one approved +100 additive increases the cost to DoD and decreases the flexibility of fuel logistics and field operations in the field and in deployed areas. The approval of additional additives for use in JP-8+100 should reduce additive procurement costs and increase additive availability. Without an alternate additive or additives to bring competition to the additive market, there is little incentive for a single additive manufacturer to consider an alternate pricing structure. However, if one or more alternate additives can be approved for use, the resulting competition could result in a significant lowering of additive costs – resulting in potentially significant savings.

Ultimately, the suitability of an additive for use in JP-8+100 is based not only on thermal stability improving performance, but also on chemical and functional characteristics as well as compatibility with existing additives and fuel system materials. Fieldability characteristics -- such as water separation, filtration performance, fungibility with existing additives and fuel delivery systems as well as detectability in the field, performance in combustor and nozzle tests, and altitude relight characteristics are critical elements that determine an additive's ultimate acceptability. Such an evaluation requires a program far more substantial in scope and cost than this Phase I program. Therefore, the scope of this Phase I program was limited to three tasks.

In **Task 1**, candidate additives were evaluated to determine their impact on fuel thermal stability. Each candidate additive was evaluated in accordance with the accepted JP-8+100 thermal stability evaluation protocol. To successfully complete this Task, candidate additives were required to exhibit thermal stability improving performance greater than or equal to the thermal stability improving performance of the currently approved Spec-Aid 8Q462 when evaluated under the testing protocol established for this program. The details of the protocol for this task are given in the section of this report discussing experimental procedures and results. Additive candidates which successfully passed the evaluation protocol were further evaluated in Tasks 2 and 3.

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4 Besse, G.B., Buckingham, J.P., Hughes, V.,"Southwest Research Institute® Aviation Fuel Filtration Cooperative R&D Program – Final Report", SwRI® Project No. 08-10844, January 2006

In **Task 2**, inter-additive compatibility was evaluated. This consisted of evaluation of additive inter-compatibility while blended in fuel. Since there would be the possibility of one or more approved additives being combined in their raw, as-delivered form in the field, compatibility studies were extended to an evaluation of co-mingled additives in their manufactured, as-delivered form. The details of the protocol for this task given in the section of this report discussing experimental procedures and results.

In the field, there is always the possibility that fuel can be additized incorrectly – resulting in additive concentrations far less or far more than the recommended dosages. Since additization below recommended parameters poses no risk to the aircraft, effects of additization at levels below recommended treat rates were not investigated. However, in cases of over-additization, there is always a concern that this could cause a degradation of fuel properties and fuel thermal stability performance – resulting in increased risk to the aircraft. Therefore, additives that showed no inter-compatibility issues in Task 2 were evaluated in **Task 3** – a study of the effects of additive concentration. The details of the protocol for this task are given in the section of this report discussing experimental procedures and results.

3. Experimental Results

3.1 Program Fuels

A range of fuels were selected and used for this program – representing JP-8s and Jet As of various thermal stability levels. As will be described later in this section, a baseline fuel was established for each test device to maximize the fidelity of that particular test for thermal stability performance evaluation. In the small bench-scale tests requiring small amounts of fuel, it was possible to establish a baseline fuel and stay with this baseline for the duration of the Phase I testing. However, in test rigs requiring larger amounts of fuel, it was not possible to keep the same baseline fuel for the entire program. Where a fuel change was required, a baseline fuel was selected that was equivalent to the fuel it was replacing with respect to thermal stability. The list of fuels used in this Phase I program are given below along with a brief description of the origin, age and characteristics of the fuel. It is worth noting that the majority of the thermal stability testing for this program occurred during 2005 - 2006.

POSF-3084 (Jet A) – a commercial Jet A, circa 1994. This fuel was considered to be a difficult to treat fuel from a thermal stability standpoint. It was available in limited quantity and was used as a baseline fuel by both the Extended Duration Thermal Stability Test (EDTST) and Isothermal Corrosion Oxidation Tester (ICOT). When the supply of this fuel ran low, it was no longer used on the EDTST and the remaining quantity of the fuel was isolated and reserved for the ICOT exclusively. In the EDTST, this fuel was replaced by POSF-2827.

POSF-3773 – a standard garden-variety JP-8 (circa 2000) received from WPAFB flightline. Used as a baseline fuel in the ICOT.

POSF-3804 - another garden-variety JP-8 (circa 2000) received from the WPAFB flightline. This fuel was also used as a baseline for the ICOT.

POSF-3166 – an AMOCO Jet A (circa 1995). This fuel is used exclusively by the Quartz Crystal Microbalance (QCM) as a baseline fuel.

POSF-2827 – a commercial Jet A (circa 1991). This fuel was considered to be one of the nastiest fuels in the inventory due to its age and water contamination level. This fuel had significant entrained water and water bottoms in the storage tank. It was primarily used as a hard-to-treat baseline fuel for the EDTST. Prior to using this fuel in the EDTST, drum quantities were allowed to stand to allow the water to settle out.

POSF-4177 – another garden-variety JP-8 (circa 2002) received from the WPAFB flightline. This fuel was used as the baseline fuel for both the EDTST and the Advanced Reduced Scale Fuel System Simulator (ARSFSS). When the supply of this fuel was depleted, it was replaced by POSF-4751 – another JP-8 from the WPAFB flightline.

POSF-4751 – a garden-variety JP-8 of moderate thermal stability (circa 2004). This fuel replaced POSF-4177 as the baseline fuel for both the EDTST and ARSFSS when 4177 was depleted.

In the case of fuel 3084 (Jet A), this fuel was converted to a ‘JP-8’ for testing by additizing with the standard military additive package (See Appendix A). For this program, the standard military additive package consisted of Fuel System Icing Inhibitor (FSII) (consisting of 100% diethyleneglycol monomethylether – DiEGME) added to the fuel at a minimum of 0.11 volume percent, Static Dissipater Additive (SDA)(STADIS® 450) dosed to the fuel at a rate of between 1.5 and 2.5 mg/L of fuel, and a Corrosion Inhibitor/Lubricity Improver (CI/LI) dosed at 16 mg/L fuel and finally, Antioxidant (AO) at a rate of 20 mg/L

3.2 Test Rigs and Testing Protocols

When the initial evaluations of JP-8+100 candidate additives began in the late 1980's there was no specific protocol established to provide a way of measuring the degree of success of a particular additive. Most of the work that was done in that program involved breaking new ground with regard to testing equipment and methodologies. For this program, researchers reviewed over a decade of experience and established a logical methodology for qualifying candidate additives as alternates to the existing +100 additive. Figure 3 represents the testing and evaluation protocol that was established at the beginning of this program. This protocol, with exception of using the ALCOR Hot Liquid Processing System (HLPS) test, was followed for the duration of this Phase I effort in order to assure consistency of test methods and results. The use of the HLPS was discontinued as a protocol test due to the unavailability of that test within the program's resources. The red line in the Figure 3 diagram represents the portion of the protocol that was exercised during this Phase I program.

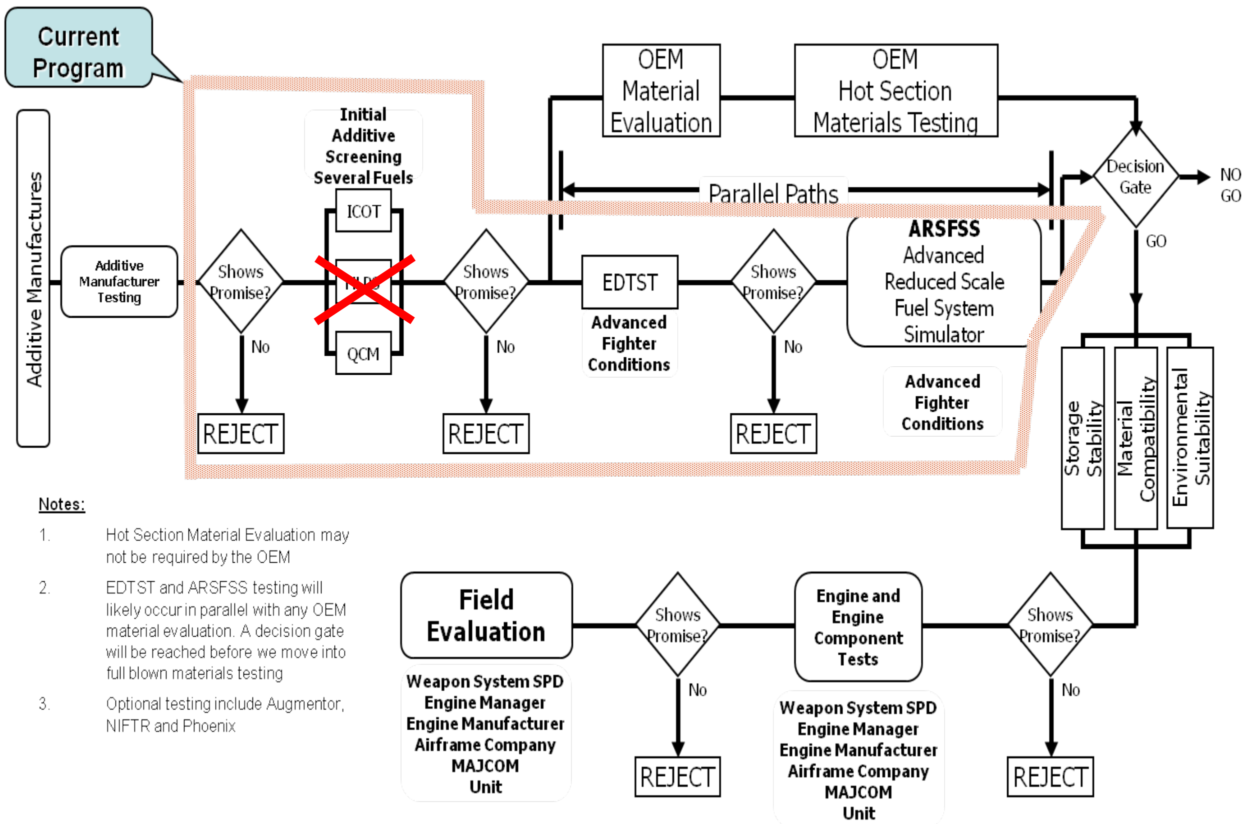


Figure 3. Testing Protocol For Candidate Additives

For each test represented in the outlined portion of the protocol in Figure 3, exit criteria were established based on past experience. Recognizing that the exit criteria was dependent upon the particular nature and characteristics of the test, Baseline Fuel Selection Criteria were also established for each test based on decades-worth of experimental experience. These criteria are shown in Figure 4.

As illustrated by the protocol flow depicted in Figure 3, the evaluation testing was accomplished in a hierarchical fashion. Not just any additive was evaluated. In order to be considered for entry into this program, the additive manufacture was asked to provide thermal stability data based on whatever testing protocol and apparatus was available to them. This thermal stability information was used to determine if the additive had sufficient potential to merit being included in this program. Once this potential was determined, upon receipt, an additive was first evaluated in the Isothermal Corrosion Oxidation Tester

Test Method	Baseline Fuel Selection Criteria	General Acceptance Criteria
ICOT	•Deposition between 50 and 200 mg/L •For information on currently accepted baseline fuels, contact AFRL/PRTG	**•Reduces deposition to <= 20 mg/L in any two out of three accepted baseline fuels**
QCM	•Max Deposition: 3-10 μg/cm^2 •For information on currently accepted baseline fuels, contact AFRL/PRTG	**•<= 1.0 μg/cm^2 in accepted baseline fuel** **OR** **•At least as good as the currently accepted +100 additive in the accepted baseline fuel**
EDTST	•At 350 °F bulk fuel temperature and 500 °F wetted wall temperature • Preheater max deposit > 5 and <20 μg/cm^2 • Heater max deposit > 1000 μg/cm^2 • 7-micron filter > 10,000 μg	**•At 375 °F bulk fuel temperature and 500 °F wetted wall temperature** • **Preheater max deposit <= 8 μg/cm^2** • **Heater max deposit <= 300 μg/cm^2** • **Cold Visual Strip – clean to slight** • **Hot Visual Strip – clean to slight**
ARSFSS	•Typical on-spec JP-8 Fuel	**Meets or exceeds when compared to currently accepted +100 additive by direct comparison**

Figure 4. Additive Evaluation Acceptance Criteria

(ICOT) and the Quartz Crystal Microbalance (QCM) since these are fairly rapid turn-around tests and require minimal fuel/additive. For details regarding the operating conditions for the ICOT and QCM, see the appropriate appendices for these devices at the end of this report.

If an additive candidate failed to meet the acceptance criteria for either the ICOT or the QCM, the additive was rejected and the manufacture notified. In many cases, the manufacture responded with a completely new or slightly adjusted formulation -- depending upon the results of these two tests. Any re-submitted additive was evaluated again from the start of the protocol.

If the additive met acceptance criteria as shown in Figure 4 in both of these tests, it was then evaluated in the Extended Duration Thermal Stability Test (EDTST). The EDTST more closely represents the conditions present in actual aircraft fuel systems therefore providing a more realistic simulation than small bench-scale devices. As a result of this more realistic simulation, it was not uncommon for an additive to pass the exit criteria for both the ICOT and QCM yet not pass in the EDTST. Although not specifically required by the protocol, we found it advantageous to evaluate additives in the EDTST using more than one fuel baseline fuel – thereby demonstrating additive performance in fuels with a range of thermal stability characteristics.

The operational conditions for the EDTST were dependent upon whether the fuel was additized or not. For non-additized fuel baseline runs, the temperatures of 350 °F bulk fuel temperature and 400 °F wetted wall temperature (to more fully understand the significance of these temperatures and their locations in the rig, see Appendix D – Extended Duration Thermal Stability Test). For an additive run, to demonstrate the effect of the additive on thermal stability, the bulk fuel temperature was increased to 375 °F and wetted wall temperatures were increased to 500 °F. At the end of the test, carbon deposition in the preheater and heater tubes was determined by Leco Carbon Analyzer. Witness strips, showing bulk fuel deposition in both ‘cold’ and ‘hot’ areas were also examined and compared. As further demonstration of the effect of the additive under test, sometimes the baseline non-additized fuel was tested at the additized fuel test conditions of 375 °F bulk fuel temperature and 500 °F wetted wall temperature conditions. In these cases, the test was typically only run for only 24 hours instead of the normal 96 hours. This was because these elevated temperatures caused so much deposition in the non-additized fuel that after 24 hours the EDTST operation and control would become severely impacted by extensive deposition and the test would have to be terminated.

Once an additive had passed in the EDTST, the next step was to run it in the Advanced Reduced Scale Fuel System Simulator (ARSFSS). The ARSFSS is a detailed, 1/72nd scale rig that simulates the airframe and engine fuel systems for a high performance aircraft. In the engine simulator, some actual engine components are used where appropriate. The ARSFSS 'flies' missions – where each mission represents a typical generic durability cycle that the aircraft might experience in the real world. Simulation points include Ground Idle, Take-off, Cruise, High Power Cruise, Low Power Cruise and Idle Descent. A complete run consisted of a total of 65 of these generic durability test cycle missions. The fuel flow profile for a typical mission is shown in Figure 5. In this figure, the core fuel flow represents fuel flow through the engine to the combustor nozzles that is used for propulsion. The recirculation fuel flow is flow that is recycled from some point in the engine/airframe fuel system back to the airframe tanks and represents fuel flow that is primarily used for system cooling purposes. At the conclusion of the run, carbon deposition analysis by Leco Carbon Analyzer was performed on fuel tubes from the Fuel Cooled Oil Cooler (FCOC) and the Burner Feed Arm (BFA). In addition, valve hysteresis measurements were determined for the Servo Valve (SV) and the Flow Divider Valve (FDV). The Servo Valve was used to control the rate of recirculation fuel flow and represents an item that sees relatively low temperature fuel. However, it does see fuel whose temperature has been at that lower temperature for an extended time. The Flow Divider Valve represents the valve located in the combustor nozzle that controls fuel flow between primary and secondary nozzle orifices. At this location, the fuel is at a significantly elevated temperature but it has been at this temperature for a very short time. For both of these valves, post-test valve hysteresis was compared to pre-test valve hysteresis to assess the impact of deposition on valve performance. In addition to engineering measurements on simulator components, many of the components were photographed for comparison to clean, new components. This provided an estimate of the amount of visual deposition in these compo-

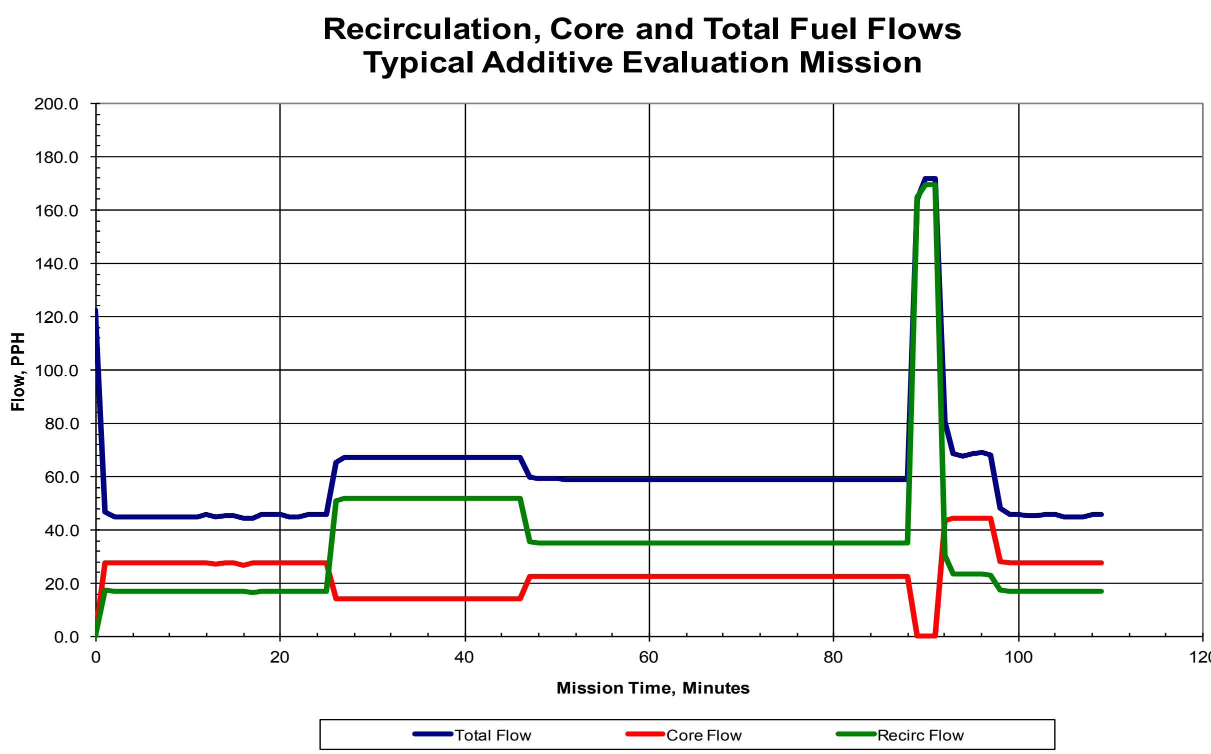


Figure 5. Generic Durability Test Cycle Mission

nents.

3.3 Task 1 – Additive Thermal Stability Evaluation

Armed with an overall testing protocol, Baseline Fuel Selection Criteria, Test Operation Parameters and General Acceptance Criteria, evaluation of candidate additives submitted by multiple manufactures was begun. Over the course of this Phase I program, dozens of additive candidates were submitted by additive manufactures. Some manufactures submitted multiple formulations of candidate additives for consideration. In many cases, reformulations and reformulations of reformulations were evaluated.

In the end, only three of the candidate additives were selected by virtue of passing all the appropriate criteria in all rigs at all levels. In order to maintain manufacturer anonymity (at the request of all the additive manufactures), the additives passing the criteria were designated as P39, P41, P44 and P47. The currently approved GE Betz Spec-Aid® 8Q462 is among these designated additives. For the duration of this program, additives were referred to by this 'P-Code' designation in order to maintain manufacture anonymity while being able to compare and share results during period program reviews to which all additive manufactures were invited. Since this report is being prepared after the completion of this work, it is now possible to reveal the additive manufactures involved and the additive P-Code and the additive manufacturer's product codes (see Table 1). The internal POSF Designator code is simply an internal sample code assigned to any chemical when it comes into the Fuels Branch. In some cases, multiple POSF codes appear for the same P-Code. In these cases, this is due to a replacement additive being received as initial samples were consumed in testing. Where these substitutions were made, the manufacture verified that the sample being received was from the same sample lot at the originally-coded sample, thus maintaining the

Additive Codes and Manufacturers			
Additive P-Code	**POSF Designator**	**Manufacturer**	**Manufacture Code**
P39	POSF-3974	BP/Lubrizol	OS 169558F
P41	POSF-4160/4580	GE Betz	Spec-Aid 8Q462
P44	POSF-4471/4550	Nalco	VX-7603
P47	POSF-4753	Infineum/ExxonMobil	NB-31011-33 a.k.a. AV100

Table 1. Additive Codes and Manufactures

integrity of the testing across multiple receipted samples.

3.3.1 Isothermal Corrosion Oxidation Tester (ICOT) and Quartz Crystal Microbalance (QCM) Testing

The ICOT is used to evaluate the effectiveness of thermal stability additives in aviation turbine fuels by stressing the baseline fuel and additized fuel at a constant temperature in the presence of flowing air. The thermal stability of the fuel is measure by the amount of solids formed in the bulk fuel which are collected when filtered.

The QCM is designed to evaluate the formation of solids on a surface in the presence of a decreasing amount of oxygen. The purpose of the QCM is to quantitatively evaluate the ability of an additive to prevent formation of these surface deposits

The general acceptance criteria for the ICOT (See Figure 4) is that in order to be considered successful, an additive must reduce deposition in the ICOT to 20 mg/L or less in any two out of three baseline fuels. Figure 6 is a table summarizing the data for these selected additives in the ICOT and QCM. Additives P39 and P41 passed in two out of three ICOT fuels while additives P44 and P47 passed in all the baseline fuels. Thus, all of the additives successfully passed the ICOT test.

The deposition for additive P39 in the QCM was numerically higher than the criteria allows (maximum of 1.0 µg/cm²) but at the time the QCM test was run, the deposition level produced by additive P39 in the QCM baseline fuel (2.2 µg/cm²) was commensurate with the levels being produced by the sample of the GE Betz Spec-Aid® 8Q462 that was available to the program at that time. As testing proceeded on newer samples, P39 was never re-evaluated – especially since (as will be seen in later pages of this section) the additive performed well in both the EDTST and ARSFSS. The remaining additives (P41, P44 and P47) performed well in the QCM. In the table in Figure 6, a range of values are given for QCM deposition for P41. This additive seemed to vary in its performance over time – hence the range of values reported. Even at 1.4 µg/cm², this value is not significantly higher than the protocol amount of 1.0 µg/cm². This additive was considered to successfully meet the QCM test criteria since this additive is the defacto baseline additive to which every other additive in this program was ultimately compared.

Based on this information, these four additives were evaluated in the EDTST. In the following figures, EDTST carbon deposition and witness strip visual information is presented comparing these four additives.

Additive	ICOT Deposition, mg/L[1]			QCM Deposition[2], µg/cm²
	Fuel 3084 (Jet A)	Fuel 3773 (JP-8)	Fuel 3804 (JP-8)	Fuel 3166 (Jet A)
P39	74	9	2	2.2
P41	31	10	0	0.6-1.4
P44	17	8	3	0.6
P47	18	8	10	0.7

Figure 6. Results of Additives in ICOT and QCM Tests

3.3.2 Extended Duration Thermal Stability Test (EDTST) Evaluations

While the ICOT and QCM offer valuable insight into thermal stability performance, both of these tests are performed at conditions not necessarily representative of conditions in an aircraft fuel system. Both of these tests attempt to maximize deposition at certain conditions. However, in an aircraft fuel system, these maximum deposition-forming conditions represent only a small portion of the life experience of the fuel. What is not represented in these single-condition bench scale tests is the time/temperature history experienced by fuel in an operating fuel system. For these reasons the Extended Duration Thermal Stability Test (EDTST) system was developed to evaluate fuels at temperature, residence time conditions and recirculation modes that are more representative of aircraft/engine fuel systems than small bench-

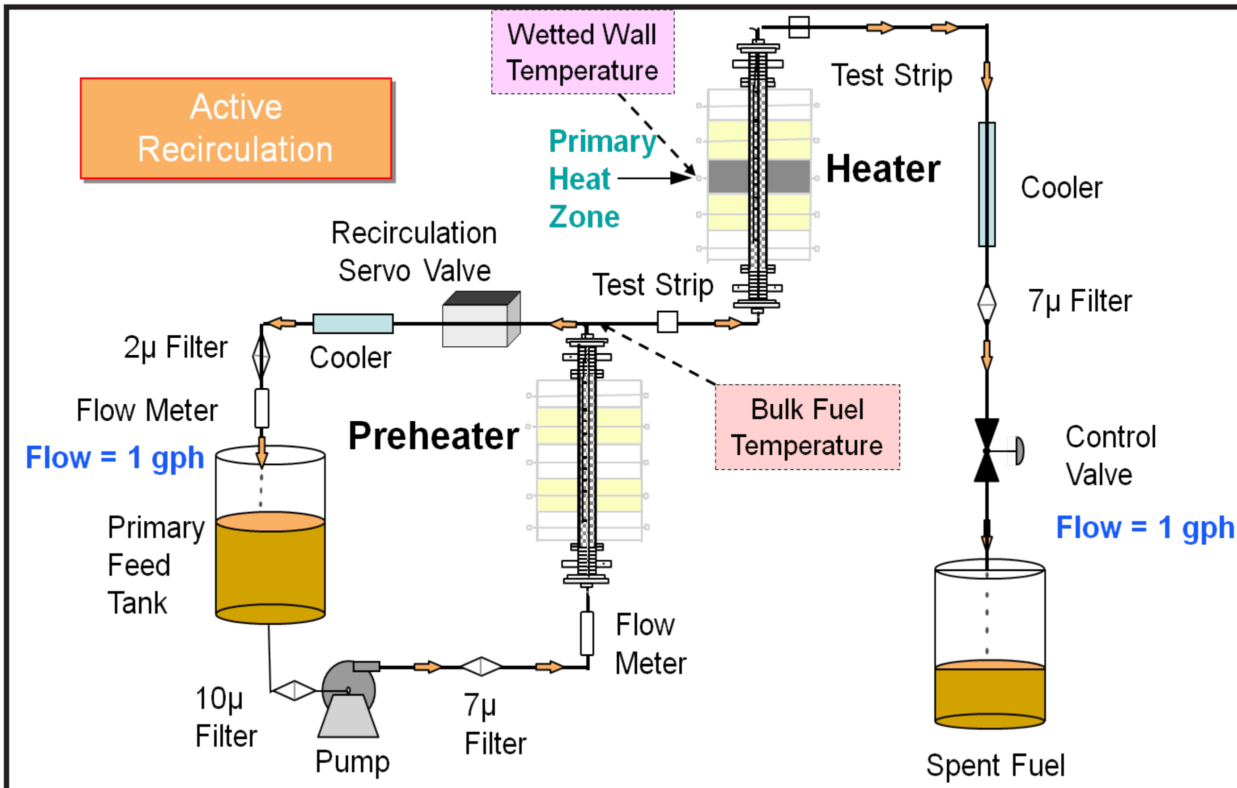


Figure 7. Extended Duration Thermal Stability Test (EDTST) Flow Diagram

scale test such as the ICOT and QCM. A basic flow schematic of the EDTST system is shown in Figure 7. The EDTST system is computer-controlled and can run unattended for long periods.

The first heater (preheater) in the system is used to establish both the desired bulk fuel temperature into the second heater and the desired fuel bypass temperature. The bulk temperature represents the fuel temperature that results from aircraft and engine heat loads and generally represents the temperature of the fuel in the bulk of the aircraft fuel system. The thermal conditions established in the second heater (main heater) are typically selected to achieve the appropriate wetted wall temperatures associated with engine fuel injection nozzles for the system being simulated. A typical main heater assembly is shown in Figure 8. A fuel bypass line is installed downstream of the preheater to represent the aircraft recirculation line from the engine to the airframe tanks. A water/fuel cooler is installed in this line to represent the cooling of fuel by an aircraft ram air heat exchanger cooler that is typical on many systems. Metal test strips are installed in housings immediately downstream of the preheater and after the cooler in the heater outlet line (see Figure 7). In each witness strip location, two strips are placed back-to-back and inserted into the fuel flow path. These strips are not actively heated so any deposition that occurs on these strips is related to bulk fuel temperature and therefore bulk fuel deposition. Witness strips represent a qualitative assessment of the nature of fuel deposits at temperature and flow conditions in recirculation areas of the fuel system. While the appearance of these witness strips is a part of the acceptance criteria for the EDTST, their qualitative nature makes this data subjective and as such, is of secondary importance or relevance to the carbon deposition data. Witness strip data is most valuable in providing additional guidance in interpreting EDTST results when carbon deposition data is suspect or inconsistent. As such, witness strip appearance information is not a deciding factor in and of itself.

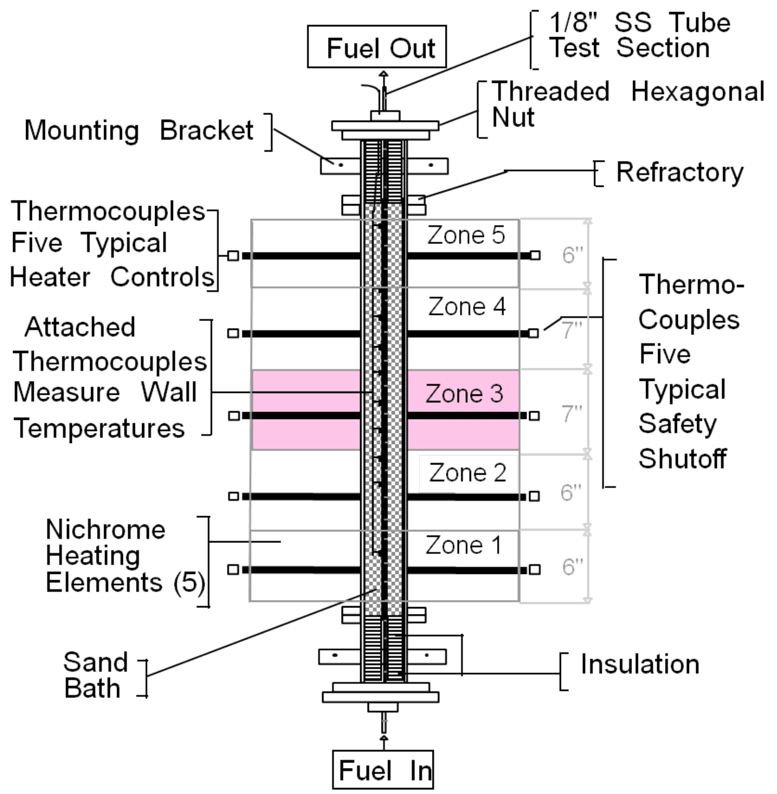


Figure 8. EDTST Heater Diagram

For this program, approximately 100 gallons of fuel was used for each 96-hour EDTST run. Upon completion of the run, the heated tube sections of both the preheater and heater were removed and rinsed with either hexane or heptane to remove residual fuel without removing carbon deposits. The tubes were then cut into two-inch sections and analyzed for the amount of carbon deposition using the LECO carbon analyzer and a testing protocol developed for that purpose. Witness strips were also removed from the system and rinsed to remove residual fuel but not carbon deposits and then photographed.

The following plots show Leco carbon deposition data for the EDTST preheater and heater tubes. In order to provide a proper basis of comparison, a baseline JP-8 fuel was run at standard JP-8 conditions (350 °F bulk fuel temperature and 500 °F wetted wall, referred to later in this report as 350/500 °F or JP-8 conditions) and at JP-8+100 conditions (375 °F bulk fuel temperature and 500 °F wetted wall, referred to later in this report as 375/500 °F or JP-8+100 conditions). As previously mentioned in this section, when a baseline JP-8 fuel was run at +100 conditions, the test duration was, by necessity, limited to a maximum of 24 hours.

Figure 9 shows carbon deposition in the EDTST preheater for all four candidate additives tested along with baseline JP-8 (POSF-4177) at both neat and additited conditions. The horizontal line mid-plot shows the acceptance criteria of maximum allowed for deposition in the EDTST preheater (8 $\mu g/cm^2$). The dashed black line rising toward the right of the plot shows deposition data for the baseline fuel POSF-4177 under JP-8+100 conditions (375 °F bulk fuel temperature and 500 °F wetted wall temperature). At first look, this deposition may not appear to be too significant when compared to the other data presented but recall that **this particular data set is for deposition in just 24 hours**. Extrapolating visually, one can see how significantly the additives reduce deposition in this preheater. The grey dashed line at the bottom of the plot shows the deposition for that same baseline JP-8 only under JP-8 conditions (350 °F bulk fuel

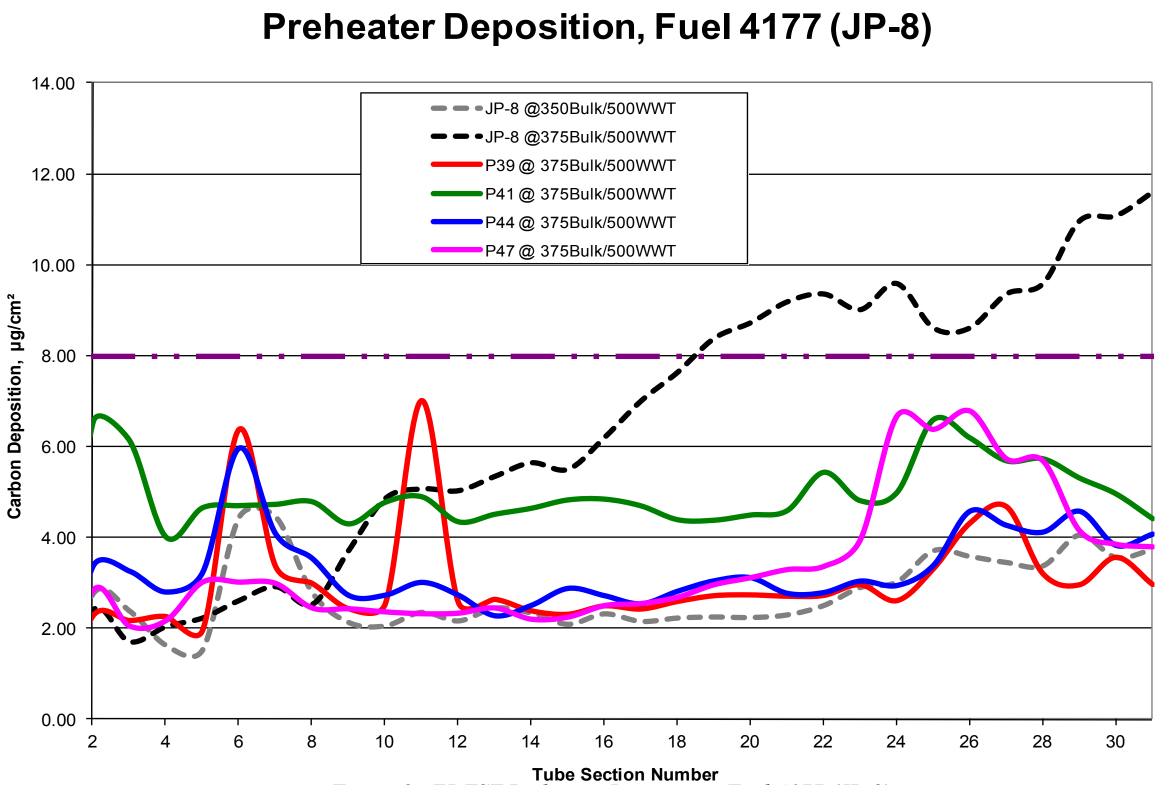


Figure 9. EDTST Preheater Deposition, Fuel 4177 (JP-8)

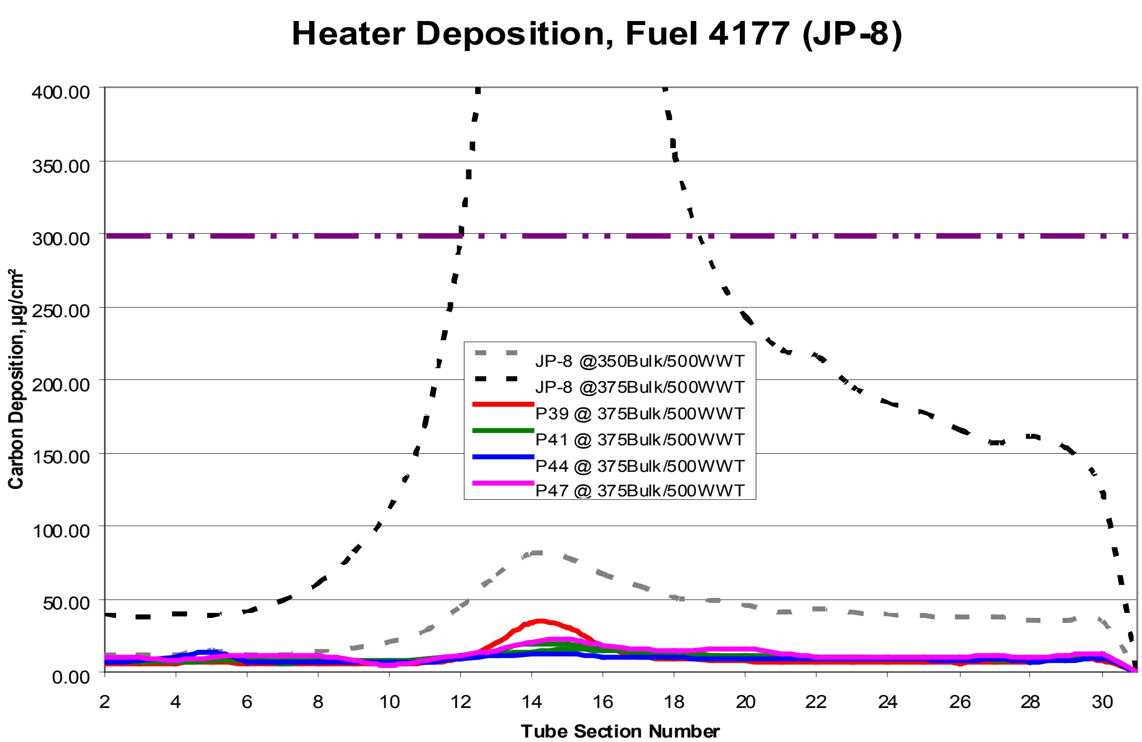


Figure 10. EDTST Heater Deposition, Fuel 4177 (JP-8)

and 500 °F wetted wall). This demonstrates that a significant change in deposition occurs given a small rise in bulk and wetted wall temperatures. Clearly, these JP-8 conditions represent the upper operability limit for conventional JP-8. Figure 9 also shows that while the details of the deposition curves for the additives may vary slightly, the difference is only about ± 2 μg/cm². This is within the experimental error of the Leco carbon deposition analysis method. Some of the additive deposition curves also exhibit some anomalies at the entrance and exit to the preheater tube. The deposition peaks in these areas appear to be, based on our experience, more a function of the tube material, entrance and exit effects and the way the tube is interfaced to the rest of the EDTST flowing system rather than to any real deposition characteristic of the fuel.

Figure 10 shows carbon deposition for these same fuels and additives in the EDTST heater. The two dashed lines represent the deposition of the baseline JP-8 at JP-8 conditions and JP-8+100 conditions. The deposition curve for POSF-4177 departs the bounds of the plot and rises to approximately 2000 μg/cm². Yet, the additives are able to maintain deposition levels below 20 μg/cm² - clearly demonstrating the effectiveness of these additives.

Figures 11 and 12 show the carbon deposition thermal stability performance of only three of the candidate additives – P39, P41 and P44 in the baseline fuel POSF-3084 with the standard military additive package of FSII, SDA, AO and CI/LI. The limited supply of this baseline fuel prevented running

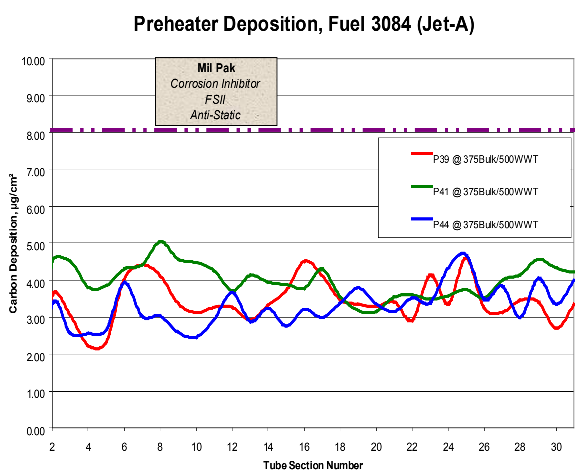


Figure 11. EDTST Preheater Deposition, Fuel 3084(Jet A)

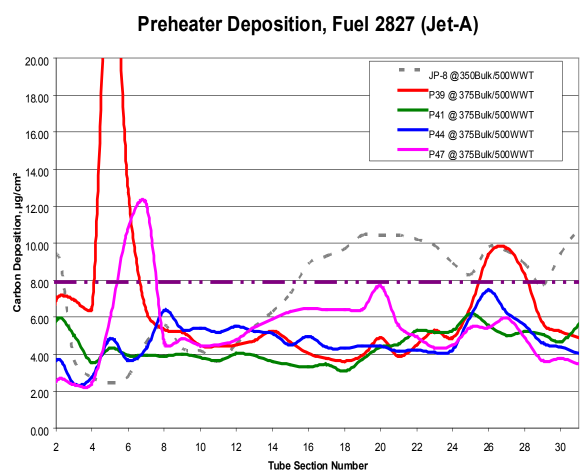


Figure 13. EDTST Preheater Deposition, Fuel 2827(Jet A)

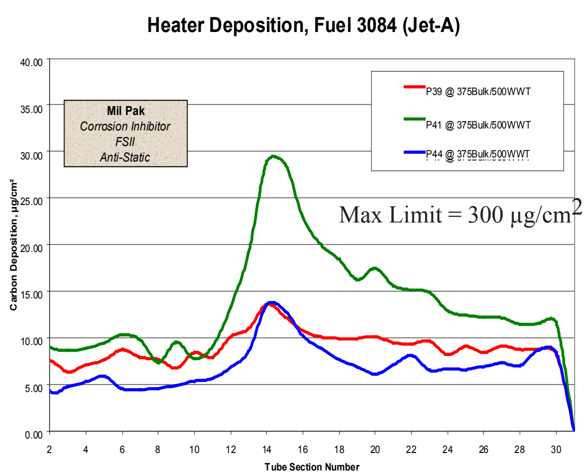


Figure 12. EDTST Heater Deposition, Fuel 3084(Jet A)

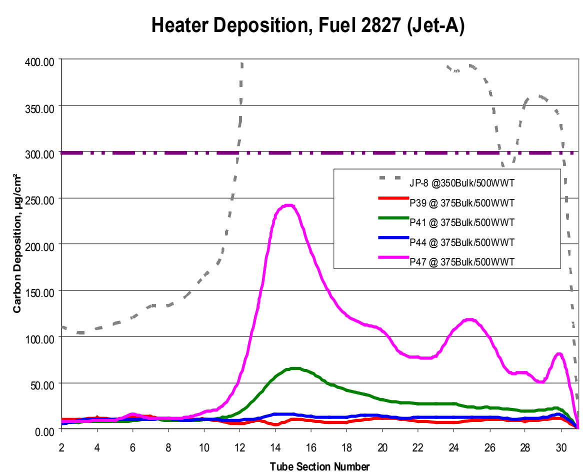


Figure 14. EDTST Heater Deposition, Fuel 2827(Jet A)

the baseline fuel with candidate additive P47 or by itself without the mil-pack of additives. It can be seen from the data plot in Figure 11 that the preheater deposition using these additives was typically limited to between 3 and 5 µg/cm^2 – well below the maximum acceptable deposition of 8 µg/cm^2. Similarly, Figure 12 shows heater deposition with these three additives to be well below the upper limit of 300 µg/cm^2

Figures 13, 14 and 15 show the carbon deposition thermal stability performance of all four candidate additives in fuel POSF-2827. Recall that this fuel was considered one of the worst possible fuels one might encounter and had been retained by RZPF in the fuel farm tanks since 1991 for the sole purpose of being used as a worst-case example fuel. For the testing here, this Jet A fuel was not additized with the standard military package of additives and was evaluated strictly as a Jet A. The 'badness' of this baseline 2827 fuel is not readily apparent in Figure 13, the EDTST Preheater Deposition plot. However, in Figure 14, the EDTST Heater Deposition Plot, it can be seen that even at JP-8 baseline test conditions of 350 °F bulk fuel and 500 °F wetted wall temperatures, fuel 2827 is a very high-depositing fuel. Yet, all of the additive candidates were able to lower deposition in this fuel to well below acceptance criteria limits of 8 µg/cm² in the preheater and 300 µg/cm² in the heater. Additive candidates P39 and P41 exhibit the poorest performance of the additives in this fuel. This may serve to conclude that there is a performance variability amongst the candidate additives. Yet in spite of this variability in performance, all of the candidate additives are able to reduce deposition to below acceptance criteria level and are therefore performing acceptably in a wide range of fuels. It should be noted that Figures 14 and 15 are plots of the same data but at different Y-axis ranges so that the magnitude of the deposition of the baseline 2827 fuel can be observed.

Figures 16 and 17 represent a compilation of Figures 9 through 14 – showing all the deposition data for all additives in all fuels. Figure 16 shows that all of the additives perform equally well in the EDTST preheater. Figure 17 shows that in the EDTST heater, the performance ratings amongst the additives begins to be observed but is primarily dependent up how 'bad' the baseline fuel is.

Figure 18 shows the typical appearance of both preheater and heater witness strips for a baseline fuel – in this case, POSF-4751. Fuel 4751 was used

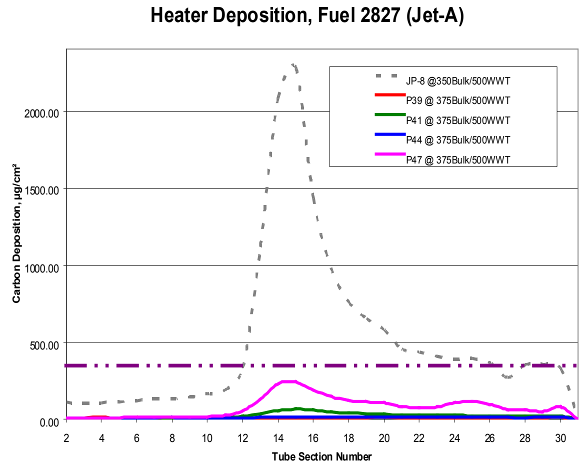


Figure 15. EDTST Preheater Deposition, Fuel 2827(Jet A)

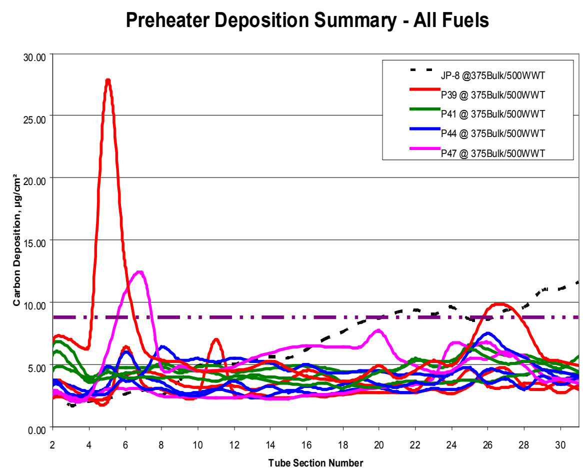


Figure 16. EDTST Heater Deposition, Fuel 2827(Jet A)

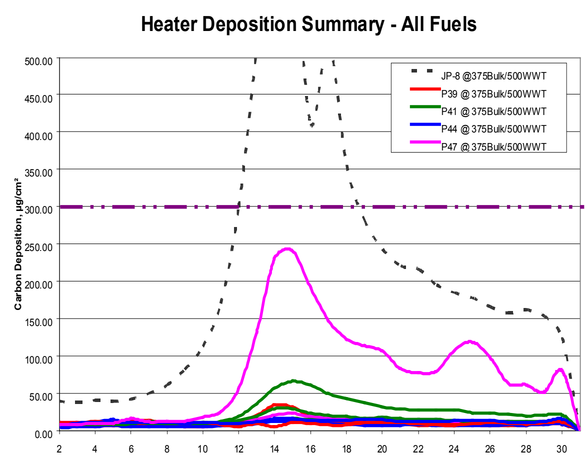


Figure 17. Heater Deposition Summary, All Fuels

in this Phase I thermal stability evaluation as being equivalent to baseline fuel 4177 and was used after all of the 4177 fuel was consumed in testing. Each image present here shows both the front and the back witness strips separated by a clean, never used strip for comparison. Deposition on the left and right strips may appear differently and this is due to unique flow patterns that develop within the witness strip containing device. Note, as expected, the heater witness strip exhibits a darker, more substantial deposit than the preheater as these strips see substantially hotter fuel. Comparison of these images to the images in Figures 19 and 20 to follow indicate the decrease in deposition observed when a thermal stability improving additive is used.

Figure 18. Typical Appearance Preheater/Heater Witness Strip

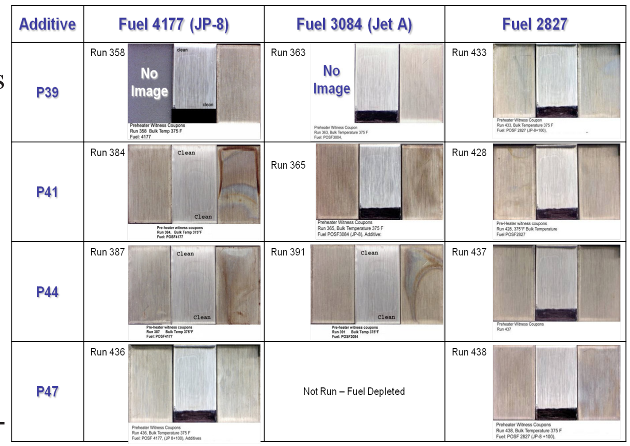


Figure 19. EDTST Preheater Deposition Summary, All Fuels

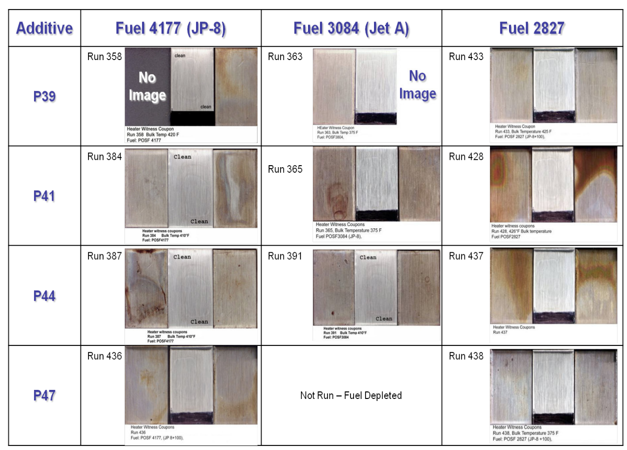


Figure 20. Heater Deposition Summary, All Fuels

Figures 19 and 20 show a series of images of witness strips representing evaluation of candidate additives in selected fuels. Additive P47 was not evaluated in fuel 3084 because this fuel was depleted before the test could be run. Note that in some images there is a significant difference between the left- and right-hand images. These differences are due to how the witness strips stacked together. The witness strip holder device is not a precision instrument designed to hold each strip exactly the same. Each setup of a witness strip in the EDTST is a unique situation, resulting in what can be very different and unique flow patterns. For this reason, these different deposits do not represent a poor performance of the additive but rather it represents a unique, non-standardized flow pattern. Qualitative phenomena such as this is why witness strip appearance is a secondary consideration in ranking of additive performance. It can be seen by comparing the images in Figures 19 and 20 to Figure 18 that in all cases in all fuels, the candidate additives have a significant impact in reducing the deposition apparent on these witness strips. Even in what is considered to be a very nasty fuel (2827), the additives are performing very well. Based on the appearance of these strips, the additives can be evenly ranked with regard to performance in reducing deposition in what would be considered a typical JP-8 or Jet A fuel meeting normal thermal stability specifications. However, in a severely degraded fuel such as 2827, two additives – P39 and P47 - seem to show better performance than the other two additives. The reader should keep in mind that the currently approved Spec-Aid 8Q462 additive is represented in these images in addition to other candidate additives.

Summarizing the EDTST deposition results, all additives performed equally well in the preheater with none of the additives distinguishing themselves above another candidate. However, in the heater, a discernible ranking amongst the additives started to emerge. Additives P39, P44 and P41 perform relatively similarly with P41 performing possibly slightly less well than P39 and P44. Additive P47 appears to rank as the least well performing additive – mainly due to it's performance in fuel 2827 – the worst of the baseline fuels. If this particular fuel is not considered, then there is little discernible difference in performance of the additives in a typical JP-8 and Jet A.

Summarizing EDTST results based on witness strip appearance, it can again be said that in the preheater, all additives preformed equally well. In the heater, again a slight difference in performance is discernible with P41 and P44 being the poorer performers but only in the worst baseline fuel. Again, if the performance in the worst baseline fuel is not considered, then all additives perform equally well in the heater for a typical JP-8 and Jet A.

Based on these observations, all of the candidate additives (including the currently approved Spec-Aid 8Q462) performed equally well in the EDTST. Therefore, no additives were removed from consideration and were considered acceptable for further testing in the Advanced Reduced Scale Fuel System Simulator (ARSFSS).

3.3.3 Advanced Reduced Scale Fuel System Simulator (ARSFSS) Evaluations

The Advanced Reduced Scale Fuel System Simulator (ARSFSS) represents a thermal stability evaluation device that more closely represents and replicates aircraft fuel system operating conditions than any other sub-aircraft scale test device in the world. Designed as a joint effort between AFRL, Boeing and Rolls Royce (UK) in the mid 1980s, the ARSFSS has been used to evaluate fuels and additives under realistic aircraft fuel system conditions. With more extensive capabilities than the EDTST, the ARSFSS is used by AFRL as the last test before releasing a fuel or additive for testing and evaluation in the field. Not only is the ARSFSS capable of realistically simulating the flow, temperature, pressure and residence time profiles for a real aircraft fuel system, it is capable of imposing these conditions on system hardware in real time with changes to flow, pressure and temperature conditions following a pre-established mission profile. In this way, the ARSFSS can 'fly' missions sequentially over time. An ARSFSS test run typically consists of between 65 and 150 missions executed sequentially operating 24 hours per day, 7 days a week. The ARSFSS control system is sophisticated enough to allow the test to operate unattended for days at a time.

The ARSFSS rig itself consists of three major subsystems – a fuel conditioning system, an airframe fuel system simulator and an engine fuel system simulator. A schematic of the ARSFSS is show in Figure 21. Figure 22 shows a front view of the engine portion of the simulator. The ARSFSS test rig is modifiable so that many different fuel system configurations and many different aircraft systems can be simulated. For this program, the ARSFSS was configured to simulate an F-22 aircraft with a Pratt & Whitney F119 engine. Rig scaling is based on 1/3 scale of a single F119 nozzle – making the ARSFSS scaled overall at 1/72nd scale for the F119 engine. Total fuel required for each ARSFSS test is between 900 and 1500 gallons – depending on the mission profile used for the testing. For more details on how the ARSFSS is designed and the components used, see Appendix E.

For this additive evaluation program, a modified generic durability test cycle mission profile was used. 65 mission cycles were executed for each test run requiring approximately 900 gallons of fuel.

Key data elements from the ARSFSS consist of both qualitative and quantitative information. The key comparison points for the ARSFSS are the fuel's behavior in the Servo Valve, Flow Divider Valve, Fuel-Cooled Oil Cooler and Burner Feed Arm. These devices are described as follows:

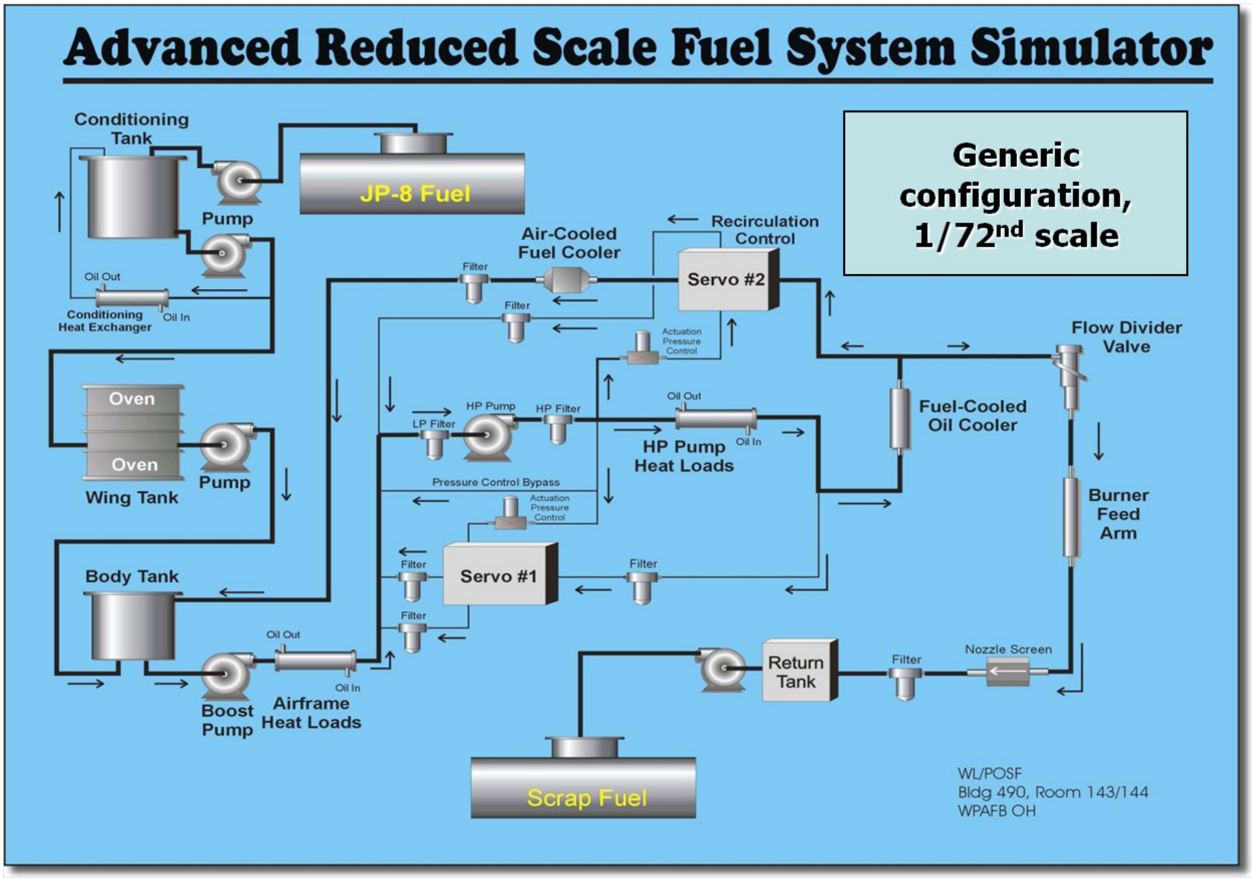


Figure 21. Flow Schematic for Advanced Reduced Scale Fuel System Simulator (ARSFSS)

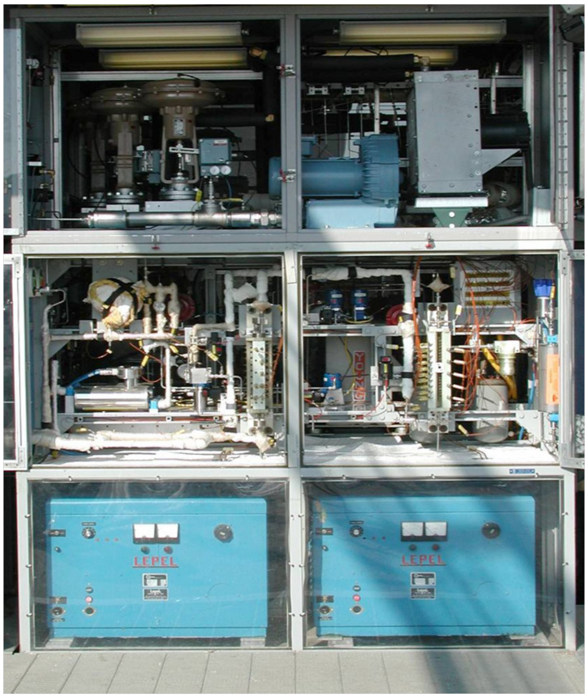


Figure 22. Advanced Reduced Scale Fuel System Simulator (ARSFSS)

3.3.3.1 Servo Valves 1 and 2

For the ARSFSS, the Servo Valve component is the second stage or hydraulic portion of an Electro-Hydraulic Servo Valve (EHSV) commonly found in F119 and similar systems. In an EHSV, the first stage of the control is an electrical servo mechanism that responds to an input current or voltage. Increasing current or voltage results in a small movement of the electrical servo components. The electrical servo components are coupled to a hydraulic component – the second stage of the control of the valve. The hydraulic portion of the valve consists of a spool and sleeve arrangement where a specially designed spool moves within a sleeve. Movement of the spool causes clearances within the spool/sleeve assembly to change and thus, control flow through the valve. Because the hydraulic portion of the valve is driven by pressures within the fuel system, the small forces generated by electrically positioning the electrical servo portion of the valve are amplified by system hydraulic pressures resulting in a substantial moving force being applied to a hydraulic component. These combined electrical and hydraulic components give engine manufactures the ability to exert substantial hydraulic forces upon the fuel system control using small electrical forces. However, since the hydraulic portion of the valve sees the fuel flow at bulk fuel system temperatures, coking and fouling can occur in these components. Since the ability of the EHSV to regulate fuel flow is dependent upon the unrestricted movement of the spool and sleeve valves that make up the hydraulic portion of the valve, even the slightest amount of deposition occurring in this valve can impact valve performance by causing hysteresis in the valve. Hysteresis in a valve can basically be described as the tendency of the performance of the valve (in terms of valve flow and pressure) to be dependent on its previous position along with whether the change in pressure to cause a change in valve flow is increasing or decreasing when reacting to an external control signal. Hysteresis leads to varying degrees of inaccuracy relative to valve actuation and operating forces and can drastically affect the performance of an engine fuel system. Under the best of circumstances, a well designed and well-functioning control valve has little or no hysteresis thereby allowing the control algorithms that predict and impose control movements to reliably and predictably position the valve for stable system control. As hysteresis increases, control algorithms may not properly compensate and system control can become unstable. For details on how valve hysteresis was determined for the Servo Valve, see Appendix E.

In addition to the hysteresis measurements made on the Servo Valve, at the end of each test run the Servo Valve was disassembled and photographed to document the type, degree and nature of the fuel deposits inside and on the valve components. This deposition, along with Servo Valve hysteresis measurements, was used to document the condition of the valve at the end of each test.

The very nature of the EHSV tends to minimize the impact of hysteresis naturally so no firm value for hysteresis in this component was established as an acceptable amount. Instead, it was determined that EHSV performance for a candidate additive would be acceptable as long as the overall hysteresis was better than or equivalent to the approved Spec-Aid 8Q462 additive.

3.3.3.2 Flow Divider Valve (FDV)

In addition to the EHSV, valve hysteresis is a significant issue in the combustor nozzle Flow Divider Valve (FDV). Each of the 24 combustor fuel nozzles for the F119 contains two fuel flow paths to the injector nozzle – a Primary and a Secondary. The Primary path typically handles fuel flow in the 'low' regime - for example, engine starting and ground idle and idle descent and conditions. Once the engine requires fuel flows outside of this 'low flow' regime, a Secondary 'high flow' path is opened up to deliver the necessary flow to the engine. This 'dividing' of the fuel flow is accomplished using a pressure-driven 'Flow Divider Valve' (FDV). This valve is physically positioned upstream of the fuel nozzle face and is located outside of the combustor in the compressor bypass or fan air flow path. Since this air flow can reach high temperatures, the FDV is subject to occurrence of coking. As with any other valve that is used to regulate flow that is subject to coking, any coking or fouling of the FDV can result in significant valve hysteresis. Unlike the EHSV, this FDV is driven only by inlet fuel pressure and does not have the benefit of multiplied hydraulic forces to overcome hysteresis. Thus, this valve can be quite sensitive to hysteresis brought on by fuel fouling.

In the ARSFSS, an actual FDV from the F119 is used. The flow slot has been modified by narrowing its width so that the typical stroke of the valve in the ARSFSS' reduced flow environment is essentially the same as for the full flow in an F119.

In discussions with Pratt and Whitney, it was determined that the acceptability criteria for FDV hysteresis would be 7% or less. According to engineers at Pratt & Whitney, hysteresis values beyond 7% could adversely impact the fuel flow to the nozzles and thus change the combustor temperature profile in the engine. An altered combustor temperature profile can have serious and deleterious impact on engine performance, reliability and safety. For details on how valve hysteresis was determined for the Flow Divider Valve, see Appendix E.

As with the Servo Valve, in addition to determining FDV valve hysteresis, the FDV is disassembled and photographed at the end of each ARSFSS run to document the type, nature and extent of the deposition that occurred in and on the valve components. These components include the FDV valve body, valve stem and strainer screen that surrounds the entire assembled valve and protects it from large pieces of debris.

3.3.3.3 Fuel-Cooled Oil Cooler (FCOC)

Aircraft fuel is used for cooling as well as propulsion. One area where fuel is used as a cooling medium is in the cooling of engine lubrication oil. In most systems, this involves simply exchanging heat between the engine oil and the fuel in a simple heat exchanger device – a Fuel-Cooled Oil Cooler (FCOC). Normally, the FCOC is base on a shell-and-tube heat exchanger design where fuel passes through the inside of the tube and engine lubrication oil passes on the outside of the tube, inside the shell of the heat exchanger. The number of tubes used in the FCOC depends upon the engine design and the amount of heat dissipation required. Normally, accepted engine design criteria dictates that bulk fuel temperature out of the FCOC should never exceed 325 °F which is the limit for oil operability in the engine. Obviously, at these temperatures, fuel can foul and coke can be deposited on the inside of the tubes of the FCOC. As with any heat exchanger, any fouling, either on the inside or the outside of the tubes, is detrimental to FCOC performance and can result in engine oil temperatures exceeding design limits. In the ARSFSS, the device simulating the engine FCOC is designed with three 3/8-inch diameter 0.035-inch thick walled stainless steel tubes. The tubes are connected via manifolds at either end of the FCOC device so that the fuel sees three complete end-to-end passes within the FCOC before emerging. The tube that is used for the final pass is removed at the end of each test and cut into 2-inch long segments. A LECO Carbon Analyzer is used to measure the amount of carbon deposition that has occurred inside this tube. This carbon deposition data is plotted as part of the data for the ARSFSS run. For this reason, no firm quantitative acceptance criteria was developed for this device. Acceptance was base on the deposition for a candidate additive being not more than the deposition for the currently approved Spec-Aid 8Q462 additive.

3.3.3.4 Burner Feed Arm (BFA)

In the a typical F119-type engine, each combustor nozzle is actually an assembly of three components – the FDV (which was discussed in a previous paragraph), the tubular pathways connecting the FDV to the nozzle (often referred to as the 'Burner Feed Arm' (BFA)) and either a pressure-atomizing or air-blast nozzle. The FDV regulates fuel flow to the Primary and Secondary fuel flow paths which transport fuel through the flow tubes (Burner Feed Arms) to the nozzle. In the actual F119 nozzle assembly, since this portion of the nozzle assembly is subjected to high temperature compressor discharge air, these BFA paths are contained within a complex shroud assembly for thermal isolation and protection. As previously described, the performance of the combustor fuel nozzle is critical to engine performance and control. This performance and control is not only impacted by the performance of the FDV in each combustor nozzle assembly, but it is impacted by the ability of the BFA flow paths to deliver unrestricted fuel flow to the nozzle. Significant coke deposits can, however, develop inside these tubes which can restrict fuel flow to the nozzle and therefore impact nozzle assembly overall performance - even though these paths are shrouded for thermal protection.

In the ARSFSS, these flow paths are simulated with the Burner Feed Arm (BFA). The BFA is inductively heated and consists of a 1/8-inch, 0.020-inch thick wall stainless steel tube placed in a ½-inch stainless steel clamshell. This clamshell helps evenly distribute the inductively-generated heat along the length of the BFA device. Thermocouples are located on the outside of the 1/8-inch tube along the whole flow path and are used to measure and control the wetted-wall temperature profile. At the end of each run, this 1/8-inch tube is removed and cut up into 1-inch segments. A LECO Carbon Analyzer is then used to measure the amount of deposition that has occurred inside the tube. This deposition is plotted and provides a quantitative measurement of relative additive performance. Again since a quantitative limit could not be established for acceptance criteria for the BFA, acceptance was based on the deposition for a candidate additive being not more than the deposition for the currently approved Spec-Aid 8Q462 additive.

In summary, acceptance criteria for the ARSFSS is as follows:

- Servo Valve Hysteresis – Better than or equivalent to approved additive
- Servo Valve Deposition Appearance - Better than or equivalent to approved additive
- FDV Hysteresis – Better than or equivalent to approved additive (<= 7% maximum anywhere in the valve performance curve)
- FDV Deposition Appearance (Valve components and Screen) - Better than or equivalent to approved additive
- FCOC and BFA Deposition (Leco Carbon Analyzer)- Better an or equivalent to approved additive

3.3.3.5 ARSFSS Testing Results and Discussion

Figure 23 shows the hysteresis curves and component deposition appearance of the ARSFSS Servo Valve and FDV for a baseline JP-8 run (POSF 4751 fuel). Deposition on the Servo Valve components results in a dark brown staining of the spool. Staining is more prevalent on one end of the spool and is likely due to this being the fuel flow entrance area of the valve where residence times can be a little longer because of the presence of stagnant areas in this end of the valve. The blue line in the hysteresis plot shows the pre-test hysteresis in the valve. The red line show the post-test hysteresis of the valve. There is an anomaly in the plot around the actuation value of about 155 PSID for the post-test curve. This anomaly has been observed before for the Servo Valve and is typically attributed to normal wear and tear of the valve causing the spool to either sit slightly 'cocked' inside the sleeve or for there to be a specific wear point in this area of the valve stroke. Therefore, this anomaly was declared to have no root cause in deposition due to either additive or fuel. Other than this anomaly, there is not a significant variance of hysteresis of the valve throughout its operating pressure curve.

Also in Figure 23, there is a significant amount of deposition on the face of the FDV valve body, especially below the lip where the spool head mates with the body face. This again is a stagnant flow

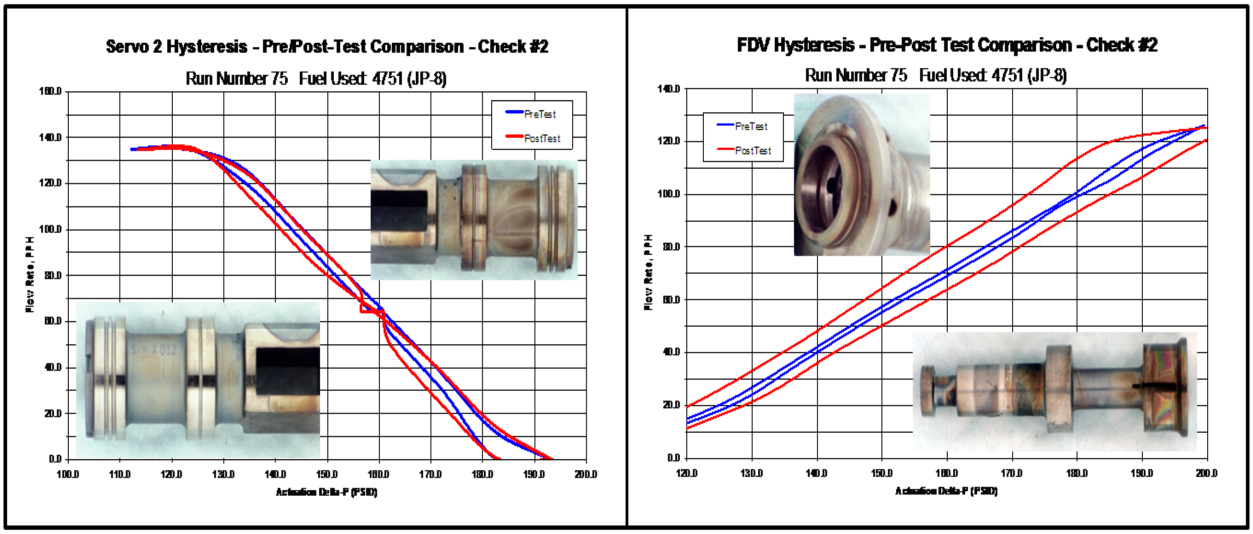


Figure 23. ARSFSS Servo and Flow Divider Valve Hysteresis

area so it is not surprising that deposition would be increased in this area. The FDV spool shows significant deposition around the metering slot and surrounding area. There is a ‘rainbow’ effect to the deposition which typically indicates deposition of various thicknesses. There is little or no deposition on the guide land for the spool because this is the area that rubs against the inner wall of the valve body and therefore any deposition that occurs there is constantly being removed by friction. The FDV pre-test hysteresis plot shows little hysteresis for a new clean valve. However, the post-test hysteresis plot shows the dramatic impact that the deposition that appears in the photos has on valve performance.

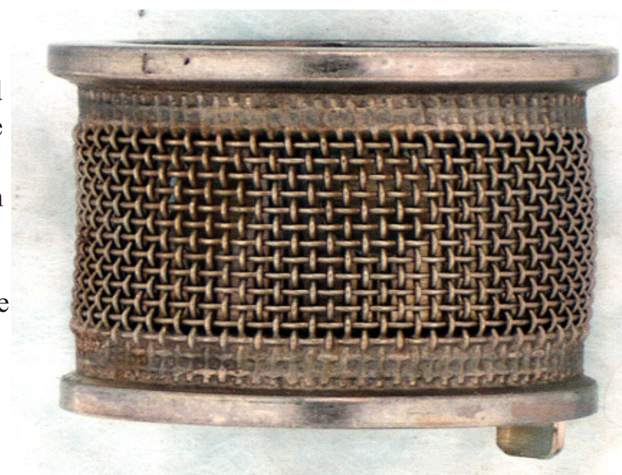


Figure 24. Flow Divider Valve Body Screen

Figure 24 shows the appearance of the FDV screen. This screen surrounds the entire valve body and protects the moving valve mechanisms from large particles of debris and is exposed to only bulk fuel at temperature so all of the deposition observed on this component is from bulk fuel deposition. In Figure 24 it can be readily seen that significant tarnishing of the screen is visible. This is consistent with the condition of the spool and the valve body.

Figure 25 shows hysteresis plots and component photographs for the Servo Valve for the candidate additives. Additive P39 showed very little deposition on the Servo Valve spool. Even in areas where fuel becomes stagnant, little or no deposition is evident. This is also borne out in the hysteresis plot for this valve. With the exception of a slightly anomalous data point in the pre-test curve at the lower right in the plot, the post-test and pre-test flow vs. pressure drop curves lay virtually on top of one another – indicating that hysteresis remained unchanged during this test for this additive. For additive P41, a little more deposition is evident in the photographs of the spool. Even this minimal tarnishing of the spool, however, manifested itself in a slight shift in the hysteresis curve for that valve and that additive. Even though tarnishing is present and there is a slight change in the hysteresis performance of the valve, the deposition and its impact is minimal.

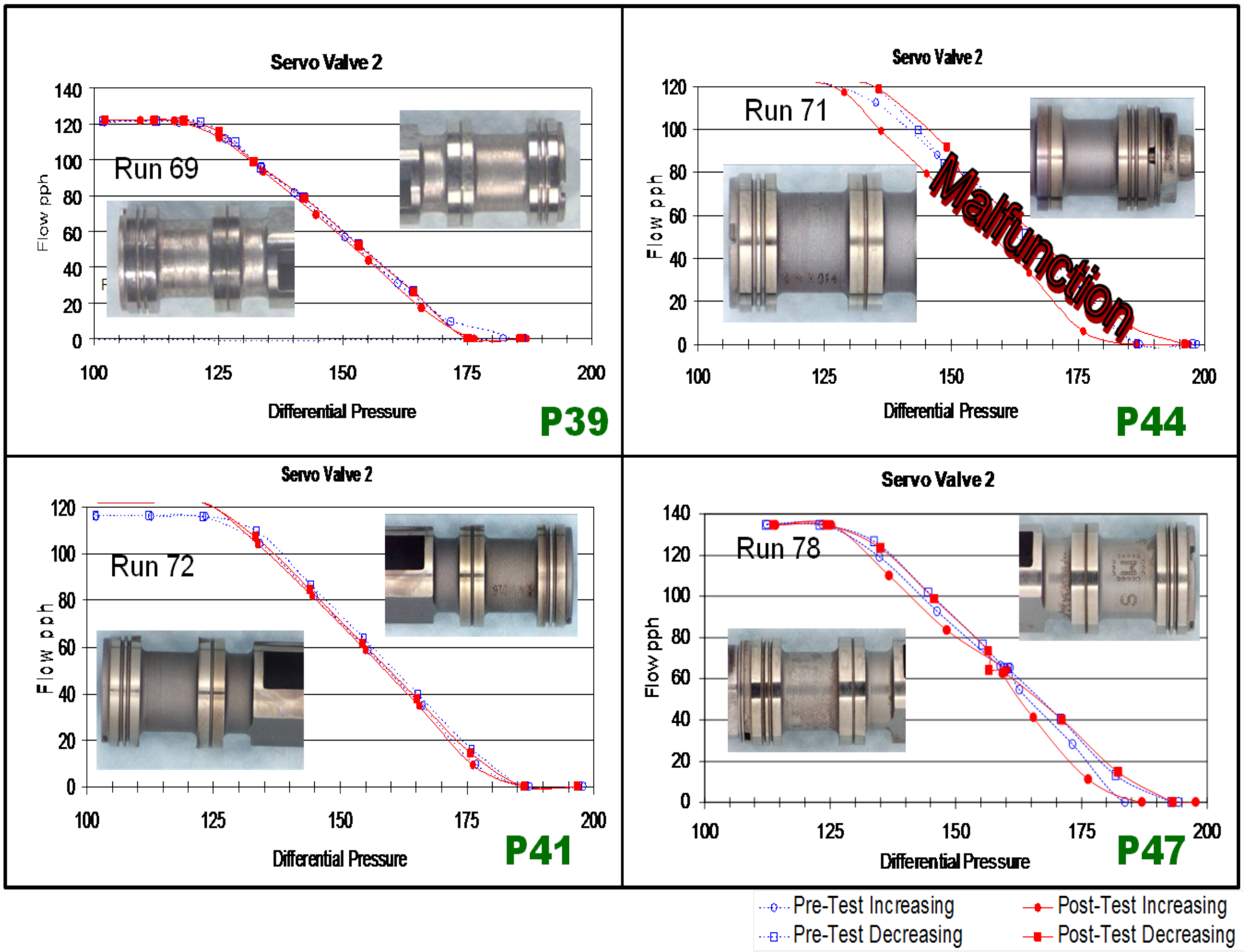


Figure 25. EDTST Heater Deposition, Fuel 2827(Jet A)

For additive P44, slightly more deposition is evident on the spool than for either P41 or P39 – especially at one end of the spool. The hysteresis data was gathered, of course, before the valve was disassembled and the measurements indicated a significant change in valve hysteresis for this additive. Once the valve was opened up and the spool was exposed for observation, there was concern that the amount of hysteresis shift was significantly larger than would be expected for the degree of deposition apparent on the spool. To make sure the hysteresis data was valid, all the components and controls for that part of the ARSFSS system were checked. It was discovered that a control valve used to control the pressure to the servo valve during hysteresis measurement was malfunctioning. The curve represented for additive P44 was therefore a combined hysteresis for the control valve and the servo valve. It was not possible to acquire hysteresis data on just the control valve so it was not possible to adjust the calculation of servo valve hysteresis to accommodate for the impact of the hysteresis of the control valve. Hence, the data in this plot is not valid and was not considered in the final ranking of the performance of P44.

For additive P47, the photographs of the spool show deposition that is lighter in appearance than in either P41 or P44 yet not as clean as P39. As with additive P44, the hysteresis data was gathered before the valve was disassembled. Based on the slight shift in valve hysteresis performance for this additive, slightly more staining of the spool was expected. In addition, the hysteresis plot showed an uncharacteristic anomaly at about the 155 PSID input pressure point. This same type of anomaly was observed for the baseline fuel run for this servo valve. Again, an investigation was undertaken to determine what was causing this anomaly. It was determined that there was still a slight malfunction of the pressure regulation device used during hysteresis measurements. Since earlier repairs to this valve were not completely successful, the valve was completely replaced but since the servo valve had already been disassembled, it was not possible to re-measure the hysteresis for these valves. Therefore, the ranking of the performance of these additives in the Servo Valve was determined based primarily on the appearance of the spool valve and not necessarily based on hysteresis performance. Lacking consistent hysteresis performance data for the additives in the Servo Valve, the deposition appearance became the primary deciding factor in ranking the additives' performance in the Servo Valve. Based on the photographic evidence, all the additives were ranked as equivalent to one another and were therefore successful performers in the Servo Valve.

Figure 26 shows both hysteresis performance data photographs of the condition of Flow Divider Valve (FDV) components for the candidate additives. The hysteresis performance data for the FDV was considered to be more reliable than for the Servo Valve because there was no intermediate valve used to control pressure to the FDV. Instead, fuel pressure drop across the FDV was changed by changing fuel pump operating RPM. This RPM was directly measurable and considered to be far more reliable than manipulating a pressure control valve. For additive P39, the condition of the FDV components was similar to the Servo Valve components – very clean with no apparent deposition. The hysteresis performance pre- and post-test plots lie almost exactly on top of one another indicating that there was no shift in hysteresis performance in the FDV for additive P39.

For additive P41, as with the Servo Valve for that additive, slight staining is apparent on the FDV components. Staining is particularly apparent in areas where fuel is normally stagnant – such as below

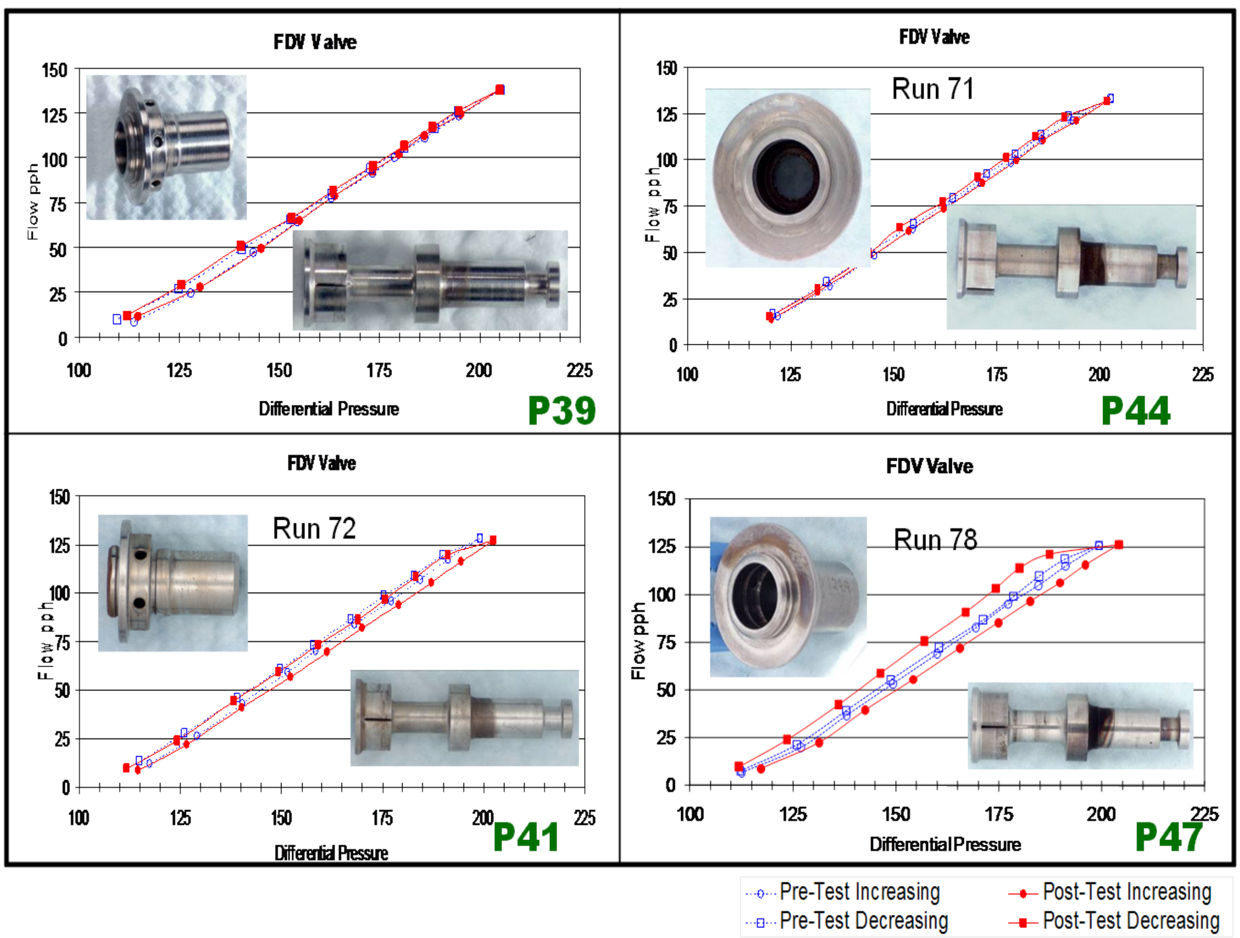


Figure 26. Servo Deposition and Hysteresis for Additives P39, P41, P44 and P47

the guide land. The hysteresis performance plot for the FDV using P41 also shows a significant change. In most cases where there is a shift in the hysteresis performance, the post-test curves usually straddle the pre-test curves indicating a relatively even shift in hysteresis regardless whether the valve is opening or closing. However, for additive P41, while there is a slight 'broadening' of the hysteresis post-test plot compare to the pre-test plot, the entire post-test plot has shifted to the right indicating that whether the valve is opening or closing, more pressure is required to actuate the valve to a specific flow rate target. Several reasons for this change were considered and it was eventually concluded that this shift was most likely due to a change in either the valve position within the valve body housing or perhaps a slight alteration in the position of the spring in the valve assembly. Either of these conditions could cause this shift but it was not possible to exactly determine the cause. Since the shift affected the whole curve (whether the valve was opening or closing), it was determined that the important performance factor was the broadening of the performance curve and not necessarily its position relative to the pre-test curve. On this basis, the hysteresis performance degradation in the FDV for this additive was minimal.

For additive P44 the pre-and post-test hysteresis plots lie almost directly on top of one another – an indication that there was little or no hysteresis deterioration experienced by this valve. Observing the photos of the FDV valve components for this plot, it can be readily seen that there was little or no deposition in this FDV. There was a significant darkening of the valve stem below the guide land but again, this is in an area in the valve where the fuel is very stagnant so this kind of deposition is not unexpected.

For additive P47 the hysteresis plot shows a significant broadening between the pre- and post-test plots. While the photographs of the FDV components do not indicate a substantial amount of deposition, except below the guide land, there was a substantial shift in the hysteresis curve between pre- and post-test. The typical broadening of the post-test curve when compared to the pre-test is evident in this plot. The hysteresis percentage was well in excess of 7%. It is speculated that the discrepancy between valve appearance and hysteresis performance degradation may be due to unobserved deposits inside the valve body that impacted spool movement. Even though the hysteresis performance curve for the FDV using additive P47 exceeded the hysteresis criteria limit, since significant deposition was not observed on the spool or valve body components, it was determined that FDV condition and hysteresis performance could be considered equivalent for all the additives and so all additives were ranked as satisfactory in this component.

Figure 27 shows photographs of the FDV screen for each of the candidate additives. In all cases, the conditions of the screen for each additive are relatively similar with only the screen for additive P44 exhibiting slightly more deposition than the other three additives. But even with the screen for additive P44 being darker than the others, it still was similar to the condition of the baseline fuel screen show in Figure 23. Based on these observations, the deposition performance in the FDV screen was determined to be equivalent for all additives.

Figure 28 shows a combined carbon deposition plot for the Fuel-Cooled Oil Cooler (FCOC) for all the candidate additives. The spread on the data lines is approximately 3 $\mu g/cm^2$ maximum over the length of the FCOC tube. This is within the repeatability of the Leco instrument so the performance of these additives in the FCOC is considered to be equivalent.

Figure 29 shows a combined carbon deposition plot for the Burner Feed Arm (BFA) for all the candidate additives. As with the FCOC carbon analyses, the deposition measurements for all the additives are essentially equivalent across the length of the BFA tube with the exception of deposition for additive P39 at around the segment 7 and 8 position. In this case, deposition was lower than the other additives but not enough lower that would lead to a conclusion that this additive had significantly better performance in deposition reduction than the other additives. Based on the data in this plot, the deposition reduction performance for all the candidate additives is considered to be equivalent in the BFA.

Figure 27. Flow Divider Valve Screen Deposition Additives P39, P41, P44 and P47

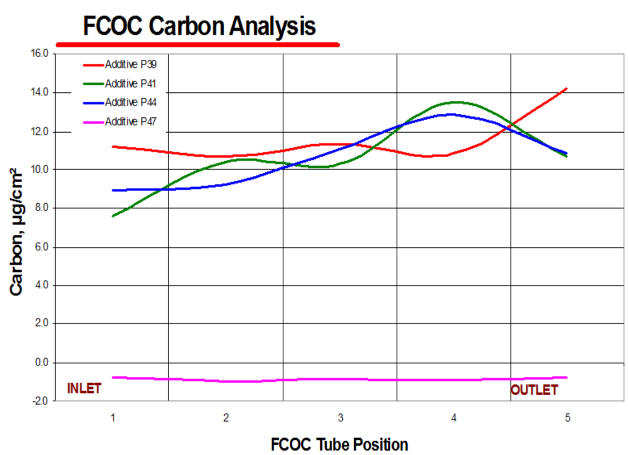


Figure 28. Fuel Cooled Oil Cooler Carbon Deposition

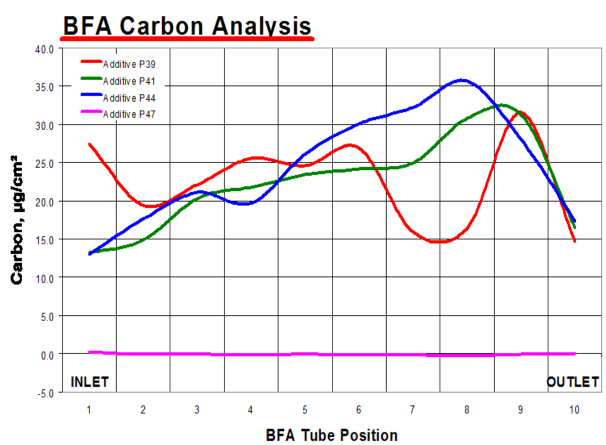


Figure 29. Burner Feed Arm Carbon Deposition

3.3.4 Summary of Thermal Stability Evaluations

Many candidate additives were received from additive manufactures for consideration in this program. These were initially evaluated in the Isothermal Corrosion Oxidation Tester (ICOT) and the Quartz Crystal Microbalance (QCM). The most promising candidates from these initial evaluations were additives designated as P39, P41, P44 and P47. The currently approved Spec-Aid 8Q462 additive is included amongst these. These remaining four additives were then evaluated in the Extended Duration Thermal Stability Test (EDTST) and the Advanced Reduced Scale Fuel System Simulator (ARSFSS). After completion of these evaluations and examination of the data, it was determined that **all four of these additives (three new candidates and the currently approved Spec-Aid 8Q462) all performed acceptably as thermal stability improving additives and therefore all were recommended for continued evaluation** in Task 2 – evaluation of inter-additive compatibility.

3.4 Task 2 – Evaluation of Additive Co-Compatibility

Where more than one additive is approved for use for a particular function such as thermal stability improvement, it is a virtual certainty that one or more of the additives will come into frequent contact with one another – either in the bulk condition as delivered from the manufacture and stored for use or as additized in fuel and then fuels being co-mingled. Therefore, an important part of approving any new additive(s) for field use would be to make sure there are no compatibility issues between the additives themselves as well as with other additives already approved for use in fuel. While a full and complete evaluation of compatibility amongst the candidate thermal stability additives and between these additives and existing approved and often used additives in JP-8 – such as FSII, Corrosion Inhibitor/Lubricity Improver, Antistatic additives, etc. - was far beyond the scope and resource limitations of this program, a series of simple compatibility tests were conducted in order to uncover any obvious problems.

There are fundamentally two different ways the candidate additives could come in contact with one another in the field. In most cases for Spec-Aid 8Q462 used in the field, the additive is injected into fuel as the fuel is being loaded into a refueler truck that will service aircraft with fuel on the flight line or perhaps even directly at the ‘skin of the aircraft’. This is the case for locations that use truck-mounted additive injectors and additize the fuel as it enters the aircraft fuel tank. In cases where hydrant systems are used to refuel aircraft, injection occurs at some location downstream of the fuel operating day-tank and additized fuel is refueled directly on-board the aircraft. In either case, bulk additive is stored in one or more bulk storage containers. Typically a ‘day tank’ of additive feeds the injector. Spec-Aid 8Q462 is delivered periodically to the bulk storage tank, from which the day tank is replenished. While not recommended, in a scenario where more than one additive is approved for use in JP-8+100, the bulk storage tank could take receipt of any one of the approved additives – in which case the additive being delivered would be added to the additive bulk storage tank on top of whatever additive was previously delivered. In this case, the additives become co-mingled in their ‘as delivered’ concentrated form. So the first way in which additives can become co-mingled is in the bulk storage tank in their ‘as delivered’, concentrated form. The likelihood of compatibility issues under this scenario is significant because the additives are in their most concentrated state.

The second way additives can become co-mingled is when fuel that has been additized with one additive becomes co-mingled with a fuel that contains another additive. In this case, the likelihood of compatibility issues is dramatically decreased because the additives are only present in a concentration of approximately 256 mg/L.

3.4.1 Evaluation of Additive Compatibility in Their Raw, As Delivered State

To evaluate the additives for compatibility issues in their raw, ‘as delivered’ state, a matrix of binary blends of raw additives was established. The blend components are show in Table 1 at the beginning of this report. The scope of the testing was limited to these binary blends based on the assumption that it would be far more likely for two of the additives to come into contact with one another that for three to come into contact with one another – especially in the bulk ‘as-delivered’ from the manufacture state.

Since the bulk additive storage tank at a User location is typically stored outside, it can experience a range of temperatures depending upon the season of the year. It is therefore possible that compatibility issues might not be present at one temperature condition but might manifest themselves at another temperature condition. To test for these temperature variances, once a binary blend of raw additives was prepared, it was separated into three equal parts. One part of the additive blend was subjected to a low temperature environment (4 °C/ 39 °F) for at least 7 days, one part was subjected to a room temperature (21 °C/ 70 °F) for at least 7 days and the remaining part was subjected to a hot environment (49 °C/120 °F) for at least 7 days. Once the exposure time was complete, the raw mixed additives were inspected for any physical changes such as turbidity, product separation, precipitation of solids or other materials and other evidences of incompatibility. If the mixed additive sample exhibited none of these physical evidences of incompatibility, the sample was used to dose a baseline fuel and that fuel/additive blend was evaluated in the QCM for thermal stability performance. In order to conserve an ever-dwindling supply of baseline fuel for EDTST use, these binary blends of co-mingled raw additives were not evaluated in the EDTST. QCM data, which had in the past tracked very well with EDTST data, was deemed sufficient to determine

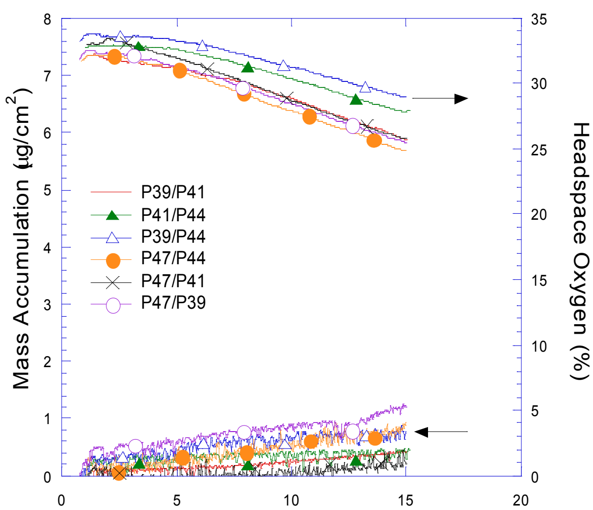


Figure 30. QCM Results For Cold Storage 50/50 Binary Blends of Additive Blends

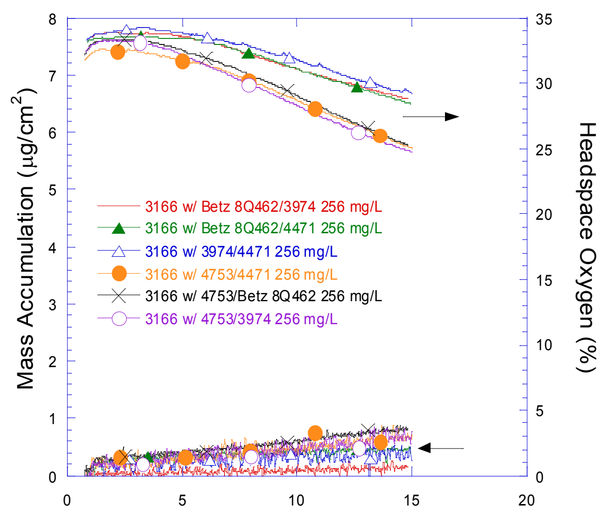


Figure 32. QCM Results For Room Temperature Storage 50/50 Binary Blends of Additive Blends

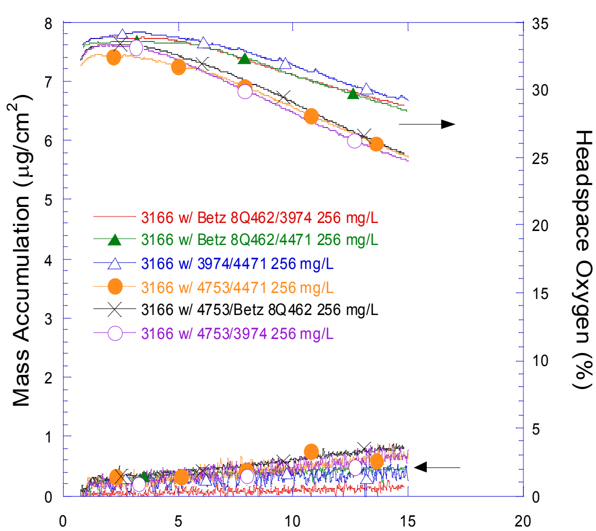


Figure 31. QCM Results For Hot Storage 50/50 Binary Blends of Additive Blends

the thermal stability impact of co-mingled additives.

Figures 30 through 32 show QCM results for the binary additive blends from Table 1. Figure 30 shows QCM results for additive stored at 4 °C (39 °F) for 8 days. All but additive blend P39/P47 produced maximum deposition of less than 1 µg/cm². The P39/P47 blend produced deposition of 1.2 µg/cm². This difference is inconsequential in light of the relative order of magnitude of the deposition and the reproducibility of the QCM and was therefore considered to be equivalent to the other additive blends. Figure 31 shows results for the additive blend stored at 49 °C (120 °F) for 9 days. All six additive blends maintained deposition rates at or below 1 µg/cm². Figure 32 shows the QCM deposition results for the binary additive blends stored at room temperature (approximately 21 °C or 70 °F) for 21 days. Again, all six additive blends maintained deposition rates at or below 1 µg/cm².

Table 2. Binary Fuel Blend Compositions for QCM Deposition Study

Additive Compatibility Blend Matrix				
Blend Designation	**% P39**	**%P41**	**%P44**	**%P47**
Blend A	50	50		
Blend B		50	50	
Blend C	50		50	
Blend D			50	50
Blend E		50		50
Blend F	50			50

3.4.2 Evaluation of Additive Compatibility When Blended In Fuels

As discussed earlier, another way that additives can become co-mingled is by the blending of fuels to which they are added. To evaluate this compatibility scenario, a series of binary fuel blends were prepared from fuels that were additized with a single candidate additive to a standard dosage rate of 256 mg/L. Enough of each binary fuel blend was prepared to execute one EDTST run and several QCM tests. Unfortunately, the supply of baseline fuel for the EDTST was depleted before all the binary blends could be prepared so the binary additive blends did not include additive P47. Table 2 shows the binary fuel blends used for this evaluation. Note that blends A, B and C were the only fuel blends used in the EDTST due to the limited availability of the baseline fuel.

Figure 33 shows the results of the QCM evaluations for each of the additive binary blends. All binary

ADDITIVE #1	ADDITIVE #2	QCM Deposition, µg/cm²
P41	P39	0.9
P41	P44	0.7
P41	P47	1.0
P39	P44	1.0
P39	P47	.5
P44	P47	.9

Figure 33. QCM Results For Room Temperature Storage 50/50 Binary Blends of Additive Blends

blends passed testing in the QCM by limiting deposition rates to 1 μg/cm² or below. Figure 34 shows the results of EDTST evaluations. In Figure 34, the deposition performance of the binary fuel blend is compared to the performance of a single additive fuel blend for each of the fuels used as a component in the binary blend. Deposition data for both the heater and preheater indicate thermal stability deposition performance is unaffected by additives being combined. The appearance of the EDTST witness strips for the single additive blend fuel is equivalent to the binary fuel blends with the possible exception of the

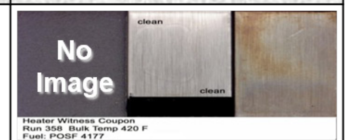
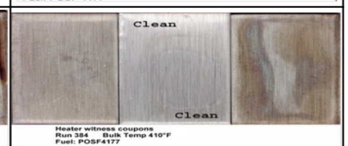
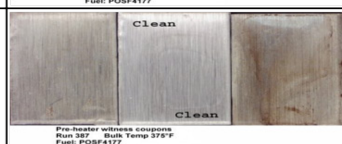
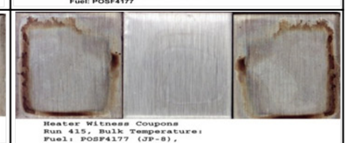
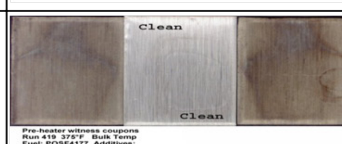
Additive	Preheater Deposition μg/cm² (<= 8 μg/cm²)	Heater Deposition μg/cm² (<= 300 μg/cm²)	Witness Strips	
			Preheater	Heater
P39	4	34		
P41	6	20		
P44	5	12		
P39/P41 50/50 Blend	4	10		
P39/P44 50/50 Blend	6	15		
P41/P44 50/50 Blend	6	36		

Figure 34. EDTST Deposition Performance for Additive Blends

P39/P44 additive combination. In this case, the witness strips appear a little darker but not as dark as the baseline fuel witness strips shown in Figure 18.

In conclusion, there does not appear to be any significant detrimental effect of combining the raw as delivered additives directly or after being additized in fuel. Therefore there does not appear to be any issues with additive compatibility.

3.5 Task 3 – Additive Dosage Study

Additive injection in the field is not as exact a science, especially in an operational environment where additive and injectors are subject to varying environmental factors and only periodic calibration. While the specifications for additive injection may state that additive is to be injected at a strict 256 mg/L, this exact dosage rate is rarely achieved. In the 15 June 2011 release of the Technical Manual "Quality Control of Fuels and Lubricants", TO 42B-1-1, the target injection rates for the Spec-Aid 8Q462 additive have been bracketed to be ± 50 ppm. In reality however, given the mechanical/hydraulic nature of additive injection equipment, it is conceivable that additive could occasionally be seriously underdosed or overdosed. The consequences of under-dosing a thermal stability additive are simply that the User does not get the benefit of the full function of the additive. However, with additive overdosing, there could be serious consequences, depending upon how large the overdose is. Most additives, especially in the case of thermal stability additives, consist of a small amount of active ingredient in a relatively large amount of hydrocarbon carrier. In the case of Spec-Aid 8Q462, of the 256 ppm of bulk as-delivered additive injected into a fuel, less than 50 ppm is actually the active ingredient. For a typical additive, the active ingredient usually a viscous material sometimes consisting of high molecular weight chemicals. In the worst case, overdosing could cause an overconcentration of active ingredient in the fuel which could lead to undesirable fuel characteristics ranging from increased existent gum measurements (ASTM D 381) to seriously detrimental effects like decreased fuel thermal stability. While it is very unlikely that any significant amount of fuel overdosing would occur in the field primarily due to the limited size of additive day tanks, none the less, the potential exists.

To evaluate the impact of overdosing additives in fuel, each additive was evaluated at both the normal concentration (1X = 256 mg/L) and high concentration (4X = 1024 mg/L) in the EDTST. Figure 35 shows the tabulated results of these tests. Additive P39 passed EDTST acceptance criteria at both the 1x

Additive	Dosage	Preheater Deposition µg/cm² (<= 8 µg/cm²)	Heater Deposition µg/cm² (<= 300 µg/cm²)	Heat Exchanger µg	Recirc Filter Deposition µg	Core Filter Deposition µg	Strips (Clean to Slight)	
							PH	H
P41	1X	6	20	15	278	64,220	S	M
	4X	10	142	26	600	113,130	H	M
P39	1X	4	34	67	36	43,140	S	M
	4X	7	14	6	193	12,640	S	S
P47	1X	7	23	15	610	19,110	S	S/ M
	4X	4	73	10	393	230	S	S/ M
P44	1X	5	12	44	217	60,650	S	S
	4X	7	25	6	193	12,640	S	S

Figure 35. EDTST Results - Additive Dosage Study

and 4x dosage rates. At the 4X dosage rate, the preheater deposition approached the acceptability limit of 8 µg/cm². At the 1X dosage rate, the Preheater deposition was well within acceptability limits. Heater deposition for additive P39 tended to be the opposite of preheater deposition with the 1X dosage rate being slightly higher in deposition than the 4X dosage rate. However with the acceptability for Heater deposition being 300 µg/cm², the values of 34 µg/cm² for 1X and 14 µg/cm² for 4X are very well within the repeatability limits for the EDTST. Additives P44 and P47 all demonstrated preheater and heater deposition rates within acceptability limits.

Additive P41 was the only additive that showed results for preheater deposition in excess of the EDTST acceptability criteria – giving a deposition rate of 10 µg/cm² for the 4X dosage rate. However, heater deposition remained low at 142 µg/cm² for the 4X dosage rate.

Upon subjective examination, the preheater and heater witness strips were rated for each additive at the 1X and 4X dosage rates. Figure 36 shows the Preheater witness strips for each additive at the two dif-

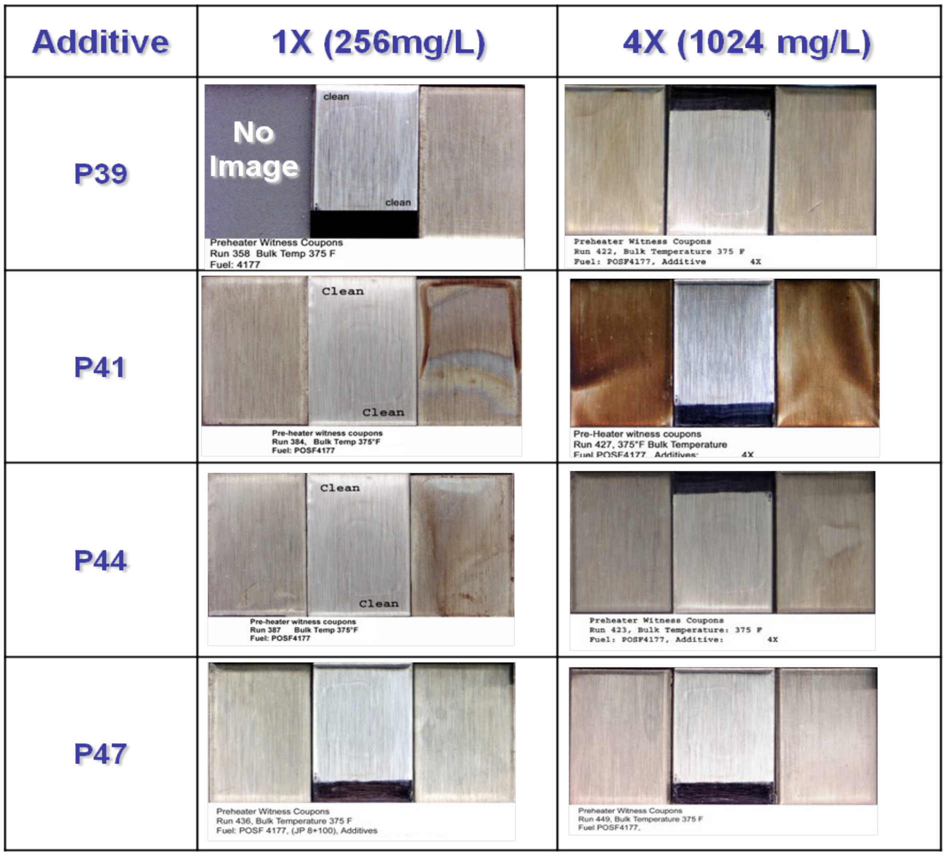


Figure 36. EDTST Preheater Deposition Performance for Additive Evaluations

ferent dosage rates. Figure 37 shows the Heater witness strips for each additive at the two different dosage rates. In Figures 36 and 37, all of the witness strips have a similar appearance at both dosage rates with the exception of additive P41. The witness strips for this additive at the 4X dosage rate show significantly more deposition than for the 1X dosage. In Figure 35, the Core Filter Deposition rating was in excess of 113,000 µg for the 4X dosage. This is consistent with the somewhat higher Preheater and significantly higher Heater deposition rates and the appearance of the preheater witness strips.

While this single data point is insufficient to support a broad sweep conclusion, one could easily conclude that there is a potential issue of increased deposition if fuel is over-dosed with additive P41. To understand this more thoroughly and to draw a specific conclusion, additional testing would have been required which was beyond the scope of this effort. However, it can reasonably be concluded that while all the other additives showed no hint of increased deposition propensity at the elevated dosage rate, there might be concern with additive P41.

3.6 Inclusion of a 5th Additive Late in the Evaluation Program

As thermal stability evaluations on candidate additives were being completed, BASF requested admission to the program with an additive they believed could be a successful candidate for consideration. However, since the program had already been established, a funding and research plan had already been put in place, there was no additional funding or testing time available for a retro-evaluation of their candidate. After discussion, it was agreed that if BASF would perform its own evaluation of their additive using the protocols established for this program and if AFRL and DLA agreed that the testing had been performed satisfactorily in accordance with this protocol and if the data showed the additive was at least

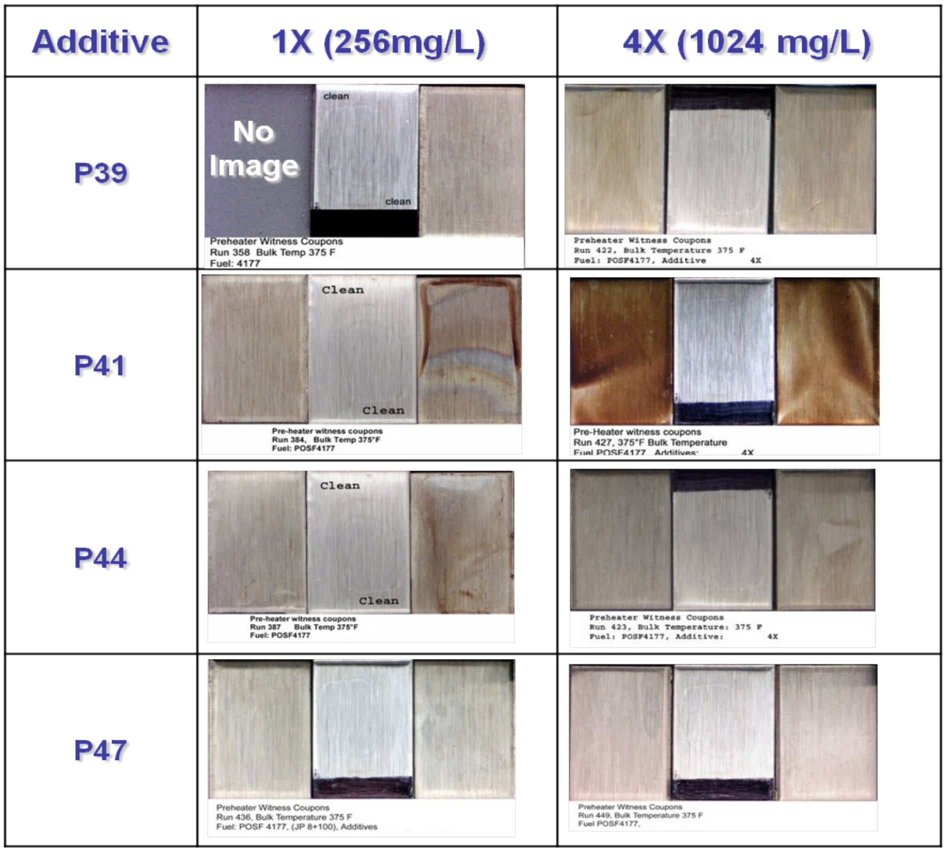


Figure 37. EDTST Heater Deposition Performance for Additive Evaluations

as good as the other candidate additives being considered, then the new candidate additive would be able to enter the program at the start of Phase II – Fit-For-Purpose and Specification Evaluations.

BASF initiated its own thermal stability evaluations to document the thermal stability performance of their additive. Compliance to the program protocol was ensured by UDRI performing thermal stability evaluations under a Cooperative Research And Development Agreement (CRADA) with BASF. BASF also took the opportunity of this CRADA to further refine the formulation of their additive. At the conclusion of that CRADA program, BASF demonstrated that their additive, Kerocom 69781, internal sample code POSF-5090, performed at least as well as the currently approved JP-8+100 additive from a thermal stability perspective[5].

After evaluating the data, AFRL and DLA agreed to accept Kerocom 69781 as an approved Phase I candidate additive with the designation “P50”. The Phase I approved additive suite then became as follows in Table 3 below. These designations are carried through into the follow-on Phase II program.

NOTE: At the time this report will have been issued, Infineum will have officially changed the designation of 'NB-31011-33' to "AV100" as the marketing name designation and BASF will have officially changed the name of 'Kerocom 69781' to Kerojet® 100.

5 *Zabarnick, S. "Evaluation of BASF Additives for Entry to JP-8+100 Phase II: Final Report For The Period February 2006 to May 2007", University of Dayton Research Institute Report, June 2007*

Table 3. Approved Additives for Specification Compliance/Fit-For-Purpose Evaluations

Additive Codes and Manufacturers			
Additive P-Code	**POSF Designator**	**Manufacturer**	**Manufacture Code**
P39	POSF-3974	BP/Lubrizol	OS 169558F
P41	POSF-4160/4580	GE Betz	Spec-Aid 8Q462
P44	POSF-4471/4550	Nalco	VX-7603
P47	POSF-4753	Infineum/ExxonMobil	NB-31011-33 a.k.a. AV100
P50	POSF-5090	BASF	Kerocom 69781 (a.k.a. Kerojet® 100)

4. Conclusions and Recommendations

In summary, the additives in Table 3 were determined to have the same or better thermal stability performance in JP-8 fuel as the currently approved additive, Spec-Aid 8Q462.

These additives along with Spec-Aid 8Q462 (designated P41) are recommended for further evaluation in the Phase II Fit-For-Purpose and Specification Compliance Testing.

Appendix A - Additizing Jet A to JP-8 Equivalent Using The Military Standard Additive Package

In some cases, it may be difficult or impossible to acquire a bona fide JP-8. In this case, a 'psuedo-JP-8' can be created from virtually any spec-grade Jet A or Jet A-1 by the addition of a military package of additives. Jet A is a kerosene-based fuel, produced to an ASTM specification. It has the same flash point as Jet A-1 but a higher freeze point maximum (-40°C). It is supplied against the ASTM D1655 (Jet A) specification. Jet A-1 is also a kerosene-based fuel. It is produced to a stringent internationally agreed standard, has a flash point above 38°C (100°F) and a freeze point maximum of -47°C (See Table A-1 shows a brief comparison of these properties between Jet A and Jet A-1).

Table A-1. Comparison of Properties of Jet A and Jet A-1

Property	Jet A-1	Jet A
Flash Point	> 38 °C (100.4 °F)	
Autoignition Temperature	210 °C (410 °F)	
Freeze Point	< −47 °C (−52.6 °F)	< −40 °C (−40 °F)

Jet A-1 is widely available outside the U.S.A. JP-8 is the military equivalent of Jet A-1 with the addition of a military package of additives. This military package of additives typically consists of a combination of the following:

Fuel System Icing Inhibitor (FSII) – the specification limit is 0.10 – 0.15 volume %

Static Dissipation Additive (SDA) - the additive shall be blended into the fuel in sufficient concentration to increase the conductivity of the fuel to within the range specified – usually between 200 and 400 pS/M. Generic Air Force field blending guidance is 1.5 ppm per T.O. 42B-1-1. Commercial standards indicate Re-doping limits for Static Dissipater additive are 5.0 mg/L Cumulative concentration for Stadis 450.

Corrosion Inhibitor/Lubricity Improver (CI/LI) – the additization level is based on the particular additive used. According to the JP-8 specification, the amount of CI/LI used shall be equal to or greater than the minimum effective concentration and shall not exceed the maximum allowable concentration listed in QPL-25017. Typical Air Force field blending guidance is to additize CI/LI to 15 ppm per T.O. 42B-1-1. The concentrations listed in QPL-25017 range from 9-24 mg/L. The Table A-1 contains current guidance for the minimum effective concentration for CI/LI additives in the QPL.

Antioxidant (AO) - N,N'-disalicylidene 1,2-propanediamine – The specification allows for additizing to not less than 17.2 mg/L nor more than 24.0 mg/L to all JP-8 fuel that contains blending stocks that have been hydrogen treated or Synthetic Paraffinic Kerosene (SPK) derived from hydrotreated, hydrocracked, or hydroisomerized products of a Fischer-Tropsch process. At the option of the supplier, not more than 24.0 mg/L may be added to JP-8 fuels that do not contain hydrogen treated blending stocks or SPK derived from hydrotreated, hydrocracked, or hydroisomerized products of a Fischer-Tropsch process.

Metal Deactivator (MDA) - This is an optional additive and is only used when needed to comply with the thermal stability specification limits. Initial additization dosage is not to exceed 2 mg/L.

Re-additization may occur as required as long as the total additive used does not exceed 5.7 mg/L.

For this program, where 3084 was additized to a pseudo-JP-8, the target dosages were:

- FSII: 0.11% Volume
- SDA: Dosage was used to target a conductivity range between 200 and 400 pS/m. To achieve this conductivity range, a dosage rate of between 1.5 and 2.5 mg/L was used.
- CI/LI: 16 mg/L
- Antioxidant: 20 mg/L
- Metal Deactivator – not used

Table A-2. CI/LI Concentrations - QPL-25017

CI/LI Min and Max Concentrations (QPL-25017)		
Product	**Minimum Effective Concentration mg/L (g/m^3)**	**Maximum Allowable Concentration mg/L (g/m^3)**
DCI-4A	9	24
DCI-6A	9	15
Hitec 580	15	22.5
Nalco 5403	12	22.5
Nalco 5405	11	11
Spec-Aid 8Q22	10	24
Tolad 351	9	24
Tolad 4410	9	22.5
Unicor J	9	22.5

Appendix B - Isothermal Corrosion Oxidation Tester (ICOT)

B-1. Scope:

The Isothermal Corrosion Oxidation Tester (ICOT) is used to evaluate the effectiveness of thermal stability additives in aviation turbine fuel by stressing the baseline fuel and the additized fuel at a constant temperature in the presence of flowing air. The fuel is filtered after it has cooled. The thermal stability of the fuel is measured by the amount of solids collected on a filter.

B-2. Summary:

Operating conditions require 100 ml of the fuel sample to be stressed at 180 °C with air flowing at 1.3 L/hr for a duration of 5 hours. The fuel sample is completely cooled then filtered through a 0.7 to 1 μm glass microfiber filter. Solids are measured gravimetrically. The thermal stability of the baseline fuel and the baseline fuel with the thermal stability additive is based on the amount of solids collected on the filter. The thermal stability additive is considered acceptable based on the total solids produced.

B-3. Apparatus:

See ASTM Method D4871-88 for a description of the apparatus. The filter shall be a glass microfiber filter with a particle retention of 0.7 to 1 μm. See Figure B-1.

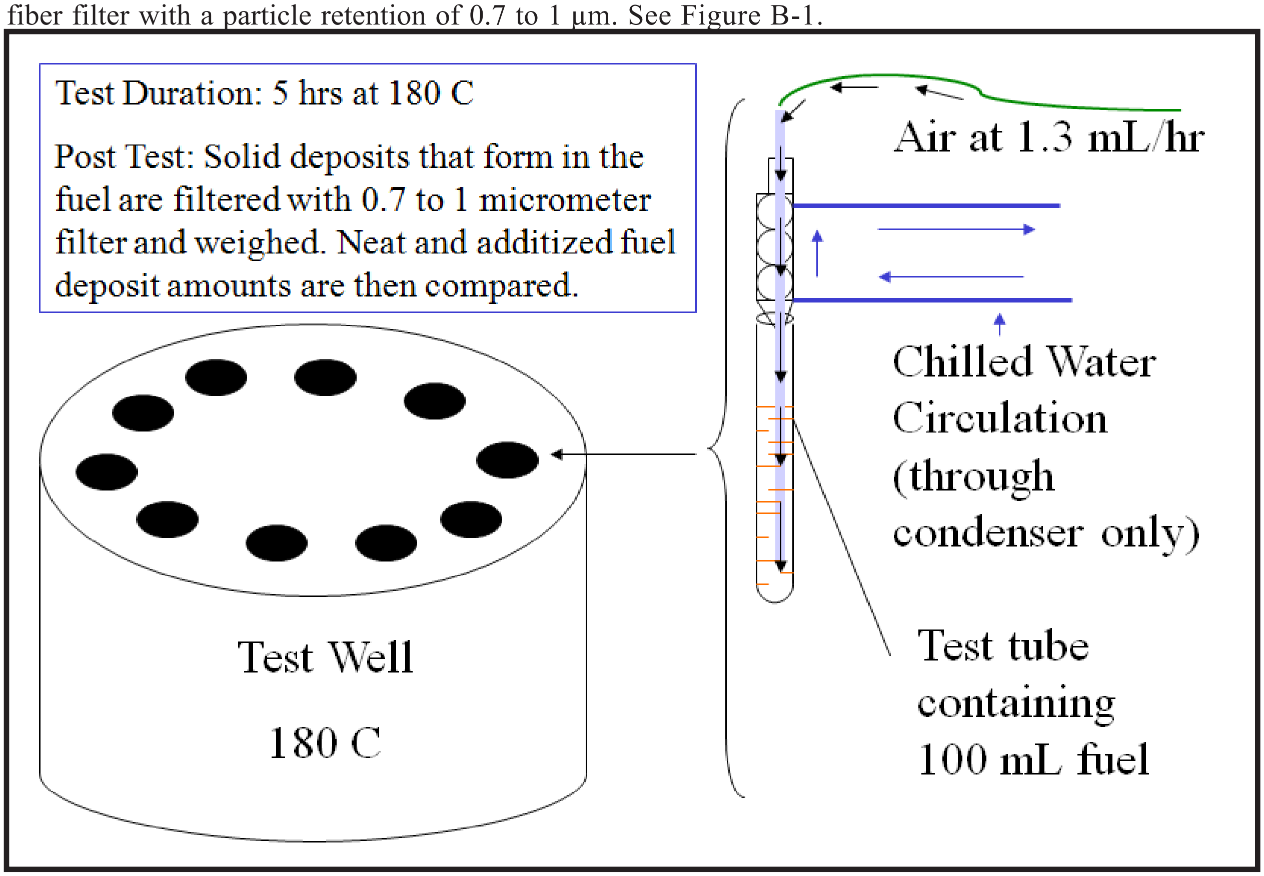


Figure B-1: The Isothermal Corrosion Oxidation Tester (ICOT)

B-4. Materials:

Not all fuels are suitable for evaluating the thermal stability additive. Some fuels, such as JPTS, do not produce significant deposition (< 20 mg/L) at these testing conditions. On the other hand, some fuels will produce copious amounts of deposits (> 200 mg/L). These fuels are generally fast oxidizing fuels that may benefit for a short period of time from the thermal stability additive. However, over a five hour period either the additive package will be consumed or the amount of insolubles generated will be so great that the ability of the additive to influence thermal stability will be exceeded. So, the required fuel for this test is a fuel that produces a moderate amount of deposits (between 50 and 200 mg/L). Three suitable fuels must be used to evaluate a thermal stability additive. Contact AFRL for information on currently accepted baseline fuels.

B-5. Calculations:

Report the amount of deposits in mg of solid per liter of fuel using the following formula:

((weight of filter with deposits in mg) - (weight of filter in mg) + (weight of control filter before rinsing in mg) – (weight of control filter in mg after rinsing in mg)) / 0.1 liter

Appendix C - Quartz Crystal Microbalance (QCM)

C-1. Scope:

This document describes the Quartz Crystal Microbalance System (QCM) which is used to thermally stress aviation turbine fuel and determine the quantity of surface deposits produced. The purpose of which is to quantitatively evaluate the ability of an additive to prevent formation of surface deposits in aviation turbine fuels.

C-2. Summary of Test Method:

An aviation turbine fuel or aviation turbine fuel with additive is aerated to fully saturate the fuel with dissolved oxygen. The fuel is subsequently heated to 140 °C for 15 hours. A quartz crystal microbalance is used to monitor the surface deposition produced. An oxygen sensor is used to monitor the oxidation process by measuring the amount of oxygen remaining in the reactor vessel headspace. Surface deposits produced on a quartz crystal oscillator lower its characteristic frequency. This frequency change is converted to a surface deposit in micrograms/cm^2 ($\mu g/cm^2$) versus time.

C-3. Apparatus:

Stainless steel reactor. The reactor consists of a 100 ml 316-stainless steel pressure vessel with access for the following: RF feed through, gas inlet tube, gas outlet tube, thermocouple, and pressure vent. The reactor is heated with a clamp-on band heater and the temperature is controlled by a PID controller with a thermocouple immersed in the liquid fuel. The controller must control the temperature to within ±0.1 °C of the setpoint during the entire run. The heater must be capable of reaching and stabilizing at the test temperature in less than one hour. A magnetic stirrer and stir bar are used to minimize spatial temperature gradients.

Quartz crystal microbalance. The quartz crystals used are 5 MHz, 2.54 cm diameter, 0.33 mm thick, AT cut wafers. The crystals have gold electrode surfaces and are overtone polished. An oscillator circuit tracks the impedance variations of the crystal, while a frequency counter measures the frequency to a precision of ±0.1 Hz. A suitable clamp assembly is used to connect the crystal electrodes to the RF feed through of the reactor. The crystal is oriented vertically and completely immersed in the liquid fuel. Satisfactory crystals are available from Maxtek, Inc., Torrance, CA.

Oxidation monitoring. A polarographic oxygen sensor is used to monitor the oxygen level in the reactor headspace. This sensor should be approximately 0.5 inches in diameter to allow attachment to the reactor lid. The oxygen sensor should be capable of measuring oxygen levels in the reactor headspace from zero to 100 percent with a precision of ±0.1 %.

Data acquisition system. A computer data acquisition system should be used which allows the following parameters to be recorded at one minute intervals: run time, crystal frequency, temperature, and headspace oxygen concentration.

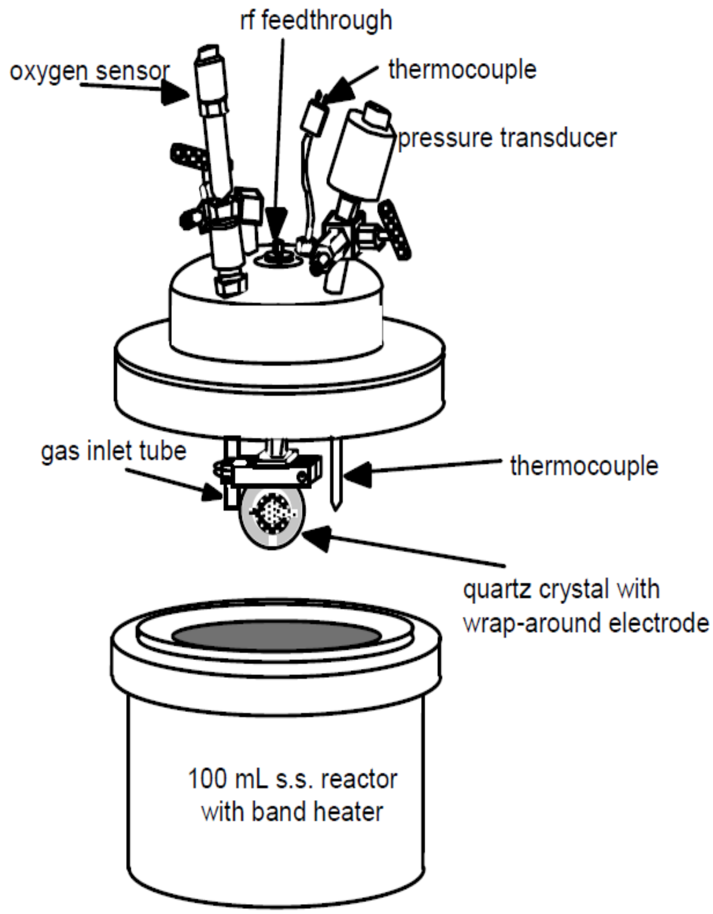


Figure C-1. Quartz Crystal Microbalance Reactor Detail

C-4. Fuels:

In order to evaluate a thermal stability improving additive at least one suitable baseline fuel must be chosen. If possible, two baseline fuels should be available for these evaluations. Any baseline fuel used should have a final (15 hour) deposit between 3 and 10 µg/cm^2.

C-5. Procedure:

The vessel is filled with 60±1 ml of aviation turbine fuel or aviation turbine fuel with additive, and the reactor lid closed. The fuel is sparged for one hour with air to insure that the fuel is air saturated. After sparging is complete the sparge gas is turned off and the gas inlet/outlet valves are closed at ambient pressure. At this point the heater, which is set at 140 °C, is turned on and computer data acquisition is begun. The run time, crystal frequency, reactor temperature, and headspace oxygen concentration are monitored and recorded at one minute intervals by the data acquisition system. Runs are conducted for 15 hours; at the end of this time the heater is turned off. After the reactor has cooled to room temperature, it is opened and the fuel and crystal are discarded. All surfaces that contact the fuel are cleaned repeatedly with an equivolume mixture of toluene, acetone, and methanol with laboratory wipes, cotton-tipped swabs, and pipe cleaner brushes, until brown deposit residue is completely removed. The reactor must be completely dry before another fuels is tested. The crystal is replaced with a new, unused crystal prior to each run.

C-6. Data analysis:

The equation used to convert frequency change to mass accumulation is:

$$\rho_s = -\left(2.21 \text{ x } 10^5 \text{ g}/(\text{cm}^2\text{s})\right)\frac{\Delta f}{f_0^2}$$

where f_0 is the initial resonant frequency, Δf is the change in frequency (i.e., the current frequency – the initial frequency), and p_s is the area surface mass density (mass/area). The initial frequency, f_0, is chosen by observing the temperature-time heat-up history of the run (See Fig. B-2). The initial time, t_0, is when the reactor stabilizes at the run temperature (i.e., within 0.2 °C of the temperature controller set point). Frequency points that are not within 0.2° C of the setpoint are discarded. The initial frequency is the measured frequency at the initial time. The above equation is used to convert the measured frequencies into a real mass density versus time. For example, the frequency at 15 hours is used to calculate the final deposition as follows: for an initial frequency of 4.988300 MHz and a final frequency of 4.988100 MHz

$$\rho_s = -\left(2.21 \text{ x } 10^5 \text{ g}/(\text{cm}^2\text{s})\right)\frac{4,988,100 - 4,988,300\text{s}^{-1}}{4,988,300^2 \text{ s}^{-2}} = 1.78\mu\text{g}/\text{cm}^2$$

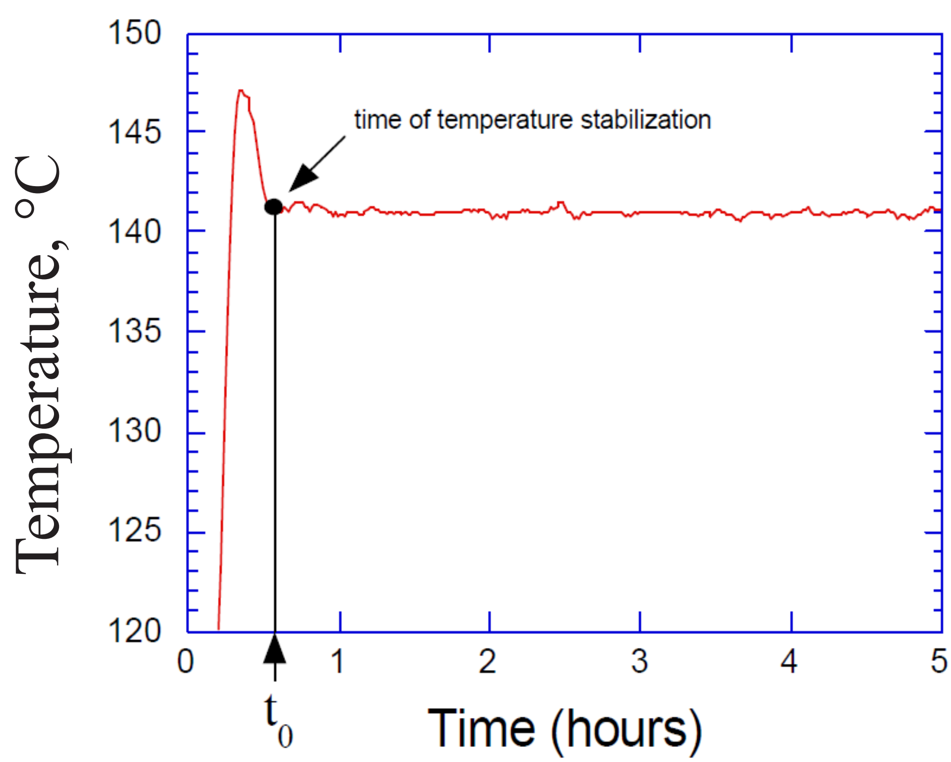


Figure C-2. QCM Data Plot

Appendix D - Extended Duration Thermal Stability Test (EDTST)

D-1. Scope:

This is a description of the Extended Duration Thermal Stability Test (EDTST) and its application in the evaluation of Next Generation +100 additive candidates. The purpose of the EDTST is to simulate the fuel flow and heat cycle characteristics of a typical aircraft fuel system and to evaluate fuels and additives under these conditions. Since this test does not operate at conditions that accelerate thermal degradation (high temperature, long residence times), longer duration times are necessary to evaluate fuels and additives.

D-2. Summary:

The EDTST subjects the fuels to specified bulk fuel and wetted wall temperatures at residence times related to those occurring in gas turbine fuel systems. A fuel bypass line is incorporated to represent Military aircraft designs for thermal management that recirculate fuel from the engine back to the airframe tanks. Also, the fuel is exposed to the specified wetted wall temperatures for very short durations and then is scraped. This is representative of the fuel exposed to the engine injection nozzles.

D-3. Apparatus:

The EDTST system consists of a 60 gallon feed tank, an electrical motor driven gear pump, two clamshell furnace heaters, and a scrap tank. A schematic of the EDTST system is shown in Figure D-1. The first furnace heater (preheater) in the system is used to establish the desired fuel bulk temperature into the second heater and to establish the desired fuel bypass temperature. The fuel bulk temperature represents the temperature that results from aircraft and engine heat loads. JP-8+100 fuel will provide a capability to operate at or above 375°F (204°C) bulk fuel temperatures.

Another requirement for JP-8+100 fuel is to provide a wetted wall temperature capability of 500°F (260°C) for engine fuel injection nozzle design. The temperature is established in the second furnace heater (main heater) to represent the wetted wall temperatures associated with engine injection nozzles.

Both furnace heaters are 0.81 meters long and resistance heated. They each have 5 heating element zones that are independently controlled. The fuel flows upward through a single stainless steel tube in each heater. The tube in the preheater has an O.D. of 1.27 cm and a wall thickness of 0.0889 cm. The tube in the main heater has an O.D. of 0.32 cm and a wall thickness of 0.0889 cm. Each tube is assembled inside a thick walled furnace tube that has an I.D. of 2.54 cm and an O.D. of 5.08 cm. The tubes have thermocouples attached to the outer wall for measuring wetted wall temperatures. The annular space between the furnace tube and heater tubes is filled with sand. A typical main heater assembly is shown in Figure D-2. A fuel bypass line is installed downstream of the preheater to represent the aircraft recirculation line from the engine to the airframe tanks. A water/fuel cooler is installed in this line to represent the aircraft ram air heat exchanger. A 2μ filter is also installed in the line for 4 hours to measure particles in the recirculated bulk fuel. Since effects of recirculation are one of the purposes of this test, the filter is installed only for a short duration. Aircraft fuel systems will probably not have a

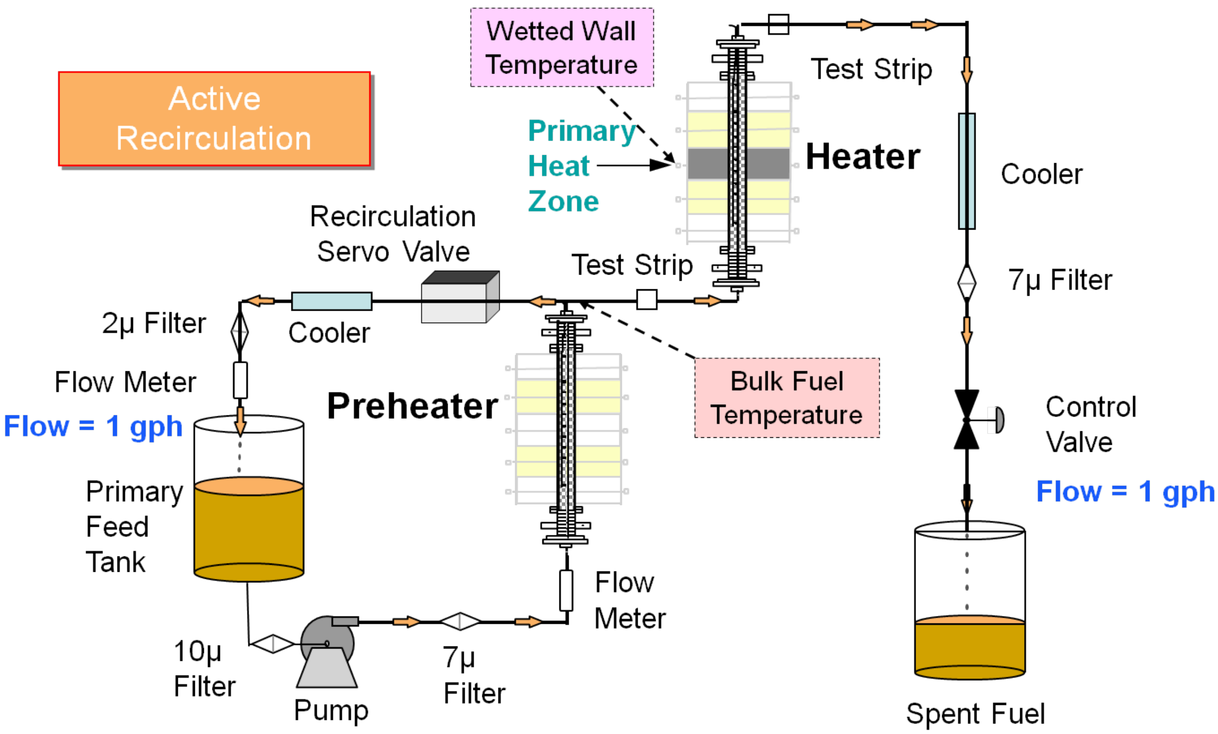


Figure D-1. EDTST Flow Schematic

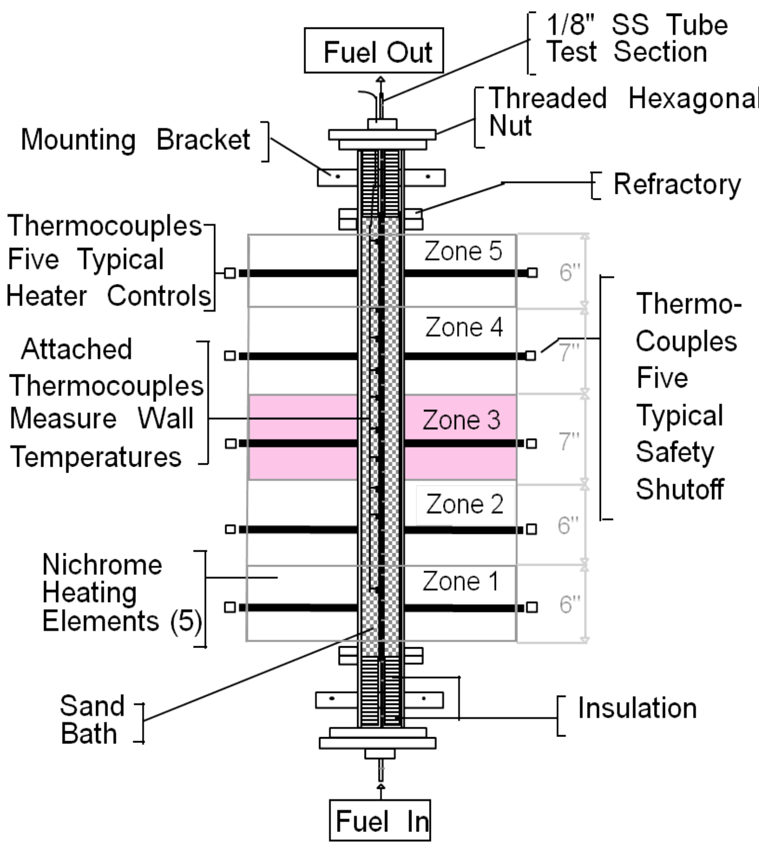


Figure D-2. EDTST Heater Diagram

filter in the recirculation line. A 7µ filter is also installed downstream of the heater. This filter provides an indication of particles that the fuel nozzles will experience in the advanced system design with a heat exchanger downstream of the engine fuel controls. Witness strips in housings are located after the preheater and immediately in front of the bypass line heat exchanger.

D-4. Procedure:

The feed tank is filled with 55 gallons of fuel to be tested. The pump is turned on to establish flow of 1 gallon per hour in both the preheater bypass line and though the heater. The system heaters are then turned on to establish a bulk temperature of 375°F out of the preheater and a maximum wetted wall temperature of 500 °F on the heater tube. When these conditions are reached, the test is conducted for 96 hours. The feed tank is refilled at the 48-hour test interval. After 96 hours the heaters are turned off and the heater clamshells are opened to cool down the system. After the system is cool, the pumps are turned off and the system is partially disassembled. The preheater, heater and heat exchanger tubes are cut up in segments for LECO analysis. The 2 and 7-micron filters are also subjected to LECO analysis. The witness strips shall be inspected and appearance due to deposition shall be noted systems. The EDTST system is computer controlled and can run unattended for long periods of time.

D-5. Baseline Fuel Selection

To select fuels as baseline, tests shall be conducted at 350°F bulk fuel and 500°F wetted wall temperature conditions. A fuel will be considered acceptable for use as a baseline fuel if, after a

96-hour test run without additive, it meets the following criteria:

- Preheater tube segment maximum deposition of > 5 and = 20, µg/cm2
- Heater tube segment maximum deposition of = 1000 µg/cm2
- Deposition in the 7-micron filter of = 10,000 µg

D-6. Reporting:

Report the following for each baseline fuel and additized fuel.

a) The quantity of carbon deposition on the preheater, heater, and heat exchanger tube segments. The deposit per tube segment is divided by the surface area and reported in units of µg/cm2. Typical plots used to report the results are shown in Figures E3, E4 and E5. It should be noted that the bulk temperature was 350°F for the JP-8 Fuel and 400°F for the JP-8+100 (Betz 8Q462, POSF-3549) fuel for the plots.

b) The amount of the filter deposits in units of µg's.

c) Inspection of the witness strips shall be conducted and their appearance in regards to deposition shall be noted.

Appendix E - Advanced Reduced Scale Fuel System Simulator (ARSFSS)

E-1. Scope:

The Advanced Reduced Scale Fuel System Simulator (ARSFSS) is designed to closely simulate the hardware, thermal and fuel flow characteristics of an advanced aircraft fuel system. It provides the last analysis of potential new fuels and additives prior to going into actual engine testing.

E-2. Summary:

The Advanced Reduced Scale Fuel System Simulator was designed to realistically simulate the thermal and flow profiles of the fuel system (airframe and engine)of an advanced aircraft. The simulator consists of three integrated subsystems: 1) the fuel conditioning system, 2) the airframe fuel system, and 3) the engine fuel system. A schematic of the simulator is shown in Figure E-1. The simulator is currently configured to simulate the F-22 aircraft with the F119 engine. The fuel flow established in the simulator is 1/72 scale of the F119 engine and the burn flow is 1/3 of the flow for a single F119 fuel nozzle. The total fuel required for each test ranges from 900 to 1200 gallons, depending on the mission profile and the number of missions executed.

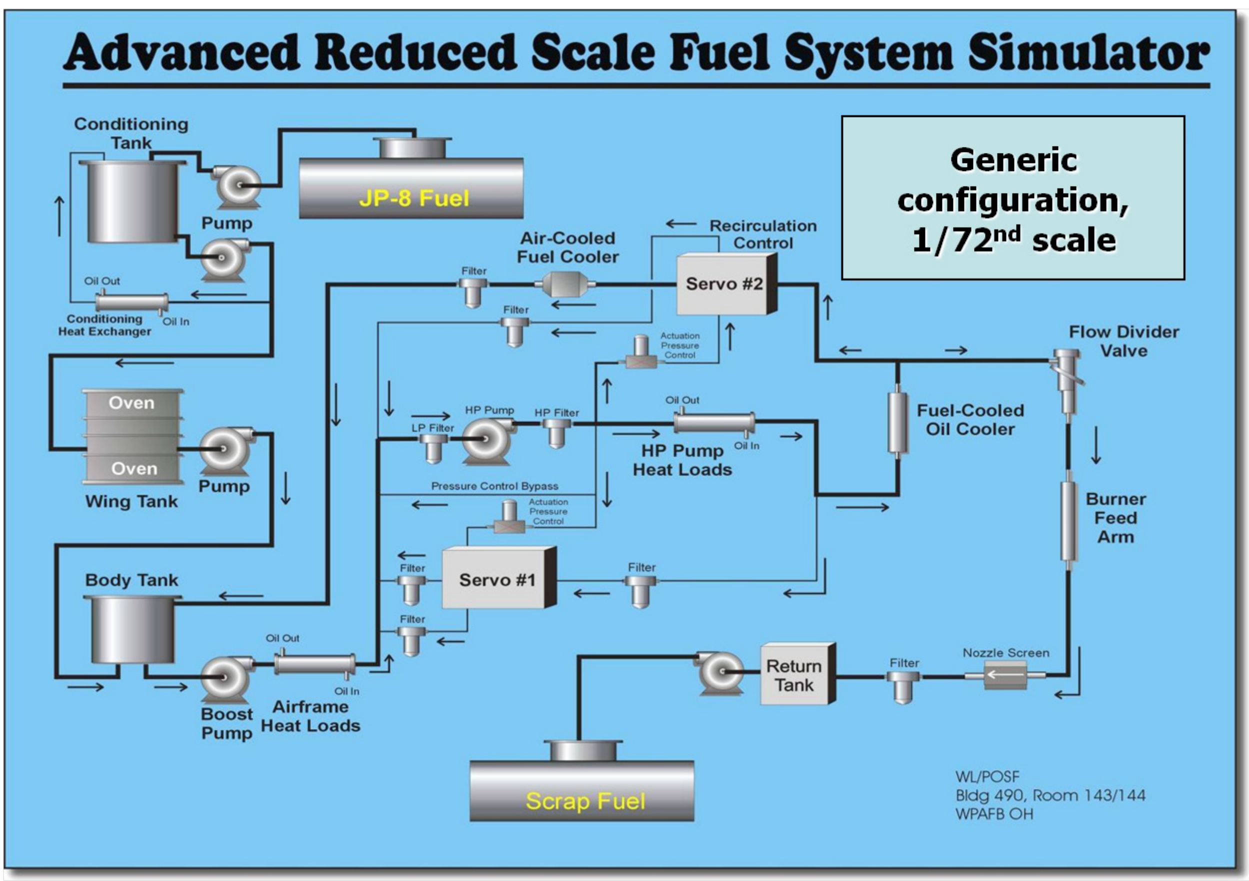


Figure E-1. ARSFSS Flow Diagram (Typical)

E-3. Apparatus:

To the extent possible, full-scale actual engine hardware has been incorporated into the engine portion of the simulator to evaluate the impact of fuel deposits on component performance. These include a Flow Divider Valve (FDV) and two servo valves. The FDV (Figure E-2) is an actual F119 valve that has been modified by changing the slot width to allow the stroke of the valve during Simulator operations to approximate the stroke of that same valve when operated in the actual engine. The servo valves (Figure E-3) are modified versions of the second stage of an F119 Electro-Hydraulic Servo Valve (EHSV). The

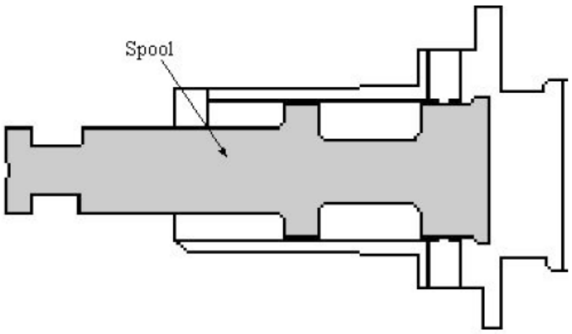


Figure E-2. Flow Divider Valve

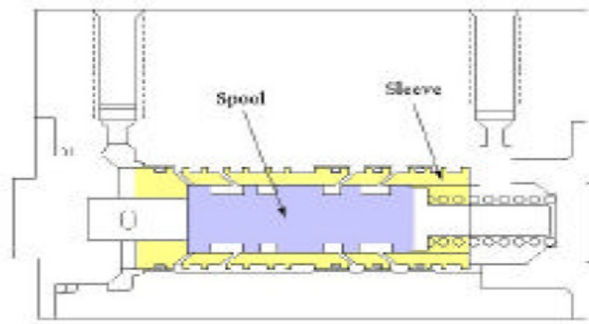


Figure E-3. Servo Valve Spool and Sleeve

materials, clearances and function is representative of the Servo Valves on the F119 engine. The performance of the FDV and Servo Valves is determined by measurement and comparison of valve hysteresis pre- and post-test as well as visual inspection of valve components.

Simulations of the Fuel-Cooled Oil Cooler (FCOC) and the Burner Feed Arm (BFA) are also incorporated to study thermal stability effects. The FCOC represents the engine lube oil cooler. It consists of an induction heater and a steel manifold with three 3/8" tubes and associated thermocouples. The tubes are connected via a manifold and provide for three passes through the heater. The tube that is used for the final pass is removed after each test. It is cut into 2 inch segments and subjected to carbon analysis. The burner feed arm is RF induction heated. It consists of a steel clamshell with a 1/8 inch stainless steel tube installed in middle of the clamshell. Thermocouples on the outside of the tube are positioned along the entire length to measure the temperature profile of the tube. At the end of the tests, this tube is cut up into 1-inch segments and subjected to carbon analysis as well. A bulk fuel temperature of 350°F (177°C) out of the FCOC and a wetted wall temperature of 500°F (260°C) in the BFA form the baseline test conditions that are typically used for testing.

E-4. Determining Flow Divider Valve and Servo Valve Hysteresis in the Advanced Reduced Scale Fuel System Simulator (ARSFSS)

E-4.1 What Is Hysteresis?

Hysteresis in a valve can basically be described as the tendency of the performance of the valve (in terms of flow through the valve vs. valve position) to be dependent on its previous position. Hysteresis leads to varying degrees of inaccuracy relative to valve actuation and operating forces and can drastically affect the performance of an aircraft systems and subsystems.

Under the best of circumstances, a well designed and well-functioning control valve has little or no hysteresis thereby allowing the control algorithms that predict and impose control movements to do so reliably and accurately. As hysteresis increases, control algorithms may not properly compensate and system control can become unstable. When this happens, control can depart from normal calibration and can result in modified performance or under severe circumstances, out-of-control performance. Of course in a flight system, the occurrence of he later can be detrimental to aircraft system safety and good ordered and controlled flight.

For the ARSFSS, fuel system valve hysteresis typically results from one or two occurrences: either there is coke/varnish/gum in the valve that hinders normal movement of valve components or there is wear of moving valve components which changes clearances of moving valve parts. While there is always the possibility that wear can happen in the short duration time-frames experienced during an ARSFSS test, it is far more likely that any change in valve hysteresis is the result of the presence of gums, varnishes or coke deposits from fuel.

In order to determine the hysteresis characteristics in a valve, the valve must be tested on a flow bench by measuring the flow through the valve based on it closed or open position. To do this, flow measurements are made starting with the valve completely closed and at various degrees of openness until the valve is fully open. Then, with the valve fully open, flow measurements are made starting at this full open position and then at various degrees of closure until the valve returns to a fully closed position. In general, a data curve similar to that in Figure F-1 is generated from this data. Once the flow measurements are made, data is plotted and calculations of %Hysteresis are made according to the equation :

$$\%Hysteresis = \left(\frac{FLOW_{DEC} - FLOW_{INC}}{FLOW_{INC}}\right) \times 100 \qquad (1)$$

Where :

$FLOW_{DEC}$ = Flow through the valve measured when manipulating the valve from OPEN to CLOSED

$FLOW_{INC}$ = Flow through the valve measured when manipulating the valve from CLOSED to OPEN

The following paragraphs describe how this hysteresis measurement is made for the Flow Divider Valve and Servo Valve on the ARSFSS.

E-4.2 Servo Valve (SV)

The SV on the ARSFSS is a hydraulically actuated spool and sleeve valve and designed to emulate the second stage (hydraulic stage) of a typical Electro Hydraulic Servo Valve (EHSV) used in fuel systems. In an EHSV, the first stage of the control is an electrical servo mechanism that responds to an input current or voltage. Increasing current or voltage results in a small movement of the electrical servo components. The electrical servo components are coupled to a hydraulic component – the second stage of the control of the valve. The hydraulic portion of the valve consists of a spool and sleeve arrangement where a specially designed spool moves within a sleeve. Movement of the spool causes clearances within the spool/sleeve assembly to change and thus, control flow through the valve. Because the hydraulic portion of the valve is driven by pressures within the fuel system, the small forces generated by electrically positioning the electrical servo portion of the valve are amplified by system hydraulic pressures resulting in a substantial moving force being applied to a hydraulic component. These combined electrical and hydraulic components give engine manufactures the ability to exert substantial hydraulic forces upon the fuel system control using small electrical forces.

For the ARSFSS, the electrical servo mechanism has been removed and just the second stage hydraulic components are changed. To generate the Valve Control Delta-P vs. Flow data curve, the ARSFSS engine pump is operated at high RPM to generate fuel pressures necessary to actuate the SV. Fuel flow from the pump is regulated by a control valve (FCV801) starting with the control valve open to about 75% which applies pressure to the SV and forces it to a 'closed' position. Since the SV is not a 'shut-off' valve, there is always flow through the valve to some degree. With FCV801 at 75% (SV essentially closed), a flow measurement is made once it is determined that the flow through the valve is stabilized. Once that measurement is taken, FCV801 is put to 70% open and another measurement of flow is made. This stepwise closing of FCV801/opening of the SV continues in 5% increments until the SV is essentially full open (which is about 30% on FCV801). Once the final flow measurement is made at this condition, FCV801 is changed again, in 5% increments until FCV801 is back at the starting position of 75%. Of course, flow measurements are made at each of these incremental positions and the results tabulated.

These SV measurements are made on the SV as installed in the ARSFSS both pre-test and post-test. The cyclic measurement process is executed a minimum of two and a maximum of three times and the data collected and tabulated (See Figures E-5 and E-6 as examples). The cyclic measurement process is repeated because it is common for the first sequence of measurements to be 'off' slightly as a result of the valve 'seating' itself and getting fully wetted and lubricated with fuel. The second measurement series tends to be more what is actually experienced when the SV is in test mode. The third and final series tends to virtually duplicate the second series so it is most times not performed. In the post-test mode, the third series is only performed if there are too many anomalies evident in the first two series because valve movement tends to remove deposition from the valve thereby returning the valve to a near-pre-test condition and thus eliminating the ability to assess the impact of coking on valve performance.

E-4.3 Flow Divider Valve (FDV)

The FDV on the ARSFSS represents the valve that controls primary and secondary burn flows in the engine combustor nozzle. At low engine speeds, the engine fuel pump generates low pressures and the FDV remains closed, allowing only primary orifice fuel flow to the combustor. At higher engine speeds (higher thrust), the engine fuel pump pressure causes the FDV to open sending fuel flow to the secondary orifice in the fuel nozzle thus giving the engine the fuel necessary for the thrust levels required. This FDV is subjected to high temperatures often in the 300+ °F range. At these temperatures, coking can occur which can affect the way the FDV operates and responds to engine fuel pump pressures thus potentially changing the performance curve parameters of the valve.

As with the SV, a series of measurements are made on this valve both pre- and post-test. To get the Flow vs. Pressure Delta-P data for the valve, the ARSFSS engine pump is operated at high speed. Flow control valve FCV301 is used to regulate flow to the FDV. The initial data point is taken with FCV301

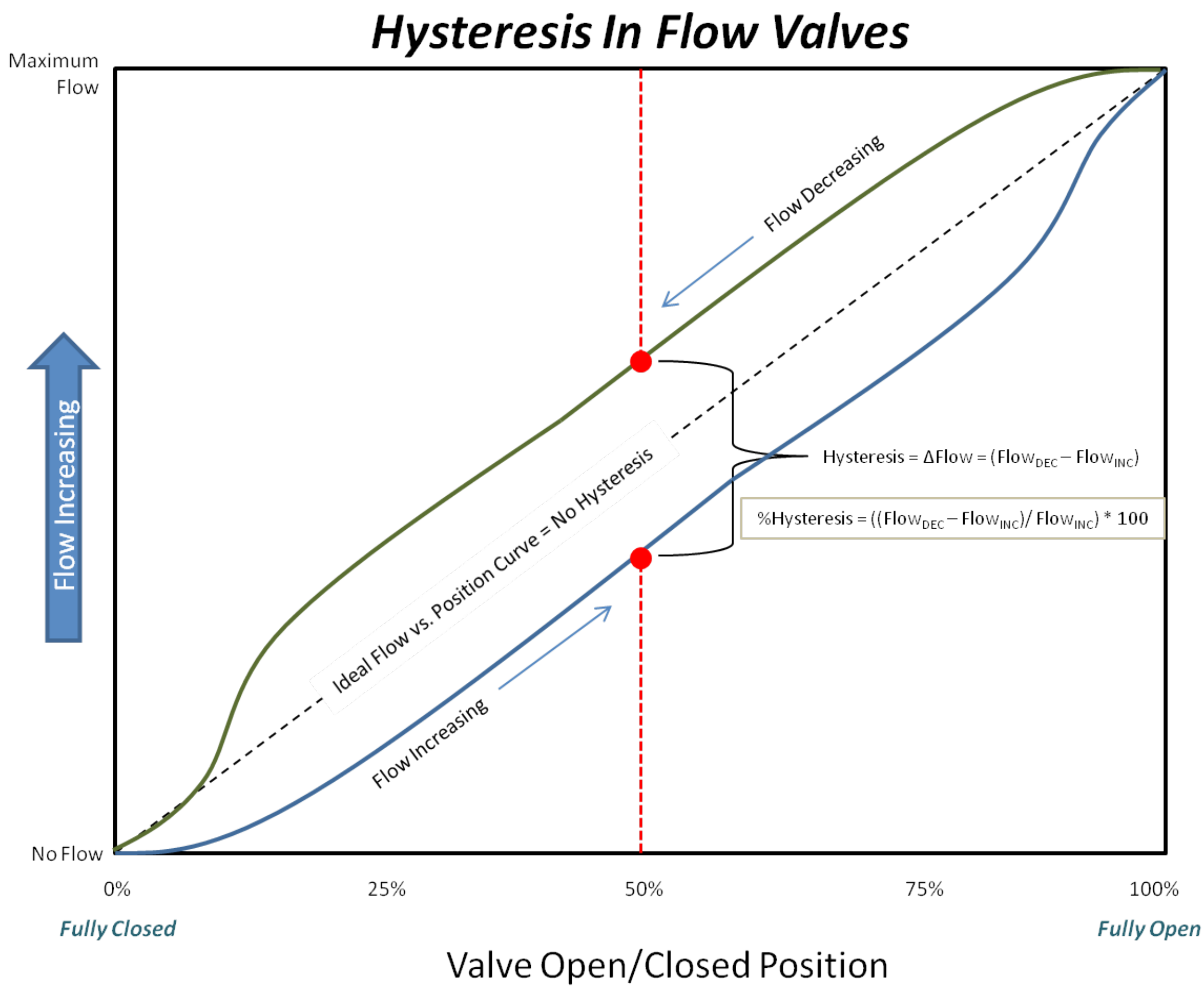


Figure E-4. Generic Hysteresis Flow Curve

at 10% open. Fuel flow through the FDV and the fuel differential pressure across the FDV are measured. Flow control valve FCV301is opened in increments of 10% and flow and differential pressure measurements are made at each incremental position until FCV301 if fully open. Once this fully open position is attained, a reverse incremental positioning of FCV301 is executed until it is again at 10%. At each incremental position, both flow through the FDV and fuel differential pressure across the FDV are measured and tabulated (See Table F-2). These measurements are, of course, made both pre- and post-test.

E-4.4 Analysis of Hysteresis Data

Of course, the goal of these measurements is to determine the maximum amount of hysteresis experienced by the SV and FDV as a result of fuel deposition. To do this, two 'check flow' points are picked – a high flow checkpoint and a low flow checkpoint. Check flow points chosen are not at the extreme ends of the stroke of the valve because at these ends, the clearances of a valve nearly closed or nearly open are subject to 'end effects' which results in anomalous and unrepeatable behaviors in these areas. Instead, check flow points are chosen at about 20%-30% and75%-85% of the stroke range. For the FDV, check points of 140 PSID and 190 PSID corresponding to flow rates of approximately 45 pounds of fuel per hour (PPH) and 110 PPH respectively. For the SV, these check flow points are typically 175 PSID and 130 PSID corresponding to flow rates of 4-5 PPH and 100 PPH respectively.

Since it is virtually impossible to ‘hit’ the flow check points during the flow hysteresis measurement and tabulation phase of this analysis, a least-squares linear fit is applied to the data so that a flow rate through either the SV or FDV can be calculated at specific points. Once the valve flow is calculated at the check flow points from this linear curve fit analysis, the pre- vs. post test hysteresis value is calculated from the ‘flow increasing’ and ‘flow decreasing’ least-squares linear fit. The goal is that pre- vs. post-test hysteresis at the flow checkpoints should be less than 7%. This limit was chosen based on recommendations from Pratt & Whitney which indicated that, for the SV and FDV, as at values higher than 7%, fuel flow control is compromised. The percent hysteresis value is calculated according to equation (1).

Servo #2 Recirculation Hysteresis Test

Run Number		76	Date:	2-Feb-05		Time:	10:00 AM			Date:	10-Feb-05		1:00 PM				
Valve Serial No.		X013	Body No.		2			Shardo		Fuel Description:	4751						Oper:
	Pre-Test #1			Pre-Test #2			Pre-Test #3			Post-Test #1			Post-Test #2			Post-Test	
	Check Delta-P		175.00	Check Delta-P		175.00	Check Delta-P		175.00	Check Delta-P		175.00	Check Delta-P		175.00	Check Delta-P	
	Check Flow, Inc		10.69	Check Flow, Inc		9.99	Check Flow, Inc		#DIV/0!	Check Flow, Inc		8.08	Check Flow, Inc		8.68	Check Flow, Inc	
	Check Flow, Dec		10.04	Check Flow, Dec		9.72	Check Flow, Dec		#DIV/0!	Check Flow, Dec		10.20	Check Flow, Dec		10.41	Check Flow, Dec	
	% Hysteresis:		-6.14%	% Hysteresis:		-2.74%	% Hysteresis:		#DIV/0!	% Hysteresis:		26.28%	% Hysteresis:		19.99%	% Hysteresis:	
	Check Delta-P		130.00	Check Delta-P		130.00	Check Delta-P		130.00	Check Delta-P		130.00	Check Delta-P		130.00	Check Delta-P	
	Check Flow, Inc		103.15	Check Flow, Inc		102.03	Check Flow, Inc		#DIV/0!	Check Flow, Inc		100.80	Check Flow, Inc		101.00	Check Flow, Inc	
	Check Flow, Dec		104.03	Check Flow, Dec		101.50	Check Flow, Dec		#DIV/0!	Check Flow, Dec		101.81	Check Flow, Dec		101.98	Check Flow, Dec	
	% Hysteresis:		0.86%	% Hysteresis:		-0.52%	% Hysteresis:		#DIV/0!	% Hysteresis:		1.00%	% Hysteresis:		0.97%	% Hysteresis:	
FCV801	Delta	Flow, Inc	Flow, Dec	Delta	Flow, Inc	Flow, Dec	Delta	Flow, Inc	Flow, Dec	Delta	Flow, Inc	Flow, Dec	Delta	Flow, Inc	Flow, Dec	Delta	Flow, Inc
Valve %	P	PPH	PPH	P	PPH	PPH	P	PPH	PPH	P	PPH	PPH	P	PPH	PPH	P	PPH
75	194.50	0.10		193.00	0.10					195.10	0.10		193.00	0.10			
70	184.00	0.10		182.50	0.10					184.60	0.10		182.60	0.10			
65	173.80	6.90		172.10	10.10					174.30	0.10		172.30	7.10			
60	163.30	30.90		161.60	34.10					163.60	27.30		161.80	31.30			
55	152.60	54.80		151.10	57.90					153.00	51.80		151.30	55.70			
50	146.60	69.50		146.30	69.00					146.10	68.70		146.20	68.70			
45	146.60	69.10		146.20	69.10					146.10	68.80		146.00	68.80			
40	135.90	89.10		135.70	89.20					136.40	86.60		136.30	87.10			
35	124.60	115.30		124.50	113.90					124.50	112.50		124.90	111.90			
30	113.20	127.40		113.20	127.00					113.30	126.90		113.20	126.90			
30	112.70		127.30	112.60		126.90				113.10		126.80	112.60		126.90		
35	123.60		117.70	123.30		115.60				123.80		114.50	123.30		115.60		
40	134.40		95.00	134.10		93.10				134.40		93.10	134.00		94.20		
45	144.90		71.30	144.80		69.80				145.10		70.10	144.70		71.30		
50	145.50		69.10	145.10		69.00				145.10		68.70	144.80		69.30		
55	148.90		62.60	149.30		61.30				149.00		61.80	148.60		63.20		
60	160.10		37.60	160.30		36.30				160.20		37.10	160.40		36.90		
65	171.10		12.90	171.30		11.80				171.30		12.70	171.30		13.50		
70	181.90		0.10	182.00		0.10				182.10		0.10	182.00		0.10		
75	192.70		0.10	192.80		0.10				192.70		0.10	192.70		0.10		
	Average High-Range Pre-Test Hyst, %					-4.44%				Average High-Range Pre-Test Hyst, %					23.14%		HR Delta
	Average Low-Range Pre-test Hyst., %					0.17%				Average Low-Range Pre-test Hyst., %					0.99%		LR Delta
Subtitle	Run Number 76, Valve Serial No. X013, Body No. 2																

Figure E-5. Generic Hysteresis Flow Data

E-4.5 Operations

A generic F119 mission profile was developed based on potential mission flight conditions that the aircraft might experience over its lifetime. This mission profile, call a Generic Durability Test Cycle (GDTC) is the ‘standard’ mission profile used to evaluate the deposition tendencies of the fuel or additive under evaluation (See Figure E-7). A comparison of the deposits produced in the FCOC and BFA along with an evaluation of the hysteresis in FDV and Servo Valves provides an assessment of the performance of a fuel and/or additives at the GDTC conditions.

Flow Divider Valve (FDV) Hysteresis Check

Run Number	76	Date:	3-Feb-05	Time:	10:00 AM		
FDV Serial No.	1248	FDV Body No.	A00143	Oper:	Shardo		
Date:	10-Feb-05	Time:	9:00 AM				
Fuel Description:	4751					Oper:	

	Pre-Test #1	Pre-Test #2	Pre-Test #3	Post-Test #1	Post-Test #2	Post-Test #
Check Delta-P	140.00	140.00	169.50	140.00	140.00	
Check Flow, Inc	43.28	43.56	#DIV/0!	41.39	42.06	
Check Flow, Dec	45.36	44.27	#DIV/0!	42.27	42.77	
% Hysteresis:	4.80%	1.63%	#DIV/0!	2.14%	1.68%	
Check Delta-P	190.00	190.00	190.00	190.00	190.00	
Check Flow, Inc	113.64	114.11	#DIV/0!	112.65	112.32	
Check Flow, Dec	118.60	118.46	#DIV/0!	115.85	115.86	
% Hysteresis:	4.36%	3.81%	#DIV/0!	2.84%	3.15%	

FCV303 Valve %	P	Flow, Inc PPH	Flow, Dec PPH	Delta P	Flow, Inc PPH	Flow, Dec PPH	Delta P	Flow, Inc PPH	Flow, Dec PPH	Delta P	Flow, Inc PPH	Flow, Dec PPH	Delta P	Flow, Inc PPH	Flow, Dec PPH	Delta P	Flow, Inc PPH
10	115.80	12.90		116.80	13.90					109.40	6.80		110.50	7.80			
20	128.70	27.60		129.40	28.70					123.10	19.70		123.90	21.20			
30	140.90	44.60		141.30	45.80					136.10	37.90		137.30	39.70			
40	152.10	60.00		152.30	61.40					148.20	54.10		149.10	55.80			
50	161.50	74.80		163.80	76.80					161.00	70.50		161.30	71.70			
60	171.30	87.30		171.50	88.90					169.50	83.50		169.90	84.50			
70	178.50	97.50		179.60	99.30					177.10	94.20		177.70	95.10			
80	185.60	107.10		186.20	108.20					184.80	104.50		185.50	105.50			
90	192.40	117.20		192.40	117.80					191.40	115.00		192.50	116.10			
100	199.50	127.60		200.10	127.90					199.50	125.70		200.20	126.60			
100	199.50		127.60	200.10		127.90				199.50		125.70	200.20		126.60		
90	190.40		119.30	190.70		120.10				190.50		116.90	191.50		118.10		
80	185.20		110.80	186.20		111.50				185.50		108.60	185.70		109.40		
70	179.90		102.50	180.00		102.90				178.50		98.90	179.20		99.50		
60	172.80		91.20	172.70		91.80				170.10		86.70	170.90		87.50		
50	163.60		77.40	164.40		78.30				160.80		72.10	160.80		73.40		
40	151.30		62.00	151.80		62.10				148.60		54.90	149.30		56.10		
30	141.20		46.50	141.90		47.00				136.20		39.10	136.80		40.10		
20	128.90		29.60	129.30		30.00				123.40		21.10	123.80		21.80		
10	116.10		14.30	116.80		15.00				108.70		7.50	109.50		8.10		
	Average Low-Range Pre-Test Hyst, %					3.21%				Average Low-Range Post-Test Hyst, %					1.91%		LR Delta
	Average High-Range Pre-test Hyst., %					4.09%				Average High-Range Post-test Hyst., %					2.99%		HR Delta

Figure E-6. Generic Hysteresis Flow Data

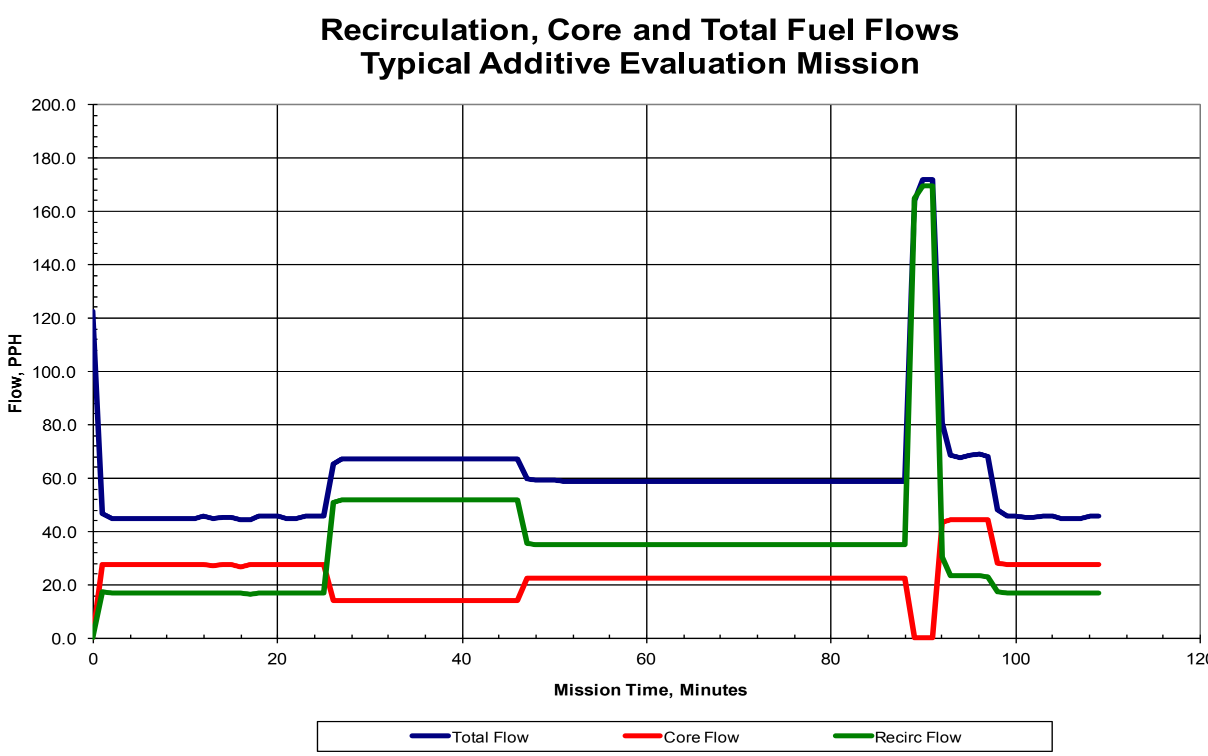


Figure E-7. ARSFSS Generic Mission Core and Recirculation Burn Fuel Flows

E-4.6 Data Reporting:

The following data will typically be reported: FCOC carbon burnoff

- BFA carbon burn-off
- Visual appearance of valves and components
- Hysteresis measurements on Servo Valves and Flow Divider Valves
- Any other pertinent data

E-4.7 Pass/Fail Criteria and Interpreting ARSFSS Results

While the ARSFSS makes a faithful attempt at a high integrity simulation of an aircraft and engine fuel system, insufficient data exists to tie simulator results obtained in a fixed number of missions to actual aircraft/engine performance degradation in real-world time. This is due to many factors - including the reduced scale of operation and the use of a generic mission which represents a compilation of operating conditions and mission styles.

Given this, the ARSFSS data is typically viewed in a comparison mode or maybe more aptly described as a 'do no harm' mode. In this mode, baseline and data tests are run at the same conditions. The data from the baseline and data runs are then compared. A successful data run is one in which the comparative data between baseline and data runs are the same (within reason). Therefore a test is considered a 'passing' test if the results show no significant deviation from the same results of a baseline test.

For this program, a two-tier baseline approach was used. The first tier baseline was a standard JP-8 with the military package of additives. The second tier baseline was a fuel additized with the currently accepted Betz additive. Candidate additives were considered to 'pass' the ARSFSS if they did not deviate significantly from second tier baseline. Comparison to the first tier baseline was primarily to demonstrate the overall impact on thermal stability for each additive.

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