AFRL-RQ-WP-TR-2013-0108

U.S. AIR FORCE HYDROPROCESSED RENEWABLE JET (HRJ) FUEL RESEARCH

James T. Edwards

Fuels & Energy Branch
Turbine Engine Division

Linda M. Shafer

University of Dayton Research Institute

James K. Klein

Klein Consulting LLC

JULY 2012
Interim Report

Approved for public release; distribution unlimited.

See additional restrictions described on inside pages

STINFO COPY

AIR FORCE RESEARCH LABORATORY
AEROSPACE SYSTEMS DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7542
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

NOTICE AND SIGNATURE PAGE

AFRL-RQ-WP-TR-2013-0108 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

*//Signature//
JAMES T. EDWARDS
Program Manager
Fuels & Energy Branch
Turbine Engine Division

//Signature//
MIGUEL A. MALDONADO, Chief
Fuels & Energy Branch
Turbine Engine Division
Aerospace Systems Directorate

*Disseminated copies will show "//Signature//" stamped or typed above the signature blocks.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE ***(DD-MM-YY)***
July 2012

2. REPORT TYPE
Interim

3. DATES COVERED *(From - To)*
24 November 2008 – 24 April 2012

4. TITLE AND SUBTITLE
U.S. AIR FORCE HYDROPROCESSED RENEWABLE JET (HRJ) FUEL RESEARCH

5a. CONTRACT NUMBER
In-house

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62203F

5d. PROJECT NUMBER
5330

5e. TASK NUMBER
N/A

5f. WORK UNIT NUMBER
Q0N9

6. AUTHOR(S)
James T. Edwards (AFRL/RQTF)
Linda M. Shafer (University of Dayton Research Institute)
James K. Klein (Klein Consulting LLC)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Fuels & 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

University of Dayton Research Institute
300 College Park
Dayton, OH 45469

Klein Consulting LLC
4479 E. Helenwood Drive
Beavercreek, OH 45431

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-RQ-WP-TR-2013-0108

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-2013-0108

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

13. SUPPLEMENTARY NOTES
PA Case Number: 88ABW-2012-5966; Clearance Date: 08 Nov 2012. This report contains color.

14. ABSTRACT
This report summarizes the specification, fit-for-purpose, and rig test results for the Air Force purchased HRJ fuels, as well as data collected on other fuels to support Air Force certification and to support ASTM Research Reports in support of HRJ commercial certification.

15. SUBJECT TERMS
alternative fuels; synthetic fuel; aircraft certification; airworthiness certification; fuel certification; hydrotreated renewable jet (HRJ); hydroprocessed esters and fatty acids (HEFA); HRJ fuel test results

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor) / 19b. TELEPHONE NUMBER *(Include Area Code)*
Unclassified	Unclassified	Unclassified	SAR	96	James T. Edwards / N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

TABLE OF CONTENTS

TABLE OF CONTENTS *(Cont'd)*

LIST OF FIGURES

LIST OF FIGURES *(Cont'd)*

LIST OF TABLES

LIST OF TABLES *(Cont'd)*

FOREWORD

A significant amount of research has been performed on the class of alternative aviation fuels known as Hydroprocessed Renewable Jet (HRJ), also known as bio-SPK (synthetic paraffinic kerosene) or Hydroprocessed Esters and Fatty Acids (HEFA). This class of fuel uses triglycerides and free fatty acids from plant oils and animal fats as the feedstock that is processed to create a hydrocarbon aviation fuel. The near term application of this fuel is as a 50/50 blend with conventional jet fuel, following the path followed by the previous alternative fuel certified in military and commercial specifications – Fischer-Tropsch SPK. The DARPA "Biojet" program and commercial flight demonstrations in Dec 2008-Jan 2009 led to the Air Force decision to proceed with a certification effort that involved purchases of more than 400,000 gallons of HRJ from camelina, tallow and mixed fat feedstocks, and included flights on the A-10 (March 2010), the C-17 (August 2010), and the F-15 (October 2010), as well as various engine tests, with more planned. This report summarizes the specification, fit-for-purpose, and rig test results for the USAF purchased HRJ fuels, as well as data collected on other fuels to support Air Force certification and to support ASTM Research Reports[1] in support of HRJ commercial certification.

---

[1] References 1 and 2

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support and contributions of several persons and organizations that made it possible to obtain the data described in this report:

Southwest Research Institute, Mr. Gary Bessee, Mr. Scott Hutzler, David Yost et al. for laboratory studies

Rolls-Royce Liberty Works, Mr. Nader Rizk and Mr. David Turner et al. for conduct of combustion experiments

AFRL/RQTF emission team lead Edwin Corporan, for conduct of emissions testing

University of Dayton Research Institute, Ms. Linda Shafer, Ms. Rhonda Cook, Mr. Richard Striebich, Dr. John Graham, Matthew DeWitt, Chris Klingshirn et al. for conduct of laboratory experiments

Universal Technology Corporation, Ms. Pamela Kearney for report formatting and editing

United States Air Force Petroleum Agency (AFPET/AFPA/PTPLA) for conduct of specification testing

1.0 EXECUTIVE SUMMARY

A significant amount of research has been performed on the class of alternative aviation fuels known as Hydroprocessed Renewable Jet (HRJ), also known as bio-SPK (synthetic paraffinic kerosene) or Hydroprocessed Esters and Fatty Acids (HEFA). This class of fuel uses triglycerides and free fatty acids from plant oils and animal fats as the feedstock that is processed to create a hydrocarbon aviation fuel. The near term application of this fuel is as a 50/50 blend with conventional jet fuel, following the path followed by the previous alternative fuel certified in military and commercial specifications – Fischer-Tropsch SPK. The DARPA "Biojet" program and commercial flight demonstrations in Dec 2008-Jan 2009 led to the Air Force decision to proceed with a certification effort that involved purchases of more than 400,000 gallons of HRJ from camelina, tallow and mixed fat feedstocks, and included flights on the A-10 (March 2010), the C-17 (August 2010), and the F-15 (October 2010), as well as various engine tests and other flight tests, with more planned. This report summarizes the specification, fit-for-purpose, and rig test results for the AF-purchased HRJ fuels, as well as data collected on other fuels to support Air Force certification and to support ASTM Research Reports in support of HRJ commercial certification. The data in this reports supplements earlier data (listed below) that supported the June 2011 approval of HRJ/HEFA in ASTM D7566. This report supplements the ASTM Research Report for Bio-SPK (HRJ/HEFA), D02-1739.

Kinder, J. et al., "Evaluation of Bio-Derived Synthetic Paraffinic Kerosenes (Bio-SPKs)," ASTM Research Report published May 2010. Addendum published October 2010.

Klein, J. K., "Production Demonstration and Laboratory Evaluation of R-8 and R-8X Hydrotreated Renewable Jet (HRJ) Fuel," AFRL-RZ-WP-TR-2011-2020, May 2010.

Bessee, G. et al. "Analysis of Synthetic Aviation Fuels," Interim Report on SwRI Project No. 08-14406, Nov. 2010. AFRL-RZ-WP-TR-2011-2084 published April 2011.

2.0 INTRODUCTION

The United States Air Force Research Laboratory has accomplished and sponsored comprehensive studies of the Hydroprocessed Renewable Jet (HRJ) class of fuels. In general, the evaluations proceed through specification properties (MIL-DTL-83133/ASTM D7566) and compositional analysis, fit-for-purpose properties and rig/small engine testing as the Technology Readiness Level (TRL) increases from Level 1 to Level 5/6. At this point, evaluation is taken over by the USAF Alternative Fuel Certification Division for full-scale engine and flight testing. The purpose of this report is to document the results of the AFRL studies, comparing to the certified Fischer-Tropsch (FT SPK) fuels as appropriate.

Table 1. Technology Readiness Level Definitions

TRL 1	Basic Fuel Properties Observed and Reported
TRL 2	Fuel Specification Properties
TRL 3	Fit for Purpose
TRL 4	Extended Laboratory Fuel Property Testing
TRL 5	Component Rig Testing
TRL 6	Small Engine Demonstration
TRL 7	Pathfinder: APU & On-Aircraft Evaluation, Afterburning Engine Test
TRL 8	Validation/Certification
TRL 9	Field Service Evaluations

The values[2] that follow were primarily generated by the Air Force Petroleum Agency Laboratory (AFPET) at Wright-Patterson Air Force Base (WPAFB), the University of Dayton Research Institute Laboratory at WPAFB, and the Southwest Research Institute (SwRI) in San Antonio Texas. Current and previous FT SPK and HRJ reports and technical memorandums are incorporated by reference and are listed in section 6.0. The figures and tables provided herein show comparative information taken from these various sources and references.
The various fuels and blends evaluated are shown in Table 2 and Table 3. HRJ Fuel manufacturers include the Syntroleum Corporation, Tulsa Oklahoma, Honeywell's UOP LLC, Des Plaines, Illinois, and the Dynamic Fuels LLC, Geismar, Louisiana. The POSF number is the USAF Fuels Branch (AFRL/RZPF) unique identification number assigned.

[2] The various laboratory investigations occurred over the course of several years with testing re-run, updates and improvements. As would be expected, there are minor variances within the data sets however these variances are all within procedural limits. An attempt is made herein to provide the most current data.

Table 2. Air Force HRJ Fuel ID Numbers

HRJ Fuel Feedstock	Date Delivered	POSF Number	POSF number with JP-8 additive	Details
Camelina	12/4/2009	6152	6183	UOP, 5800 gal
Camelina	2/16/2012	7720		UOP, 6000 gal
Tallow	3/11/2010	6308	6346	UOP, 6200 gal
Reprocessed tallow	3/24/2010	6411	6418	UOP, 6600 gal
Mixed fat	11/12/2010	7272	7385	Dynamic Fuels "R-8", 40,000 gal
Mixed fat	8/1/2008	5469	5480	Syntroleum "R-8" 600 gal
Halophyte Salicornia oil from sea plants	8/1/2008	5470	none	Syntroleum "R-8X" 10 gal

Table 3. List of Other Fuel Samples and Blends

POSF No.	Manufacturer/ Source	Fuel Description
4909	Syntroleum	F-T SPK + JP-8 additives
6169	WPAFB	Reference JP-8
4751	WPAFB	Reference JP-8
6399	UOP/WPAFB	50/50 Blend (6346/6169)
6406	UOP/WPAFB	50/50 Blend (6346/4751)
6184	UOP/WPAFB	50/50 Blend (6183/4751)
6185	UOP/WPAFB	50/50 Blend (6183/6169)
7721	UOP/WPAFB	50/50 Blend (7720/6169)
4913,5644	Syntroleum/WPAFB	50/50 Blend (4909/4751)
7386	Dynamic Fuels/WPAFB	50/50 Blend (7385/4751)
6357	WPAFB/AEDC	Tallow HRJ
6358	WPAFB/AEDC	50/50 Blend Tallow HRJ/JP-8
5768	WPAFB/EGLIN	Camelina HRJ for A-10 flight
5769	WPAFB/EGLIN	50/50 Blend Camelina HRJ/JP-8

3.0 METHODS, ASSUMPTIONS, AND PROCEDURES

The alternative aviation fuel evaluation/certification process is summarized in MIL-HDBK-510 and commercial aviation standard practice ASTM D4054. The military process includes several military unique considerations such as low temperature viscosity for aerial refueling, auxiliary power unit (APU) cold start, low temperature freeze for high altitude operations, military additive compatibility, ground vehicle diesel engine compatibility, special airframe and engine materials compatibility (including self-sealing materials and explosion protection fuel cell foam), afterburner start and operation, high temperature thermal stability, lower lubricity for legacy systems, special fuel storage and special filtration considerations.

These documents provide a framework for the acceptance of new fuels and new fuel additives. The specific evaluations therein do not constitute an endorsement of a particular fuel or fuel additive but are intended to provide the necessary information for use by approval authorities. To initiate the process, the supplier must have identified and confirmed a viable feedstock and conversion process, established a laboratory-scale production, and provided a satisfactory product Material Safety Data Sheet (MSDS). Standard and tailored ASTM, SAE, and military and commercial specification test methods are employed for the evaluations except as noted.

4.0 RESULTS AND DISCUSSION

4.1 Basic Fuel Properties Observed and Reported

4.1.1 Material Safety Data Sheet (MSDS)

A MSDS must be provided by the manufacturer/supplier for every fuel delivery. It identifies and describes the fuel/chemical and provides composition, information on ingredients, hazards identification, first aid measures, fire fighting measures, accidental release measures, handling and storage recommendations, exposure controls and personal protection including eye irritation, physical and chemical properties, stability and reactivity information, toxicological information, disposal considerations, transport information and various regulatory information. NEPA ratings are provided for the product for health, fire and reactivity. As expected these ratings show similarity to JP-8 jet fuel.

Table 4. HRJ MSDS Hazard Ratings

HRJ Fuel Feedstock	POSF Number	NEPA Rating Health[3]	NEPA Rating Fire	NEPA Rating Reactivity
Camelina	6152	2	2	0
Camelina	7720	2	2	0
Tallow	6308	2	2	0
Reprocessed tallow	6411	2	2	0
Mixed fat	7272	1	2	0
Mixed fat	5469	1	2	0
Halophyte Salicornia oil from sea plants	5470	1	2	0
JP-8	4751	2	2	0

4.1.2 Compositional Measurements – Hydrocarbons

The petroleum jet fuel specifications contain few compositional requirements, notably the 25 vol% maximum limit on aromatics. With the advent of alternative fuels, much more compositional information is desired. ASTM D7566 and MIL-DTL-83133F/G require hydrocarbon speciation into classes by ASTM D2425, as well as measurements of trace contaminants. Tables 5 and 6 show the absence of aromatics (consistent with SPK fuels) for the neat fuels and low aromatic levels for the blended fuels. The typical specification aromatic measurement (ASTM D1319) is not sensitive at lower aromatic levels, so ASTM D6379 is used to assess aromatic levels.

Tables 8 and 9 show that the HRJ fuels are primarily paraffinic (n- and iso-paraffins). Interestingly, the camelina HRJ fuel contains measurable levels of cycloparaffins (~10%), similar to the Sasol IPK F-T SPK fuel. While ASTM D2425 does not separate n- and iso-paraffins, (Tables 8 – 10), GC-MS can be used to separately measure n-paraffins; measurements show that the HRJ fuels are primarily iso-paraffinic. The n-paraffin distribution is plotted in

[3]Ratings: 0-minimal hazard, 1- slight hazard, 2- moderate hazard, 3- serious hazard, 4- severe hazard.

Figure 1, where it can be seen that the n-paraffin peak for the HRJ fuels is a bit lower than in SPK and JP-8 fuels.

Table 5. Aromatic Species Analysis by D6379 for HRJs, F-T SPK, and JP-8s (vol %)[4]

POSF	6308	6152	4909	6169	4751	5470	7272	5469
Feedstock	**Tallow**	**Camelina**	**Nat Gas**			**Sea Plants**	**Mixed Fats**	**Mixed Fats**
Designation	**HRJ8**	**HRJ8**	**FT SPK**	**JP-8**	**JP-8**	**HRJ8 R-8X**	**HRJ8 R-8 Production**	**HRJ8 R-8 Pilot**
D6379 (vol %)								
Mono-aromatics	<0.2	<0.2	<0.2	13.7	17.5	0.6	<0.2	0.3
Di-aromatics	<0.1	<0.1	<0.2	1.2	1.2	<0.2	<0.1	<0.1
Total Aromatics	**<0.2**	**<0.2**	**<0.2**	**14.9**	**18.7**	**0.6**	<0.2	**0.3**
Total Saturates	**>99.8**	**>99.8**	**>99.8**	**85.1**	**81.3**	**99.4**	**>99.8**	**99.7**

Table 6. Aromatic Species Analysis by D6379 for HRJs, F-T SPK, and JP-8s (mass %)[5]

POSF	6308	6152	7720	4909	6169	4751	7272	5469
Feedstock	**Tallow**	**Camelina**	**Camelina**	**Nat Gas**			**Mixed Fats**	**Mixed Fats**
Designation	**HRJ8**	**HRJ8**	**HRJ8**	**FT SPK**	**JP-8**	**JP-8**	**HRJ8 R-8 Production**	**HRJ8 R-8 Pilot**
D6379 (mass %)								
Mono-aromatics	<0.2	<0.2	<0.2	<0.2	14.6	19.3	<0.2	0.4
Di-aromatics	<0.1	<0.1	<0.1	<0.1	1.5	1.3	<0.1	<0.1
Total Aromatics	**<0.2**	**<0.2**	**<0.2**	**<0.2**	**16.1**	**20.6**	<0.2	**0.4**
Total Saturates	**>99.8**	**>99.8**	**>99.8**	**>99.8**	**83.9**	**79.4**	**>99.8**	**99.6**

[4] Table 5 data generated by UDRI, (References 3 and 6)
[5] Table 6 data generated by UDRI, (References 3 and 6)

Table 7. Aromatic Content by D1319 for HRJ Blends[6]

POSF	6406 + JP-8	6184 +JP-8	5675 + Jet-A	5674+ Jet-A	5673 + Jet-A	5469 + Jet-A
Feedstock	Tallow	Camelina	Camelina Jatropha Algae	Camelina Jatropha Algae	Camelina Jatropha Algae	R-8 Mixed Fats
Designation	50/50 Blend	50/50 Blend	CAL Blend	JAL Blend	ANZ Blend	50/50 Blend
D1319 (vol %)						
Aromatics	9.4	9.0	9.1	8.7	9.3	7.8
Olefins	1.3	0.9	0.5	0.7	0.7	0.5
Saturates	89.3	90.1	90.4	90.6	90.0	91.7

Table 8. Hydrocarbon Type Analysis by D2425 for HRJs, F-T SPK, and JP-8s (vol %)[7]

POSF	6308	6152	4909	6169	4751	5470	7272	5469
Feedstock	Tallow	Camelina	Nat Gas			Sea Plants	Mixed Fats	Mixed Fats
Designation	HRJ8	HRJ8	FT SPK	JP-8	JP-8	HRJ8 R-8X	HRJ8 R-8 Production	HRJ8 R-8 Pilot
D2425 (volume %)								
Paraffins (normal + iso)	98	90	97	59	49	96	98	91
Cycloparaffins	2	10	3	26	30	3	2	9
Alkylbenzenes	<0.3	<0.3	<0.3	10	13	0.5	<0.3	0.4
Indans and Tetralins	<0.3	<0.3	<0.3	3.2	5.8	<0.3	<0.3	<0.3
Indenes and C_nH_{2n-10}	<0.3	<0.3	<0.35	<0.3	0.6	<0.3	<0.3	<0.3
Naphthalene	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Naphthalenes	<0.3	<0.3	<0.3	1.1	1.0	<0.35	<0.3	<0.3
POSF	6308	6152	4909	6169	4751	5470	7272	5469
Acenaphthenes	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Acenaphthylenes	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Tricyclic Aromatics	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Total	100	100	100	100	100	100	100	100

[6] Data generated by SwRI (References 5)
[7] Data generated by UDRI (References 3 and 6)

Table 9. Hydrocarbon Type Analysis by D2425 for HRJs, F-T SPK, and JP-8s (mass %)[8]

POSF	6308	6152	7720	4909	6169	4751	7272	5469
Feedstock	Tallow	Camelina	Camelina	Nat Gas			Mixed Fats	Mixed Fats
Designation	HRJ8	HRJ8	HRJ8	FT SPK	JP-8	JP-8	HRJ8 R-8 Production	HRJ8 R-8 Pilot
D2425 (mass %)								
Paraffins (normal + iso)	98	89	95	98	57	49	98	91
Cycloparaffins	2	11	5	2	27	30	2	9
Alkylbenzenes	<0.3	<0.3	<0.3	<0.3	10.6	13	<0.3	0.4
Indans and Tetralins	<0.3	<0.3	<0.3	<0.3	3.8	5.8	<0.3	<0.3
Indenes and C_nH_{2n-10}	<0.3	<0.3	<0.3	<0.3	<0.3	0.6	<0.3	<0.3
Naphthalene	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Naphthalenes	<0.3	<0.3	<0.3	<0.3	1.3	1.0	<0.3	<0.3
Acenaphthenes	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Acenaphthylenes	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Tricyclic Aromatics	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Total	100	100	100	100	100	100	100	100

[8] Data generated by UDRI (References 3 and 6)

Table 10. Hydrocarbon Type Analysis by D2425 for HRJ Blends[9]

POSF	6406 + JP-8	6184 +JP-8	5675 + Jet-A	5674+ Jet-A	5673 + Jet-A	5469 + Jet-A
Feedstock	Tallow	Camelina	Camelina Jatropha Algae	Camelina Jatropha Algae	Camelina Jatropha Algae	R-8 Mixed Fats
Designation	50/50 Blend	50/50 Blend	CAL Blend	JAL Blend	ANZ Blend	50/50 Blend
D2425 (mass %)						
Paraffins (normal + iso)	74.5	67.6	64.5	58.1	63.5	70.7
Cycloparaffins	15.5	20	24.9	30.6	24.6	19
Alkylbenzenes	5.5	5.4	6.4	5.3	7.3	6.1
Indans and Tetralins	3.3	4.6	3.4	3	3.5	3.5
Indenes and C_nH_{2n-10}	0.2	0.3	<0.1	0.6	<0.1	<0.1
Naphthalene	0.3	0.4	0.3	0.4	0.4	0.3
Naphthalenes, Alkyl	0.5	1.4	0.3	1.6	0.6	0.3
Acenaphthenes	0.1	0.3	0.1	0.2	<0.1	0.1
Acenaphthylenes	0.1	0.1.	0.1	0.2	0.1	0.1
Tricyclic Aromatics	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Total	100	100	100	100	100	100

Table 11. Carbon/Hydrogen Content by D5291 for HRJ Fuels[10]

POSF	6308	6152	5675	5674	5673	5469
Feedstock	Tallow	Camelina	Camelina Jatropha Algae	Camelina Jatropha Algae	Camelina Jatropha Algae	R-8 Mixed Fats
Designation	HRJ8	HRJ8	CAL	JAL	ANZ	HRJ
D5291 (mass %)						
Carbon		83.98				86.32
Hydrogen		15.26				14.12

[9] Data generated by SwRI (Reference 5)
[10] Data generated by SwRI (References 3 and 5)

Table 12. Carbon/Hydrogen Content by D5291/3701 for HRJ Blends[11]

POSF	6406 + JP-8	6184 +JP-8	5675 + Jet-A	5674+ Jet-A	5673 + Jet-A	5469 + Jet-A
Feedstock	**Tallow**	**Camelina**	**Camelina Jatropha Algae**	**Camelina Jatropha Algae**	**Camelina Jatropha Algae**	**R-8 Mixed Fats**
Designation	**50/50 Blend**	**50/50 Blend**	**CAL Blend**	**JAL Blend**	**ANZ Blend**	**50/50 Blend**
D5291 (mass %) D3701 (mass %)						
Carbon D5291	85.29	84.7	85.50	85.50	85.49	84.94
Hydrogen D5291	14.57	14.56	14.58	14.39	14.56	14.64
Hydrogen D3701	14.61	14.58	14.65	14.39	14.49	14.66

Table 13. Weight Percent of n-Paraffins for HRJs, F-T SPK, and JP-8s[12]

	6308 HRJ8-Tallow	6152 HRJ8-Camelina	4909 FT-SPK	6169 JP-8	4751 JP-8	5470 HRJ8-R-8X	5469 HRJ8 R-8	7272 HRJ8 -R-8
n-Paraffins (weight %)								
n-Heptane	<0.001	0.017	0.14	0.13	0.10	0.11	0.13	0.30
n-Octane	0.12	0.71	1.32	0.50	0.34	0.89	0.80	0.61
n-Nonane	2.01	3.20	2.60	1.85	1.21	2.92	2.28	0.94
n-Decane	1.88	2.80	3.23	4.32	3.48	2.59	2.47	1.37
n-Undecane	1.52	1.20	3.18	4.70	4.24	2.20	2.10	1.38
n-Dodecane	1.25	0.87	2.46	4.14	3.71	1.78	1.64	1.24
n-Tridecane	0.82	0.60	1.94	3.01	2.84	1.53	1.23	0.92
n-Tetradecane	0.86	0.41	1.18	1.75	1.79	0.94	0.92	1.40
n-Pentadecane	0.35	0.37	0.70	0.78	0.87	0.66	0.80	0.38
n-Hexadecane	0.004	0.061	0.35	0.24	0.27	0.21	0.60	0.66
n-Heptadecane	<0.001	0.015	0.090	0.081	0.089	0.033	0.052	0.021
n-Octadecane	<0.001	0.006	0.010	0.023	0.024	0.009	0.026	0.007
n-Nonadecane	<0.001	0.001	0.002	0.008	0.008	<0.001	<0.001	<0.001
Total n-Paraffins	**8.8**	**10.2**	**17.2**	**21.5**	**19.0**	**13.9**	**13.1**	**9.2**

[11] Data generated by SwRI (References 3 and 5)
[12] Data generated by UDRI (References 3 and 6)

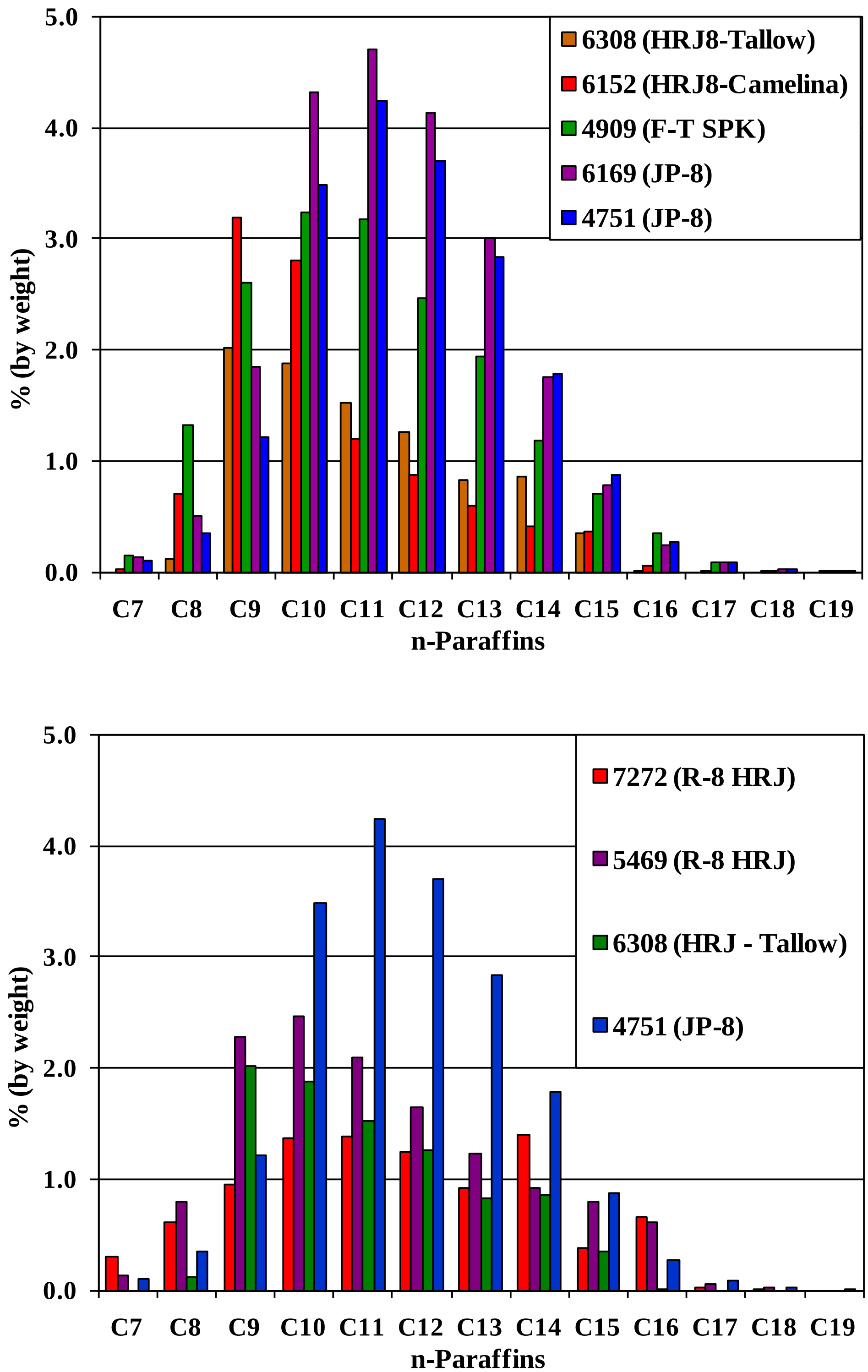
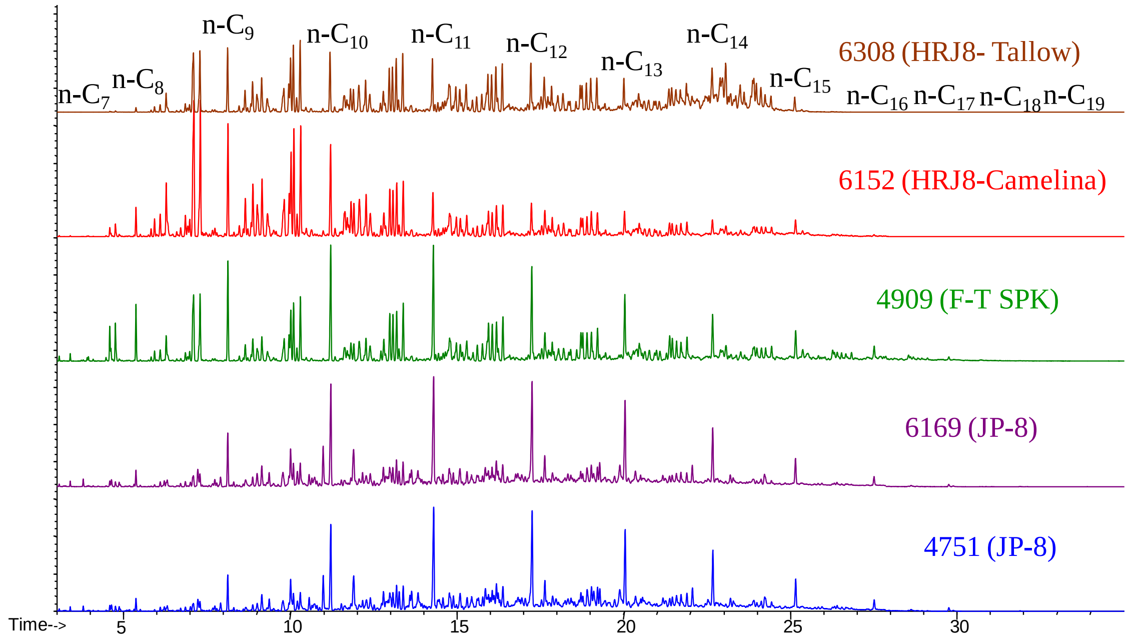


Figure 1. Weight Percent of n-Paraffins (C7-C19) for HRJs, F-T SPK, and JP-8s

Gas chromatographic traces for the various fuels are shown in Figures 2 and 3. Overall, the molecular distribution of the various neat alternative fuels is similar – and all the 50/50 blends look very similar to JP-8. The GC traces do show that there is more “light”/low molecular weight material in the camelina HRJ (POSF 6152) than in the other fuels. There are correlations that can be used to calculate average molecular weight from fuel boiling and density data [Maxwell, J. B., “Data Book on Hydrocarbons,” page 21, Van Nostrand, New York, 1950]. This data is shown in Table 14, which confirms that the camelina HRJ is slightly “lighter” than the other fuels, although the Shell SPK is the lightest alternative fuel tested to date, both in terms of density and average molecular weight.

Table 14. Average Molecular Weight Calculation

	Density, g/cc	**T10, C**	**T50, C**	**T90, C**	**Heat of combustion, MJ/kg**	**MW [from Maxwell]**
S-8 5018	0.755	170	209	247	44.1	174
Shell 5172	0.739	161	168	185	44.2	148
Sasol IPK 5642	0.762	167	180	208	44.0	154
R-8 HRJ 5469	0.762	175	215	260	44.1	178
Tallow HRJ 6308	0.758	179	210	243	44.1	174
Camelina HRJ 6152	0.751	161	182	237	44.3	160
JP-7 3327	0.793	203	214	234	43.7	170
JP-8 3773	0.799	173	198	239	43.1	160



	Weight % n-Paraffins			
	C_7-C_9	C_{10}-C_{13}	C_{14}-C_{16}	C_{17}-C_{19}
7272	1.9	4.9	2.4	0.03
5469	3.2	7.4	2.3	0.08
6308	2.1	5.5	1.2	<0.003
4751	1.7	14.3	2.9	0.12

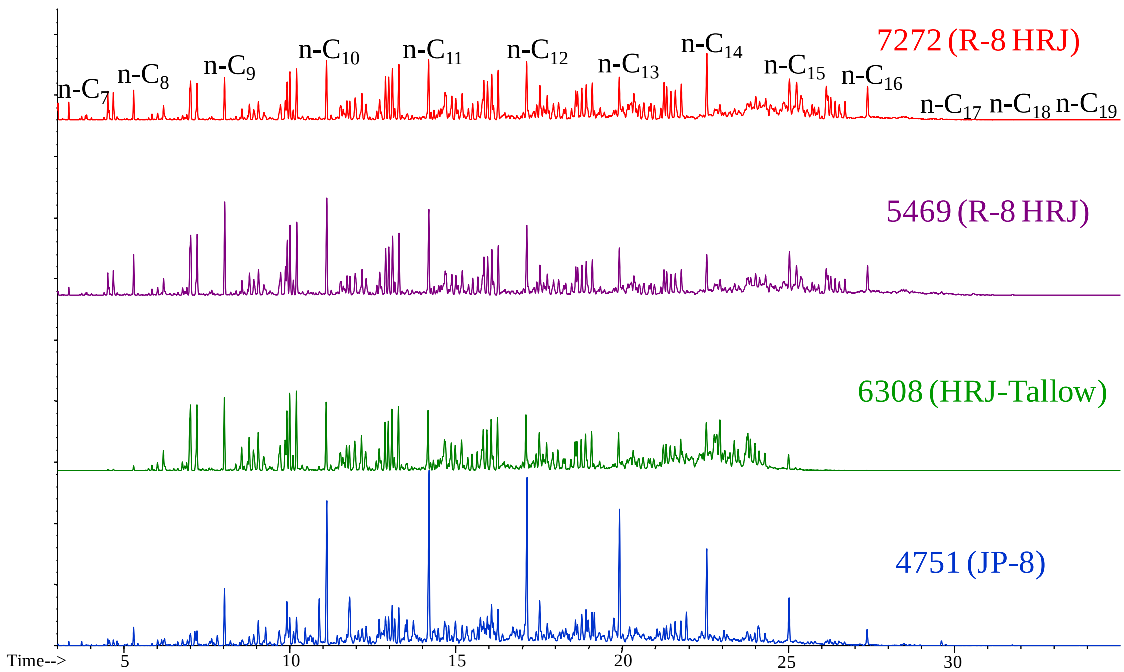


Figure 2. Chromatograms of HRJs, F-T SPK, and JP-8s

Approved for public release; distribution unlimited.

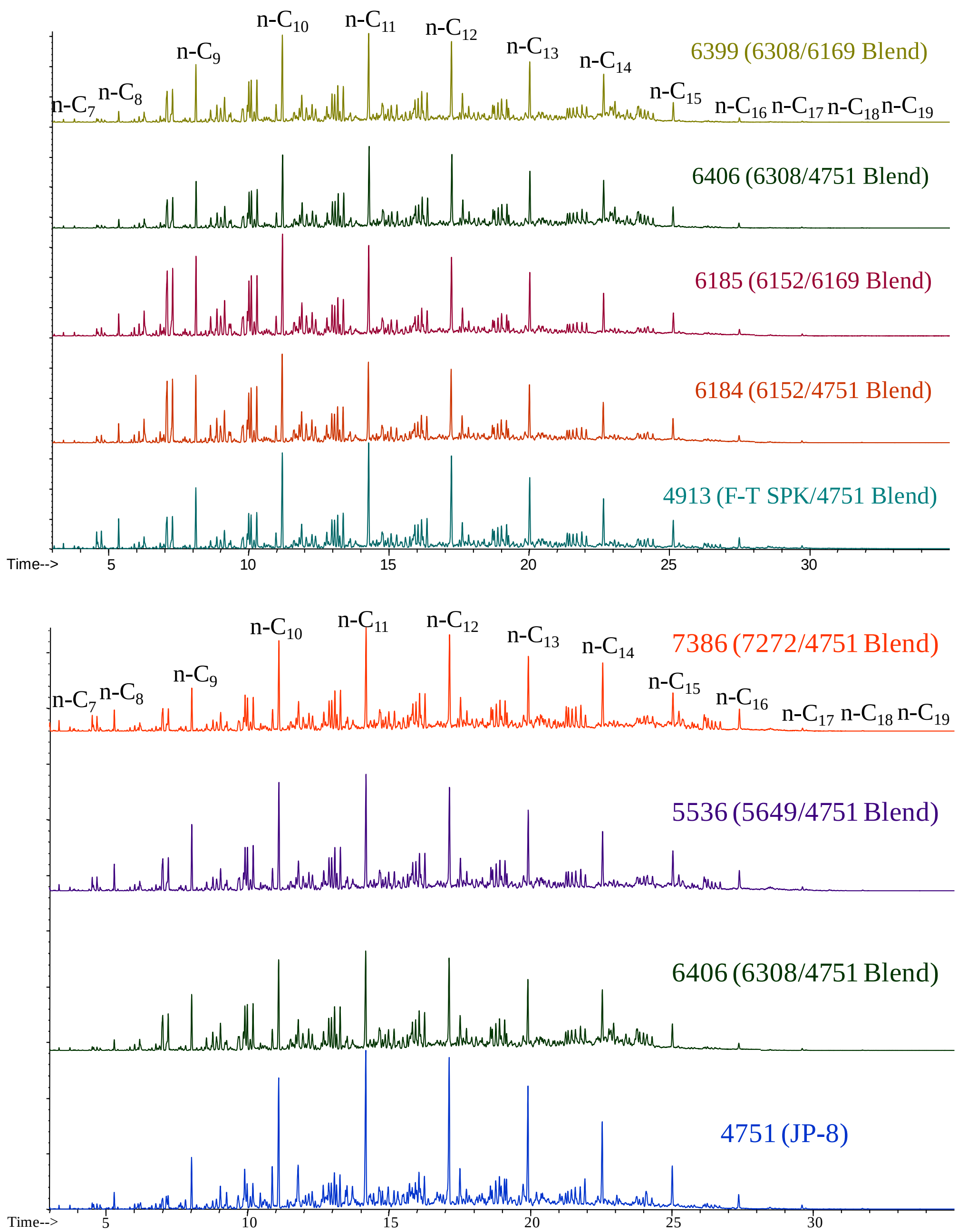


Figure 3. Chromatograms of Blends

More recent production of the Camelina HRJ (POSF 7720) shows more "heavy" molecular weight material than the earlier production (POSF 6152). This is shown by the comparative GC trace, Figure 4.

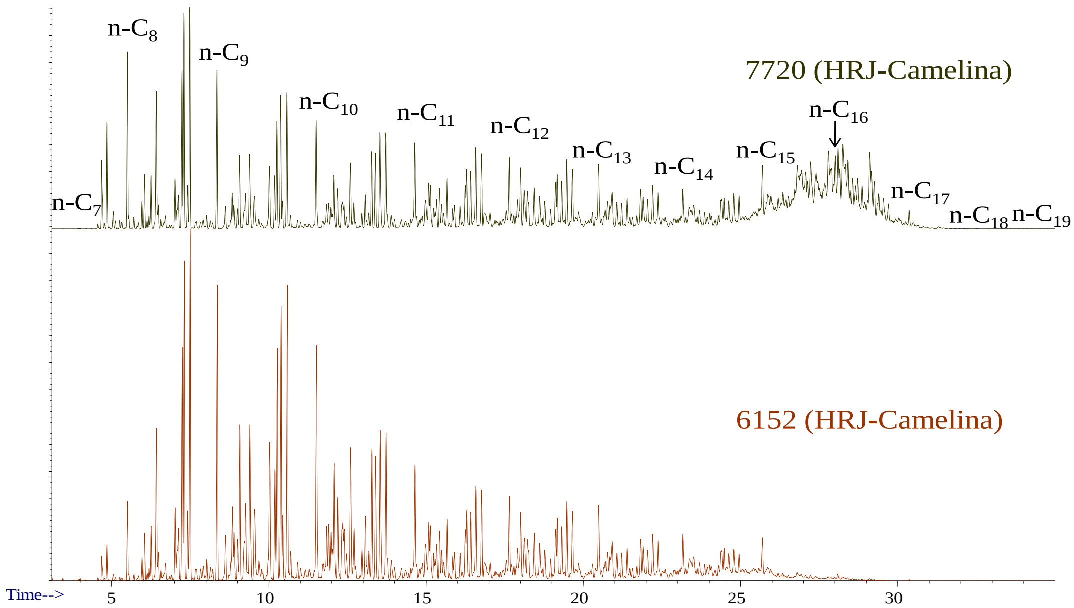


Figure 4. Camelina HRJ GC Traces Comparing Early and More Recent Production

4.1.3 Biobased Determination Using ASTM-D6866-08

The ASTM D6866 carbon dating method[13] was used to verify that the HRJ fuels were actually "bio", in that this test differentiates between "modern" (bio) carbon and fossil carbon. Measurements were performed for AFRL by Beta Analytic Inc., Miami, Florida. Table 15 shows that petroleum JP-8 and GTL fuels are indeed "fossil", while the HRJ fuels are "bio", with blends being correctly measured as 50% bio.

Table 15. HRJ Bio Content

Fuel	JP-8	HRJ8 R-8	HRJ8 R-8X	R-8 JP-8 Blend	S-8 NatGas	HRJ8 Camelina	Camelina Blend	HRJ8 R-8	HRJ8 Tallow
POSF	4751	5469	5646	5536	4820	6152	6184	7272	6308
Bio Content	0%	96%	100%	49%	0%	97%	47%	99%	99%

[13] ASTM-D6866 cites precision on The Mean Biobased Result as +/- 3% (absolute). The accuracy of the result relies upon all the carbon in the analyzed material originating from either recently respired atmospheric carbon dioxide (within the last decade) or fossil carbon (more than 50,000 years old). "Percent biobased" specifically relates % renewable (or fossil) carbon to total carbon, not to total mass or molecular weight.

4.1.4 Compositional Measurements – Trace Materials

ASTM D7566 and MIL-DTL-83133G require a significant amount of trace contaminant testing for the alternative fuels – much more testing than is required for Jet A or JP-8. There is a 100 ppb requirement for a long list of contaminants, (in many cases this stringent requirement is pushing the limit of available analytical techniques). The specifications cite UOP 389 as a test method, but often the only available data comes from other tests methods, such as ASTM D7111. Also, certain contaminants are often introduced through exposure to glassware during handling, thus contamination from these "glass metals" (Ca, Na, K, Al) is often discounted. Note also that contaminant data found in the alternative fuel but not the blend (or vice versa) can also be discounted due to the difficulty of the measurement. Nonetheless, the "metal" contaminant data from SwRI and Dynamic Fuels (Table 16) and the AFPET laboratory (Table 17) indicate very low contaminant levels. The ICP-OES data appears to be somewhat inconsistent, but the HRJ contaminant levels are consistently below the F-T SPK levels. There is an ongoing debate about the validity and necessity of these measurements, given the stringent nature of the 325 C JFTOT thermal stability requirements.

Table 16. Elemental Analysis by D7111[14]

	Camelina	**Camelina Blend**	**Tallow Blend**	**Mixed Fats**	**R-8 Blend**
POSF	**6152**	**6152/4751**	**6406**	**7272**	**5469/Jet A**
Al	157ppb	<100ppb	162ppb		280ppb
Ba	<100ppb	<100ppb	<100ppb		<100ppb
Ca	102ppb	397ppb	159ppb	<0.1 mg/kg	<100ppb
Cr	<100ppb	<100ppb	<100ppb	<0.1 mg/kg	<100ppb
Cu	<100ppb	<100ppb	<100ppb	<0.1 mg/kg	<100ppb
Fe	<100ppb	<100ppb	<100ppb	<0.1 mg/kg	<100ppb
Li	<100ppb	<100ppb	<100ppb		<100ppb
Pb	<100ppb	<100ppb	<100ppb	<0.1 mg/kg	<100ppb
Mg	<100ppb	<100ppb	<100ppb	<0.1 mg/kg	<100ppb
Mn	<100ppb	<100ppb	<100ppb	<0.1 mg/kg	<100ppb
Mo	<100ppb	<100ppb	<100ppb	<0.1 mg/kg	<100ppb
Ni	<100ppb	<100ppb	<100ppb	<0.1 mg/kg	<100ppb
K	<1ppm	<1ppm	<1ppm	<0.1 mg/kg	<1000ppb
Na	<1ppm	<1ppm	<1ppm	<0.1 mg/kg	<1000ppb
Si	2.9ppm	<100ppb	523ppb		<100ppb
Ag	<100ppb	<100ppb	<100ppb		<100ppb
Ti	<100ppb	<100ppb	<100ppb		<100ppb
V	<100ppb	<100ppb	<100ppb	<0.1 mg/kg	<100ppb
Zn	<100ppb	161ppb	<100ppb	<0.1 mg/kg	<100ppb

[14] Data generated by SwRI and Dynamic Fuels LLC (References 5 and 6)

Table 17. Metals Analysis by ICP-OES for HRJ, F-T SPK, and JP-8 (AFPET)

Element	Concentration (ppb wt)			Quantitation Limit
	6308 HRJ8-Tallow	4909 FT-SPK	4751 JP-8	
Ag	18	41	19	14
Al	92	210	120	70
Ca	160	1160	580	120
Cd	16	29	29	12
Cr	210	BQL[15]	BQL	160
Cu	5	BQL	BQL	4
Fe	1	BQL	BQL	1
K	20	300	65	15
Mg	2	44	15	1
Mn	3	BQL	BQL	3
Mo	40	190	83	30
Na	170	680	350	130
Ni	80	190	140	61
P	330	1040	560	250
Sn	53	460	260	40
Ti	18	BQL	BQL	14
V	53	BQL	BQL	40
Zn	33	BQL	38	23

[15] BQL = Below quantitation limit

Table 18. Metals Analysis by ICP-MS[16]

Element	Concentration (ppb wt.) 7272 R-8 HRJ	5469 R-8 HRJ	6308 HRJ Tallow	6152 HRJ Camelina	4909 F-T SPK	6169 JP-8	4751 JP-8
Aluminum	315	306	242	165	332	133	306
Arsenic	<5	6	<5	<5	<5	7	<5
Barium	<5	<5	<5	<5	<5	<5	<5
Beryllium	<5	<5	<5	<5	<5	<5	<5
Cadmium	<5	<5	<5	<5	<5	<5	<5
Calcium	8	<5	6	<5	10	9	7
Chromium	<5	<5	<5	<5	<5	<5	<5
Cobalt	<5	<5	<5	<5	<5	<5	<5
Copper	<5	<5	<5	<5	<5	7	<5
Iron	<5	<5	<5	<5	<5	<5	<5
Lead	<5	<5	<5	<5	<5	<5	<5
Magnesium	9	11	6	5	8	<5	7
Manganese	<5	<5	<5	<5	<5	<5	<5
Mercury	<2	<2	<2	<2	<2	<2	<2
Molybdenum	<5	<5	<5	<5	<5	<5	<5
Nickel	<5	<5	<5	9	<5	9	<5
Phosphorus	<500	<500	<500	<500	<500	<500	<500
Potassium	59	<5	<5	<5	<5	<5	<5
Silver	<5	<5	<5	<5	<5	<5	<5
Sodium	14	<5	5	<5	<5	5	49
Tin	<5	<5	<5	<5	<5	<5	<5
Titanium	<5	<5	7	16	<5	8	<5
Vanadium	32	36	<5	12	<5	21	10
Zinc	<5	<5	<5	<5	<5	13	6
Selenium	<5	<5	14	<5	<5	72	<5
Strontium	<5	<5	<5	<5	<5	<5	<5

Mil-DTL-83133H Spec for SPKs is ≤100 ppb.

Separate tests for nitrogen and copper (the most deleterious metal) were performed, as shown in Table 19. UDRI also performed a test where “polar” species (typically oxygenates) were extracted from the fuel using solid phase extraction/methanol, and then analyzed on an HPLC. The alternative fuels had very low level of polar species as expected – significantly lower than the two baseline JP-8 fuels.

---

[16] Data generated by SGS for UDRI (Reference 6)

Table 19. Nitrogen Content & Copper by AA[17]

POSF		6152	6184	6406	5469	R-8/Jet A	7272
Nitrogen D4629	**mg/kg**	**2**	**2**	**3**	**.1**	**2**	**1**
Copper D3237M	**ppb**	**<5**	**<5**	**<5**	**.013**	**6**	

Table 20. Phenolic Polars Analysis by HPLC for HRJs, F-T SPK, and JP-8s

	6308 HRJ8-Tallow	**6152** HRJ8-Camelina	**4909** F-T SPK	**6169** JP-8	**4751** JP-8	**5469** HRJ - Fats	**7272** HRJ - Fats
Phenolic Polars (mg/L)	< 20	< 20	< 20	240	160	< 20	< 20

4.1.5 EPA Testing

The complete reports for the EPA testing for carbonyls, alcohols, esters, and phenols were accomplished by Columbia Analytical Services for SwRI and AFRL. These reports are provided in Reference 5 in the following Appendices:

- Camelina HRJ – Appendix K
- Camelina/JP-8 Blend – Appendix K
- R-8 HRJ – Appendix K
- R-8/Jet A Blend – Appendix K
- Tallow/JP-8 Blend – Appendix L

The reports conclude that none of the identified compounds (primarily alkyl aromatics) are remarkable as they could just as likely be found in a typical aviation fuel.

4.1.6 Water Content (D6304) vs. Temperature

Aviation fuels, like Jet A, tend to be relatively dry due to their saturated hydrocarbon composition. For a typical aviation fuel, temperature is the primary factor that affects water content; additives and contaminants may also play a role. Although there is a clear distinction between “free” and “dissolved” water, the specific aim here is to measure total water content. Unaware of any standard procedure to perform this test, SwRI developed the following approach. A sample composed of water (1mL) and fuel (7mL) are sealed in a 10mL septum vial. The vial is gently shaken and then placed in an oven or cold box and allowed to equilibrate to the test temperature. After approximately four hours, the vial is gently shaken again. The vial is then allowed to rest for a period of at least 24 hours at the test temperature. After the rest period, a sample is carefully withdrawn through the septum using a syringe without agitating the vial contents. The total water content of the sample is measured using a Karl Fischer coulometric

[17] References 5 and 6

water titrator (ASTM D6304). Finally, the temperature of the fuel itself is measured using a thermocouple probe. The SwRI results for selected fuels are shown in Figure 5.

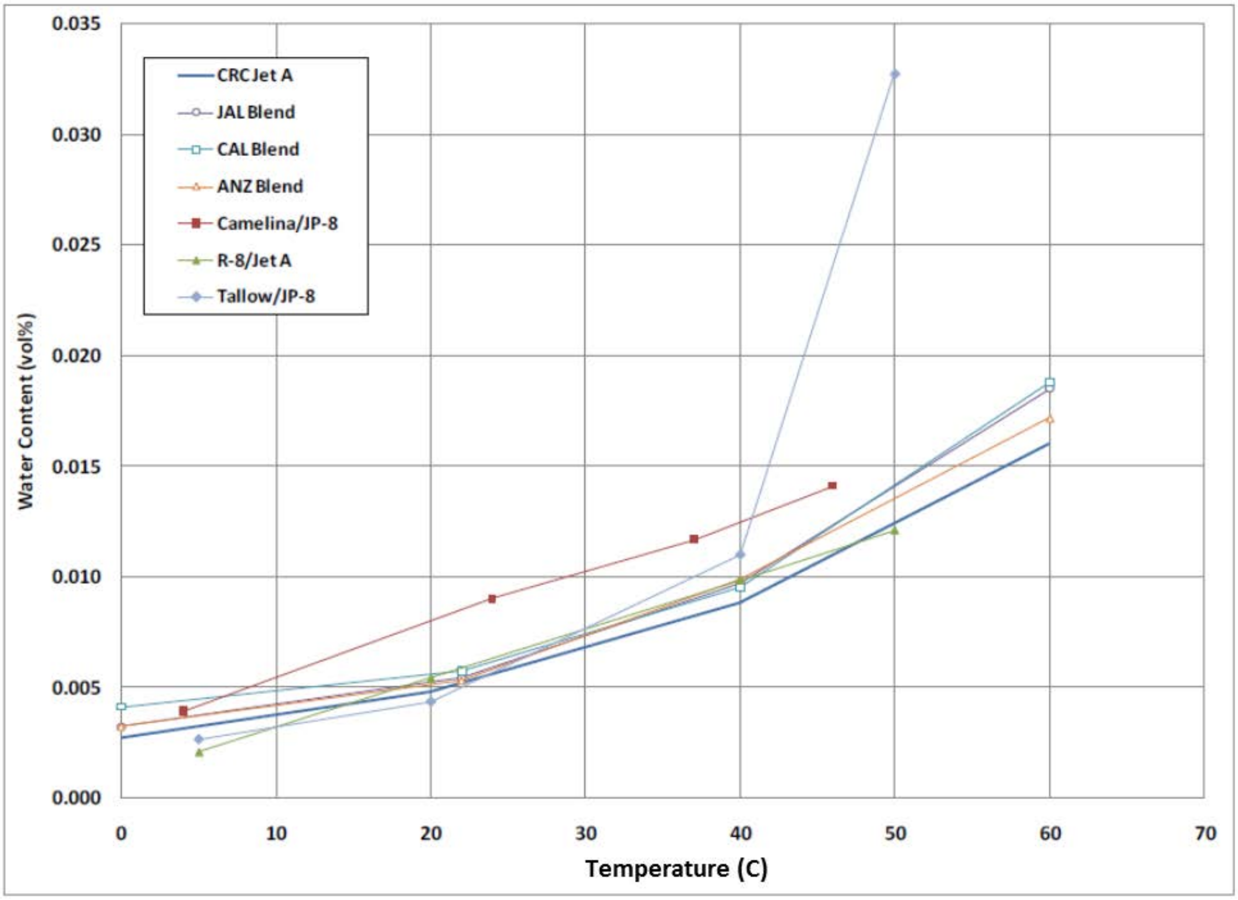


Figure 5. Water Content (6304) vs. Temperature[18]

The water content of POSF-7272 (28 mg/kg) meets the specification for SPKs (75 mg/kg maximum), and is somewhat above the water content of the other HRJs: 16 mg/kg for POSF-5649 and 19 mg/kg for POSF-6308.

4.1.7 Dissolved Water Measurement Investigation[19]

Dissolved water is an important consideration in evaluating experimental results. The seven fuels used in the sealed sample experiments were all low in water content, as shown in Table 21. The fuels and their blends all contained less than 26 ppm by weight of water, which is only a fraction of the *saturated* water content of the fuel. These water levels are consistent with those reported in the HRJ/bio-SPK Research Report. In order to determine the saturated water content

[18] The tallow blend is apparently holding unexpected amounts of water at the 50°C temperature. It is speculated that the fuel has something that's acting as a dispersant or emulsifier to help hold the water and that given the source of the product, there could be some fatty acid remnants that survived the processing and that is causing the problem.

[19] Investigation by UDRI

of the fuel, the third set of samples was tested. These samples contained each of the seven fuels with 5 mL water added to each sample and the sample agitated and allowed to separate. Water levels in the water-saturated fuel layer are shown in Table 22; results for water saturated fuel are 2-3 times the level of water in the native fuels and fuel blends. Again, these results are consistent with the HRJ Research Report, which states “As expected, due to their chemical composition (i.e. non-polar alkanes and very low aromatic concentration), the neat Bio-SPKs should have a lower saturation point than a typical petroleum-based jet fuel.”

Table 21. Room Temperature Dissolved Water Measurement by Karl Fisher Titration

Sample I.D.	Average ppm (Weight)[20]
HRJ 6308	10.6
HRJ 6152	25.7
SPK 5018	19.6
Jet A 4658	25.9
6308/Jet A Blend	16.3
6152/Jet A Blend	23.1
5018/Jet A Blend	16.1

Table 22. Water Saturated Fuel Dissolved Water Measurement by Karl Fisher Titration[21]

Sample I.D.	Average ppm (Weight)
HRJ 6308 water saturated	56.3
HRJ 6152 water saturated	62.0
SPK 5018 water saturated	58.1
Jet A 4658 water saturated	89.7
6308 Blend, water saturated	72.2
6152 Blend, water saturated	78.4
5018 Blend, water saturated	75.6

The as-received fuels contained only a fraction of the dissolved water they might have contained if the samples were water saturated. However, as these experiments were performed in the winter months in Ohio, laboratory relative humidity was low. Therefore, since the only water in the sealed vials could have come from the fuel (the relative humidity in the fuel vial headspace was low since it was purged with nitrogen), and the fuel contained very little water, even a drop in temperature might only produce a very small amount of free water (in this case, it could not be seen).

[20] Average values represent a duplicate analysis (n=2).
[21] Room Temperature

In addition, the fuels and blends exposed to laboratory air at –23.5 C were tested for water content after the large pieces of ice had accumulated at the bottom of each vial. The results for water content in the fuel above the ice are given in Table 23. These dissolved water measurements were taken at temperature (-23.5 C). These data, taken at low temperature, generally reflect a similar water level than the level at which each fuel started. Some levels were slightly higher, some slightly lower. None were near the water saturation values. Considering there was accumulated, visible ice in the samples at low temperature (a non-homogeneous sample), these values seem to indicate that the dissolved water content was relatively constant, in spite of the drop in temperature.

Table 23. Water Saturated Fuel Dissolved Water Measurement from Fuels at -23.5C[22]

Sample I.D. Samples taken at -23.5°C	Average ppm (Weight)
6308	**6.6**
6152	**28.6**
5018	**17.3**
4658	**34.6**
6308 Blend	**9.3**
6152 Blend	**24.0**
5018 Blend	**29.3**

4.2 Fuel Specification Properties

In most cases, specification tests were run on both the "neat" (100%) HRJ fuel (Table 24)[23] and blends with JP-8 (Table 25)[24]. For AFRL testing, two different JP-8 fuels were used to construct 50/50 blends, with both fuels coming from the WPAFB flight line. The JP-8 additives were added to the HRJ fuels prior to blending with JP-8, so the blend was fully "additized" to JP-8 levels.

As can be seen in Tables 24 and 25, the HRJ fuels typically met the specification requirements for both the neat HRJ and as a 50/50 blend with JP-8. Unlike the F-T SPK fuels from Shell and Sasol, boiling range slope was not an issue. Boiling curves are plotted in Figure 6 and Figure 7. Note that the camelina and R-8 HRJ fuel's boiling range are outside of the typical JP-8 experience as seen in PQIS (but within the specification), with camelina being below the typical boiling curve and R-8 being above. However, 50/50 blends fell back within typical JP-8 experience. Figure 6 includes both boiling data from WPAFB and SwRI (more points). The two sets of data are consistent.

Low contaminants equates to high thermal stability. As seen in Table 26, Fats, Oils, and Greases (FOG), also called mixed fats HRJs, tallow HRJs and the camelina HRJ all passed 325 °C JFTOT. The neat HRJ fuels are very thermally stable.

[22] Karl Fisher Titration, Average values represent a duplicate analysis (n=2).
[23] AFPET Laboratory
[24] AFPET Laboratory

Table 24. Results of Specification Testing for HRJs, F-T SPK, and JP-8s

Specification Test	**MIL-DTL-83133H Spec Requirement** *(SPK)*	**6308** HRJ8-Tallow	**6152** HRJ8-Camelina	**4909** F-T SPK w/ JP-8 additives	**6169** JP-8	**4751** JP-8	**7272** HRJ8-FOG
Color, Saybolt (ASTM D156)		+30	+30	+30	+21	+16	+30
Total Acid Number, mg KOH/g (ASTM D3242)	**≤0.015**	0.002	0.002	0.004	0.000	0.003	0.002
Aromatics, vol % (ASTM D1319)	**≤25**	0.4	0.0	0.0	15.7	18.8	0.0
Olefins, vol % (ASTM D1319)		0.4	0.0	0.0	0.8	0.8	0.5
Mercaptan Sulfur, % mass (ASTM D3227)	**≤0.002**	0.000	0.000	0.000	0.001	0.000	0.000
Total Sulfur, % mass (ASTM D2622)	**≤0.3**	<0.0003	0.0018	0.0023	0.0526	0.0383	0.0006
Distillation (ASTM D86):							
IBP, °C		165	151	144	158	159	144
10% recovered, °C	**≤205**	179	161	167	177	182	178
20% recovered, °C		185	166	177	184	189	192
50% recovered, °C		210	182	206	203	208	221
90% recovered, °C		243	237	256	241	244	259
EP, °C	**≤300**	255	259	275	268	265	270
Residue, % vol	**≤1.5**	1.2	1.1	1.5	1.0	1.3	1.2
Loss, % vol	**≤1.5**	0.8	0.9	0.9	0.4	0.8	1.0
T90-T10, °C	*(≥22)*	64	76	89	64	62	81
Flash point, °C (ASTM D93)	**≥38**	55	43	45	46	51	45
Freeze Point, °C (ASTM D5972)	**≤-47**	-62	<-77	-51	-50	-51	-49
Viscosity @ -20°C, cSt (ASTM D445)	**≤8.0**	5.3	3.3	4.9	4.2	4.9	5.6
Viscosity @ -40°C, cSt		10.6	6.5	9.5	8.7	9.9	12.6
Viscosity @ 40°C, cSt		1.4	1.1	1.3	1.3	1.4	1.5

Table 24. Results of Specification Testing for HRJs, F-T SPK, and JP-8s *(Cont'd)*

Specification Test	MIL-DTL-83133H Spec Requirement *(SPK)*	**6308** HRJ8-Tallow	**6152** HRJ8-Camelina	**4909** F-T SPK w/ JP-8 additives	**6169** JP-8	**4751** JP-8	**7272** HRJ8-FOG
Heat of Combustion (calculated), MJ/kg	**≥42.8**	44.1	44.1	44.2	43.4	43.2	44.0
Heat of Combustion (measured), MJ/kg (ASTM D4809)	**≥42.8**	44.5	44.3	44.3	45.1	43.3	44.1
Hydrogen Content, % mass (ASTM D3343)	**≥13.4**	15.3	15.4	15.4	14.0	13.8	15.3
Smoke Point, mm (ASTM D1322)	**≥19**	>40	50	42	26	22	50
Naphthalenes, vol % (ASTM D1840)	**≤3**	<0.1	0.0	0.1	1.1	1.2	0.0
Copper Strip Corrosion (ASTM D130)	**≤1**	1a	1a	1a	1a	1a	1a
Thermal Stability @ 260°C: (ASTM D3241)					**	**	
Thermal Stability @ 325°C: (ASTM D3241)		**	**	**			**
Tube Deposit Rating	**<3**	2	1	1	1	1	2
Change in Pressure, mm Hg	**≤25**	0	0	0	0	2	0
Existent Gum, mg/100mL (ASTM D381)	**≤7.0**	<1	<1	0.6	<1	0.4	<1
Particulate Matter, mg/mL (ASTM D5452)	**≤1.0**	0.3	0.4	1.0	0.9	0.7	0.3 (1.2)*
Filtration Time, minutes	**≤15**	3	4	10	4	4	4
WSIM, MSEP rating (ASTM D3948)	**≥70** *(≥85)*	96	95	84	68*	78	98 (64)*
Water Reaction (ASTM D1094)	**≤1b**	1	1	1	1	1	1
FSII, % vol (ASTM D5006)	**0.10-0.15**	0.00* (0.12)	0.00* (0.10)	0.10	0.10	0.07*	0.00* (0.11)
Conductivity, pS/m (ASTM D2624)	**150 to 600** *(50 to 600)*	53 (284)	400 (113*)	441	270	287	34* (316)
API Gravity @ 60°F (ASTM D4052)	**37.0 - 51.0** *(52.0 - 57.0)*	55.1	56.8	55.6	45.9	44.4	54.3
Density, kg/L @ 15°C (ASTM D4052)	**0.775 - 0.840** *(0.751 - 0.770)*	0.758	0.751	0.756	0.798	0.804	0.762

Table 24. Results of Specification Testing for HRJs, F-T SPK, and JP-8s *(Cont'd)*

Specification Test	**MIL-DTL-83133H Spec Requirement** *(SPK)*	**6308** HRJ8-Tallow	**6152** HRJ8-Camelina	**4909** F-T SPK w/ JP-8 additives	**6169** JP-8	**4751** JP-8	**7272** HRJ8-FOG
Lubricity (BOCLE), wear scar mm (ASTM D5001)		0.76 (0.51)	0.76 (0.50)	0.58	0.59	0.53	0.80 (0.60)

NA = Not analyzed
*Value outside specification limits
Values in parentheses are for HRJs with JP-8 additives

Table 25. Results of Specification Testing for Blends

Specification Test	MIL-DTL-83133H Spec Requirement *(Blend)*	**6399** 6308/6169 Blend	**6406** 6308/4751 Blend	**6185** 6152/6169 Blend	**6184** 6152/4751 Blend	**4913** 4909/4751 Blend	**7386** 7385/4751 Blend
Color, Saybolt (ASTM D156)		+25	+21	+25	+22	+16	+19
Total Acid Number, mg KOH/g (ASTM D3242)	**≤0.015**	0.006	0.004	0.003	0.002	0.004	0.002
Aromatics, vol % (ASTM D1319)	**≤25** *(≥8)*	7.6*	9.3	8.3	10.1	9.4	9.3
Olefins, vol % (ASTM D1319)		0.8	0.5	0.6	0.6	0.5	1.1
Mercaptan Sulfur, % mass (ASTM D3227)	**≤0.002**	0.000	0.000	0.000	0.000	0.000	0.000
Total Sulfur, % mass (ASTM D2622)	**≤0.3**	0.0294	0.0210	0.0255	0.0190	0.0219	0.0189
Distillation (ASTM D86):							
IBP, °C		160	162	157	158	155	150
10% recovered, °C	**≤205**	176	180	168	170	176	179
20% recovered, °C		184	187	174	177	185	190
50% recovered, °C		206	210	195	199	209	214
90% recovered, °C		242	244	240	242	251	253

Table 25. Results of Specification Testing for Blends *(Cont'd)*

Specification Test	MIL-DTL-83133H Spec Requirement *(Blend)*	**6399** 6308/6169 Blend	**6406** 6308/4751 Blend	**6185** 6152/6169 Blend	**6184** 6152/4751 Blend	**4913** 4909/4751 Blend	**7386** 7385/4751 Blend
EP, °C	**≤300**	260	261	273	275	271	268
T50-T10, °C	*(15)*	30	30	27	29	33	35
T90-T10, °C	*(40)*	66	64	72	72	75	74
Residue, % vol	**≤1.5**	1.3	1.3	1.0	0.9	1.3	1.4
Loss, % vol	**≤1.5**	0.2	0.1	0.4	0.1	1.1	0.7
Flash point, °C (ASTM D93)	**≥38**	50	52	44	46	47	50
Cetane Index (calc.) (ASTM D4737)		57.0	57.1	55.4	55.1	56.8	56.8
Freeze Point, °C (ASTM D5972)	**≤-47**	-55	-54	-56	-56	-51	-51
Viscosity @ -20°C, cSt (ASTM D445)	**≤8.0**	4.6	5.0	3.9	4.0	4.7	5.1
Viscosity @ -40°C, cSt		9.6	10.1	7.5	7.8	9.7	11
Viscosity @ 40°C, cSt		1.3	1.4	1.2	1.2	1.4	1.4
Heat of Combustion (calculated), MJ/kg	**≥42.8**	43.8	43.7	43.6	43.6	43.7	43.7
Heat of Combustion (measured), MJ/kg (ASTM D4809)	**≥42.8**	43.9	43.8	43.8	43.8	43.9	43.5
Hydrogen Content, % mass (ASTM D3343)	**≥13.4**	14.7	14.5	14.6	14.5	14.5	14.5
Smoke Point, mm (ASTM D1322)	**≥19**	36	35	37	35	33	34
Naphthalenes, vol % (ASTM D1840)	**≤3**	0.6	0.6	0.5	0.4	0.5	0.5
Copper Strip Corrosion (ASTM D130)	**≤1**	1a	1a	1a	1a	1a	1a
Thermal Stability @ 260°C: (ASTM D3241)							
Tube Deposit Rating	**<3**	1	1	1	1	1	1
Change in Pressure, mm Hg	**≤25**	0	0	0	0	2	0

Table 25. Results of Specification Testing for Blends *(Cont'd)*

Specification Test	**MIL-DTL-83133H Spec Requirement** *(Blend)*	**6399** 6308/6169 Blend	**6406** 6308/4751 Blend	**6185** 6152/6169 Blend	**6184** 6152/4751 Blend	**4913** 4909/4751 Blend	**7386** 7385/4751 Blend
Existent Gum, mg/100mL (ASTM D381)	**≤7.0**	<1	<1	<1	<1	0.5	<1
Particulate Matter, mg/mL (ASTM D5452)	**≤1.0**	0.3	0.3	0.1	0.1	NA	1.0
Filtration Time, minutes	**≤15**	4	4	4	4	NA	4
WSIM, MSEP rating (ASTM D3948)	**≥70**	90	86	72	70	78	70
Water Reaction (ASTM D1094)	**≤1b**	1	1	1	1	1	1
FSII, % vol (ASTM D5006)	**0.10-0.15**	0.11	0.08*	0.10	0.11	0.08*	0.12
Conductivity, pS/m (ASTM D2624)	**150 to 600**	210	275	217	310	186	352
API Gravity @ 60°F (ASTM D4052)	**37.0 - 51.0**	50.3	49.5	51.1	50.4	49.9	49.2
Density, kg/L @ 15°C (ASTM D4052)	**0.775 - 0.840**	0.778	0.781	0.775	0.778	0.780	0.783
Lubricity (BOCLE), wear scar mm (ASTM D5001)		0.55	0.55	0.54	0.53	0.53	0.54

NA = Not analyzed
*Value outside specification limits

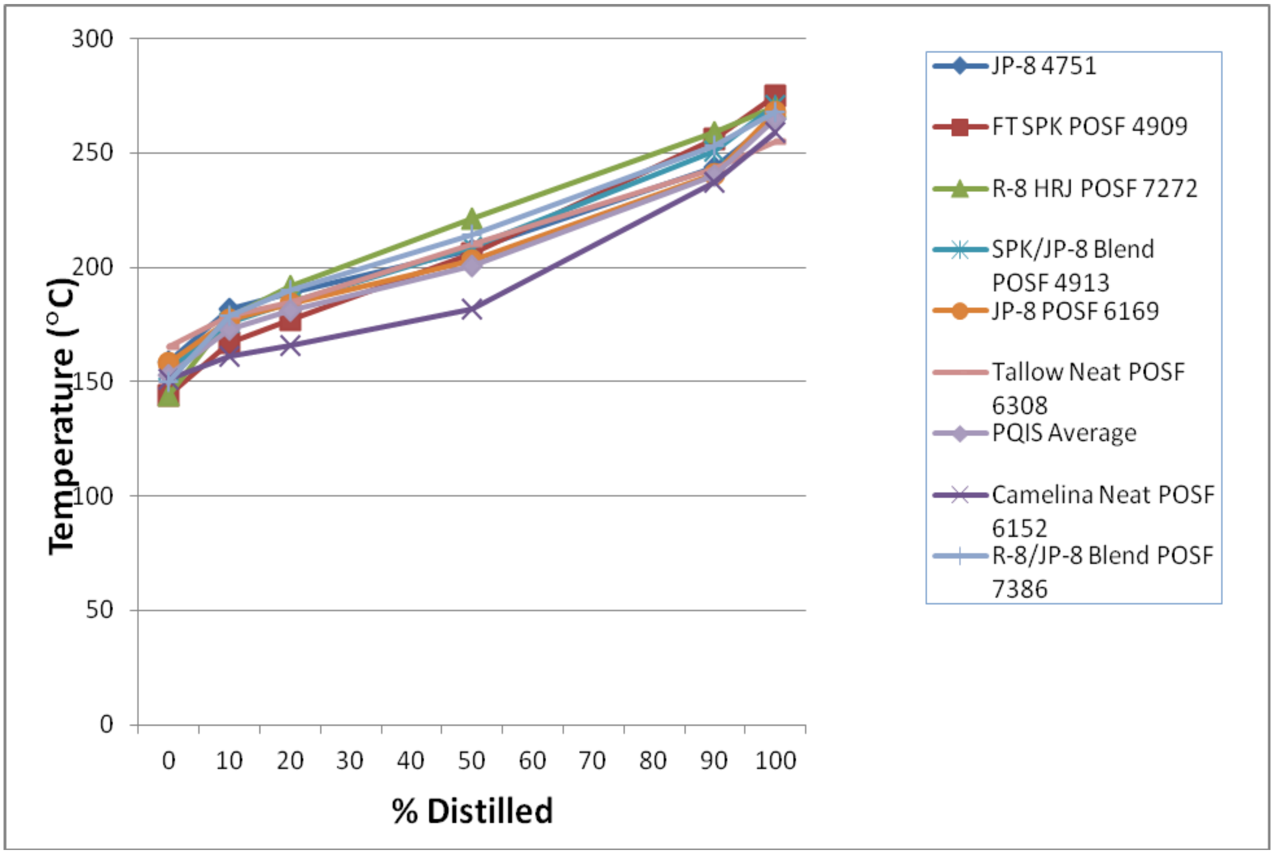


Figure 6. Boiling Distributions for Various HRJ Fuels and Blends (AFPET)

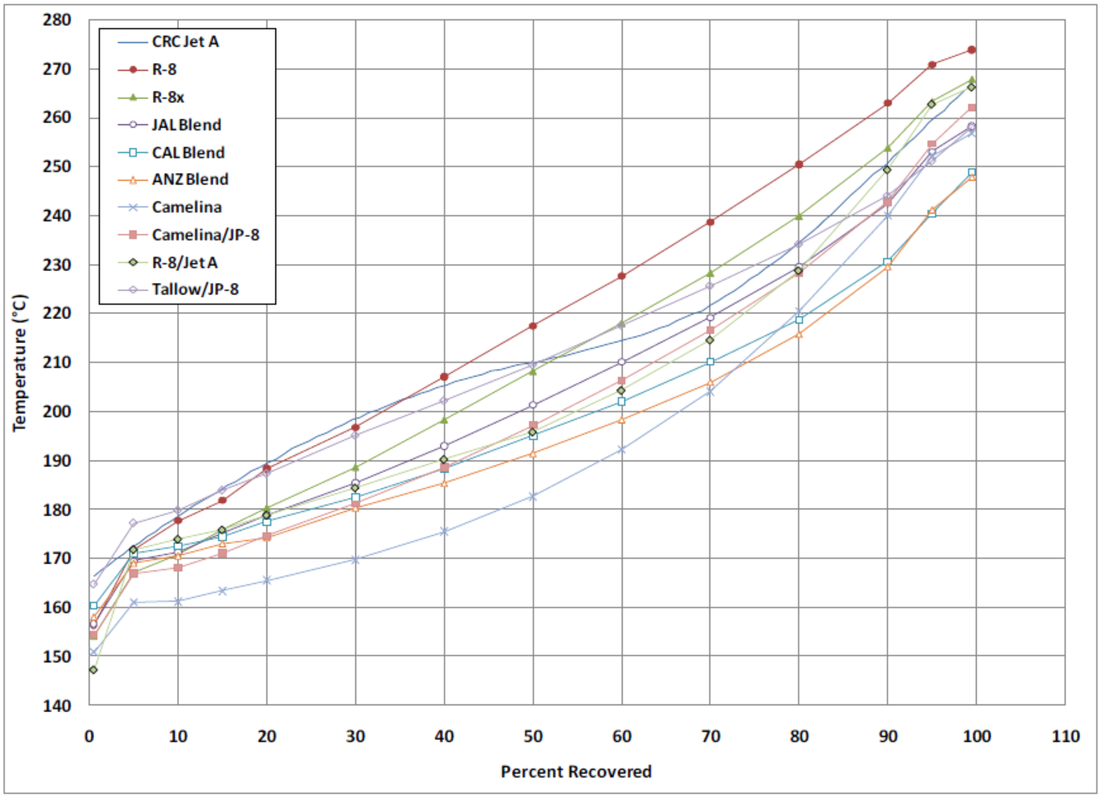


Figure 7. Distillation (D86) for Various Fuels and Blends (SwRI)[25]

Table 26. JFTOT Breakpoint (D3241BP) at Elevated Test Temperature

POSF #	Test Temperature (°C)	ASTM Code (rating)	Maximum Pressure Drop (mm Hg)
5469	>340	>2	0.1
6406	325	2	0.10
6152	335	2	0.1
6184	305	<3	1.0
7272	325	2	0
6308	325	2	0

[25] Reference 5

4.3 Fit for Purpose (FFP)

The ASTM D4054 (Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives) is used for the qualification and approval of new fuels and new fuel additives for use in commercial and military aviation gas turbine engines. The practice was developed as a guide by the aviation gas-turbine engine Original Equipment Manufacturers (OEMs) with ASTM International member support. One of the elements of the ASTM D4054 test program is "fit-for-purpose"; table 1 of the ASTM D4054 lists the required FFP property tests and corresponding test methods.

These FFP properties are usually defined as those properties needed for effective aviation fuel operation, but not specifically called out in the specification. One example is dielectric constant – fuel gauges need the dielectric constant behavior as a function of temperature and density to be known to operate correctly. Also generally defined as FFP are specification properties as a function of temperature. For example, the specification requires density at 16 °C, where density over a larger range would be defined as a FFP property.

Military unique operations necessitate additional FFP properties including low temperature viscosity, low temperature freeze point, military fuel additive compatibility, additional airframe and engine materials compatibility, high temperature thermal stability, lower lubricity for legacy systems, special fuel storage and special filtration considerations.

FFP evaluations per D4054 have been performed for AFRL by SwRI for the HRJ fuels[26]. The reader is referred to these references for specific data for the following:

- Additive Compatibility
- Auto ignition Temperature
- Bulk Modulus
- Density vs. Temperature
- Dielectric Constant vs. Temperature (plotted versus density)
- Elastomer Compatibility
- Electrical Conductivity vs. Temperature
- Electrical Conductivity vs. SDA Concentration
- Flammability Limits
- Flash Point
- Freeze Point
- Hot Surface Ignition
- Ignition Delay and Derived Cetane Number (by IQT™) – D6890
- Lubricity vs. CI/LI Concentration

[26] References 3,5,and 6

- Specific Heat vs. Temperature
- Storage stability
- Surface Tension vs. Temperature
- Thermal Conductivity
- Vapor Pressure vs. Temperature
- Viscosity vs. Temperature

Additional comment and discussion relative to FFP is provided below for certain properties.

4.3.1 Density vs. Temperature

The various data from the different laboratories are showing consistent results. As seen in Table 24 and Figure 11, none of the neat HRJ fuels meet the MIL-DTL-83133F minimum requirement and the MIL-DTL-83133G SPK requirement is just met. This is one of the driving influences for the 50% blend requirement. Also refer to paragraph 4.8.1 for aircraft range implications.

Also none of the neat HRJs meet the ASTM D1655 standards for the density. But all of the neat SPKs do meet the density requirements for hydroprocessed fuels per the new ASTM D7566-09 standard.

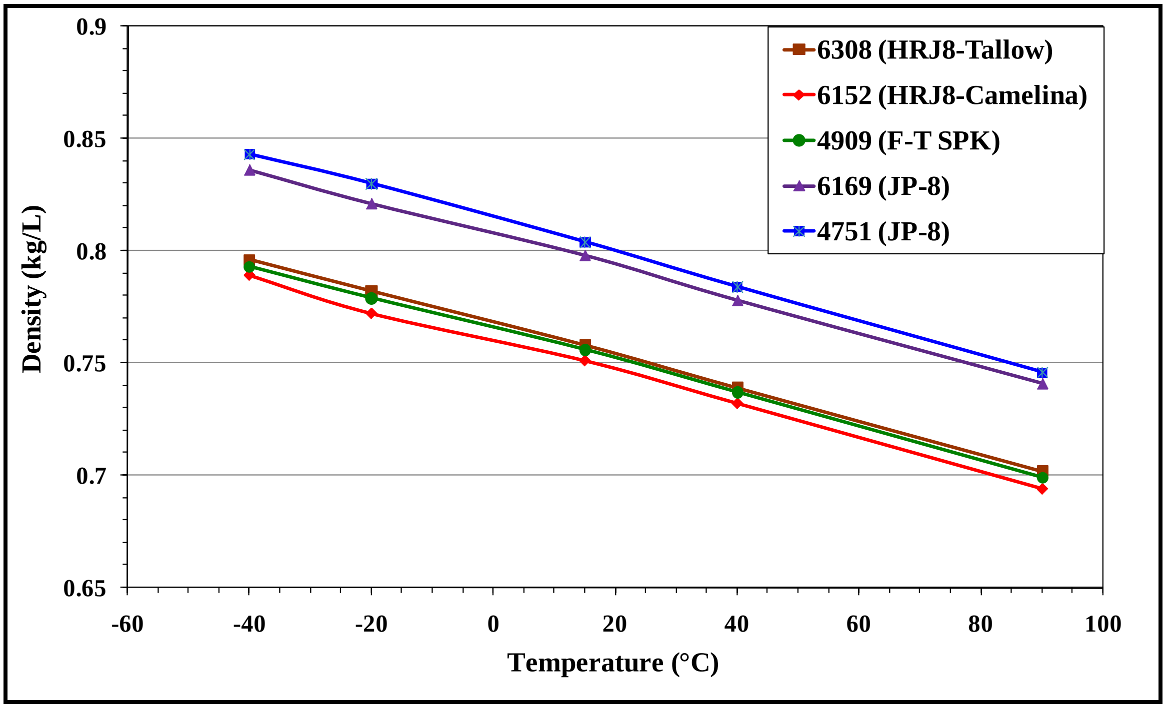


Figure 8. Density vs. Temperature for HRJ, FT and JP-8 Fuels (UDRI/AFPET)

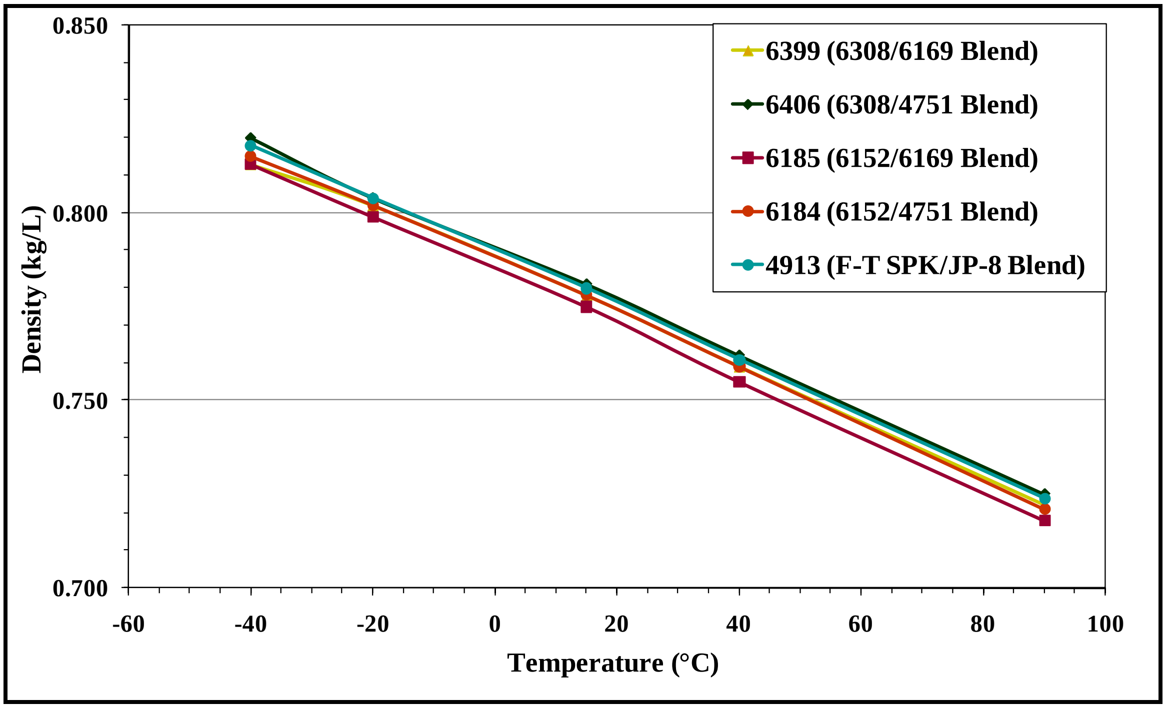


Figure 9. Density vs. Temperature for HRJ and FT Blends (UDRI/AFPET)

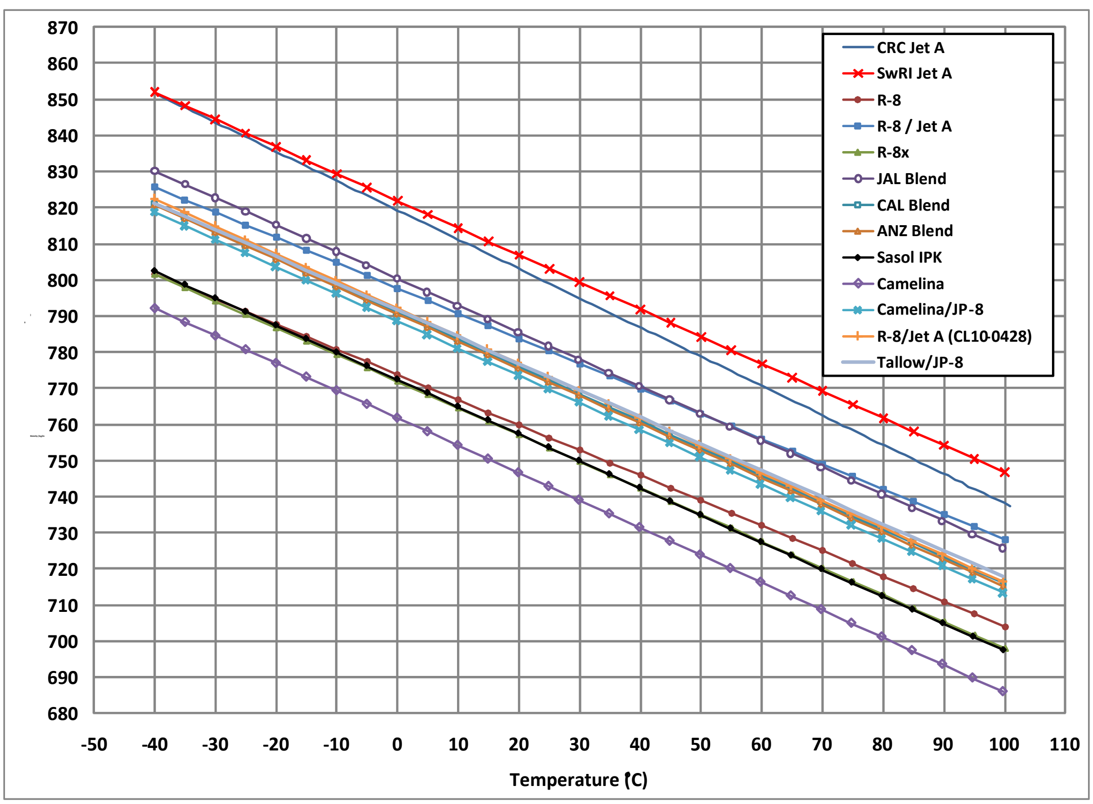


Figure 10. Density vs. Temperature for Blended HRJ Fuels (SwRI)

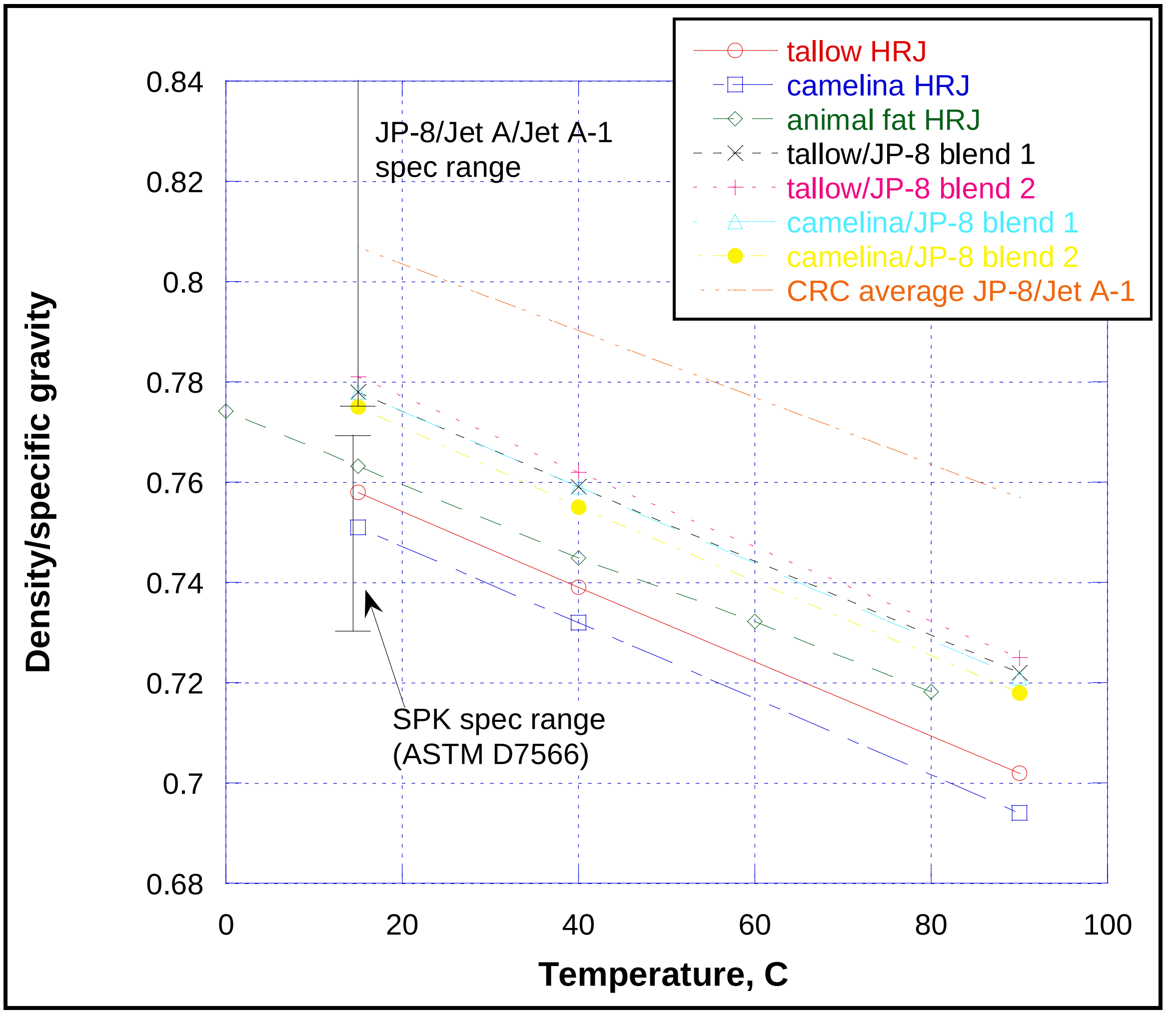


Figure 11. Density vs. Temperature of HRJs and JP-8s (Research Report)

4.3.2 Speed of Sound and Bulk Modulus

The isothermal tangent bulk modulus of the fuels as determined by ASTM D6793 is being reported in references 3 and 5. From the literature, the preferred approach is to determine isentropic (a.k.a. adiabatic) bulk modulus from speed-of-sound measurements. Based on some preliminary speed-of-sound measurements performed at SwRI, it was concluded that these isothermal bulk modulus values are biased high.

AFRL authorized a study on speed of sound and isentropic bulk modulus at SwRI. Utilizing the U.S. Army's prototype apparatus, SwRI began to build a library of speed-of-sound and isentropic bulk modulus data for a large set of fuels provided by the Air Force. Based on the accuracy of the cyclohexane speed-of-sound verification run and the accuracy with which density is normally measured, it is believed that the isentropic data[27] shown in Table 28 is accurate and is a better and more useful data set from that previously reported.

---

[27] Reference 7

Further comments were provided by SwRI and AFRL as follows:

"By itself, the velocity of sound in a fuel is important as it may relate to some aircraft tank gauging systems. This information is more likely to be viewed as a function of density rather than temperature although all are intertwined and none are perfect discriminators. Based on the limited set of data gathered to date, petroleum-derived aviation fuels (JP-8 and Jet A) seem to have nominal values in the 1250-1300 m/s range. Diesel fuels and biodiesel fuel are generally well above 1300 m/s. The neat, synthetic aviation fuels are more likely to fall in the 1200-1250 m/s range. So, the 50/50 HRJ blends seem to fall in a narrow range around 1250 m/s.

The speed of sound data from NIST is consistent with the SwRI data (and agrees that plotting as a function of density does not improve the correlation). The World Survey speed of sound data is also consistent, although it implies that the upper limit (taking into account a dense JP-8) might better be estimated at 1320 m/s at 30 C. Based on this information the following evaluation criteria are suggested until additional studies can be performed."

Table 27. Suggested Evaluation Criteria for Speed of Sound

	Velocity of Sound @ 30°C and Ambient Pressure
R	<1220
Y	1220-1240 m/s
G	1245-1285 m/s
Y	1285-1320 m/s
R	>1320 m/s

"The sound speed and density data were used to determine an acceptable region for isentropic bulk modulus (subject to OEM concurrence) as follows: 170-210 kpsia as "green" and outside that region as "yellow"."

Table 28. Isentropic Bulk Modulus (SwRI)

POSF	Description	Speed of Sound @30°C (ms)	Density @30°C g/cm^3)	Isentropic Bulk Modulus @30°C (psi)
7385	HRJ (R-8)	1247	0.7503	169,283
6308	HRJ (Tallow)	1241	0.7463	166,620
6152	HRJ (Camelina)	1220	0.7391	159,600
6406	Tallow Blend	1258	0.7697	176,642
6184	Camelina Blend	1247	0.7661	172,710
7386	R-8 Blend	1267	0.7721	179,717
	JP-8	1284	0.8016	191,712
	Jet A	1262	0.7873	181,872

4.3.3 Viscosity as a Function of Temperature

The low temperature viscosity at and below -40°C is being closely examined for military operations. The Scanning Brookfield Viscosity so-called knee point or temperature at 25cp is being used in lieu of pour point. For JP-8 this is shown as <-53 C.

All of the HRJ fuels and blends show lower viscosities than the reference JP-8. The R-8 HRJ (POSF 7272) and the R-8 HRJ Blend (POSF 7386) have the highest viscosities for the HRJ fuels.

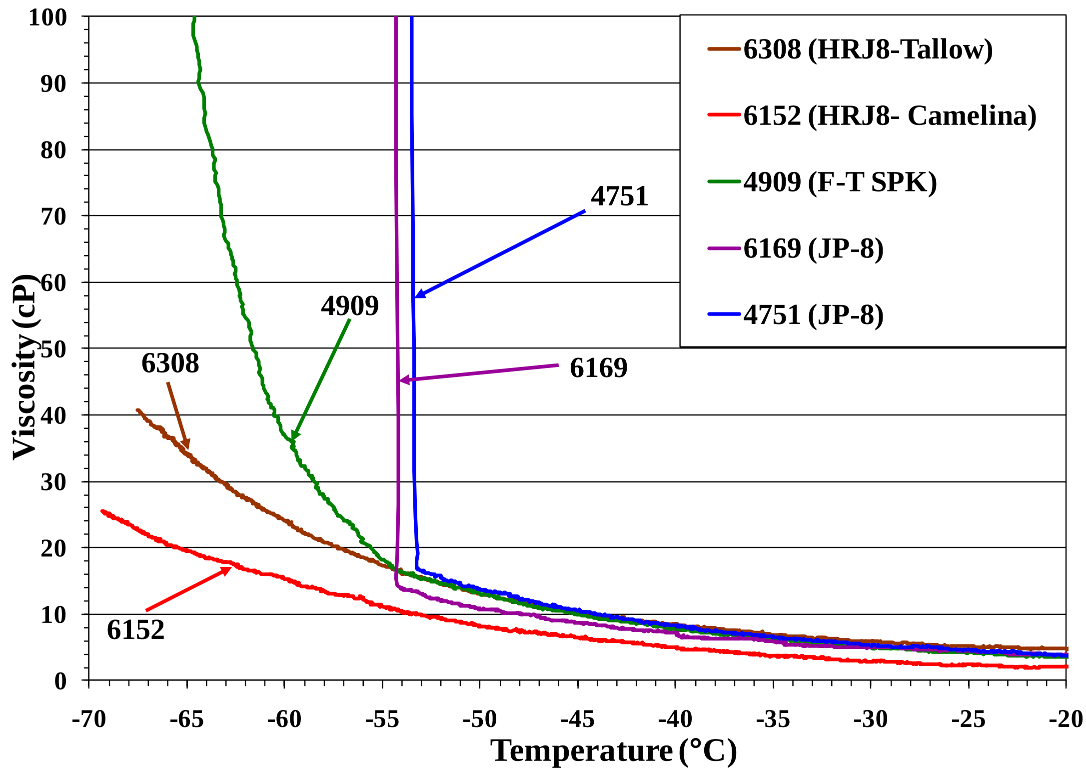


Figure 12. Scanning Brookfield Viscosity Curves of HRJs, F-T SPK, and JP-8s (UDRI)

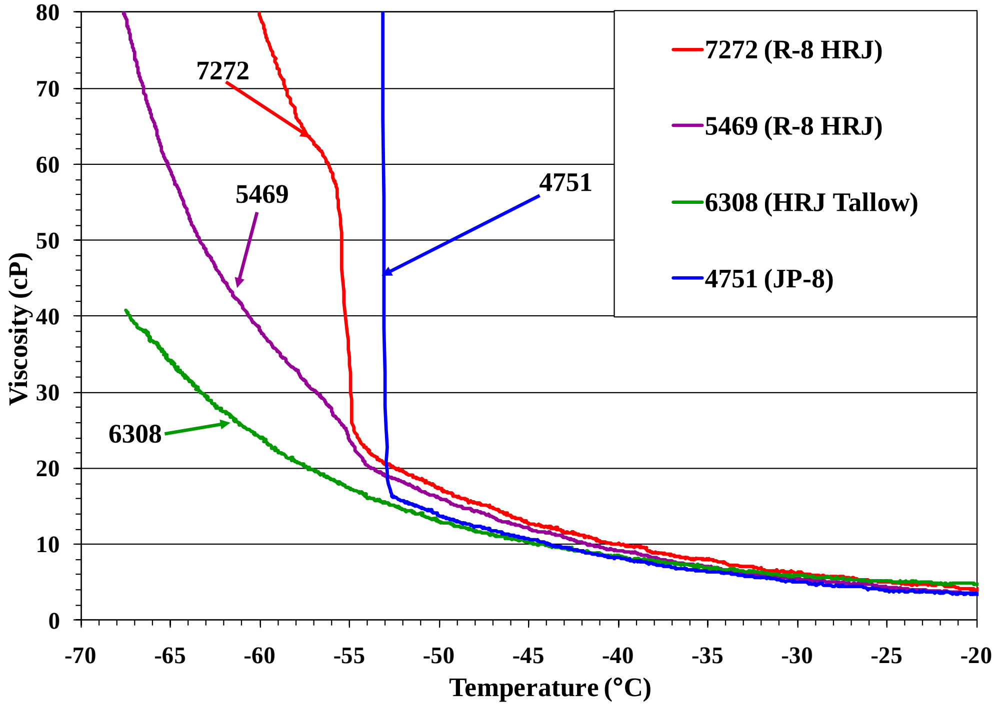


Figure 13. Scanning Brookfield Viscosity Curves of HRJs and JP-8 (UDRI)

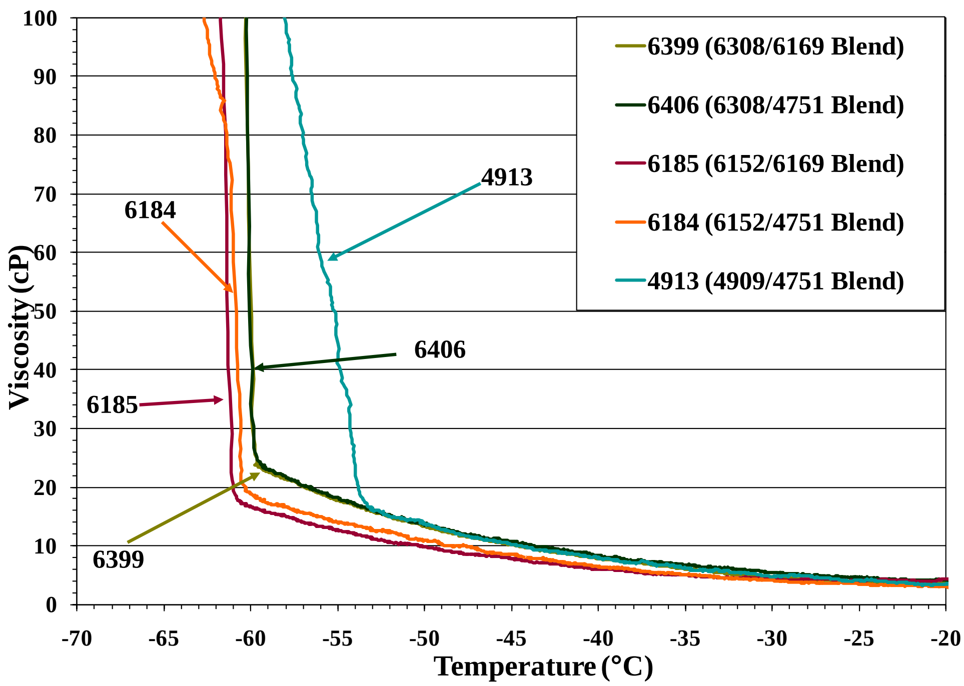


Figure 14. Scanning Brookfield Viscosity Curves of Blends (UDRI)

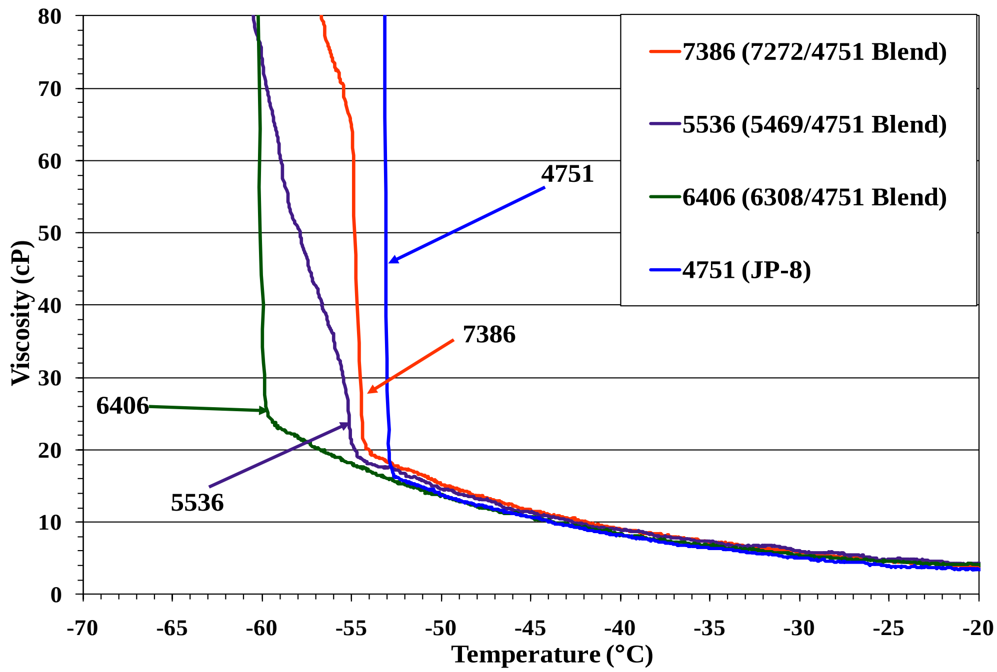


Figure 15. Scanning Brookfield Viscosity Curves of Selected Blends (UDRI)

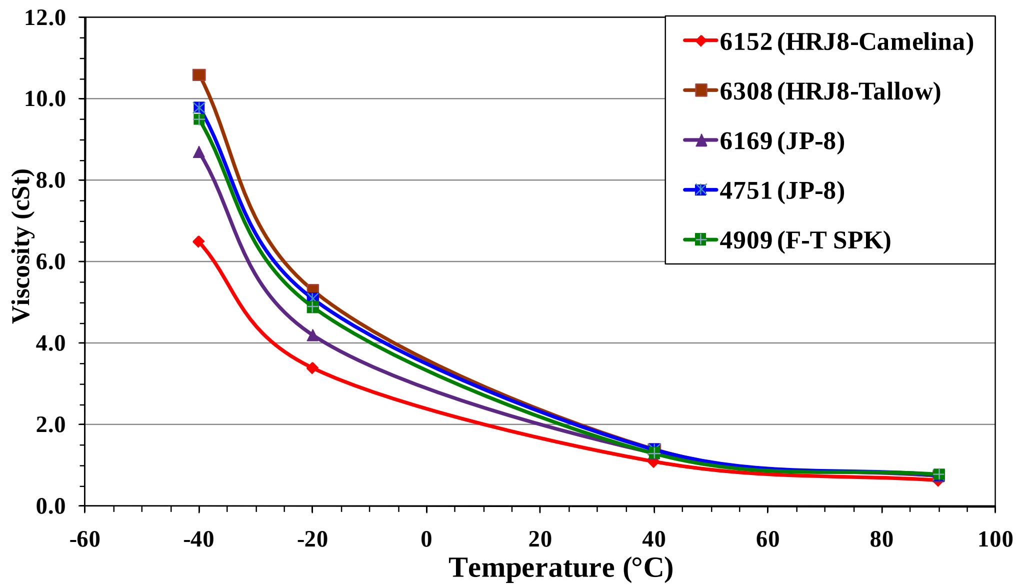


Figure 16. Viscosity vs. Temperature for HRJs, F-T SPK, and JP-8 (UDRI/AFPET)

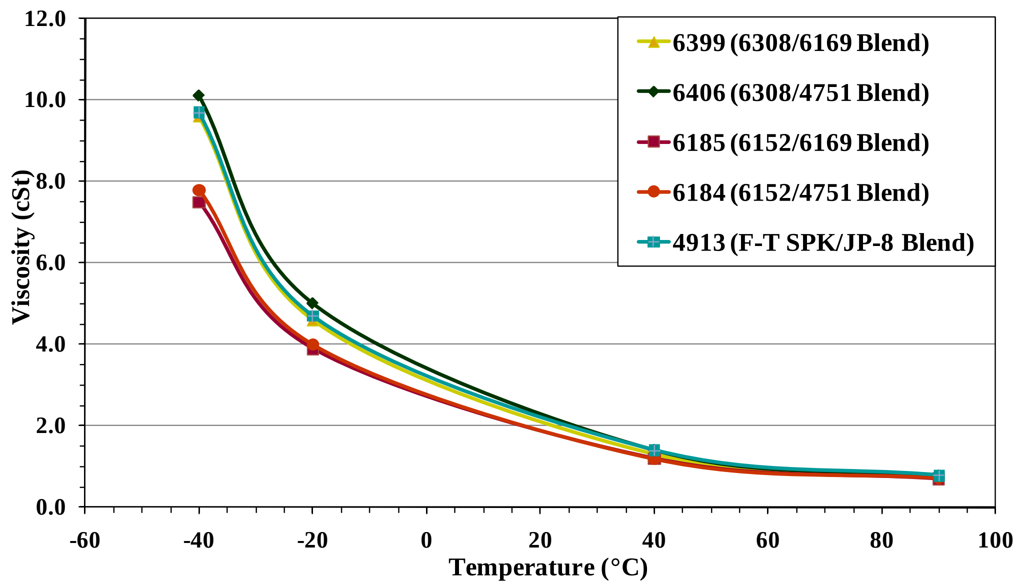


Figure 17. Viscosity vs. Temperature for HRJ and F-T SPK Blends (UDRI/AFPET)

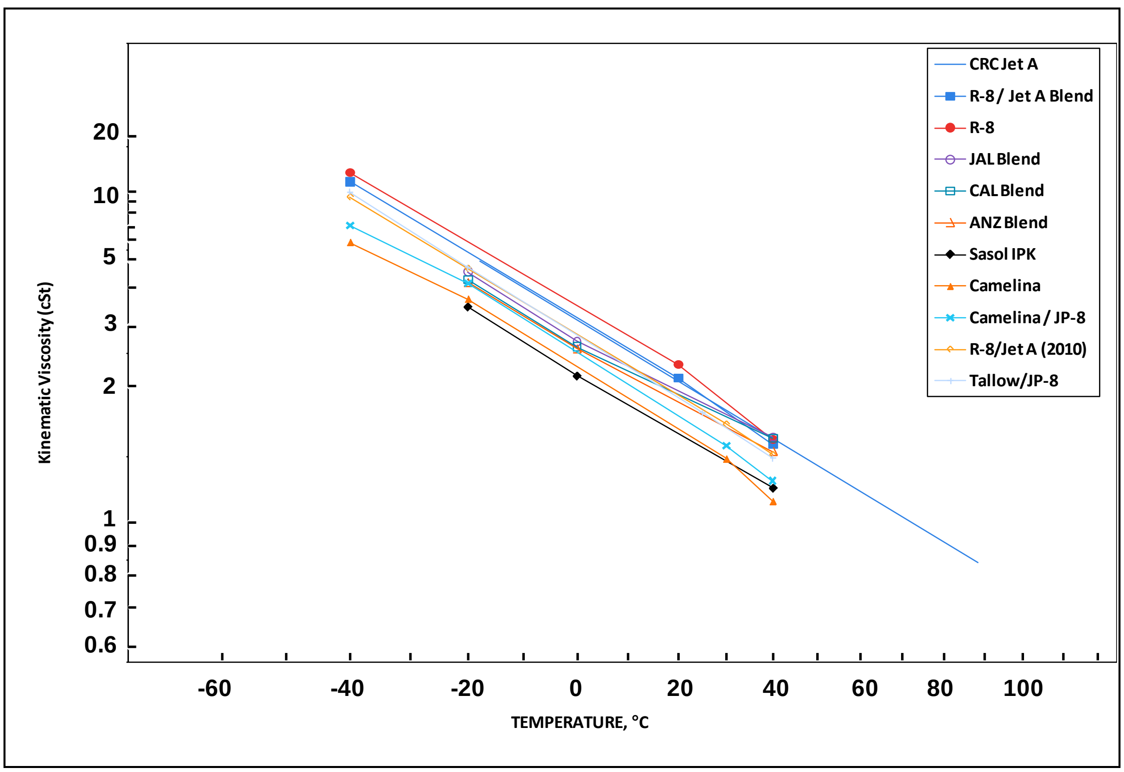


Figure 18. Viscosity vs. Temperature for HRJs and Blends (SwRI)[28]

[28] Reference 5

4.3.4 Military Fuel Additive Compatibility

Additive compatibility testing was performed using modified ASTM D4054-09 Annex A2 methodology[29]. ASTM 4054 Annex 2 is intended to test the compatibility of new additives with the currently approved additives. The purpose of this test was to evaluate the compatibility of new HRJ fuels and HRJ/JP-8 fuel blends with the currently approved additives. The ASTM method was modified in that the currently approved additives were combined in the fuels at two times the normal concentrations instead of two times the maximum concentrations currently permitted in Specification D1655. Seven jet fuel samples were prepared to determine their compatibility with the currently approved additives:

POSF 6152 (UOP - HRJ Camelina)

POSF 6308 (UOP - HRJ Tallow)

POSF 7272 (Dynamic Fuels R-8 HRJ Mixed Fats)

POSF 4751 (WPAFB Baseline JP-8)

POSF 4751/POSF 6152 (50/50 Blend)

POSF 4751/POSF 6308 (50/50 Blend)

POSF 4751/POSF 7272 (50/50 Blend)

For each of the four neat jet fuels to be evaluated, 0.9 liters was transferred to a 1 liter glass bottle. The jet fuel samples were blended with the following currently approved additives to achieve two times the normal concentrations. Additives were mixed with the jet fuel in the following order:

1. DiEGME (POSF 5160 – Dow METHYL CARBITOL(TM) SOLVENT FUEL ADDITIVE GRADE)
2. Corrosion Inhibitor/Lubricity Improver (Innospec Fuel Specialties DCI-4A)
3. Static Dissipator Additive (POSF 5166 – Innospec Fuel Specialties Stadis® 450)
4. +100 Additive (POSF 5831 – GE Betz, Inc. SPEC-AID 8Q462)

Normal concentrations are considered to be 0.10 to 0.11 volume % DiEGME, 16mg/L CI/LI (middle of the approved range), 1.5 mg/L SDA (resulting conductivity between 250 to 350 pS/m), and 256 mg/L +100 additive. The following concentrations were added to the jet fuel samples:

---

[29] University of Dayton Research Institute (UDRI) & AFRL/RZPF, (Ms. Rhonda Cook, Ms. Linda Shafer, and Dr. James T. Edwards

Table 29. Quantity of Additives Combined into Jet Fuel Samples

Additive:	SPKs	JP-8
DiEGME	0.22 Vol%	0.19 Vol%
CI/LI	32 mg/L	16 mg/L
SDA	3.0 mg/L	1.5 mg/L
+100 Additive	512 mg/L	512mg/L

Note: Different amounts were added to the JP-8 because it already contained 1x of CI/LI and SDA, as well as 0.03 vol. % DiEGME. The conductivity of each of the four samples was measured after addition of each additive (Table 30). Normally, SDA is the last additive to be combined into the fuel. Due to the fact that the +100 additive has such a significant effect on the conductivity, it was added last.

Table 30. Effect of Additives on Conductivity of Jet Fuel Samples

	Conductivity (pS/m)				
Fuel	Initial	FSII (0.22 Vol %)	CI/LI (32 mg/L)	SDA (3 mg/L)	+100 (512 mg/L)
6152	264	213	75	481	1471
6308	29	26	0	367	1190
7272	27	23	0	447	1190
4751	286	268	240	787	1734

The 50/50 HRJ/JP-8 blends were prepared by adding 15 mL of each SPK sample to a 40-mL scintillation vial (in duplicate) combined with15 mL of POSF 4751 (JP-8 baseline). 30 mL of each of the neat HRJs and the JP-8 baseline were also transferred in duplicate to 40-mL scintillation vials. The DiEGME concentration of each of the samples was quantified using GC/MS. Results are shown in Table 31.

Table 31. Measured DiEGME Concentrations

Fuel	DiEGME Concentration (Vol. %)
6152	0.22
6308	0.21
7272	0.21
4751	0.20
6152/4751 Blend	0.21
6308/4751 Blend	0.20
7272/4751 Blend	0.20

All 14 sample vials were placed in an environmental chamber at -17.8°C (0°F) for 24 hours. At the conclusion of the 24 hour period, the samples were removed, visually inspected, and photographed. There was no indication of precipitation, cloudiness, darkening or any other signs of incompatibility (Figure 19).

The samples were then placed back in the environmental chamber at 38.0° C for 24 hours. At the conclusion of the 24 hour period, the samples were removed, visually inspected, and photographed. Again, there was no indication of precipitation, cloudiness, darkening or any other signs of incompatibility (Figure 20).

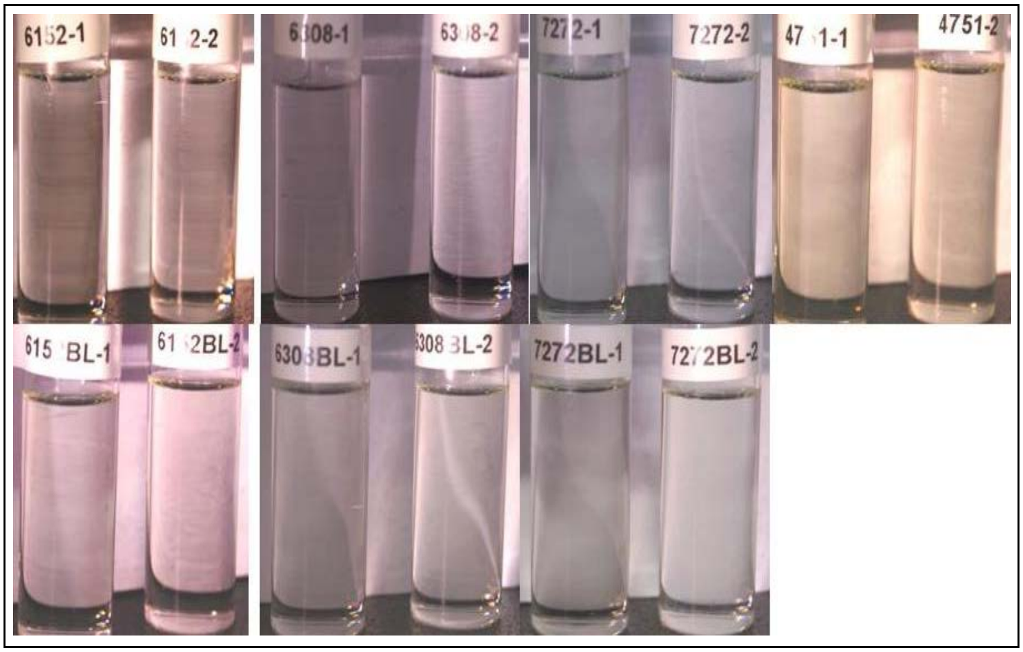


Figure 19. Samples After 24 Hours at -17.8° C[30]

[30] Differences in color are due to lighting/background.

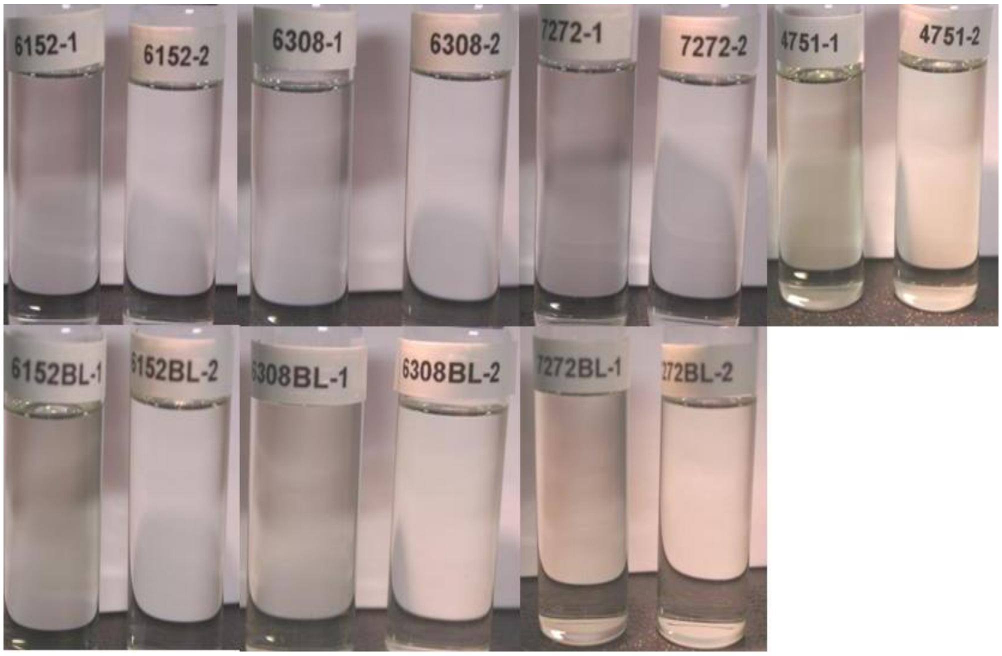


Figure 20. Samples after 24 hours at 30.0° C

4.3.5 Airframe and Engine Materials Compatibility

The ASTM FFP o-ring elastomer compatibility test is being performed by SwRI and is a useful screening tool when a full material compatibility test is cost prohibitive. Three types of o-rings are used in this test - fluorosilicone, nitrile, and viton. Four o-rings are evaluated for each test for statistical purposes. The o-rings are placed on a stainless steel rack, covered in test fuel, and soaked for 7 days at room temperature. Prior to soaking, the elastomers for volume swell are sent to the lab to take baseline measurements. Once the soak period is complete, the samples are returned to the lab where they tested for tensile strength and volume swell.

Some comparative results by SwRI are shown in Figure 21[31]. Since no hard limits exist for either of these measurements, the data is primarily qualitative. What does appear significant is the shrinkage of all three elastomers in the neat R-8. This effect could possibly lead to o-ring failure and leaks in the system. R-8 also seems to cause some loss of tensile strength in Viton and all fuels seem to have a minor effect on the fluorosilicone. The overriding factor is the lack of aromatics in the neat HRJ fuels and this is another driving influence in the blending strategy.

[31] Reference 5

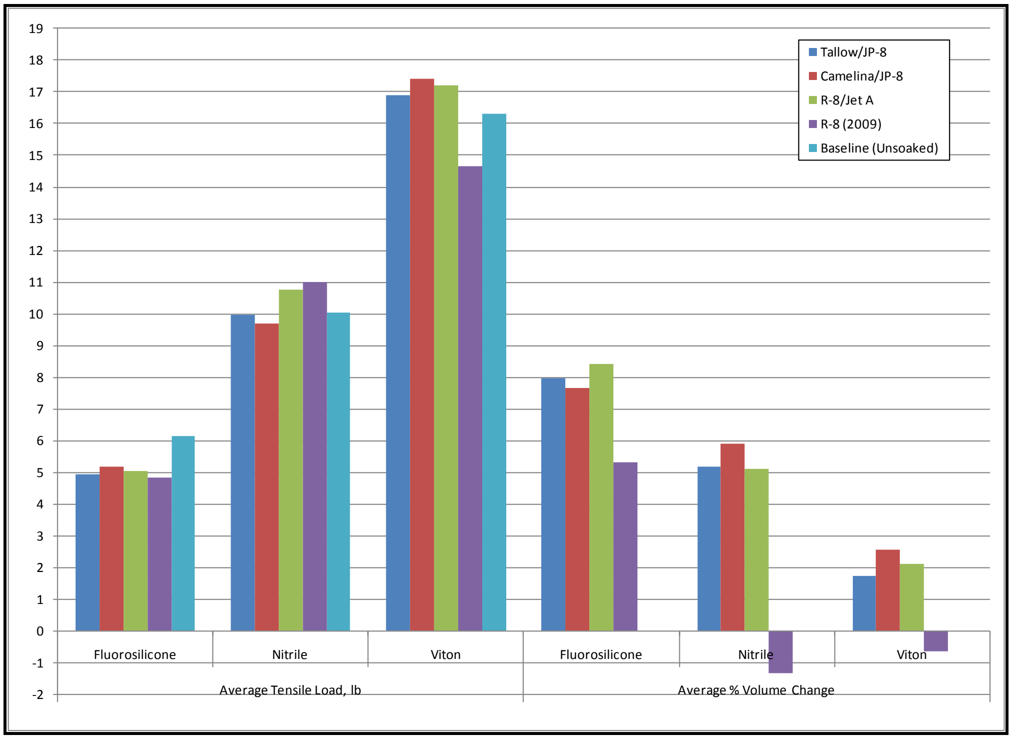


Figure 21. Elastomer Compatibility HRJ Blends, R-8 HRJ

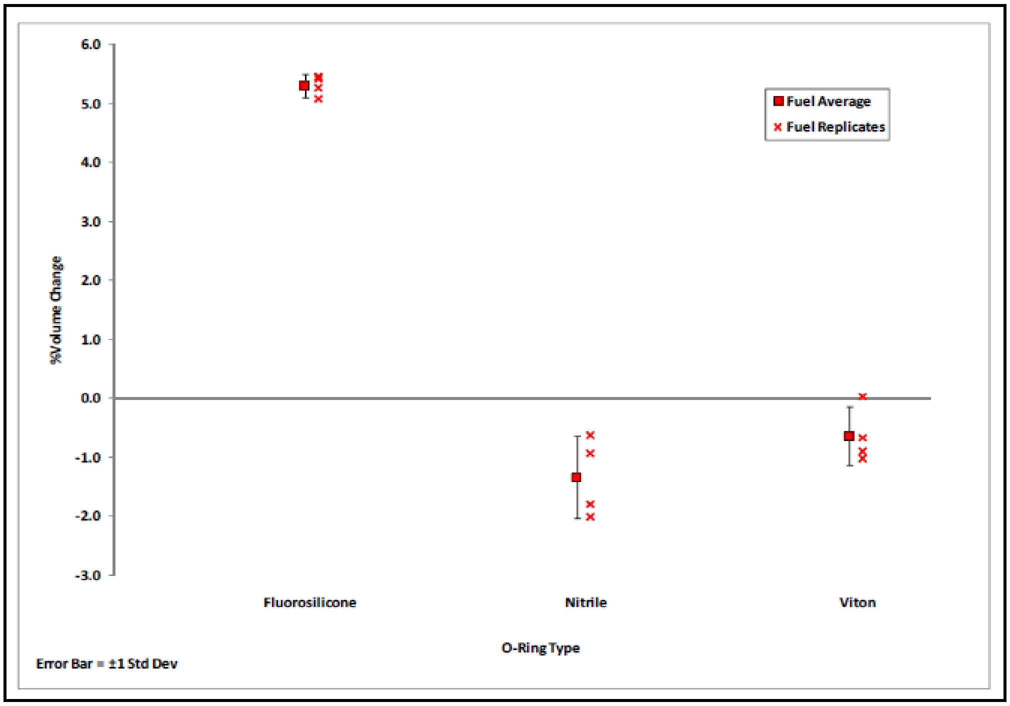


Figure 22. O-Ring Volume Change for R-8HRJ (POSF 5469)[32]

---

[32] Reference 6

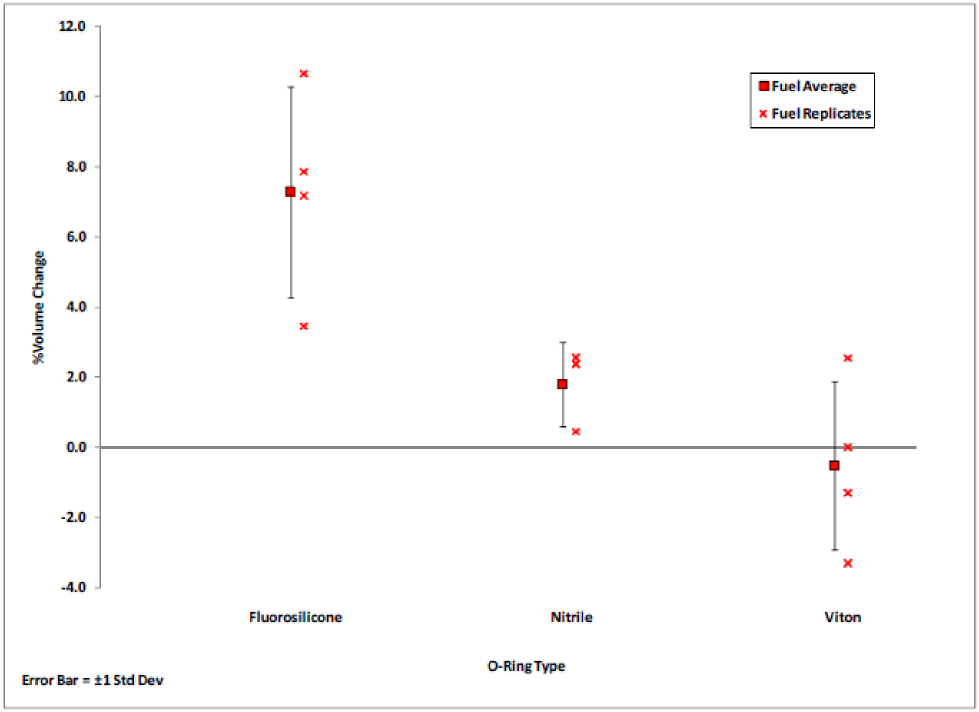


Figure 23. O-Ring Volume Change for R-8 HRJ Blend (POSF 7386)[33]

Volume swell evaluation reports were also accomplished for AFRL for the R-8 HRJ by Dr. John Graham, (UDRI).[34] O-rings, hoses, bladders, sealants, films, fuel cell foam and polysulfide potting compound were examined.

Table 32. Summary of the Volume Swell Results for POSF 7385 (R-8 HRJ)

Description	Sample ID	4751 JP-8	5644 FT + JP-8	7385 Test Fuel
O-rings	N0602	12.3	6.6	-1
	L1120	6.7	7.2	5.8
	V0835	0.7	0.7	0.9
	V1226	0.3	0.2	0.5
Hoses & Bladders	AC-603-01	-0.9	-6.6	-11.1
	EC-614-01	2.5	0.6	-1.8
	EF 51956	1	0.1	-0.4
	EF 5904 C	19.4	13.1	6.1
	MIL-T-5578	592	438	474

[33] Reference 6
[34] Reference 6

Table 32. Summary of the Volume Swell Results for POSF 7385 *(Cont'd)*

Description	Sample ID	4751 JP-8	5644 FT + JP-8	7385 Test Fuel
Sealants	PR 1422	3.5	1.6	0.3
	PR 1440	0.4	-1.2	-2.2
	PR 1776	0.6	-0.6	-2.3
	PR 1828	4.6	2.6	0.7
	PR 2911	5.8	3.3	2.1
	Q4-2817	-0.9	-1.2	-1.7
Films	Teflon	0.1	0	0.2
	Kapton	0	0	-0.1
	Nylon	0.2	0.3	0.2
	Polyethylene	2.3	1.8	1.2
Misc	MIL-PRF-87260*	13.3	8.5	10.8
	CS 3100	-0.4	-1.7	-1.6

* For the foam, the data are based on the mass fraction of fuel absorbed, %m/m.

Table 33. Summary of the Volume Swell Results for POSF 7386 (R-8/JP-8)

Description	Sample ID	4751 JP-8	5644 FT + JP-8	7386 Test Fuel
O-rings	N0602	12.3	6.6	4.2
	L1120	6.7	7.2	6
	V0835	0.7	0.7	1.1
	V1226	0.3	0.2	0.6
Hoses & Bladders	AC-603-01	-0.9	-6.6	-5.9
	EC-614-01	2.5	0.6	1.1
	EF 51956	1	0.1	0.5
	EF 5904 C	19.4	13.1	12.2
	MIL-T-5578	592	438	520
Sealants	PR 1422	3.5	1.6	2.2
	PR 1440	0.4	-1.2	-0.9
	PR 1776	0.6	-0.6	-1.5
	PR 1828	4.6	2.6	2.7
	PR 2911	5.8	3.3	5
	Q4-2817	-0.9	-1.2	-0.6

Table 33. Summary of the Volume Swell Results for POSF 7386 *(Cont'd)*

Description	Sample ID	4751 JP-8	5644 FT + JP-8	7386 Test Fuel
Films	Teflon	0.1	0	0
	Kapton	0	0	0
	Nylon	0.2	0.3	0
	Polyethylene	2.3	1.8	1.7
Misc	MIL-PRF-87260*	13.3	8.5	9.8
	CS 3100	-0.4	-1.7	0

Dr. Graham concludes that:

- "Based on the analysis of the volume swell results and the assumption that the reference fuels are representative of fuels acceptable for use interchangeably with JP-8, POSF 7385 as a neat fuel may not be compatible with JP-8 with respect to its interactions with polymeric fuel system materials. Overall, it is anticipated that the volume swell character of POSF-7385 is expected to be significantly lower than an average JP-8. However, the behavior of this fuel is similar to other complex paraffinic fuels such as those produced by the Fischer-Tropsch process and therefore this fuel may serve well as a blending stock with JP-8."
- "Based on the analysis of the volume swell results and the assumption that the reference fuels are representative of fuels acceptable for use interchangeably with JP-8, the volume swell character of POSF 7386 is expected to be similar to a very low aromatic JP-8. The most acute concern is for the performance of nitrile rubber O-rings which may exhibit a volume loss that is somewhat greater than what is normally experienced with JP-8."

4.3.6 BOCLE (D5001) vs. CI/LI Concentration (DCI-4A)

A standard BOCLE test of neat fuel provides an indication of the inherent lubricity of the fuel. Equally important is to determine the response of a unadditized fuel to the addition of a standard lubricity improver (DCI-4A). Prior to testing, the selected fuels are clay-treated to remove all additives. The fuels are then re-additized and their lubricity re-evaluated.

The general finding is that the neat HRJ fuels show high BOCLE unadditized and that most fuels respond immediately to low dosages of additive but quickly plateau at higher levels. Selected fuels are shown below in Figure 24. This has implications for mechanical component wear; the reader is referred to paragraph 4.5.1.

For comparison purposes, Figure 24 shows BOCLE vs. CI/LI Concentration for some HRJ fuels and Table 34 shows the shows the Scuffing-Load BOCLE (D6078) and HFRR (D6079).

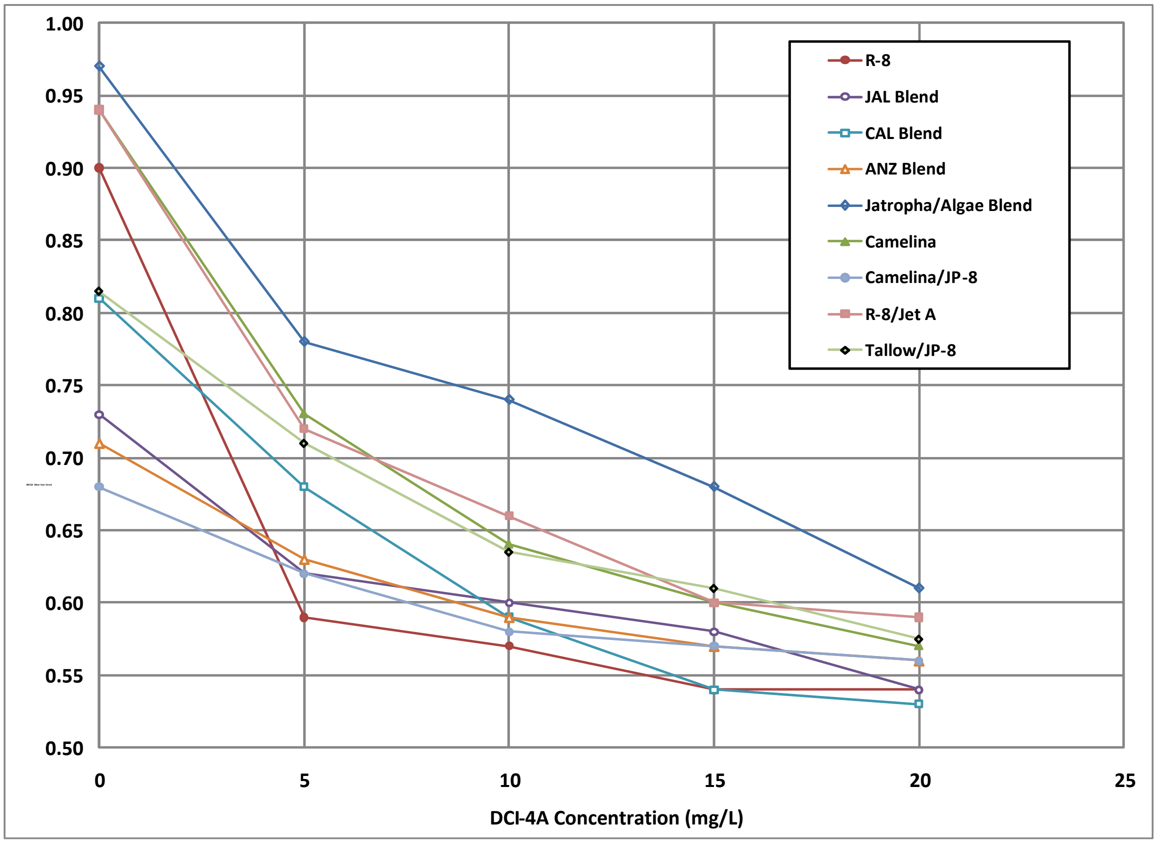


Figure 24 BOCLE Wear Scar (mm) (D5001) vs. CI/LI Concentration (DCI-4A)

Table 34. Comparative Lubricity Data[35]

Sample ID	Fuel Description	BOCLE (D5001) mm	Scuffing-Load BOCLE (D6078) grams	HFRR (D6079) mm
	Clay-Treated Jet A	0.75	2700	0.72
	Jet A (Valero)	0.84	2650	0.72
	Sasol IPK	0.86	1950	0.84
POSF 5469	R-8 HRJ	0.99	1950	0.73

[35] Reference 7

Table 34. Comparative Lubricity Data *(Cont'd)*

Sample ID	Fuel Description	BOCLE (D5001) mm	Scuffing-Load BOCLE (D6078) grams	HFRR (D6079) mm
POSF 6406	Tallow HRJ / JP-8	0.61	3900	0.71
POSF 5140	TS-1	0.58	2950	0.74
	JP-5	0.57	3950	0.71
	JP-8	0.53	3850	0.73
POSF 6308	Tallow HRJ	0.95	2450	0.71
POSF 6152	Camelina HRJ	0.93	2000	0.79
POSF 6184	Camelina HRJ / JP-8	0.62	3100	0.73
	R-8 HRJ / Jet A	0.86	2150	0.69

4.3.7 Fuel Storage and Filtration Considerations

Per ASTM D4054, candidate fuels should have no impact on coalescer filtration relative to a typical Jet A fuel. The standard method for evaluating filtration performance for aviation use is API/EI 1581 5th Edition. A single element test (SET) is performed to evaluate the water and dirt removal characteristics. The test equipment is well defined in this standard but a test typically requires the use of approximately ***12,000*** gallons of test fuel. Testing on this scale requires a large facility and therefore limits its widespread application. To evaluate the water removal characteristics of alternative aviation fuels given very limited quantities of test fuel, a test method utilized by the automotive industry (Society of Automotive Engineers (SAE) J1488 Emulsified Water/Fuel Separation Test Procedure) was considered. A typical J1488 test requires approximately 50-L of fuel which would typically be available even in pre-production runs of fuel.

The intended purpose of the two test methods is somewhat different. The primary intent of API/EI 1581 is to qualify aviation fuel filters while J1488 is primarily used to determine water removal efficiency (WRE) for a given filter. The J1488 test measures only free water using a Karl Fisher coulometric water titrator (the fuel saturation limit is subtracted out of the total water content). There are no pass/fail criteria when applying the J1488 test in this manner. The test is simply used as a screening tool to identify obvious signs of fuel/water separation issues. For instance, if a test were run that resulted in a 50% WRE, that should cause some immediate concern and additional investigations would be warranted. That's not to say that a fuel that gives a >95% WRE by J1488 will always pass the API/EI 1581 test but it provides some confidence that the fuel doesn't have any significant fuel/water separation issues.

Results for the HRJ fuel blends and R-8 HRJ are shown in Table 35. There is no sign of fuel/water separation issues with any of the HRJ fuel blends. The HEFA/HRJ blends have been shown to perform the same as conventional and military jet fuels in the SAE J1488 test.

Table 35. J1488 Test Results for HRJ Blended Fuels[36]

Test Fluid	POSF 5674		POSF 6184	POSF 6406	POSF 5469
Fluid Designation	Jet A/JAL Blend	R-8/Jet A Blend	Camelina HRJ Blend	Tallow HRJ Blend	R-8 HRJ
Average Water Content, ppm	2548	2589	2296	2426	2278
Time Weighted Average Water Removal Efficiency (%)	100.00%	100%	99.10%	99.00%	99.40%

4.3.8 Cetane

When necessary, USAF ground support equipment operate on military aviation jet fuels. The cetane number is an experimental measurement relevant to the operation of diesel engines and is being used for HRJ fuel evaluation. It has been seen that as the cetane number begins to increase past 65, performance impacts are observed due to combustion timing effects. It is also stated that very low cetane numbers, below 37, will result in difficult cold starting, cold smoke, and reduced life for most diesel engines and immediate structural failure of others.[37] A comparison of derived cetane numbers for various fuels is provided in Figure 25. The low aromatic HRJ fuels and HRJ blends typically show a higher cetane value than the typical JP-8 and Jet-A fuels. Thus cetane could be a consideration factor in the blending strategy.

[36] References 3,5
[37] Excerpts from MIL-HDBK-510

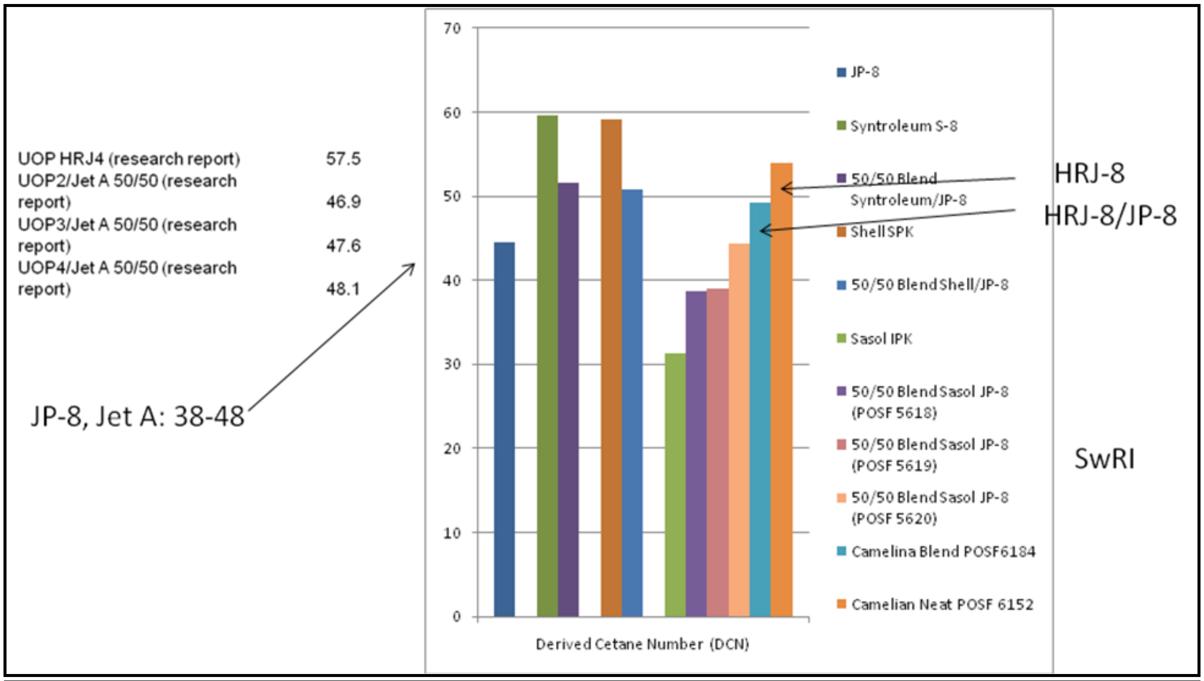


Figure 25. Derived Cetane Numbers for Various Fuels

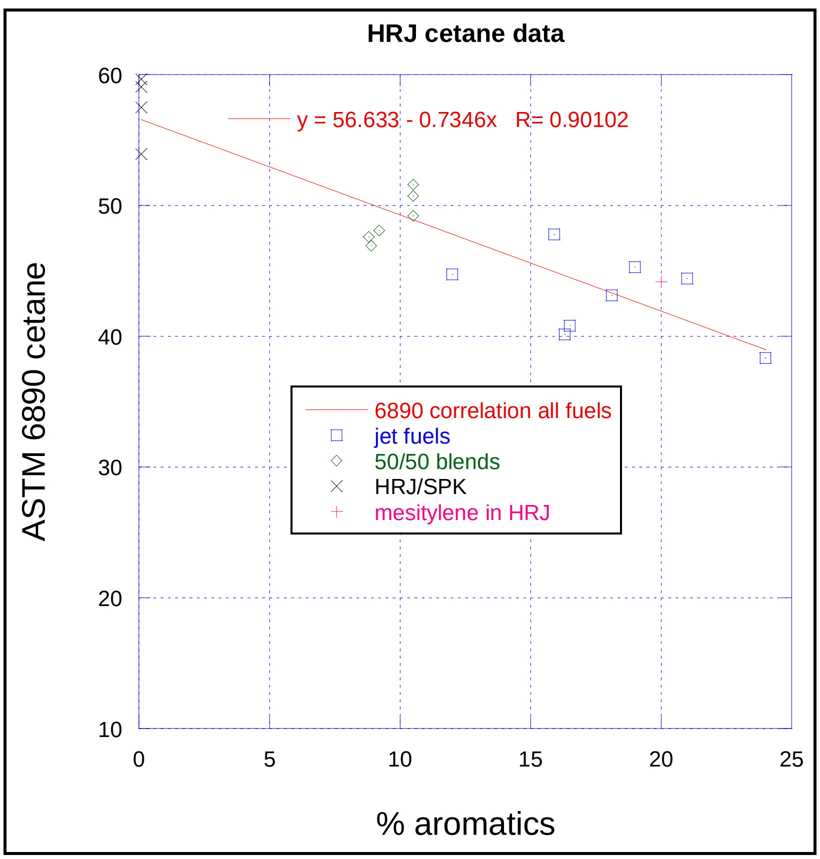


Figure 26. Correlation of Cetane vs. % Aromatics

4.3.9 Thermal Stability

The thermal stability of the HRJ fuels was assessed using the QCM under typical experimental conditions (140°C, air saturated fuel, 15 hours). Total mass accumulation results for the fuels are shown in Table 36. The level of deposition for POSF-7272 is similar to that of POSF-4751 (3.0 $\mu g/cm^2$); while the level of deposition for POSF-7386 is higher than that of the JP-8 blending fuel. In addition, POSF-7272 is a faster oxidizer than the other HRJs and the JP-8 fuel, which would indicate lack of antioxidant. As a result, the antioxidant level was checked and found to be 10 mg/L, which is below the specification minimum of 17 mg/L. Furthermore, POSF-7386 behaved differently than the other HRJ/JP-8 blends, as well as JP-8 POSF-4751. It showed a marked increase in rate of deposition that coincided with a marked increase in rate of oxygen consumption after approximately 7 to 8 hours.

Table 36. Data from QCM Thermal Stability Analysis

POSF No.	Fuel Description	15 Hr Mass Accumulation ($\mu g/cm^2$)
6308	HRJ8-Tallow	0.5
6152	HRJ8-Camelina	0.2
4909	F-T SPK	0.4
6169	JP-8	4.2
4751	JP-8	3.0
6399	50/50 Blend (6308/6169)	1.0
6406	50/50 Blend (6308/4751)	2.0
6184	50/50 Blend (6152/4751)	0.8
6185	50/50 Blend (6152/6169)	0.8
4913	50/50 Blend (4909/4751)	0.9
7272	R-8 HRJ	2.4
7386	50/50 Blend (7272/4751)	5.3
5469	R-8 HRJ	0.3
5536	50/50 Blend (5649/4751)	1.3

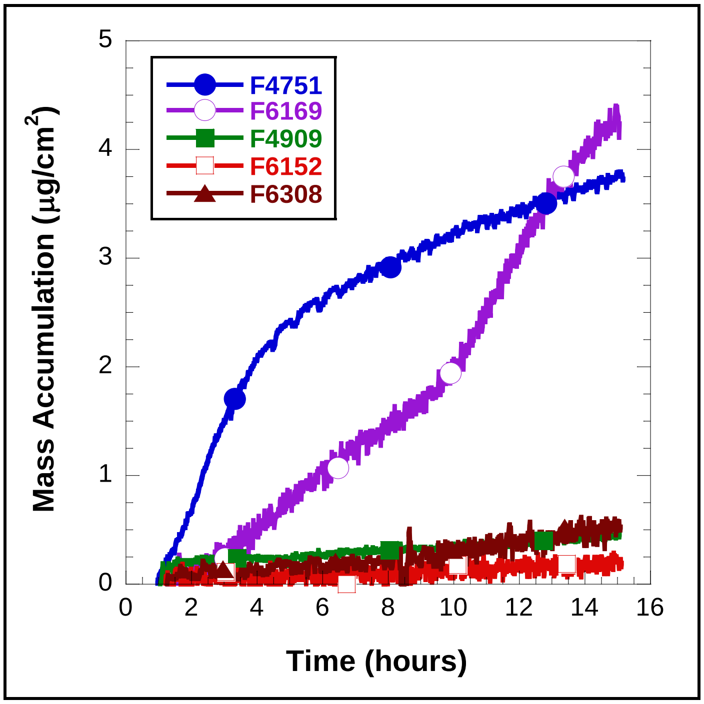


Figure 27. Mass Accumulation from QCM Analysis of HRJs, F-T SPK, and JP-8

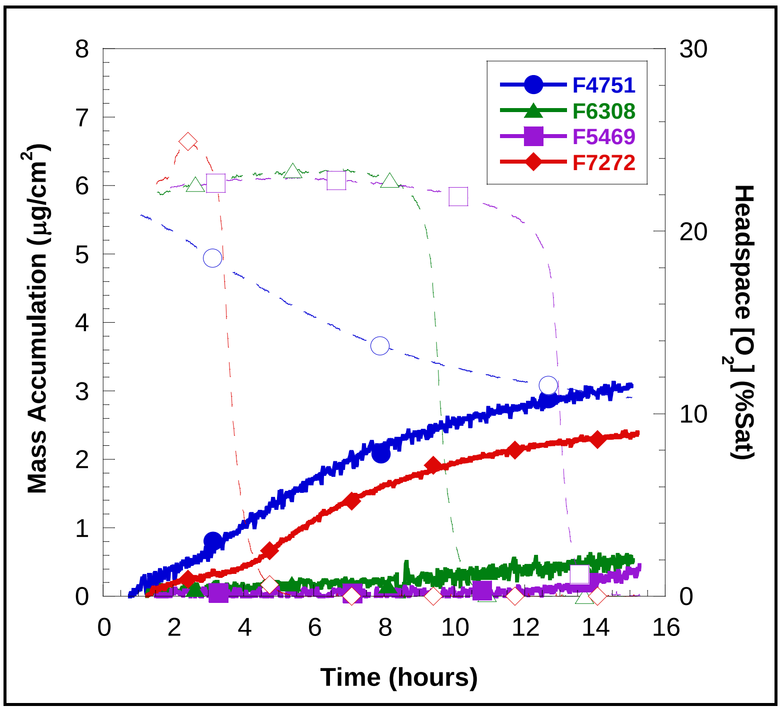


Figure 28. Mass Accumulation (Solid Curves, Closed Symbols) from QCM Analysis of HRJs and JP-8 and Headspace Oxygen Profiles (Dashed Curves, Open Symbols)

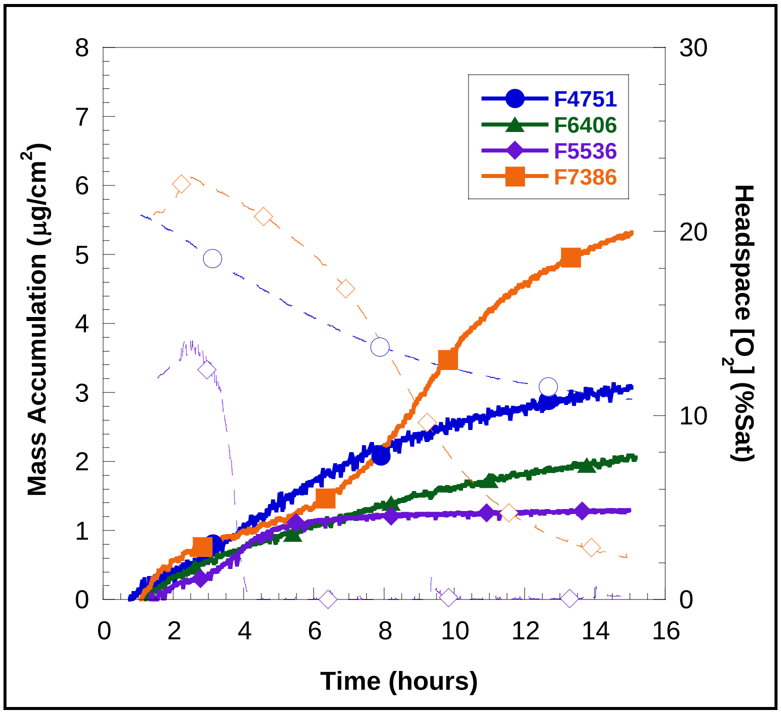


Figure 29. Mass Accumulation (Solid Curves, Closed Symbols) from QCM Analysis of HRJ Blends and JP-8 and Headspace Oxygen Profiles (Dashed Curves, Open Symbols)

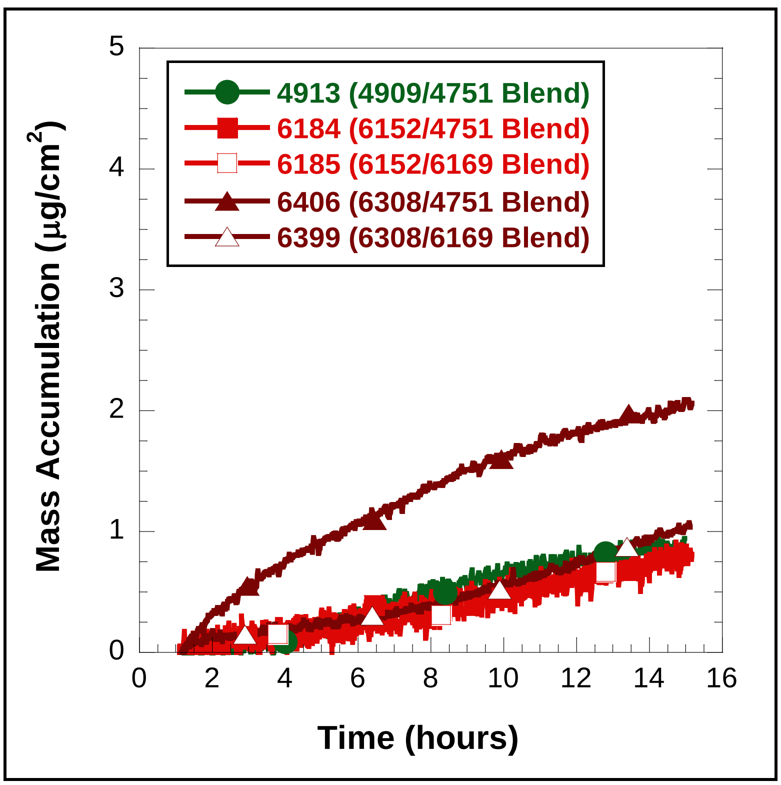


Figure 30. Mass Accumulation from QCM Analysis of Blends

4.4 Extended Laboratory Fuel Property Testing

The various HRJ fuels are seen to be chemical and physical similar in sections 4.1 thru 4.3 above; hence these fuels are being considered as a class of fuels. Expensive component and rig demonstration and testing are being conducted for the fuel class (not all specific HRJ fuels are being tested in every test rig). Conclusions and results are applicable to HRJ class of fuels unless noted otherwise.

4.4.1 Investigation of Oxidative Stability Characteristics Using ECAT Flow Reactor System

The AFRL ECAT Flow Reactor System was used to preliminarily evaluate the relative oxidative stability characteristics of a hydroprocessed renewable for jet (HRJ) research fuel, termed R-8, (POSF 5469) in a flowing environment. It is reported that the R-8 fuel demonstrated excellent oxidative stability characteristics during testing resulting in minimal surface deposition on the reaction tube. In addition, the bulk deposits collected on the downstream filter were reduced by over an order of magnitude. The stability characteristics exhibited by this fuel are similar to those observed for a JP-7 fuel, which is a specialty fuel designed to be stable for high-temperature applications.[38]

4.4.2 Advanced Reduced Scale Fuel System Simulator Studies

The AFRL Advanced Reduced Scale Fuel System Simulator (ARSFSS) is designed to closely simulate the hardware, thermal and fuel flow characteristics of an aircraft fuel system. It provides the last evaluation of potential high heat sink fuel additives prior to going into actual engine testing. The ARSFSS was designed to realistically simulate the thermal and flow profiles of 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. The simulator is currently configured to simulate the F-22 aircraft with the F119 engine. The specific test articles of the engine simulator are (1) the fuel cooled oil cooler (FCOC), (2) the flow divider valve (FDV), (3) the burner feed arm (BFA), and (4) a servo valve. The FCOC represents the engine lubrication system cooler. The total fuel required for each test is approximately 900 gallons. A generic F-22 duty cycle, established by Pratt and Whitney, was used for these tests.

ARSFSS evaluations were conducted by back to back evaluations of a baseline JP-8 fuel (POSF-6169) and a 50/50 blend (POSF-6185) of this JP-8 fuel and the camelina HRJ (POSF 6152). Each evaluation consisted of 65 missions with a total time of approximately 123 hours. ARSFSS test conditions are shown in Table 37. The results of the evaluations did not indicate any significant differences between the baseline fuel and the 50/50 blend. A comparison of the carbon deposits in the BFA tubes for these evaluations is shown in Figure 31. The deposits were slightly higher for the blend, but the deposits are considerably lower than the 300mg/cm^2 limit normally established as acceptable for meeting nozzle life requirements. The slight difference between the two evaluations was later determined to have been caused by a difference in drying procedure of the BFA tube segments. The servo valve and FDV hysteresis data before and after the evaluations are shown in Figures 32-35. There were no significant hysteresis shifts in any of the valves. The FDV for the blend did indicate a null shift due to an unknown load shift, but the

---

[38] Reference 3, Appendix E, Dr. Matthew J. Dewitt, University of Dayton Research Institute

actual valve hysteresis indicated a slight improvement after the evaluation. Photographs of the servo valve and flow divider parts after both tests are shown in Figure 36 for comparison purposes. There was no deposition on any of the valves after these tests. Based on these results there was no thermal stability impacts with the 50/50 blend of the baseline JP-8 and camelina HRJ fuel.

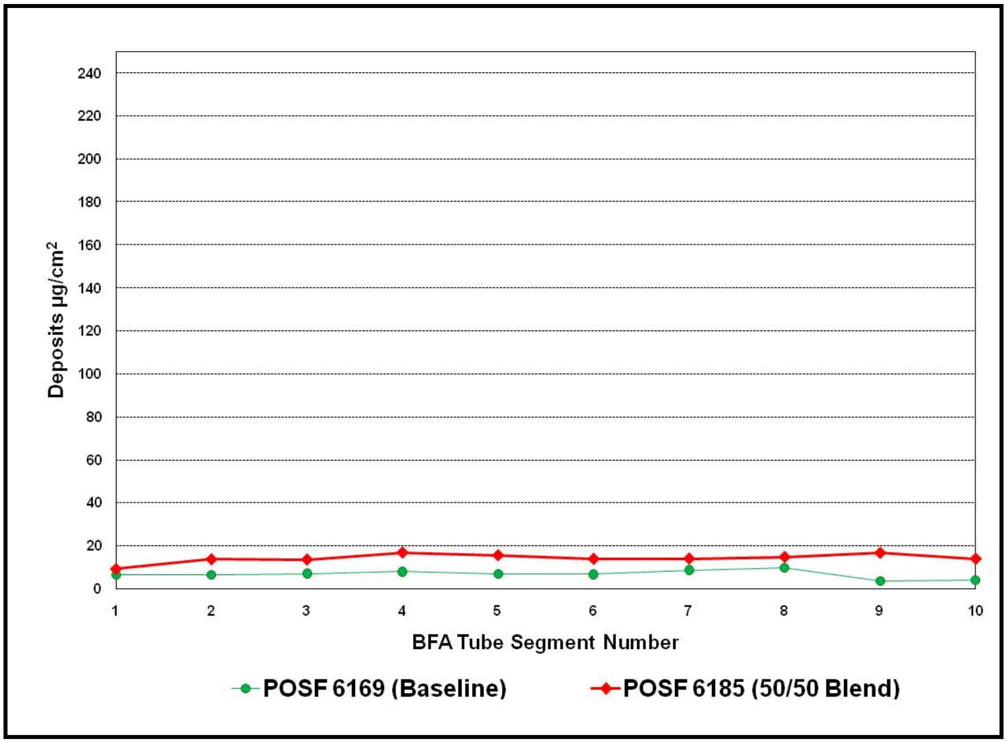


Figure 31. Comparisons of BFA Carbon Deposits between Baseline and 50/50 Blend

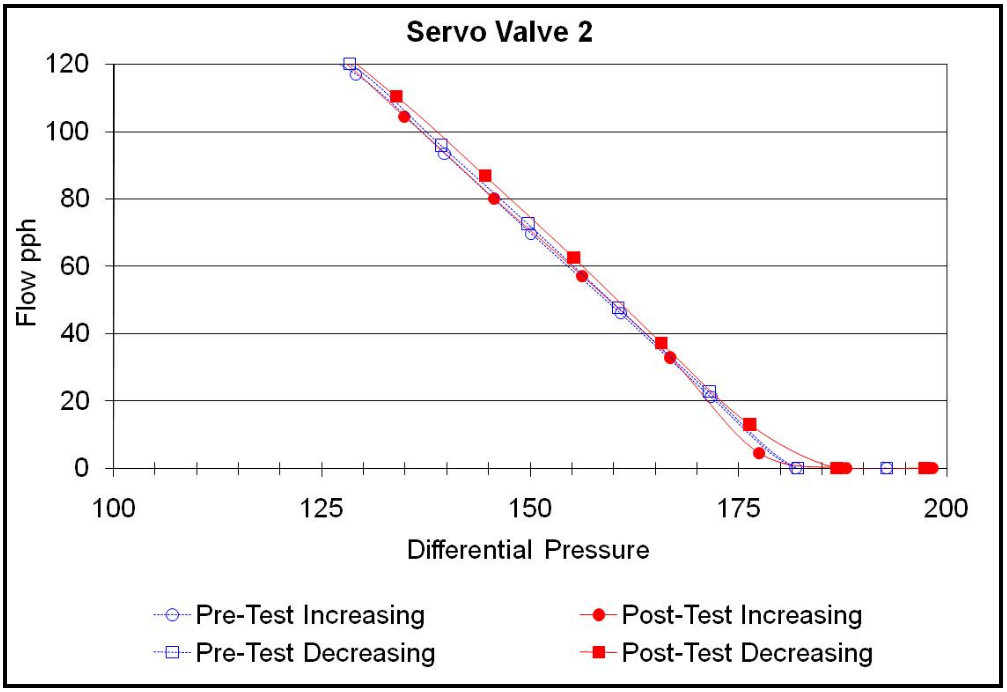


Figure 32. Hysteresis of Servo Valve with Baseline Fuel

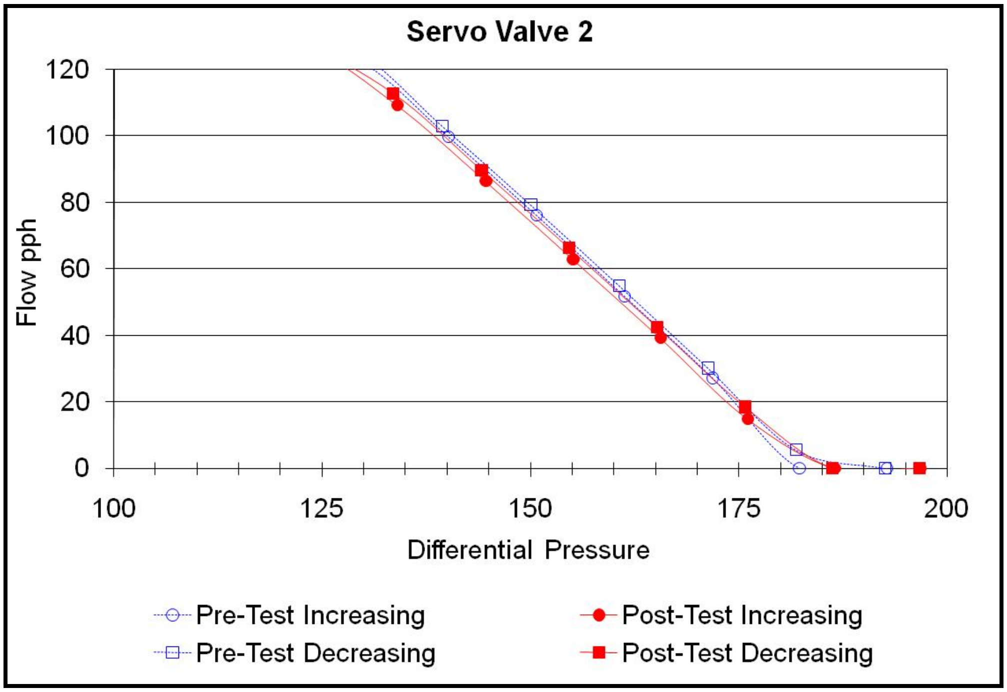


Figure 33. Hysteresis of Servo Valve with a 50/50 Blend

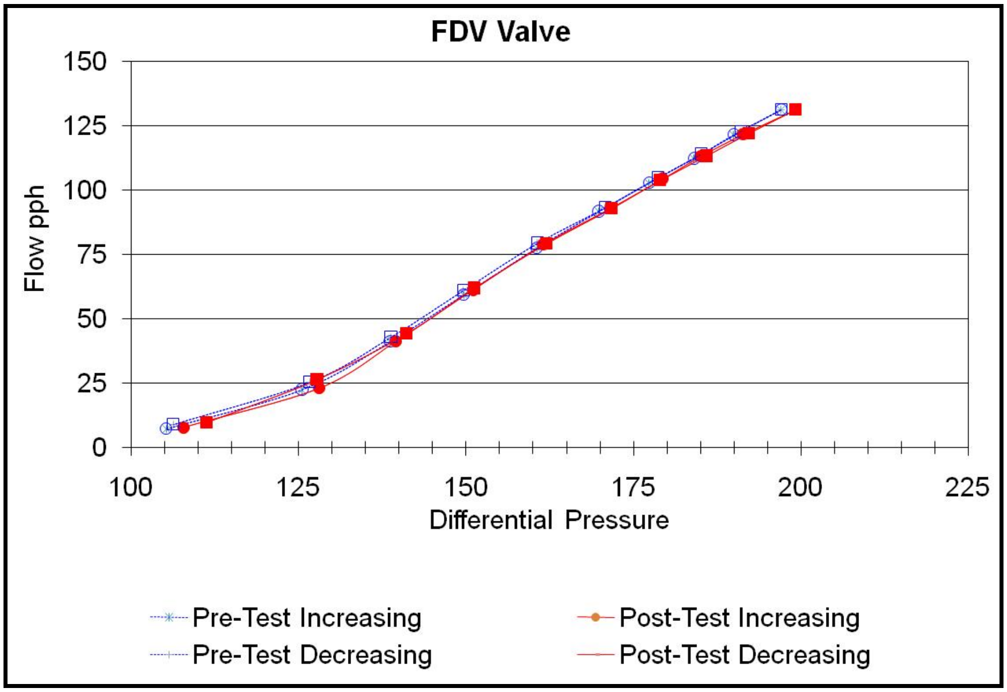


Figure 34. Hysteresis of FDV with Baseline Fuel

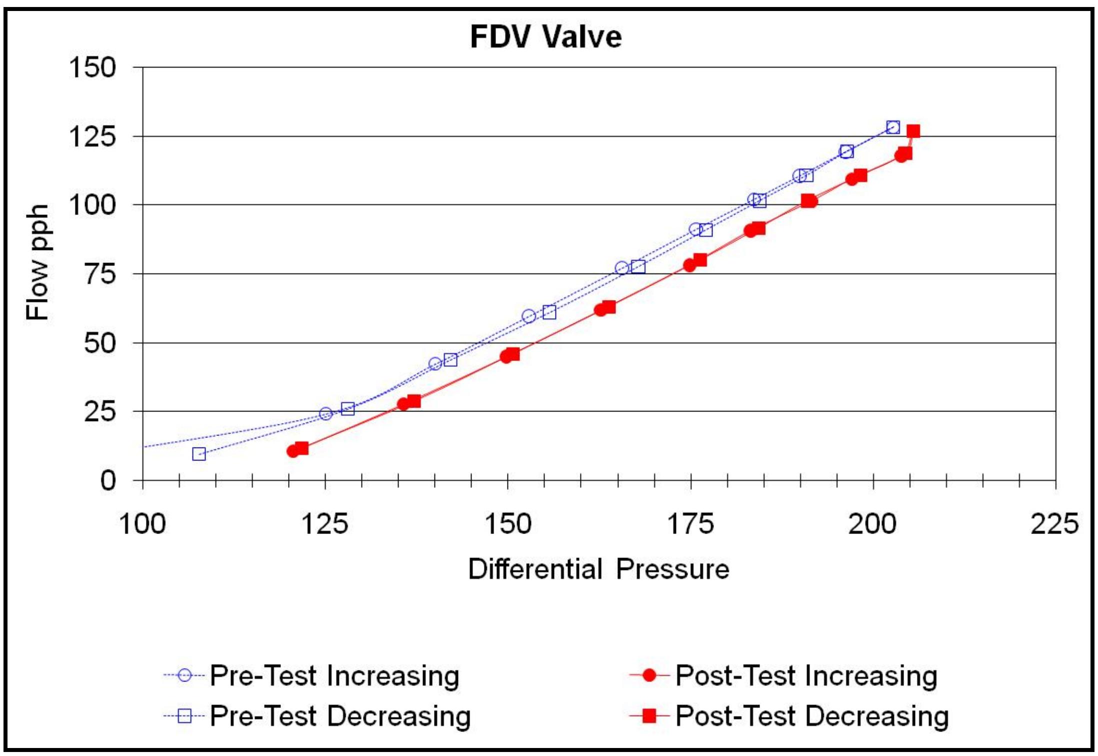


Figure 35. Hysteresis of FDV with a 50/50 Blend

Table 37. ARSFSS Test Conditions

Mission Parameter	Mission Segment Number and Name					
	Ground Idle 1	Hi Power Cruise 2	Lo Power Cruise 3	Combat 4	Descent 5	Ground Idle 6
Start Time (el. min)	0	25	46	88	91	97
End Time (el. min)	25	46	88	91	97	112
Duration (min)	25	21	42	3	6	15
Burn Flow (PPH)	16.7	52	35	169.1	23.2	16.7
Recirc Flow (PPH)	27.5	14	23	0	44.2	27.5
FCOC IN (°F)	300	300	300	NC	300	300
FCOC OUT(°F)	325	325	325	NC	325	325
AFHX Fuel(°F)	285	285	285	NC	285	285
BFA WWT(°F)	450	450	450	NC	450	450

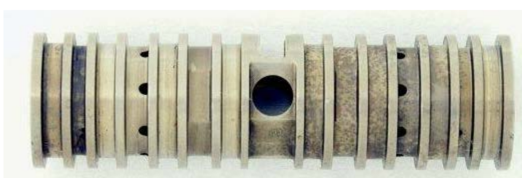
Baseline Neat Fuel	50/50 Blend
 FDV Valve Stem	 FDV Valve Stem
 FDV Screen	 FDV Screen
 SERVO Valve Spool	 SERVO Valve Spool

Figure 36. Pictures of Flow Divider and Servo Valve Components

4.4.3 Material Compatibility (Soak) Tests – 28 Days

The purpose of these tests was to evaluate the compatibility of several synthetic fuels with nonmetallic engine and airframe materials. Tests were performed by AFRL, Boeing and independent laboratories. The majority of testing and evaluation were done by the University of Dayton Research Institute for the Air Force Research Laboratory/Materials Integrity Branch (AFRL/RXSA) to determine the material compatibility of R-8 and other synthetic fuels with nonmetallic fuel system materials.[39,40] The materials that were tested were exposed for 28 days to 100% R-8 HRJ and a 50/50 blend of JP-8 and R-8 fuels at elevated temperatures.

Materials tested included adhesives, fuel bladders, coatings, sealants and potting compounds, composites, foam, o-rings, hoses, and wire insulation. It was concluded by UDRI that based on comparison to the JP-8 baseline results and JP-8/S-8 SPK blend results, the JP-8/R-8 HRJ blend generally affected materials similarly to the JP-8/S-8 blend. However, similar to previous studies, it cannot be concluded that the 100 percent alternative fuels would be suitable for use.

In conclusion, it does not appear the Bio-SPK (HRJ) alternative fuels and blends degraded material properties any more than did the baseline JP-8s, F-Ts, and JP-8/FT blends.

4.4.4 Dynamic Seal Testing[41]

Turbojet engine fuel control systems employ sealing surfaces that move or slide over an elastomer sealing material. These seals are generally referred to as dynamic seals, and the usual configuration is an o-ring. SwRI designed and built a laboratory bench top apparatus, which is shown in Figure 37. This apparatus, called the dynamic seal test rig, is being used for the evaluation of elastomeric o-rings exposed to alternative fuels and fuel blends on a reciprocating shaft, under dynamic conditions. The test rig is designed to simulate temperatures ranging from 15^{o}F to 300^{o}F. A small cavity at the end of each aluminum block, formed within the end caps, collects fuel that leak past the o-ring under test. The failure time of the elastomer material, causing leaks is used to evaluate the performance of elastomer seals with the different types of alternative fuels.

A unique feature of the test rig is its ability to switch fuels during a test run. The test can start with one particular fuel that is brought into contact with the o-ring seals and then switched to a second fuel with a different composition. This simulates a common situation that occurs in the field where there are frequent changes of fuel composition on elastomer material.

---

[39] Reference 3 Appendix J, Ryan P. Osysko, University of Dayton Research Institute, Report # AFRL/RXS 10-002 and AFRL/RXS 10-003

[40] Reference 2

[41] Draft Interim Report, November 2011, "Elastomer-Fuel Compatibility Studies for Dynamic Seal Applications, SwRI Project # 08-16246.08.001

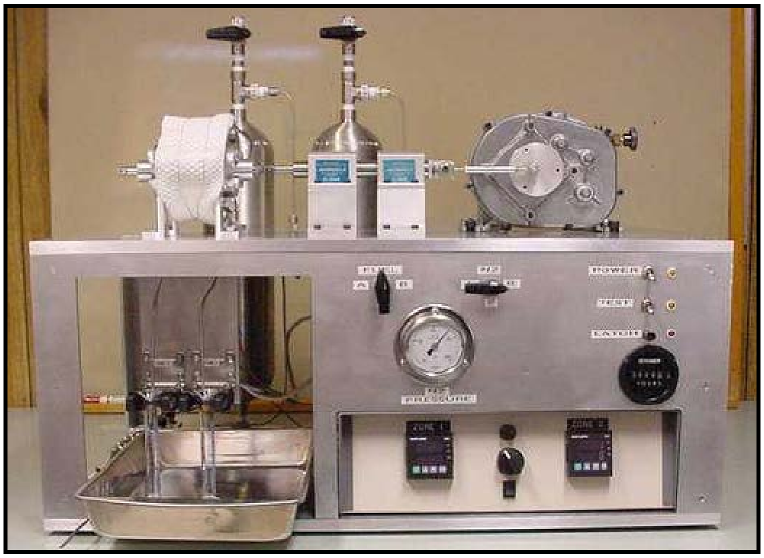


Figure 37. SwRI Dynamic Seal Tester

The dynamic tests for all three elastomer materials, (fluorosilicone, buna, and viton o-rings) with Jet-A and R8 HRJ have been completed, (all three elastomer materials were constantly exposed to 200°F operating temperatures). The dynamic test for R8HRJ-JP8 (50/50) blend is currently in progress and switch loading has not yet been examined. These important investigations will be reported separately at a later date.

The o-rings that were tested in the dynamic seal test rig with Jet-A yielded the following results for failure time. Samples of buna-N and viton o-rings lasted more than 309 and 407 hours respectively. The exact failure time (maximum limit) for these materials were not determined.

Fluorosilicone: 42.1 – 136.4 hours

Buna-N: 183.4 – greater than 309 hours

Viton: greater than 407 hours

The performance of the elastomer materials with the baseline Jet-A fuel is shown in Figure 38 and the performance of the elastomer materials with 100% R-8 HRJ fuel is shown in Figure 39. The average performance of buna-N, viton, and fluorosilicone o-rings reduced significantly with R8 fuel. It is seen that the average performance of fluorosilicone o-rings decreased by half; from 85.34 hours with Jet-A to 45.68 hours with R8 fuel, whereas the performance of buna-N and viton o-rings with R8 fuel, was drastically reduced by a factor of 17 and 10 respectively. Thus, the lack of aromatics, thermal effects and fuel lubricity reduces the performance of buna-N and viton o-rings to the level of fluorosilicone o-rings.

This testing is still under development and the test rig has not yet been fully validated. Nonetheless, the performance of the viton o-rings is unexpected, and points to the use of caution with use of unadditized 100% HRJ fuel in service until further information is determined.

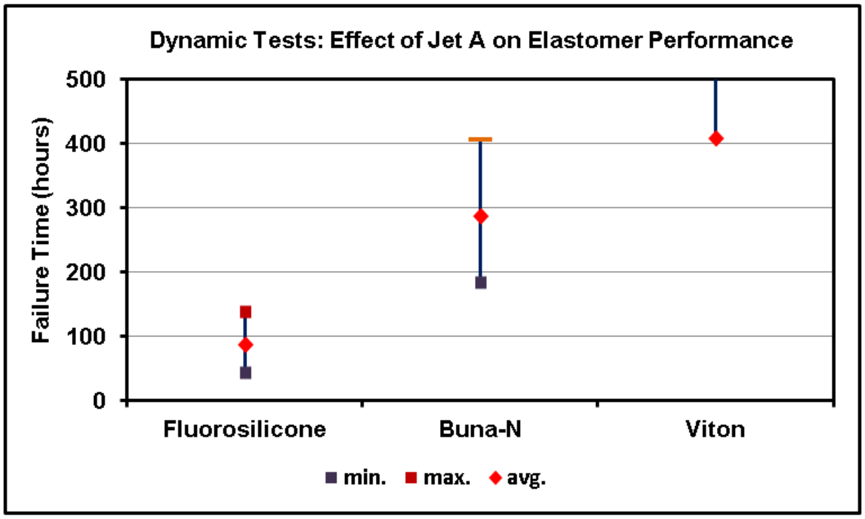


Figure 38. Dynamic Seal Performance for Jet-A Fuel

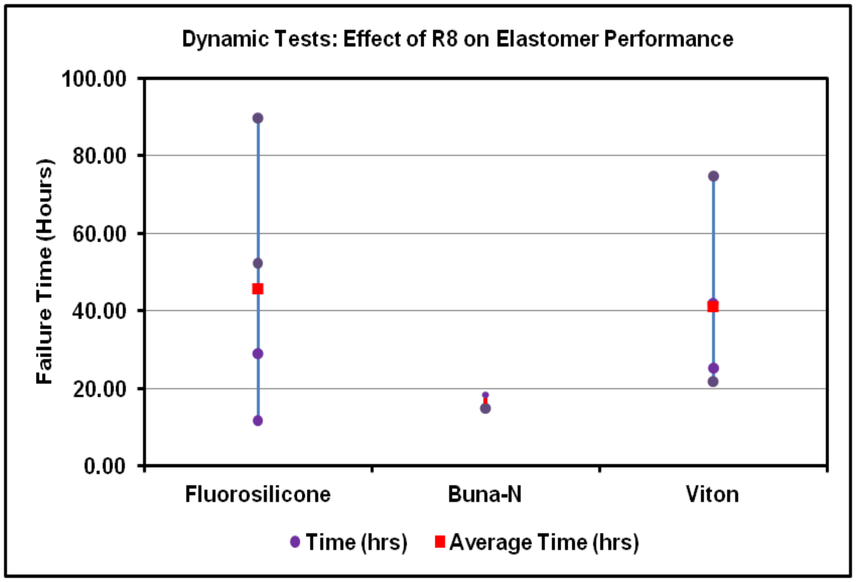


Figure 39. Dynamic Seal Performance for Jet-A Fuel

4.4.5 Turbine Engine Hot Section Materials Compatibility

High velocity burner rigs are being used to evaluate the combined effects of cyclic oxidation, hot corrosion, erosion and thermal fatigue on the durability of turbine engine hot section materials.

Rolls-Royce Liberty Works (RR-LW), Indianapolis Indiana, conducted testing relative to their AE 3007 engine materials using a modified Becon burner rig. The Becon combustor rig is a commercially available unit used primarily to expose gas turbine hot end alloys to prolonged high temperature operation in a combustion gas products environment. The combustion chamber is operated much like a rocket, with kerosene and air being injected into a chamber with a single nozzle exit. A set of alloy specimen rods are mounted in a rotating carousel and cycled between hot and cold jets. Two positions are occupied by rods having the same external dimensions but hollowed, to accept platinum reference/control thermocouples. At the request of AFRL, the test duration for each set of specimens was set at 400 hr (1600 cycles) which has been determined to be sufficient exposure for screening tests. The specimen rods all run at similar temperatures because carousel rotation ensures that every specimen traverses the jet temperature profile in a similar fashion.

Figure 40. Becon Thermocouple Rods

A set of twelve pin specimens tested in the RR-LW Becon test with the 50/50 UOP HRJ-8 Tallow/JP-8 (POSF 6399) were submitted to UDRI for examination. The samples were tested by two main methods: (1) Visual Analysis and Optical Metallography and (2) X-ray Fluorescence (XRF) and Scanning Electron Microscopy (SEM). Comparisons were made to previous analyses performed on pins similarly exposed to JP-8 and FT fuels[42].

Overall, the 50/50 UOP HRJ-8 Tallow/JP-8 test pins compare favorably with their Fischer-Tropsch counterparts in that no significant compositional or physical appearance differences are observed. The use of the 50/50 UOP HRJ-8 Tallow/JP-8 fuel did not produce any unexpected features or compositional concerns.

[42] Samples had also been tested previously in the Liberty Works Becon rig using a JP-8 fuel, but some interferences caused by excess iron (rust) that was deposited on the original JP-8 samples created difficulties in making direct comparisons to the JP-8 samples. The Fischer-Tropsch samples were found to show minimal if any differences from the JP-8 samples after accounting for this excess iron, so the Fisher-Tropsch tested samples are considered equivalent to the JP-8 samples.

4.4.6 T63 Emissions and Endurance Testing

HRJ fuel evaluation, performance, and emissions in a T63 turbine engine are reported in the proceedings of ASME Turbo Expo 2011, GT2011-46572, June 2011. Pertinent information is excerpted below:

"Tests were conducted to evaluate the performance and emissions characteristics of a T63 engine operated on camelina and tallow HRJ fuels, 50/50 blends by volume with JP-8, and a 16% aromatic/tallow-HRJ blend. In addition, a long duration (150 hr) test was completed. As anticipated no anomalies in engine performance were observed with the alternative fuels and blends. Due to the lack of aromatics and sulfur in the HRJ fuel, and consistent with previous studies, reduced soot and sulfur oxide emissions were observed with the neat and blended fuels compared to operation on JP-8. Reductions in HAPS (except for formaldehyde and acetaldehyde) were observed for the alternative fuels and blends. For the 150 hours endurance test with the 50/50 HRJ/JP-8 fuel, emissions measurements at 50, 100, and 150 hours of test operation, demonstrated adequate engine performance with no degradation (i.e. increase) in emissions as a function of run time[43]."

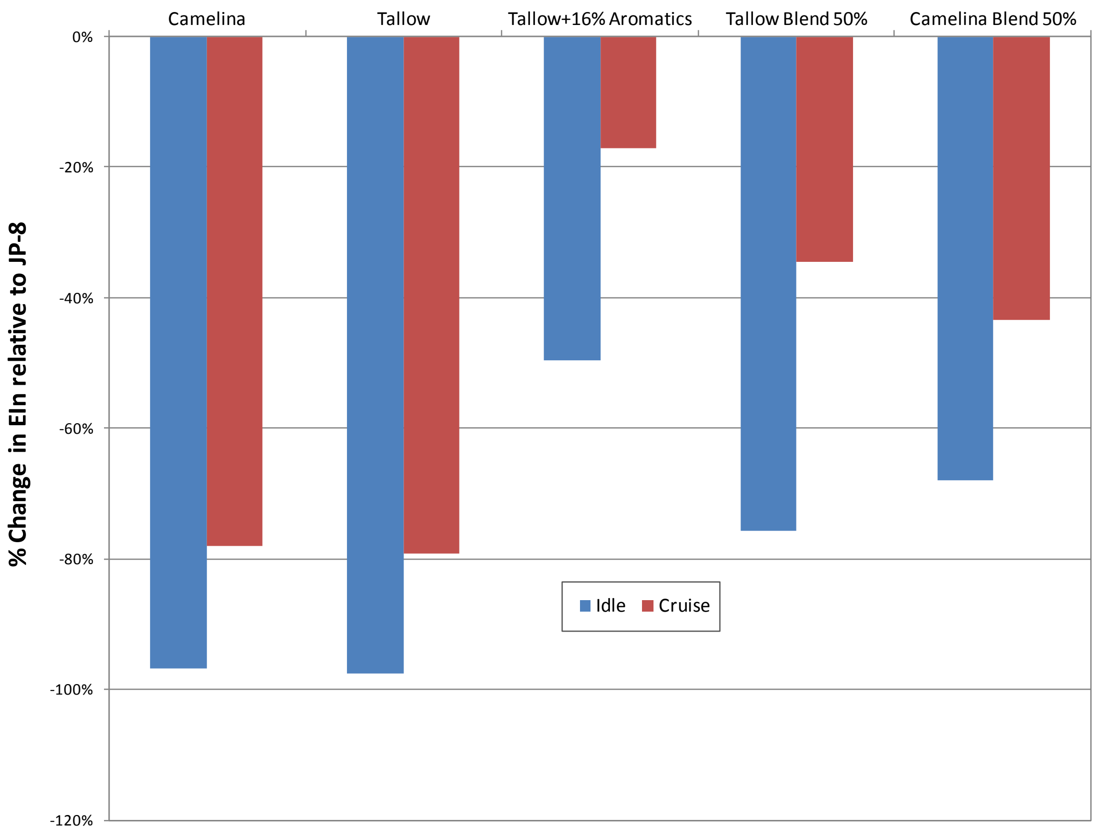


Figure 41. Change in Emission Indice of HRJ Fuels and HRJ Blends Relative to JP-8

[43] Reference 8

"Preliminary testing of the emission propensity of an alternatively-derived fuel supplied by Syntroleum (termed R-8) was also performed using a T63 turbo shaft helicopter engine. Exhaust samples were collected at the engine exit plane and were analyzed for aerosol, gaseous and PM emissions. Testing with neat R-8 and a 50/50 volume percent R-8/JP-8 fuel blend showed a significant reduction in aerosol and PM emissions; these trends were similar to previous testing with an F-T derived SPK produced by Syntroleum (S-8). Gaseous emissions were minimally impacted, with only slight reductions in carbon monoxide observed.[44]"

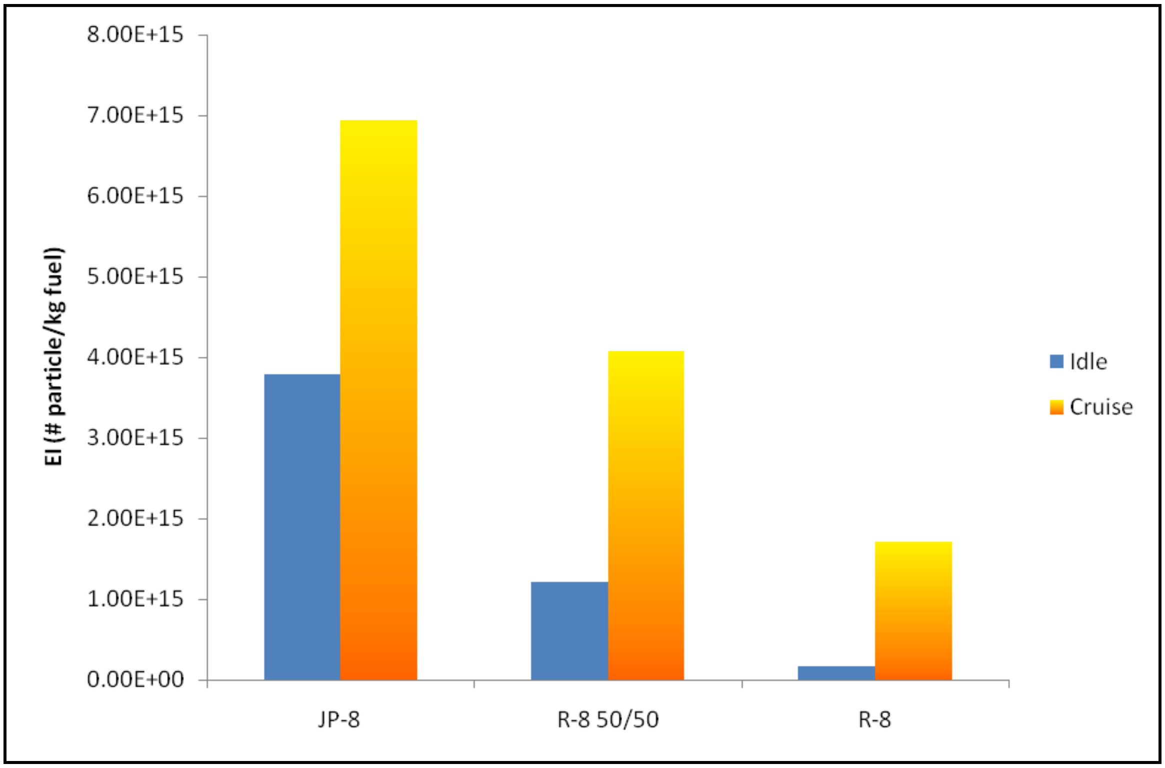


Figure 42. Total Particle Number Emission Indice (EI) (Particles/kg of Fuel) as a Function of Fuel and Engine Condition

4.5 Component Rig Testing

As noted above, the various HRJ fuels are seen to be chemical and physical similar and expensive component and rig demonstration and testing are being conducted for the fuel class, i.e. not all specific HRJ fuels are being tested in every test rig. Conclusions and results are applicable to HRJ class of fuels unless noted otherwise.

4.5.1 Fuel Pump Durability – 500 hrs

SwRI performed pump demonstrations and component wear evaluations for the R-8 HRJ fuel.[45] The purpose of this study was to determine the impacts of a QPL-25017 CI/LI additive on fuel

[44] Reference 3, Appendix G, Christopher D. Klingshirn, University of Dayton Research Institute

[45] Reference 3, Appendix I, Douglas Yost, Southwest Research Institute, January 2010

injection pump durability. Both additized and unadditized R-8 fuels were evaluated. The CI/LI additive DCI-4A was used at a 22.5-ppm concentration in R-8 fuel and in a 50/50-percent blend of R-8/Jet-A fuel.

The Stanadyne arctic pumps used for this testing were opposed-piston, inlet metered, positive-displacement, rotary distributor, fuel-lubricated injection pumps, model DB2831-5209, for a General Electric Products 6.5L HMMWV engine application. As discussed in the reference, rotary distributor fuel injector pumps are sensitive to fuel lubricity and highly refined, low sulfur, and low aromatic fuels can cause substantial performance degradation; wear seen in these results could be interpolated to rotary distributor pumps of other manufacturers.

As expected, the R-8 (unadditized) fuel performed poorly in the pump-down test. The test was stopped at 25 hours. Thus, it should be recognized that this fuel has poor lubricity characteristics without CI/LI being added.

In conducting the pump stand tests with the R-8 and R-8 Blended additized fuels, it was found that both tests had completed 500-hours of operation with the following observations:

- Minor fuel delivery loss at rated speed
- Small fuel delivery loss at idle speed
- Wear debris minimal
- No unusual deposits
- Polishing to light scuffing wear was seen on components
- Wear normal for 500-hours of operation
- Rotary fuel injection pumps functioning normally at 500-hours

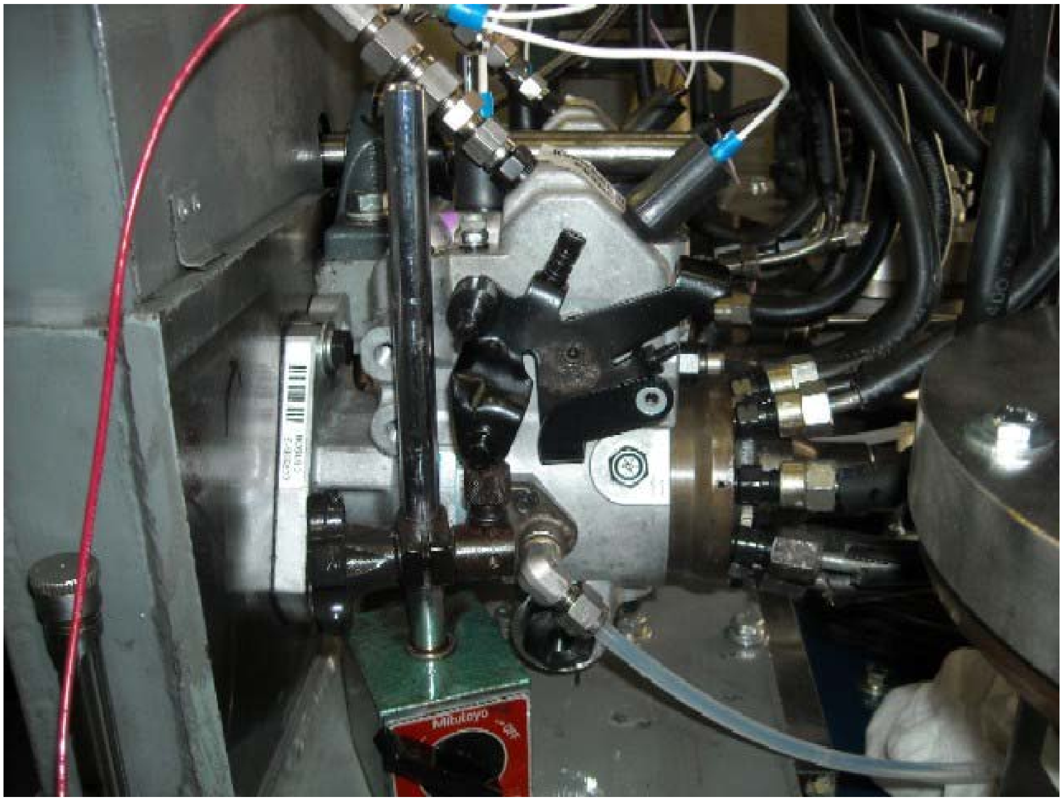


Figure 43. Stanadyne Rotary Fuel Injection Pump

The following conclusions were reached:

1) In conducting the R-8 fuel blends pump stand tests, it was found that the tests could be operated to conclusion at 500-hours:
   - R-8 fuel with 22.5-ppm DCI-4A CI/LI additive
   - R-8/Jet-A fuel blend with 22.5-ppm DCI-4A CI/LI additive
   - Light component wear
   - Substantial durability increase over neat R-8 fuel
2) The most frequent out of specification parameters during the post-test pump and fuel injector performance checks were:
   - Tip dryness and seat sealing of fuel injectors with R-8/Jet-A fuel blend
   - Decreased fuel flow at idle and rated speeds
3) R-8 fuel with 22.5-ppm DCI-4A CI/LI additive was slightly more erratic in fuel delivery throughout the 500-hour test.
4) R-8/Jet-A fuel blend with 22.5-ppm DCI-4A CI/LI additive had slightly less component wear, and slightly better 500-hour delivery performance.

4.5.2 Combustor Section Performance

Performance tests (ignition, lean blowout (LBO), gaseous and smoke emissions) were successfully accomplished by the Rolls-Royce North American Technologies, Inc. (RR-LW) for AFRL using an AE3007 combustor 3 cup sector.[46] Details of these tests are being reported separately. Preliminary conclusions are that JP-8 shows a slight advantage in LBO and ignition. Also there were no significant differences in the results of the alternative fuels tested with regard to UHC and CO emissions. And the results of the biojet fuels demonstrated better combustion efficiencies under lower combustor exit temperatures. The NOx emissions results demonstrated insignificant differences between all the biojet and JP-8 fuels. However, both the 50-50 Camelina blend and the 50/50 Tallow blend showed slightly higher NOx emissions under most operating points. The higher aromatic content of the JP-8 also results in a more luminous flame causing higher combustor liner temperatures. The 100% HRJ fuel resulted in the lowest liner temperatures due to the almost absent aromatic content in this fuel.

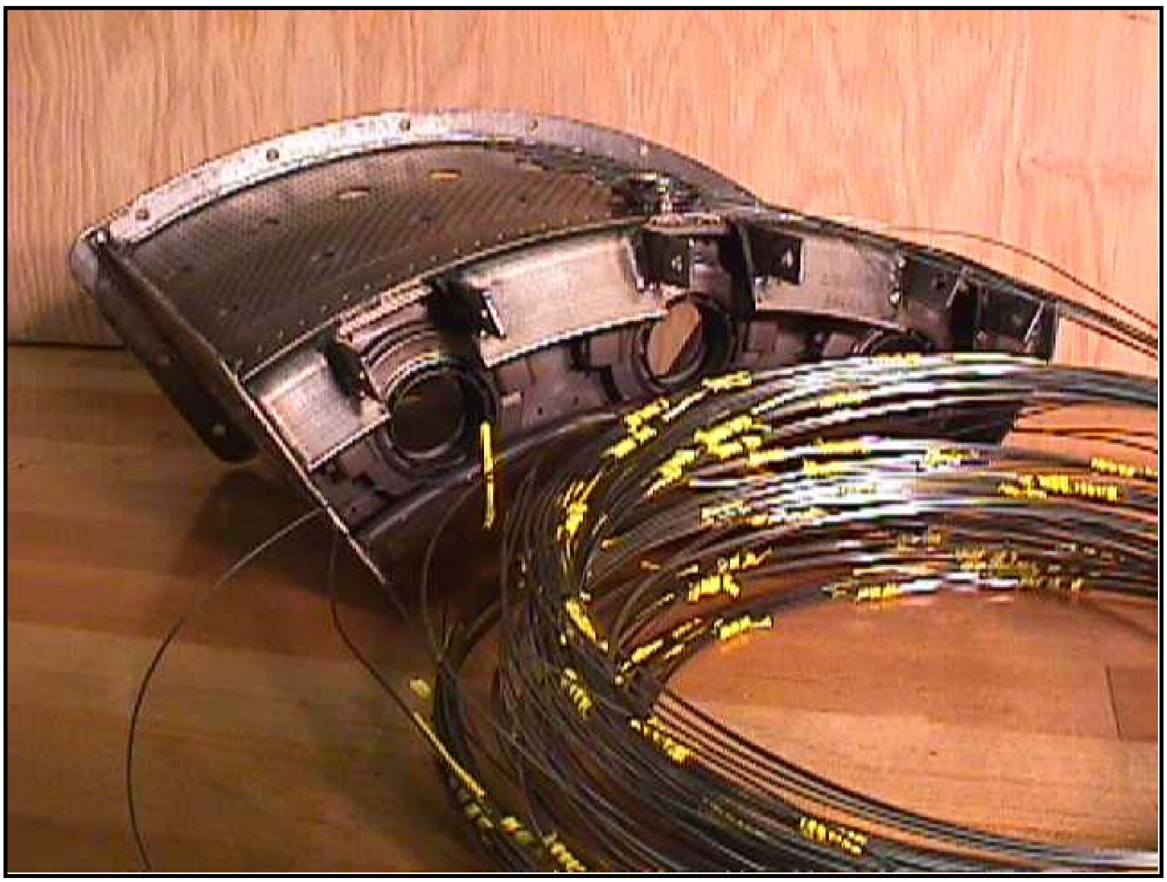


Figure 44. AE3007 Annular Combustor Sector Rig

[46] References 3 and 10

4.5.3 Combustor Nozzle Coking Evaluation

RR-LW conducted a 25 hour nozzle deposition test in the AE3007 Sector Rig under AFRL contract for the following fuels:

- JP-8, (POSF 4843)
- 100% FT, (POSF 5018)
- 50/50 FT/JP-8 Blend, (POSF 5014)
- 50/50 Camelina (HRJ)/JP8 Blend, (POSF 6169 & POSF 6152),
- 50/50 Tallow HRJ/JP8 fuels, (POSF 6399).

Details of these tests are also being reported separately. Preliminary conclusions are that the HRJ fuel does not promote coking of the nozzles. Inspection of the face and exit fuel passages of the nozzles after completing the coking tests for the HRJ blend showed no noticeable carbon build up at any locations and measured flow numbers at different stages of the nozzle fouling test over a 25-hour period with biojet fuels showed no adverse impact on flow capacity of the nozzles.

4.5.4 Full Annular Combustor Evaluation

RR-LW conducted a full annular AE3007 combustor evaluation for AFRL of a baseline JP-8, a FT fuel and the 50/50 tallow HRJ/JP-8 Blend, (POSF 7446). The evaluations included combustor operability, emissions readings, ignition and LBO data, and pattern factor (liner thermal paint). Again, details of these tests are being reported separately.

Preliminary results by RR-LW show fairly similar levels of ignition fuel / air ratios of the tallow HRJ 50/50 blend and JP-8 fuels with some advantage demonstrated by the HRJ blend. Insignificant differences in lean blowout characteristics between the two fuels were demonstrated. The results of the tallow blend and the baseline JP-8 for UHC and CO were close to each other confirming similarity between the two fuels. The results also showed somewhat lower UHC emissions resulting in higher combustion efficiency for the tallow blend.

As expected, the JP-8 fuel produced much higher smoke numbers than that for the HRJ blend due to the higher aromatic content of the JP-8. The aromatic content in JP-8 and the 50-50 tallow blend were 18% and 8.0% by volume, respectively. It is reasonable to estimate more than 50% reduction in smoke could be achieved using the HRJ fuel.

The combustor exit temperature profiles for the tallow 50/50 blend and JP-8 were fairly similar with the JP-8 case showing slightly more peaked profile. Also, the HRJ blend tended to have higher temperatures near the hub and lower temperatures towards the tip of the exit section as compared to that of the JP-8. However, the differences between the HRJ blend and JP-8 were within the experience base.

The liner wall temperature levels were comparable between the two fuels, with the HRJ blend showing somewhat lower temperatures at a number of locations. The thermal paint did not reveal any alarming trend with the HRJ blend with regard to hot streaks or spots. Comparison with thermal paint results obtained in the previous phase of this project for 100% Syntroleum FT fuel showed fairly similar temperature levels. No combustion test anomalies or streaking were realized.

In summary, testing of the HRJ blend in the AE3007H full annular combustor did not reveal any adverse impact on the performance or the emissions compared to those for the baseline JP-8 fuel. The experimental data also demonstrated some possible benefits of using the HRJ blend, in particular for smoke, exit temperature profile, and liner wall temperatures. The HRJ blend, however, showed some increase in NOx emissions relative to those of the JP-8 at the higher end of the NOx levels measured in this study.

Figure 45. AE3007 Full Annular Combustor Rig[47]

4.5.5 Dielectric Constant/Fuel Tank Gauging

At the start of the SPK/HRJ laboratory evaluation, little was known or documented about measuring dielectric constant specifically for aviation fuel. The only group known at the time to be conducting this measurement was Goodrich Sensors and Integrated Systems, Inc. To help support the AFRL study, Goodrich agreed to loan SwRI one of their k-cells. SwRI invested in the necessary peripheral equipment and subsequently adopted a variation of the Goodrich procedure to determine dielectric constant vs. density and temperature. It was concluded that dielectric constant varies inversely as a function of temperature and shows distinguishable

[47] Reference 11

differences between fuel types. Relative to density, the differences between fuel types are shown to be minimal, but the variation across a range of densities was thought to still be significant.[48]

Hence, specific aircraft evaluation is still considered necessary since the fuel gauging system is expected to accurately measure and display fuel quantity for all synthetic fuels and blends. The fuel gauging system can also provide important center of gravity information to the aircraft for stability control. Goodrich Simmonds Precision Products, Inc. performed studies of the effects of alternative fuels and fuel blends on several military aircraft for the AFCO using specific aircraft configuration and geometry and the data generated by the AFRL/SwRI study. There were no HRJ fuels or blends that yielded results that were outside the requirements over the full aircraft operating temperature range.

4.6 Small Engine Demonstration

4.6.1 T63 Engine Testing[49]

A 150-hour endurance test was conducted on a T63 engine (Figure 46) at the Engine Environment Research Facility (EERF) in the Propulsion Directorate at Wright-Patterson Air Force Base. The evaluation consisted of measuring engine parameters (i.e. temperatures, fuel flows, power output, etc.) and particulate matter (PM) and gaseous emissions with the engine operating with a 50/50 blend of a tallow-derived HRJ and JP-8 at a pre-determined engine cycle. The cycle consisted of 15 minutes at idle, 60 minutes at cruise and then 15 minutes at idle. A total of 100 cycles were completed in a period of 24 test days. Engine flows and performance parameters were recorded throughout the tests, and emissions were measured at several intervals to assess any degradation as a function of engine run time and to compare with engine performance and emissions using conventional jet fuel. In addition, at the end of the test period the engine was removed from the stand, disassembled and the combustor and fuel nozzle were inspected and photographed. For the 150 hours endurance test with the 50/50 HRJ/JP-8 fuel, emissions measurements at 50, 100, and 150 hours of test operation, demonstrated adequate engine performance with no degradation (i.e. increase) in emissions as a function of run time.

[48] Reference 5
[49] Reference 9

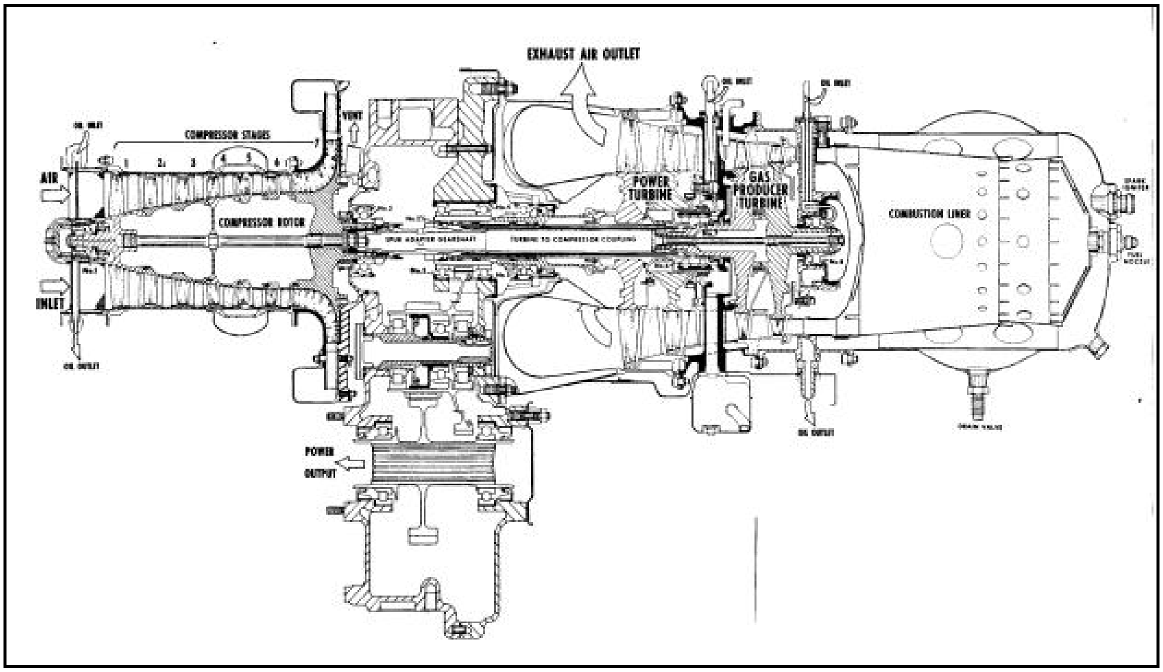


Figure 46. T63 A-700 Engine

As expected, the engine operated normally on the HRJ blend with no discernable differences in performance compared to operation on JP-8. Combustor and fuel nozzles displayed "very similar heating and sooting patterns compared to those for operation with JP-8 for 175 hours." Emissions and tear down analysis are underway. Reduced soot and sulfur oxide emissions were observed with the neat and blended fuels compared to operation on JP-8. Reductions in HAPS (except for formaldehyde and acetaldehyde) were observed for the alternative fuels and blends.

4.6.2 Diesel Engine

A performance and endurance evaluation of a modern high pressure common rail diesel fuel injection system when operated on a 50/50% volumetric blend of JP8 and HRJ fuel was accomplished by the SwRI. Testing was completed following a modified double-length version of the 210-hour Tactical Wheeled Vehicle Cycle engine endurance test cycle (CRC Report No.406, Development of Military Fuel/Lubricant/Engine Compatibility Test). Evaluations included performance and durability, fuel system hardware interactions, engine performance changes, and engine out emissions evaluations.

The Ford 6.7L high pressure common rail diesel engine was chosen for testing as a representative engine utilizing modern high pressure common rail fuel injection technology. The Ford 6.7L engine is a V8, direct injected, turbocharged, intercooled engine, which employs a fuel lubricated high pressure common rail injection pump and piezo-electric fuel injectors. The 6.7L engine used for testing was produced by Ford as an "export" version, intended for sale outside of U.S boarders or to military forces. The 6.7L export version engine is rated at approximately 320hp (238kW) at 2800rpm, and produces approximately 700 lb*ft (950 Nm) of torque at 1800rpm when using diesel fuel.

Figure 47 shows the 6.7L engine test installation. The test engine was purchased new directly from Ford Motor Company for testing, and all new fuel system hardware present on the engine was used for testing.

Figure 47. Ford 6.7 L Diesel Engine Test Installation

This testing is being reported separately. The testing conducted supports that the Ford 6.7L fuel lubricated high pressure common rail fuel injection system can be successfully operated using military specified fuels at normal ambient conditions, including a fuel blend of 50% JP-8/50%HRJ with 9-ppm of a QPL-25017 additive. Even at the minimum lubricity enhancing treat rates, the tested JP-8/HRJ synthetic fuel blend provided adequate component protection and system performance compared to previous fuels testing. No unusual fuel related operating conditions were experienced throughout testing, and engine performance remained consistent and satisfactory throughout. Post test fuel injection system inspection found used components to be in similar condition throughout all tests, for all fuels operated to date in a Ford 6.7L engine, despite the large differences in fuel lubricity from the baseline to synthetic fuel tests, and for the double duration JP-8/HRJ fuel test.

4.7 On-Aircraft Evaluation

4.7.1 C-17 Aircraft Emissions Characteristics[50]

Emissions evaluations were conducted on a C-17 Globemaster III F117-PW-100 engine operated with alternative fuels blends. The tests took place at Edwards Air Force Base on the period of 16-27 August 2010 as part of the United States Air Force (USAF) Alternative Fuels Certification Office (AFCO) ground and flight tests to certify the C-17 on a 50/50 by volume JP-8/HRJ fuel blend. Emissions were collected from engine #3 of the parked aircraft operated on conventional JP-8 and 50/50 blends of JP-8 and a beef tallow-derived HRJ, and a 50/25/25 blend of JP-8, HRJ and a coal-derived Fischer-Tropsch (FT) fuel. Gaseous and particulate matter (PM) emissions

[50] Reference 12

were measured. PM measurements included particle number (concentration), mass and size distribution. In addition, hazardous air pollutant (HAPs) emissions, smoke numbers and chemical analysis of soot samples were performed for the engine operated with the three fuels. Emissions were collected for five engine operating conditions ranging from 4% (idle) to ~63% of rated maximum thrust.

Emissions instrumentation was transported to the test site and housed during testing in the AFRL Fuels and Energy Branch Turbine Engine Research Transportable Emissions Laboratory (TERTEL), (Figure 48). The TERTEL is equipped with state-of-the-art instrumentation for the measurement and analysis of turbine engine gaseous and PM emissions.

Test results show that the alternative fuel blends resulted in no operational anomalies or detrimental impacts on the gaseous or PM emissions of the F117 engine for any of the conditions tested. Moderate reductions in carbon monoxide (CO) emissions (~30%) and more significant reductions in sulfur oxides (50%), measured HAPs (>60%) and PM emissions (30-60%) relative to operation with JP-8 were observed. The alternative fuels had negligible impact on nitrogen oxides (NOx) emissions. The relative reductions in particle concentrations and smoke were higher at lower power settings and results consistent with previous tests by the Air Force Research Laboratory (AFRL) on TF33, T701C, CFM56 and T63 engines. The lower aromatic content, and hence, lower carbon content in the fuel blend, is the primary cause for the resultant lower PM emissions.

Figure 48. TERTEL

4.8 Validation/Certification

4.8.1 Aircraft Performance (Range)

A spreadsheet based analytical model has been developed for AFRL to assess the impact of alternate fuels on aircraft mission range. This model is shown to be within 15 % of the results generated by simulation for 100 % of cases, within 10 *%* of the results generated by simulation for 85 % of cases, and within 5 % of the results generated by the simulation for 35 % of cases. The model can be applied to fighter/attack missions, strike missions with afterburner dash, and cargo/ferry missions. The primary model assumption is that the impact of fuel properties on range is due to changes in Volume Based Heating Value (BTU/Gal). The cargo mission with HRJ and HRJ blended fuels was modeled with the following results. The baseline fuel shown as zero impact in Figure 49 is the JP-8 PQIS average fuel value. The effect of the lower density from the PQIS average is evident. However all of the blended HRJ fuel mission impacts are less than for a minimum specification JP-8 fuel.

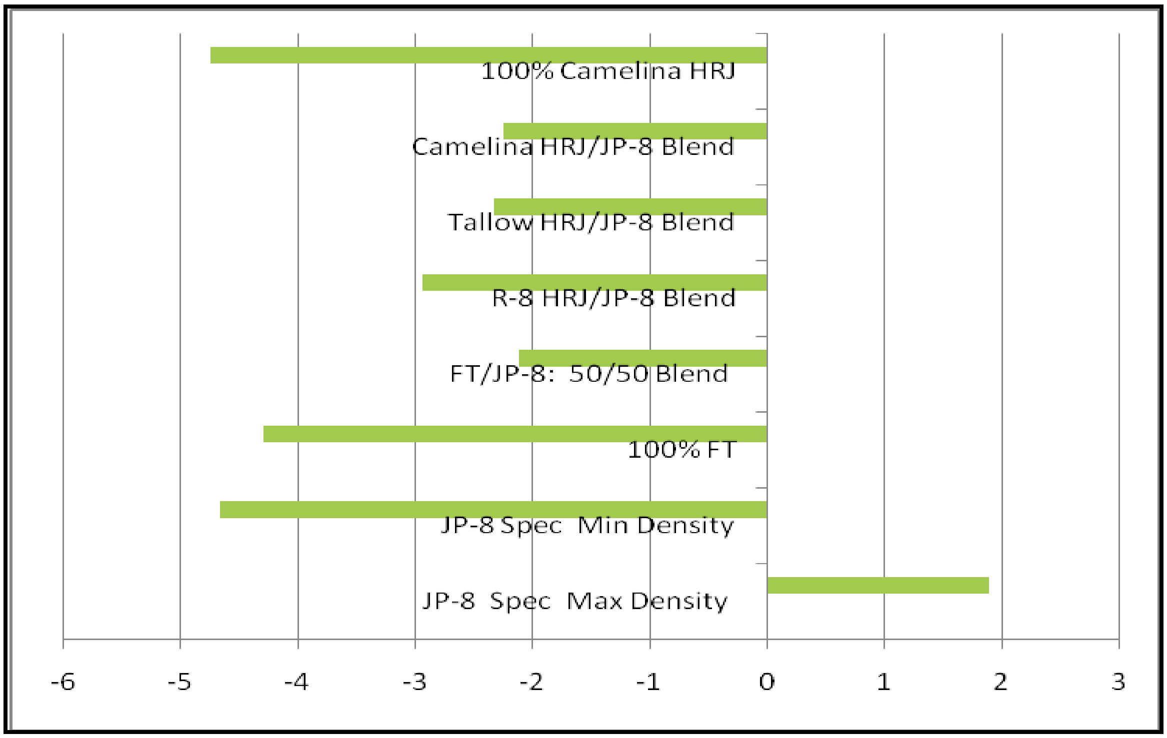


Figure 49. Cargo Aircraft Range Impact Assessments (%)

5.0 CONCLUSIONS AND RECOMMENDATIONS

The testing performed to date provides strong evidence that blends composed of up to 50% HRJ synthetic fuel and 50% petroleum-based fuel will be more than adequate as drop-in replacements for current petroleum-based fuels.

It is noted that each of the synthetic fuels evaluated in this study exhibit unique behaviors most likely related to characteristics imparted on the fuel by the various feedstocks. Additional research to determine why these characteristics are transferred to the fuel and not removed by the refining process could prove useful.

For most of the synthetic fuels studied in this effort, the overriding differences probably stem from the lack of aromatics. This would likely affect several properties such as material compatibility (elastomer swelling/shrinkage), tank gauging (density), and additive compatibility (solubility). These minor issues are resolved by blending strategy. It is also seen that unblended unadditized HRJ exhibits very high lubricity causing concern for wear of component moving parts.

Second, some additive separation (FSII and part of the additive cocktail) was initially seen when added to R-8HRJ/Jet A at the 4X treat rate. A subsequent re-blending of the sample showed no separation. This may be attributable to insufficient blending and demonstrates the need to blend thoroughly. The electrical conductivity of the R-8 HRJ also varied considerably with SDA treatment. Splash blending should certainly be avoided.

The neat camelina fuel did exhibit some unusual properties relative to the other fuels. The predominant differences were its low density, low viscosity, low boiling point distribution, and high vapor pressure. However, as a Camelina/JP-8 blend, these characteristics disappeared.

The most unusual characteristic of the Tallow/JP-8 blend was its affinity for water especially at high temperature. This was verified several times. In addition, similar to the R-8 / Jet A, the Tallow / JP-8 showed signs of additive separation when tested at the 4X treat rate. Like the R-8 blend, the FSII and the additive cocktail seemed to have the most problems staying in solution. A re-blend of this sample showed no improvement. Further investigation is likely necessary.

The fit-for-purpose testing identified several shortcomings in the methods currently suggested. The problems include undocumented procedures, non-standard practices, impractical procedures, and limited availability of laboratories to perform the procedures. Further development and improvement of test methodologies is suggested.

6.0 REFERENCES

1. Moses, C., “Comparative Evaluation of Semi-Synthetic Jet Fuels,” final report for CRC Project No. AV-2-04a, September 2008; Moses, C., “Comparative Evaluation of Semi-Synthetic Jet Fuels - Addendum: Further Analysis of Hydrocarbons and Trace Materials to Support Dxxxx,” final report for CRC Project No. AV-2-04a, April 2009. (DXXXX later became D7566)

2. Kinder, J. et al., “Evaluation of Bio-Derived Synthetic Paraffinic Kerosenes (Bio-SPKs),” ASTM Research Report published May 2010. Addendum published October 2010.

3. Klein, J. K., “Production Demonstration and Laboratory Evaluation of R-8 and R-8X Hydrotreated Renewable Jet (HRJ) Fuel,” AFRL-RZ-WP-TR-2011-2020, May 2010.

4. Hadaller, O. J., Johnson, J. M., “World Fuel Sampling Program,” Coordinating Research Council Report No. 647, June 2006.

5. Bessee, G., et al., “Analysis of Synthetic Aviation Fuels,” Final Report on SwRI Project No. 08-14406, AFRL-RZ-WP-TR-2011-2084, April 2011.

6. Klein, J. K., et al., “Technical Memorandum: Comparison of pre-production R-8 HRJ fuel to production R-8 HRJ fuel”, May 2011, including Attachment 1, Dynamic Fuels LLC final report, December 2010. Limited document, but no limited information from this reference has been included in this report.

7. Bessee, G., et al., “Advanced Propulsion Fuels Research and Development” Progress Report for SwRI Project No. 08.16246, April 2011.

8. Corporan, E., et al., “Hydroprocessed Renewable Jet Fuel Evaluation, Performance, and Emissions in a T63 Turbine Engine”, Proceedings of ASME Turbo Expo 2011, GT2011-46572, June 2011.

9. Corporan, E., et al., “Chemical, Thermal Stability, Seal Swell, and Emissions Studies of Alternative Jet Fuels”, Energy & Fuels, January, 2011.

10. Nader Rizk, Rolls-Royce, Indianapolis, IN, “Alternate Fuel Development for Aviation Engines”, 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 25 - 28 July 2010.

11. Nader Rizk, Robert Moritz, Alan Blackwell, Rolls-Royce, Indianapolis, IN, “Combustion and Material Compatibility Tests of Syntroleum Fischer-Tropsch Iso-Paraffinic Kerosene, Alternative Energy Now Conference, February 20-21, 2008.

12. Corporan, E., et al., “Alternative Fuels Tests On a C-17 Aircraft: Emissions Characteristics”, AFRL-RZ-WP-TR-2011-2004, December 2010.

13. Rahmes, T., et al., “Sustainable Bio-Derived Synthetic Paraffinic Kerosene (Bio-SPK) Jet Fuel Flights and Engine Tests Program Results”, AIAA 2009-7002, AIAA Aviation Technology, Integration and Operations (ATIO), 21-23 September 2009.

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

Acronym	**Description**
AFCO	Air Force Certification Office
AFPET	Air Force Petroleum Office
AFRL	Air Force Research Laboratory
ANZ	Air New Zealand
AIT	Auto-ignition Temperature
AO	Antioxidant Additive
ARSFSS	Advanced Reduced Scale Fuel System Simulator
ASTM	American Society of Testing and Materials
BOCLE	ball-on-cylinder lubricity evaluator
BQL	Beyond quantitation limit
BTU	British thermal unit
BFA	Burner Feed Arm
C°	Celsius
CI/LI	Corrosion Inhibitor/Lubricity Improver
CAL	Continental Airlines
cSt	centistokes
CU	Conductivity Units
DARPA	Defense Advanced Research Projects Agency
DiEGME	DiEthylene Glycol Monomethyl Ether
DOD	Department of Defense
DTIC	Defense Technical Information Center
EAR	Export Administration Regulation
EI	Emissions Indice
FCOC	Fuel Cooled Oil Cooler
FDV	Flow Divider Valve
FFP	Fit for Purpose
FOG	Fats, Oils, and Greases
FSII	Fuel System Icing Inhibitor
FT	Fischer-Tropsch
GC	Gas Chromatograph
GTL	Gas to Liquid
HAPs	Hazardous Air Pollutants
HEFA	Hydroprocessed Esters and Fatty Acids
HFRR	High Frequency Reciprocating Rig

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS *(Cont'd)*

Acronym	**Description**
HRJ	Hydro processed Renewable Jet fuel
Hz	Hertz (international unit of frequency)
IPK	Iso-paraffinic kerosene
IQT	Ignition Quality Test
ITAR	International Traffic in Arms Regulation
JAL	Japan Airlines
JFTOT	Jet Fuel Thermal Oxidation Tester
Kg	Kilogram
LBO	Lean Blow Out
MIE	Minimum Ignition Energy
mg	Milligram
MSDS	Material Safety Data Sheet
NEPA	National Eire Protection Association
NIST	National Institute of Science and Technology
OEM	Original Equipment Manufacturer (jet engines)
POSF	Fuels Designator
PQIS	Petroleum Quality Information System
PPB	Part per billion
PPM	Part per million
QCM	Quartz Crystal Microbalance
RR-LW	Rolls-Royce Liberty Works
RZ	Propulsion Directorate
RZP	Energy, Power, and Thermal Division
RZPF	Fuels and Energy Branch
R8, R-8x	Designation for Syntroleum HRJ fuels
SAE	Society of Automotive Engineers
SDA	Static Dissipater Additive
SLBOCLE	Scuffing Load BOCLE
SPK	Synthesized Paraffinic Kerosene
S-8	Designation for Syntroleum SPK fuel
SwRI	Southwest Research Institute
TERTEL	Turbine Engine Research Emissions Transportable Emissions Laboratory
TWA WRE	Time-weighted average water removal efficiency

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS *(Cont'd)*

Acronym	Description
TRL	Technology Readiness Level
UDRI	University of Dayton Research Institute
UOP	Limited Liability Company, formerly Universal Oil Products
USAF	United State Air Force
UTC	Universal Technology Corporation
WPAFB	Wright-Patterson Air Force Base