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WORLD FUEL SAMPLING PROGRAM

June 2006

COORDINATING RESEARCH COUNCIL, INC.
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ERRATA (Jan. 2007)

CRC Report 647, World Fuel Sampling Program – Errata

Paragraph 6.3, Surface Tension, Figure 6.3.2, Surface Tension Values of Surveyed Fuels and CRC Data, and Figure 6.3.3, Surface Tension of Fuels and Blends. On the Ordinate (Y) axis, delete "x 10^4" that follows "mN/m".

Appendix B, Fuel Sample Property Data, and column heading on page 93, add "mN/m" after "Surface Tension".

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CRC Aviation Fuel, Lubricant & Equipment Research Committee
of the
Coordinating Research Council, Inc

World Fuel Sampling Program

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JUNE 2006

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1. Introduction

This document contains the data from a fuel-sampling and testing program conducted jointly by Boeing, Goodrich, General Electric, ChevronTexaco, and the United States Air Force. The program goal was to characterize jet fuels and assemble a “snap-shot” database of aviation fuel properties. Fifty-seven jet fuel samples were obtained from 18 countries. The fuels were tested for the properties identified in References [1] to [4] and listed in Table 1.1.

Boeing

- Fuel Appearance
- Density
- Distillation
- Flash Point
- Freezing Point
- Pour Point
- Sulfur Content
- Olefin Content (Bromine Index)
- Hydrogen Content
- Net Heat Content
- Kinematic Viscosity
- Refractive Index
- Electrical Conductivity

ChevronTexaco

- Aromatic Content (mono and di-aromatics)
- Naphthalenes
- Saturates
- Olefin Content (FIAM)
- Simulated Distillation

General Electric

- Thermal Stability
- Specific Heat Capacity
- Acid Number
- Surface Tension

Goodrich

- Density vs. Temperature
- Dielectric vs. Temperature
- Speed of Sound vs. Temperature

Air Force (Mukilteo, WA)

- Lubricity (BOCLE)

Naval Research Labs

- Lubricity
- pH of Water Extraction

Air Force Research Labs, AFRL (WPAFB)

- Hydrocarbon Compound Identification by Mass Spectrometry
- Sulfur Species Separation
- ICP
- HPLC Polar Species Analysis
- Mercaptan Sulfur

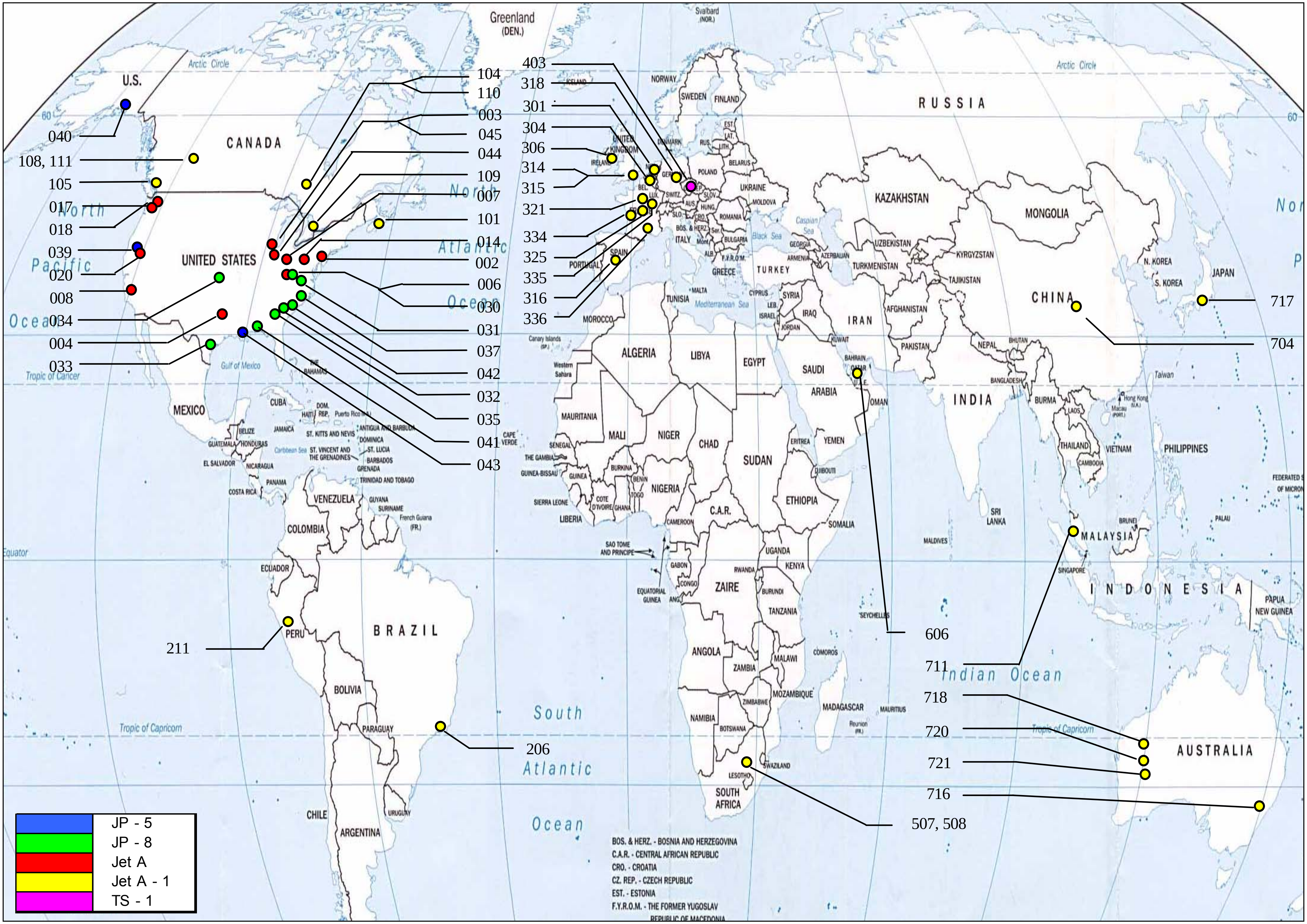
Table 1.1. Fuel Property Tests and Program Participants

2. Sampling

Jet fuel samples were collected from around the world and included Jet A, Jet A-1, JP-5, and JP-8 jet fuels, Figure 2.1. A diversity of samples was sought. Included in the survey were jet fuels made from coal by Sasol in South Africa, from oil shale in Australia, and from oil sands in Canada. There were only two JP-5 samples; therefore, the reader is cautioned about making any correlations of JP-5 properties to other fuel types. This caution should also be applied to any regional correlations as some regions have few fuel samples (The Middle East, Africa, and the Former Soviet Union for example). Sample fuel type was assigned based on the label that accompanied the fuels during shipping. No assessment was made as to the validity of these labels. The exception to this was a fuel that arrived marked as TS-1. However, based on measured property data, it was decided that the fuel should be treated (and relabeled) as Jet A-1.

Some of the samples collected were not delivered jet fuel. There were samples of a Stoddard solvent, a 100% synthetic fuel (Sasol), and a fuel that had failed the jet fuel thermal oxidation tester (JFTOT). None of these materials was actually delivered or used in an aircraft. In addition, there were fuels, including three samples of oil shale (Australian), where it is not known whether they were delivered and used as jet fuel. Some of the fuels originated from pilot plants that have since been shut down. There is no reason to believe these fuels would not be ‘fit for purpose’ and the data are included in the database and in all conclusions and supporting calculations.

Fuel samples, per HAZMAT shipping requirements, had to be packaged and shipped by properly trained and certified individuals. The fuel was loaded into 5-gal, epoxy-lined metal cans at the specific geographical locations. The exact sample point at that location was not identified; therefore, statements regarding any effect the sampling point had on fuel properties cannot be made. However, any effect is probably minor. Once filled, the cans were packaged in sealed plastic bags, boxed, and shipped to Goodrich. From there, the samples were repackaged and distributed to all parties in 1-gal, epoxy-lined cans. Some 5-gal cans were not full, making it impossible to conduct all tests on these samples.



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507, 508
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JP - 5
JP - 8
Jet A
Jet A - 1
TS - 1

Figure 2.1. Location of Fuel Samples

3. Fuel Sample Properties—Boeing

The fuel properties reported in this section were measured in the Boeing Fuel Laboratory in Renton, Washington, except as noted. The laboratory has the capability of performing most ASTM D 1655 tests and routinely participates in the ASTM inter-laboratory crosscheck program. Although not determined, the reproducibility and repeatability of the test methods are expected to be within the limits stated in the ASTM test methods. The data obtained during testing are summarized here to show the range in property values and to highlight any anomalies. Many of the following sections briefly discuss the test method used in obtaining the data. A detailed description of the test methods used can be found in Appendix A. A complete table of fuel sample property data is provided in Appendix B.

3.1 Density

Jet fuel density can have a significant effect on aircraft performance and range. Severe hydrotreating is thought to decrease fuel density by increasing the hydrogen content in the fuel. Hydrogen-rich petroleum fuels have higher heat content per unit mass, but have lower heat content per unit volume. The net effect can cause long-range aircraft to become volume limited, which decreases their payload / range capability.

3.1.1 Density Test Results

Specification ranges for jet fuel density, taken at 60°F, are shown in Table 3.1.1. The density of the fuel samples by region and fuel type are shown in Figure 3.1.1. The density of the North American fuel samples, especially the California sample (0.825 g/cm^3), is relatively high, while the South African synthetic, Middle East and Asian fuel samples had a relatively low density when compared to those of the rest of the world. The average density of all samples tested was 0.803 g/cm^3 (6.70 lb/gal) (to convert grams per cubic centimeter into pounds per gallon, multiply by 8.3454).

Fuel	Value (g/cm^3 at 60°F)	Specification
Jet A	0.775 to 0.840	ASTM D 1655 [1]
Jet A-1	0.775 to 0.840	Def Stan 91-91 [2]
JP-5	0.788 to 0.845	MIL-DTL-5624U [3]
JP-8	0.775 to 0.840	MIL-DTL-83133E [4]

Table 3.1.1. Density Specifications

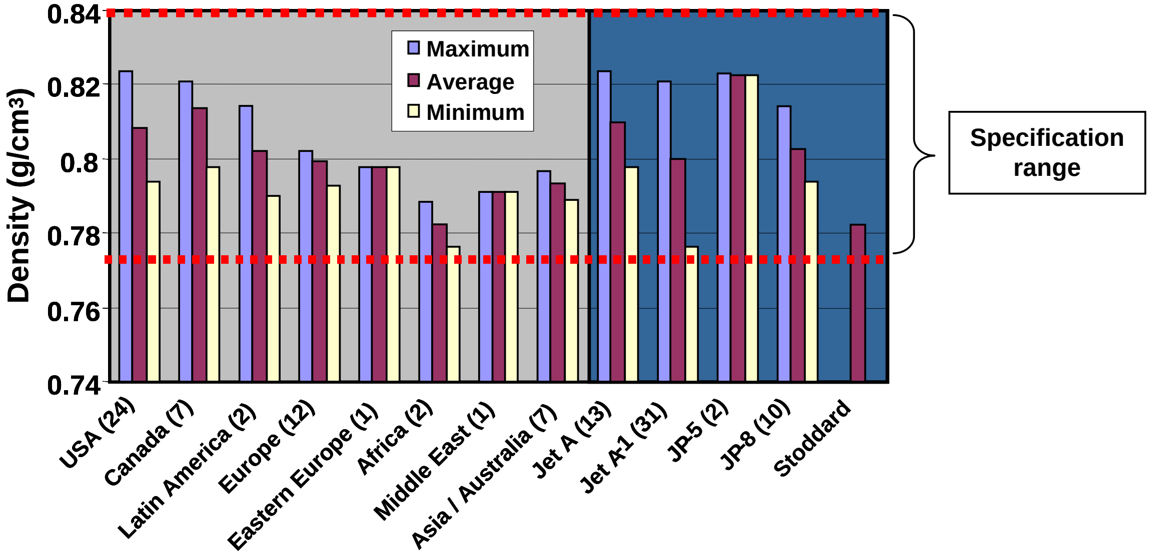

FIGURE 3.1.1. DENSITY DISTRIBUTION OF WORLD FUEL SAMPLES

3.2 Sulfur Content

Several issues, including concern for the environment, have brought much attention to the subject of the sulfur content in all fuels. New on-road diesel legislation in the United States, slated to come into effect in mid-2006, will restrict sulfur levels in diesel to 15 ppm (called ultra-low sulfur diesel or ULSD) [5]. Similar off-road diesel legislation is being negotiated, and this new legislation may also require 15-ppm fuel in the 2006 to 2010 timeframe. Similar legislation will restrict the sulfur content in U.S. gasoline beginning in 2004 and gradually lower it to a 30-ppm requirement in 2006 [6]. The European Union has also enacted legislation that will require a 50 ppm sulfur level in diesel and gasoline by 2005, and there is discussion to further restrict sulfur levels to ~10 ppm [7].

Currently, the effect of aircraft sulfur emissions on atmospheric chemistry is not fully understood. Issues such as sulfur's role in particulate emissions and contrail formation are being investigated, and additional testing is planned.

Current specifications generally restrict sulfur levels in jet fuel to a maximum of 3,000 ppm (see Table 3.2.1). Some countries, such as Russia, China, and Sweden, have lower limits on permitted sulfur content.

Fuel	Value (ppm)	Specification
Jet A	3,000 maximum	ASTM D 1655
Jet A-1	3,000 maximum	Def Stan 91-91
JP-5	3,000 maximum	MIL-DTL-5624U
JP-8	3,000 maximum	MIL-DTL-83133E

Table 3.2.1. Sulfur Specifications

In addition to sulfur's role in atmospheric chemistry, sulfur and sulfur compounds can be corrosive to fuel system components and can affect fuel properties and performance [8]. Sulfur is also known to poison fuel cells and fuel cell reformers and may limit or delay the introduction of fuel cells to aviation.

3.2.1 Sulfur Content Test Results

The level of sulfur in the fuel samples was determined by ASTM D 2622 and ranged from 0.7 to 2,500 ppm, Figure 3.2.1. No sample had a sulfur content that exceeded the specification limit. The average of all samples was 460 ppm, a factor of nearly 10 below the allowed maximum. Ninety-six percent of fuel samples had a sulfur content under 2000 ppm, 90% had a sulfur content under 1,000 ppm, and nearly half of the samples had a sulfur content less than 300 ppm, Figure 3.2.2.

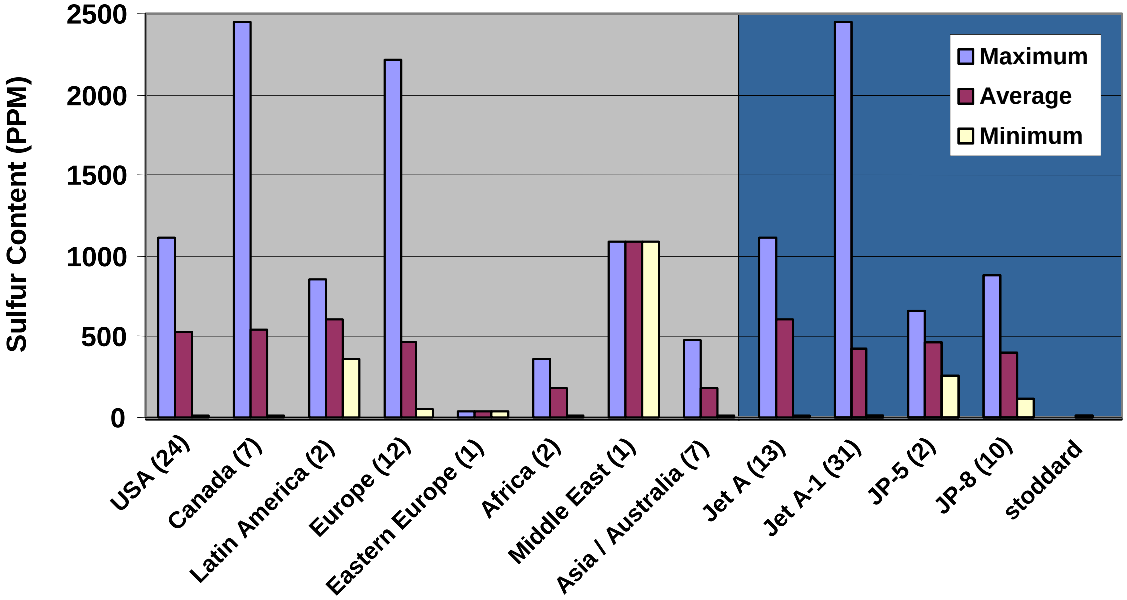

FIGURE 3.2.1. SULFUR CONTENT DISTRIBUTION

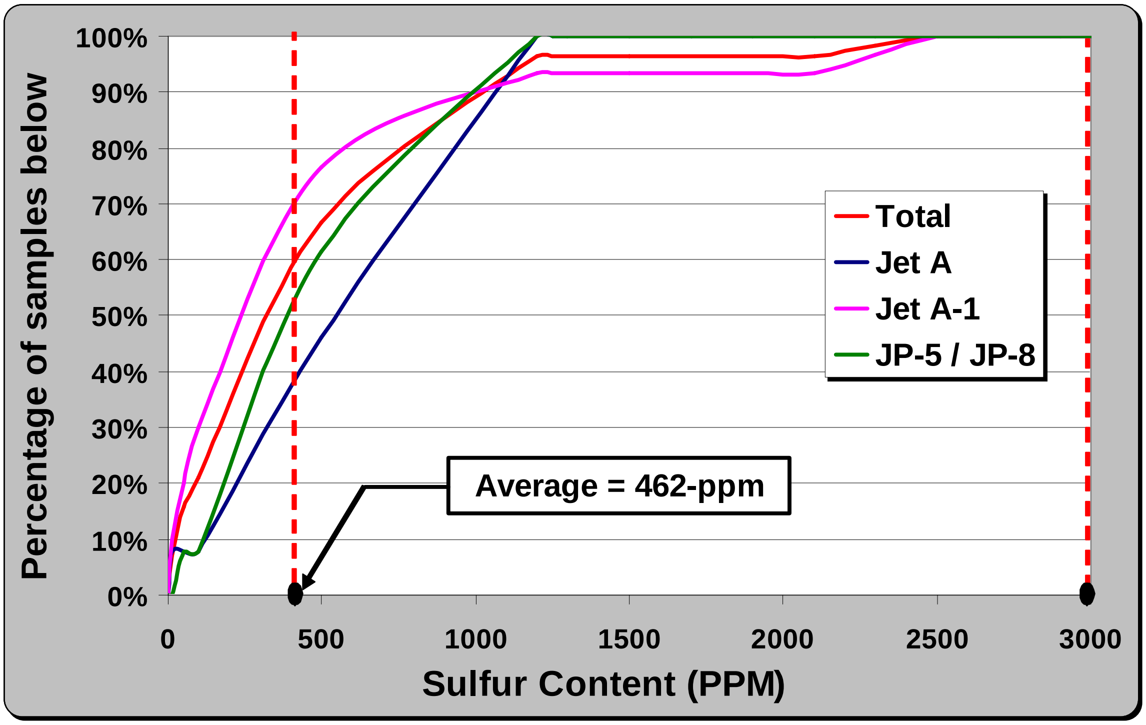

FIGURE 3.2.2. SULFUR CONTENT OF SAMPLED JET FUEL

3.2.2 Sulfur Content Versus Fuel Lubricity and Thermal Stability Test Results

Results obtained from fuel testing indicate that fuel sulfur levels do not have a significant influence on other fuel properties. When wear scar diameters (lubricity) and breakpoint temperatures (thermal stability) were compared to the sulfur level in the fuels, there was no overall trend observed in the data, Figures 3.2.3 and 3.2.4. It does appear that as sulfur levels reach extremely low levels (less than ~50 ppm), the wear scar diameter starts to increase. Among the fuels with the poorest lubricity (largest wear scar), three out of the four had a sulfur level below 131 ppm. Test data showed that sulfur content did not correlate to hydrogen content (see Section 3.6). Likewise, data did not show a reduction in aromatic level as sulfur levels declined, Figure 3.2.5. The recent introduction of new, more selective, catalysts may allow the removal of sulfur atoms without breaking molecular bonds or saturating molecules with hydrogen.

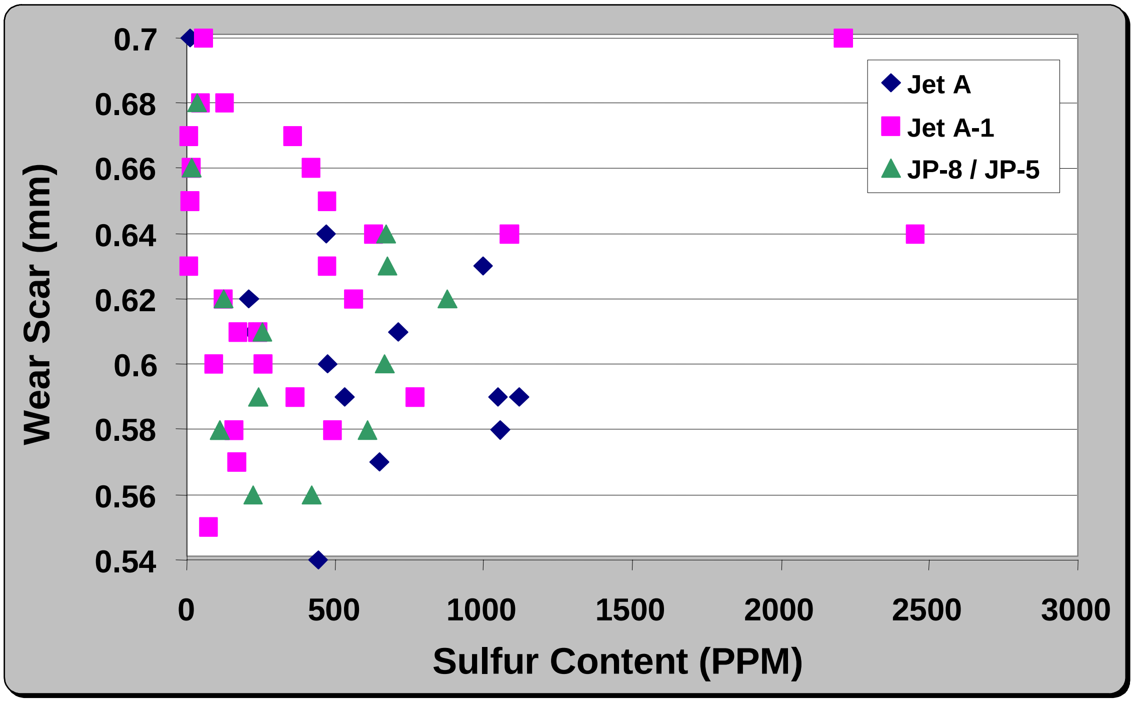

FIGURE 3.2.3. LUBRICITY (WEAR SCAR) AS A FUNCTION OF FUEL SULFUR CONTENT

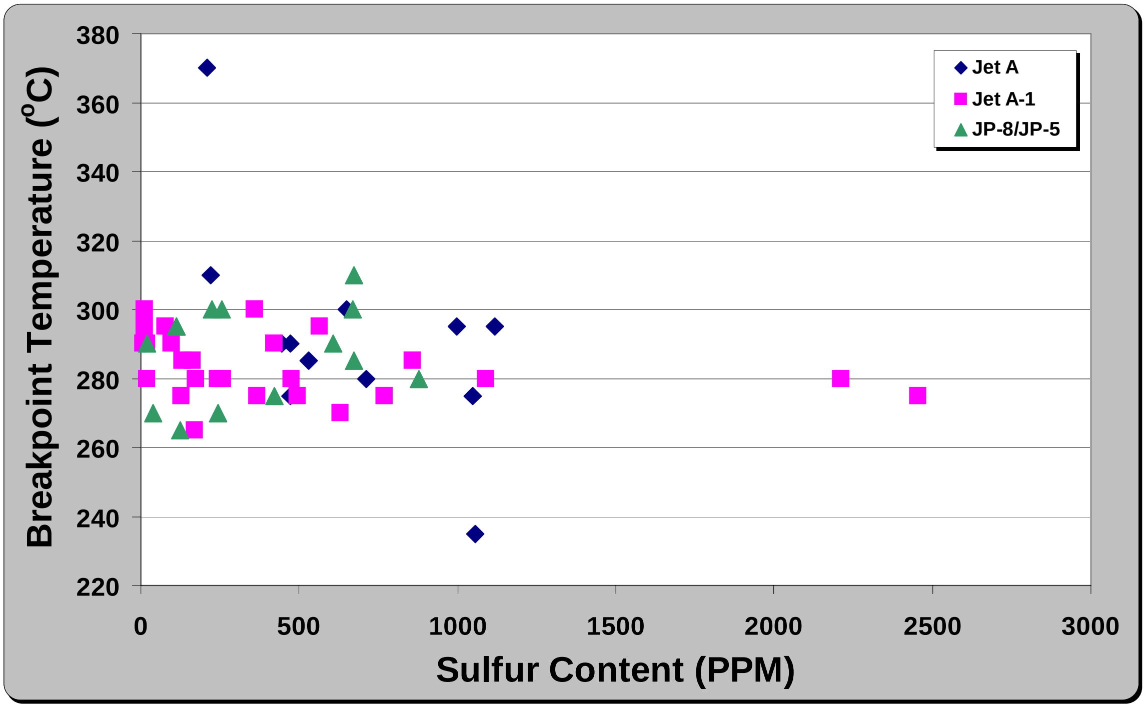

FIGURE 3.2.4. THERMAL STABILITY VERSUS SULFUR CONTENT

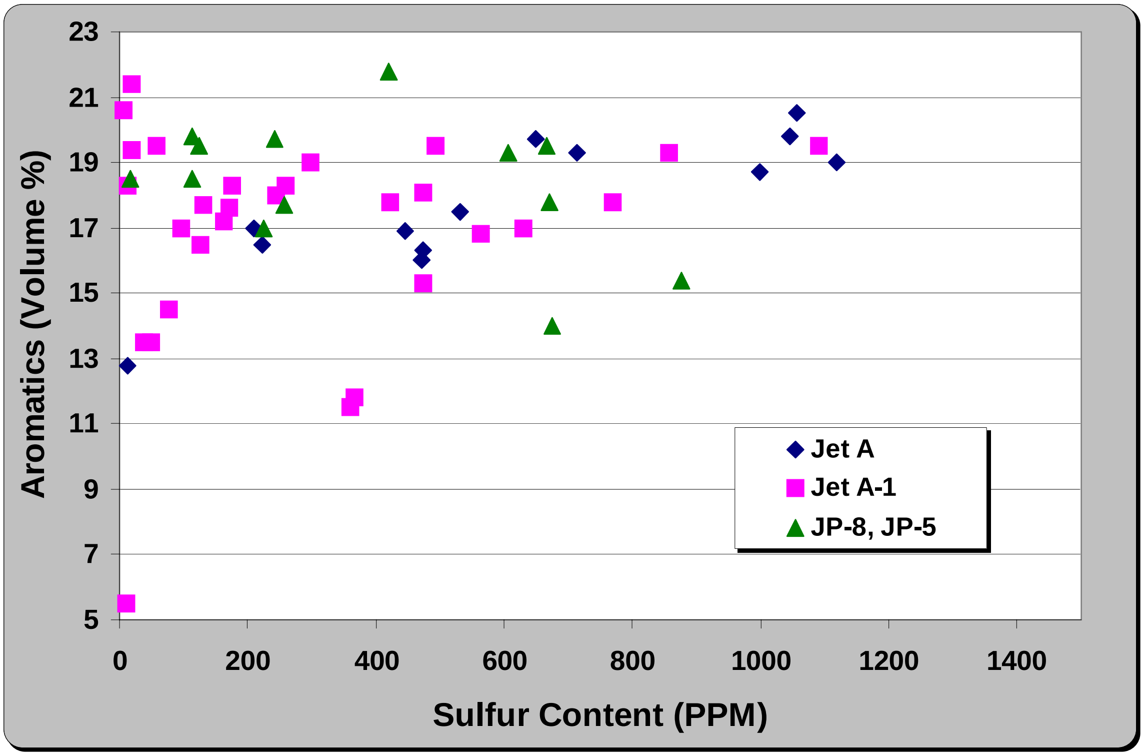

FIGURE 3.2.5. AROMATIC CONTENT VERSUS SULFUR CONTENT

3.3 *Freezing Point Temperature*

The temperature at which jet fuel begins to form waxy particles is crucial in determining aircraft operability at low temperatures. Polar route flights are becoming increasingly more popular as they can provide time and economic advantages to airlines [9]. As a result, more attention is being paid to the freezing point of jet fuel and the behavior of jet fuel at very low temperatures.

Table 3.3.1 lists the specified maximum freezing points for jet fuels. The test procedure calls for the freezing point temperature to be measured as the last wax crystal melts. That is, the fuel is initially cooled below the point where wax crystals form. Samples are then allowed to warm, at a prescribed rate, to the point where the last wax crystal melts. The temperature at which this last crystal melts and the fuel is in an entirely liquid state is referred to as the freezing point temperature of the fuel. See Appendix A for a more detailed description of this test method.

Fuel	Value (°C)	Specification
Jet A	– 40 maximum	ASTM D 1655
Jet A-1	– 47 maximum	Def Stan 91-91
JP-5	– 46 maximum	MIL-DTL-5624U
JP-8	– 47 maximum	MIL-DTL-83133E

Table 3.3.1. Freezing Point Temperature Specifications

3.3.1 *Freezing Point Test Results*

The distribution of sample freezing point temperatures by region and fuel type is shown in Figure 3.3.1. Unexpected was the lower than anticipated average freezing point temperature of the Jet A fuel samples. This indicates that other refining considerations are driving Jet A fuel freezing point and not the specification maximum.

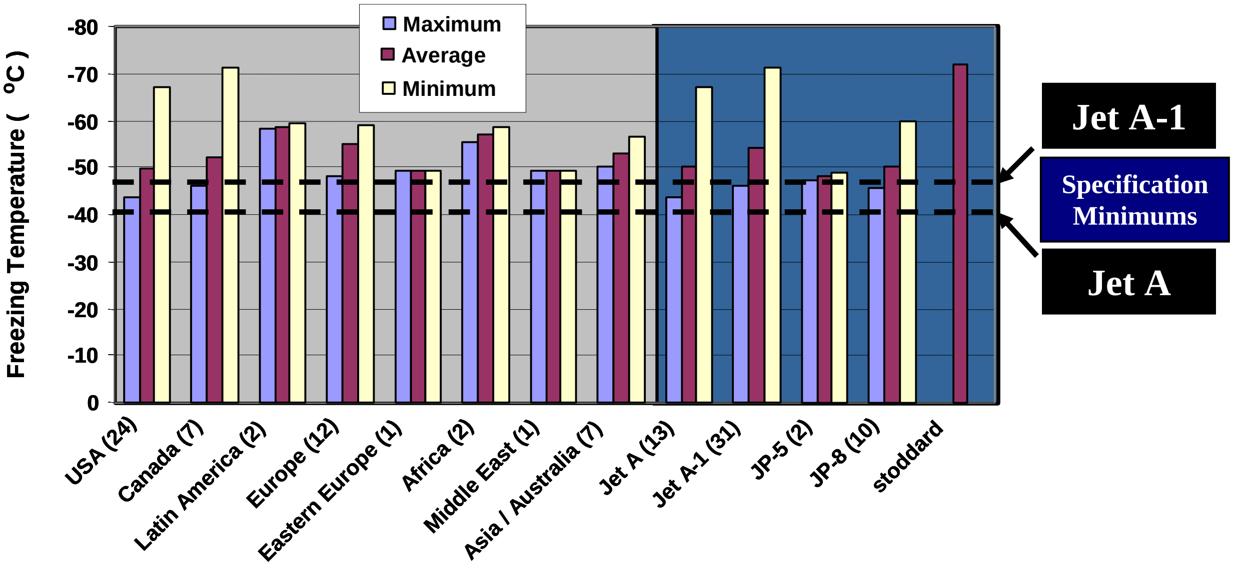

FIGURE 3.3.1. FREEZING POINT TEMPERATURE DISTRIBUTION

3.4 *Pour Point Temperature*

As temperatures drop below the temperature at which wax crystals begin to form (freezing point), the fuel will eventually set up into a solid waxy form. This is referred to as the “pour point” of the fuel. When the fuel temperature drops below the pour point temperature, fuel ceases to flow to pump inlets. Pour point is defined in ASTM D 5949 as “the lowest temperature at which movement of the (fuel) specimen is observed under the prescribed conditions of the test.” For the fuel samples, the pour point was below the freeze point by some 4°C to 26+°C.

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3.4.1 *Pour Point Test Results*

Figure 3.4.1 shows the maximum (warmest) pour point temperature of the samples as a function of location and fuel type. Apparatus used for pour point testing had a low temperature limit of –70°C, and many of the samples had pour point temperatures below –70°C. These are shown as a jagged line at –70°C on the chart. In Figure 3.4.2, the percentage distribution, of pour point temperatures is shown. The warmest pour point was –60°C. The coldest pour point could not be determined because of the limitation of the test apparatus.

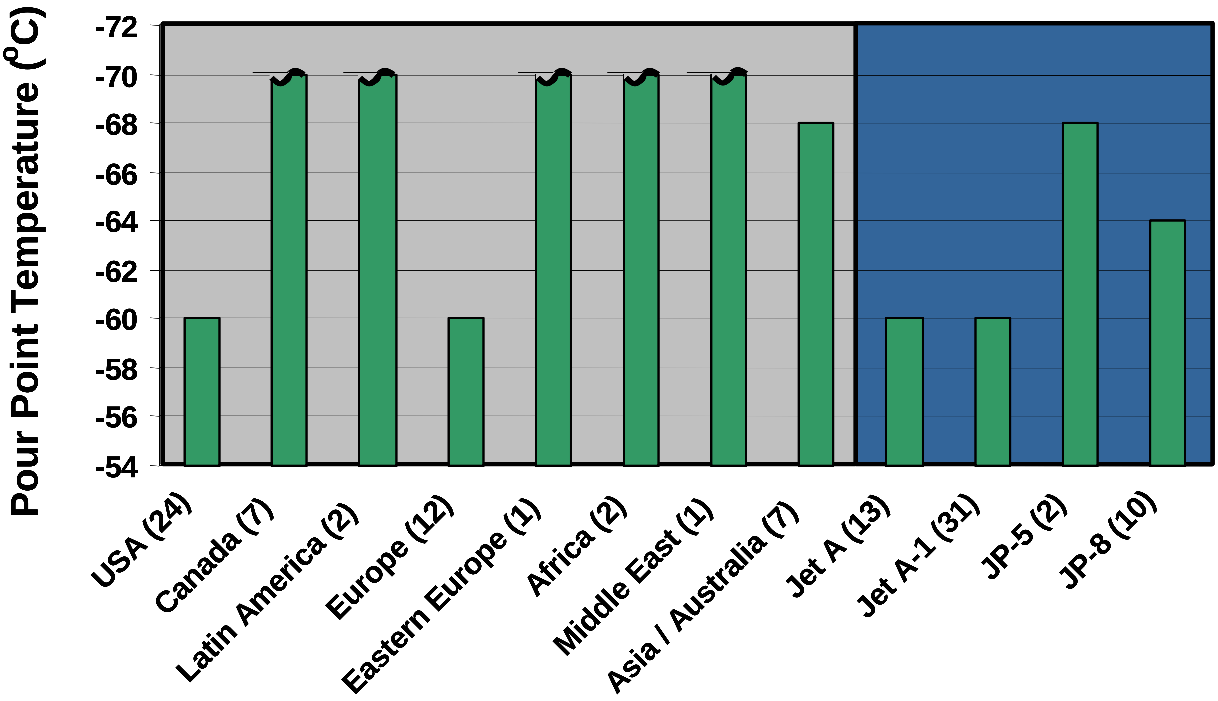

FIGURE 3.4.1. POUR POINT DISTRIBUTION (MAXIMUM POUR POINTS FOR EACH CATEGORY)

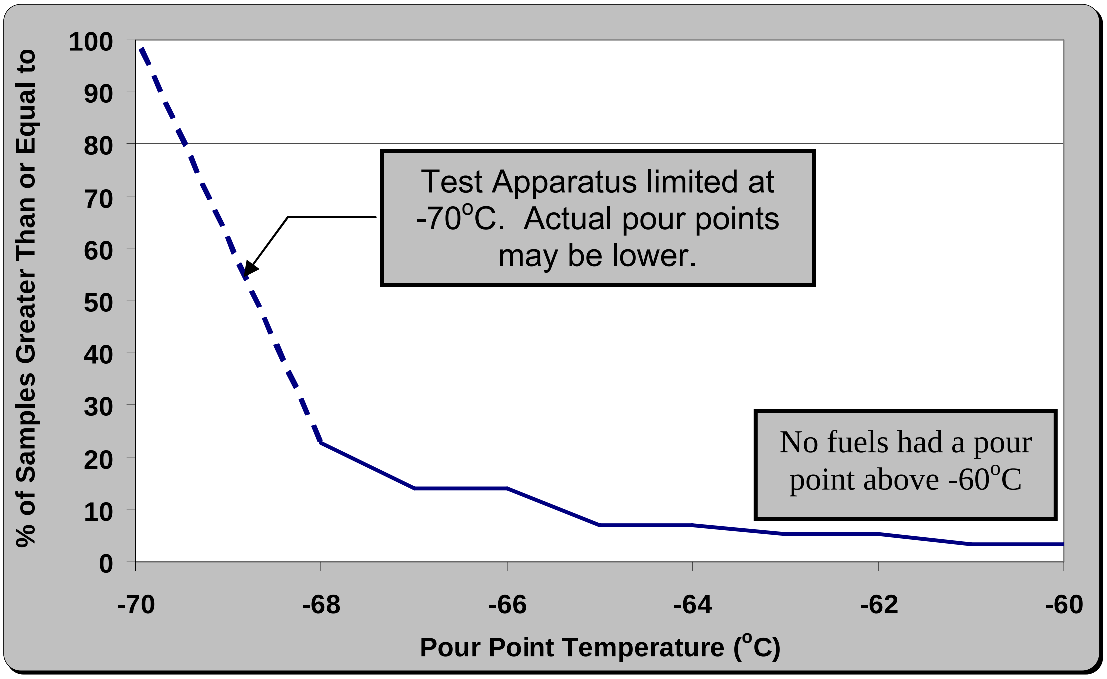

FIGURE 3.4.2. POUR POINT OF FUEL SAMPLES

3.5 Olefin Content

Olefins are hydrocarbons that contain one or more carbon-carbon double bonds. As such, these molecules have lower hydrogen content and can react to form polymers. Because of the higher reactivity of olefins and their tendency to form polymers, they typically exhibit poor storage stability. Although jet fuel contains only small amounts of olefin molecules, they can play a significant role in fuel chemistry, Figure 3.5.1.

Two different test methods were used during the sampling program to determine olefin content. Boeing used ASTM method D 2710, "Bromine Index of Petroleum Hydrocarbons by Electrometric Titration," and ChevronTexaco used method ASTM D 1319, "Standard Test Method for Hydrocarbon Types in Liquid Petroleum Products by Fluorescent Indicator Adsorption." See Appendix A for further discussion of these test methods.

Comparison of the two methods showed that the fluorescent indicator adsorption (FIA) method (ASTM D 1319) typically produced higher olefin contents. The delta difference between the test results for the two methods was not consistent over the entire sample set. The lower olefin content fuels showed the poorest correlation. Data for the two methods are shown in Figure 3.5.1.

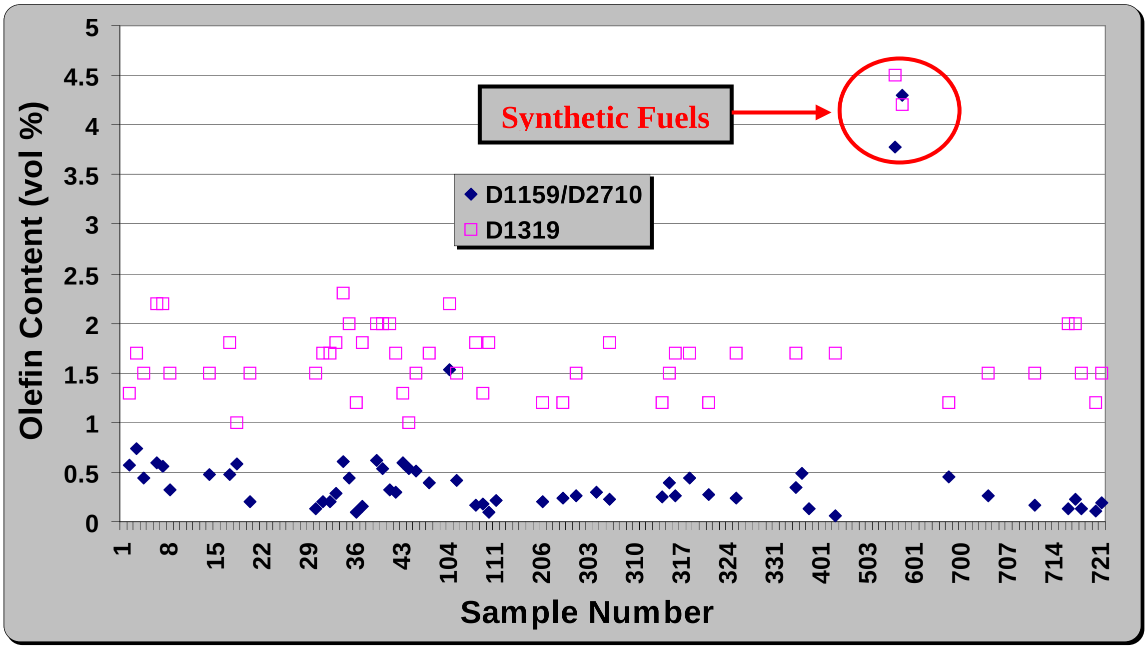

FIGURE 3.5.1. COMPARISON OF ASTM D 1159/D 2710 WITH ASTM D 1319

3.5.1 Olefin Content Test Results

The olefin content in fuels with synthetic components was significantly higher than that of conventional crude oil sources. The fuels with synthetic components had olefin content above 3.5%, Figures 3.5.2 and 3.5.3. The average olefin content was 0.35 vol% by ASTM method D 2710, excluding the two synthetic fuel samples, and the average olefin content by D 1319 was 1.67 vol%. Due to uncertainty related to the test method, low levels of olefin content carry a degree of uncertainty (see Appendix A).

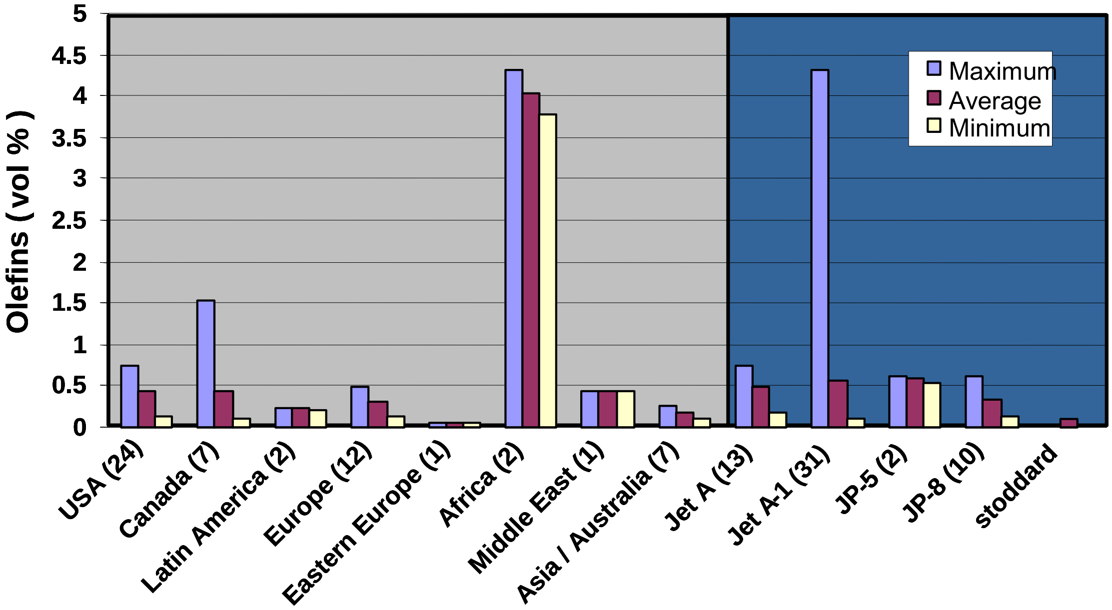

FIGURE 3.5.2. OLEFIN CONTENT DISTRIBUTION (ASTM D 1159/D 2710)

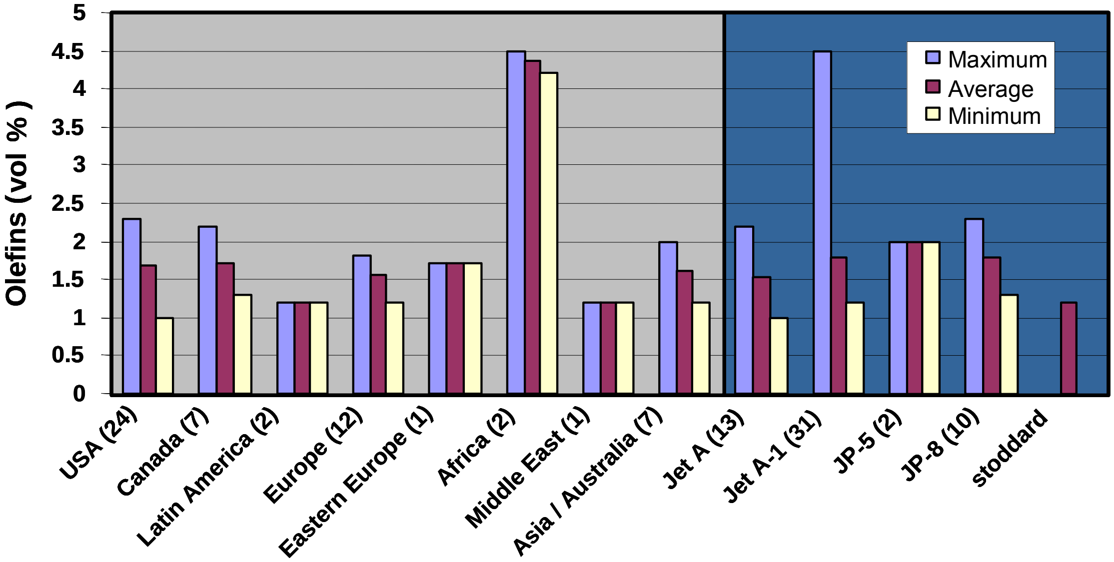

FIGURE 3.5.3. OLEFIN CONTENT DISTRIBUTION (ASTM D 1319)

Previous research has indicated that olefins, although thought to be clean burning, are considered to be a precursor to deposit formation and may contribute to the formation of gums and polymers that lead to low stability jet fuel [8, 10]. This study was not able to support those claims, as breakpoint temperature was not a function of olefin content (see Figure 3.5.4) for the samples tested. Olefins are also considered to be a long-term storage stability issue; however, no testing for storage stability was conducted on the fuel sample set.

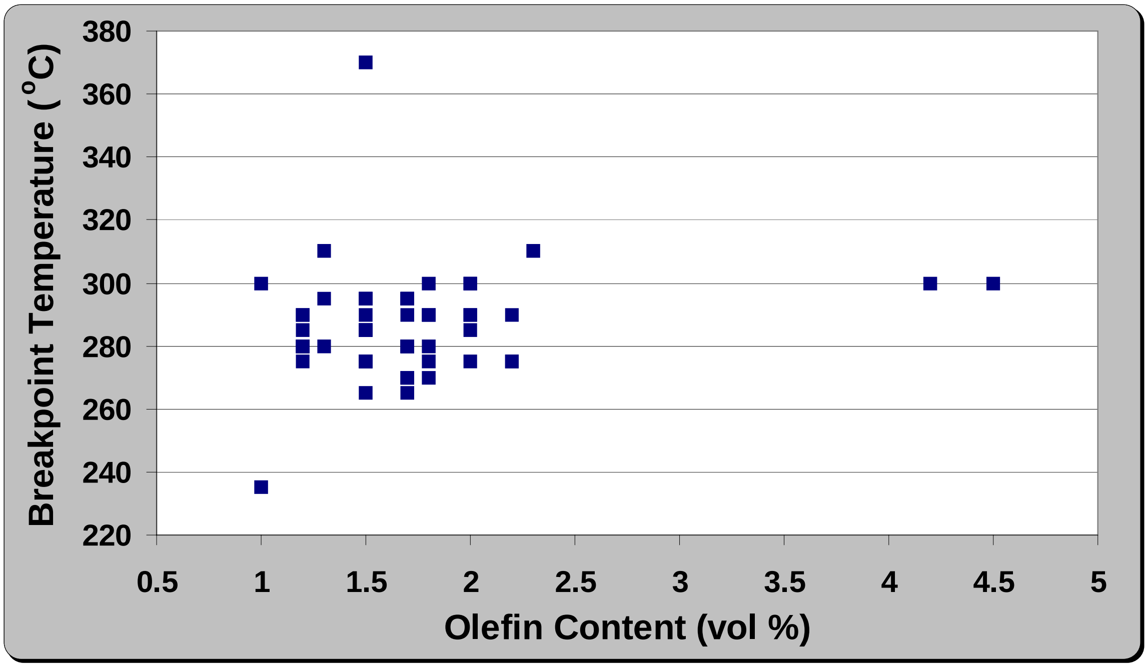

FIGURE 3.5.4. OLEFIN CONTENT VERSUS BREAKPOINT TEMPERATURE

3.6 *Hydrogen Content*

How cleanly a fuel burns and the amount of heat released are functions of hydrogen content. Higher hydrogen content fuels will burn cleaner and produce more energy per unit of fuel weight. The disadvantage of high hydrogen content fuels is the relatively lower heat content per unit volume. As a result, long-range aircraft can be fuel-volume limited rather than weight limited. That is, a fuel that has low heat content per unit volume can reduce the range of the aircraft, which could prevent airlines from flying certain long-range routes.

Civil specifications do not require a minimum hydrogen content; however; U.S. military specifications have a minimum of 13.4 wt%, Table 3.6.1. All of the fuel samples tested were above the 13.4% requirement.

Fuel	Value (wt%)	Specification
Jet A	—	ASTM D 1655
Jet A-1	—	Def Stan 91-91
JP-5	Minimum 13.4	MIL-DTL-5624U
JP-8	Minimum 13.4	MIL-DTL-83133E

Table 3.6.1. Hydrogen Content Specifications

3.6.1 Hydrogen Content Test Results

Hydrogen levels in jet fuel are typically in the 14% to 14.5% range (by weight). Synthetic fuels were found to have higher hydrogen contents, which are the result of the synthesis process. JP-5 fuels tended to have slightly lower hydrogen content, Figure 3.6.1.

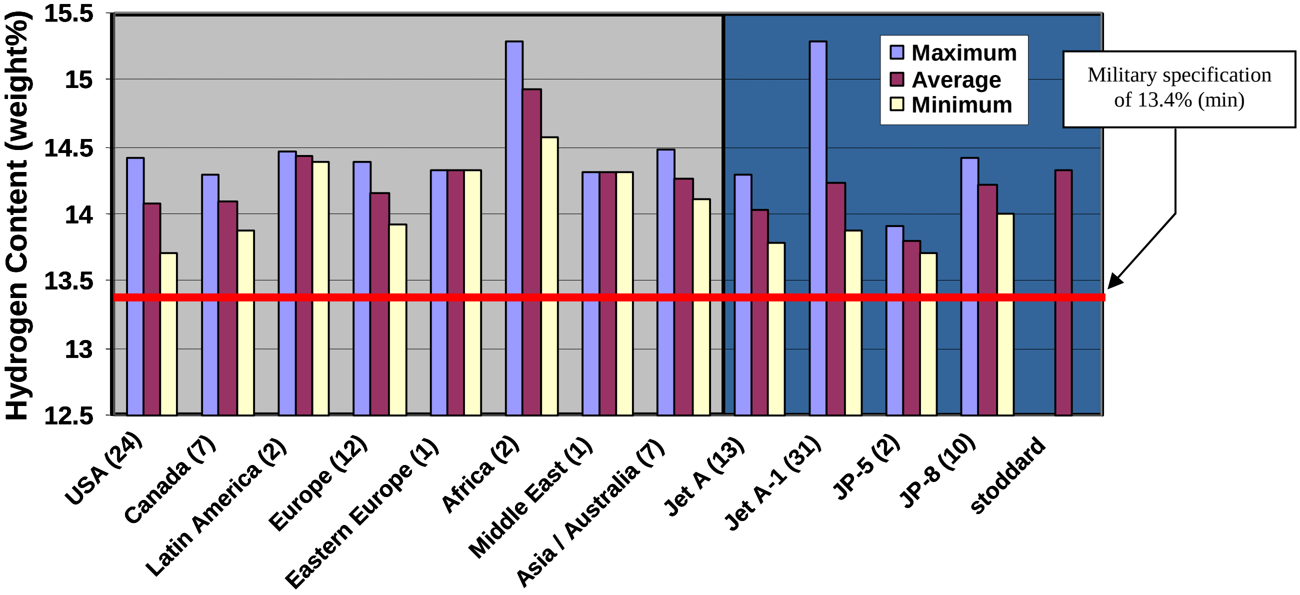

FIGURE 3.6.1. HYDROGEN CONTENT DISTRIBUTION

Refineries use hydrotreating to remove sulfur and other trace compounds from fuel. The hydrogen content in the fuels is commonly believed to increase with increased hydrotreating. The fuel sample data did not support this belief, as shown in Figure 3.6.2. There was little, if any, correlation of hydrogen content to sulfur content. The introduction of new, more selective, catalysis may reduce the amount of hydrogen imparted to the fuel upon processing as well as the severity of hydrotreating that is required. However, the primary factor related to jet fuel sulfur is the sulfur content of the crude oil source. Some crudes have low sulfur and will yield low sulfur jet fuel with little or no hydrotreating, therefore, little hydrogen will be imparted to the fuel. High sulfur crudes will require significant hydrotreating and will impart a larger amount of hydrogen to the fuel. For this reason, the lack of a general relationship between hydrogen content and sulfur content is not entirely unexpected.

Aromatics are plotted as a function of hydrogen content in Figure 3.6.3.

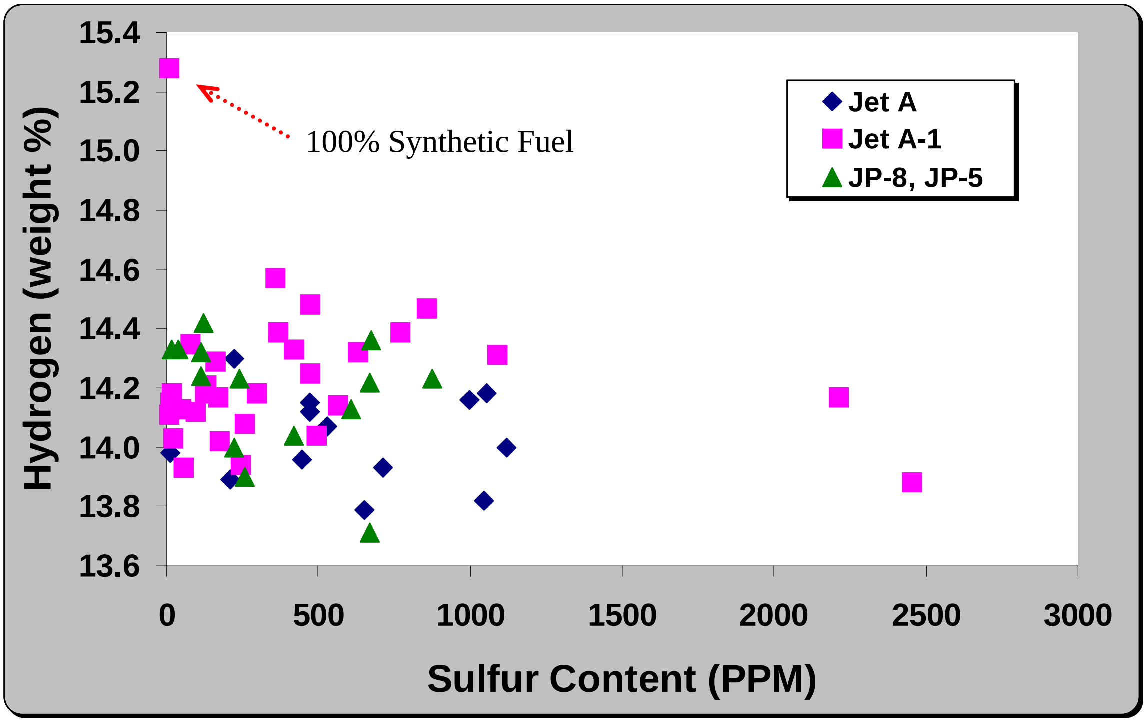

FIGURE 3.6.2. HYDROGEN CONTENT AS A FUNCTION OF SULFUR CONTENT

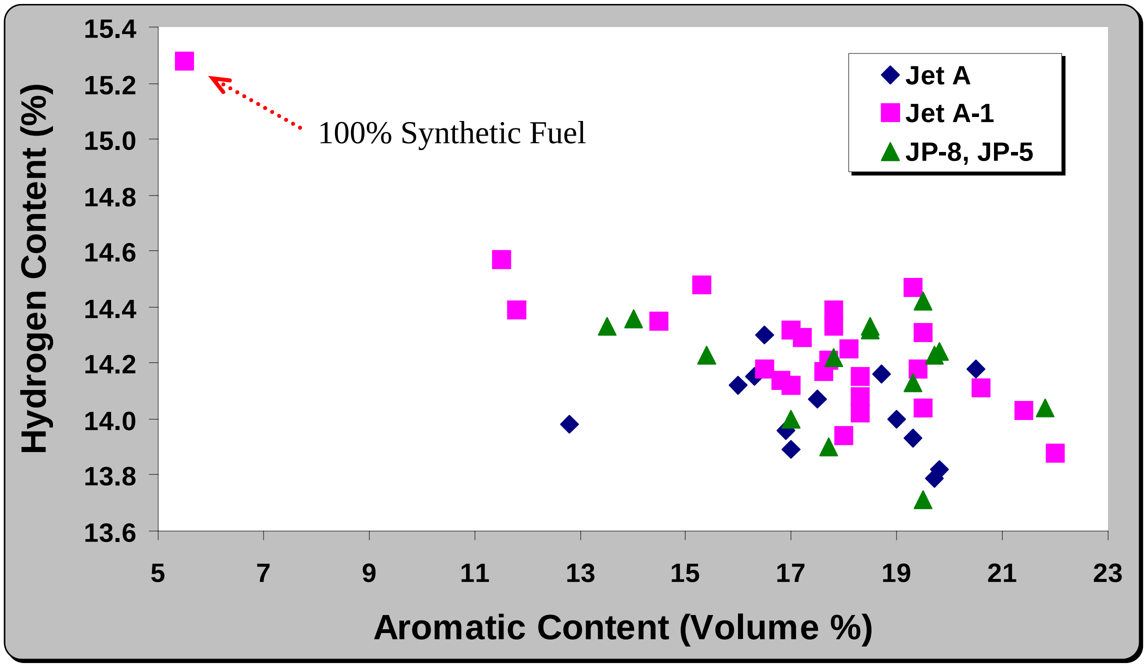

FIGURE 3.6.3. HYDROGEN CONTENT AS A FUNCTION OF AROMATIC CONTENT

3.7 Heat Content

Heat content is a measure of the energy released by a fuel when fuel and air are burned to carbon dioxide and water vapor (lower heating value). In the strictest sense, it is this heat that powers the aircraft. As airlines work under thin profit margins, maximizing fuel efficiency is always important. Jet fuel specifications require a minimum heat content, Table 3.7.1.

ASTM D 4809 was the test method used to determine heat content per unit weight (see Appendix A). The value obtained for heat content per unit weight was used, along with the density, to calculate the heat content per unit volume.

Fuel	Value (Btu/lb)	Specification
Jet A	Minimum 18,400 (42.8 MJ/kg)	ASTM D 1655
Jet A-1	Minimum 18,400 (42.8 MJ/kg)	Def Stan 91-91
JP-5	Minimum 18,300 (42.6 MJ/kg)	MIL-DTL-5624U
JP-8	Minimum 18,400 (42.8 MJ/kg)	MIL-DTL-83133E

Table 3.7.1. Specific Energy Content Specifications

3.7.1 Heat Content Test Results

Fuel test results showed that all but two samples were above the minimum requirements, Figure 3.7.1. The average heat content of samples was 18,512 Btu/lb, with a range of 18,331 to 18,785 Btu/lb. The highest heat content per unit weight was a synthetic fuel sample at 18,785 Btu/lb.

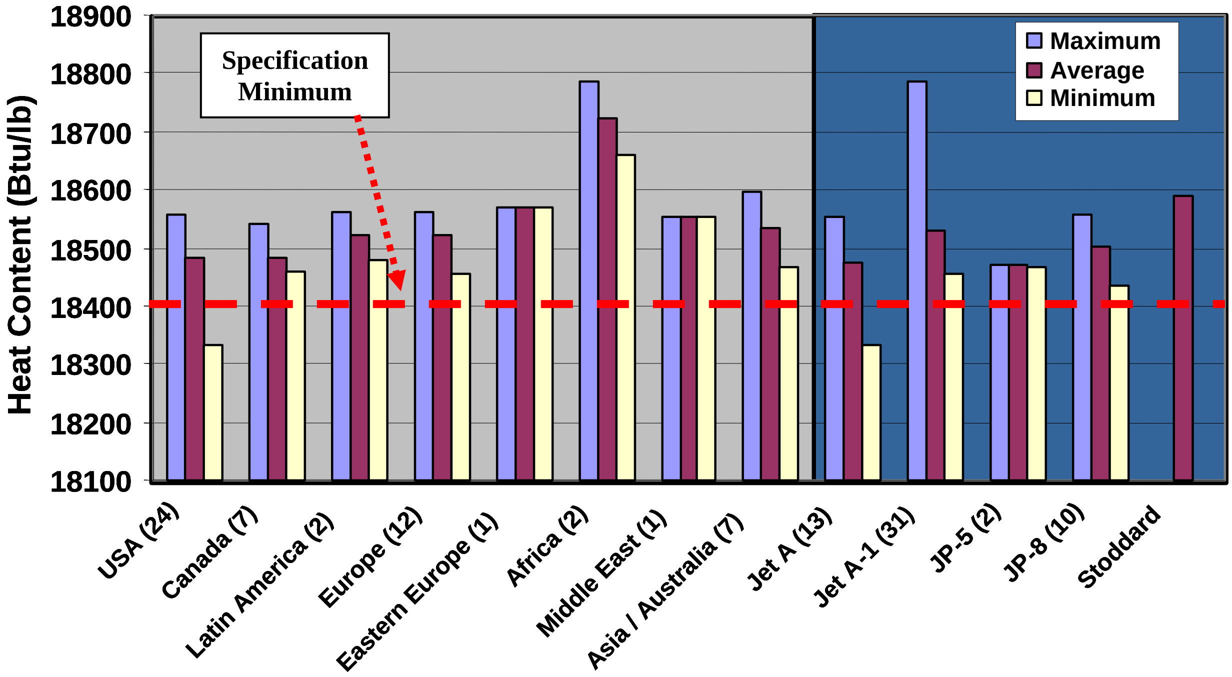

FIGURE 3.7.1. HEAT CONTENT OF WORLD FUELS IN BTU/LB

The airlines are becoming more interested in the long-range capability of aircraft. For these long-range routes, an aircraft can be volume limited. In this case, it is fuel heat content per unit volume that is critical in determining the range of the aircraft, Figure 3.7.2.

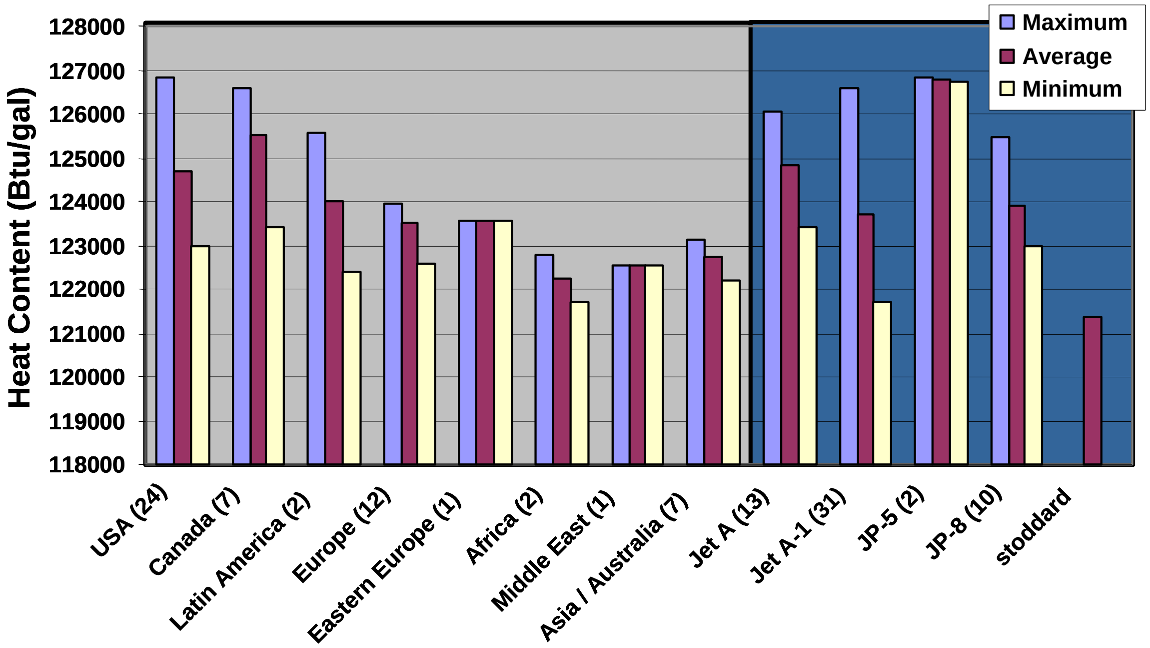

FIGURE 3.7.2. HEAT CONTENT OF WORLD FUELS IN BTU/GAL

The average heat content per volume of the samples was 124,070 Btu/gal. The SASOL synthetic fuel, which had the highest heat content per pound, 18,785, had the lowest heat content per gallon, 121,707. The 1.9% difference below the average is significant when planning the fuel requirements for long-range flights. The two lowest heat content fuels (18,331 and 18,343 Btu/lb) had above-average heat content per gallon (124,585 and 126,056 Btu/gal). Jet A has an average heat content per gallon that is approximately 1% above the average for Jet A-1.

In addition to ASTM D 4809, ASTM D 3338 was also used to calculate heat content per unit weight. For this method, the heat content is calculated based on fuel density, aromatic content, distillation profile (average of 10%, 50%, and 90% points), and the sulfur content. ASTM D 3338 is commonly used throughout industry to qualify aviation fuel. Average heat content calculated by this method was 18,587 Btu/lb, with a maximum of 18,812 Btu/lb (synthetic sample from SASOL) and a minimum value of 18,481 Btu/lb. Figure 3.7.3 compares values obtained by the two methods.

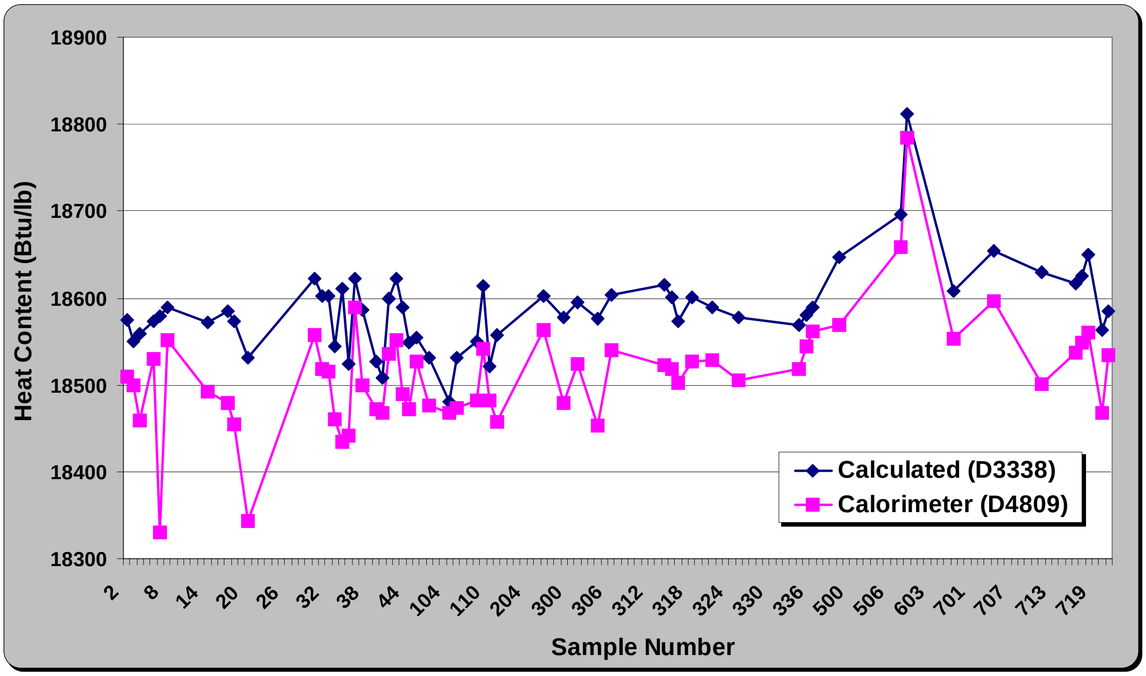

FIGURE 3.7.3. COMPARISON OF ASTM D 3338 AND ASTM D 4809

Figure 3.7.3 shows that ASTM D 3338 yields higher values of heat content when compared to ASTM D 4809. The average difference between the two methods is 76 Btu/lb, with a maximum difference of 248 Btu/lb and a minimum difference of 14 Btu/lb.

3.8 *Kinematic Viscosity*

The viscosity of jet fuel is important when calculating the pressure drop in aircraft fuel systems and in the atomization of fuel from the engine fuel nozzles (spray pattern and droplet size). Fuels become much more viscous in the tanks at the very low temperatures experienced by aircraft flying at cruise altitude. Viscosity is especially important when considering engine cold starting and relight. For these reasons, a maximum fuel viscosity has been established, Table 3.8.1.

Fuel	Value	Specification
Jet A	Maximum 8.0 cSt at –20°C	ASTM D 1655
Jet A-1	Maximum 8.0 cSt at –20°C	Def Stan 91-91
JP-5	Maximum 8.5 cSt at –20°C	MIL-DTL-5624U
JP-8	Maximum 8.0 cSt at –20°C	MIL-DTL-83133E

Table 3.8.1. Viscosity Specifications

3.8.1 *Viscosity Test Results*

All fuels were below the 8.0 cSt at –20°C requirement and JP-5 fuel had the highest viscosity, Figure 3.8.1.

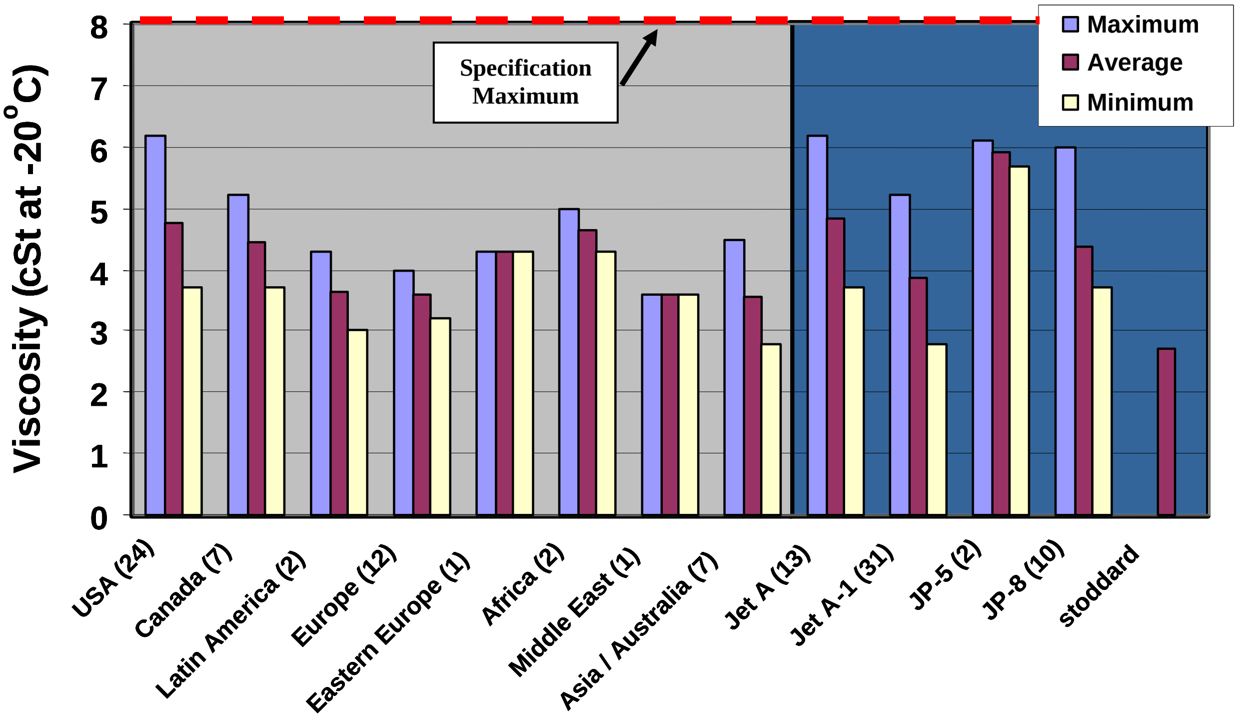

FIGURE 3.8.1. VISCOSITY DISTRIBUTION OF WORLD FUEL SAMPLES (VISCOSITY AT –20°C)

Viscosity data were taken at three temperatures for the fuel sample set (+20°C, –20°C, and –40°C). Results show that 10% of the fuels (6 fuels out of 57) had viscosities over 12 cSt at –40°C Figure 3.8.2. A maximum value of 12 cSt is set to limit where engines are able to operate for cold starts and engine altitude ignition [11].

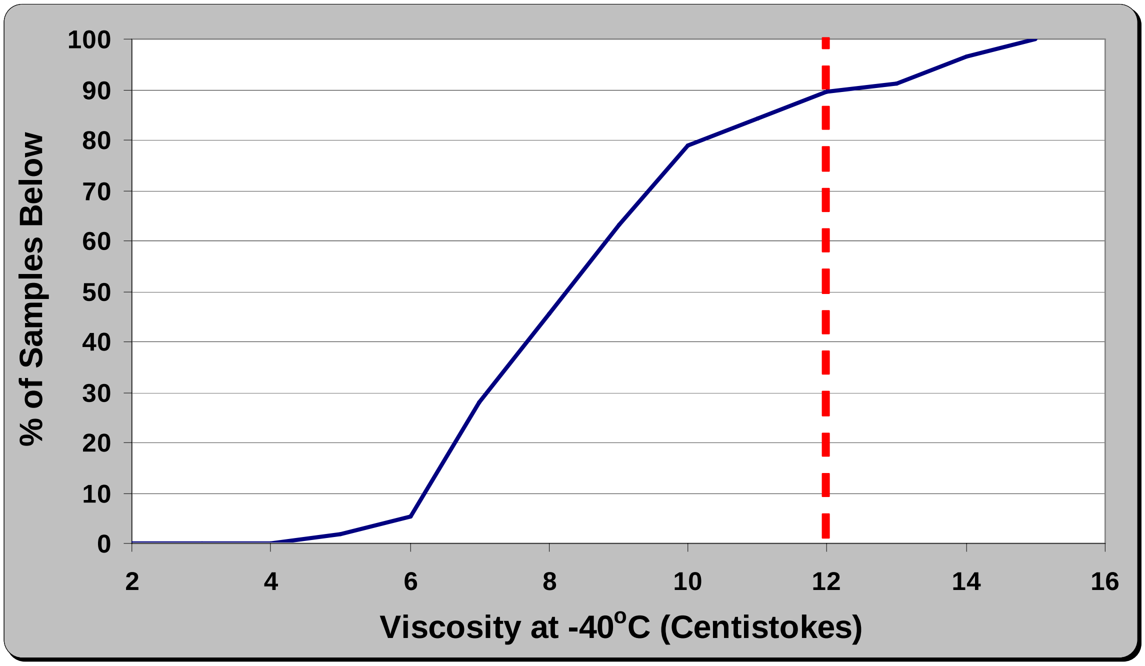

FIGURE 3.8.2. SAMPLE VISCOSITIES AT –40°C

There have been discussions for the technical justification to extrapolate viscosity data to –40°C using data taken at –20°C. Figures 3.8.3 and 3.8.4 plot the viscosities of the worst case fuels and the viscosities of the overall average as a function of temperature. The worst case fuels group consists of the six fuels that had viscosities over 12 cSt at –40°C. The charts show that, although essentially linear between +20°C and –20°C, values at –40°C increased significantly above the linear fit. Figure 3.8.3 is a semi-log plot, and the extrapolation methods are based on assumption that the data are linear on the semi-log plot. Figure 3.8.4 is the same set of data plotted in a Cartesian coordinate system to emphasize the bias at –40°C. The data would indicate that this extrapolation should not be made. Bias between the extrapolated values and the actual values, Figure 3.8.4, was 26% for the overall average and 30% for the worst case fuels. These data are justification for actually measuring the viscosity at –40°C for determining the specification requirement. There may also be justification for using viscosity in addition to freezing point temperature to determine aircraft cold weather operability, for in Figure 3.8.3, it can be seen that all fuels have a viscosity below 12 cSt at temperatures warmer than approximately –35°C.

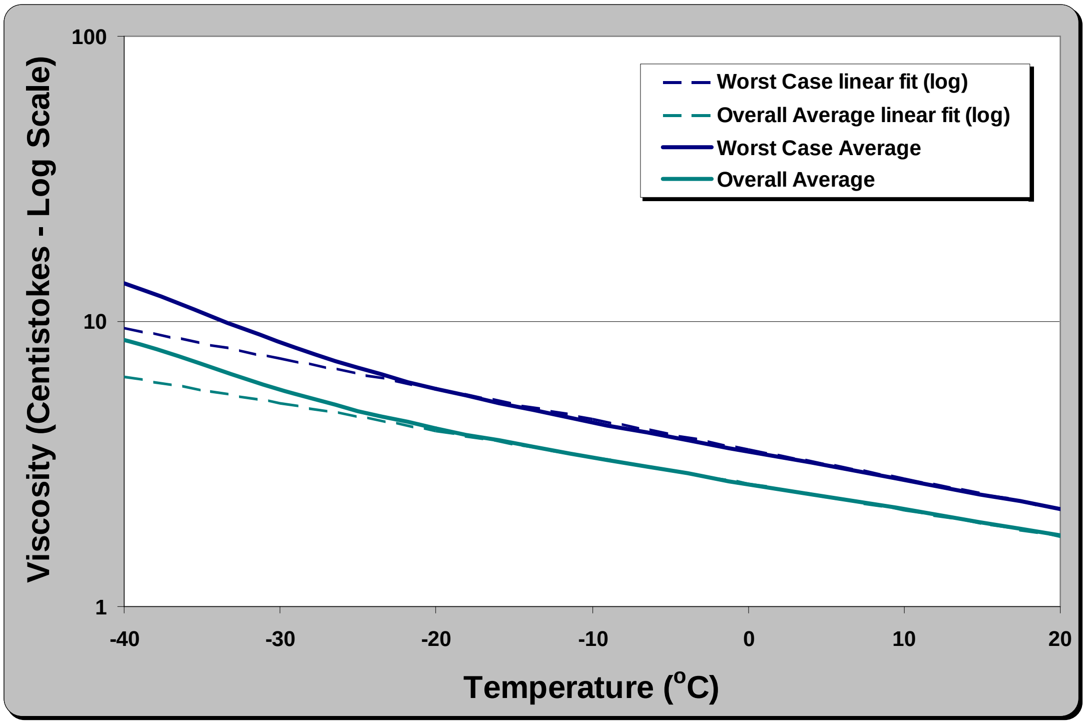

FIGURE 3.8.3. TEMPERATURE VERSUS FUEL SAMPLE VISCOSITY (SEMI-LOG SCALE)

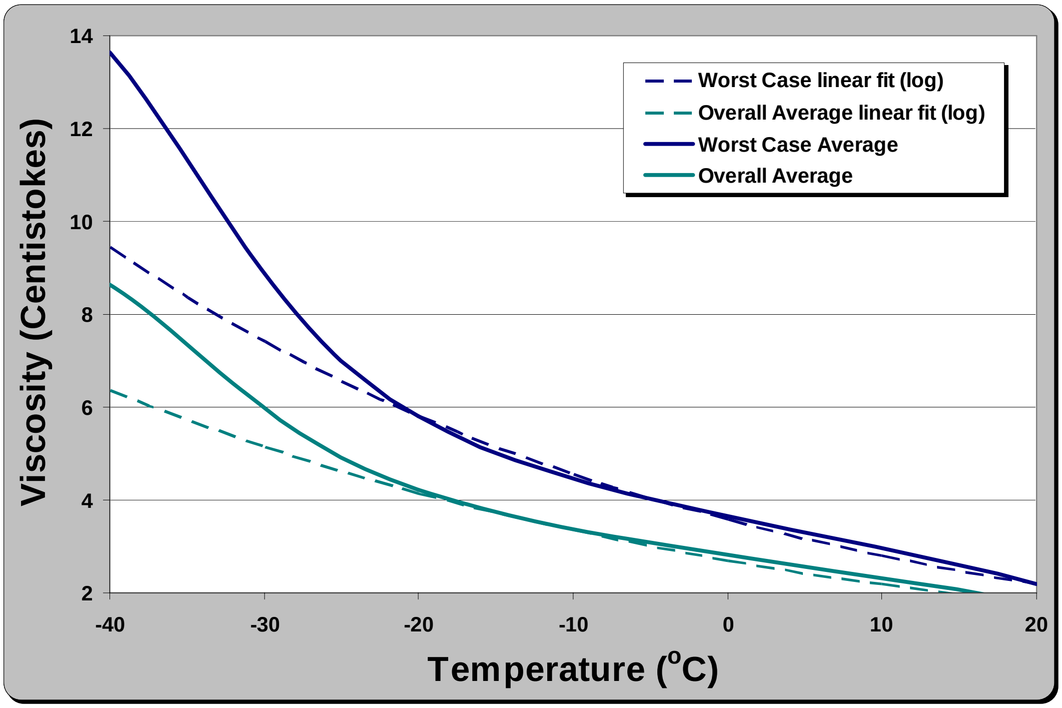

FIGURE 3.8.4. TEMPERATURE DEPENDENCE ON FUEL SAMPLE VISCOSITY

3.9 Electrical Conductivity

Pure hydrocarbons of the type found in aviation turbine fuel are essentially non-conductive, and it is the trace elements (polar molecules) that account for any conductivity [12]. When uplifting fuel into an aircraft, the fuel must travel through various hoses, pipes, and filter elements. Static charge is generated whenever the fuel passes through these materials. The static charge travels with the fuel and into the tank. The built-up charge will eventually dissipate. However, if the charge is not dissipated at a fast enough rate, the charge could build and discharge by means of a spark leading to ignition of fuel vapors that may be present in the tank.

Only some fuels have specification requirements for conductivity. Conductivity can be increased by using an approved fuel additive. Table 3.9.1 shows the specification requirements for several fuel types. These conductivity requirements provide additional assurance that any static electricity generated while refueling will dissipate safely. Maximum conductivity values are specified to ensure proper operation of the aircraft fuel quantity indicating systems (FQIS). If fuel conductivity is too high, the aircraft fuel tank gauges may give erroneous readings.

Fuel	Value (pS/m)	Specification
Jet A	—*	ASTM D 1655
Jet A-1	50 to 450	Def Stan 91-91
JP-5	—	MIL-DTL-5624U
JP-8	150 to 450**	MIL-DTL-83133E

*When purchaser specifies electrical conductivity additive, conductivity shall be 50 to 450 at point of delivery.
**Limits are 150 to 700 pS/m for JP-8 +100.

Table 3.9.1. Electrical Conductivity Specifications

3.9.1 Electrical Conductivity Test Results

Electrical conductivity measurements were taken at three temperatures: 42°F, 72°F, and 100°F. These temperatures reflect the operating temperature of the laboratory refrigerator, the laboratory ambient room temperature, and an elevated temperature chosen to be below the fuel flash point, respectively. Soon after fuel samples arrived at Boeing, a portion (approximately 1 L) of the fuel was transferred to glass jars, sealed, and stored in the refrigerator for the duration of testing for 49 of the 57 fuels. The remaining 9 fuels remained in their epoxy-lined cans. Sample jars were 1-L containers composed of USP type III glass, which is a soda-lime type glass. Conductivity of the fuel samples is shown in Figure 3.9.1.

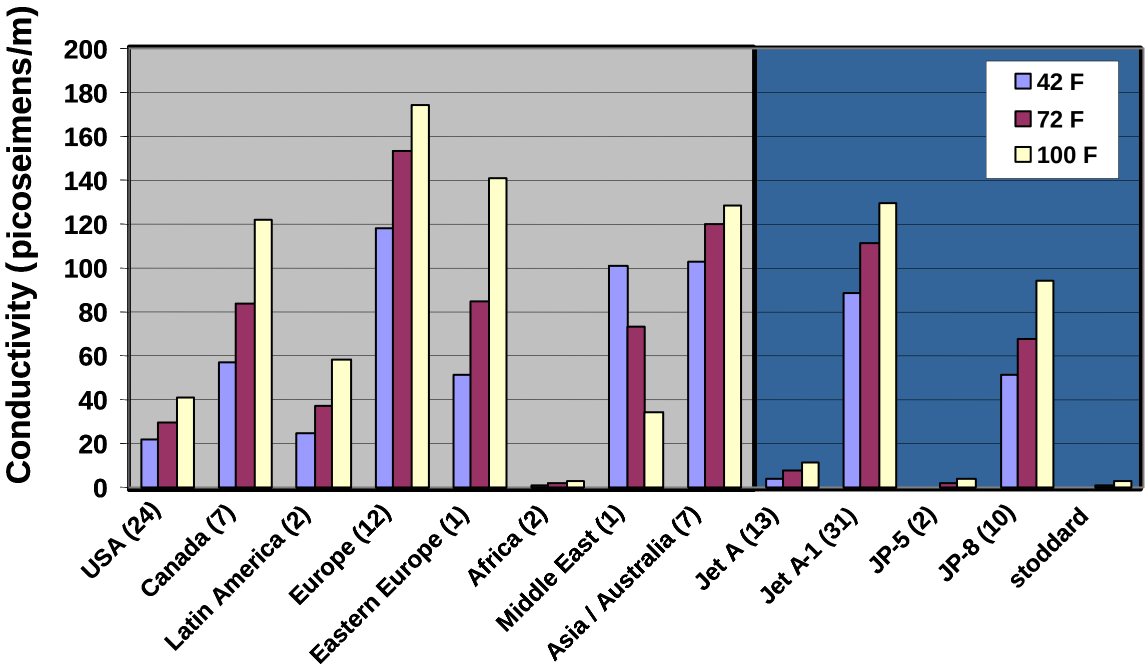

FIGURE 3.9.1. CONDUCTIVITY DISTRIBUTION OF WORLD FUEL SAMPLES (AVERAGED AT EACH TEMPERATURE)

As expected, the JP-8 and Jet A-1 samples were found to have the highest conductivity because the specifications for these particular fuel types require the addition of the static dissipater additive (SDA). Synthetic fuels had extremely low conductivity, probably due to the inherent lack of polar components in the synthetic fuels. Jet A and JP-5 fuels do not require a conductivity additive and reflect fuels without SDA. The conductivity of fuels without the additive ranged from 0 to 64 pS/m at 72°F. The data showed some anomalies, which are discussed in more detail in Section 9.1.

3.10 Distillation

Distillation profile is one of the important characteristics for identifying fuels quantitatively. Fuel volatility as well as low-temperature performance are a result of the distillation profile. Distillation values were measured using two methods: ASTM D 86 and ASTM D 2887.

3.10.1 Distillation Test Results—ASTM D 86

Average distillation profiles are fairly consistent between fuel types, Figure 3.10.1. In this figure, the maximum and minimum are plotted using the maximum and minimum values at each respective recovery point from all of the samples. The averages are by fuel type and are the averages for that specific recovery point and for that fuel type. Note: The synthetic fuel samples had a distillation profile that has a different slope compared to the petroleum samples (see Section 10).

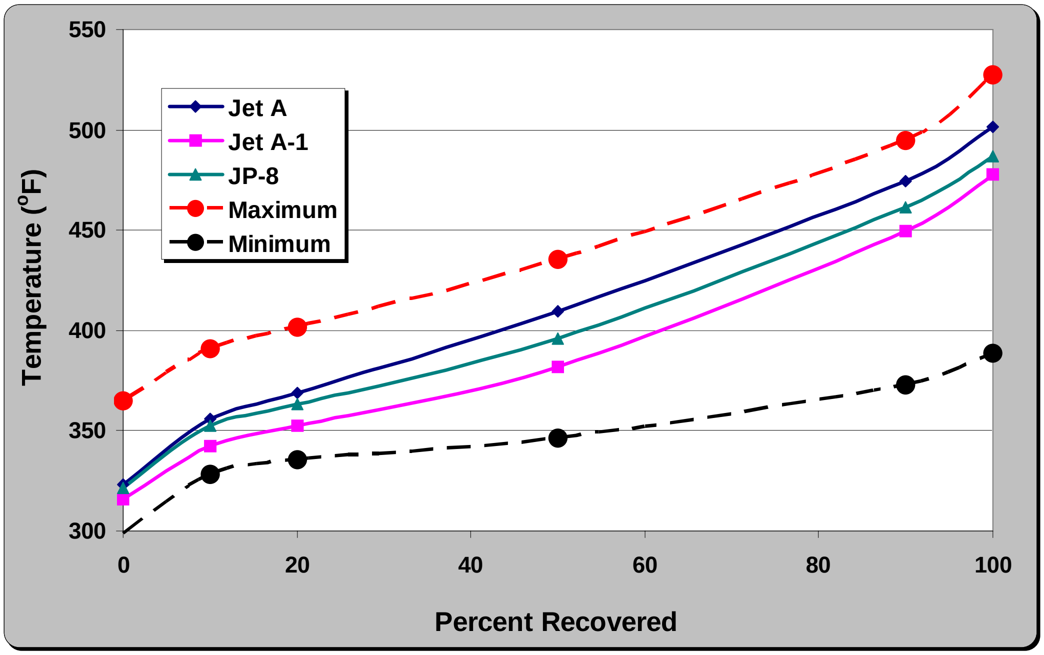

FIGURE 3.10.1. ASTM D 86 DISTILLATION TEST RESULTS BY FUEL TYPE

The quantity of residue left after the ASTM D 86 test method was completed exceeded the test method allowance in a large number of the fuels tested, Figure 3.10.2. The average distillation residue was greater than 1.45% (by volume), and 12% of the samples tested would have failed under the ASTM D 1655 criteria of a 1.5% maximum. This anomaly is discussed further in Section 9.2.

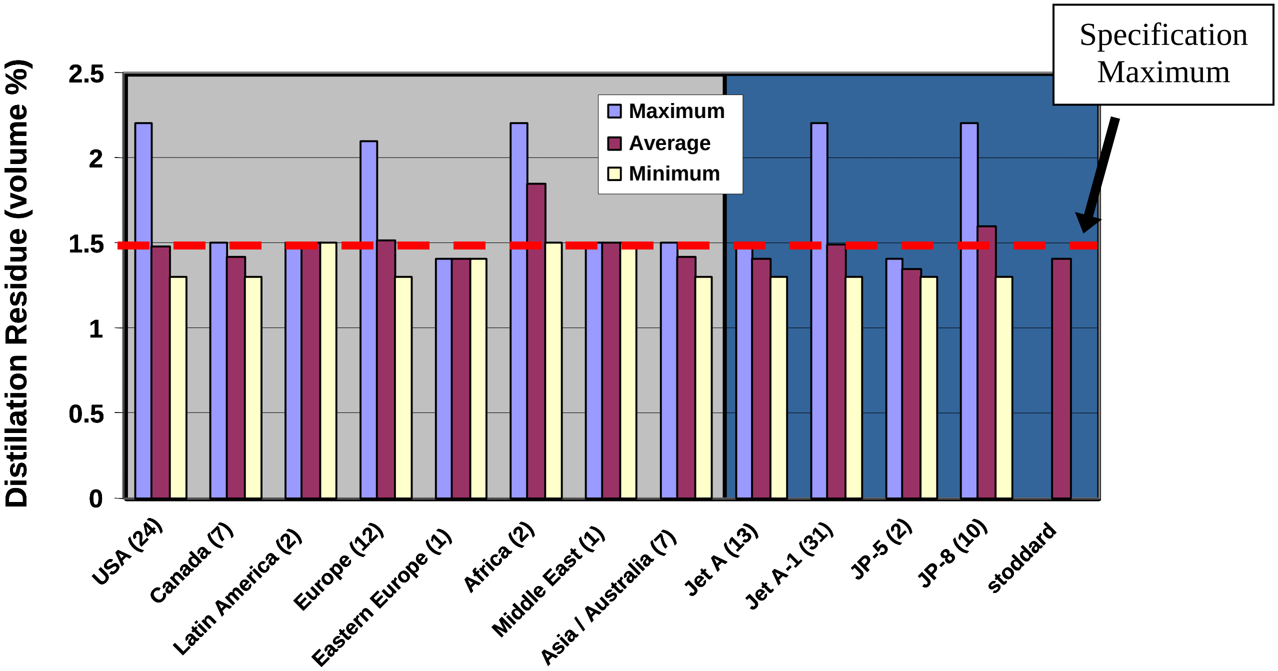

FIGURE 3.10.2. DISTRIBUTION FOR DISTILLATION RESIDUE (ASTM D 86)

3.10.2 Distillation Test Results—ASTM D 2887, Simulated Distillation

Simulated distillation was completed by ChevronTexaco and is a gas chromatography method. This test method accounts for the complete boiling range of the sample (i.e., there is no residue or volume unaccounted for). Because the residue left over in ASTM D 86 is typically high boiling components, final boiling point (FBP) values tend to be higher for the simulated distillation method (i.e., simulated distillation records the boiling temperature of these components, whereas ASTM D 86 leaves them behind as residue). In addition, there is no delay prior to the initial boiling point (IBP) value. ASTM D 86 records the IBP after the first drop forms from the distillate. Simulated distillation does not have the delay associated with drop formation and retention time through the apparatus; therefore, IBP from the simulated methods tends to be lower. D 86 is a low efficiency distillation and has approximately 1 theoretical plate efficiency. D 2887 has a higher efficiency which gives more accurate boiling point temperatures. Figure 3.10.3 shows results from the simulated distillation testing. Figure 3.10.4 compares simulated distillation results with those of ASTM D 86. For the reasons discussed above, simulated distillation tends to have a lower IBP and higher FBP when compared to the ASTM D 86 method. Correlation equations have been derived that will predict ASTM D 86 values from ASTM D 2887 test data.

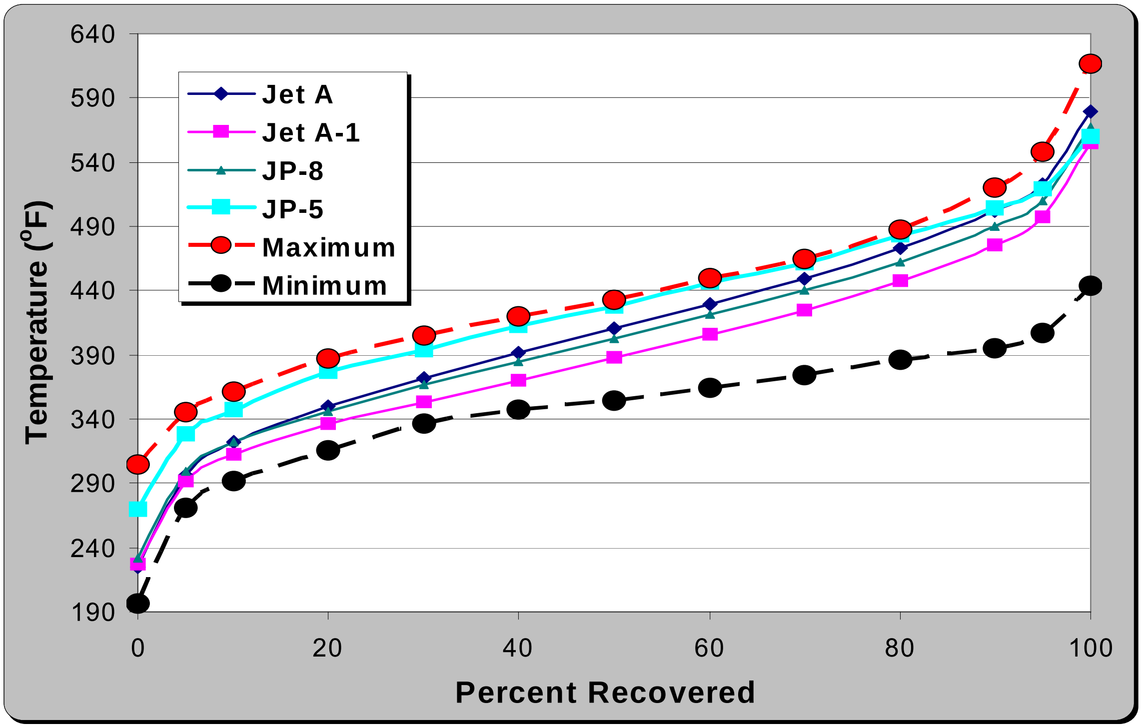

FIGURE 3.10.3.ASTM D 2887, SIMULATED DISTILLATION METHOD

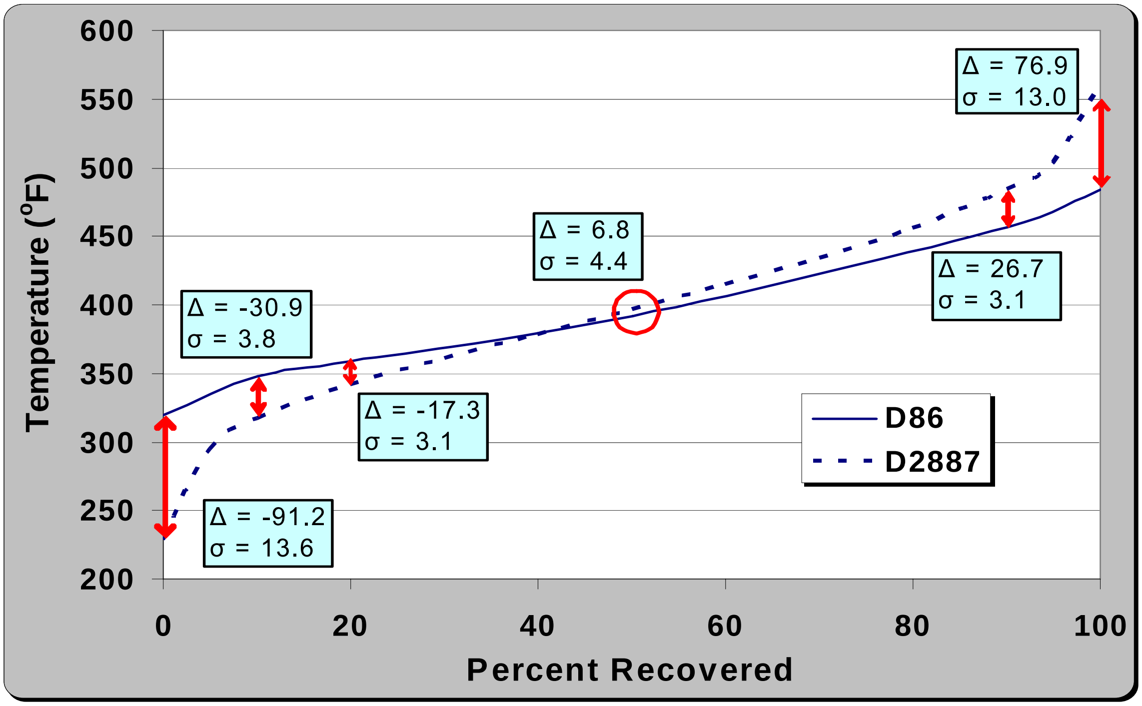

FIGURE 3.10.4. ASTM D 2887 VERSUS ASTM D 86. DATA AVERAGED OVER ALL SAMPLES

3.11 Flash Point

Flash point is defined as the lowest temperature at which the vapors above a flammable liquid will ignite upon application of an ignition source [13] under the conditions of the test. Flash point is, therefore, a measure of the volatility/flammability of the fuel and is frequently referred to when discussing the subject of fuel safety.

Jet fuel specifications require a minimum flash point temperature to control fuel volatility, which is related to fuel system performance as well as ground handling and aircraft flight safety issues, Table 3.11.1. The kerosene fuels listed in the table have vapor pressures that are too low to measure by conventional test methods. Vapor pressure testing is more commonly used for high-volatility fuels like gasoline and JP-4.

Fuel	Value, °C (°F)	Specification
Jet A	38° (100°) minimum	ASTM D 1655
Jet A-1	38° (100°) minimum	Def Stan 91-91
JP-5	60° (140°) minimum	MIL-DTL-5624U
JP-8	38° (100°) minimum	MIL-DTL-83133E

Table 3.11.1. Flash Point Specifications

3.11.1 *Flash Point Test Results*

Figure 3.11.1 shows the distribution of flash points for the fuel samples. Boeing used ASTM D 93 test method, which is approved for use in military fuel specifications but is not approved for commercial fuels. The approved methods for commercial fuels are ASTM D 56 and D 3828. All but one fuel sample passed the minimum specification requirement. That particular sample was determined to have a flash point of 96°F.

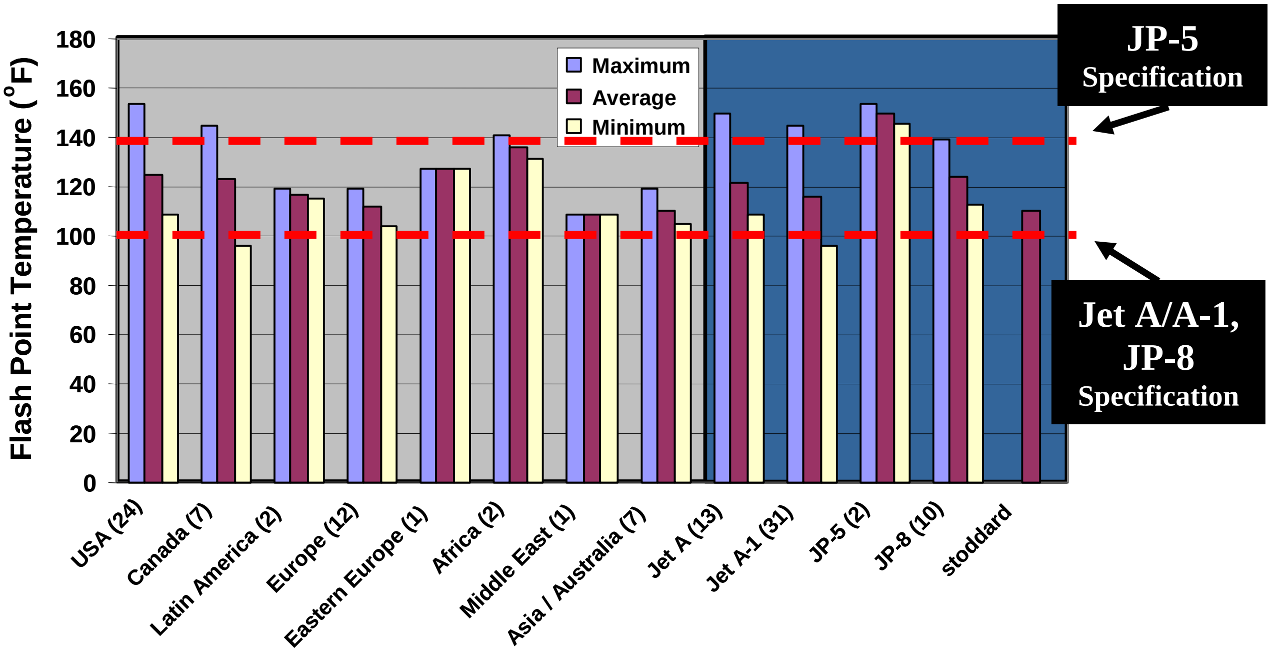

FIGURE 3.11.1. FLASH POINT DISTRIBUTION

Average flash point of the fuels was 120°F including the higher flash JP-5 samples and 119°F not including the JP-5 samples, significantly higher than the required 100°F flash. Pipelines commonly require a higher flash point, on the order of 105°F or 108°F. Jet fuel flash point is also commonly affected by refinery product distribution. Refineries often maximize production of high value fuels such as gasoline, which often results in a higher flash point in jet fuel. These are the primary reasons why flash point is significantly higher than the specification requirement.

3.12 Fuel Appearance

Samples were inspected for the presence of particulates and water as well as for any other noticeable anomalies such as odd odor or color. Any deviation or anomalies were noted. Among the observations were comments such as “typical jet fuel aroma, tangy odor, sulfurous odor, sour odor, clear, and yellowish color.” None of the observations were particularly alarming and no obvious signs of particulates or water droplets were noted.

In summary, no trend could be seen between the above-mentioned observations and fuel properties and/or composition. For example, some fuels that were noted to have a sulfurous smell had low sulfur content and some had somewhat high sulfur content. Of the two fuels with the highest measured sulfur content (over 2,000 ppm), one was noted to be clear with a normal jet fuel aroma and the other was noted to have a slightly tangy odor. Similar observations were made for other fuel properties, including aromatic content and distillation residue.

3.13 Refractive Index

Refractive index is a comparison of how quickly light travels through air versus fuel and is defined as the ratio of the velocity of light in air to the velocity of light in fuel [14]. Refractive index is not a required fuel property test but may provide insight to other fuel properties. Information gained might be used in new gauging systems or to increase aircraft fuel loading accuracy.

Refractive index testing was conducted at room temperature (the average temperature was approximately 20.6°C with a low of 20.0°C and a high of 21.3°C). Data were plotted to correlate test temperature versus refractive index measurements. Because fuel density will decrease at higher temperatures, the refractive index should also decrease when the temperature is increased. ASTM D 1218 predicts a change in refractive index of $-3\text{x}10^{-4}$ to $-5\text{x}10^{-4}$ per degree Celsius change in temperature for hydrocarbons. A linear regression of fuel sampling data actually shows a curve with a slightly positive slope. Because of these factors, it is determined that the relatively small temperature difference seen during testing did not factor into the validity of the data or any conclusions made from it.

3.13.1 Refractive Index Test Results

Results show that the refractive index of the fuel samples correlated well with several fuel properties, including density, heat content per unit volume, heat content per unit weight, and hydrogen content. Refractive index shows the best correlation (highest R^2 value) to density and is shown below in Figure 3.13.1. The figure also shows that SASOL synthetic fuels had a low refractive index when compared to the other fuel samples but correlated well to a linear extrapolation of density.

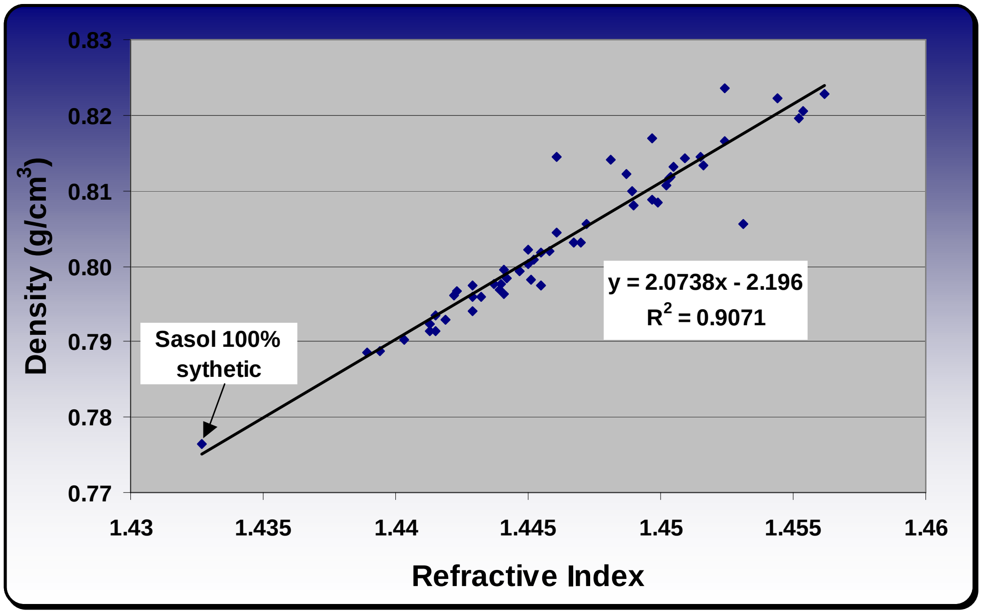

FIGURE 3.13.1. REFRACTIVE INDEX VERSUS DENSITY CORRELATION

4. Fuel Sample Properties—ChevronTexaco

4.1 Aromatic Content

Aromatic content of jet fuel is important to aviation for two reasons:

1) Aromatics are known to produce soot and smoke emissions [13, 15]. (However, the smoke point test was not conducted on the fuel samples.)

2) Aromatics can cause seals and sealants to swell. When seals swell, they can take a "set." Then, when a jet fuel with a different type of, or a very low aromatic content, is used, the absorbed petroleum leaches out, causing the seal material to shrink to less than its manufactured dimensions. In some cases, fuel leaks can occur. It is this alternating of fuel with different aromatic types that can cause problems in aircraft fuel systems.

   Seal swell (or shrinkage) is known to be a function of both aromatic constituents and exposure time. If an aircraft that has previously been using JP-4 (a wide-cut fuel with many single ring aromatics) is exposed to Jet A-1 or JP-8 (a kerosene fuel with fewer single ring aromatics that can have many side chains), the leaching can proceed relatively quickly because the aromatics in JP-4 are different from the aromatics in kerosene jet fuels. This is a concern particularly for older military aircraft that have seen lengthy in-service times and have operated on both JP-4 and JP-8. With the military switch to JP-8, this is not a problem today.

> Alternating between kerosene jet fuels with different aromatic content but similar aromatics structure is less likely to create the swell/shrink behavior. Most O-rings are installed with a squeeze, and minor changes in swell are easily handled by design. Few problems have occurred in the commercial fleet.

Jet fuel specifications limit aromatics to a maximum of 25 vol%, Table 4.1.1. The seal-swelling issue has prompted discussion of possibly including a minimum aromatic content in the specification.

Fuel	Value (vol%)	Specification
Jet A	25 maximum	ASTM D 1655
Jet A-1	25 maximum	Def Stan 91-91
JP-5	25 maximum	MIL-DTL-5624U
JP-8	25 maximum	MIL-DTL-83133E

Table 4.1.1. Aromatic Content Specifications

Testing for aromatics was completed by ChevronTexaco, which utilized two different methods to determine aromatic content. One method is ASTM D 6379, which is a high performance liquid chromatography (HPLC) method. The second method is ASTM D 1319, which is a FIA method. These methods are discussed further in Appendix A.

Correlation between the two methods was very good, with the average difference between the two methods being less than 10%. Testing by ASTM D 6379 typically showed a slightly larger aromatic content for the same fuel. The repeatability for both methods is approximately 1.3 vol%, which is approximately 7.5% of the average value. Average aromatic content by ASTM D 1319 is 17.5 vol% and the average by ASTM D 6379 is 19.2 vol%.

The aromatic content of the fuel samples, as determined by ASTM D 1319, are shown in Figure 4.1.1. Synthetic fuel samples from Africa were notably low in aromatics, and the Canadian samples were slightly high. Jet fuels made from Canadian heavy oil have both high density and high aromatic content because of the very nature of the heavy crude oil that is common from that region.

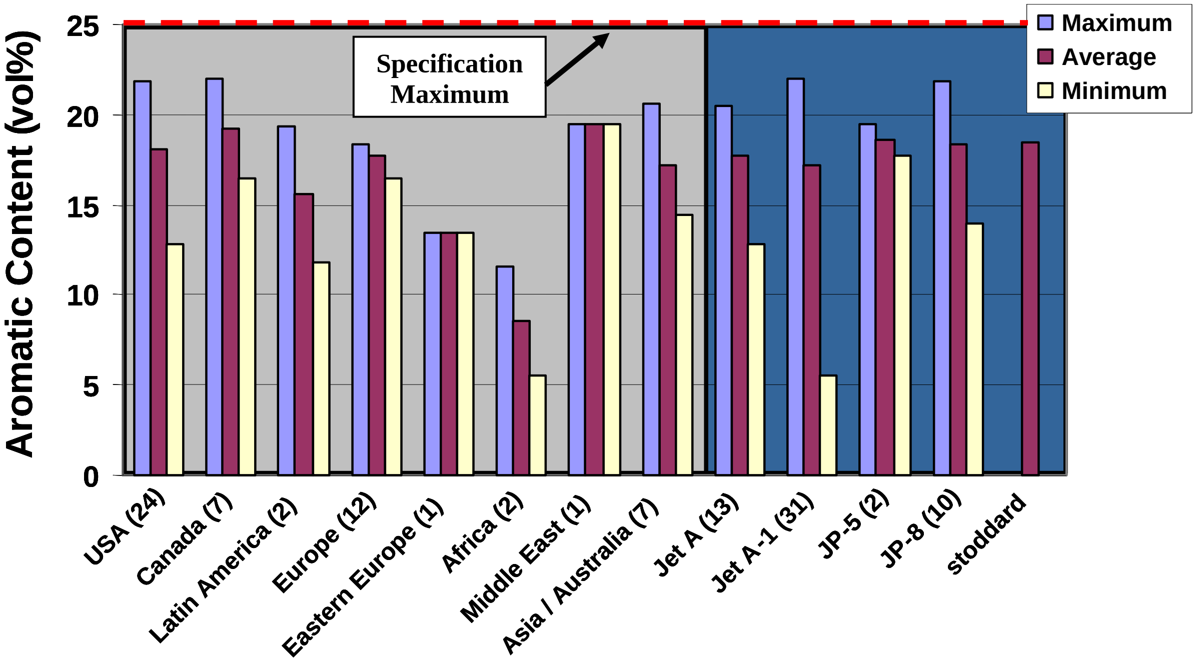

FIGURE 4.1.1. AROMATIC CONTENT OF FUEL SAMPLES BY ASTM D 1319

4.2 Naphthalene Content

ChevronTexaco used ASTM D 1840 to determine naphthalene content. See Appendix A for further discussion of the test method.

Naphthalene is a dicyclic aromatic hydrocarbon. It is composed of two benzene rings that share one side. Naphthalenes exhibit particularly poor combustion characteristics. Because of the relatively low hydrogen content, naphthalenes tend to have low heat content per pound. However, their high density tends to give them relatively high heat content per unit volume. Naphthalene molecules produce smoke and these large amounts of soot particles tend to radiate more heat to engine components which exposes engines to increased risk of thermal damage leading to component reduced life, and increased maintenance costs.

Naphthalenes are restricted to 3.0% (by volume) if the fuel has a smoke point below 25 mm, by ASTM D 1655, Def Stan 91-91, and MIL-DTL-83133E (JP-8). In that case, the smoke point must be above 19 mm (18 mm for Jet A) and naphthalenes must be below 3.0%. However, if the fuel has a smoke point at or above 25 mm, a naphthalene test is not required, Table 4.2.1.

Fuel	Value	Specification
Jet A	25-mm smoke point minimum or 18-mm smoke point (minimum), and 3.0 % naphthalenes (maximum)	ASTM D 1655
Jet A-1	25-mm smoke point minimum or 19-mm smoke point (minimum), and 3.0 % naphthalenes (maximum)	Def Stan 91-91
JP-5	None (19-mm smoke point minimum)	MIL-DTL-5624U
JP-8	25-mm smoke point minimum or 19-mm smoke point (minimum), and 3.0 % naphthalenes (maximum)	MIL-DTL-83133E

Table 4.2.1. Naphthalene Content Specifications

Of the 57 fuels sampled, only one sample exceeded 3.0% naphthalenes. This JP-5 fuel had 3.8% naphthalene content, Figure 4.2.1.

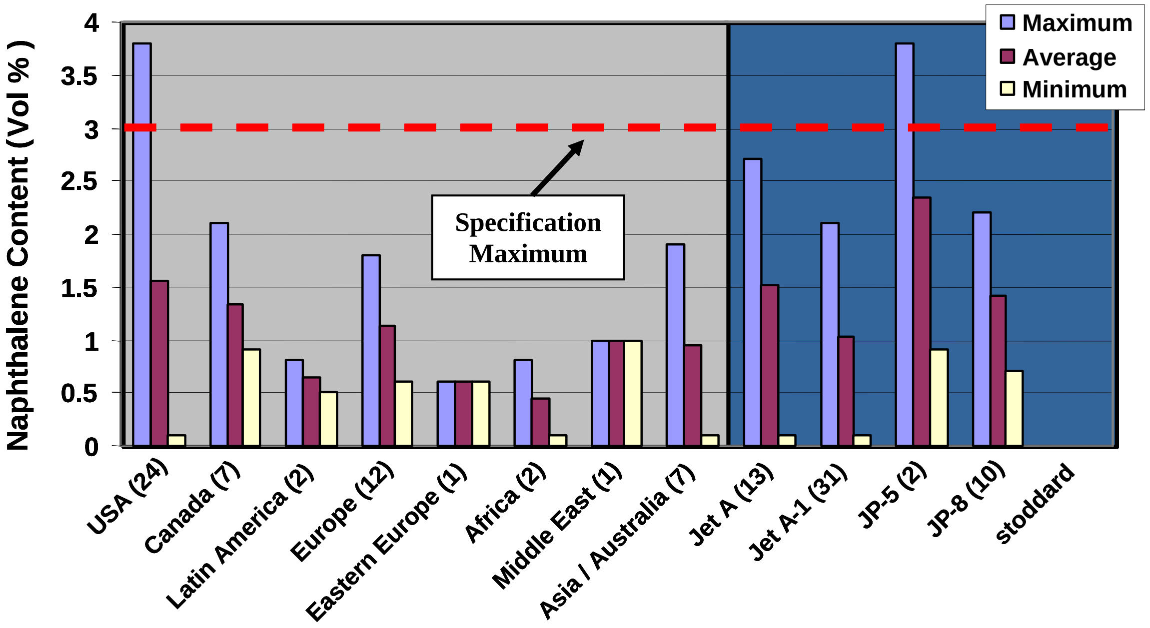

FIGURE 4.2.1. NAPHTHALENE CONTENT OF FUEL SAMPLES

4.3 *Saturate Content*

Saturates are paraffinic and naphthenic hydrocarbon molecules. Saturates are the major component in jet fuel. All of the fuel samples had a saturate content greater than 75% (by volume). As expected, synthetic fuels had a higher saturate content than conventional petroleum-derived jet fuel, Figure 4.3.1.

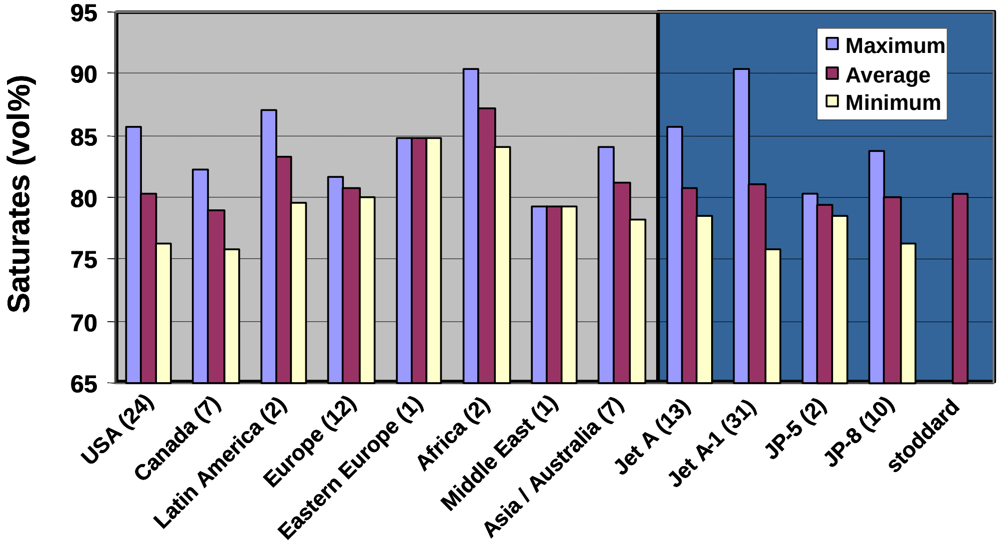

FIGURE 4.3.1. SATURATE CONTENT IN FUEL SAMPLES

4.4 *Olefin Content*

See section 3.5 for a discussion of the ChevronTexaco generated data.

4.5 *Simulated Distillation*

See section 3.10 for a discussion of the ChevronTexaco generated data.

5. Fuel Sample Properties—Goodrich

Goodrich Corporation analyzed the fuel samples for density, dielectric constant, and velocity of sound over the temperature range from -40°C to +70°C. The baseline data are used for the design of aircraft gauging devices and instrumentation. Subtle changes in aviation fuel may result in the degraded performance of legacy gauging systems.

5.1 Density Versus Temperature

Correlation between temperature and density is very predictable for jet fuel samples. Linear fit and regression fit values (R^2 values) confirm that the relationship is linear and predictable, Table 5.1.1.

As shown in Figure 5.1.1, there is some variance between fuel types. The high flash point of JP-5 results in a higher density, while the low freezing point of Jet A-1 and JP-8 fuels produces a lower density. Synthetic fuels are known for their high hydrogen content and low density, which is confirmed in the figure below.

Summary—Density (kg/m^3) Versus Temperature (°C)		
Fuel	Linear Fit Equation	Regression Fit Value (R^2)
Jet A	**D** = -0.7308x**T** + 821.67	0.9407
Jet A-1	**D** = -0.7354x**T** + 810.96	0.8858
Jet A-1 Syn	**D** = -0.7172x**T** + 791.92	0.9473
JP-5	**D** = -0.7212x**T** + 833.64	0.9993
JP-8	**D** = -0.7292x**T** + 813.35	0.9308

Table 5.1.1. Regression Analysis of Density Versus Temperature

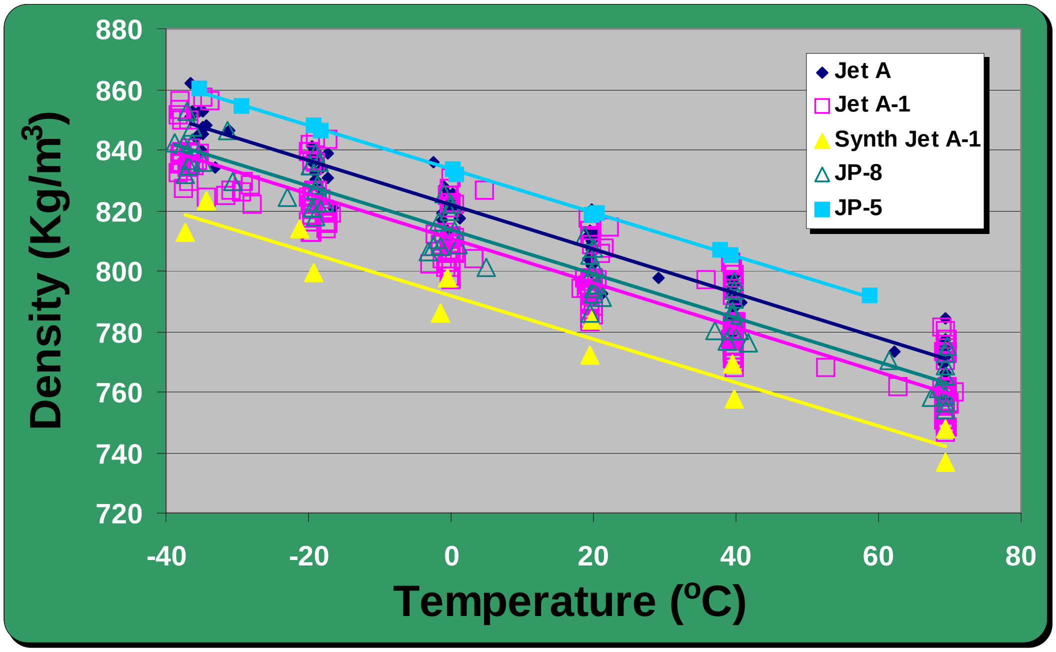

Figure 5.1.1. Density Versus Temperature With Best Fit Trendlines

5.2 *Dielectric Versus Temperature and Density*

Dielectric constant is defined as the ratio of the capacitance of the sample fuel in a test cell to the capacitance of the same cell without the sample fluid. Testing showed that when the dielectric constant was plotted versus temperature, the trends were linear. Figure 5.2.1 illustrates the nearly parallel trend between fuels. Table 5.2.1 shows the equations associated with the test data. The large R^2 values imply a good linear fit.

Summary—Dielectric Constant Versus Temperature (°C)		
Fuel	Linear Fit Equation	Regression Fit Value (R^2)
Jet A	**K** = -0.0015x**T** + 2.1608	0.9572
Jet A-1	**K** = -0.0014x**T** + 2.1435	0.9274
Jet A-1 Syn	**K** = -0.0013x**T** + 2.1000	0.9319
JP-5	**K** = -0.0015x**T** + 2.1869	0.9286
JP-8	**K** = -0.0015x**T** + 2.1518	0.9518

Table 5.2.1. Analysis of Dielectric Constant (K) Versus Temperature

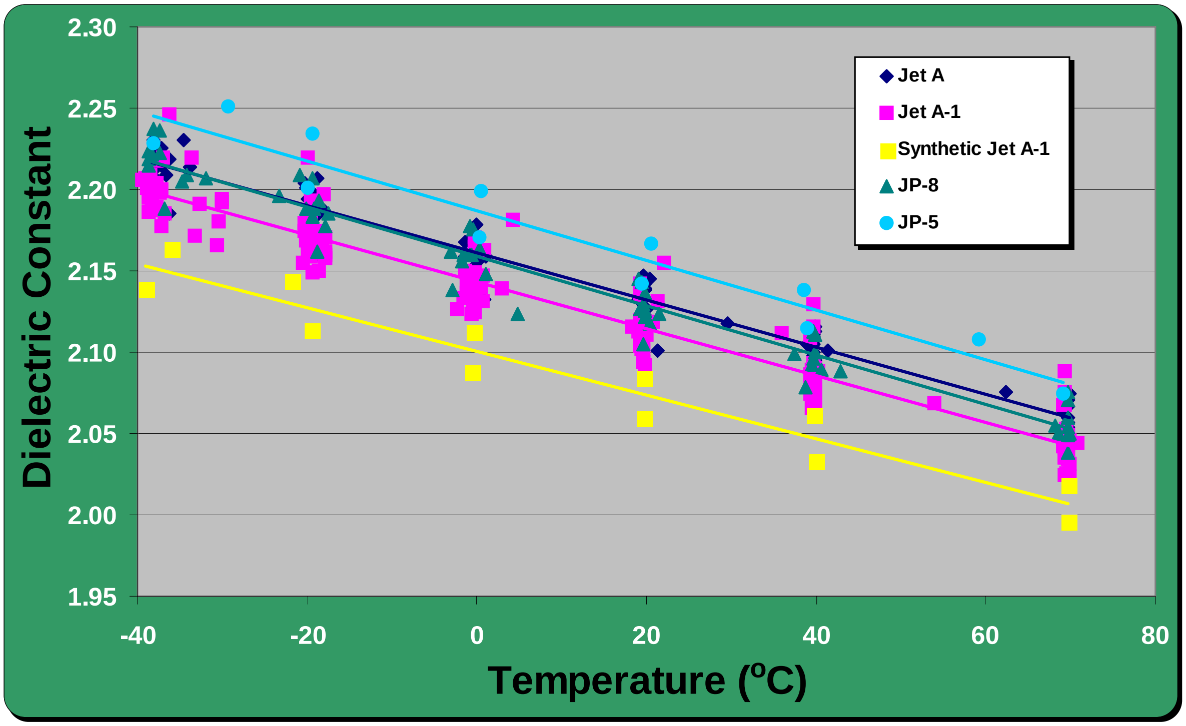

FIGURE 5.2.1. DIELECTRIC CONSTANT VERSUS TEMPERATURE

Similar results were seen when dielectric constant was plotted against density, Table 5.2.2.

Summary—Density (kg/m^3) Versus Dielectric Constant		
Fuel	Linear Fit Equation	Regression Fit Value (R^2)
Jet A	**D** = 491.50x**K** - 240.38	0.9616
Jet A-1	**D** = 504.81x**K** - 271.05	0.9565
Jet A-1 Syn	**D** = 514.02x**K** - 287.46	0.9817
JP-5	**D** = 420.61x**K** - 86.459	0.9168
JP-8	**D** = 467.41x**K** - 195.50	0.9672

Table 5.2.2. Linear Regression of Density Versus Dielectric Constant

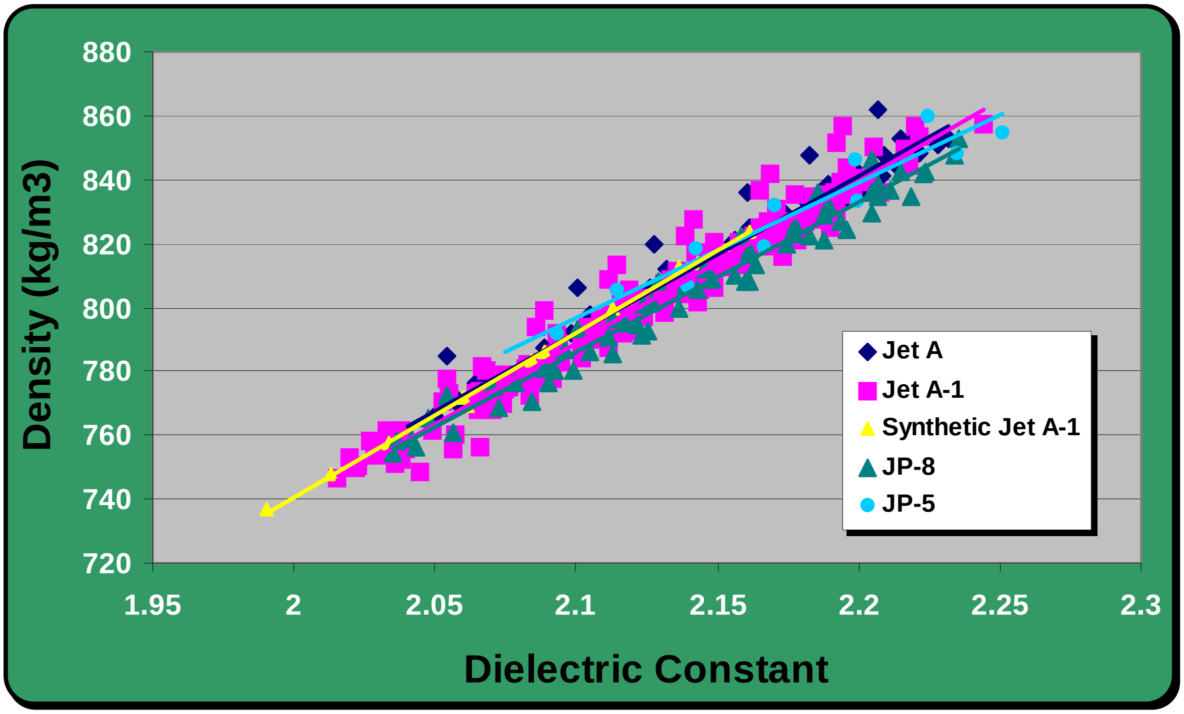

Figure 5.2.2. Dielectric Constant Versus Density

5.3 Velocity of Sound Versus Temperature and Density

On some aircraft, velocity of sound (Vos) data are used to design the fuel gauging system. Vos testing was performed by Goodrich and is plotted as a function of temperature in Figure 5.3.1. In general, there was a nearly linear correlation for all fuel types. All R^2 values were above 0.96, Table 5.3.1. Because sound moves through dense materials faster, it follows that Jet A-1 and JP-8 fuels, which contain lighter, lower freezing components, should have a slightly lower velocity of sound when compared to Jet A and JP-5.

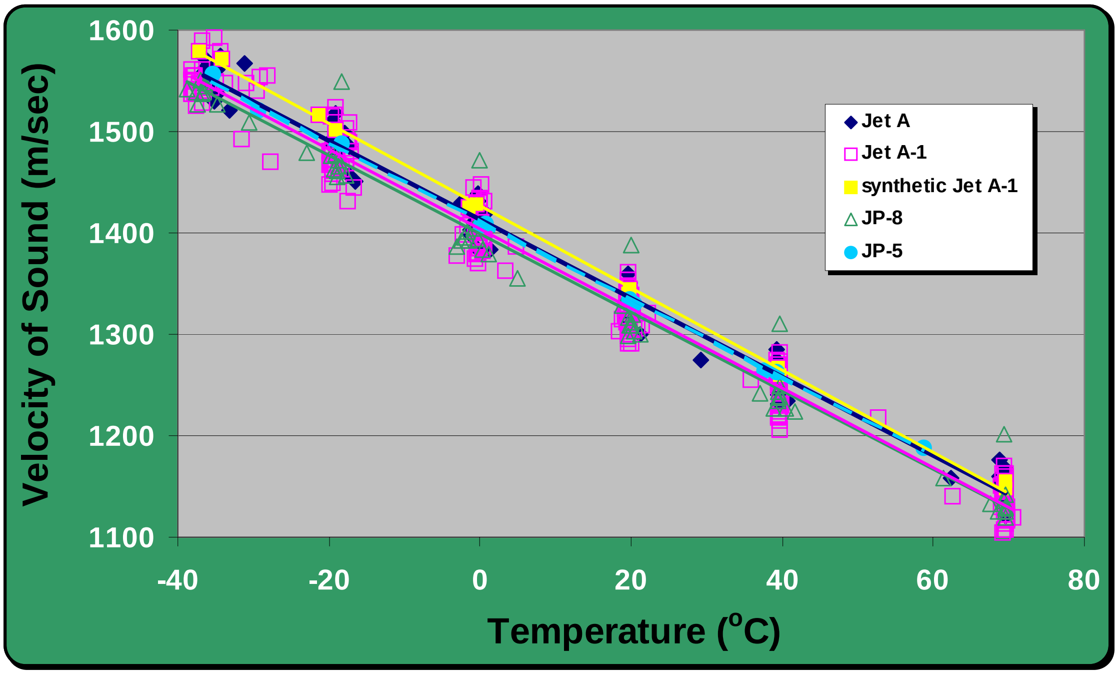

FIGURE 5.3.1. VELOCITY OF SOUND VERSUS TEMPERATURE WITH BEST FIT TRENDLINES

Summary—Velocity of Sound (m/s) Versus Temperature (°C)		
Fuel	Linear Fit Equation	Regression Fit Value (R^2)
Jet A	**Vos** = –3.8850x**T** + 1413.7	0.9860
Jet A-1	**Vos** = –3.9106x**T** + 1402.2	0.9779
Jet A-1 Syn	**Vos** = –4.0467x**T** + 1426.4	0.9986
JP-5	**Vos** = –3.8276x**T** + 1413.0	0.9985
JP-8	**Vos** = –3.8678x**T** + 1399.4	0.9658

Table 5.3.1. Regression Analysis of Vos Versus Temperature

When the velocity of sound is plotted against density, similar results are seen, Figure 5.3.2. It may be noted that the synthetic fuel samples were shifted in relation to the other samples.

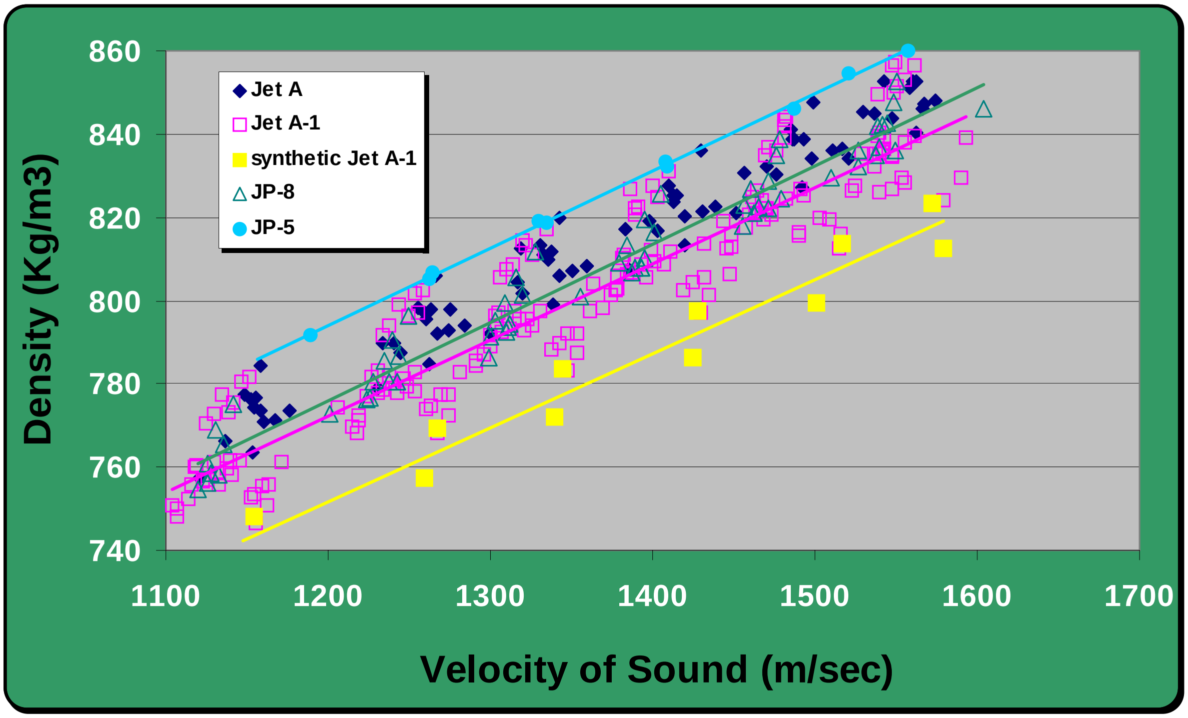

FIGURE 5.3.2. DENSITY VERSUS VELOCITY OF SOUND WITH BEST FIT TRENDLINES

Summary—Density (kg/m^3) Versus Velocity of Sound (m/s)		
Fuel	Linear Fit Equation	Regression Fit Value (R^2)
Jet A	**D** = 0.1879x**Vos** + 556.05	0.9539
Jet A-1	**D** = 0.1847x**Vos** + 551.82	0.8740
Jet A-1 Syn	**D** = 0.1780x**Vos** + 538.09	0.9565
JP-5	**D** = 0.1850x**Vos** + 572.21	0.9989
JP-8	**D** = 0.1881x**Vos** + 550.06	0.9599

Table 5.3.2. Regression Analysis of Density Versus Vos

6. Fuel Sample Properties—General Electric/ Southwest Research Institute

6.1 Thermal Stability

At high temperatures, jet fuels can form deposits and coatings within engine components such as fuel nozzles, heat exchangers, and control valves [16]. These deposits can interfere with the component operation such as nozzle spray pattern, creating hot spots in the combustion chamber, which leads to decreased operating life. Deposits can also adversely affect fuel flow and heat exchanger efficiency.

Jet fuel specifications limit the amount of deposits that a fuel can produce by setting a minimum passing temperature of 260°C per ASTM D 3241. Deposit formation is measured by the JFTOT, defined by ASTM D 3241. In this method, fuel is passed over a heated aluminum tube and then through a 17-μm stainless steel mesh filter. The tube surface is examined for deposits and assigned a numerical rating to quantify the visual appearance on a JFTOT tube. Higher numerical ratings indicate greater deposit formation. Pressure drop through the filter is also recorded, and excessive values can fail a fuel. See Table 6.1.1 for JFTOT tube color and pressure drop requirements per ASTM D 1655. The JFTOT can be run at successively higher test temperatures until a failed rating is produced. Generally, 'breakpoint testing' is run at 5°C intervals. The highest temperature at which the fuel passed (i.e., had a tube rating below 3 and a pressure drop below 25 mmHg) is called the "fuel break point." Fuel specifications do not require testing to determine the break point temperature; however, a fuel must have a tube rating of less than three and a pressure drop of less than 3.3 kPa (25 mmHg) at 260°C. The fuel samples were tested to determine their breakpoint temperature to provide a basis to compare thermal stability between fuels.

Fuel	Value (Tube rating, Pressure Drop)	Specification
Jet A		
Tube rating (visual)	<3	ASTM D 1655
Pressure drop (kPa)	3.3 maximum	
Jet A-1		
Tube rating (visual)	<3	Def Stan 91-91
Pressure drop (mmHg)	25 maximum	
JP-5		
Tube rating (visual)	<3	MIL-DTL-5624U
Pressure drop (mmHg)	25 maximum	
JP-8		
Tube rating (visual)	<3	MIL-DTL-83133E
Pressure drop (mmHg)	25 maximum	

Table 6.1.1. Thermal Stability Specifications at a Test Temperature of 260°C

Figure 6.1.1 shows the thermal stability break point temperatures of the fuel sample set by region and fuel type. ***Of the 57 samples, only one sample failed JFTOT acceptance criteria, 260°C. That sample had a breakpoint of 235°C. However, it was known prior to testing that this jet fuel failed JFTOT. It was included in the database of samples to gain knowledge on what other fuel properties are affected when a jet fuel fails the JFTOT requirement. The analysis showed that no other property was off specification or looked abnormal***. When this sample is excluded, JFTOT testing showed that all fuel from all regions performed similarly. The average breakpoint temperature was approximately 287°C.

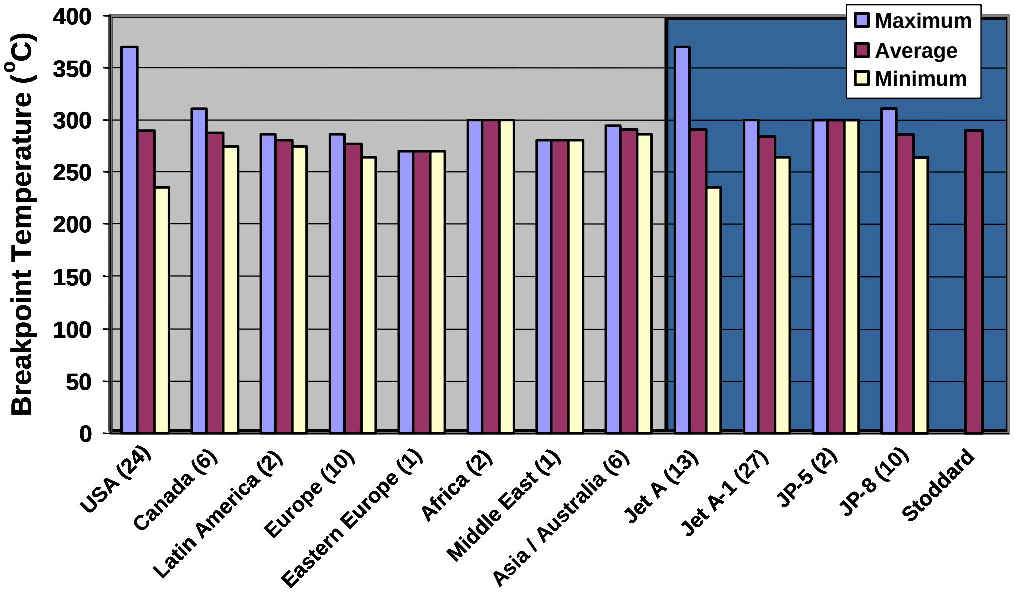

FIGURE 6.1.1. BREAK POINT TEMPERATURE DISTRIBUTION

Further research that analyzed these fuels, along with 19 other fuels, was completed by Southwest Research Institute®. The research investigated the affect of aging on fuel thermal stability. The report submitted by SwRI is attached, in its entirety, as Appendix E.

6.2 Specific Heat Capacity

Specific heat capacity (J/g/K) is the amount of heat (in joules) required to raise the temperature of one gram of fuel 1ºC (or K). Specific heat is used in fuel system design and analysis.

Heat capacity measurements were done at the University of New Hampshire, using a slightly modified ASTM E 1269-01 test method. A more detailed discussion can be found in Appendix A.

Test data were measured at several temperatures over the range from –30°C to 144°C. The heat capacities of the samples were found to be linear. The heat capacity data are recorded in J/g/K at 0°C, and each sample has an associated slope (as a function of temperature), which can be incorporated into an equation to determine the specific heat at any temperature within the given range.

Specific heat capacities and corresponding slopes are shown in Figures 6.2.1 and 6.2.2.

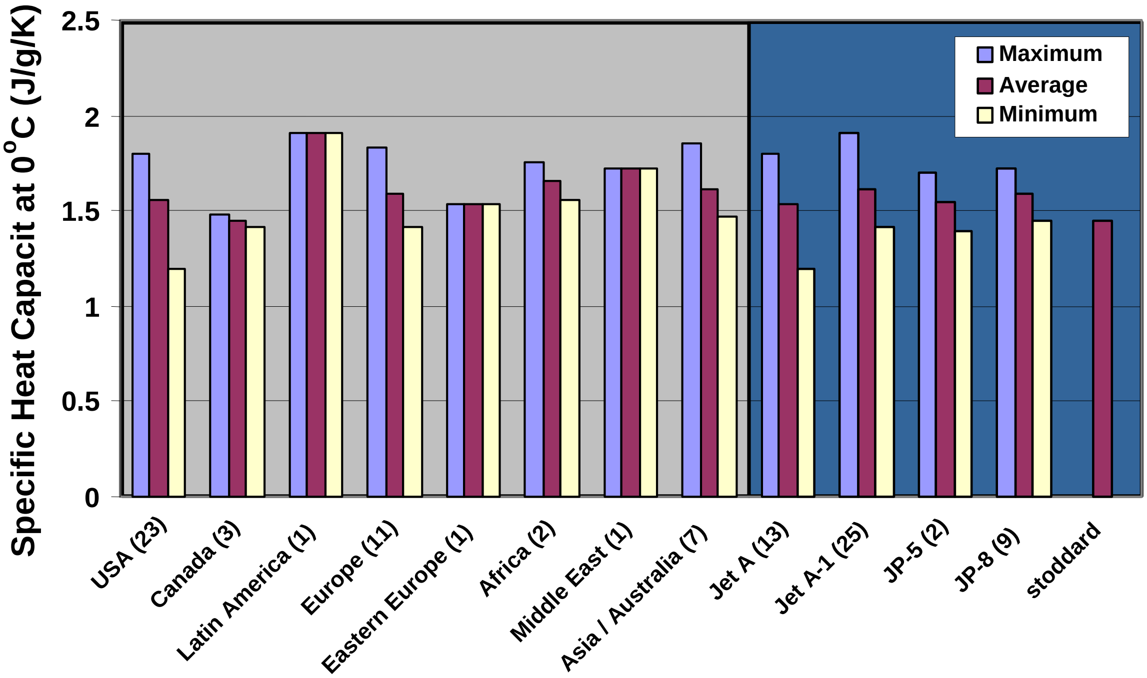

FIGURE 6.2.1. DISTRIBUTION OF SPECIFIC HEAT CAPACITY VALUES

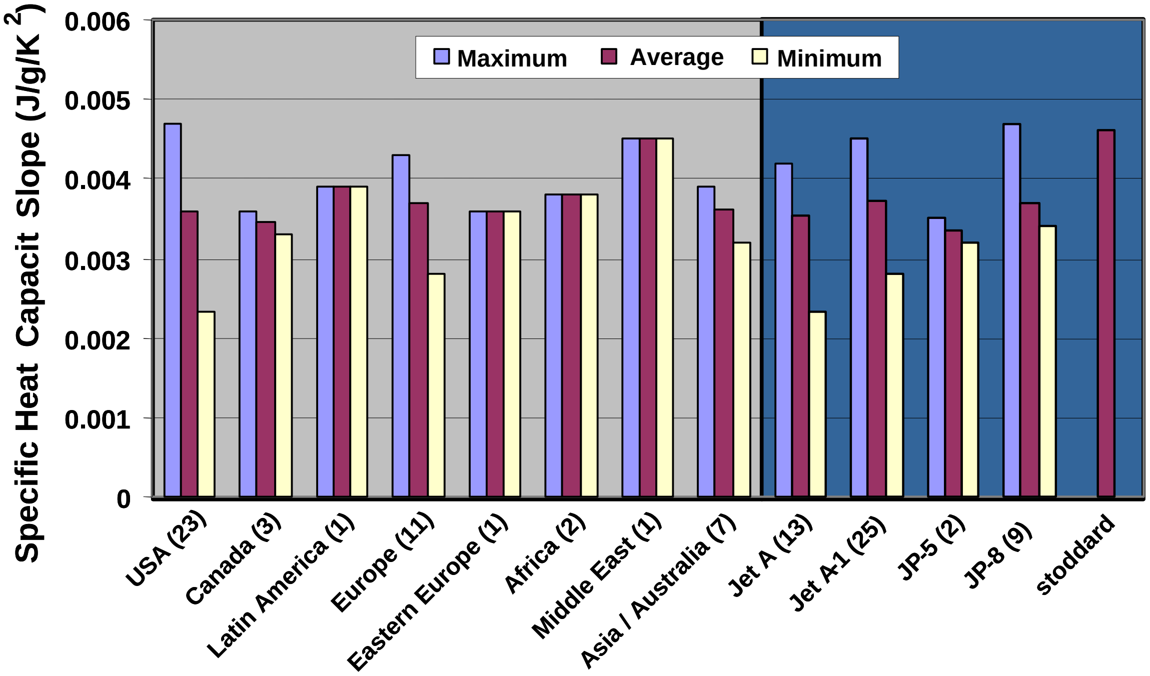

FIGURE 6.2.2. SLOPE OF HEAT CAPACITY: AS A FUNCTION OF TEMPERATURE

These specific heat data are low when compared to other literature values. Figure 6.2.3 compares this program's test data with that found in the CRC Handbook [12]. Also see Appendix I for continued discussion based on testing done a year after these results.

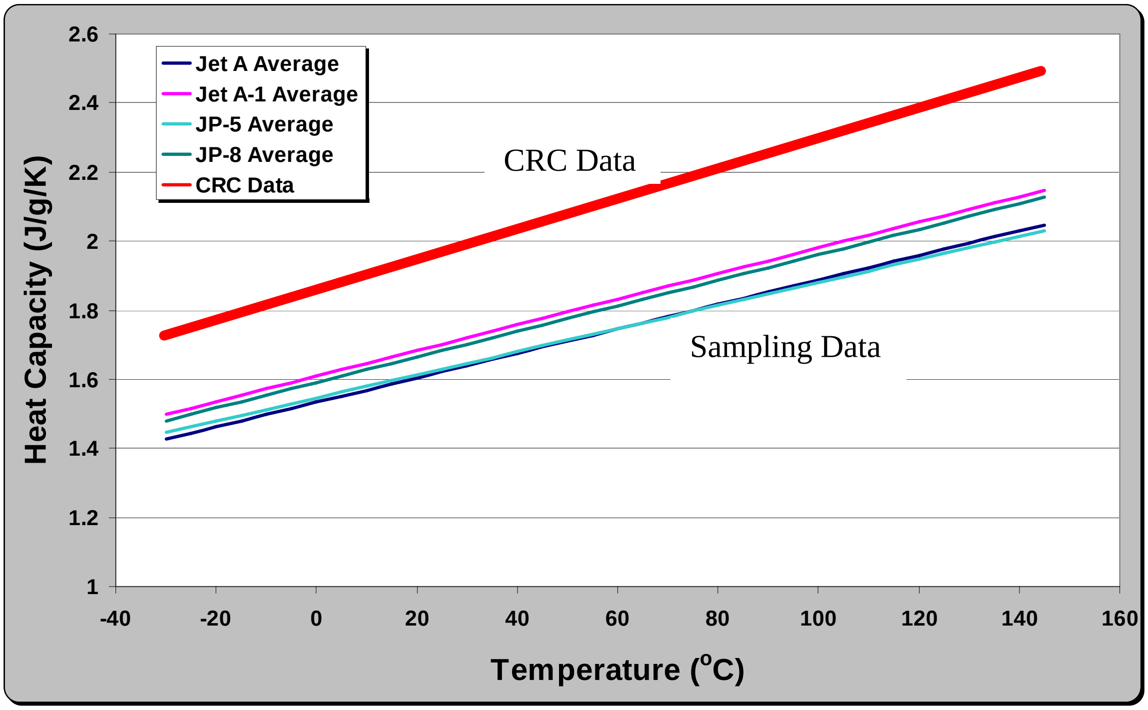

FIGURE 6.2.3. FUEL SAMPLING DATA COMPARED TO CRC DATA

6.3 Surface Tension

Atomization of fuel in engines is affected by the fuel surface tension. Polar substances, such as water tend to have high surface tension. Hydrocarbon substances, such as jet fuel, tend to have lower surface tension values [12]. Testing was done at three temperatures: ambient (approximately 22°C), -10°C, and 40°C. Surface tension values for Sasol synthetic fuels were low when compared to the rest of the sample set, Figure 6.3.1.

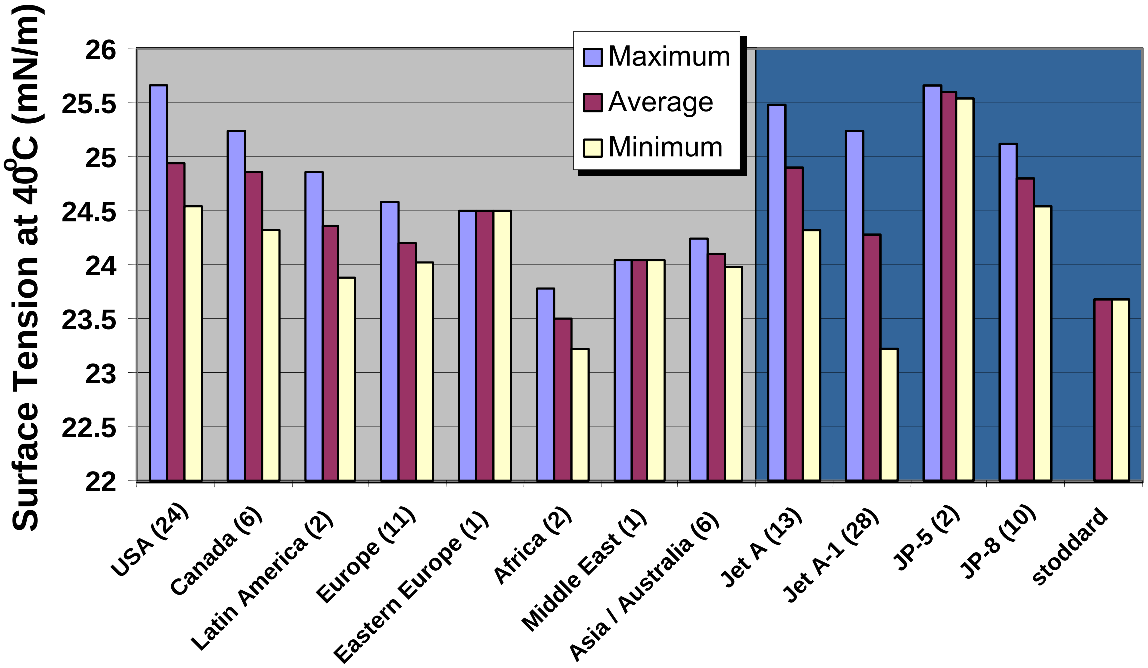

FIGURE 6.3.1. SURFACE TENSION DISTRIBUTION

Surface tension values found in the survey were high when compared to values found in the CRC handbook [12], Figure 6.3.2.

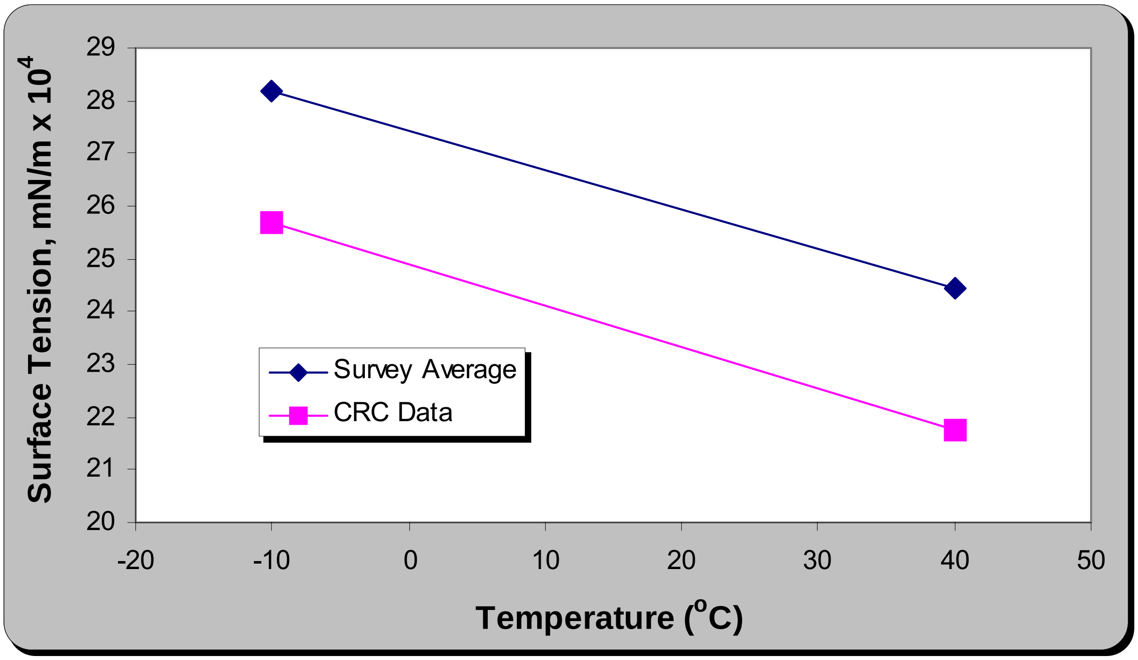

Figure 6.3.2. Surface Tension Values of Surveyed Fuels and CRC Data

According to SwRI, values quoted in the CRC Handbook [12] are mathematical estimates calculated from the chemical properties of individual fuels. A review of the references quoted in the CRC Handbook suggests that the calculations were based on simple hydrocarbons and did not take into account the hydrocarbon structure. To investigate this theory, four additional samples were tested. These samples consisted of:

1. IPK –Iso Paraffinic Kerosene: This is the basic building block of synthetic jet fuel. The material selected was in the same boiling point range as jet fuel
2. B 85-15: This is a blend of 85% IPK and 15% Aromatic 150
3. B 80-10-10: This is a blend of 80% IPK, 10% Aromatic 150 and 10% Decalin
4. Aromatic 150: A blend of single ring aromatic chemicals in the jet fuel boiling point range

The results of these additional tests show the effects of chemical structure on surface tension, Figure 6.3.3. While the actual test results are still above the CRC estimates, they show the difference is most likely influenced by the exact chemical nature of the fuels in question.

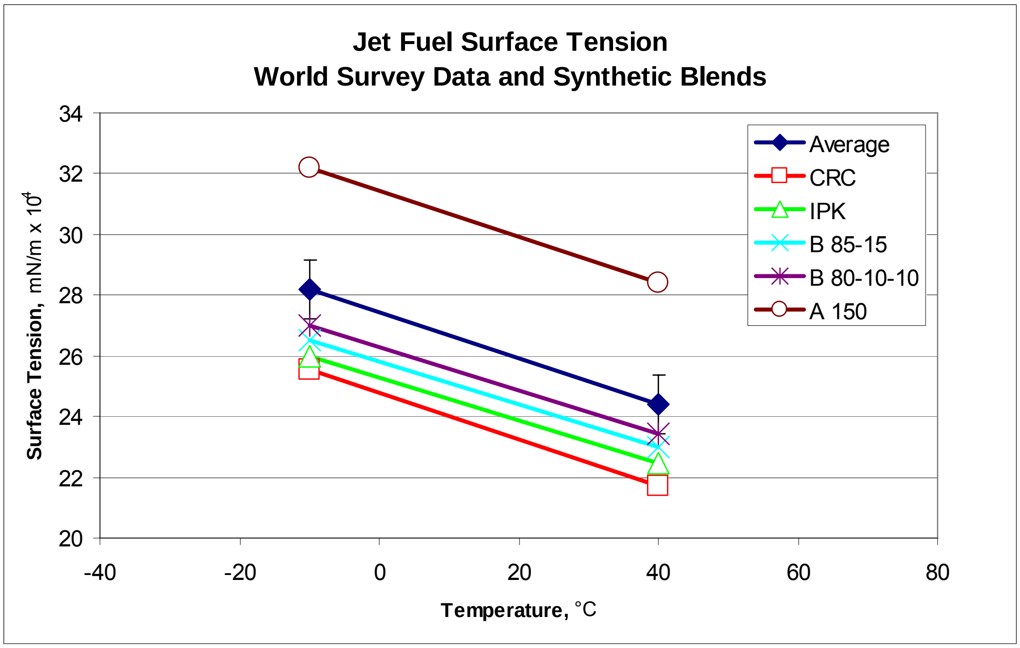

Figure 6.3.3. Surface Tension of Fuels and Blends

6.4 *Acid Number*

Acid levels in jet fuel are a concern due to their corrosive nature and affect on water separation properties. Acids can be naturally occurring in crude oil or can be added as a result of refinery processing. Table 6.4.1 shows specification requirements for typical fuels. Jet A has a noticeably higher allowed acidity per ASTM D 1655.

Fuel	Value (mg KOH/g)	Specification
Jet A	0.100 *Max*	ASTM D 1655
Jet A-1	0.015 *Max*	Def Stan 91-91
JP-5	0.015 *Max*	MIL-DTL-5624U
JP-8	0.015 *Max*	MIL-DTL-83133E

Table 6.4.1. Acidity Specifications

Figure 6.4.1 shows the distribution of acid number by location and fuel type. One JP-8 sample would have failed acidity under the current specification limit of 0.015 mg KOH/g. It had an acidity of 0.019 mg KOH/g. This particular sample also had a low breakpoint temperature of 265°C. However, no general correlation was found between thermal stability and acidity over the entire sample set.

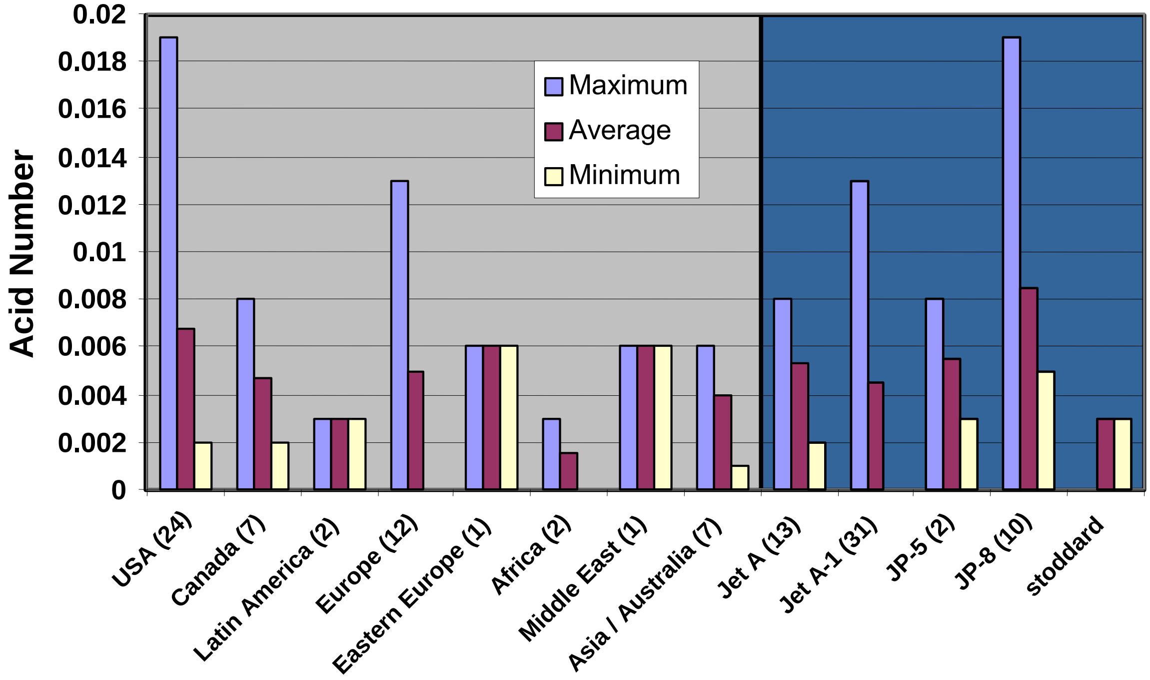

FIGURE 6.4.1. ACID NUMBER DISTRIBUTION

7. Fuel Sample Properties—Air Force Research Labs

7.1 Sulfur Compounds

This section of testing focused on separating and identifying specific sulfur compounds based on class and/or ring number. A novel pre-separation method was used to enable the more efficient use of detection methods such as mass spectrometry (MS) and atomic emission detection (AED). Methods used to separate and identify the sulfur classes are summarized in Reference 18.

Of the sulfur-containing species in the fuel, the "reactive" group, consisting of thiols, sulfides, and disulfides, made up the vast majority of the total sulfur composition, Figure 7.1.1. On average, 63% of the sulfur content is composed of the reactive sulfur compounds. The remaining sulfur composition was approximately 21% benzothiophenes, 13% dibenzothiophenes, and 3% thiophenes.

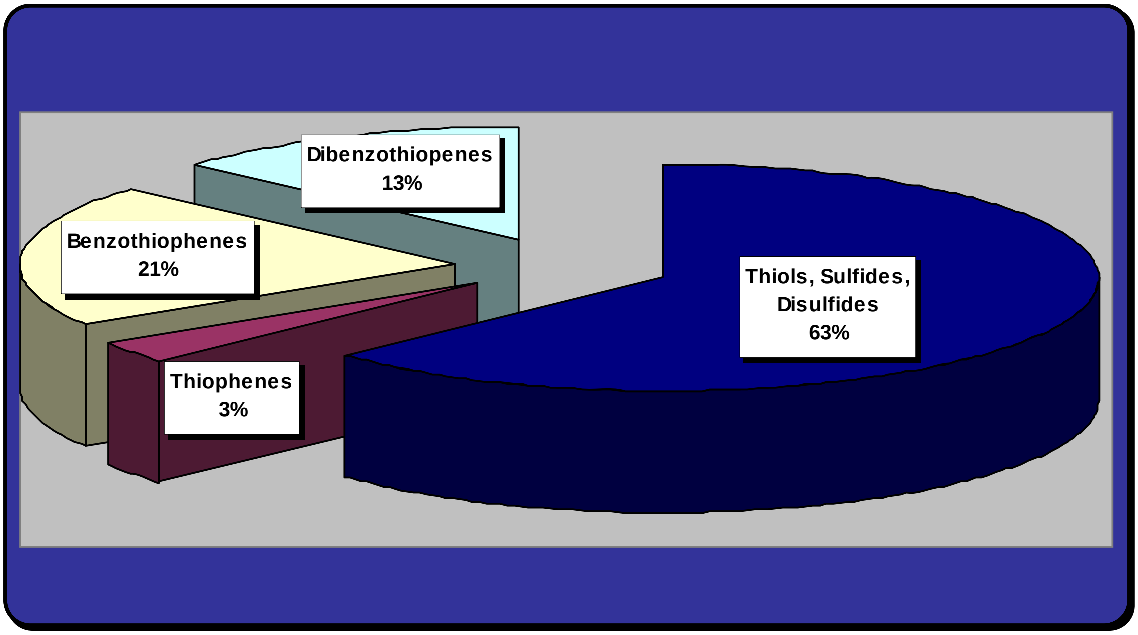

FIGURE 7.1.1. SULFUR COMPOSITION FOR AN AVERAGE FUEL

The four classes of sulfur compounds are plotted as a function of location and fuel type in Figures 7.1.2 through 7.1.5. AFRL also determined the total sulfur in the samples by an internal test method, and results are shown in Figure 7.1.6. A comparison of the Boeing sulfur data and the AFRL data highlighted some inconsistencies believed to be inherent in the two test methods. The average sulfur level by the AFRL method was 456 ppm, which is similar to the Boeing data. However, on a sample-by-sample comparison between the two methods, the average difference was 81 ppm. This highlights a concern as to what sulfur detection method should be used for jet fuels, especially for low-sulfur jet fuels.

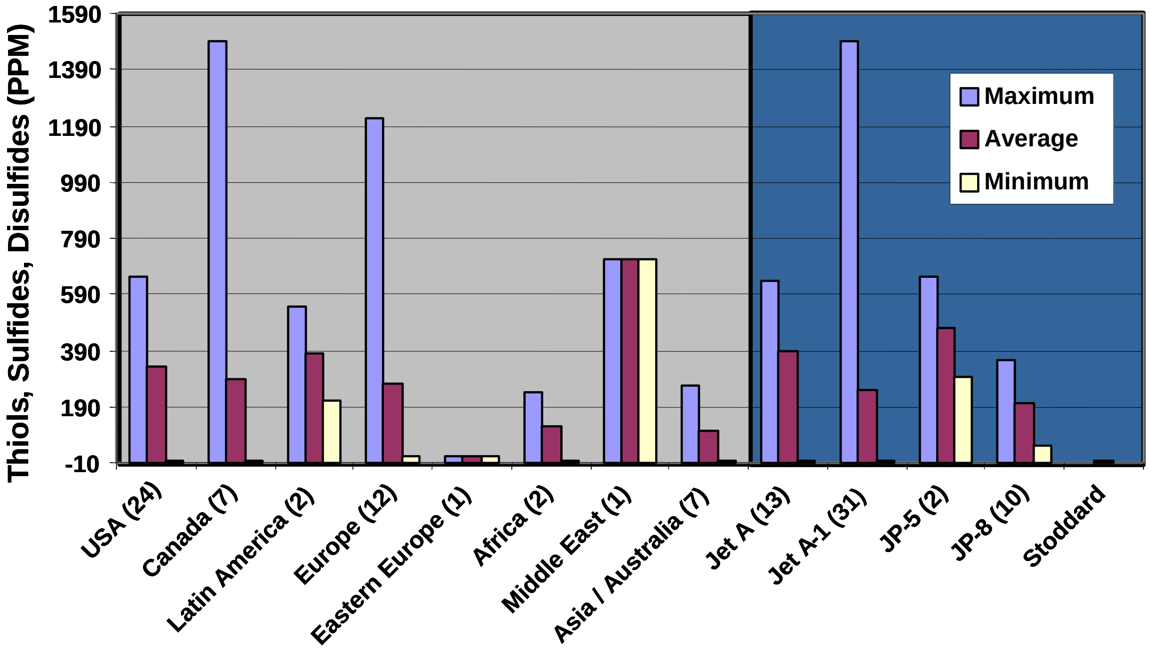

FIGURE 7.1.2. CONTENT OF THIOLS, SULFIDES, AND DISULFIDES

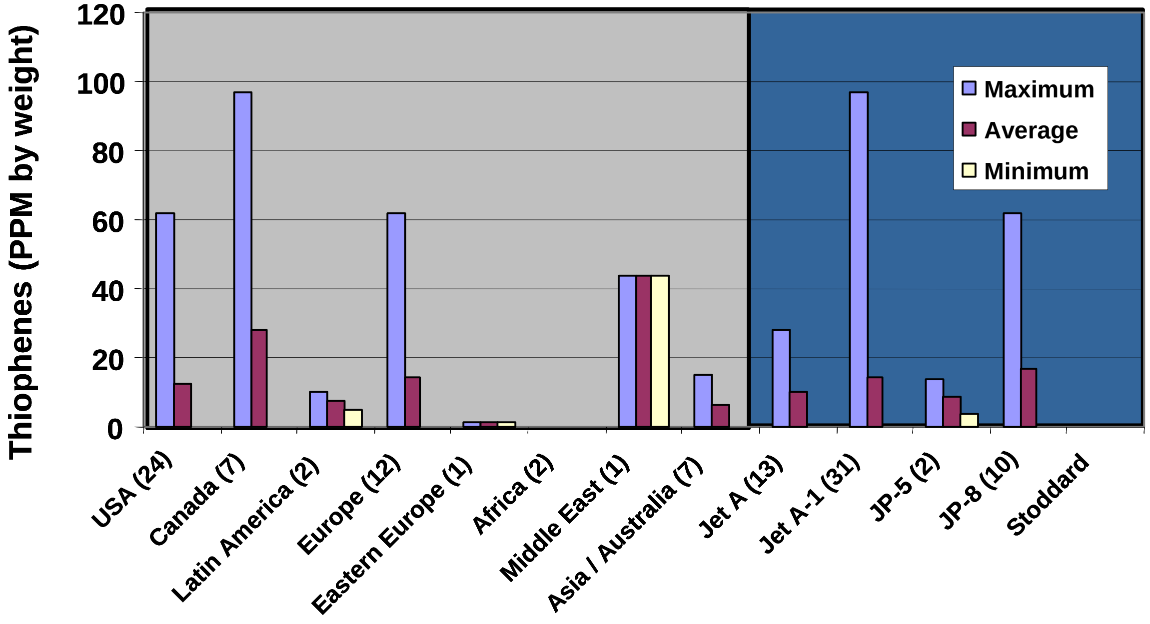

FIGURE 7.1.3. THIOPHENE CONTENT DISTRIBUTION

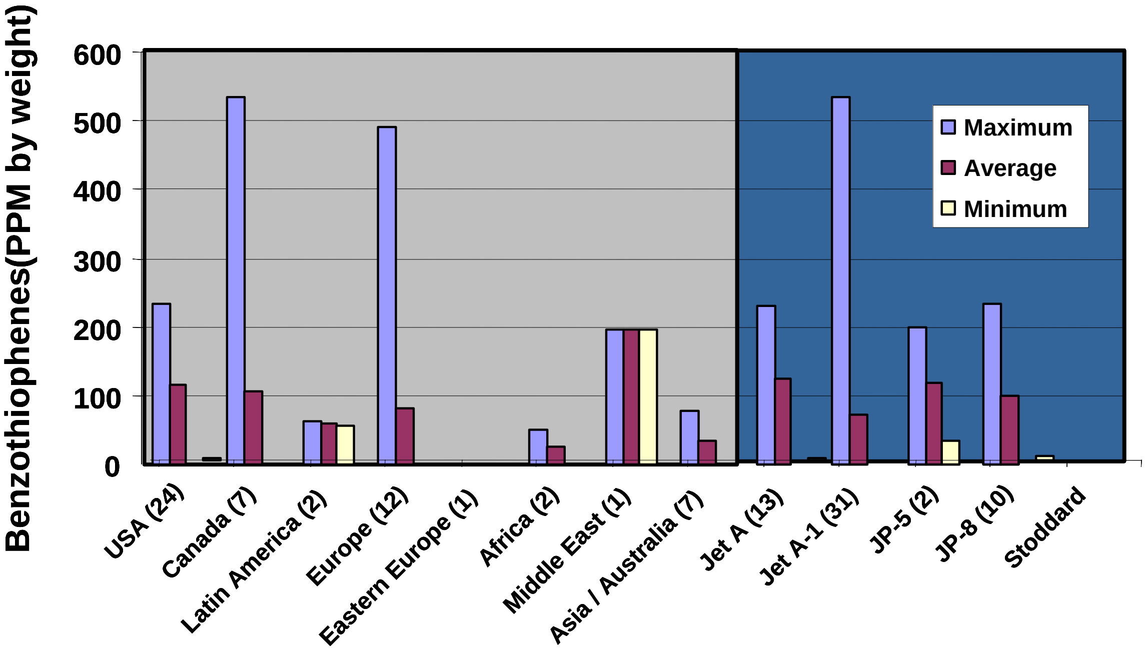

FIGURE 7.1.4. BENZOTHIOPHENE CONTENT DISTRIBUTION

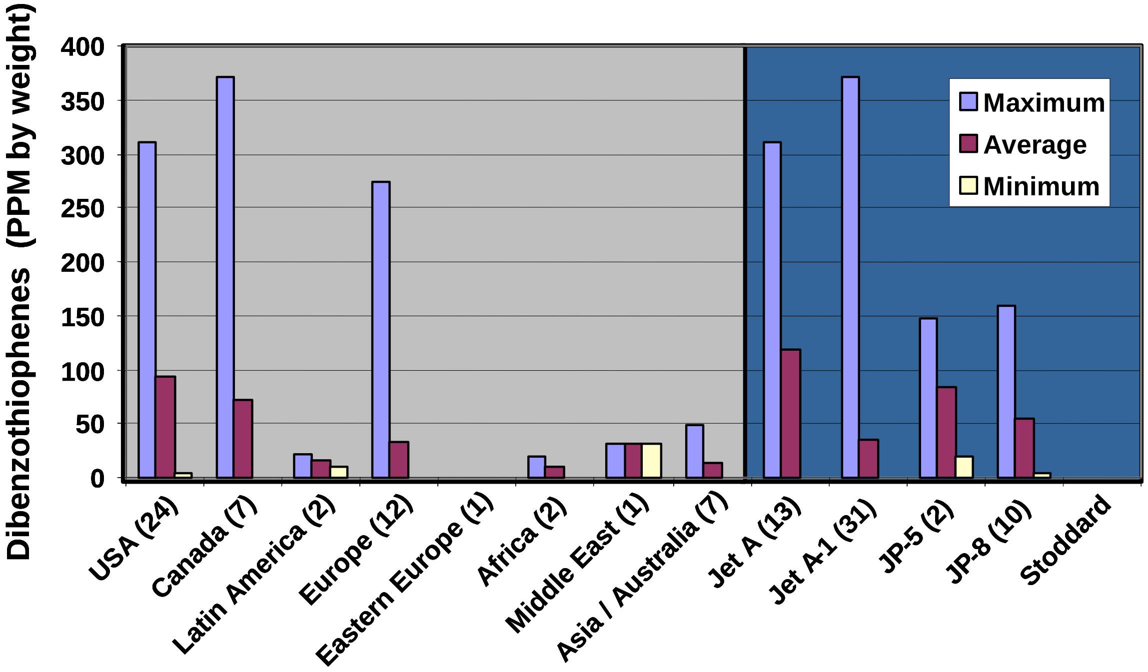

FIGURE 7.1.5. DIBENZOTHIOPHENE CONTENT DISTRIBUTION

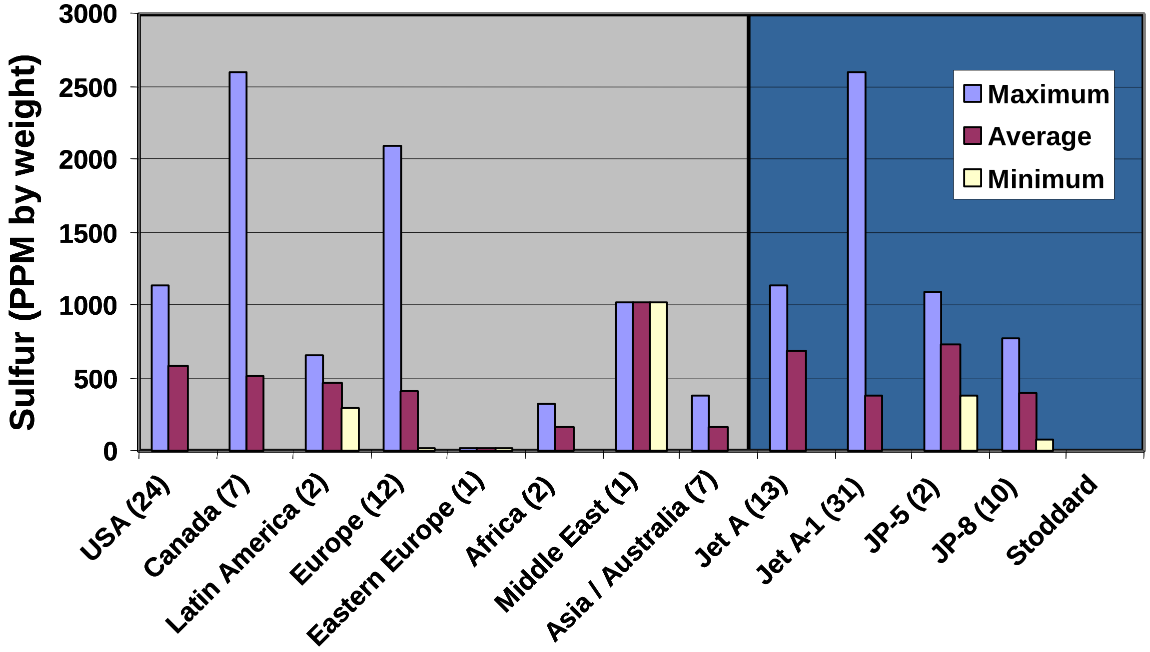

FIGURE 7.1.6. TOTAL SULFUR CONTENT DISTRIBUTION

7.2 Mercaptan Sulfur

Mercaptan-type sulfur molecules are a particularly unpleasant species of sulfur as they are known to be corrosive to fuel system components and they tend to have a foul odor. Due to these affects, specifications for jet fuel restrict the allowed concentration, as shown in Table 7.2.1. Mercaptan sulfur content is determined using ASTM D 3227.

Fuel	Value, °C (°F)	Specification
Jet A	0.003 wt% *max* *Or* Negative Doctor Test	ASTM D 1655
Jet A-1	0.003 wt% *max* *Or* Negative Doctor Test	Def Stan 91-91
JP-5	0.002 wt% *max* *Or* Negative Doctor Test	MIL-DTL-5624U
JP-8	0.002 wt% *max* *Or* Negative Doctor Test	MIL-DTL-83133E

Table 7.2.1. Mercaptan Sulfur Specifications

Under the specifications listed in Table 7.2.1, a fuel may also pass this requirement with a negative result from ASTM D 4952 (Doctor Test). The doctor test will indicate the presence of hydrogen sulfide or mercaptan sulfur species. In this test, sodium plumbite is mixed with the fuel sample, which is then inspected for discoloration. If no discoloration occurs, the fuel passes the test and the mercaptan sulfur test is not needed.

A significant portion of jet fuel is processed by either hydrotreatment or Merox® (Mercaptan Oxidation) conversion. Hydroprocessing reacts the sulfur species with hydrogen gas, which is subsequently removed as H_2S, lowering the overall sulfur content. Merox conversion converts the mercaptan sulfur to a disulfide, which remains in the fuel, keeping the overall sulfur content the same. Some Merox processes do remove some of the disulfides.

In general, levels of mercaptan sulfur are low in fuels and this is supported by the fuel sampling data presented herein. Average mercaptan sulfur content was 0.00021 wt%; a factor of 10 below the maximum allowed, Figure 7.2.1. Mercaptan sulfur content was compared to fuel appearance and, specifically, odor. Mercaptans are often correlated with foul odor, however; no trend was observed for these fuel samples.

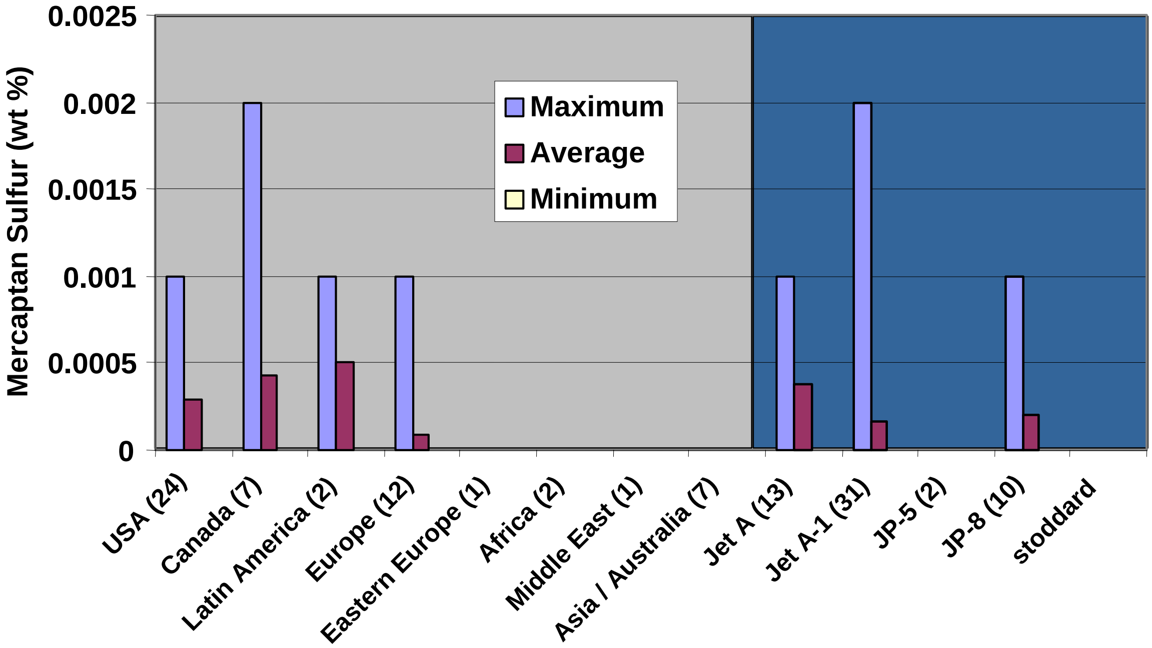

FIGURE 7.2.1. DISTRIBUTION OF MERCAPTAN SULFUR CONTENT

8. Fuel Sample Properties—Air Force; Mukilteo (Washington) Laboratory

8.1 Lubricity

Aircraft components such as valves and pumps rely on the fuel to provide adequate lubrication to moving parts. Fuel that has poor lubricating properties will cause components to degrade and will lead to premature failure and increased maintenance costs. Polar components, such as oxygen, nitrogen, and sulfur, are thought to provide much of the lubricating properties to aviation jet fuels [8, 13, 19].

Only one jet fuel specification has a lubricity requirement, and the requirement in that specification is only for some specifically manufactured jet fuel, Table 8.1.1. JP-5 and JP-8 require a corrosion inhibitor additive that improves lubricity; although, the military specifications do not explicitly require a lubricity test or maximum wear scar value. Test results showed that JP-5 and JP-8 had lower wear scar values when compared to Jet A and Jet A-1 fuels (see Figure 8.1.1). ASTM D 5001, BOCLE test, was performed on the fuel samples at the Air Force Mukilteo Laboratory, which has since been shut down and the equipment moved. As a consequence, one sample (#304) was tested in the ChevronTexaco laboratory.

Fuel	Value (wear scar diameter, mm)	Specification
Jet A	—	—
Jet A-1	0.85*	Def Stan 91-91
JP-5	—	—
JP-8	—	—

*Applies only to fuels containing more than 95% hydroprocessed fuel, where at least 20% of it is severely hydroprocessed, and for all fuels containing synthetic components.

Table 8.1.1. Lubricity Specifications

The BOCLE test results are shown in Figure 8.1.1. The average wear scar diameter (WSD) was approximately 0.63 mm, with a range of 0.45 to 0.75 mm.

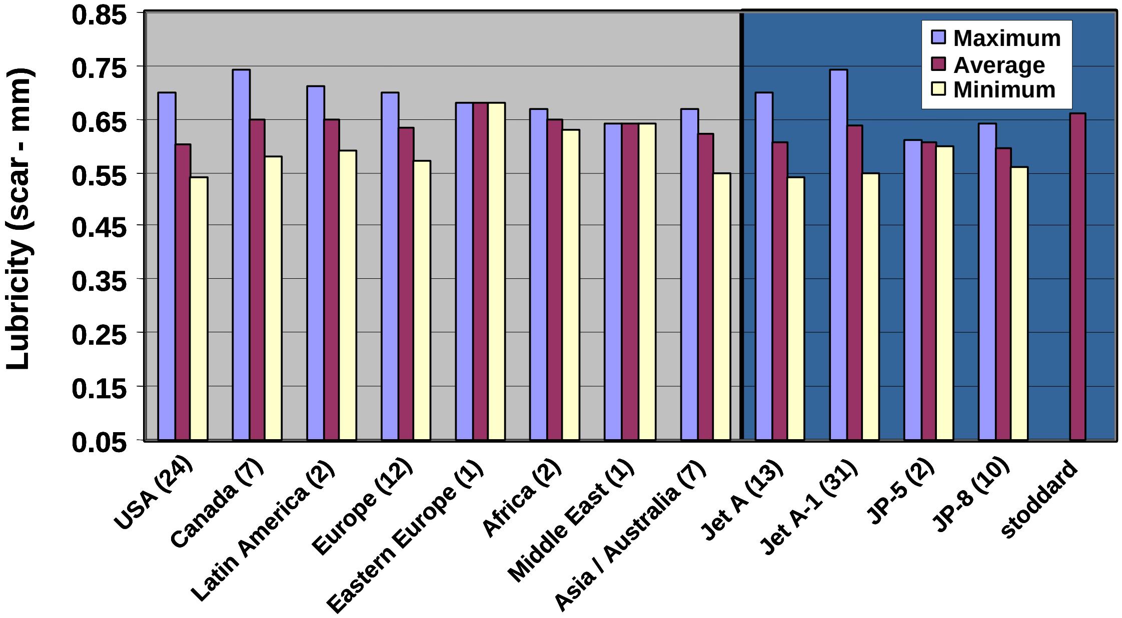

FIGURE 8.1.1. LUBRICITY TEST RESULTS

Test data showed no correlation with sulfur content. However, at extremely low sulfur levels (less than 100 ppm), there does appear to be a noticeable increase in WSD, Figure 8.1.2. It should be noted, however, that all fuels had a WSD less than the DEF-STAN maximum permited requirement, 0.85 mm.

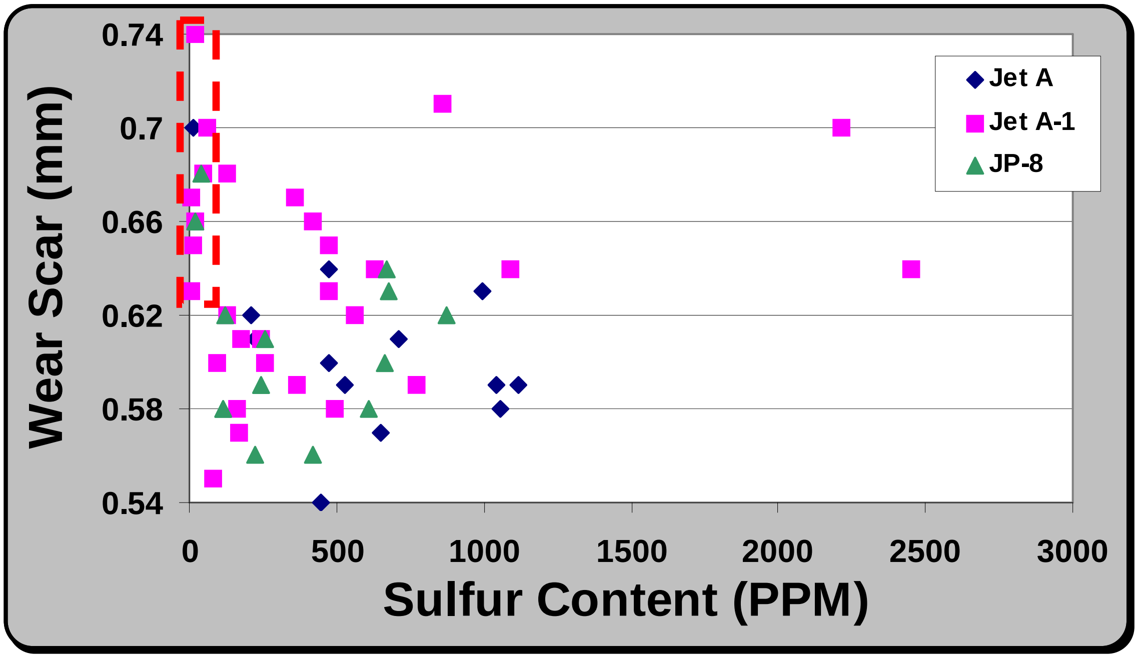

FIGURE 8.1.2. WEAR SCAR DIAMETER AS A FUNCTION OF SULFUR CONTENT

9. Anomalies

Some anomalies were noted in the test results from the 57 samples. These are discussed below.

9.1 Conductivity

In general, sample data behaved according to theory in that conductivity increased with increasing temperature. However, some samples behaved erratically or even contrary to theory. Of these, the majority of the samples have conductivity values that are low and data tends to be erratic. The erratic values are close to the reproducibility of the instrument [20], especially at these low values. However, some fuels had higher readings and still showed erratic behavior. An example of this is sample 606 (United Arab Emirates), which showed a decrease in conductivity as temperature was increased. There have been some reports of these fuels but they are rare. Figure 9.1.1 is a plot of some samples that behaved erratically.

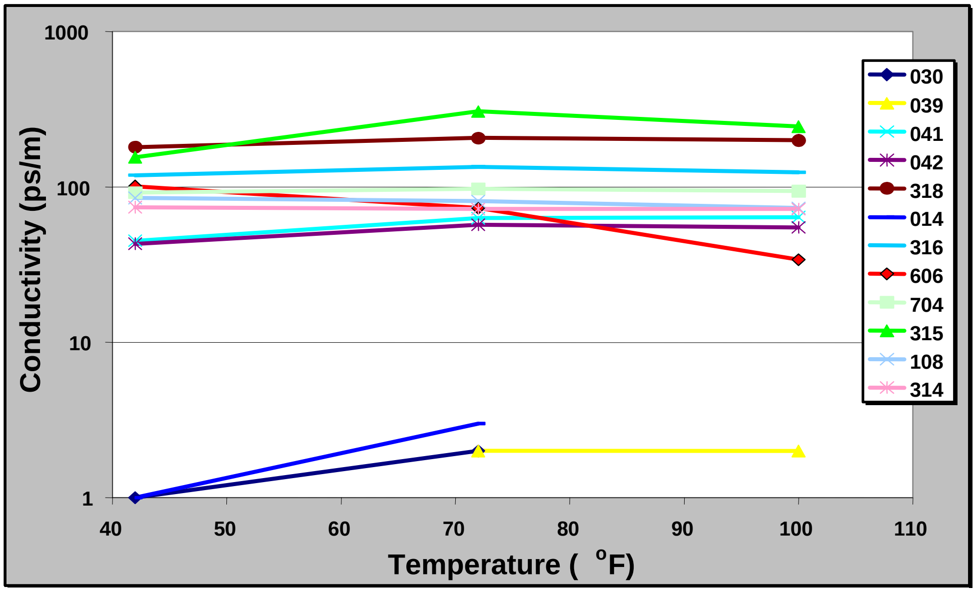

FIGURE 9.1.1. OUTLIERS IN CONDUCTIVITY TESTING

9.2 Distillation

Even as distillation profiles fell within specifications, the leftover residue was excessive in a large portion of the fuels tested, Figure 9.2.1. Overall, the average distillation residue was greater than 1.45% (by volume) and 12% of the samples tested would have failed under the ASTM D 1655 criteria of 1.5% maximum, Figures 9.2.2 and 9.2.3.

The excessive residue may lower the final boiling point somewhat, but no attempt was made to quantify the temperature impact. It is believed to be small.

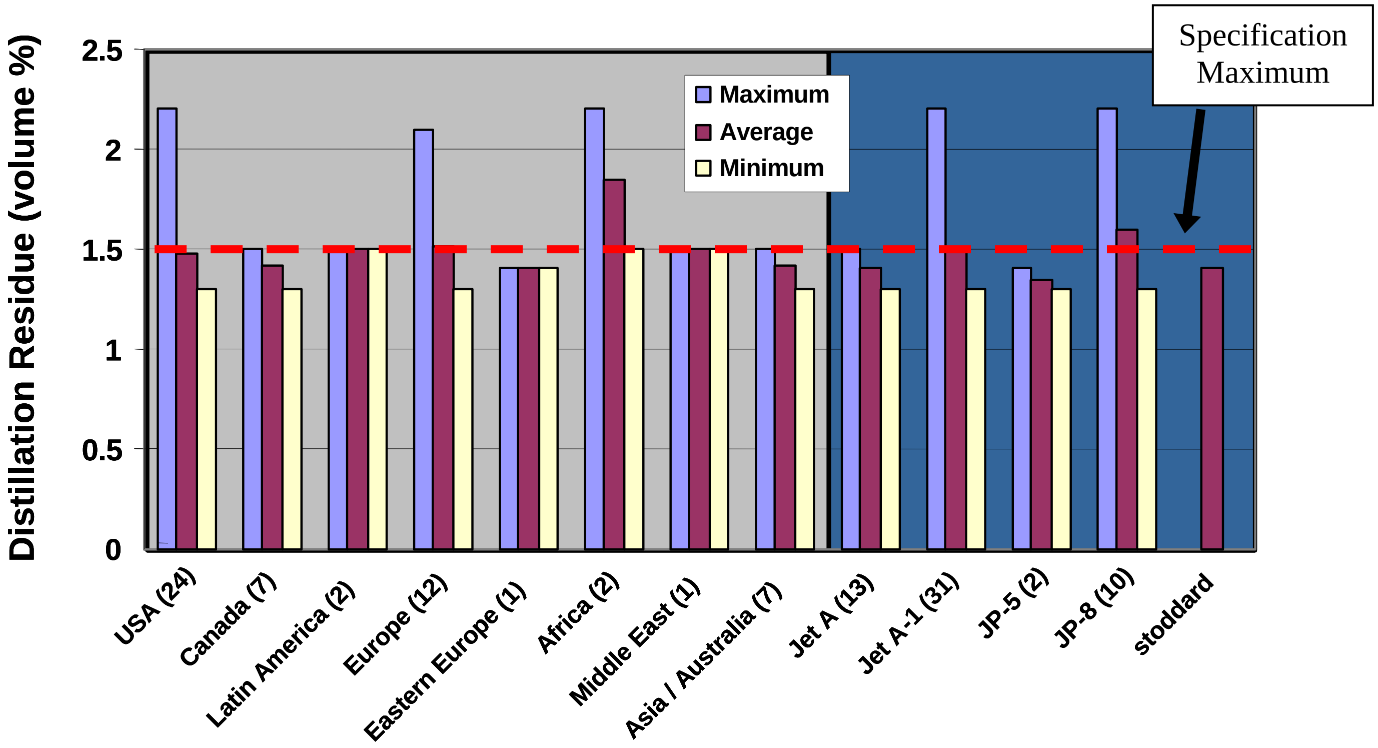

FIGURE 9.2.1. DISTRIBUTION FOR DISTILLATION RESIDUE

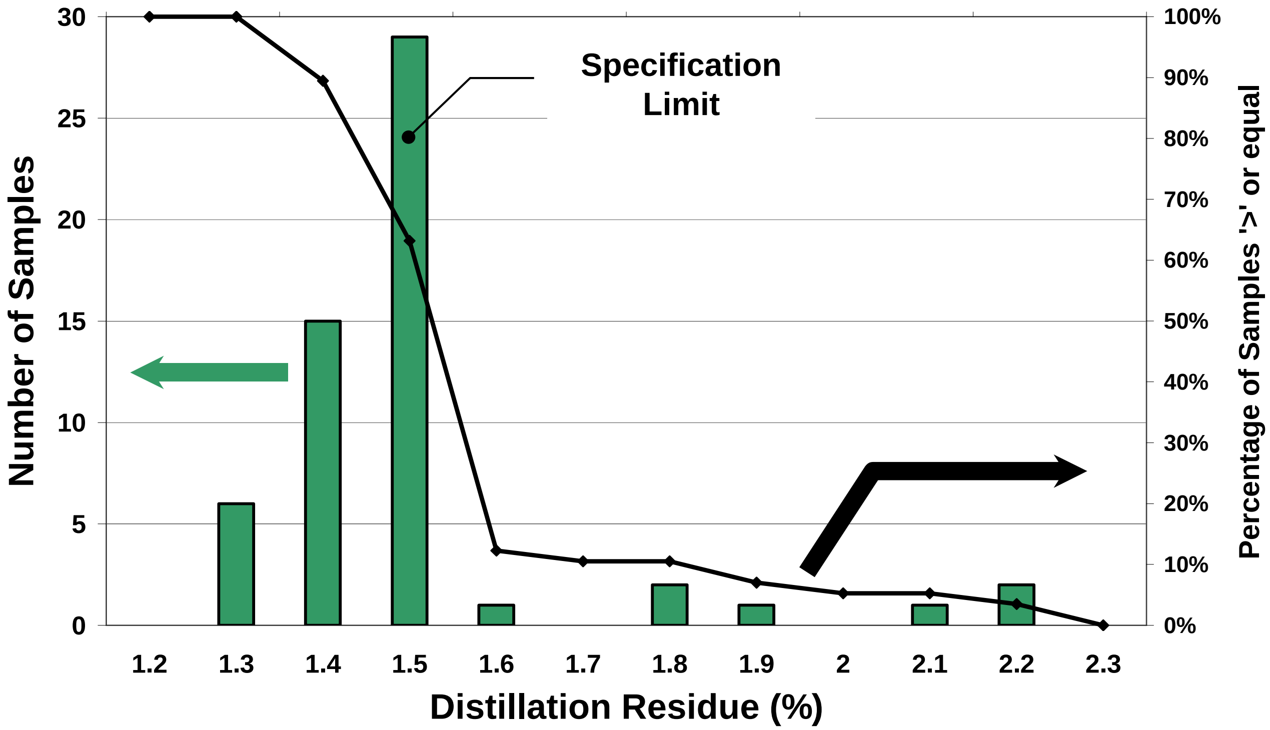

FIGURE 9.2.2. RANGE OF RESIDUE VALUES

Residue levels from this testing program were found to be high when compared with typical values found in literature, Figure 9.2.3. The deviation may be due to differences in laboratory test apparatus, specifically located in the software of automated distillation apparatus. ISL AD 5G was the automated device used for testing under this program and came pre-packaged with software that controlled the heat setting during testing. It was discovered that it is a relatively common practice in many laboratories to manually adjust the heat settings found in the software so that the heat applied at the end of the run is increased 5% to 10% above the factory settings (this is allowed under the ASTM test method). Increasing the heat addition helps to compensate for the relative inefficiency of the distillation method and acts to decrease the residue found for each sample. Because of inefficiencies related to this method, high residues may be an artifact of the test method and may not reflect a real fuel property. Distillation apparatus software used in this round of testing was not adjusted, which could have contributed to the observed high residue values when compared to literature values.

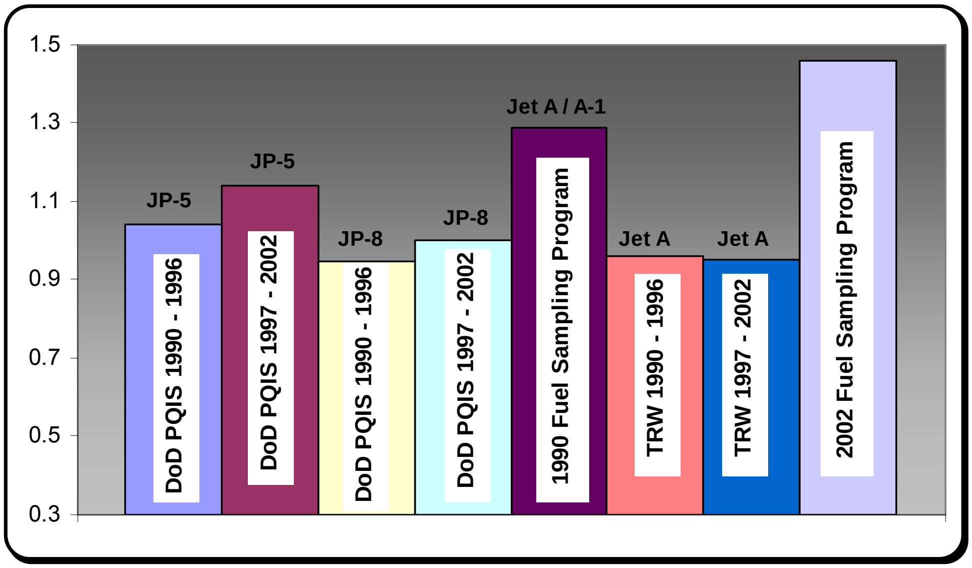

FIGURE 9.2.3. SELECTED LITERATURE VALUES OF DISTILLATION RESIDUE

9.3 Heat Content

Two of the fuel samples, numbers 007 and 020 (both Jet A fuel type), had heat contents below 18,400 Btu/lb. High density, low hydrogen content fuels often exhibit low heat content per pound. Typically, heat content follows a linear trend with both density and hydrogen content. However, the two fuels referred to fell off this linear trend line as can be seen in Figure 9.3.1 and Figure 9.3.2.

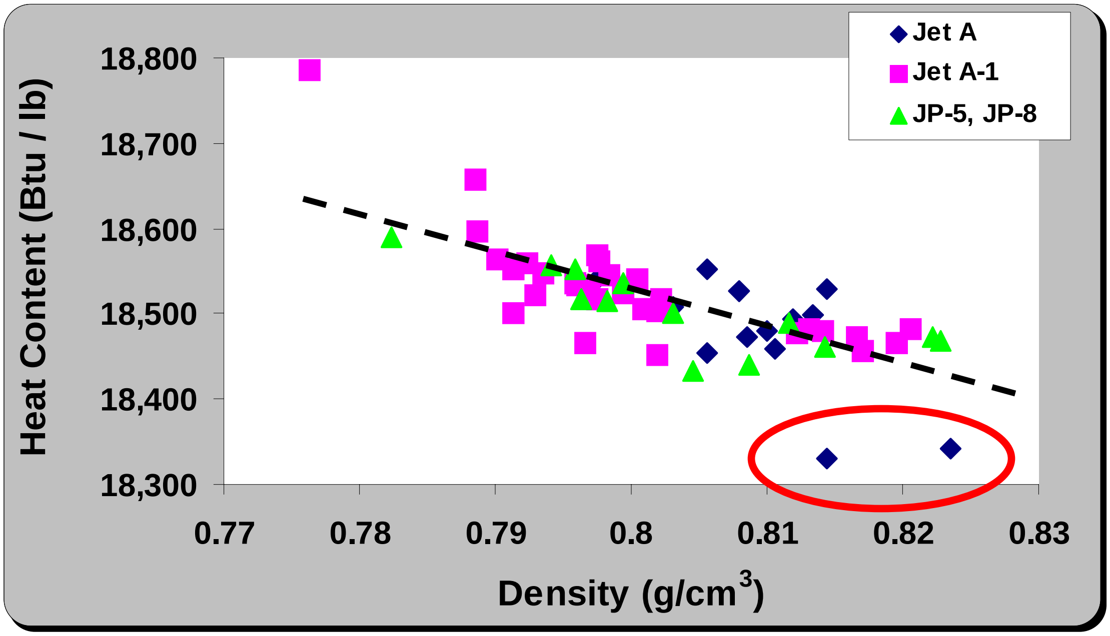

Figure 9.3.1. Heat Content (Btu/lb) as a Function of Density

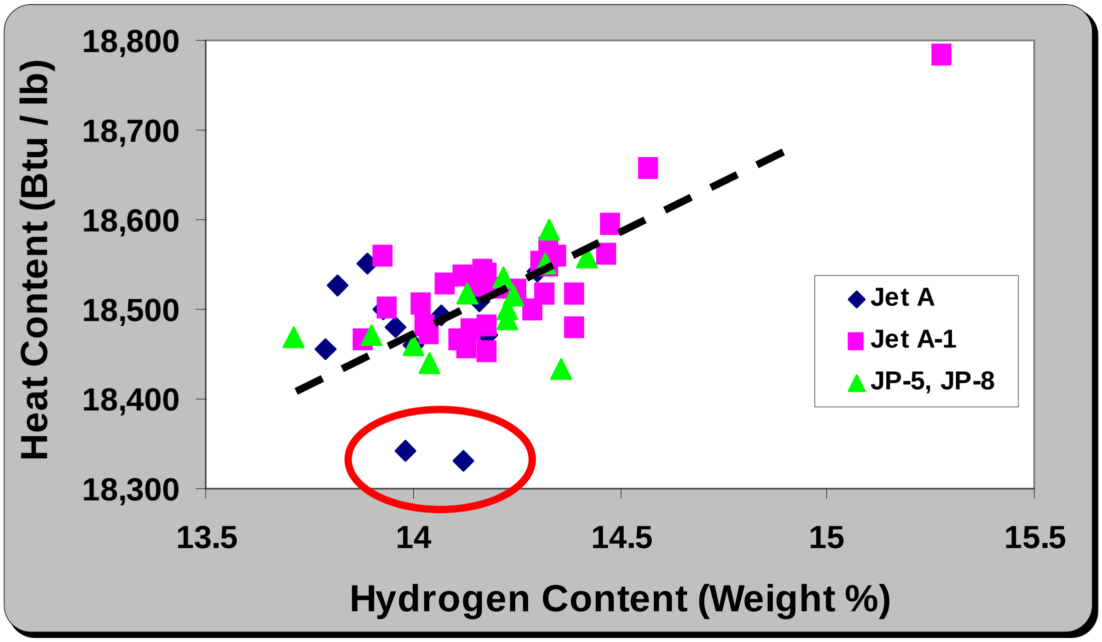

Figure 9.3.2. Heat Content (Btu/lb) as a Function of Hydrogen Content

Other properties associated with these fuels were analyzed. This analysis did not reveal sufficient information to identify the cause this behavior.

10. Synthetic Fuels

SASOL Synthetic Jet Fuels

Among the samples tested were two synthetic fuels; one was 50% synthetic blend (mixed with 50% traditional petroleum fuel) and the other was 100% synthetic from Africa. The synthetic portions of the fuels are produced using the Fischer-Tropsch process. Synthesis gas (carbon monoxide and hydrogen) is processed in the presence of a catalyst, under specific temperature and pressure requirements, to form mixtures of hydrocarbons, including those in the jet fuel boiling range. SASOL uses coal in the production of its synthesis gas [17]. Because this process essentially builds hydrocarbon molecules from the single carbon synthesis gas, the finished product can be relatively easily tailored. Synthetic fuel producers are continuously fine-tuning their fuel composition to ensure that their fuel will perform in aircraft. Data gathered in sampling programs such as this may provide valuable data to synthetic fuel producers.

Oil Shale and Oil Sand Jet Fuels

Among the samples tested was one of jet fuel made from shale oil. Also included was a sample from oil sands. These fuels are not synthetic in the true sense, but the type and severity of the processing can produce a fuel that is very similar to the SASOL fuel. The following section on synthetics may well apply to some oil shale and oil sand jet fuels.

True synthetic fuels have some unique properties when compared to ordinary petroleum-derived fuel. The following paragraphs summarize some of the unique properties noted during fuel testing, many of which were mentioned earlier in this document. Data obtained from testing do not indicate that synthetic fuels are superior or inferior when compared to petroleum fuels. Because of the uniqueness of these fuels, composition, and fuel properties such as density, seal swell, and lubricity need to be evaluated.

Low Density. The synthesis process produces mainly normal paraffins and very low levels of cyclic paraffins and aromatic compounds. These molecules are high in heat content on a mass basis, but have low heat content per unit volume, Figures 3.7.1 and 3.7.2. There is some concern that fuels too low in heat content on a volume basis will cause some aircraft (especially longer range aircraft) to become fuel-volume limited. Certain city pair routes may be impossible for current aircraft because of lack of fuel tank volume.

Fuel Leaks. There is a concern about how synthetic fuels will behave in an aircraft. Because synthetic fuels are naturally low in aromatics, there has been some concern about the effect on aircraft components such as O-rings and sealants. Fuels high in aromatics tend to cause swelling in certain compounds commonly used for O-rings. When the O-rings swell, they will set up tightly. When a low aromatic fuel is used, the aromatics will leach out of the material and the O-ring will contract and possibly leak. The problem is particularly a concern for older aircraft.

Poor Lubricity. Lubricity is commonly believed to be a function of the polar molecule content in fuels. That is, the polar molecules are what give the fuel its lubricating capability. Although these fuel tests did not indicate a higher than normal wear scar, there have been reports that indicate that non-additized synthetic fuel does tend to produce relatively large WSDs due to the lack of components such as sulfur and aromatics. If the lubricating properties of the fuel become an issue, the addition of a corrosion inhibiter/lubricity improver additive will solve this problem.

Poor Electrical Conductivity. Electrical conductivity of synthetic fuels is very low, which is also likely due to the lack of polar components. Low conductivity is not unusual in petroleum fuel, and Def Stan 91-91 requires the addition of an SDA as a precaution. There is no worldwide consensus on the need for SDA in jet fuel or on a minimum conductivity level.

High Olefin Content. It was also noted that the olefin content of the coal-derived synthetic fuels in this survey was significantly higher than the olefin content of the rest of the fuel samples (see Section 3.5). Levels were on the order of three to nine times higher for these synthetic fuels (depending on test method). High olefin content is believed to be a concern regarding fuel thermal and storage stability. There was no indication from JFTOT test results that the high olefin content had a detrimental effect on fuel thermal stability. The storage stability of the fuel samples was not tested.

Abnormal Refractive Index. The refractive index is a property that is not normally measured in industry. However, the coal-derived synthetic fuels did not produce the usual relationship to heat content per pound when compared to the other fuels, Figure 10.1. This abnormal relationship did not occur for all properties correlated to refractive index.

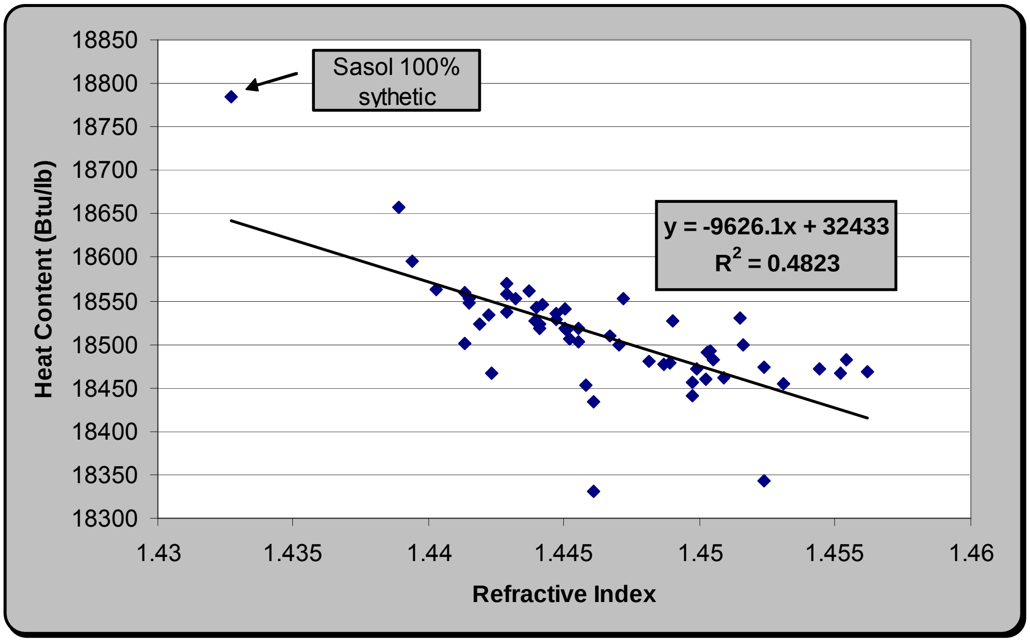

FIGURE 10.1. REFRACTIVE INDEX VERSUS HEAT CONTENT

Flattened Distillation Profile. The distillation profile for the coal-derived synthetic fuel was different when compared to the Jet A/A-1 fuels. However, the profile does not fall outside specification requirements, Figure 10.2. The flattened distillation profile is more typical of a solvent-type fluid. Flexibility offered by synthetic fuel production may allow producers to further tailor properties such as distillation profile to match petroleum jet fuels.

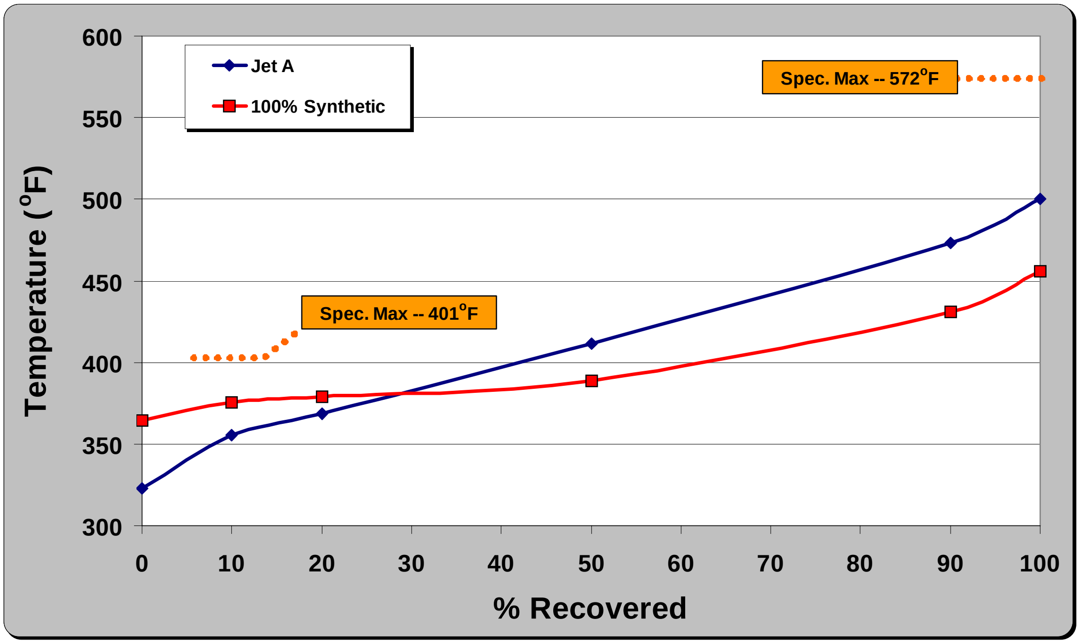

FIGURE 10.2. DISTILLATION OF SYNTHETIC FUELS COMPARED TO PETROLEUM FUELS (ASTM D 86)

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Appendix A
Test Method Descriptions

A1 Description of Test Methods

The following is a brief summary of testing techniques used for fuel testing during the fuel-sampling program. In most cases, and wherever possible, ASTM standard tests were followed. The test methods, in full, can be found in Reference 1. In some cases, ASTM techniques were slightly modified or non-ASTM methods were used.

A1.1 Density at 60°F

Fuel density at 60°F was determined per ASTM D 4052, “Standard Test Method for Density and Relative Density of Liquids by Digital Density Meter,” using an Anton-Paar DMA 58 density meter. A small volume of fuel is introduced into an oscillating sample tube. The tube is oscillated and the change in oscillating frequency due to fuel mass present is used to calculate the density. Data was collected at 60°F. The repeatability is reported as 0.0001 (g/mL) for the range 0.68 to 0.97 g/mL. The reproducibility is reported as 0.0005 over the same range.

A1.2 Total Sulfur Content

Sulfur content in fuel is a closely watched property for automobiles as well as for aircraft. In aircraft, it is thought to adversely affect the environment in several ways, including acid rain and small particulate emissions caused by SO_3 production in engine exhaust streams as well as the increase of contrail formation due to sulfur levels. In ground transportation vehicles, sulfur in gasoline and diesel is known to poison the catalyst in new-technology catalytic converters, preventing their introduction to the new vehicle market. Many discussions on this topic can be found in literature; the subject is beyond the scope of this project.

To determine total sulfur content in jet fuel, the procedure in ASTM D 2622, “Standard Test Method for Sulfur in Petroleum Products by Wavelength Dispersive X-ray Fluorescence Spectrometry (XRF),” was followed. The necessary equipment included a Siemens SRS 303 X-ray fluorescence spectrometer. In this method, the specimen is subjected to an X-ray beam and the resulting intensity is compared to the intensity of a sample with known sulfur content. The precision on the procedure is a function of the mass percent of sulfur and a relationship is given in D 2622. For the high range of sulfur content (700 ppm = 0.07%), the repeatability is approximately 0.002%. For the same sulfur content, the reproducibility is 0.008%.

A1.3 Freezing Point

Cold temperatures at high altitudes and over polar regions necessitate attention to fuel temperature and knowledge of its freezing temperature. As the frequency of polar routes increases and freezing temperatures are approached, current data on fuel properties are needed. Fuel freezing temperature was determined per ASTM D 5972, “Standard Test Method for Freezing Point of Aviation Fuels (Automatic Phase Transition Method),” using a Phase Technology PSA-7V. The freezing point of the fuel is defined as the temperature at which the last solid hydrocarbon (wax) crystal, formed on cooling, disappears as the temperature is increased. ASTM D 5972 employs incident light and optical sensors to detect the presence of these wax crystals. The specimen is initially cooled below the freezing point until crystals are formed. The specimen is then warmed until the last remaining crystal disappears and the solution becomes a homogeneous liquid. The repeatability for this test is reported as 0.69°C and the reproducibility is reported as 1.30°C.

A1.4 Pour Point

The freezing point of the fuel is the commonly published property when defining fuel performance. However, the property that helps define the actual usability of the fuel under cold weather conditions is the pour point. At the freezing point of the fuel, it is likely that the fuel will still flow and will be able to be pumped to and burned in the turbines. Below the pour point, the fuel becomes virtually unusable as, at this temperature, pumping becomes difficult or impossible as a result of the crystal formation in the fuel. ASTM D 5949, "Standard Test Method for Pour Point of Petroleum Products (Automatic Pressure Pulsing Method)," defines the pour point of a specimen as the lowest temperature at which movement of the specimen surface is observed upon a pulse of nitrogen gas blown over the surface of the fuel. The apparatus used was a Phase Technology PSA-70V, which was also used for fuel freezing temperature. Pour point is the coldest temperature at which the fluid still flows. That is, the fluid is cooled in ~2°C increments. Once the fluid no longer pours, the temperature at which it last did (or ~2°C warmer) is reported as the pour point.

A1.5 Olefins

Olefins are hydrocarbon molecules that contain one or more double bonds between carbon atoms. Their presence is thought to affect the stability of fuels (thermal stability and storage stability) because the double bonds lead to polymerization and the formation of long-chain gums and deposits.

Two test methods were used during the sampling program. One method, ASTM D 2710, "Standard Test Method for Bromine Index of Petroleum Hydrocarbons by Electrometric Titration," involved titration of the fuel sample with a bromide-bromate solution from which the bromine index was calculated. Because ASTM D 2710 does not include a method for the calculation of olefin content from this bromine index, a rule-of-thumb factor of 1,000 was used to convert the bromine index to a bromine number (the bromine index divided by 1,000 is approximately equal to the bromine number). To obtain olefin content by using the bromine number, the method outlined in ASTM D 1159, Annex 2, was used. ASTM D 1159, Std. Test Method for Bromine Numbers of Petroleum Distillates and Commercial Aliphatic Olefins by Electrometric Titration, cautions that the practice of using the factor of 1,000 may not be applicable to fuels with a low bromine index.

In ASTM D 2710, a test specimen is titrated with a standard bromide-bromate solution. Titration end point is indicated by a jump in the electrical potential, caused by the presence of free bromine in the solution. The amount of bromine solution added prior to potential jump yields the bromine index and is an indication of olefin content. The bromine number is the number of grams of bromine that will react with 100 grams of test sample. The bromine number was approximated as the bromine index divided by 1,000.

Annex 2, from method D 1159 uses bromine number, average molecular weight of olefins, and a boiling range correction factor to calculate olefin content according to the following equation:

$$olefins, mass\,\% = \int B\,M \big/ 160$$

Where: $\int$ = boiling range correction
B = bromine number
M = molecular weight (relative molecular mass) of olefins

The boiling range correction is estimated from the boiling point range (initial to final boiling point). The correction factor is obtained from a chart in the appendix. Relative molecular weight of olefins is estimated from the 50% boiling point of the samples. Volume % olefins are calculated using the following equation.

$$olefins, volume\ \% = \left(\frac{A}{B}\right) \times C$$

Where: A = density of sample (from test data, ASTM D 4052)
B = average density of the olefins (from chart in annex 2, based on 50% boiling point)
C = mass percentage of olefins

The other method employed was ASTM D 1319, "Standard Test Method for Hydrocarbon Types in Liquid Petroleum Products by Fluorescent Indicator Adsorption," and was carried out by ChevronTexaco. This method utilized the tendency of hydrocarbon groups to have unique retention times in packed columns. With this method, the column is packed with an activated silica gel, and fluorescent dyes are used to create the boundaries between the hydrocarbon types in the column (specific dyes have retention times equivalent to the different hydrocarbon groups in the fuels). Volume % olefins are calculated based on the length between certain dye bands in the column. Reproducibility for this test method is 1.7 vol% at an olefin level of 1% and 2.9% for an olefin level of 3%. Error is due to uncertainty in the measurements of length between bands.

Comparison of the two methods showed that the FIA method (ASTM D 1319) typically gave higher olefin contents. It can also be seen that both methods tracked high olefin levels well (synthetic fuels, for example, were high using both test methods), but lower olefin values did not track as well between methods. Figure A1.5.1 compares the two methods.

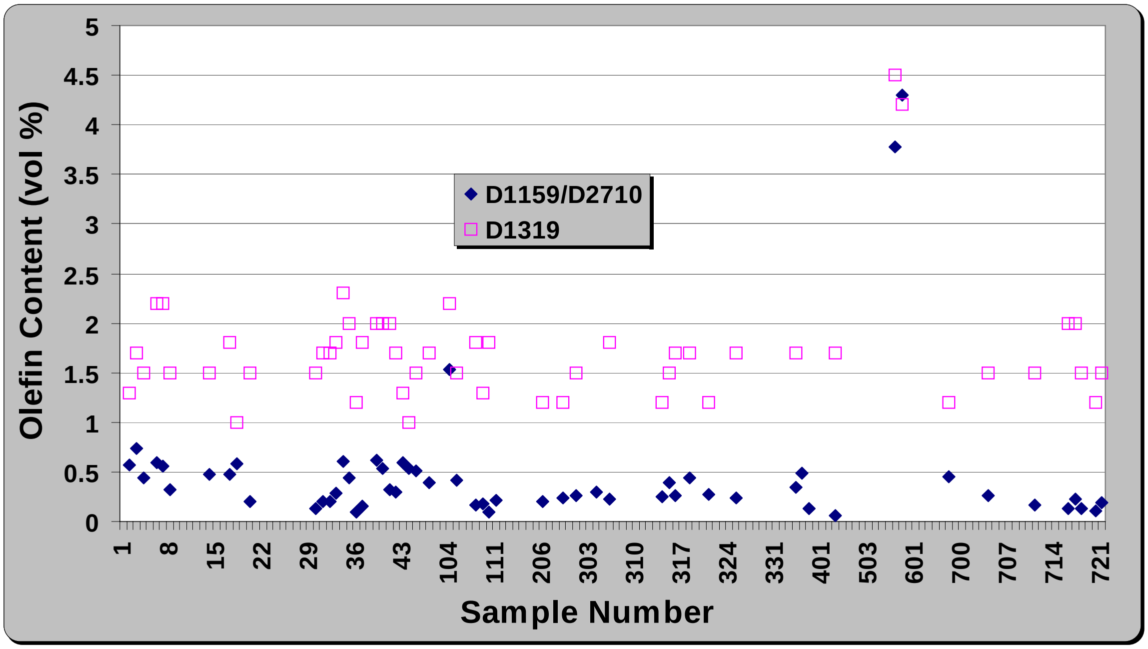

Figure A1.5.1. Comparison of ASTM D 1159/D 2710 With ASTM D 1319

A1.6 Hydrogen Content (Mass Percent)

Hydrogen content in fuel is an indicator of a fuel’s ability to burn cleanly and of the energy content of the fuel. It also indicates the degree of saturation in the hydrocarbon molecules. In ASTM D 3701, “Standard Test Method for Hydrogen Content of Aviation Turbine Fuels by Low Resolution Nuclear Magnetic Resonance Spectrometry,” a sample is compared in a continuous wave, low-resolution, nuclear magnetic resonance (NMR) spectrometer to a reference standard of pure hydrocarbon. For this test, the repeatability is reported as 0.09 mass% and the reproducibility is reported as 0.11 mass%. An Oxford 4000 spectrometer was used to acquire data.

A1.7 Net Heat Content (Net Heat of Combustion—Btu/lb)

Knowledge of the energy created when a fuel is burned is critical. The energy created per unit mass (or volume) is necessary when considering power availability and the distance the aircraft is able to travel. The heat of combustion can be determined by burning a specimen in an oxygen-bomb calorimeter. ASTM D 4809, “Standard Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter,” defined the procedure for the calorimetry. The instrument used for testing was a Parr 1281 Isoparabolic Calorimeter. The specimen is burned in an oxygen-rich environment surrounded by a monitored water bath. The change in temperature of the water bath is measured and used to calculate the net heat of combustion per unit mass of fuel. The repeatability reported in D 4809 is 0.096 MJ/kg (41 Btu/lb) and the reproducibility is reported as 0.324 MJ/kg (139 Btu/lb).

A1.8 Kinematic Viscosity

The kinematic viscosity is defined as the resistance of flow of a fluid under gravity. This property is important when sizing various components of the fuel system, from plumbing to fuel nozzles. The test method followed was ASTM D 445, “Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids.” This test measures the time it takes for a known volume of liquid to flow a known distance under the force of gravity through the capillary of a calibrated viscometer at a constant temperature. The kinematic viscosity is the product of the measured time for the fuel flow and the calibration factor of the viscometer. The viscosity was measured at +20°C, –20°C, and –40°C. The precision of this test is given as a function of average value for jet fuels at –20°C. Using a high-viscosity measurement to get a worst case value, the repeatability is estimated at 0.0434 mm^2/s (centistokes) and the reproducibility is 0.1178 cSt. A Scott-Gerate AVS440 viscometer (auto viscometer) was used for viscosity measurements at +20°C. A manual method was used at –20°C and –40°C. ASTM D 445 still applies to the manual method.

A1.9 Electrical Conductivity

Electrical charge is built up in fuel during pumping, filtering, and other operations related to fuel movement and purification/filtration. Electrical conductivity is the ability of the fuel to dissipate this charge buildup. If too much charge is allowed to build up, a spark will result, and if the fuel-to-air mixture is in the flammable range, an explosion could result. ASTM D 2624, “Standard Test Methods for Electrical Conductivity of Aviation and Distillate Fuels,” (EMCEE) was used to determine conductivity values for fuel samples, in picoseimens/m. In this method, voltage was applied across two electrodes, and the resulting current is measured and expressed as a conductivity value.

Electrical conductivity measurements were taken at three temperatures: 42°F, 72°F, and 100°F. Temperatures chosen reflect the operating temperature of the laboratory refrigerator, the laboratory ambient room temperature, and an elevated temperature chosen below the fuel flash point, respectively.

Fuel samples sent to Boeing were separated into two sampling containers. Approximately 1 L of the sample was transferred to a glass jar, which was used to store the fuel under refrigerated conditions for the duration of the testing. The glass jars were composed of USP type III glass, which is a soda-lime type glass. Fuel remaining in the original 1-gal epoxy-lined can was stored at outside ambient conditions. However, nine fuels were never transferred into glass jars. The fuel contained in these nine samples remained refrigerated in the original epoxy-lined cans for the duration of testing. Table A1.9.1 lists these nine samples.

Sample Number	Location
101	Nova Scotia, Canada
105	British Columbia, Canada
111	Alberta, Canada
206	Rio de Janeiro
211	Talara City, Peru
304	Brussels, Belgium
334	Bordeaux, France
335	Lyon, France
336	Montpellier, France

Table A1.9.1. Samples That Remained Stored in Epoxy-Lined Cans

It should be pointed out that the use of the glass storage containers may have an effect on the conductivity measurements because of interactions between trace components in the fuel and the soda-lime glass. Analysis of the sample data could neither support nor counter these claims.

A1.10 Distillation

Distillation gives an indication of relative volatility of the fuel specimen. The information is used for many parameters and property correlations. In general terms, the distillation profile can be used as an indication of how a fuel will behave in an engine (properties such as flash and freezing points, as well as operability parameters such as engine relight).

ASTM D 86 Test Method

ASTM D 86, "Standard Test Method for Distillation of Petroleum Products at Atmospheric Pressure," (automated method) was the method followed during the sample testing. An ISL AD 86 5G was used, which provides approximately one theoretical plate fractionation. The heat supply to the specimen remains constant, while the specimen slowly boils. The initial boiling temperature is the temperature at which the first drop of condensate drips into the receiving flask, and the dry point is the composition at the end that will not distill. Temperature readings are taken at the initial boiling point (IBP), recovered volumes of 10%, 20%, 50%, 90%, and the final boiling point (FBP). Also recorded was the volume of residue remaining after the FBP and the volume lost during distillation. The repeatability is reported as 3.5°C and is taken at the end point of the distillation.

ASTM D 2887, Simulated Distillation

Another method was used to obtain distillation data. ASTM D 2887, "Standard Test Method for Boiling Range Distribution of Petroleum Fractions by Gas Chromatography," is the test standard used by ChevronTexaco. In this method, a nonpolar column is heated at a constant rate, and the hydrocarbon components are separated based on boiling point temperature.

A1.11 Flash Point

The volatility of a fuel can be characterized by its flash point temperature. Fuels with a low flash point tend to be more flammable and can increase the risk of vapor holdup in the fuel system.

However, in cold weather, the high vapor content improves engine startup. Flash point temperatures were calculated using ASTM D 93, “Standard Test Methods for Flash-Point by Pensky-Martens Closed Cup Tester.” The fuel specimen is subjected to a constant temperature increase and constant stirring. Equilibrium is not achieved because of the constant heating required. At intervals of 2°F, the stirring is interrupted and the ignition source is directed into the test cup. Flash point is defined as the lowest temperature that, when a flame is applied to the vapor above the liquid, ignition occurs and the flame quickly propagates over the surface. Two measurements are taken and the average flash point is reported. The repeatability is reported to be approximately 1.8°C and the reproducibility is reported to be approximately 4.4°C. ASTM D 93 is allowed by the U.S. military for JP-8 and JP-5; however, it is not listed in aviation fuel specifications, ASTM D 1655 or Def Stan 91-91, for Jet A/A-1 fuel.

A1.12 Fuel Appearance/Initial Observations

An initial inspection of fuel was conducted upon receiving the fuel samples. Samples were analyzed for visible particulates, water, and/or strange odors. Typical observations included appearance (e.g., clear, cloudy) and odor (sulfurous or tangy smell). The inspections were done on fuel in clear test tubes or beakers approximately 100 mL in volume. All fuel samples were inspected by the same experienced individual and provide an overall subjective rating of the fuel.

A1.13 Refractive Index

The refractive index is the ratio of velocity of light in air to the velocity of light through the specimen. The angle of refraction is measured when monochromatic light is shown through two prisms and the specimen fuel between them. ASTM D 1218, “Standard Test Method for Refractive Index and Refraction Dispersion of Hydrocarbon Liquids,” was followed. The values were obtained using a Reichert Abbe Mark II digital refractometer. The repeatability for this calculation is 0.0002 and the reproducibility is 0.0005.

A1.14 Aromatic Content Using ASTM D 6379

ChevronTexaco completed aromatic testing using two different test methods. One test method used was ASTM D 6379, “Standard Test Method for Determination of Aromatic Hydrocarbon Types in Aviation Fuels and Petroleum Distillates – High Performance Liquid Chromatography (HPLC) Method with Refractive Index Detection.” Mono-aromatic and di-aromatic compounds are determined separately, with the resulting sum being the reported total aromatic content.

Liquid chromatography passes the sample through a packed column, which separates the fuel components based on relative affinity for the packing material. The packing material is referred to as the “stationary phase” because it does not exit the column with the fuel. This test method calls for an amino-bonded silica stationary phase. It is a polar column that has an affinity for the aromatic molecules. The attraction separates the aromatic molecules from the bulk of the fuel, which gives aromatic compounds a unique retention time in the column. A refractive index detector is used to detect the relative amount of aromatics in the fuel, based on the retention time.

Relative aromatic contents are determined in mass % by ASTM D 6379. Specifications such as ASTM D 1655 and Def Stan 91-91 call out volume % for aromatic content and, as such, it is desirable to refer to aromatic content in volume % in this document. The following equation was used in the conversion from mass % aromatics to volume % aromatics:

$$V = w\left(\frac{RD_{fuel}}{RD_A}\right)$$

Where: W is the mass % aromatics
V is the volume % aromatics
RD_{fuel} is the relative density of fuel samples
RD_A is the relative density of the aromatics

Mono-aromatic and di-aromatic mass percentages were each determined using this test procedure. The above equation was applied separately to the mono-aromatic and di-aromatic components and the sum was reported as the total aromatic content. Relative densities for the aromatics (RD_A) were taken to be 0.88020 for mono-aromatic content and 1.02025 for the di-aromatic component. The mono-aromatic value is based on 1,2-dimethylbenzene (o-Xylene) and the di-aromatic value is based on 1-methylnaphthalene [Reference 2].

A1.15 Naphthalenes

ChevronTexaco measured the naphthalene content of the fuel samples following ASTM D 1840, “Standard Test Method for Naphthalene Hydrocarbons in Aviation Turbine Fuels by Ultraviolet Spectrophotometry.” The percent composition of naphthalenes is calculated using the measured absorbance of ultraviolet light at 285 nm.

Naphthalenes are double-ring aromatic molecules that are controlled by specification (by means of direct limitation or by a specified smoke point) because of their poor combustion quality. Typically, fuels high in naphthalene content will not pass smoke point specification.

A1.16 Saturates, Olefins, and Aromatics Using ASTM D 1319

ASTM D 1319, “Standard Test Method for Hydrocarbon Types in Liquid Petroleum Products by Fluorescent Indicator Adsorption,” was used by ChevronTexaco to calculate the composition of saturates, olefins, and aromatics in the fuel samples.

The fuel sample is injected into an adsorption column packed with silica gel that includes a mixture of fluorescent dyes that can be seen under ultraviolet light. Alcohol is used to move the fuel down the column. Aromatics, olefins, and saturates are separated based on their relative adsorption affinities. Each group has a unique retention time in the column. Along with the fuel, the dyes are separated with the specific hydrocarbon types. The dye mixture separates into different colors, which define the hydrocarbon zone. The composition (volume percent) of each type is calculated by measuring the length of the respective hydrocarbon zone under ultraviolet light.

D 1319 is a normalized (to 100%) analysis. This test yields saturates, aromatics, and olefins and the summation of the results should be 100% for each sample.

A1.17 Dielectric Constant

The ratio of the capacitance of the sample in a test cell to the capacitance of the same cell without the sample fluid is called the dielectric constant. It is a measure of the fluid's ability to store energy under a potential energy difference and is needed in the design of some aircraft gauging systems.

Dielectric and velocity of sound data were compared with density measurements. For density measurements, a Solartron densitometer was used. Density was measured from the period of oscillation of a vibrating spool. Conversion from the spool oscillation period to density was as follows:

$$\rho\left({}^{kg}\!\!\diagup\!_{m^3}\right) = -846.7160 + 0.316163 \times T$$

Where T is in microseconds and ρ is density.

A1.18 Velocity of Sound

Velocity of sound testing was conducted by Goodrich. The velocity of sound is calculated by measuring the time difference of reflected sound waves from an oscillating crystal. The Panametrics instrument generates and receives ultrasonic pulses that are sent to and reflected from a target within the fuel. Time difference of the reflected sound wave was measured with a digital oscilloscope to an accuracy of better than 0.01 microsecond. Fuel quantity indication systems based on the velocity of sound in fuel have been developed and are being evaluated.

A1.19 Thermal Stability

Southwest Research Institute® was contracted to test fuel samples for thermal stability. Testing followed ASTM D 3241, "Standard Test Method for Thermal Oxidation Stability of Aviation Turbine Fuels (JFTOT Procedure)." The method uses the jet fuel thermal oxidation tester (JFTOT) and measures the high-temperature thermal performance of jet fuels. The data are meant to correlate with deposit formation in fuel systems.

Fuel is first passed over an aluminum heater tube at a specified temperature and then passed through a 17-μm stainless steel filter. Fuel flow rate is 2.7 to 3.3 mL/min and test duration is approximately 150 min. The color profile of the heater tube correlates with the amount of deposits, with darker colors signifying a relatively high rate of deposit formation. Tubes have a coating number rating scheme that indicates the extent of deposit formation. Deposit formation on the stainless steel filter will inhibit flow and cause a pressure drop. A fuel can fail the JFTOT test as a result of filter plugging as well. Failure is indicated by a visual tube rating (VTR) of 3 or greater or a pressure drop across the filter greater than 25 mmHg when tested at 260°C. The break point temperature is the highest temperature at which a fuel has a tube rating under 3 and a pressure drop under 25 mmHg.

A1.20 Specific Heat Capacity

Specific heat capacity measurements were completed at the University of New Hampshire's Advanced Polymer laboratory using a slightly modified ASTM E 1269-01 method. Heat capacity is determined using a modulated differential scanning calorimeter, in this case a TA Instrument Q100.

Thirteen to 29 mg of fuel is placed in aluminum pans, equilibrated at –60°C and heated at a controlled rate of 20°C per minute. Heat flow is measured and compared to that of a reference material, which in this case was a sapphire disk. Heat capacity is a function of the heat flow profiles of the fuel sample and the reference sapphire disk.

Heat capacities were determined between –30°C and 144°C, and the data showed that values varied linearly in this range. Data were reported as a heat capacity at 0°C and a corresponding slope for that fuel sample.

A.1.21 Surface Tension

ASTM D 971, "Standard Test Method for Interfacial Tension of Oil Against Water by the Ring Method" was the test method used by SwRI to determine the surface tension for fuel samples. This method is, typically, used for mineral oils. However, because a standard test method for the surface tension of aviation fuels does not exist, it is occasionally used for this purpose. Surface tension in this method is a function of the force required for a platinum ring to be pulled through a fuel/water interface, the densities of the fuel and water, and the dimensions of the ring.

A1.22 Acid Number

Acid number testing was done by SwRI per ASTM D 3242, "Standard Test Method for Acidity in Aviation Turbine Fuel." Fuel samples are dissolved in toluene and isopropyl alcohol and are titrated with an alcoholic potassium hydroxide. The end point of the titration is indicated by a sharp change in the electrical potential that is measured by a potentiometer.

A1.23 Sulfur Compounds

A brief summary of the methods used to separate jet fuel sulfur content into specific chemical classes follows. For a detailed description of the method used, see Reference 3.

A method was developed by the U.S. Department of Energy, AFRL, and the University of Dayton Research Institute for separating, classifying, and quantifying the sulfur content, by class, in aviation fuel. Various methods such as HPLC and wet chemical oxidation procedures were used as a sort of pre-separation procedure. By pre-separating the samples, the fuel matrix was simplified, allowing detection methods such as mass spectrometry to be used more efficiently. It also enhanced the ability of element-specific detection methods, such as atomic emission detection (AED).

One separation technique used iodine and hydrogen peroxide to oxidize certain classes of sulfur compounds. Sulfur compounds that were oxidized by iodine were classified as thiols; those that were not oxidized by iodine but were oxidized by hydrogen peroxide were classified as sulfides or disulfides. These oxidizable classes of sulfur compounds were known as reactive species. Thiophenes, benzothiophenes, and dibenzothiophenes were not oxidized by iodine or hydrogen peroxide and were classified as non-reactive. The samples were also run through an HPLC column to further separate the sulfur species, based on retention times in the polar column.

A1.24 Hydrocarbon Analysis

An analysis was conducted using ASTM D 2789, “Standard Test Method for Hydrocarbon Types in Low Olefinic Gasoline by Mass Spectrometry.” It is not known how accurate and applicable this test method is when used for jet fuel. Further research is under way to determine the accuracy.

The following hydrocarbon types were identified and quantified using mass spectrometry: paraffins, monocycloparaffins, dicycloparaffins, alkylbenzenes, indans and tetralins, and naphthalenes. A mass spectrometer measures the mass-to-charge ratio of molecules that have been converted into ions (Reference 4). Hydrocarbon types are separated based on their characteristic mass fragments and quantified based on the spectral analysis (peak location and height).

A1.25 Mercaptan Sulfur

Levels of mercaptan sulfur were determined by ASTM D 3227, “Standard Test Method for (Thiol Mercaptan) Sulfur in Gasoline, Kerosene, Aviation Turbine, and Distillate Fuels (Potentiometric Method).” Samples are dissolved in an alcoholic sodium acetate solvent and titrated with silver nitrate solution. The potential change between a glass electrode and a silver electrode determines the endpoint of the titration, which is used to calculate the mercaptan sulfur present in the sample. Because hydrogen sulfide may interfere with the results, any hydrogen sulfide must be removed. $CdSO_4$ is used to precipitate out the H_2S.

A1.26 Lubricity

Moving parts in an aircraft system often rely on the lubricating properties of the fuel. Components such as pumps, servovalves, and fuel controls are examples of parts most often affected. A fuel with low lubricating properties can cause excessive wear and increase maintenance costs.

The Air Force Laboratory in Mukilteo, Washington, measured lubricity using ASTM D 5001, “Standard Test Method for Measurement of Lubricity of Aviation Turbine Fuels by the Ball-on-Cylinder Lubricity Evaluator (BOCLE).”

A rotating steel cylinder is forced against a non-rotating steel ball with an applied load of 1,000 g. Sample fuel is kept in a reservoir, and the rotating cylinder is partially immersed in the fuel. This creates a condition in which the cylinder is always wet at the cylinder-ball interface. Atmospheric air is kept at 10% relative humidity and 25°C. Test duration is 30 min. At completion of the test, the scar generated at the ball-cylinder interface is measured under a microscope to yield a WSD.

A2 References

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Appendix B
Fuel Sample Property Data

Fuel Study Matrix	Sample Number	Fuel Type	Fuel Appearance	Density at 60°F (g/cm^3)	Flash Point °F	Freezing Point °C	Pour Point (°C)
Test Methods (ASTM)				D 4052	D 93	D 5972	D 5949
USA							
Boston, MA	002	Jet A	Clear, Fuel aroma, slight yel.	0.8031	118	-52.6	-70
Chicago, IL	003	Jet A	Clear, Jet Fuel Aroma	0.8134	125	-46.7	-70
Dallas/Ft. Worth	004	Jet A	Clear, Jet Fuel Aroma	0.8106	117	-43.6	-70
Lebanon, OH	006	Jet A	Clear, Jet Fuel Aroma	0.8144	142	-44.2	-60
Lima, OH	007	Jet A	Clear, Jet Fuel Aroma	0.8144	150	-44.0	-62
Los Angeles, CA	008	Jet A	Clear, fuel aroma, slight yel.	0.8056	113	-59.1	-70
Pittsburg, PA	014	Jet A	Clear, Jet Fuel Aroma	0.8119	130	-45.7	-70
Seattle, WA	017	Jet A	Clear, Jet Fuel Aroma	0.8100	110	-48.2	-70
Seattle/Boeing, WA	018	Jet A	Clear, Jet Fuel Aroma	0.8056	109	-49.8	-70
Shell Martinez Refinery, CA	020	Jet A	Clear, Jet Fuel Aroma	0.8235	113	-67.0	-80
Lebanon, OH	030	JP-8	Clear, Sulfurous Smell	0.7941	116	-49.7	-70
Langley AFB, VA	031	JP-8	Clear, Jet Fuel Aroma	0.7964	113	-47.5	-66
Shaw AFB, SC	032	JP-8	Clear, Jet Fuel Aroma	0.7983	124	-45.8	-66
Randolph AFB, TX	033	JP-8	Clear, Jet Fuel Aroma	0.8143	128	-60.0	-64
McConnell AFB, KS	034	JP-8	Clear, sharp 'tangy' smell	0.8045	128	-48.9	-66
Robins AFB, KS	035	JP-8	Clear, Sulfurous Smell	0.8087	117	-52.2	-70
Stoddard Solvent	036	Stoddard	Clear	0.7824	111	-72.0	-70
Seymour Johnson AFB, NC	037	JP-8	Clear, Jet Fuel Aroma	0.8031	122	-50.5	-70
Valero Benicia Refinery	039	JP-5	Clear, Sulfurous Smell	0.8222	146	-47.3	-68
Petro Star Valdez Refinery, AK	040	JP-5	Clear, Jet Fuel Aroma	0.8229	154	-48.8	-68
Trend Western Fuels, Tyndall	041	JP-8	Clear, Tangy sulfur smell	0.7994	125	-51.1	-66
Charleston AFB, SC	042	JP-8	Clear, slight sulfurous smell	0.7960	126	-50.1	-68
Placid Refining, LA	043	JP-8	slight yellow, sulfur tang aroma	0.8116	139	-46.2	-68
Buckeye Pipeline, IN	044	Jet A	Slight yellow, sulfur tang	0.8085	119	-47.6	-70
Monee, IL (TEPPCO)	045	Jet A	Clear, jet fuel aroma	0.8080	117	-47.2	-70
CANADA							
Dartmouth / Halifax	101	Jet A-1	Clear, Jet Fuel Aroma	0.8122	119	-46.2	-70
Toronto	104	Jet A-1	Clear, slight sulfur tang	0.8195	145	-49.4	-70
Richmond / Vancouver	105	Jet A-1	Clear, Jet Fuel Aroma	0.8166	117	-46.2	-70
Edmonton	108	Jet A-1	Clear, jet fuel aroma	0.8132	122	-50.4	-70
Ontario, Canada	109	Jet A	Slightly yellow, sulfur tang	0.7976	121	-53.0	-70
Ontario, Canada	110	Jet A-1	Clear, Jet Fuel Aroma	0.8206	143	-50.0	-70
Edmonton, Oil Sands	111	Jet A-1	Clear, Jet fuel aroma	0.8170	96	-71.0	<-78
LATIN AMERICA							
Rio de Janiero, Brazil	206	Jet A-1	Clear, Slight Sulfur Tang	0.7902	115	-59.5	-70
Talara City, Peru	211	Jet A-1	Clear, Jet Fuel Aroma	0.8141	119	-58.0	-70
EUROPE							
Amsterdam, Netherlands	301	Jet A-1	Clear, slight 'sour' aroma	0.7994	112	-55.2	-70
Brussels, Belgium	304	Jet A-1	Clear, Jet fuel aroma	0.8019	112	-53.4	-70
Dublin, Ireland	306	Jet A-1	Clear, Jet Fuel Aroma	0.8004	108	-50.6	-70
London, England	314	Jet A-1	Clear, Jet fuel aroma	0.7929	110	-53.4	-70
London, England	315	Jet A-1	Clear, Jet fuel aroma	0.7975	107	-54.5	-70
Madrid, Spain	316	Jet A-1	Clear, Jet Fuel Aroma	0.8019	104	-58.8	-70
Munich, Germany	318	Jet A-1	Clear, Jet Fuel Aroma	0.7969	119	-57.1	-70
Paris, France	321	Jet A-1	Clear, Jet Fuel Aroma	0.7994	109	-53.4	-70
Toulouse, France	325	Jet A-1	Clear, Jet Fuel Aroma	0.8008	115	-58.3	-72
Bordeaux, France	334	Jet A-1	Clear, Slight Sulfur Tang	0.8021	115	-58.8	-70
Lyon, France	335	Jet A-1	Clear, Jet fuel aroma	0.7983	119	-48.0	-60
Montpellier, France	336	Jet A-1	Clear, Jet fuel aroma	0.7977	117	-55.5	-70
FSU							
Praha (Prague), Czech Republic	403	TS-1/Jet A-1	Clear, Jet Fuel Aroma	0.7974	127	-49.4	-70
AFRICA							
South Africa (part synth)	507	Jet A-1	Clear, Jet Fuel Aroma	0.7885	131	-55.4	-70
South Africa (100% synth)	508	Jet A-1	Clear, Jet Fuel Aroma	0.7764	141	-58.6	-70
MIDDLE EAST							
Abu Dhabi, UAE	606	Jet A-1	Clear, Jet Fuel Aroma	0.7913	109	-49.2	-70
ASIA / AUSTRALIA							
Beijing, China	704	Jet A-1	Clear, Jet Fuel Aroma	0.7887	112	-56.5	-70
Kuala Lumpur, Malaysia	711	Jet A-1	Clear, Jet Fuel Aroma	0.7913	106	-50.3	-70
Sydney, Australia	716	Jet A-1	Clear, Jet Fuel Aroma	0.7959	108	-52.9	-68
Tokyo, Japan	717	Jet A-1	Clear, Jet Fuel Aroma	0.7935	107	-53.2	-70
Oil Shale, Australia	718	Jet A-1	Clear, Jet Fuel Aroma	0.7924	105	-50.8	-70
Oil Shale, Australia (low nit.)	720	Jet A-1	Yellow, Jet Fuel Aroma	0.7966	119	-54.1	-70
Oil Shale, Australia (high Nit.)	721	Jet A-1	Yellow, Jet Fuel Aroma	0.7961	117	-52.4	-70

Fuel Study Matrix	Sample Number	Distillation (°F)													
		IBP (Test 1)	IBP (Test 2)	10% (Test 1)	10% (Test 2)	20% (Test 1)	20% (Test 2)	50% (Test 1)	50% (Test 2)	90% (Test 1)	90% (Test 2)	FBP (Test 1)	FBP (Test 2)	Residue (Test 1)	Residue (Test 2)
Test Methods (ASTM)		D 86	D 86	D 86	D 86	D 86	D 86	D 86	D 86	D 86	D 86	D 86	D 86	D 86	D 86
USA															
Boston, MA	002	314.8	314.5	344.5	344.0	355.1	356.9	390.7	392.0	464.1	469.3	494.5	495.5	1.5	1.4
Chicago, IL	003	330.8	328.3	365.1	368.0	377.9	380.5	413.4	415.9	479.6	487.0	503.0	511.0	1.5	1.4
Dallas/Ft. Worth	004	308.2	312.3	347.0	348.9	363.0	363.7	440.7	404.5	492.0	494.4	518.8	520.3	1.4	1.4
Lebanon, OH	006	338.3	345.8	381.5	380.6	393.0	392.5	423.8	422.3	477.9	477.6	496.0	497.7	1.1	1.3
Lima, OH	007	361.5	364.9	388.6	393.0	400.0	402.6	424.6	425.2	474.4	475.8	490.8	493.7	1.3	1.3
Los Angeles, CA	008	317.2	315.1	345.2	345.6	358.0	358.9	395.5	395.3	468.6	472.1	502.2	502.2	1.6	1.5
Pittsburg, PA	014	333.8	335.3	364.4	364.6	377.0	375.6	439.0	410.6	479.6	477.8	508.3	509.4	1.4	1.5
Seattle, WA	017	305.2	307.2	335.0	337.9	350.9	353.3	434.3	437.0	488.3	496.1	520.5	526.5	1.5	1.4
Seattle/Boeing, WA	018	304.0	302.5	350.5	348.0	366.9	364.9	407.5	406.1	478.6	479.6	507.8	509.6	1.5	1.4
Shell Martinez Refinery, CA	020	312.7	311.1	341.4	341.8	354.1	354.7	391.1	391.5	466.5	466.8	495.4	494.7	1.4	1.5
Lebanon, OH	030	300.4	301.1	348.1	349.2	358.5	358.1	391.4	392.2	457.2	460.7	478.8	481.6	1.5	1.9
Langley AFB, VA	031	316.1	311.1	343.2	342.1	353.6	352.2	386.8	386.7	459.9	459.6	484.3	486.2	1.3	1.4
Shaw AFB, SC	032	320.8	310.0	349.4	351.5	362.1	364.0	396.0	396.6	453.7	455.6	477.6	477.3	1.4	1.4
Randolph AFB, TX	033	329.1	329.9	356.7	356.9	369.0	368.3	396.4	396.0	449.0	447.0	466.8	468.0	1.4	1.3
McConnell AFB, KS	034	326.6	329.8	355.7	356.0	367.9	369.1	401.8	401.1	463.3	463.7	483.9	482.0	1.5	1.8
Robins AFB, KS	035	313.0	313.2	332.1	331.4	340.6	339.8	375.5	386.3	464.0	465.4	500.0	499.0	1.5	1.5
Stoddard Solvent	036	294.1	320.1	331.8	331.7	335.2	335.7	346.4	346.7	372.4	373.1	386.8	390.0	1.5	1.4
Seymour Johnson AFB, NC	037	317.1	320.7	353.5	352.7	365.7	365.6	400.5	399.7	469.9	468.3	496.2	497.4	1.4	1.5
Valero Benicia Refinery	039	348.2	353.5	382.5	353.5	393.9	396.6	424.5	425.9	471.6	475.9	485.5	488.7	1.2	1.3
Petro Star Valdez Refinery, AK	040	362.8	358.4	381.8	383.4	391.0	390.8	416.8	415.8	475.1	472.5	501.0	496.8	1.4	1.4
Trend Western Fuels, Tyndall	041	322.0	315.4	348.9	350.1	361.4	361.6	390.9	390.3	454.9	452.6	486.0	477.4	1.9	2.2
Charleston AFB, SC	042	324.4	327.1	355.6	356.5	366.6	366.8	395.4	395.8	452.3	452.7	478.3	479.3	1.3	1.4
Placid Refining, LA	043	348.4	353.2	378.5	379.1	388.7	389.8	419.1	420.3	486.7	491.6	517.1	519.5	1.5	1.5
Buckeye Pipeline, IN	044	323.8	321.6	353.4	353.4	366.4	366.5	403.2	403.0	475.8	476.7	507.7	508.4	1.4	1.3
Monee, IL (TEPPCO)	045	323.2	323.8	354.1	353.6	366.8	366.3	402.4	402.9	475.1	474.5	505.3	506.5	1.3	1.3
CANADA															
Dartmouth / Halifax	101	312.0	316.5	344.3	343.9	352.3	352.4	373.6	374.9	430.3	434.1	463.6	462.6	1.4	1.4
Toronto	104	352.1	353.4	374.6	372.9	383.2	382.2	412.4	411.8	482.0	477.9	508.0	503.9	1.2	1.3
Richmond / Vancouver	105	315.6	312.0	352.1	353.7	366.6	367.8	407.0	407.8	488.3	490.3	521.7	517.3	1.4	1.5
Edmonton	108	319.3	318.3	361.9	360.7	378.1	377.6	409.8	409.8	465.9	465.4	498.4	497.2	1.2	1.3
Ontario, Canada	109	322.1	324.8	349.7	350.1	359.2	358.8	384.7	385.2	435.7	435.4	456.6	455.4	1.3	1.5
Ontario, Canada	110	363.1	364.1	378.8	379.5	385.0	385.0	411.4	410.4	495.6	493.8	527.1	527.5	1.3	1.4
Edmonton, Oil Sands	111	306.2	307.5	331.5	332.0	342.8	343.6	383.4	385.5	484.8	486.0	520.2	519.6	1.4	1.5
LATIN AMERICA															
Rio de Janiero, Brazil	206	309.6	312.6	337.8	336.5	345.7	346.3	366.6	367.2	422.7	425.6	456.7	456.3	1.4	1.5
Talara City, Peru	211	322.5	315.9	349.3	351.2	361.4	361.6	395.1	395.2	455.3	455.4	474.8	477.5	1.5	1.5
EUROPE															
Amsterdam, Netherlands	301	309.6	308.5	333.9	334.2	346.0	346.1	380.2	379.7	451.2	449.6	479.6	479.5	1.5	1.5
Brussels, Belgium	304	305.2	301.9	335.3	333.6	347.5	345.1	385.5	382.8	456.3	454.9	484.0	484.1	1.5	1.4
Dublin, Ireland	306	302.9	294.4	332.4	332.8	344.7	345.1	381.8	383.4	457.1	459.6	485.4	487.5	1.4	1.5
London, England	314	299.8	303.4	329.3	330.1	340.2	339.9	374.1	374.4	450.2	451.5	481.4	484.5	1.5	1.3
London, England	315	308.4	306.4	335.7	338.6	349.7	349.9	383.1	383.5	456.1	458.6	478.2	485.4	1.8	2.1
Madrid, Spain	316	304.2	303.2	329.8	329.4	338.3	338.7	367.6	368.5	447.3	451.1	480.7	480.5	1.2	1.4
Munich, Germany	318	322.1	321.2	338.7	339.1	346.6	345.9	368.5	367.6	444.1	440.7	477.4	476.3	1.5	1.5
Paris, France	321	302.1	303.5	329.1	329.2	340.3	341.0	377.4	378.3	455.9	459.0	487.2	488.7	1.5	1.5
Toulouse, France	325	305.4	306.1	339.4	340.5	349.3	350.4	375.6	376.5	430.8	431.3	455.4	458.2	1.4	1.3
Bordeaux, France	334	313.1	313.5	337.3	339.9	345.9	350.4	366.5	376.8	420.6	429.4	454.0	454.9	1.5	1.5
Lyon, France	335	316.0	316.4	345.0	344.7	356.5	356.8	391.5	391.0	465.7	465.3	491.5	493.6	1.5	1.4
Montpellier, France	336	311.6	310.9	333.5	334.2	343.2	343.3	373.0	373.0	450.7	449.3	494.0	486.1	1.6	1.8
FSU															
Praha (Prague), Czech Republic	403	331.7	332.3	357.5	360.2	368.7	370.1	393.1	393.9	437.2	440.4	463.4	463.9	1.5	1.4
AFRICA															
South Africa (part synth)	507	338.4	336.9	355.1	354.3	361.5	361.5	382.2	382.8	444.6	443.3	475.3	472.8	1.5	1.5
South Africa (100% synth)	508	364.1	365.5	375.6	375.0	378.7	378.4	388.4	387.9	430.7	426.6	456.2	450.9	2.0	2.2
MIDDLE EAST															
Abu Dhabi, UAE	606	303.9	308.5	338.8	338.2	349.9	350.2	380.6	380.0	447.7	446.6	472.0	471.1	1.4	1.5
ASIA / AUSTRALIA															
Beijing, China	704	311.1	310.7	331.9	332.6	341.4	342.2	371.6	372.2	448.7	448.1	485.8	482.2	1.5	1.5
Kuala Lumpur, Malaysia	711	300.8	299.8	332.9	331.6	344.5	342.9	375.3	373.6	441.5	437.8	465.5	462.3	1.3	1.5
Sydney, Australia	716	300.2	301.4	329.2	327.7	341.1	339.6	379.2	376.5	454.1	453.4	481.2	482.6	1.4	1.4
Tokyo, Japan	717	311.4	310.0	336.4	337.2	346.7	346.9	380.8	380.8	460.0	460.9	489.7	488.1	1.3	1.4
Oil Shale, Australia	718	302.2	302.9	341.8	341.7	354.4	354.1	381.7	381.8	432.7	432.8	455.1	457.7	1.4	1.3
Oil Shale, Australia (low nit.)	720	319.5	317.3	333.0	332.6	338.0	338.3	358.0	359.8	409.1	413.4	427.4	429.5	1.4	1.3
Oil Shale, Australia (high Nit.)	721	315.7	313.0	330.6	330.3	338.0	337.4	361.3	360.0	415.7	412.6	433.2	429.3	1.4	1.5

Fuel Study Matrix	Sample Number	Simulated Distillation (°F)												
		IBP	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	FBP
Test Methods (ASTM)		D 2887		D 2887		D 2887		D 2887		D 2887		D 2887		
USA														
Boston, MA	002	226.7	290.4	312.0	336.3	356.4	379.6	396.6	419.8	440.0	459.7	490.3	514.5	576.6
Chicago, IL	003	225.6	304.5	331.5	360.1	385.1	402.7	421.8	441.5	458.0	483.7	509.7	528.2	579.9
Dallas/Ft. Worth	004	213.6	287.0	317.4	344.8	366.3	386.7	411.0	432.7	456.5	484.6	516.8	540.4	593.4
Lebanon, OH	006	244.1	321.5	345.6	379.0	395.9	413.5	427.9	446.9	462.4	486.4	509.0	522.3	565.5
Lima, OH	007	252.0	330.1	360.6	386.5	404.7	419.6	430.6	446.9	460.4	483.8	507.3	521.0	562.0
Los Angeles, CA	008	215.4	288.7	313.4	338.6	360.9	384.5	401.5	421.9	444.4	467.0	497.0	520.6	592.3
Pittsburg, PA	014	242.0	304.9	330.1	356.8	383.3	399.2	420.6	438.4	456.9	481.4	508.8	530.2	598.2
Seattle, WA	017	214.8	278.7	299.5	331.2	356.2	381.1	401.0	423.6	449.6	479.8	516.8	544.6	602.3
Seattle/Boeing, WA	018	196.1	282.3	315.5	346.1	371.9	391.4	413.0	432.6	454.9	479.6	507.9	528.6	584.5
Shell Martinez Refinery, CA	020	225.4	279.0	302.9	333.3	356.4	376.1	394.5	413.5	432.8	455.6	488.4	513.0	581.1
Lebanon, OH	030	207.9	291.1	318.2	344.1	360.5	383.7	397.7	420.4	439.0	457.7	488.6	507.1	570.3
Langley AFB, VA	031	215.6	293.0	316.4	336.0	353.6	374.0	392.7	416.9	437.7	458.0	489.4	508.8	562.0
Shaw AFB, SC	032	231.4	291.4	318.8	346.0	370.3	386.7	404.0	421.6	439.5	458.0	488.1	505.2	558.6
Randolph AFB, TX	033	232.7	300.4	325.9	351.9	372.4	386.7	403.9	420.6	435.1	453.2	477.7	490.4	529.3
McConnell AFB, KS	034	225.8	303.0	324.2	346.5	370.0	386.6	408.0	425.8	447.5	467.2	491.0	511.2	560.3
Robins AFB, KS	035	257.4	288.5	303.0	322.0	340.2	360.3	384.8	405.9	430.6	457.2	491.5	518.9	578.5
Stoddard Solvent	036	233.0	293.2	305.3	326.1	336.9	347.1	353.9	363.5	373.4	386.1	394.6	406.4	443.1
Seymour Johnson AFB, NC	037	227.0	302.5	323.7	347.0	371.6	387.1	408.1	425.7	447.6	471.6	497.1	519.4	578.1
Valero Benicia Refinery	039	255.8	321.9	345.6	380.6	398.0	417.7	432.1	449.3	464.3	484.6	503.5	516.6	542.6
Petro Star Valdez Refinery, AK	040	282.5	334.5	347.9	373.1	388.6	408.3	423.4	444.2	458.0	481.7	504.5	520.8	576.3
Trend Western Fuels, Tyndall	041	216.5	293.6	318.8	345.1	365.5	385.0	396.1	414.5	428.0	452.1	482.3	505.5	575.7
Charleston AFB, SC	042	241.5	302.5	323.3	346.7	371.1	386.5	403.3	420.9	436.0	456.3	481.7	498.4	557.9
Placid Refining, LA	043	257.8	325.5	345.2	372.2	389.6	409.4	425.2	445.2	461.7	487.4	515.9	538.7	600.9
Buckeye Pipeline, IN	044	216.7	296.3	322.3	346.3	371.1	389.2	410.6	428.4	450.8	475.4	504.9	526.2	592.6
Monee, IL (TEPPCO)	045	221.8	296.1	322.2	346.1	370.8	388.6	410.3	427.8	449.8	474.1	503.5	524.7	589.0
CANADA														
Dartmouth / Halifax	101	217.7	291.2	315.3	336.7	351.3	364.9	380.9	392.6	409.1	427.1	455.3	480.8	541.1
Toronto	104	259.5	327.1	345.2	364.3	385.1	400.2	420.6	438.0	456.7	481.0	507.5	526.4	577.8
Richmond / Vancouver	105	213.9	290.9	319.4	346.5	372.8	393.5	414.9	435.2	456.9	484.2	518.5	547.2	607.3
Edmonton	108	210.1	292.0	329.8	363.9	385.9	399.1	419.4	432.6	450.9	468.2	491.4	514.6	600.1
Ontario, Canada	109	233.8	295.0	318.3	344.2	359.3	380.1	391.3	409.3	423.2	444.1	459.6	480.6	518.2
Ontario, Canada	110	304.7	336.4	346.9	369.7	386.0	398.6	418.7	437.2	458.0	486.6	519.6	547.2	616.2
Edmonton, Oil Sands	111	215.5	280.5	296.4	322.8	344.5	365.7	386.9	410.3	435.8	466.7	508.8	538.2	595.6
LATIN AMERICA														
Rio de Janiero, Brazil	206	207.6	290.6	313.7	331.8	346.4	358.0	373.0	386.9	403.7	422.0	449.5	474.1	533.2
Talara City, Peru	211	215.7	295.6	317.9	338.5	359.0	382.2	401.1	421.6	441.5	457.8	483.1	496.4	544.1
EUROPE														
Amsterdam, Netherlands	301	213.2	279.0	302.0	328.0	345.7	365.0	385.2	403.8	422.5	447.9	477.7	496.4	551.1
Brussels, Belgium	304	208.9	279.1	302.3	330.0	347.2	370.7	387.6	409.9	430.0	456.1	486.2	505.8	563.6
Dublin, Ireland	306	207.1	274.5	302.5	327.3	345.7	364.9	385.8	408.8	428.8	455.0	484.7	504.5	556.2
London, England	314	214.8	280.4	295.4	323.3	344.8	360.9	384.2	398.8	421.6	445.9	479.2	502.4	564.6
London, England	315	207.4	282.5	304.3	332.1	347.2	369.8	386.5	407.5	426.7	453.2	484.3	505.7	568.8
Madrid, Spain	316	214.3	282.5	303.0	322.4	336.3	349.3	370.4	392.4	416.8	443.2	474.5	492.7	567.9
Munich, Germany	318	240.6	292.6	314.6	332.6	345.8	355.6	370.4	386.0	406.8	432.7	466.7	489.8	546.5
Paris, France	321	214.5	277.8	294.0	321.5	342.5	360.5	384.6	404.5	425.1	452.4	483.9	505.0	571.4
Toulouse, France	325	214.6	283.3	306.0	333.6	346.7	364.9	384.7	396.8	416.1	431.8	455.8	475.1	545.3
Bordeaux, France	334	214.7	283.5	305.8	334.7	348.2	368.1	385.5	397.4	415.9	430.6	455.4	471.9	527.6
Lyon, France	335	215.3	292.2	315.0	337.5	357.1	380.4	397.2	421.3	441.9	461.4	491.0	514.0	567.2
Montpellier, France	336	239.2	282.8	303.3	328.5	345.9	361.8	381.9	395.9	417.6	440.7	476.5	507.4	614.4
FSU														
Praha (Prague), Czech Republic	403	231.9	301.8	329.4	354.9	374.3	386.7	399.5	416.6	425.5	444.7	462.4	486.9	546.1
AFRICA														
South Africa (part synth)	507	245.8	313.8	330.1	346.4	359.2	374.3	386.4	403.3	421.4	444.1	472.8	490.7	545.0
South Africa (100% synth)	508	303.2	344.9	357.5	372.2	380.2	385.1	390.1	399.3	411.7	427.8	455.7	481.4	533.5
MIDDLE EAST														
Abu Dhabi, UAE	606	206.0	287.9	305.5	332.2	346.7	368.9	386.1	405.8	423.1	449.6	477.1	490.6	529.8
ASIA / AUSTRALIA														
Beijing, China	704	223.5	282.9	303.3	324.1	344.7	357.9	379.6	393.8	417.3	438.4	470.1	494.6	568.9
Kuala Lumpur, Malaysia	711	207.5	281.2	302.9	327.2	345.4	359.5	384.4	395.3	420.8	440.4	458.3	485.4	520.6
Sydney, Australia	716	213.8	270.6	291.4	322.8	344.7	360.6	384.7	400.2	421.9	448.8	482.0	498.8	549.4
Tokyo, Japan	717	214.8	285.8	304.0	326.7	345.5	363.1	385.6	405.7	425.6	453.5	482.4	501.1	567.6
Oil Shale, Australia	718	196.8	281.9	309.5	340.0	355.6	374.0	387.1	403.8	421.7	436.3	457.2	476.5	518.5
Oil Shale, Australia (low nit.)	720	269.9	295.4	304.7	318.1	337.7	347.6	364.1	385.8	395.0	419.1	432.4	453.9	472.6
Oil Shale, Australia (high Nit.)	721	257.5	291.1	303.8	314.8	336.9	347.5	365.5	386.1	397.3	421.4	439.2	456.3	481.4

Fuel Study Matrix	Sample Number	Total Sulfur (PPM)	Olefins (Vol %)	Hydrogen (weight %)	Naphthalenes (vol %)	Aromatics (vol %)	Aromatics (vol %)	Saturates (vol %)	Olefins (Vol %)
Test Methods (ASTM)		D 2622	D 1159	D 3701	D 1840	D 6379	D 1319	D 1319	D 1319
USA									
Boston, MA	002	998	0.5741	14.16	1.1	20.63	18.7	80.0	1.3
Chicago, IL	003	713	0.7412	13.93	2.2	21.10	19.3	79.0	1.7
Dallas/Ft. Worth	004	1118	0.4397	14.00	0.2	18.36	19.0	79.5	1.5
Lebanon, OH	006	473	0.5901	14.15	2.3	19.16	16.3	81.5	2.2
Lima, OH	007	472	0.5571	14.12	2.2	17.45	16.0	81.8	2.2
Los Angeles, CA	008	210	0.3169	13.89	0.7	19.70	17.0	81.5	1.5
Pittsburg, PA	014	531	0.4721	14.07	2.0	19.76	17.5	81.0	1.5
Seattle, WA	017	445	0.4761	13.96	1.4	18.86	16.9	81.3	1.8
Seattle/Boeing, WA	018	650	0.5817	13.79	2.7	20.92	19.7	79.3	1.0
Shell Martinez Refinery, CA	020	13	0.2009	13.98	0.1	14.45	12.8	85.7	1.5
Lebanon, OH	030	124	0.1325	14.42	0.7	21.42	19.5	79.0	1.5
Langley AFB, VA	031	607	0.2043	14.13	1.7	21.40	19.3	79.0	1.7
Shaw AFB, SC	032	114	0.2025	14.24	0.7	21.82	19.8	78.5	1.7
Randolph AFB, TX	033	225	0.2900	14.00	2.2	18.15	17.0	81.2	1.8
McConnell AFB, KS	034	674	0.6074	14.36	1.5	15.66	14.0	83.7	2.3
Robins AFB, KS	035	420	0.4411	14.04	2.0	24.37	21.8	76.2	2.0
Stoddard Solvent	036	18	0.0941	14.33	0.0	18.77	18.5	80.3	1.2
Seymour Johnson AFB, NC	037	242	0.1554	14.23	1.2	21.85	19.7	78.5	1.8
Valero Benicia Refinery	039	257	0.6153	13.90	0.9	19.95	17.7	80.3	2.0
Petro Star Valdez Refinery, AK	040	667	0.5375	13.71	3.8	20.92	19.5	78.5	2.0
Trend Western Fuels, Tyndall	041	671	0.3194	14.22	1.4	18.65	17.8	80.2	2.0
Charleston AFB, SC	042	113	0.3002	14.32	0.8	19.98	18.5	79.8	1.7
Placid Refining, LA	043	876	0.5925	14.23	1.9	15.47	15.4	83.3	1.3
Buckeye Pipeline, IN	044	1056	0.5323	14.18	1.6	21.00	20.5	78.5	1.0
Monee, IL (TEPPCO)	045	1046	0.5132	13.82	1.8	20.92	19.8	78.7	1.5
CANADA									
Dartmouth / Halifax	101	564	0.3877	14.14	1.0	17.24	16.8	81.5	1.7
Toronto	104	2453	1.5292	13.88	2.1	22.92	22.0	75.8	2.2
Richmond / Vancouver	105	493	0.4103	14.04	1.6	22.46	19.5	79.0	1.5
Edmonton	108	19	0.1696	14.18	0.9	22.46	19.4	78.8	1.8
Ontario, Canada	109	222	0.1739	14.30	1.4	17.43	16.5	82.2	1.3
Ontario, Canada	110	20	0.0915	14.03	1.1	24.12	21.4	76.8	1.8
Edmonton, Oil Sands	111	49	0.2149	14.13	0.3	16.81	13.5	85.3	1.2
LATIN AMERICA									
Rio de Janiero, Brazil	206	857	0.2028	14.47	0.5	20.48	19.3	79.5	1.2
Talara City, Peru	211	366	0.2348	14.39	0.8	13.00	11.8	87.0	1.2
EUROPE									
Amsterdam, Netherlands	301	131	0.2614	14.21	0.7	19.18	17.7	80.8	1.5
Brussels, Belgium	304	297	0.2921	14.18	0.8	23.82	19.0	80.0	1.0
Dublin, Ireland	306	126	0.2272	14.18	1.8	17.18	16.5	81.7	1.8
London, England	314	474	0.2474	14.25	1.0	18.76	18.1	80.7	1.2
London, England	315	770	0.3978	14.39	1.2	18.06	17.8	80.7	1.5
Madrid, Spain	316	244	0.2573	13.94	0.6	20.15	18.0	80.3	1.7
Munich, Germany	318	171	0.4395	14.17	0.9	20.30	17.6	80.7	1.7
Paris, France	321	260	0.2690	14.08	1.4	19.66	18.3	80.5	1.2
Toulouse, France	325	175	0.2402	14.02	1.3	19.44	18.3	80.0	1.7
Bordeaux, France	334	630	0.3489	14.32	1.3	18.38	17.0	81.3	1.7
Lyon, France	335	2212	0.4851	14.17	1.1	21.39	18.5	80.5	1.0
Montpellier, France	336	58	0.1347	13.93	0.6	23.41	19.5	79.8	0.7
FSU									
Praha (Prague), Czech Republic	403	38	0.0570	14.33	0.6	16.33	13.5	84.8	1.7
AFRICA									
South Africa (part synth)	507	359	3.7779	14.57	0.8	12.13	11.5	84.0	4.5
South Africa (100% synth)	508	10	4.2999	15.28	0.1	5.93	5.5	90.3	4.2
MIDDLE EAST									
Abu Dhabi, UAE	606	1090	0.4463	14.31	1.0	20.36	19.5	79.3	1.2
ASIA / AUSTRALIA									
Beijing, China	704	473	0.2670	14.48	0.7	16.71	15.3	83.2	1.5
Kuala Lumpur, Malaysia	711	162	0.1617	14.29	1.9	17.80	17.2	81.3	1.5
Sydney, Australia	716	96	0.1279	14.12	1.8	17.83	17.0	81.0	2.0
Tokyo, Japan	717	422	0.2313	14.33	0.8	18.92	17.8	80.2	2.0
Oil Shale, Australia	718	78	0.1319	14.35	1.3	15.38	14.5	84.0	1.5
Oil Shale, Australia (low nit.)	720	7	0.1118	14.11	0.1	23.54	20.6	78.2	1.2
Oil Shale, Australia (high Nit.)	721	13	0.1948	14.15	0.1	20.93	18.3	80.2	1.5

Fuel Study Matrix	Sample Number	Conductivity (picoseimens)			Viscosity (cSt)		
		42°F	72°F	100°F	+20 °C	-20 °C	-40 °C
Test Methods (ASTM)		D 2624	D 2624	D 2624	D 455	D 455	D 455
USA							
Boston, MA	002	1	2	3	1.7	4.1	8.5
Chicago, IL	003	2	3	7	2.1	5.5	11.9
Dallas/Ft. Worth	004	1	3	5	1.9	4.9	10.4
Lebanon, OH	006	0	3	0	2.2	5.7	13.6
Lima, OH	007	0	0	1	2.3	6.2	14.6
Los Angeles, CA	008	1	3	10	1.8	4.4	9.2
Pittsburg, PA	014	1	3	0	2.0	5.2	11.7
Seattle, WA	017	1	2	4	1.8	4.4	9.3
Seattle/Boeing, WA	018	1	2	2	1.9	4.8	10.2
Shell Martinez Refinery, CA	020	0	1	0	1.9	4.7	9.7
Lebanon, OH	030	1	2	0	1.7	4.0	8.2
Langley AFB, VA	031	56	74	144	1.7	3.8	7.7
Shaw AFB, SC	032	88	113	119	1.8	4.2	8.7
Randolph AFB, TX	033	64	79	100	1.9	4.5	9.8
McConnell AFB, KS	034	49	64	203	1.9	4.6	9.9
Robins AFB, KS	035	127	161	185	1.6	3.7	7.1
Stoddard Solvent	036	0	1	3	1.3	2.7	4.8
Seymour Johnson AFB, NC	037	44	64	73	1.8	4.4	9.3
Valero Benicia Refinery	039	0	2	2	2.2	6.1	14.5
Petro Star Valdez Refinery, AK	040	0	1	6	2.2	5.7	13.4
Trend Western Fuels, Tyndall	041	45	63	64	1.8	4.0	8.4
Charleston AFB, SC	042	43	57	55	1.8	4.3	8.7
Placid Refining, LA	043	0	1	1	2.2	6.0	13.6
Buckeye Pipeline, IN	044	4	8	8	1.9	4.9	8.7
Monee, IL (TEPPCO)	045	1	1	2	1.9	4.2	9.1
CANADA							
Dartmouth / Halifax	101	120	188	289	1.6	3.9	6.8
Toronto	104	0	3	12	2.0	4.9	11.1
Richmond / Vancouver	105	39	72	132	1.9	4.6	9.7
Edmonton	108	85	81	73	2.0	4.7	9.8
Ontario, Canada	109	32	64	109	1.7	3.7	7.1
Ontario, Canada	110	1	2	3	2.1	5.2	12.2
Edmonton, Oil Sands	111	120	175	232	1.8	4.1	8.0
LATIN AMERICA							
Rio de Janiero, Brazil	206	49	71	112	3.0	3.0	6.2
Talara City, Peru	211	1	4	5	1.9	4.3	8.9
EUROPE							
Amsterdam, Netherlands	301	219	251	266	1.6	3.8	7.2
Brussels, Belgium	304	38	54	86	1.6	3.5	6.7
Dublin, Ireland	306	201	235	252	1.5	3.8	7.5
London, England	314	74	72	72	1.5	3.4	6.1
London, England	315	155	306	244	1.6	3.5	6.6
Madrid, Spain	316	119	135	124	1.5	3.5	6.4
Munich, Germany	318	180	206	199	1.5	3.5	6.7
Paris, France	321	125	151	174	1.6	3.8	7.1
Toulouse, France	325	58	107	184	1.6	4.0	6.9
Bordeaux, France	334	66	106	174	1.6	3.3	6.4
Lyon, France	335	55	54	83	1.7	3.9	7.3
Montpellier, France	336	126	163	232	1.5	3.2	6.2
FSU							
Praha (Prague), Czech Republic	403	51	85	141	1.8	4.3	8.8
AFRICA							
South Africa (part synth)	507	0	3	4	1.8	4.3	8.9
South Africa (100% synth)	508	1	1	1	2.0	5.0	10.9
MIDDLE EAST							
Abu Dhabi, UAE	606	101	73	34	1.5	3.6	6.9
ASIA / AUSTRALIA							
Beijing, China	704	92	97	94	1.5	3.4	6.6
Kuala Lumpur, Malaysia	711	43	46	51	1.5	3.3	6.6
Sydney, Australia	716	115	142	156	1.4	3.5	7.0
Tokyo, Japan	717	139	141	142	1.6	3.7	7.2
Oil Shale, Australia	718	66	83	95	1.6	3.8	7.3
Oil Shale, Australia (low nit.)	720	265	326	355	1.4	2.8	5.5
Oil Shale, Australia (high Nit.)	721	2	4	4	1.4	4.5	5.3

Fuel Study Matrix	Sample Number	Refractive Index	Net Heat Content (btu/lb)	Net Heat Content (btu/lb) - Calculated Method	Specific Heat Capacity (J/g/K)		Thermal Stability (Breakpoint Temperature - °C)	Lubricity (scar, mm)
					At 0°C	Slope		
Test Methods (ASTM)		D 1218	D 4809	D 3338	E 1269	E 1269	D 3241	D 5001
USA								
Boston, MA	002	1.4467 @ 21.2	18509	18574	1.599	0.0042	295	0.63
Chicago, IL	003	1.4516 @ 20.9	18499	18550	1.774	0.0035	280	0.61
Dallas/Ft. Worth	004	1.4502 @ 21.2	18459	18559	1.196	0.0023	295	0.59
Lebanon, OH	006	1.4515 @ 21.0	18530	18574	1.517	0.0035	275	0.60
Lima, OH	007	1.4461 @ 21.0	18331	18579	1.642	0.0035	290	0.64
Los Angeles, CA	008	1.4472 @ 20.7	18552	18588	1.800	0.0038	370	0.62
Pittsburg, PA	014	1.4504 @ 21.3	18493	18572	1.498	0.0035	285	0.59
Seattle, WA	017	1.4489 @ 21.2	18479	18585	1.584	0.0040	290	0.54
Seattle/Boeing, WA	018	1.4531 @ 20.8	18455	18574	1.443	0.0035	300	0.57
Shell Martinez Refinery, CA	020	1.4524 @ 20.9	18343	18531	1.454	0.0040	290	0.70
Lebanon, OH	030	1.4429 @ 20.9	18558	18623	1.566	0.0037	265	0.62
Langley AFB, VA	031	1.4441 @ 20.7	18518	18602	1.601	0.0036	290	0.58
Shaw AFB, SC	032	1.4451 @ 20.6	18516	18602	1.619	0.0035	295	0.58
Randolph AFB, TX	033	1.4509 @ 20.8	18461	18544	1.650	0.0035	300	0.56
McConnell AFB, KS	034	1.4461 @ 21.0	18434	18611	1.442	0.0034	310	0.63
Robins AFB, KS	035	1.4497 @ 20.7	18441	18525	1.577	0.0037	275	0.56
Stoddard Solvent	036	1.4416 @ 20.6	18589	18623	1.452	0.0046	290	0.66
Seymour Johnson AFB, NC	037	1.4470 @ 20.8	18500	18586	1.447	0.0034	270	0.59
Valero Benicia Refinery	039	1.4544 @ 21.0	18472	18526	1.699	0.0035	300	0.61
Petro Star Valdez Refinery, AK	040	1.4562 @ 21.0	18468	18509	1.392	0.0032	300	0.60
Trend Western Fuels, Tyndall	041	1.4447 @ 21.0	18535	18599	1.689	0.0047	285	0.64
Charleston AFB, SC	042	1.4432 @ 21.0	18552	18623	1.724	0.0038	295	0.58
Placid Refining, LA	043	1.4503 @ 21.0	18490	18589			280	0.62
Buckeye Pipeline, IN	044	1.4499 @ 20.3	18472	18548	1.481	0.0036	235	0.58
Monee, IL (TEPPCO)	045	1.4490 @ 20.8	18527	18555	1.499	0.0034	275	0.59
CANADA								
Dartmouth / Halifax	101	1.4487 @ 20.7	18477	18531			295	0.62
Toronto	104	1.4552 @ 20.4	18467	18481	1.418	0.0035	275	0.64
Richmond / Vancouver	105	1.4524 @ 20.5	18473	18532			275	0.58
Edmonton	108	1.4505 @ 20.2	18482	18550	1.478	0.0036	290	0.66
Ontario, Canada	109	1.4440 @ 20.2	18542	18614	1.442	0.0033	310	0.61
Ontario, Canada	110	1.4554 @ 20.2	18482	18521			280	0.74
Edmonton, Oil Sands	111	1.4497 @ 20.3	18457	18557				0.68
LATIN AMERICA								
Rio de Janiero, Brazil	206	1.4403 @ 20.0	18563	18602	1.907	0.0039	285	0.71
Talara City, Peru	211	1.4481 @ 20.2	18480	18577			275	0.59
EUROPE								
Amsterdam, Netherlands	301	1.4441 @ 21.0	18524	18595	1.833	0.0038	285	0.68
Brussels, Belgium	304	1.4458 @ 20.6	18453	18576	1.612	0.0040		0.58
Dublin, Ireland	306	1.4450 @ 21.0	18540	18603	1.472	0.0038	275	0.62
London, England	314	1.4419 @ 20.2	18523	18615			280	0.63
London, England	315	1.4433 @ 20.0	18518	18600	1.409	0.0035	275	0.59
Madrid, Spain	316	1.4455 @ 20.0	18503	18573	1.559	0.0041	280	0.61
Munich, Germany	318	1.4439 @ 20.6	18527	18601	1.762	0.0036	265	0.57
Paris, France	321	1.4447 @ 20.5	18529	18590	1.739	0.0043	280	0.60
Toulouse, France	325	1.4452 @ 21.0	18506	18577	1.581	0.0041	280	0.61
Bordeaux, France	334	1.4450 @20.1	18518	18569	1.526	0.0032	270	0.64
Lyon, France	335	1.4442 @ 20.0	18545	18580	1.512	0.0035	280	0.70
Montpellier, France	336	1.4437 @ 20.0	18561	18589	1.478	0.0028		0.70
FSU								
Praha (Prague), Czech Republic	403	1.4429 @ 21.0	18569	18647	1.534	0.0036	270	0.68
AFRICA								
South Africa (part synth)	507	1.4389 @ 20.0	18658	18697	1.750	0.0038	300	0.67
South Africa (100% synth)	508	1.4327 @ 20.0	18785	18812	1.559	0.0038	300	0.63
MIDDLE EAST								
Abu Dhabi, UAE	606	1.4415 @ 20.8	18553	18608	1.717	0.0045	280	0.64
ASIA / AUSTRALIA								
Beijing, China	704	1.4394 @ 20.0	18596	18655	1.472	0.0032		0.65
Kuala Lumpur, Malaysia	711	1.4413 @ 20.3	18501	18630	1.472	0.0036	285	0.58
Sydney, Australia	716	1.4429 @ 21.0	18537	18616	1.618	0.0033	290	0.60
Tokyo, Japan	717	1.4415 @ 21.3	18548	18625	1.855	0.0037	290	0.66
Oil Shale, Australia	718	1.4413 @ 21.3	18560	18650	1.636	0.0038	295	0.55
Oil Shale, Australia (low nit.)	720	1.4423 @ 20.6	18467	18563	1.739	0.0039	290	0.67
Oil Shale, Australia (high Nit.)	721	1.4422 @ 20.6	18534	18584	1.518	0.0038	295	0.65

Fuel Study Matrix	Sample Number	Mercaptan Sulfur (Wt. %)	Thiols, Sulfides, Disulfides (PPM -wt)	Thiophenes (PPM - wt)	Benzothiophenes (PPM - wt)	Dibenzothiopenes (PPM -wt)	Sulfur (PPM)
Test Methods (ASTM)		D 3227					
USA							
Boston, MA	002	0.000	635	12	188	127	1001
Chicago, IL	003	0.001	610	10	136	133	971
Dallas/Ft. Worth	004	0.001	520	28	229	310	1133
Lebanon, OH	006	0.000	342	20	145	74	614
Lima, OH	007	0.001	331	5	126	53	543
Los Angeles, CA	008	0.000	176	0	37	33	261
Pittsburg, PA	014	0.000	323	5	99	78	541
Seattle, WA	017	0.000	229	1	76	101	432
Seattle/Boeing, WA	018	0.000	614	11	184	255	1122
Shell Martinez Refinery, CA	020	0.000	1	3	2	3	6
Lebanon, OH	030	0.000	64	2	7	3	79
Langley AFB, VA	031	0.000	329	13	232	100	699
Shaw AFB, SC	032	0.000	72	8	12	20	123
Randolph AFB, TX	033	0.000	229	15	75	24	350
McConnell AFB, KS	034	0.000	355	17	91	89	563
Robins AFB, KS	035	0.001	177	34	209	76	512
Stoddard Solvent	036	0.000	0	0	0	0	0
Seymour Johnson AFB, NC	037	0.000	132	0	60	22	228
Valero Benicia Refinery	039	0.000	291	4	34	20	377
Petro Star Valdez Refinery, AK	040	0.000	650	14	200	148	1085
Trend Western Fuels, Tyndall	041	0.000	270	16	107	42	443
Charleston AFB, SC	042	0.000	53	2	10	4	171
Placid Refining, LA	043	0.001	328	62	190	160	772
Buckeye Pipeline, IN	044	0.001	594	13	189	185	1039
Monee, IL (TEPPCO)	045	0.001	576	7	158	190	992
CANADA							
Dartmouth / Halifax	101	0.000	279	71	94	13	458
Toronto	104	0.002	1493	97	536	370	2597
Richmond / Vancouver	105	0.001	176	10	68	114	394
Edmonton	108	0.000	0	1	0	0	1
Ontario, Canada	109	0.000	80	19	33	0	130
Ontario, Canada	110	0.000	2	0	0	2	5
Edmonton, Oil Sands	111	0.000	0	0	0	0	0
LATIN AMERICA							
Rio de Janiero, Brazil	206	0.001	550	10	61	21	648
Talara City, Peru	211	0.000	211	5	55	9	294
EUROPE							
Amsterdam, Netherlands	301	0.000	53	0	17	2	78
Brussels, Belgium	304	0.000	117	0	48	15	184
Dublin, Ireland	306	0.000	63	1	39	9	118
London, England	314	0.000	276	11	53	23	376
London, England	315	0.000	405	25	149	46	646
Madrid, Spain	316	0.000	139	9	19	10	180
Munich, Germany	318	0.000	110	2	25	2	142
Paris, France	321	0.000	234	12	39	16	307
Toulouse, France	325	0.000	161	18	16	0	192
Bordeaux, France	334	0.000	438	62	63	3	569
Lyon, France	335	0.001	1217	32	490	273	2093
Montpellier, France	336	0.000	12	2	0	4	14
FSU							
Praha (Prague), Czech Republic	403	0.000	11	1	0	0	13
AFRICA							
South Africa (part synth)	507	0.000	243	0	49	20	325
South Africa (100% synth)	508	0.000	0	0	0	0	0
MIDDLE EAST							
Abu Dhabi, UAE	606	0.000	714	44	195	32	1012
ASIA / AUSTRALIA							
Beijing, China	704	0.000	224	2	66	49	357
Kuala Lumpur, Malaysia	711	0.000	105	11	22	1	136
Sydney, Australia	716	0.000	132	0	60	22	228
Tokyo, Japan	717	0.000	264	5	78	28	379
Oil Shale, Australia	718	0.000	17	4	13	0	33
Oil Shale, Australia (low nit.)	720	0.000	-6	15	5	0	13
Oil Shale, Australia (high Nit.)	721	0.000	-5	5	0	0	0

Fuel Study Matrix	Sample Number	Acid Number	Surface Tension		
			72°F	-10°C	40°C
Test Methods (ASTM)		D 3242	D 971	D 971	D 971
USA					
Boston, MA	002	0.006	25.71	28.18	24.58
Chicago, IL	003	0.008	26.49	28.9	25.1
Dallas/Ft. Worth	004	0.008	26.37	28.57	25.01
Lebanon, OH	006	0.005	27.15	28.66	24.83
Lima, OH	007	0.006	27.25		
Los Angeles, CA	008	0.008	26.05	28.61	24.81
Pittsburg, PA	014	0.004	26.2	28.76	25.01
Seattle, WA	017	0.004	26.44	28.55	24.83
Seattle/Boeing, WA	018	0.004	26.54	29.06	25.02
Shell Martinez Refinery, CA	020	0.008	26.44	29.06	24.9
Lebanon, OH	030	0.019	26.22		
Langley AFB, VA	031	0.005	26.35		
Shaw AFB, SC	032	0.008	26.42		
Randolph AFB, TX	033	0.005	26.93		
McConnell AFB, KS	034	0.008	26.69		
Robins AFB, KS	035	0.005	26.52		
Stoddard Solvent	036	0.003	24.22	27.67	23.28
Seymour Johnson AFB, NC	037	0.008	26.54		
Valero Benicia Refinery	039	0.003	27.03		
Petro Star Valdez Refinery, AK	040	0.008	27.18		
Trend Western Fuels, Tyndall	041	0.005	26.03		
Charleston AFB, SC	042	0.013	26		
Placid Refining, LA	043	0.009	26.81	29.08	25.13
Buckeye Pipeline, IN	044	0.002	26.22	28.71	24.68
Monee, IL (TEPPCO)	045	0.004	26.47	28.48	24.58
CANADA					
Dartmouth / Halifax	101	0.008	25.96	28.37	24.52
Toronto	104	0.002	26.66	28.87	25.23
Richmond / Vancouver	105	0.005	26.97	28.61	25.13
Edmonton	108	0.006	26.64	28.31	24.88
Ontario, Canada	109	0.002	25.32	28.11	24.32
Ontario, Canada	110	0.005	27.2	28.91	25.03
Edmonton, Oil Sands	111				
LATIN AMERICA					
Rio de Janiero, Brazil	206	0.003	25.59	27.46	23.88
Talara City, Peru	211	0.003	24.87	28.18	24.85
EUROPE					
Amsterdam, Netherlands	301	0.006	25.81	27.81	24.37
Brussels, Belgium	304				
Dublin, Ireland	306	0.013	25.79	27.84	24.13
London, England	314	0.004	23.61	27.67	24.1
London, England	315	0.007	25.27	27.84	24.17
Madrid, Spain	316	0.001	25.81	27.58	24.03
Munich, Germany	318	0.009	25.64	27.74	24.16
Paris, France	321	0.003	25.74	27.82	24.25
Toulouse, France	325	0	25.81		
Bordeaux, France	334	0.002	26	27.93	24.1
Lyon, France	335	0.005	24.86	27.82	24.27
Montpellier, France	336			27.64	24.02
FSU					
Praha (Prague), Czech Republic	403	0.006	25.98	28.43	24.5
AFRICA					
South Africa (part synth)	507	0.003	24.52	27.6	23.78
South Africa (100% synth)	508	0	25.13	27.16	23.22
MIDDLE EAST					
Abu Dhabi, UAE	606	0.006	24.35	27.95	24.04
ASIA / AUSTRALIA					
Beijing, China	704				
Kuala Lumpur, Malaysia	711	0.006	25.66	27.93	24.03
Sydney, Australia	716	0.003	25.64	28.06	24.03
Tokyo, Japan	717	0.006	25.39	27.91	23.99
Oil Shale, Australia	718	0.003	25.25	27.8	24.24
Oil Shale, Australia (low nit.)	720	0.005	23.78	28.29	24.19
Oil Shale, Australia (high Nit.)	721	0.001	23.39	27.81	24.14

Fuel Study Matrix	Sample Number	Density					
		g/ml	Temp C	g/ml	Temp C	g/ml	Temp C
Test Methods (ASTM)		Solartron		Solartron		Solartron	
USA							
Boston, MA	002	0.840227	-35.0	0.827218	-18.4	0.813484	-0.4
Chicago, IL	003	0.851075	-36.6	0.838587	-19.6	0.823787	0.1
Dallas/Ft. Worth	004	0.848032	-34.4	0.836206	-19.6	0.821577	-0.2
Lebanon, OH	006	0.852781	-34.7	0.838698	-17.3	0.825414	0.3
Lima, OH	007	0.852679	-36.3	0.838615	-18.7	0.825226	-0.5
Los Angeles, CA	008	0.843868	-35.9	0.830366	-19.0	0.816849	-1.2
Pittsburg, PA	014	0.846274	-31.2	0.836506	-19.1	0.822413	-0.2
Seattle, WA	017	0.847343	-34.7	0.834338	-18.0	0.820084	0.7
Seattle/Boeing, WA	018	0.852591	-35.3	0.840980	-19.6	0.827737	-0.9
Shell Martinez Refinery, CA	020	0.861973	-36.6	0.847662	-18.7	0.836142	-2.4
Lebanon, OH	030	0.832140	-37.3	0.817982	-18.9	0.806618	-3.1
Langley AFB, VA	031	0.834832	-36.7	0.824430	-22.9	0.807876	-1.4
Shaw AFB, SC	032	0.836681	-36.6	0.822496	-18.8	0.810159	-2.0
Randolph AFB, TX	033	0.852521	-37.0	0.838652	-19.1	0.825511	-0.9
McConnell AFB, KS	034	0.842491	-36.3	0.828658	-18.8	0.816303	-1.7
Robins AFB, KS	035	0.847732	-36.4	0.834892	-19.8	0.819671	-0.2
Stoddard Solvent	036	0.818794	-33.5	0.806549	-18.3	0.792783	-0.5
Seymour Johnson AFB, NC	037	0.842158	-38.8	0.826937	-18.9	0.813127	0.4
Valero Benicia Refinery	039	0.860067	-35.3	0.846292	-18.3	0.832130	0.8
Petro Star Valdez Refinery, AK	040	0.854418	-29.3	0.848241	-19.3	0.833444	0.2
Trend Western Fuels, Tyndall	041	0.836137	-34.8	0.822785	-17.8	0.808928	1.1
Charleston AFB, SC	042	0.829611	-30.5	0.820897	-19.4	0.808100	-2.7
Placid Refining, LA	043	0.846237	-31.3	0.836022	-18.4	0.822229	0.0
Buckeye Pipeline, IN	044	0.845200	-35.2	0.830854	-17.3	0.817299	1.3
Monee, IL (TEPPCO)	045	0.845094	-34.7	0.832306	-18.9	0.819015	-1.3
CANADA							
Dartmouth / Halifax	101	0.84997	-37.9	0.83507	-19.4	0.82063	-0.2
Toronto	104	0.857235	-34.9	0.844104	-18.9	0.826849	4.8
Richmond / Vancouver	105	0.853129	-38.0	0.839136	-20.0	0.824973	-0.6
Edmonton	108	0.849658	-36.7	0.835892	-19.0	0.822105	0.6
Ontario, Canada	109	0.834200	-33.2	0.820980	-16.5	0.807505	-0.4
Ontario, Canada	110	0.856408	-33.8	0.843522	-17.2	0.830887	0.1
Edmonton, Oil Sands	111	0.856419	-38.1	0.841740	-19.7	0.827501	-0.3
LATIN AMERICA							
Rio de Janiero, Brazil	206	0.827428	-37.5	0.812995	-19.5	0.798220	-0.2
Talara City, Peru	211	0.851515	-38.2	0.836696	-19.5	0.822439	-0.1
EUROPE							
Amsterdam, Netherlands	301	0.838066	-37.7	0.824444	-19.5	0.809482	0.1
Brussels, Belgium	304	0.839608	-36.7	0.826711	-19.2	0.811808	0.1
Dublin, Ireland	306	0.839012	-38.0	0.823888	-18.3	0.812298	-2.3
London, England	314	0.832216	-38.2	0.817386	-19.6	0.802784	-0.4
London, England	315	0.835219	-36.8	0.819006	-16.7	0.804072	3.3
Madrid, Spain	316	0.839100	-35.2	0.826274	-19.2	0.812517	-0.9
Munich, Germany	318	0.835159	-36.5	0.822156	-19.8	0.806664	0.5
Paris, France	321	0.836557	-35.5	0.824260	-20.0	0.808530	0.4
Toulouse, France	325	0.840472	-36.5	0.826596	-18.7	0.811006	0.5
Bordeaux, France	334	0.839639	-37.7	0.825030	-19.6	0.810362	-0.2
Lyon, France	335	0.835687	-37.7	0.820861	-19.2	0.806311	-0.1
Montpellier, France	336	0.835198	-38.1	0.820532	-19.6	0.805808	-0.2
FSU							
Praha (Prague), Czech Republic	403	0.834804	-35.9	0.820521	-17.7	0.808759	-1.6
AFRICA							
South Africa (part synth)	507	0.823470	-34.2	0.813635	-21.3	0.797394	-0.4
South Africa (100% synth)	508	0.812559	-37.2	0.799570	-19.2	0.786283	-1.4
MIDDLE EAST							
Abu Dhabi, UAE	606	0.825129	-31.5	0.816042	-19.9	0.801364	-0.7
ASIA / AUSTRALIA							
Beijing, China	704	0.824288	-34.3	0.812641	-19.8	0.797020	0.0
Kuala Lumpur, Malaysia	711	0.829662	-36.7	0.815987	-19.4	0.801222	0.0
Sydney, Australia	716	0.834343	-37.1	0.819410	-17.8	0.805658	0.5
Tokyo, Japan	717	0.826044	-29.5	0.816418	-17.5	0.804328	-1.3
Oil Shale, Australia	718	0.826725	-30.9	0.815693	-17.3	0.802683	-0.1
Oil Shale, Australia (low nit.)	720	0.829450	-29.2	0.820029	-17.7	0.806243	0.1
Oil Shale, Australia (high Nit.)	721	0.828552	-28.2	0.819584	-17.3	0.805576	0.5

Fuel Study Matrix	Sample Number	Density					
		g/ml	Temp C	g/ml	Temp C	g/ml	Temp C
Test Methods (ASTM)		Solartron		Solartron		Solartron	
USA							
Boston, MA	002	0.799228	19.8	0.784820	39.6	0.763608	69.4
Chicago, IL	003	0.809706	19.8	0.795379	39.7	0.774375	69.5
Dallas/Ft. Worth	004	0.807162	19.7	0.793052	39.3	0.771325	68.8
Lebanon, OH	006	0.810832	19.8	0.796975	39.4	0.776169	69.1
Lima, OH	007	0.811702	19.3	0.797732	39.0	0.776495	69.0
Los Angeles, CA	008	0.801898	19.7	0.787555	39.7	0.766154	69.5
Pittsburg, PA	014	0.808297	19.6	0.794186	39.3	0.773515	68.8
Seattle, WA	017	0.806143	20.0	0.791945	39.4	0.770864	68.8
Seattle/Boeing, WA	018	0.812453	20.3	0.798448	39.7	0.777292	69.5
Shell Martinez Refinery, CA	020	0.820052	19.8	0.806079	39.3	0.784479	69.4
Lebanon, OH	030	0.786351	19.5	0.776653	38.8	0.754473	69.5
Langley AFB, VA	031	0.792400	19.9	0.780366	37.0	0.758301	67.5
Shaw AFB, SC	032	0.794345	19.9	0.780416	39.4	0.758603	69.5
Randolph AFB, TX	033	0.811739	18.8	0.796318	39.7	0.775018	69.6
McConnell AFB, KS	034	0.801400	19.3	0.786537	39.5	0.765332	69.4
Robins AFB, KS	035	0.805503	19.5	0.790457	39.7	0.768901	69.5
Stoddard Solvent	036	0.777814	19.7	0.763233	39.6	0.741244	69.4
Seymour Johnson AFB, NC	037	0.799438	19.8	0.785451	39.5	0.770221	61.8
Valero Benicia Refinery	039	0.818744	19.7	0.805379	39.2	outlier	69.2
Petro Star Valdez Refinery, AK	040	0.819171	20.4	0.806668	37.7	0.791704	58.8
Trend Western Fuels, Tyndall	041	0.795193	20.6	0.780580	40.5	0.760879	68.7
Charleston AFB, SC	042	0.791262	21.4	0.776187	41.7	0.756314	69.5
Placid Refining, LA	043	0.807789	19.9	0.793448	39.7	0.772700	69.4
Buckeye Pipeline, IN	044	0.797832	29.2	0.789588	40.7	0.769254	69.1
Monee, IL (TEPPCO)	045	0.804314	19.3	0.789679	39.5	0.773569	62.3
CANADA							
Dartmouth / Halifax	101	0.80558	20.9	0.79190	39.6	0.77037	69.5
Toronto	104	0.814437	22.3	0.801656	39.6	0.780525	69.4
Richmond / Vancouver	105	0.811048	19.4	0.796523	39.5	0.775367	69.4
Edmonton	108	0.807615	21.4	0.797153	35.8	0.773343	69.2
Ontario, Canada	109	0.792259	21.3	0.779051	39.5	0.757490	69.5
Ontario, Canada	110	0.817166	19.3	0.802683	39.3	0.781591	69.0
Edmonton, Oil Sands	111	0.813497	19.5	0.798845	39.7	0.777468	69.6
LATIN AMERICA							
Rio de Janiero, Brazil	206	0.784303	19.6	0.769603	39.7	0.748209	69.6
Talara City, Peru	211	0.808593	19.7	0.794125	39.7	0.772901	69.7
EUROPE							
Amsterdam, Netherlands	301	0.795507	19.9	0.781097	39.7	0.759567	69.5
Brussels, Belgium	304	0.797426	20.0	0.782899	39.7	0.761461	69.6
Dublin, Ireland	306	0.797540	18.8	0.782145	39.6	0.761298	68.9
London, England	314	0.788887	19.5	0.774151	39.7	0.752505	69.5
London, England	315	0.794022	18.3	0.778126	39.4	0.761573	62.6
Madrid, Spain	316	0.797536	19.6	0.782881	39.6	0.761235	69.4
Munich, Germany	318	0.793434	19.4	0.778462	39.6	0.756891	69.4
Paris, France	321	0.795389	19.2	0.780108	39.7	0.758693	69.4
Toulouse, France	325	0.797207	20.4	0.783067	40.0	0.760275	70.5
Bordeaux, France	334	0.796426	19.7	0.781760	39.7	0.760087	69.7
Lyon, France	335	0.792489	19.6	0.777911	39.8	0.756482	69.8
Montpellier, France	336	0.791871	19.6	0.777188	39.7	0.755900	69.8
FSU							
Praha (Prague), Czech Republic	403	0.794049	19.1	0.779251	39.5	0.758017	69.2
AFRICA							
South Africa (part synth)	507	0.783516	19.7	0.769272	39.5	0.748005	69.5
South Africa (100% synth)	508	0.771945	19.5	0.757544	39.7	0.736735	69.5
MIDDLE EAST							
Abu Dhabi, UAE	606	0.787087	19.5	0.772474	39.5	0.750970	69.2
ASIA / AUSTRALIA							
Beijing, China	704	0.783098	19.5	0.768137	39.7	0.746483	69.5
Kuala Lumpur, Malaysia	711	0.787332	19.6	0.772334	39.7	0.750705	69.5
Sydney, Australia	716	0.792874	19.5	0.777641	39.7	0.755945	69.5
Tokyo, Japan	717	0.789761	19.4	0.774919	39.7	0.753407	69.5
Oil Shale, Australia	718	0.788342	19.9	0.773809	39.5	0.752755	69.3
Oil Shale, Australia (low nit.)	720	0.792164	19.6	0.777465	39.5	0.755450	69.5
Oil Shale, Australia (high Nit.)	721	0.792023	19.5	0.777274	39.3	0.755873	69.3

Fuel Study Matrix	Sample Number	Dielectric Constant					
		K	Temp C	K	Temp C	K	Temp C
Test Methods (ASTM)		K-cell		K-cell		K-cell	
USA							
Boston, MA	002	2.20869	-36.6	2.18175	-19.4	2.15227	-0.4
Chicago, IL	003	2.23005	-38.1	2.20384	-20.4	2.17276	-0.2
Dallas/Ft. Worth	004	2.22562	-37.1	2.20112	-20.2	2.17013	-0.4
Lebanon, OH	006	2.22525	-38.2	2.19831	-19.3	2.17044	-0.4
Lima, OH	007	2.21829	-38.4	2.19049	-19.8	2.16169	-0.6
Los Angeles, CA	008	2.20083	-37.7	2.17415	-19.8	2.14661	-1.0
Pittsburg, PA	014	2.21392	-33.8	2.19401	-20.0	2.16413	-0.3
Seattle, WA	017	2.21359	-37.8	2.18595	-19.4	2.15603	0.2
Seattle/Boeing, WA	018	2.23055	-34.6	2.20715	-18.9	2.17819	-0.1
Shell Martinez Refinery, CA	020	2.20930	-38.3	2.18328	-19.0	2.15910	-1.4
Lebanon, OH	030	2.18841	-36.9	2.16132	-18.8	2.13785	-2.8
Langley AFB, VA	031	2.22112	-38.4	2.19627	-23.3	2.16028	-1.5
Shaw AFB, SC	032	2.21440	-38.6	2.18347	-19.4	2.15565	-1.7
Randolph AFB, TX	033	2.23595	-37.3	2.20721	-19.3	2.17734	-0.9
McConnell AFB, KS	034	2.21869	-38.7	2.18825	-19.2	2.15969	-0.7
Robins AFB, KS	035	2.23708	-38.2	2.20852	-20.8	2.17502	-0.5
Stoddard Solvent	036	2.16776	-35.9	2.14364	-19.7	2.11584	-1.1
Seymour Johnson AFB, NC	037	2.22336	-38.7	2.19350	-18.7	2.16388	0.4
Valero Benicia Refinery	039	2.22863	-38.1	2.20140	-19.9	2.17079	0.3
Petro Star Valdez Refinery, AK	040	2.25105	-29.3	2.23445	-19.3	2.19909	0.5
Trend Western Fuels, Tyndall	041	2.20467	-34.7	2.17752	-17.8	2.14781	1.1
Charleston AFB, SC	042	2.20699	-32.0	2.18501	-17.5	2.16193	-3.0
Placid Refining, LA	043	2.20850	-34.1	2.18852	-20.2	2.15973	-0.9
Buckeye Pipeline, IN	044	2.21508	-37.1	2.18758	-18.0	2.15894	1.0
Monee, IL (TEPPCO)	045	2.21868	-36.3	2.19457	-19.8	2.16748	-1.3
CANADA							
Dartmouth / Halifax	101	2.20692	-39.0	2.17814	-19.8	2.14911	-0.4
Toronto	104	2.24598	-36.2	2.21975	-20.0	2.18158	4.3
Richmond / Vancouver	105	2.22002	-37.0	2.19319	-19.5	2.16443	-0.3
Edmonton	108	2.21741	-37.7	2.19209	-19.6	2.16275	0.8
Ontario, Canada	109	2.18501	-36.3	2.15884	-18.4	2.13234	0.9
Ontario, Canada	110	2.21985	-33.7	2.19680	-18.0	2.17107	-0.2
Edmonton, Oil Sands	111	2.19537	-38.7	2.16906	-20.1	2.14210	-0.6
LATIN AMERICA							
Rio de Janiero, Brazil	206	2.18752	-37.9	2.15976	-19.8	2.13135	-0.4
Talara City, Peru	211	2.19220	-38.3	2.16559	-19.7	2.13882	-0.2
EUROPE							
Amsterdam, Netherlands	301	2.19756	-37.4	2.17013	-18.8	2.14016	0.5
Brussels, Belgium	304	2.20635	-38.5	2.17920	-20.3	2.14925	-0.4
Dublin, Ireland	306	2.19839	-38.7	2.16831	-18.3	2.14256	-1.1
London, England	314	2.18691	-38.0	2.15910	-19.6	2.13066	-0.4
London, England	315	2.20076	-38.9	2.17014	-17.8	2.13914	2.9
Madrid, Spain	316	2.20416	-37.7	2.17853	-20.2	2.15012	-1.4
Munich, Germany	318	2.19912	-38.6	2.17188	-20.2	2.14104	0.2
Paris, France	321	2.20023	-37.2	2.17490	-20.4	2.14340	0.2
Toulouse, France	325	2.20619	-39.4	2.17879	-19.6	2.14681	0.7
Bordeaux, France	334	2.19993	-37.9	2.17305	-19.7	2.14525	-0.2
Lyon, France	335	2.20884	-38.5	2.17903	-19.6	2.14920	-0.3
Montpellier, France	336	2.18974	-38.4	2.16307	-20.0	2.13502	-0.4
FSU							
Praha (Prague), Czech Republic	403	2.18506	-36.8	2.15771	-17.9	2.13362	-1.5
AFRICA							
South Africa (part synth)	507	2.16370	-36.1	2.14377	-21.9	2.11311	-0.5
South Africa (100% synth)	508	2.13876	-39.0	2.11328	-19.5	2.08788	-0.7
MIDDLE EAST							
Abu Dhabi, UAE	606	2.19138	-32.6	2.17299	-20.0	2.14281	-0.6
ASIA / AUSTRALIA							
Beijing, China	704	2.17789	-37.1	2.15517	-20.5	2.12451	-0.3
Kuala Lumpur, Malaysia	711	2.18664	-38.7	2.16049	-19.6	2.13139	0.0
Sydney, Australia	716	2.18882	-37.8	2.15938	-17.9	2.13153	0.6
Tokyo, Japan	717	2.18051	-30.4	2.16171	-17.9	2.13622	-1.1
Oil Shale, Australia	718	2.17128	-33.3	2.14985	-18.7	2.12355	-0.6
Oil Shale, Australia (low nit.)	720	2.19369	-30.1	2.17488	-18.4	2.14634	0.0
Oil Shale, Australia (high Nit.)	721	2.19184	-30.1	2.17407	-18.8	2.14480	-0.1

Fuel Study Matrix	Sample Number	Dielectric Constant					
		K	Temp C	K	Temp C	K	Temp C
Test Methods (ASTM)		K-cell		K-cell		K-cell	
USA							
Boston, MA	002	2.12227	19.8	2.09501	39.8	2.05431	69.6
Chicago, IL	003	2.14239	19.8	2.11237	39.8	2.07066	69.6
Dallas/Ft. Worth	004	2.13837	19.8	2.10947	39.6	2.06714	69.7
Lebanon, OH	006	2.13927	19.9	2.11042	39.6	2.06885	69.1
Lima, OH	007	2.13249	19.1	2.10459	39.0	2.06386	69.2
Los Angeles, CA	008	2.11556	19.7	2.08868	39.8	2.04917	69.7
Pittsburg, PA	014	2.13356	19.7	2.10518	39.6	2.06498	69.2
Seattle, WA	017	2.12607	20.0	2.09788	39.6	2.05641	69.6
Seattle/Boeing, WA	018	2.14469	20.3	2.11603	39.8	2.07463	69.8
Shell Martinez Refinery, CA	020	2.12732	19.9	2.09979	39.6	2.06001	69.6
Lebanon, OH	030	2.10459	19.6	2.07831	38.8	2.03800	69.6
Langley AFB, VA	031	2.12553	19.9	2.09857	37.5	2.05495	68.1
Shaw AFB, SC	032	2.12164	19.9	2.09230	39.5	2.05019	69.8
Randolph AFB, TX	033	2.14513	19.0	2.11265	39.7	2.07014	69.6
McConnell AFB, KS	034	2.12681	19.3	2.09573	39.6	2.05356	69.6
Robins AFB, KS	035	2.14293	19.4	2.11126	39.8	2.07580	69.6
Stoddard Solvent	036	2.08472	19.8	2.05786	39.6	2.01717	69.5
Seymour Johnson AFB, NC	037	2.13649	19.9	2.11267	39.6	2.08104	61.7
Valero Benicia Refinery	039	2.14241	19.4	2.11470	39.0	2.07443	69.2
Petro Star Valdez Refinery, AK	040	2.16645	20.6	2.13840	38.5	2.10761	59.2
Trend Western Fuels, Tyndall	041	2.11775	20.4	2.08880	40.6	2.05046	68.5
Charleston AFB, SC	042	2.12315	21.5	2.08866	42.8	2.04932	69.7
Placid Refining, LA	043	2.12898	19.7	2.10032	39.8	2.05986	69.6
Buckeye Pipeline, IN	044	2.11717	29.5	2.10118	41.3	2.06460	69.3
Monee, IL (TEPPCO)	045	2.13506	19.3	2.10704	39.6	2.07558	62.4
CANADA							
Dartmouth / Halifax	101	2.11857	20.8	2.09285	39.6	2.05283	69.5
Toronto	104	2.15526	22.0	2.12971	39.6	2.08814	69.3
Richmond / Vancouver	105	2.13574	19.3	2.10842	39.4	2.06795	69.2
Edmonton	108	2.13136	21.3	2.11213	35.9	2.06748	69.3
Ontario, Canada	109	2.10127	21.3	2.07700	39.4	2.03741	69.4
Ontario, Canada	110	2.14213	19.3	2.11523	39.6	2.07572	69.3
Edmonton, Oil Sands	111	2.11466	19.3	2.08903	39.5	2.04984	69.5
LATIN AMERICA							
Rio de Janiero, Brazil	206	2.10217	19.4	2.07431	39.4	2.03551	69.3
Talara City, Peru	211	2.11155	19.4	2.08567	39.5	2.04634	69.4
EUROPE							
Amsterdam, Netherlands	301	2.11041	20.0	2.08178	39.8	2.04066	69.7
Brussels, Belgium	304	2.11843	19.9	2.09053	39.8	2.04934	69.6
Dublin, Ireland	306	2.11239	19.0	2.08254	39.8	2.04192	69.2
London, England	314	2.10193	19.4	2.07458	39.6	2.03506	69.4
London, England	315	2.11598	18.3	2.08524	39.3	no data	
Madrid, Spain	316	2.11801	19.6	2.08858	39.8	2.04655	69.7
Munich, Germany	318	2.11209	19.4	2.08233	39.8	2.04191	69.5
Paris, France	321	2.11476	19.2	no data		2.04358	69.6
Toulouse, France	325	2.11698	20.4	2.08787	40.2	2.04421	70.9
Bordeaux, France	334	2.11434	19.5	2.08647	39.4	2.04558	69.3
Lyon, France	335	2.11963	19.3	2.09162	39.6	2.05103	69.3
Montpellier, France	336	2.10671	19.3	2.07926	39.4	2.04164	69.3
FSU							
Praha (Prague), Czech Republic	403	2.10348	19.3	2.07477	39.6	2.03546	69.5
AFRICA							
South Africa (part synth)	507	2.08407	19.6	2.06169	39.6	2.01870	69.7
South Africa (100% synth)	508	2.05967	19.6	2.03380	39.8	1.99625	69.7
MIDDLE EAST							
Abu Dhabi, UAE	606	2.11161	19.5	2.08366	39.5	2.04146	69.4
ASIA / AUSTRALIA							
Beijing, China	704	2.09405	19.6	2.06522	39.8	2.02378	69.8
Kuala Lumpur, Malaysia	711	2.10142	19.7	2.07232	39.9	2.03126	69.8
Sydney, Australia	716	2.10359	19.6	2.07531	39.9	2.03433	69.7
Tokyo, Japan	717	2.10509	19.5	2.07607	39.8	2.03530	69.7
Oil Shale, Australia	718	2.09387	19.7	2.06575	39.8	2.02566	69.5
Oil Shale, Australia (low nit.)	720	2.11631	19.6	2.08803	39.6	2.04587	69.8
Oil Shale, Australia (high Nit.)	721	2.11473	19.3	2.08518	39.5	2.04269	69.4

Fuel Study Matrix	Sample Number	Speed of Sound					
		m/sec	Temp C	m/sec	Temp C	m/sec	Temp C
Test Methods (ASTM)							
USA							
Boston, MA	002	1562.30	-35.0	1492.21	-18.4	1419.81	-0.4
Chicago, IL	003	1558.54	-36.6	1492.68	-19.6	1412.95	0.1
Dallas/Ft. Worth	004	1574.07	-34.4	1510.90	-19.6	1430.67	-0.2
Lebanon, OH	006	1560.58	-34.7	1485.77	-17.3	1412.65	0.3
Lima, OH	007	1562.61	-36.3	1487.53	-18.7	1414.96	-0.5
Los Angeles, CA	008	1547.86	-35.9	1476.37	-19.0	1402.68	-1.2
Pittsburg, PA	014	1566.79	-31.2	1517.24	-19.1	1438.35	-0.2
Seattle, WA	017	1567.27	-34.7	1497.84	-18.0	1419.71	0.7
Seattle/Boeing, WA	018	1543.04	-35.3	1484.93	-19.6	1409.78	-0.9
Shell Martinez Refinery, CA	020	1573.85	-36.6	1498.92	-18.7	1430.06	-2.4
Lebanon, OH	030	1526.82	-37.3	1455.31	-18.9	1386.82	-3.1
Langley AFB, VA	031	1537.21	-36.7	1479.09	-22.9	1392.77	-1.4
Shaw AFB, SC	032	1539.13	-36.6	1465.78	-18.8	1395.11	-2.0
Randolph AFB, TX	033	1550.89	-37.0	1477.85	-19.1	1404.54	-0.9
McConnell AFB, KS	034	1544.53	-36.3	1471.24	-18.8	1401.35	-1.7
Robins AFB, KS	035	1548.27	-36.4	1476.17	-19.8	1394.72	-0.2
Stoddard Solvent	036	1573.50	-33.5	1507.42	-18.3	1431.13	-0.5
Seymour Johnson AFB, NC	037	1541.40	-38.8	1460.61	-18.9	1384.26	0.4
Valero Benicia Refinery	039	1557.07	-35.3	1487.50	-18.3	1408.88	0.8
Petro Star Valdez Refinery, AK	040	1521.11	-29.3	outlier	-19.4	1407.69	0.2
Trend Western Fuels, Tyndall	041	1526.80	-34.8	1456.56	-17.8	1379.21	1.1
Charleston AFB, SC	042	1509.49	-30.5	1462.69	-19.4	1393.18	-2.5
Placid Refining, LA	043	1603.99	-31.3	1549.85	-18.4	1471.16	0.0
Buckeye Pipeline, IN	044	1529.77	-35.2	1456.62	-17.3	1383.50	1.3
Monee, IL (TEPPCO)	045	1537.01	-34.7	1470.32	-18.9	1398.27	-1.3
CANADA							
Dartmouth / Halifax	101	1548.90	-37.9	1469.17	-19.4	1389.39	-0.2
Toronto	104	1549.50	-34.9	1481.84	-18.9	1386.15	4.8
Richmond / Vancouver	105	1555.13	-38.0	1480.99	-20.0	1402.75	-0.6
Edmonton	108	1538.55	-36.7	1476.22	-19.0	1388.80	0.6
Ontario, Canada	109	1520.89	-33.2	1451.30	-16.5	1385.21	-0.4
Ontario, Canada	110	1547.92	-33.8	1481.01	-17.2	1409.96	0.1
Edmonton, Oil Sands	111	1561.01	-38.1	1481.21	-19.7	1400.17	-0.3
LATIN AMERICA							
Rio de Janiero, Brazil	206	1524.64	-37.5	1448.66	-19.5	1369.61	-0.2
Talara City, Peru	211	1550.82	-38.2	1470.93	-19.5	1391.38	-0.1
EUROPE							
Amsterdam, Netherlands	301	1555.65	-37.7	1481.93	-19.5	1400.87	0.1
Brussels, Belgium	304	1561.47	-36.7	1491.03	-19.2	1410.95	0.1
Dublin, Ireland	306	1542.37	-38.0	1462.15	-18.3	1398.68	-2.3
London, England	314	1537.06	-38.2	1457.64	-19.6	1378.37	-0.4
London, England	315	1528.39	-36.8	1444.05	-16.7	1363.18	3.3
Madrid, Spain	316	1593.03	-35.2	1523.26	-19.2	1445.52	-0.9
Munich, Germany	318	1539.81	-36.5	1469.11	-19.8	1387.04	0.5
Paris, France	321	1542.73	-35.5	1467.44	-20.0	1393.31	0.4
Toulouse, France	325	1540.00	-36.5	1464.67	-18.7	1382.64	0.4
Bordeaux, France	334	1538.88	-37.7	1461.03	-19.6	1381.04	-0.2
Lyon, France	335	1541.84	-37.7	1463.23	-19.2	1384.35	-0.1
Montpellier, France	336	1537.30	-38.1	1458.93	-19.6	1378.59	-0.2
FSU							
Praha (Prague), Czech Republic	403	1547.56	-36.0	1473.05	-17.7	1407.14	-1.6
AFRICA							
South Africa (part synth)	507	1572.20	-34.2	1516.66	-21.3	1428.02	-0.4
South Africa (100% synth)	508	1579.67	-37.2	1501.47	-19.2	1424.95	-1.4
MIDDLE EAST							
Abu Dhabi, UAE	606	1493.00	-31.5	1448.19	-19.9	1374.00	-0.7
ASIA / AUSTRALIA							
Beijing, China	704	1579.49	-34.3	1514.55	-19.8	1429.39	0.0
Kuala Lumpur, Malaysia	711	1590.06	-36.7	1515.99	-19.4	1434.90	0.0
Sydney, Australia	716	1547.31	-37.1	1468.77	-17.8	1396.21	0.5
Tokyo, Japan	717	1539.75	-29.5	1490.55	-17.5	1424.56	-1.3
Oil Shale, Australia	718	1547.41	-30.9	1489.77	-17.3	1419.12	-0.1
Oil Shale, Australia (low nit.)	720	1553.16	-29.2	1502.77	-17.7	1447.75	0.1
Oil Shale, Australia (high Nit.)	721	1555.64	-28.2	1508.65	-17.3	1431.92	0.5

Fuel Study Matrix	Sample Number	Speed of Sound					
		m/sec	Temp C	m/sec	Temp C	m/sec	Temp C
Test Methods (ASTM)							
USA							
Boston, MA	002	1562.30	-35.0	1492.21	-18.4	1419.81	-0.4
Chicago, IL	003	1558.54	-36.6	1492.68	-19.6	1412.95	0.1
Dallas/Ft. Worth	004	1574.07	-34.4	1510.90	-19.6	1430.67	-0.2
Lebanon, OH	006	1560.58	-34.7	1485.77	-17.3	1412.65	0.3
Lima, OH	007	1562.61	-36.3	1487.53	-18.7	1414.96	-0.5
Los Angeles, CA	008	1547.86	-35.9	1476.37	-19.0	1402.68	-1.2
Pittsburg, PA	014	1566.79	-31.2	1517.24	-19.1	1438.35	-0.2
Seattle, WA	017	1567.27	-34.7	1497.84	-18.0	1419.71	0.7
Seattle/Boeing, WA	018	1543.04	-35.3	1484.93	-19.6	1409.78	-0.9
Shell Martinez Refinery, CA	020	1573.85	-36.6	1498.92	-18.7	1430.06	-2.4
Lebanon, OH	030	1526.82	-37.3	1455.31	-18.9	1386.82	-3.1
Langley AFB, VA	031	1537.21	-36.7	1479.09	-22.9	1392.77	-1.4
Shaw AFB, SC	032	1539.13	-36.6	1465.78	-18.8	1395.11	-2.0
Randolph AFB, TX	033	1550.89	-37.0	1477.85	-19.1	1404.54	-0.9
McConnell AFB, KS	034	1544.53	-36.3	1471.24	-18.8	1401.35	-1.7
Robins AFB, KS	035	1548.27	-36.4	1476.17	-19.8	1394.72	-0.2
Stoddard Solvent	036	1573.50	-33.5	1507.42	-18.3	1431.13	-0.5
Seymour Johnson AFB, NC	037	1541.40	-38.8	1460.61	-18.9	1384.26	0.4
Valero Benicia Refinery	039	1557.07	-35.3	1487.50	-18.3	1408.88	0.8
Petro Star Valdez Refinery, AK	040	1521.11	-29.3	outlier	-19.4	1407.69	0.2
Trend Western Fuels, Tyndall	041	1526.80	-34.8	1456.56	-17.8	1379.21	1.1
Charleston AFB, SC	042	1509.49	-30.5	1462.69	-19.4	1393.18	-2.5
Placid Refining, LA	043	1603.99	-31.3	1549.85	-18.4	1471.16	0.0
Buckeye Pipeline, IN	044	1529.77	-35.2	1456.62	-17.3	1383.50	1.3
Monee, IL (TEPPCO)	045	1537.01	-34.7	1470.32	-18.9	1398.27	-1.3
CANADA							
Dartmouth / Halifax	101	1548.90	-37.9	1469.17	-19.4	1389.39	-0.2
Toronto	104	1549.50	-34.9	1481.84	-18.9	1386.15	4.8
Richmond / Vancouver	105	1555.13	-38.0	1480.99	-20.0	1402.75	-0.6
Edmonton	108	1538.55	-36.7	1476.22	-19.0	1388.80	0.6
Ontario, Canada	109	1520.89	-33.2	1451.30	-16.5	1385.21	-0.4
Ontario, Canada	110	1547.92	-33.8	1481.01	-17.2	1409.96	0.1
Edmonton, Oil Sands	111	1561.01	-38.1	1481.21	-19.7	1400.17	-0.3
LATIN AMERICA							
Rio de Janiero, Brazil	206	1524.64	-37.5	1448.66	-19.5	1369.61	-0.2
Talara City, Peru	211	1550.82	-38.2	1470.93	-19.5	1391.38	-0.1
EUROPE							
Amsterdam, Netherlands	301	1555.65	-37.7	1481.93	-19.5	1400.87	0.1
Brussels, Belgium	304	1561.47	-36.7	1491.03	-19.2	1410.95	0.1
Dublin, Ireland	306	1542.37	-38.0	1462.15	-18.3	1398.68	-2.3
London, England	314	1537.06	-38.2	1457.64	-19.6	1378.37	-0.4
London, England	315	1528.39	-36.8	1444.05	-16.7	1363.18	3.3
Madrid, Spain	316	1593.03	-35.2	1523.26	-19.2	1445.52	-0.9
Munich, Germany	318	1539.81	-36.5	1469.11	-19.8	1387.04	0.5
Paris, France	321	1542.73	-35.5	1467.44	-20.0	1393.31	0.4
Toulouse, France	325	1540.00	-36.5	1464.67	-18.7	1382.64	0.4
Bordeaux, France	334	1538.88	-37.7	1461.03	-19.6	1381.04	-0.2
Lyon, France	335	1541.84	-37.7	1463.23	-19.2	1384.35	-0.1
Montpellier, France	336	1537.30	-38.1	1458.93	-19.6	1378.59	-0.2
FSU							
Praha (Prague), Czech Republic	403	1547.56	-36.0	1473.05	-17.7	1407.14	-1.6
AFRICA							
South Africa (part synth)	507	1572.20	-34.2	1516.66	-21.3	1428.02	-0.4
South Africa (100% synth)	508	1579.67	-37.2	1501.47	-19.2	1424.95	-1.4
MIDDLE EAST							
Abu Dhabi, UAE	606	1493.00	-31.5	1448.19	-19.9	1374.00	-0.7
ASIA / AUSTRALIA							
Beijing, China	704	1579.49	-34.3	1514.55	-19.8	1429.39	0.0
Kuala Lumpur, Malaysia	711	1590.06	-36.7	1515.99	-19.4	1434.90	0.0
Sydney, Australia	716	1547.31	-37.1	1468.77	-17.8	1396.21	0.5
Tokyo, Japan	717	1539.75	-29.5	1490.55	-17.5	1424.56	-1.3
Oil Shale, Australia	718	1547.41	-30.9	1489.77	-17.3	1419.12	-0.1
Oil Shale, Australia (low nit.)	720	1553.16	-29.2	1502.77	-17.7	1447.75	0.1
Oil Shale, Australia (high Nit.)	721	1555.64	-28.2	1508.65	-17.3	1431.92	0.5

Appendix C

Acronyms, Units of Measure, Locations, and ASTM Test Methods

Acronyms & Abbreviations

ASTM	American Society for Testing and Materials
AFRL	Air Force Research Labs
BOCLE	ball-on-cylinder lubricity evaluator
CRC	Coordinating Research Council
Def Stan	Defence Standard (United Kingdom)
DoD	Department of Defense
DERA	Defence Evaluation and Research Agency
EIA	Energy Information Administration
EPA	Environmental Protection Agency (U.S.A.)
FBP	final boiling point
FIA	fluorescent indicator adsorption
FIAM	fluorescent indicator adsorption method
FQIS	fuel quantity indicating system
HAZMAT	hazardous material
HPLC	high performance liquid chromatography
IBP	initial boiling point
JFTOT	jet fuel thermal oxidation tester
Pittsburg	Pittsburgh, Appendix B
PQIS	Petroleum Quality Information System
SASOL	South African Coal, Oil, and Gas Corporation
SDA	static dissipator additive
Syn	synthesis, synthetic
TRW	(now Northrop Grumman)
ULSD	ultra-low sulfur diesel
U.S.	United States
USA	United States of America
USP	United States Pharmacopoeia
Vos	velocity of sound
WPAFB	Wright-Patterson Air Force Base
WSD	wear scar diameter
XRF	X-ray fluorescence

Units of Measure

°C	degrees Celsius
°F	degrees Fahrenheit
Btu	British thermal unit
cm	centimeter
cSt	centistoke
g	gram (mass)
gal	gallon
J	joule
K	Kelvin
kg	kilogram
KPa	kilopascal
L	liter
lb	pound (mass)
m	meter
mass%	mass percent
min	Minute or minimum
MJ	megajoule
mL	milliliter
mm	millimeter
µm	micrometer
mmHg	millimeters of mercury
nm	nanometer
ppb	parts per billion
ppm	parts per million
pS	picosiemens
s, sec	second
vol	volume
vol%	volume percent
wt%	weight percent

Locations	
AK	Alaska, USA
CA	California, USA
IL	Illinois, USA
IN	Indiana, USA
KS	Kansas, USA
LA	Louisiana, USA
MA	Massachusetts, USA
NC	North Carolina, USA
OH	Ohio, USA
PA	Pennsylvania, USA
SC	South Carolina, USA
TX	Texas, USA
VA	Virginia, USA
WA	Washington, USA

ASTM Test Methods

Test Method	Test Method Title
D 86	“Standard Test Method for Distillation of Petroleum Products at Atmospheric Pressure”
D 93	“Standard Test Methods for Flash-Point by Pensky-Martens Closed Cup Tester”
D 445	“Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids”
D 971	“Standard Test Method for Interfacial Tension of Oil Against Water by Ring method”
D 1159	“Standard Test Method for Bromine Numbers of Petroleum Distillates and Commercial Aliphatic Olefins by Electrometric Titration”
D 1218	“Standard Test Method for Refractive Index and Refraction Dispersion of Hydrocarbon Liquids”
D 1319	“Standard Test Method for Hydrocarbon Types in Liquid Petroleum Products by Fluorescent Indicator Adsorption”
D 1655	Standard Specification for Aviation Turbine Fuels
D 1840	“Standard Test Method for Naphthalene Hydrocarbons in Aviation Turbine Fuels by Ultraviolet Spectrophotometry”
D 2622	“Standard Test Method for Sulfur in Petroleum Products by Wavelength Dispersive X-ray Fluorescence Spectrometry (XRF)”
D 2624	“Standard Test Methods for Electrical Conductivity of Aviation and Distillate Fuels”
D 2710	“Standard Test Method for Bromine Index of Petroleum Hydrocarbons by Electrometric Titration”
D 2789	“Standard Test Method for Hydrocarbon Types in Low Olefinic Gasoline by Mass Spectrometry”
D 2887	“Standard Test Method for Boiling Range Distribution of Petroleum Fractions by Gas Chromatography”
D 3227	“Standard Test method for (Thiol Mercaptan) Sulfur in Gasoline, Kerosine, Aviation Turbine and Distillate Fuels (Potentiometric Method)
D 3241	“Standard Test Method for Thermal Oxidation Stability of Aviation Turbine Fuels (JFTOT Procedure)”
D 3242	“Standard Test Method for Acidity in Aviation Turbine Fuel”
D 3338	“Standard Test Method for Estimation of Net Heat of Combustion of Aviation Fuels”
D 3701	“Standard Test Method for Hydrogen Content of Aviation Turbine Fuels by Low Resolution Nuclear Magnetic Resonance Spectrometry”
D 4052	“Standard Test Method for Density and Relative Density of Liquids by Digital Density Meter”
D 4809	“Standard Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter”
D 5001	“Standard Test Method for Measurement of Lubricity of Aviation Turbine Fuels by the Ball-on-Cylinder Lubricity Evaluator (BOCLE)”
D 5949	“Standard Test Method for Pour Point of Petroleum Products (Automatic Pressure Pulsing Method)”
D 5972	“Standard Test Method for Freezing Point of Aviation Fuels (Automatic Phase Transition Method)”
D 6379	“Standard Test Method for Determination of Aromatic Hydrocarbon Types in Aviation Fuels and Petroleum Distillates – High Performance Liquid Chromatography (HPLC) Method with Refractive Index Detection”
E 1269	“Standard Test Method for Determining Specific Heat Capacity by Differential Scanning Calorimetry”

Appendix D
Metals Content by Inductively Coupled Plasma Analysis

The following data were supplied by the Air Force Research Labs.

The metal content of 29 fuel samples was analyzed by inductively coupled plasma (ICP) analysis. The results are show in Table D.1.

Sample Number	Copper (ppb)	Zinc (ppb)	Manganese (ppb)	Iron (ppb)	Calcium (ppb)	Breakpoint
508	0	9	0	0	0	300
301	7	15	0	0	6	285
14	0	0	0	0	12	285
711	2	1	0	0	20	285
41	9	32	0	0	11	285
34	7	0	0	9	1	310
44	11	1	0	0	1	235
30	0	0	0	0	7	264
206	2	0	0	0	0	285
109	0	32	0	0	0	310
211	19	8	0	0	12	175
20	11	0	0	0	2	290
304	55	0	0	0	1	***
716	0	0	0	0	20	290
42	11	5	0	0	7	295
325	2	0	0	0	3	280
321	1	0	0	0	1	280
18	4	0	103	0	0	300
40	0	0	103	0	24	300
43	0	0	0	0	6	280
704	0	0	0	0	9	***
704	7	28	0	0	20	***
718	5	9	0	3	1	295
717	195	6	0	6	1	290
720	4	1	0	0	42	290
721	5	7	0	0	2	295
110	0	0	21	0	8	280
104	0	0	0	0	3	275
111	0	1	0	0	4	***

Table D.1: Metal Content by ICP Analysis

Copper is known to degrade the thermal stability of jet fuels. Even relatively small amounts of copper (ppb levels) can have a significant effect. Figure D.1 shows fuel thermal stability versus the copper content of the fuels tested. No general trend is seen in the data.

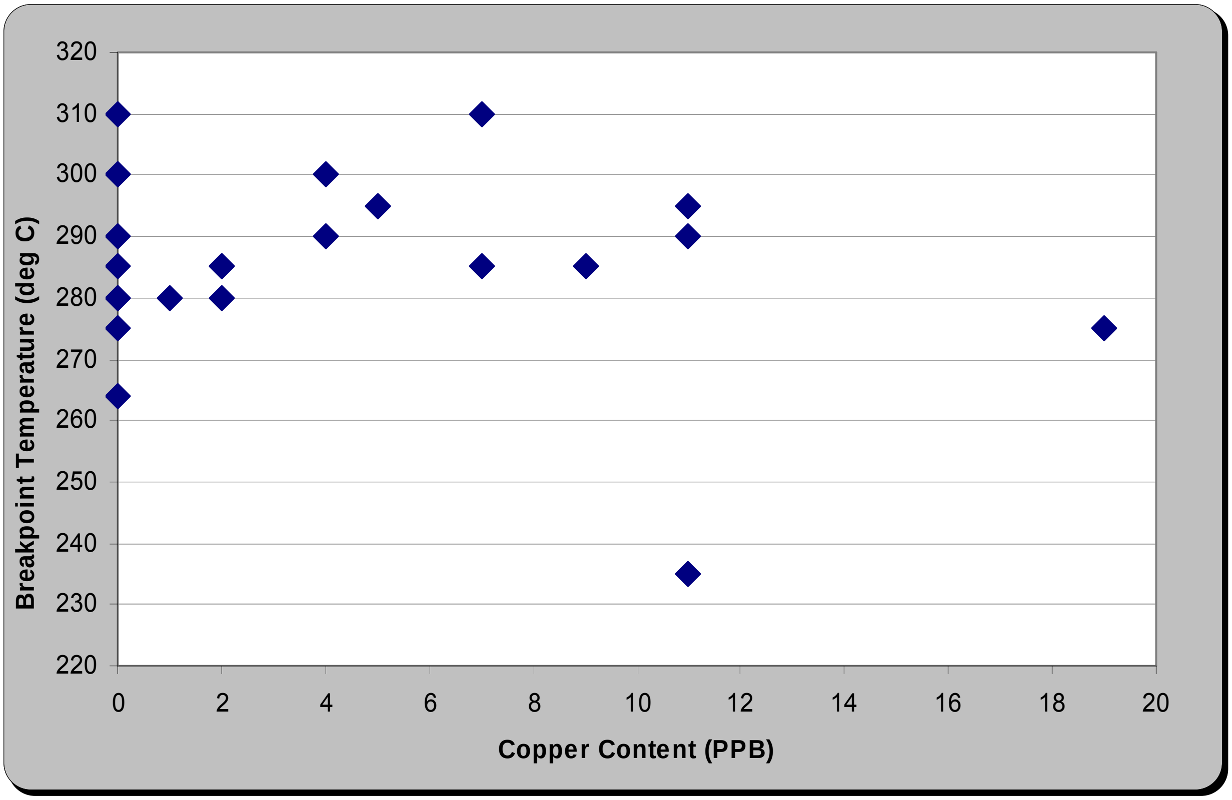


Figure D.1. JFTOT Breakpoint Temperature versus Copper Content

Appendix E

Thermal Stability Testing by Southwest Research Institute®

Southwest Research Institute®

6220 CULEBRA ROAD • POST OFFICE DRAWER 28510 • SAN ANTONIO, TEXAS, USA 78228-0510 • (210) 684-5111 • TELEX 244846

ENGINE AND VEHICLE RESEARCH DIVISION
U.S. Army TARDEC Fuels and lubricants research facility (Swri)
FAX No. 210/522-3270
http://engineandvehicle.swri.org
ISO 9001 Certified / ISO 14001 Certified

January 6, 2003

Belcan Engineering Group
Attn: Stan Seto
10200 Anderson Way
Cincinnati, OH 45242-4718

Subject: Corrected World Fuel Survey Final Report
Southwest Research Institute® (SwRI®) Project No. 03.40.50.04696.01.001

Dear Mr. Seto:

Last year, we embarked on a program to test the JFTOT Breakpoint, Surface Tension and Acid Number of 100 fuels from around the world. While events intervened to prevent completion of the originally planned program, the results of the project provide a valuable resource for a better understanding of jet fuel. In addition to generating an excellent survey on fuels in the field, this program has generated new information on the fundamental stability of jet fuel.

BACKGROUND

In 2001 a consortium comprised of General Electric Aircraft Engines (GEAE), Boeing Aircraft Company (BAC) and B.F. Goodrich Aerospace (BFG) set out to measure key specification and physical properties from fuels all over the world. As part of this program, GEAE contracted Southwest Research Institute, SwRI, to perform JFTOT Breakpoints, Surface Tensions and Acid Numbers. The original plan called for BFG to acquire 100 five-gallon samples from around the world and distribute them among the partners for testing. However, the program was significantly delayed due to the unfortunate events of September 11, 2001.

The project was reauthorized for 2002, but the total tests were reduced from 100 to 80. With new restrictions on shipping and heightened security concerns it proved impossible to generate even 80 samples. GEAE authorized using the remaining test slots in support of other pending thermal stability programs. One program is a pilot study on Breakpoint reproducibility where three fuels will be tested to Breakpoint at five locations. A second program is the BP Research effort to evaluate the Russian JFTOT.

PROGRAM RESULTS

The results of the tests are compiled in Table 1. The test codes, except for the 900 series, match the test matrix generated by BFG. These results will become part of the bigger fuel survey, but the thermal stability results bear some comment. It is interesting that a histogram (Graph 1) of the results peaks around 280°C, which corresponds well with the median value of 285°C. The fact that only 11% of the surveyed fuels have a Breakpoint of less than 275°C at the point of use suggests that a potential requirement for 275°C at the point of origin may not be an extreme requirement.

The 900 series (Table 2), fuels being screened for further work, contains 19 unique samples. These are the fuels screened for the recently completed Red Dye Contamination Program. They represent as broad a compilation of crude oil and refining processing as could be obtained at the start of that program. These fuels have been in storage for an average of three years. When the results of the current Breakpoint tests are compared (Graph 2) with the original values, no significant degradation of the fuel is evident. The median Breakpoint on receipt was 290°C, and now it is 280°C. Of particular note is how the spread was tightened. As received, only six of the fuels had Breakpoints within ±5°C of the median. At the end of the storage, 12 fuels were within ±5°C of the median.

SUMMARY

During this program, SwRI tested 80 fuels for Breakpoint and 53 of those for Surface Tension and Acid Number. The data for the 53 samples will become a permanent part of the literature, since part of the fuel survey and the remaining data will provide an ample source of selection for the coming programs. The unique opportunity to evaluate a series of fuels after a long period of storage provides new insight into the stability of jet fuel.

With this data in hand, we can now prepare for the two programs on Breakpoint reproducibility and the Russian JFTOT. We also need to consider the broader implication of the results from the storage stability tests. The way the results tightened around the 280°C median suggests that jet fuel processing typically results in a nominal stability that can be exceeded but not maintained. This has implications for continuing efforts to raise the standard test temperature and is worthy of further study.

As difficult as this program proved to maintain, it has generated an unmatched body of data. If you have further questions on the results, please contact me by phone (210-522-2587) or by e-mail (gwilson@swri.org). Thank you for this opportunity.

Approved:

Ed Owens

Edwin C. Owens
Director
Fuels & Lubricants Research Department

Sincerely,

George R. Wilson, III
Sr. Research Scientist
Petroleum Products Technology

GRW/wcm

d:\workingfiles\reports/final/grw\03.06034.01.012

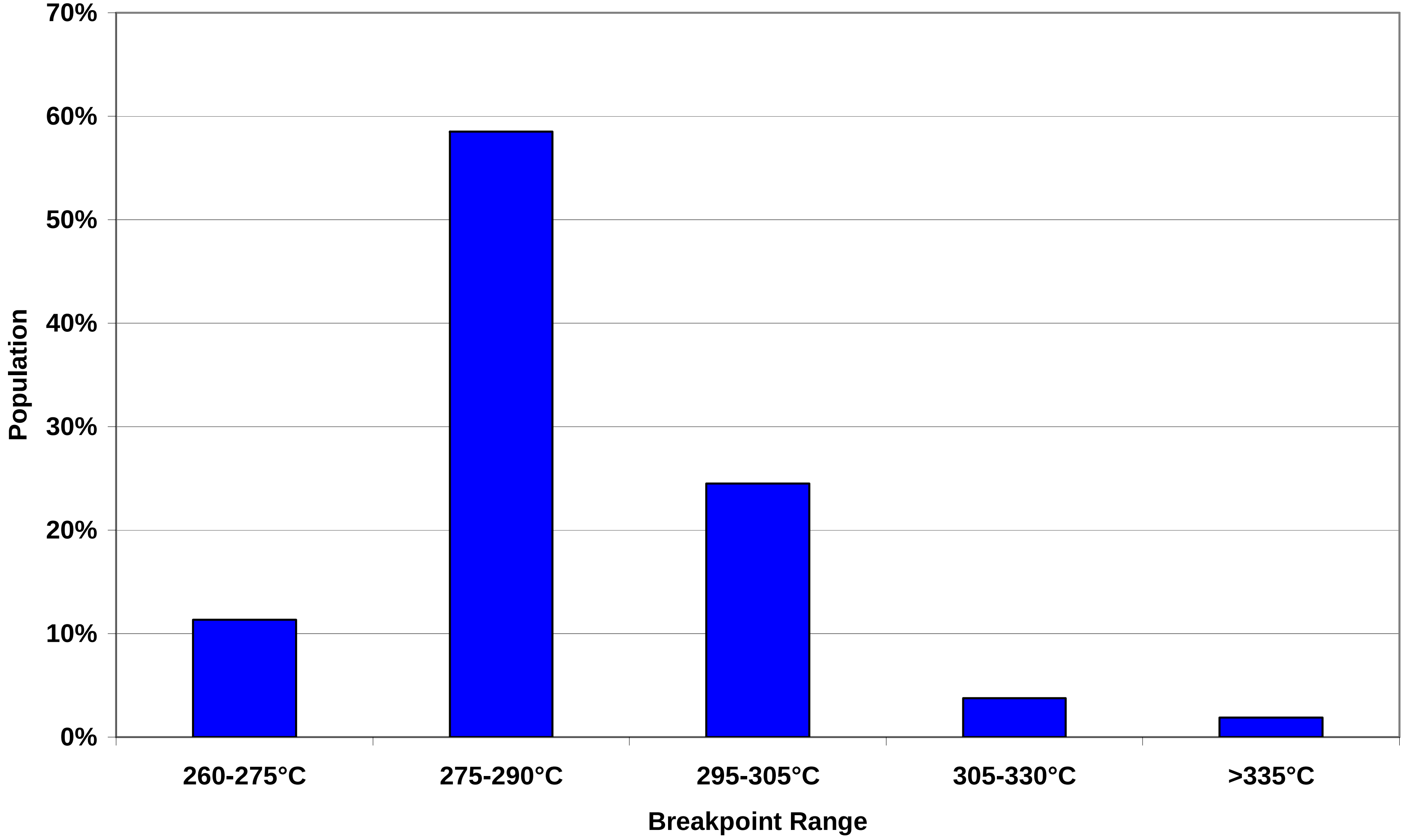
cc: SwRI: V. Parr (Contracts), B. Clark (03), L. Cura-Campos (03)

Table 1: Completed Samples: World Fuel Survey

Sample # (Program Matrix)		Breakpoint, °C	Acid Number	Surface Tension, mN/m	Reported
	006	275	0.005	27.15	9/20/01
	030	265	0.019	26.22	9/20/01
	031	290	0.005	26.35	9/20/01
	032	295	0.008	26.42	9/20/01
	033	300	0.005	26.93	9/20/01
	034	310	0.008	26.69	10/12/01
	035	275	0.005	26.52	10/12/01
	037	270	0.008	26.54	10/12/01
	039	300	0.003	27.03	10/12/01
	040	300	0.008	27.18	10/12/01
	041	285	0.005	26.03	10/12/01
	042	295	0.013	26.00	10/12/01
	003	280	0.008	26.49	12/11/01
	007	290	0.006	27.25	12/11/01
	008	>370	0.008	26.05	12/11/01
	018	300	0.004	26.54	12/11/01
	020	290	0.008	26.44	12/11/01
	301	285	0.006	25.81	12/11/01
	306	275	0.013	25.79	12/11/01
	318	265	0.009	25.64	12/11/01
	321	280	0.003	25.74	12/11/01
	325	280	0.000	25.81	12/11/01
	403	270	0.006	25.98	12/11/01
	716	290	0.003	25.64	12/11/01
	002	295	0.006	25.71	1/10/02
	004	295	0.008	26.37	1/10/02
	017	290	0.004	26.44	1/10/02
	014	285	0.004	26.2	6/14/02
	043	280	0.009	26.81	6/14/02
	507	300	0.003	24.52	6/14/02
	508	300	0.000	25.13	6/14/02
	717	290	0.006	25.39	6/14/02
	718	295	0.003	25.25	6/14/02
	720	290	0.005	23.78	6/14/02
	721	295	0.001	23.39	6/14/02
	316	280	0.001	25.81	11/1/02
	711	285	0.006	25.66	11/1/02
	036	290	0.003	24.22	11/1/02
	315	275	0.007	25.27	11/1/02
	045	275	0.004	26.47	11/1/02

Table 1: Completed Samples: World Fuel Survey

Sample # (Program Matrix)		Breakpoint, °C	Acid Number	Surface Tension, mN/m	Reported
	104	275	0.002	26.66	11/1/02
	044	235	0.002	26.22	11/1/02
	108	290	0.006	26.64	11/1/02
	110	280	0.005	27.2	11/1/02
	109	310	0.002	25.32	11/1/02
	101	295	0.008	25.96	11/1/02
	105	275	0.005	26.97	11/1/02
	206	285	0.003	25.59	11/1/02
	314	280	0.004	23.61	11/1/02
	211	275	0.003	24.87	11/1/02
	334	270	0.002	26	11/1/02
	606	280	0.006	24.35	11/1/02
	335	280	0.005	24.86	12/15/02
See Special Fuel ID List for These Fuels	901	285	NR	NR	12/15/02
	902	265	NR	NR	12/15/02
	903	285	NR	NR	12/15/02
	904	285	NR	NR	12/15/02
	905	275	NR	NR	12/15/02
	906	285	NR	NR	12/15/02
	907	260	NR	NR	12/15/02
	908	270	NR	NR	12/15/02
	909	305	NR	NR	12/15/02
	910	260	NR	NR	12/15/02
	911	285	NR	NR	12/15/02
	912	275	NR	NR	12/15/02
	913	285	NR	NR	12/15/02
	914	275	NR	NR	12/15/02
	915	285	NR	NR	12/15/02
	916	280	NR	NR	12/15/02
	917	285	NR	NR	12/15/02
	918	TBD	NR	NR	12/15/02
	919	TBD	NR	NR	12/15/02
	920	285	NR	NR	12/15/02
	921	340	NR	NR	12/15/02
	922	275	NR	NR	12/15/02
	923	285	NR	NR	12/15/02
	924	300	NR	NR	12/15/02
	925	TBD	NR	NR	12/15/02
	926	TBD	NR	NR	12/15/02
	927	TBD	NR	NR	12/15/02



Graph 1. Thermal Stability Survey

Table 2: Special Fuel ID List

Red Dye Test Program Fuels - Storage Stability

	AL Number	
901	25962	285
902	25877	265
903	25878	285
904	25831	285
905	25738	275
906	25739	285
907	25960	260
908	25762	270
909	25736	305
910	25737	260
911	25757	285
912	25763	275
913	25773	285
914	25769	275
915	25732	285
916	25784	280
917	25808	285
918	25803	TBD
919	25778	TBD

Cross Check Fuel - Fall '02

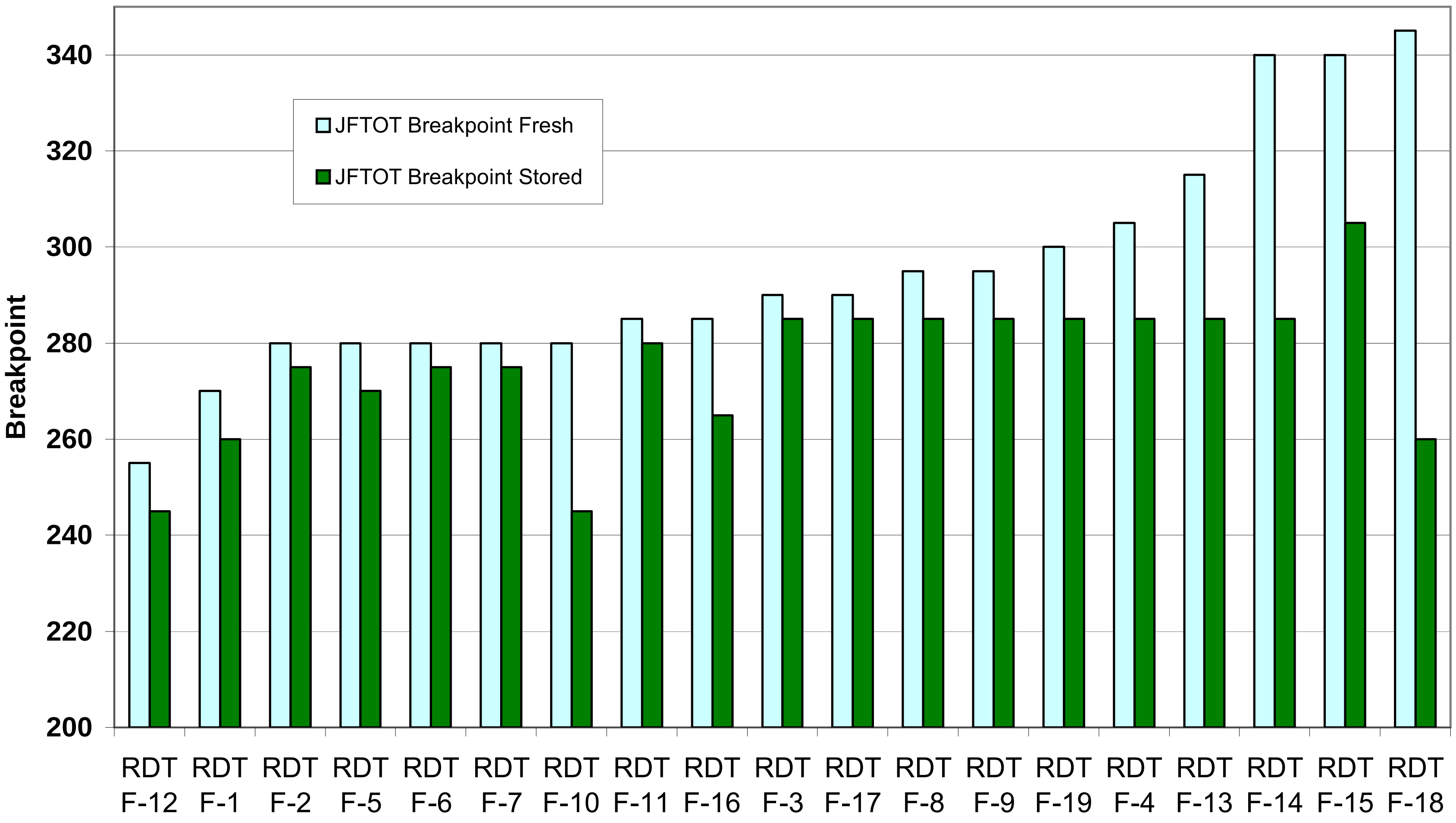
920		285

Synthetic Blends

921	Blend 1	340
922	Blend 2	275
923	Blend 3	285
924	Blend 4	300

Breakpoint Program

925	Fuel 1	TBD
926	Fuel 2	TBD
927	Fuel 3	TBD



Graph 2. Breakpoint Stability

Appendix F
Polar Species by HPLC Analysis

The following data were supplied by the Air Force Research Labs.

Fuel thermal stability can be affected by the presence of trace species including compounds of oxygen, nitrogen, and/or sulfur. These species are collectively referred to as polar species. In this test, the polar species of fuel are separated from the rest of the (non-polar) fuel via HPLC using two columns. Fuel samples are run through a silica column followed by a cyano column. Polar species in the fuels are literally held in the columns while the non-polar components pass through. The polar species are subsequently driven out of the column using a gradient of hexane to isopropanol to methanol. The polar peak area that results is measured with a UV detector at 254 nm. The area is measured from 32.5-34 minutes HPLC elution time, Figure F.1. The total polar species content of the fuel is determined by integrating the area from 32.5-34 minutes. In many cases, this polar peak area can give a rough estimation of a fuel's thermal stability (i.e., a small polar peak area indicates a fuel with high thermal stability, and a large polar peak area indicates a fuel with low thermal stability). This technique gives quantitative information for the total amount of polar species in the fuel, expressed in mg/L. Raw data can be found in Table F.1.

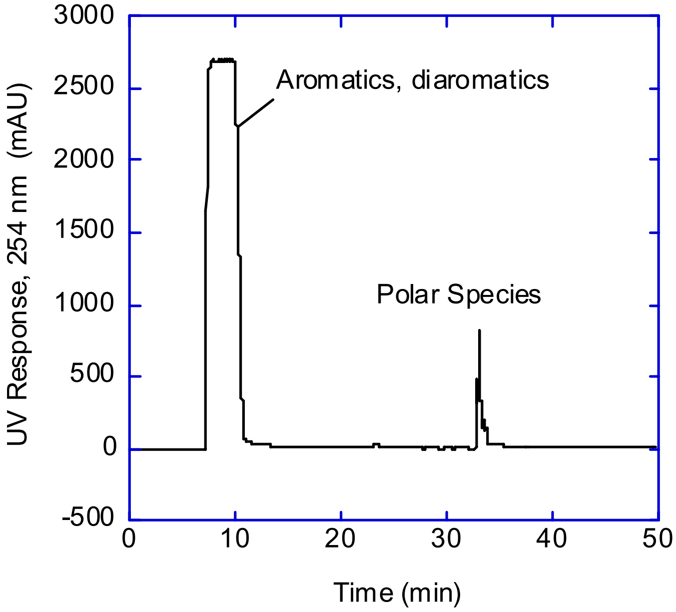


Figure F.1. Example of a HPLC Chromatogram

Sample Number	Total polar species (mg/L)	Final 0.6 min elution of polar species (mg/L)	Breakpoint Temperature (°C)
8	341.4	31.7	370
	349.9	---	370
34	390.2	48.6	310
109	476.3	47.9	310
508	111.6	5.8	300
30	624.7	92.2	265
	657.7	---	265
44	1044.1	233.1	235
403	80.1	11.6	270
41	320.4	74.5	285
	323.9	---	285
	330.7	---	285
301	109.9	11.9	285
14	668.0	158.4	285
711	353.9	19.8	285
206	106.6	9.7	285
	107.1	---	285
508	111.8	42.3	300
18	508.1	105.7	300
33	510.1	78.7	300
39	278.9	57.6	300
40	485.5	79.2	300
104	468.2	189.9	275
318	424.8	104.3	265
37	220.8	99.9	270
45	260.1	68.4	275

Table F.1: Raw data table from polar species, HPLC analysis

It is commonly believed that thermal stability is a function of polar species content in the fuel. Polar species quantities were compared to breakpoint temperature and the results are shown in Figures F.2 and F.3. Based on the figures and data analysis, a correlation between fuel thermal stability and polar species content may be possible; however, further testing is needed.

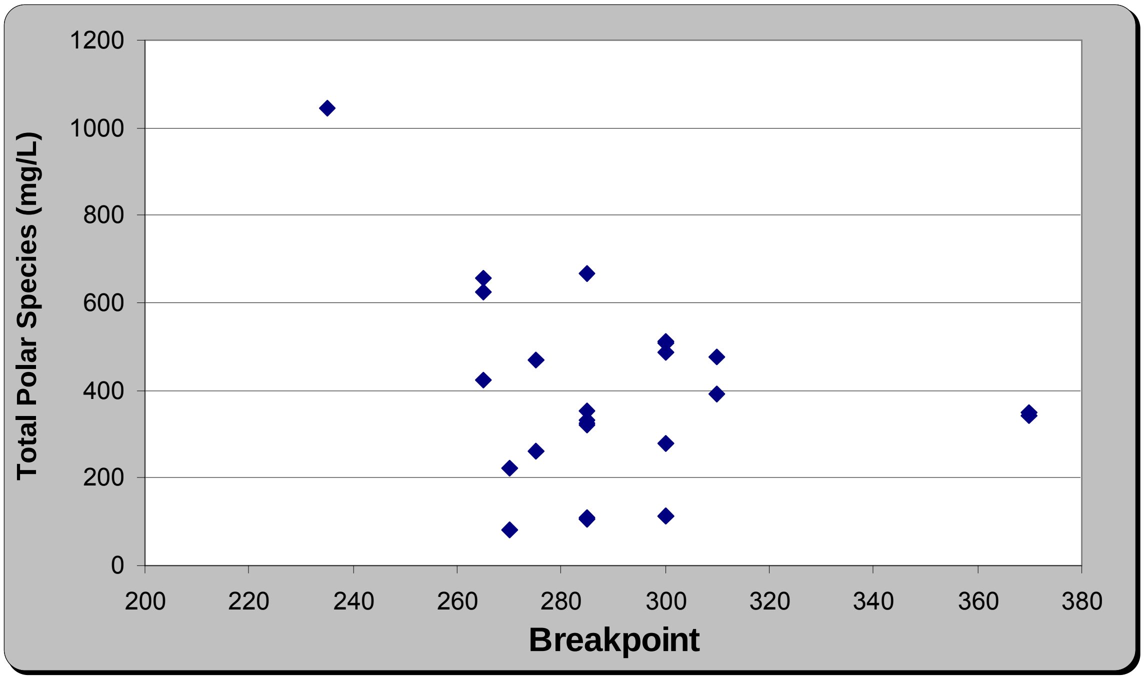


Figure F.2. Breakpoint Temperature versus Total Quantity of Polar Species

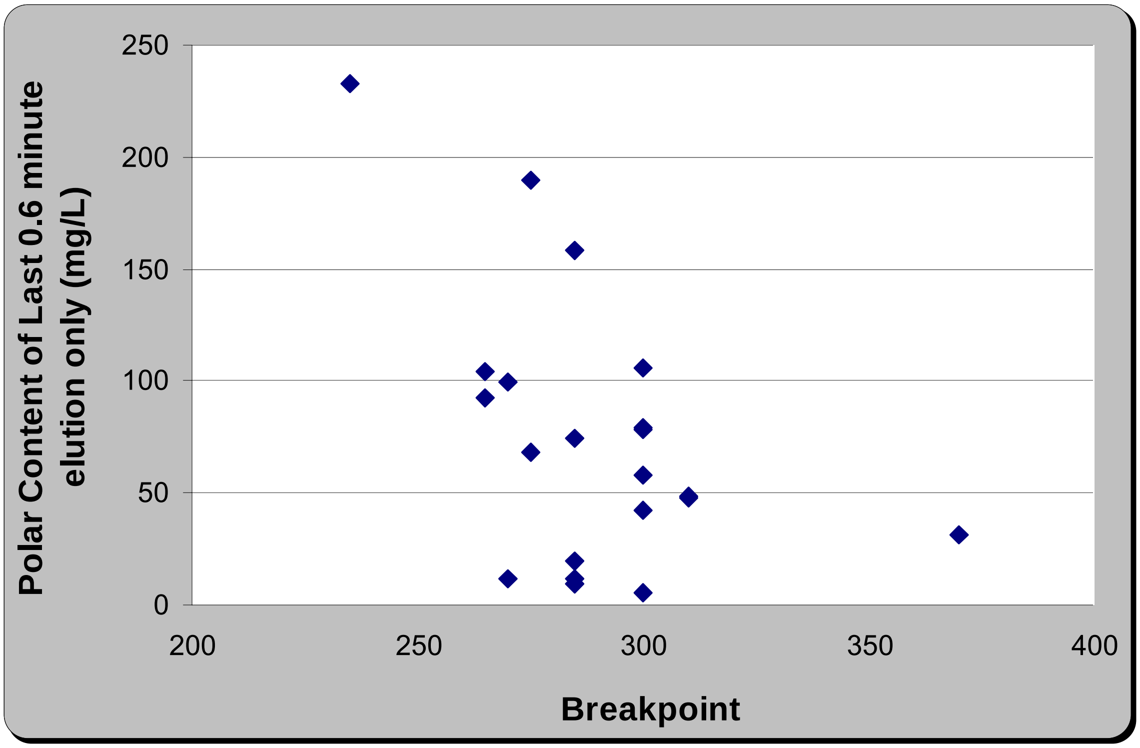


Figure F.3. Breakpoint Temperature by Polar Species Content of Last 0.6 Minutes Elution Time

Appendix G
Hydrocarbon Species Types

Explanation of Hydrocarbon Species Types by University of Dayton Research Institute (UDRI) Researchers

Traditionally, researchers in jet fuel analysis have used ASTM D2789, “Std. Test Method for Hydrocarbon Types in Low Olefinic Gasoline by Mass Spectrometry” for performing hydrocarbon type analysis. This method worked well for JP-4 but was found to be inaccurate for use with middle distillate kerosenes such as JP-8, by UDRI researchers.

The results from these analyses are based on ASTM D2425-93, “Hydrocarbon Types in Middle Distillates by Mass Spectrometry”.

In developing this method in the UDRI laboratory, the traditional ASTM D2789 results for aromatics were compared with the ASTM D1319 test for aromatics and it was found that there were large errors in predicting aromatics for D2789 (5-10% absolute). Therefore, the use of ASTM D2425 was re-developed, using the following steps:

1. Normal phase HPLC determination of saturates, monoaromatics and diaromatics by refractive index (ASTM D6379)
2. Normal phase HPLC for collecting saturate and aromatic fractions
3. GC-MS analysis of saturate and aromatic fractions
4. Calculations according to ASTM D2425 procedure, which assigns fragment ions in mass spectrometry analysis to the various classes of normal/branched paraffins, cycloparaffins, alkylbenzenes, alkylnaphthalenes, etc.

This method is believed to be more accurate, because it subdivides the whole sample into saturate and aromatic fractions using ASTM D6379, Std. Test Method for Determination of Aromatic Hydrocarbon Types in Aviation Fuels and Petroleum Distillates – High Performance Liquid Chromatography Method with Refractive Index Detection. Thus, it becomes easier to distinguish aromatic side chains from alkanes so that less misidentification can take place. Results from this technique compare favorably with aromatic determinations performed for specification testing.

Results from this analysis are shown in Table G.1 using the following classifications:

Compound	Description
Indans/tetralins	Both are two ring compounds, one is aromatic, one is not (indan has a 6-carbon and a 5-carbon ring stuck together; tetralin is two 6-carbon rings)
Indenes	The fully-aromatic version of indan, including substituted versions
Naphthalene	$C_{10}H_{18}$ (two six-carbon rings stuck together)
Naphthalenes	Substituted naphthalene (ex. methyl and ethyl groups attached to rings)
Acenaphthylenes	Naphthalene with two carbons added, forming a third 5-carbon ring (essentially a different tri-cyclic aromatic) (acenaphthylene=$C_{12}H_8$)
Acenaphthenes	Acenaphthylene, but the 5-carbon ring is not aromatic (acenaphthene=$C_{12}H_{10}$)
Tri-cyclic aromatics	Three 6-carbon rings

Fuel Study Matrix	Sample Number	Monoaromatics (vol%)	Diaromatics (vol%)	Total Aromatics (vol%)	Total Saturates (vol%)	Benzene (ug/mL)	Naphthalene (ug/mL)
Test Methods (ASTM)		D 6379	D 6379	D 6379	D 6379	GC / MS	GC / MS
USA							
Boston, MA	002	19.29	1.88	21.17	78.83	35.0	1200
Chicago, IL	003	19.41	2.62	22.03	77.97	62.5	1610
Dallas/Ft. Worth	004	18.42	3.10	21.52	78.48	102.5	1920
Lebanon, OH	006	16.41	3.52	19.93	80.07	35.0	2300
Lima, OH	007	15.44	3.40	18.84	81.16	8.5	2110
Los Angeles, CA	008	18.94	0.90	19.83	80.17	52.5	645
Pittsburg, PA	014	18.12	2.70	20.83	79.17	35.0	2050
Seattle, WA	017	17.58	2.18	19.76	80.24	100.0	1620
Seattle/Boeing, WA	018	18.01	3.95	21.96	78.04	332.5	3350
Shell Martinez Refinery, CA	020	14.10	<0.1	14.10	85.90	6.2	154
Lebanon, OH	030	21.17	0.97	22.14	77.86	67.5	572.5
Langley AFB, VA	031	20.92	2.28	23.19	76.81	67.5	1180
Shaw AFB, SC	032	21.45	1.02	22.47	77.53	52.5	827.5
Randolph AFB, TX	033	16.80	2.76	19.56	80.44	23.3	3520
McConnell AFB, KS	034	14.09	1.98	16.07	83.93	40.0	1220
Robins AFB, KS	035	22.45	2.15	24.60	75.40	23.8	1610
Stoddard Solvent	036	19.89	<0.1	19.89	80.11	0.5	275
Seymour Johnson AFB, NC	037	21.23	1.65	22.88	77.12	75.0	867.5
Valero Benicia Refinery	039	20.41	1.67	22.09	77.91	12.0	1020
Petro Star Valdez Refinery, AK	040	17.91	4.71	22.63	77.37	1.5	4090
Trend Western Fuels, Tyndall	041	18.22	1.87	20.09	79.91	97.5	1870
Charleston AFB, SC	042	21.10	0.96	22.06	77.94	22.0	770
Placid Refining, LA	043	13.47	3.11	16.58	83.42	11.2	2140
Buckeye Pipeline, IN	044	19.58	2.64	22.22	77.78	67.5	1850
Monee, IL (TEPPCO)	045	19.64	2.68	22.32	77.68	67.5	1930
CANADA							
Dartmouth / Halifax	101	16.57	1.52	18.09	81.91	40.0	2880
Toronto	104	21.49	3.24	24.73	75.27	<0.5	1890
Richmond / Vancouver	105	21.50	2.30	23.80	76.20	107.5	1400
Edmonton	108	21.90	1.28	23.18	76.82	67.5	917.5
Ontario, Canada	109	16.11	2.14	18.25	81.75	32.2	3200
Ontario, Canada	110	23.59	1.68	25.27	74.73	<0.5	506
Edmonton, Oil Sands	111	14.30	0.62	14.92	85.08	67.5	220
LATIN AMERICA							
Rio de Janiero, Brazil	206	20.80	0.54	21.34	78.66	75.0	740
Talara City, Peru	211	12.29	1.03	13.32	86.68	27.5	1120
EUROPE							
Amsterdam, Netherlands	301	18.80	1.16	19.96	80.04	57.5	1200
Brussels, Belgium	304	21.81	1.44	23.25	76.75	117.5	1380
Dublin, Ireland	306	15.86	2.50	18.36	81.64	145.0	2520
London, England	314	18.73	1.38	20.11	79.89	62.5	1390
London, England	315	17.29	1.89	19.18	80.82	62.5	647.5
Madrid, Spain	316	20.05	0.74	20.80	79.20	62.5	647.5
Munich, Germany	318	20.23	1.18	21.41	78.59	16.3	1480
Paris, France	321	19.32	1.83	21.15	78.85	47.5	1690
Toulouse, France	325	18.03	1.74	19.77	80.23	87.5	3600
Bordeaux, France	334	16.83	1.63	18.46	81.54	55.0	3100
Lyon, France	335	18.33	2.14	20.47	79.53	52.5	1060
Montpellier, France	336	20.97	0.95	21.92	78.08	75.0	1180
FSU							
Praha (Prague), Czech Republic	403	16.21	0.84	17.05	82.95	2.6	1240
AFRICA							
South Africa (part synth)	507	11.40	1.04	12.44	87.56	0.8	728
South Africa (100% synth)	508	5.60	<0.1	5.60	94.40	1.4	8.5
MIDDLE EAST							
Abu Dhabi, UAE	606	20.06	1.71	21.77	78.23	102.5	1250
ASIA / AUSTRALIA							
Beijing, China	704	17.20	0.64	17.84	82.16	24.0	687.5
Kuala Lumpur, Malaysia	711	16.12	2.50	18.62	81.38	117.5	3820
Sydney, Australia	716	16.36	2.69	19.05	80.95	18.5	2650
Tokyo, Japan	717	18.46	1.17	19.63	80.37	57.5	987.5
Oil Shale, Australia	718	13.77	2.23	16.01	83.99	142.5	3720
Oil Shale, Australia (low nit.)	720	24.92	<0.1	24.92	75.08	0.5	172
Oil Shale, Australia (high Nit.)	721	21.61	<0.1	21.61	78.39	1.2	166

Table G.1: Hydrocarbon Species Analysis – Raw Data

Fuel Study Matrix	Sample Number	Paraffins	Cycloparaffins	Dicycloparaffins	Tricycloparaffins	Alkylbenzenes	Indan and Tetralins
Test Methods (ASTM)		D 2425	D 2425	D 2425	D 2425	D 2425	D 2425
USA							
Boston, MA	002	60.9	8.3	8.7	0.9	14.5	4.7
Chicago, IL	003	56.1	10.7	9.8	1.5	12.8	6.0
Dallas/Ft. Worth	004	62.0	1.9	12.0	2.5	12.7	5.2
Lebanon, OH	006	56.8	11.8	10.2	1.2	10.0	5.7
Lima, OH	007	56.4	13.6	10.0	1.2	8.2	6.6
Los Angeles, CA	008	59.0	9.7	10.4	1.1	12.8	6.0
Pittsburg, PA	014	55.5	11.5	10.6	1.6	12.0	5.6
Seattle, WA	017	59.3	7.9	11.4	1.5	11.1	6.2
Seattle/Boeing, WA	018	53.6	12.2	11.2	1.0	12.6	4.8
Shell Martinez Refinery, CA	020	40.2	10.7	30.6	4.2	8.7	5.4
Lebanon, OH	030	66.7	6.0	5.0	<0.2	15.7	5.5
Langley AFB, VA	031	63.5	7.8	5.0	0.5	17.3	3.7
Shaw AFB, SC	032	65.3	6.6	5.3	0.4	15.2	6.5
Randolph AFB, TX	033	54.8	6.8	16.0	2.8	11.5	5.0
McConnell AFB, KS	034	57.3	15.9	10.0	0.7	9.7	4.2
Robins AFB, KS	035	50.2	15.6	8.4	1.1	15.5	6.8
Stoddard Solvent	036	61.1	16.1	2.9	<0.2	18.8	1.1
Seymour Johnson AFB, NC	037	60.9	8.7	6.9	0.6	15.8	5.4
Valero Benicia Refinery	039	48.6	9.1	17.3	2.9	11.3	8.3
Petro Star Valdez Refinery, AK	040	45.9	19.3	11.0	1.1	11.6	5.5
Trend Western Fuels, Tyndall	041	62.8	9.0	6.5	1.6	14.4	3.9
Charleston AFB, SC	042	64.6	7.9	5.1	0.3	15.7	5.6
Placid Refining, LA	043	56.5	15.5	9.8	1.6	9.8	3.1
Buckeye Pipeline, IN	044	59.7	9.7	7.9	0.5	14.0	5.3
Monee, IL (TEPPCO)	045	59.3	8.2	9.1	1.1	14.4	4.7
CANADA							
Dartmouth / Halifax	101	48.5	18.6	14.1	0.7	12.8	3.5
Toronto	104	48.4	17.0	9.3	0.7	14.3	6.7
Richmond / Vancouver	105	53.5	13.4	8.6	0.7	12.9	8.1
Edmonton	108	55.9	9.3	10.7	0.9	12.9	8.7
Ontario, Canada	109	60.5	13.8	7.0	0.4	13.0	2.9
Ontario, Canada	110	47.0	15.4	11.0	1.3	12.8	10.2
Edmonton, Oil Sands	111	37.5	24.7	21.3	1.5	8.3	5.3
LATIN AMERICA							
Rio de Janiero, Brazil	206	66.1	8.1	4.4	<0.2	18.0	3.0
Talara City, Peru	211	52.3	12.5	18.7	3.2	7.9	4.1
EUROPE							
Amsterdam, Netherlands	301	62.4	9.1	7.9	0.6	14.3	4.6
Brussels, Belgium	304	61.3	7.1	7.7	0.7	16.0	5.7
Dublin, Ireland	306	63.5	7.4	9.7	1.0	12.5	3.1
London, England	314	66.5	8.1	5.0	0.3	15.9	2.8
London, England	315	64.1	9.2	7.0	0.5	14.1	3.2
Madrid, Spain	316	57.3	11.6	9.5	0.8	16.0	4.2
Munich, Germany	318	59.6	12.4	6.2	0.3	16.1	4.3
Paris, France	321	63.0	8.3	6.9	0.7	15.3	3.9
Toulouse, France	325	59.6	10.9	9.0	0.7	14.7	3.3
Bordeaux, France	334	55.2	16.8	8.8	0.7	13.4	3.2
Lyon, France	335	65.4	8.5	5.4	0.3	14.9	3.6
Montpellier, France	336	65.7	6.6	5.7	<0.2	16.6	4.6
FSU							
Praha (Prague), Czech Republic	403	64.0	9.8	8.7	0.5	12.2	4.0
AFRICA							
South Africa (part synth)	507	77.3	2.9	7.0	0.5	9.0	2.3
South Africa (100% synth)	508	92.5	<0.2	2.6	<0.2	3.0	2.6
MIDDLE EAST							
Abu Dhabi, UAE	606	67.6	6.3	3.9	0.3	17.0	3.2
ASIA / AUSTRALIA							
Beijing, China	704	67.9	7.6	6.2	0.5	14.3	3.0
Kuala Lumpur, Malaysia	711	65.1	16.8	<0.2	<0.2	13.7	1.9
Sydney, Australia	716	66.1	7.9	6.1	0.9	13.4	2.8
Tokyo, Japan	717	65.8	7.7	6.2	0.7	14.8	3.7
Oil Shale, Australia	718	71.2	3.3	7.9	1.5	10.6	2.9
Oil Shale, Australia (low nit.)	720	48.8	21.2	4.9	<0.2	15.8	9.1
Oil Shale, Australia (high Nit.)	721	49.9	22.0	6.3	<0.2	13.7	7.9

Table G.1 (continued): Hydrocarbon Species Analysis – Raw Data

Fuel Study Matrix	Sample Number	Indenes CnH2n-10	Naphthalene	Naphthalenes	Acenaphthenes	Acenaphthylenes	Tricyclic Aromatics
Test Methods (ASTM)		D 2425	D 2425	D 2425	D 2425	D 2425	D 2425
USA							
Boston, MA	002	<0.2	<0.2	1.6	<0.2	<0.2	<0.2
Chicago, IL	003	0.4	<0.2	2.3	<0.2	<0.2	<0.2
Dallas/Ft. Worth	004	0.4	<0.2	2.7	<0.2	<0.2	<0.2
Lebanon, OH	006	0.4	0.3	3.3	<0.2	<0.2	<0.2
Lima, OH	007	0.3	0.3	3.1	<0.2	<0.2	<0.2
Los Angeles, CA	008	<0.2	<0.2	0.7	<0.2	<0.2	<0.2
Pittsburg, PA	014	0.3	<0.2	2.4	<0.2	<0.2	<0.2
Seattle, WA	017	<0.2	<0.2	1.8	<0.2	<0.2	<0.2
Seattle/Boeing, WA	018	0.4	0.4	3.5	0.3	<0.2	<0.2
Shell Martinez Refinery, CA	020	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Lebanon, OH	030	<0.2	<0.2	0.8	<0.2	<0.2	<0.2
Langley AFB, VA	031	<0.2	<0.2	2.1	<0.2	<0.2	<0.2
Shaw AFB, SC	032	<0.2	<0.2	0.7	<0.2	<0.2	<0.2
Randolph AFB, TX	033	<0.2	0.4	2.4	<0.2	<0.2	<0.2
McConnell AFB, KS	034	<0.2	<0.2	1.8	<0.2	<0.2	<0.2
Robins AFB, KS	035	<0.2	<0.2	1.7	0.3	<0.2	<0.2
Stoddard Solvent	036	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Seymour Johnson AFB, NC	037	<0.2	<0.2	1.4	<0.2	<0.2	<0.2
Valero Benicia Refinery	039	0.4	<0.2	1.5	<0.2	<0.2	<0.2
Petro Star Valdez Refinery, AK	040	0.5	0.5	4.1	0.3	<0.2	<0.2
Trend Western Fuels, Tyndall	041	<0.2	<0.2	1.4	<0.2	<0.2	<0.2
Charleston AFB, SC	042	<0.2	<0.2	0.8	<0.2	<0.2	<0.2
Placid Refining, LA	043	0.4	0.3	2.7	<0.2	<0.2	<0.2
Buckeye Pipeline, IN	044	<0.2	<0.2	2.2	<0.2	<0.2	<0.2
Monee, IL (TEPPCO)	045	<0.2	0.5	2.1	0.3	<0.2	<0.2
CANADA							
Dartmouth / Halifax	101	<0.2	0.5	1.1	<0.2	<0.2	<0.2
Toronto	104	0.5	<0.2	2.7	0.3	<0.2	<0.2
Richmond / Vancouver	105	0.3	<0.2	1.9	0.3	<0.2	<0.2
Edmonton	108	<0.2	<0.2	1.0	<0.2	<0.2	<0.2
Ontario, Canada	109	<0.2	0.5	1.7	<0.2	<0.2	<0.2
Ontario, Canada	110	0.3	<0.2	1.4	0.4	<0.2	<0.2
Edmonton, Oil Sands	111	0.4	<0.2	0.4	<0.2	<0.2	<0.2
LATIN AMERICA							
Rio de Janiero, Brazil	206	<0.2	<0.2	0.4	<0.2	<0.2	<0.2
Talara City, Peru	211	<0.2	<0.2	0.9	<0.2	<0.2	<0.2
EUROPE							
Amsterdam, Netherlands	301	<0.2	<0.2	0.9	<0.2	<0.2	<0.2
Brussels, Belgium	304	<0.2	<0.2	1.2	<0.2	<0.2	<0.2
Dublin, Ireland	306	<0.2	0.3	2.2	<0.2	<0.2	<0.2
London, England	314	<0.2	0.3	1.1	<0.2	<0.2	<0.2
London, England	315	<0.2	<0.2	1.6	<0.2	<0.2	<0.2
Madrid, Spain	316	<0.2	<0.2	0.6	<0.2	<0.2	<0.2
Munich, Germany	318	<0.2	<0.2	0.9	<0.2	<0.2	<0.2
Paris, France	321	<0.2	<0.2	1.6	<0.2	<0.2	<0.2
Toulouse, France	325	<0.2	0.6	1.3	<0.2	<0.2	<0.2
Bordeaux, France	334	<0.2	0.5	1.3	<0.2	<0.2	<0.2
Lyon, France	335	<0.2	<0.2	1.7	<0.2	<0.2	<0.2
Montpellier, France	336	<0.2	<0.2	0.6	<0.2	<0.2	<0.2
FSU							
Praha (Prague), Czech Republic	403	<0.2	<0.2	0.6	<0.2	<0.2	<0.2
AFRICA							
South Africa (part synth)	507	<0.2	<0.2	0.8	<0.2	<0.2	<0.2
South Africa (100% synth)	508	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
MIDDLE EAST							
Abu Dhabi, UAE	606	<0.2	<0.2	1.5	<0.2	<0.2	<0.2
ASIA / AUSTRALIA							
Beijing, China	704	<0.2	<0.2	0.5	<0.2	<0.2	<0.2
Kuala Lumpur, Malaysia	711	<0.2	0.7	2.2	<0.2	<0.2	<0.2
Sydney, Australia	716	<0.2	0.3	2.4	<0.2	<0.2	<0.2
Tokyo, Japan	717	<0.2	<0.2	1.0	<0.2	<0.2	<0.2
Oil Shale, Australia	718	<0.2	0.6	1.8	<0.2	<0.2	<0.2
Oil Shale, Australia (low nit.)	720	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Oil Shale, Australia (high Nit.)	721	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2

Table G.1 (continued): Hydrocarbon Species Analysis – Raw Data

Appendix H
Naval Testing Results

Haze Rating vs. Lubricity
Acid Number Comparison

Appendix H Results

Forty-eight samples of the World Wide Survey Fuels were provided to the Naval Research Laboratory, Dr. Dennis Hardy, to be tested by a new chemical test for lubricity and for acidity or pH of the fuel. The new chemical test for lubricity of diesel fuels relates fuel lubricity as measured by ASTM standard mechanical test to a standard Haze Rating Turbidity (HRT). The new test has been used successfully to correlate diesel fuel lubricity to scuffing tests such as the HRFF (High Frequency Reciprocating Rig, ASTM D 6079) and SLBOCLE (Scuffing Load Ball-on-Cylinder Lubricity Evaluation, ASTM D 6078). This data seeks to determine if the new chemical test can correlate jet fuel haze to the BOCLE.

Haze Test Results -

The Navy recently developed a simple and rapid strong base extraction of diesel fuels followed by measurement of the resulting haze or turbidity in a hand-held meter. The diesel fuel haze rating appears to be closely related to lubricity as measured by scuffing tests such as the HFRR and SLBOCLE. The higher the haze rating, the higher the fuel lubricity. The method works in the presence of dyes, seawater, dark fuels and gives excellent results for additive treatment of the diesels. The range of haze (in standard nephelometry turbidity units (NTU's)) is from 0.0 to (about) 1100, where 0.0 is crystal clear and 1100 is milky opaque to the naked eye.

When **diesel fuels** are tested on the BOCLE, ASTM D 5001, the haze rating yields poor agreement with those results since the BOCLE results for diesels are over a very narrow range compared to the range for the scuffing tests.

Testing this method with the worldwide **aviation fuels** was done to determine if a correlation between NTU and jet fuel lubricity defined by BOCLE could be obtained. The measured data had a span of just $0.03 \leq \text{NTU} \leq 13$. It was readily apparent that paired with the fuel BOCLE readings, there was no correlation with NTU units. However, when 6 of the samples (2 with high NTU values, 2 of mid range NTU values and 2 with very low NTU values) were re-run on ASTM D5001 BOCLE at a Navy lab, 2 of the 6 BOCLE results were quite different than the reported results in this report. This set of 6 aviation fuels correlated with the re-run BOCLE results very well. See the Table at the bottom of this text and Figure H2A. This warrants future investigation into a chemical test such as HRT as a field test for aviation fuel lubricity or a possible replacement of the BOCLE test for future fuel specification use.

None of the aviation turbine fuel NTU ratings was as high as the values used to rate "pass-fail" for the diesel fuels, 20 to 50 NTU units. It was interesting to note that one fourth of the aviation turbine fuels had significantly higher haze ratings (NTU>=4), implying much greater lubricity capability. Eight of these 12 fuels turned out to be military JP-8 fuels with a mandatory minimum concentration of lubricity additive as opposed to the commercial fuels with no lubricity additive allowed. The data taken are shown in Figure H.1 and H.2 arranged by sample number and increasing NTU, respectively.

CRC BFG Aviation Fuel Set. Comparison of BOCLE and HRT of Selected Samples. Ranked in order of Pax (Navy Lab) BOCLE Re-runs from Low to High Wear Scar. BFG Values Given for Comparison. Note Samples 41 and 301 gave much different values and the remaining 4 samples were similar wear scar values.

BFG Sample Code	*NRL HRT*	**Pax BOCLE (mm)**	**BFG BOCLE (mm)**
33	9	0.57	0.56
41	13	0.59	0.64
109	4	0.60	0.61
45	3	0.60	0.59
301	1	0.61	0.68
7	0.3	0.65	0.64

pH test Results -

The fuel acidity, measured value of pH, was obtained by dissolving about 20 grams of the fuel in ASTM D 664 titration solvent (125 ml) and using a combination glass electrode that had been calibrated against pH buffers to measure the initial hydrogen ion concentration in millivolts (mV). No titration was performed and thus this is not a measure of “acid number” which is the total concentration of acid present that can be titrated by a strong base. On this scale, zero (0) mV is essentially equivalent to a pH value of 7.0, or a neutral aqueous solution. In addition, an increase (or decrease) of 50 mV is equivalent to a change of 1 unit of pH. The data are listed in Table H.3 and Table H.4, below. On the figure is a table that relates the designated test number (1 through 48) to the actual worldwide survey fuel sample number. By example, designated test number 14 is worldwide sample number 325, a Jet A-1 from Toulouse Airport, France, and the sample has a pH value of 8.00.

All forty-eight (48) samples of fuel tested fall within a pH range of 4 to (slightly greater than) 10.0, or about six orders of magnitude.

Historically, most military turbine fuels measured by this technique are neutral to slightly basic. Fuels in this range, 7.0 < pH < 8.0 (or even higher) should cause no problems of surface corrosion over long periods of time. However, one of the worldwide samples, number 721, a shale derived Jet A-1 obtained from Shale Oil Australia (high Nitrogen), CALTEX, had a very low pH, 4.42, with an Acid Number of only 0.001, and should probably be further investigated regarding its corrosive properties.

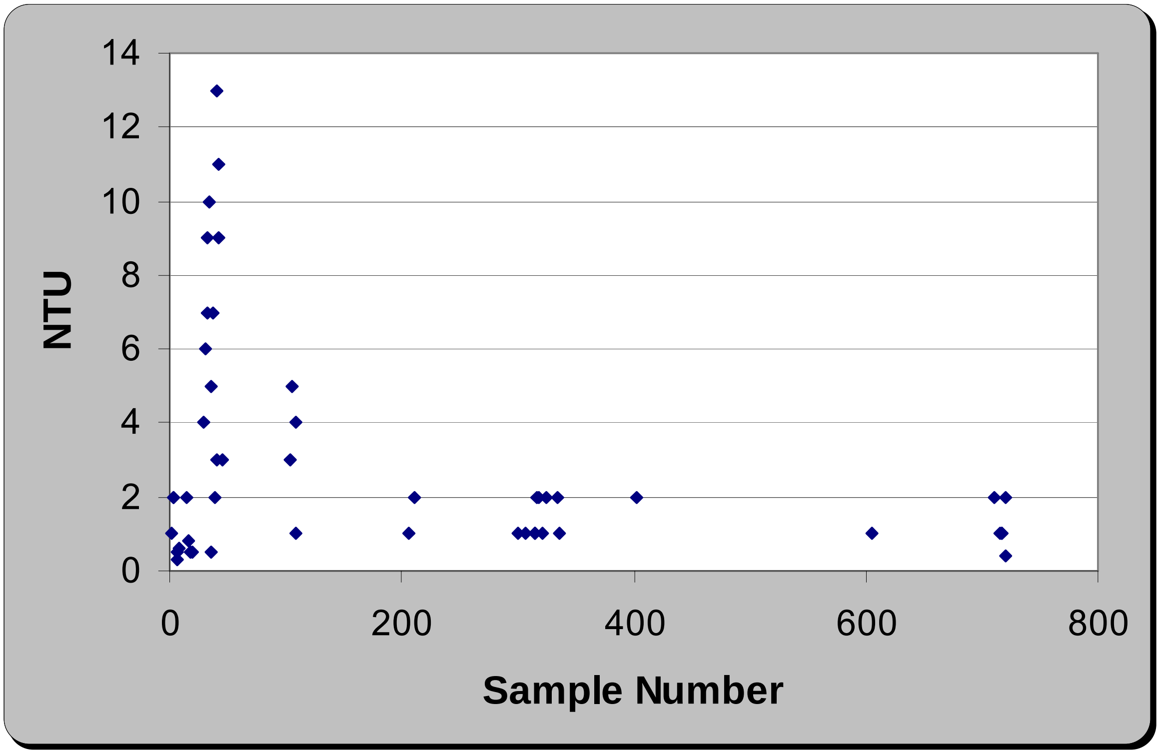


Figure H.1: NTU as a Function of Sample Number

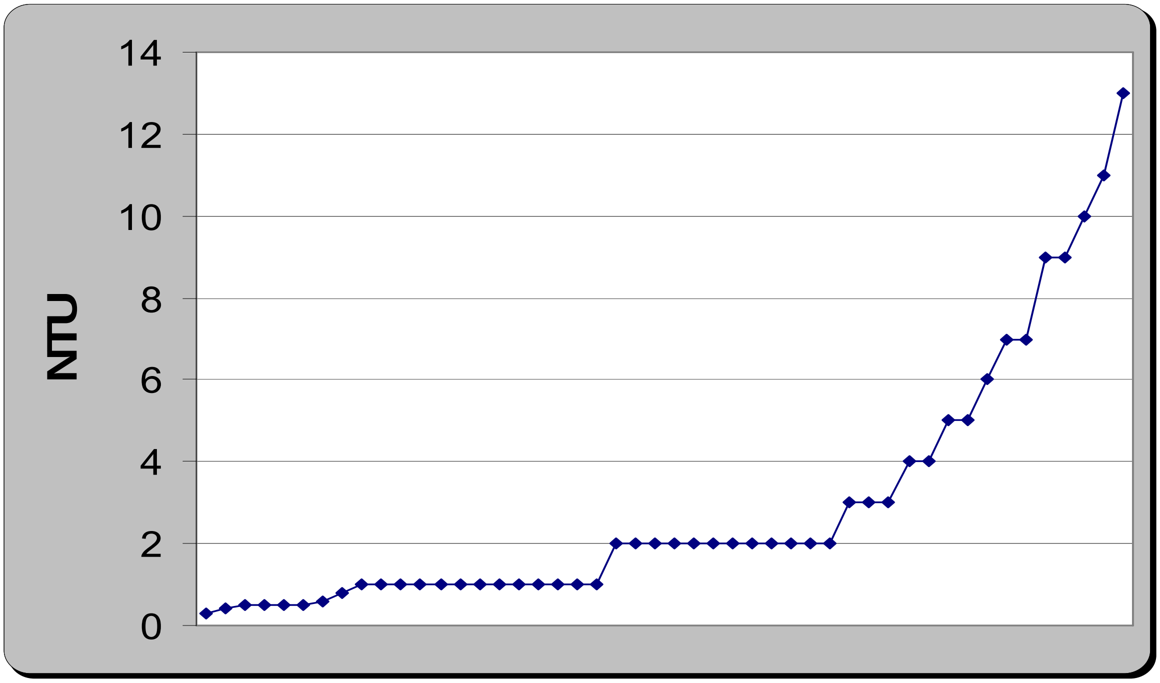


Figure H.2: Increasing NTU

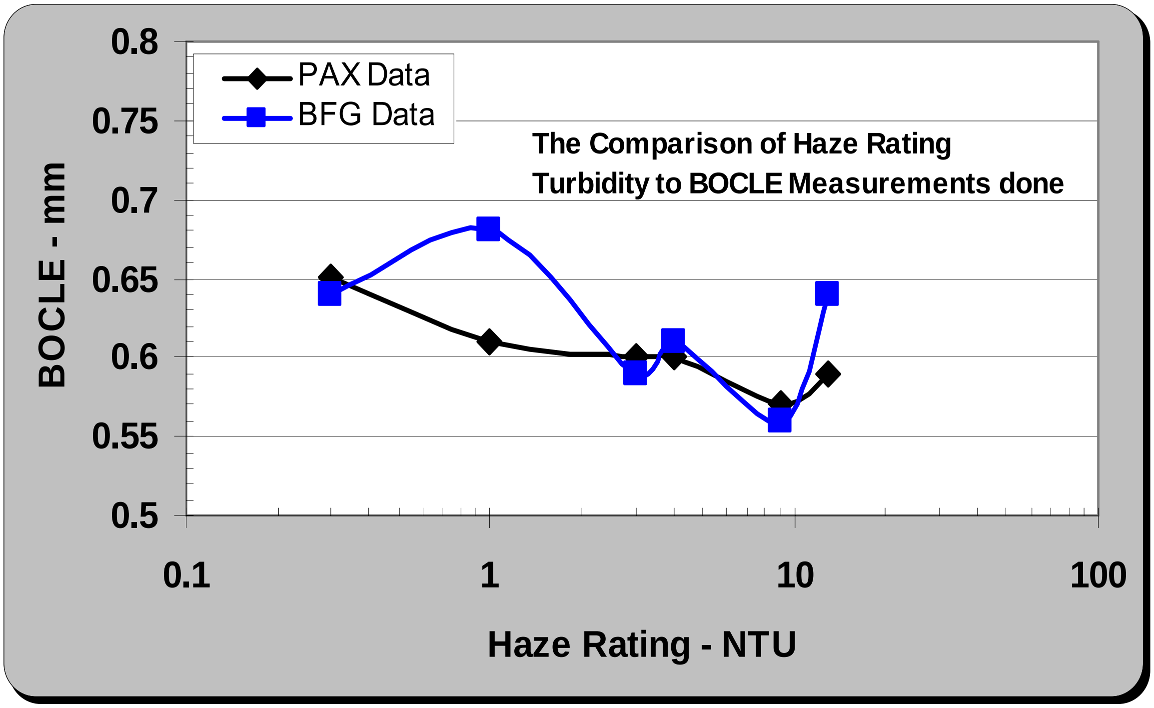


Figure H2A: Comparison of HRT to BOCLE

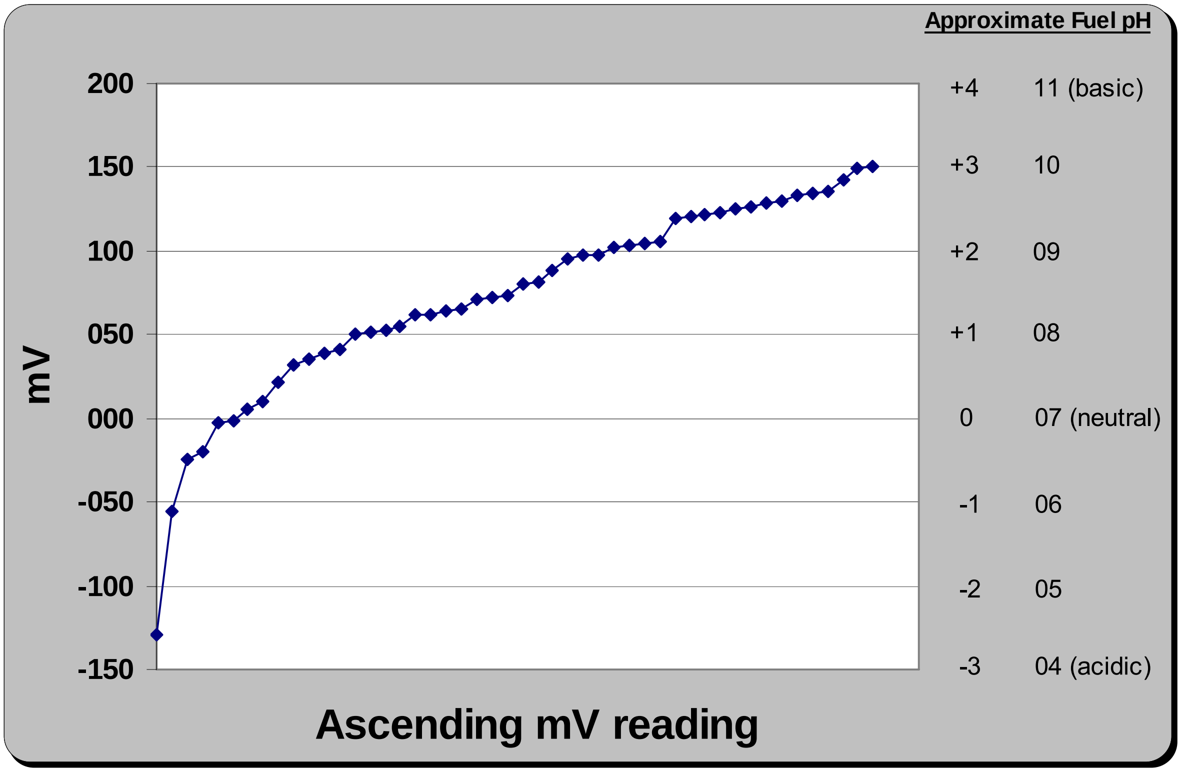


Figure H.3: Increasing mV Levels

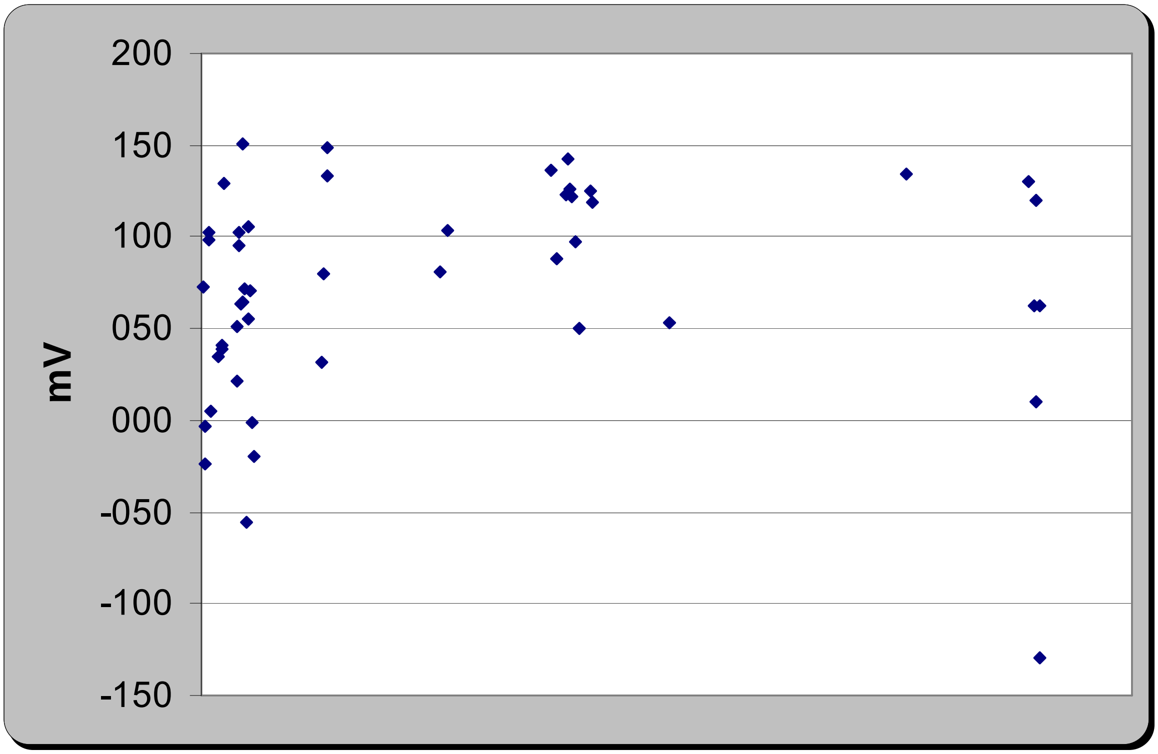


Table H.4: mV Levels by Sample Number

Appendix I
Update to Specific Heat Capacity

April 2004

Specific Heat Capacity

The original testing done by the University of New Hampshire (UNH) and reported in June of 2003 (See Section 6.2), contained the results of fifty-five fuel samples, five of which were 100% synthetic fuels from SASOL of South Africa, not part of the worldwide survey. There were six samples from the worldwide survey that were not tested in this initial effort (sample No's 101, 105, 110, 111, 211, and 314). Funding was supplied, and the untested samples were evaluated along with a retest of one of the five SASOL samples previously tested. It should be noted that the five SASOL samples are not listed in the report.

Although the procedure of the first test was followed, there were some differences in the details when this follow-on test work was done. It is not known if these differences were directly specific to the test results, but the second measured results were higher in value.
The differences in the second test were as follows:

- □ Calibration of the sealed aluminum pan was done at 60° C (100°C in the earlier test).
- □ During the test the temperature ramp was 5° C/min. (vs. 20°C/min.)
- □ The correction to account for the differential weight between the sample pan and the reference pan was 48.4 mg (vs. 18.4 mg).

The individual sample test results are shown in Figure I.1.

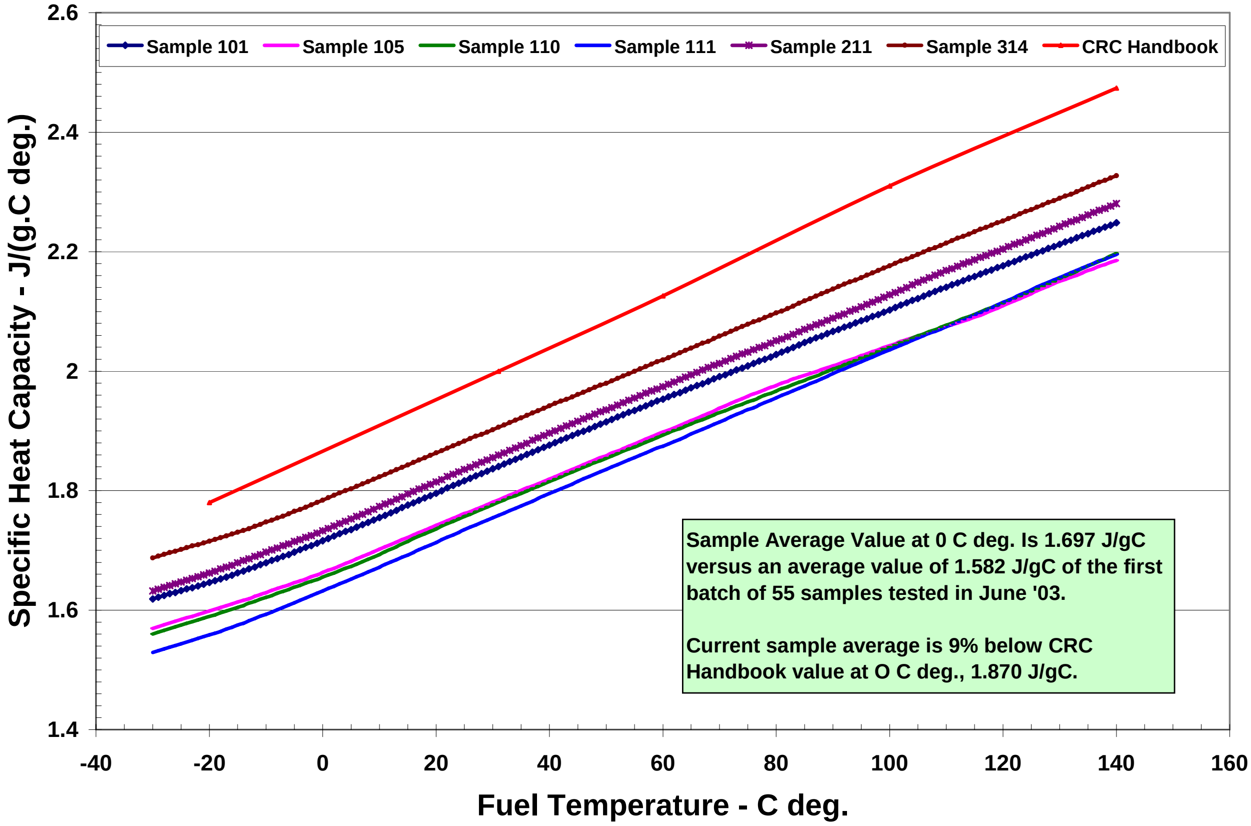


Figure I.1: UNH Fuel Sample Data Vs. CRC Handbook, Jet a-1

Comparing the average of these six worldwide Jet A-1 samples to the average of 23 Jet A-1 samples of the earlier test and at 0^oC, the average value of the six was 1.6972 $J/g/^o K$ with a slope of 0.00385, see Figure I.2, and the average value of the twenty three samples was 1.602 $J/g/^o K$ and a slope of 0.0037. The difference represents an increase of 6% in average value.

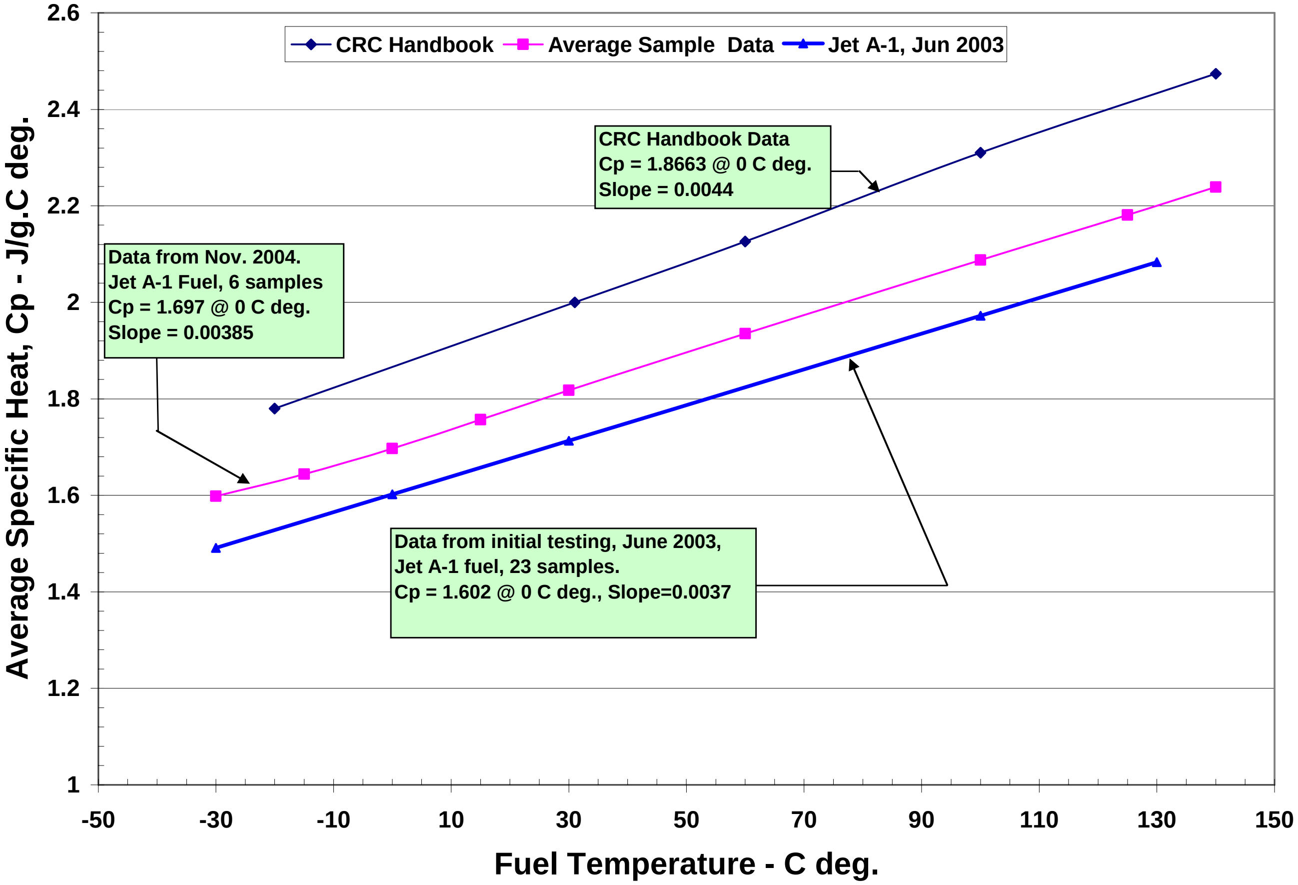


Figure I.2: Average Specific Heat Data

The one SASOL 100% synthetic fuel (sample designation 510, or CL0-236) that was tested in the original 55 sample batch and again in this second set of tests, originally yielded a Cp value of 1.532 $J/g/^o$ K and a slope of 0.0037. The value obtained in the second test was 1.799 $J/g/^o$ K and a slope of 0.0040, an increase in value of 17%.

In this test work done in 2004, samples of two alkanes, Nonane and Dodecane, were included to determine if the test set-up and procedures were producing the correct results. The test results from these compounds are shown below and compared to two sets of values from sources noted.

Cp @ 0° C (32° F), from UNH Testing, NIST Standard Ref. Database 4, ASTMI Mnl 50

Nonane, Value	Nonane, Slope	Dodecane, Value	Dodecane, Slope
1.998 J/g/°K (UNH)	0.0039	1.997 J/g/°K (UNH)	0.0036
2.011 (NIST Db 4)	0.0041	1.957 (NIST Db 4)	0.0040
2.079 (ASTMI)*	-----	1.991 (ASTMI)*	------

- Calculated by method shown in Characterization and Properties of Petroleum Fractions – M. Riazi, Page 245.

The difference in value between as-measured and the NIST Database value is 0.65 %, for Nonane, and 2.04% for Dodecane.
The difference in value between as-measured and as-calculated from ASTM Mnl. 50 is 3.9% for Nonane and 0.30% for Dodecane.
The difference between the NIST Database 4 and as-calculated from ASTM Mnl 50 is 3.3% for Nonane and 1.7% for Dodecane.

The value of Cp is a function of temperature and the comparison of reference source values suggests some variation can exist. It further appears that a Cp value for a chemical substance from various sources is good to about 5% of some actual average value. The measured data for the Nonane and Dodecane from UNH appears close aboard the reference source values for each of these substances, and trends correctly.

The origin of the CRC data is stated as a combination of experimental data from a differential scanning calorimeter, but the bulk of the data was calculated using a correlation of averaged fuel gravity and distillation from the Data Book on Hydrocarbons by J. B. Maxwell.

Further, within the data from the fuel samples, it is clear that further testing should be done to determine the sensitivity of the measuring instrument to temperatures set for the testing, and to retest a large number of the fuels when the test process is better understood. This is an activity for the future.

For using the measured data, Figure I.3 shows the mean of all the UNH data for value and slope, compared to the CRC Handbook data. Also shown on the figure is the upper three-sigma limit of the UNH data.

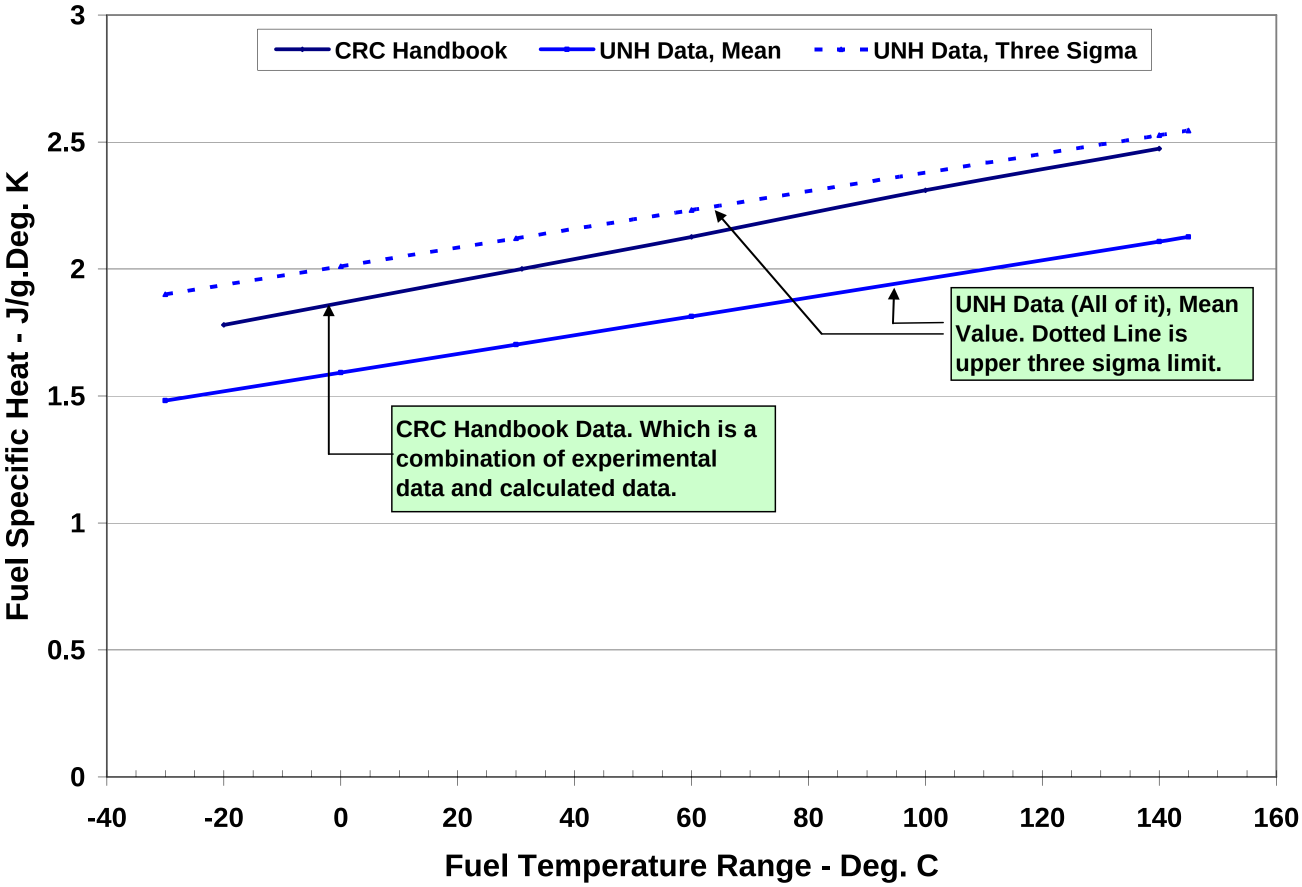


Figure I.3: Comparison of CRC Handbook Data to UNH Data - Fuel Specific Heat