# DEVELOPMENT OF THE PROTOCOL FOR ACCEPTANCE OF SYNTHETIC FUELS UNDER COMMERCIAL SPECIFICATION

## FINAL REPORT

*Prepared for*
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**Warren, MI 48397-5000**


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**San Antonio, Texas**



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SwRI Projects 08.11514 and 08.03227.23.801

**September 2007**


SOUTHWEST RESEARCH INSTITUTE®
SAN ANTONIO WASHINGTON, DC HOUSTON

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**Approved by:**

**Edwin C. Owens, Director**
**Fuels and Lubricants Technology Department**

## EXECUTIVE SUMMARY

A protocol has been developed for the acceptance of kerosenes from Fischer-Tropsch (F-T) processing of synthesis gas for use in jet fuel for civil aviation. Four possibilities are recognized: The fuel may either contain aromatics from the F-T process or contain no aromatics. These two fuel possibilities may be used either as a blending stream for a semi-synthetic jet fuel or as a fully synthetic jet fuel.

The protocol is comprised of two basic requirements:

- The fuel must meet the specification requirements of a recognized aviation fuel specification such as ASTM D 1655.

- The fuel must demonstrate that it is "fit-for-purpose" as jet fuel by having other defined properties and characteristics that fall within the range of experience with conventional, petroleum-derived jet fuel.

The fit-for-purpose tests are defined based on issues and concerns developed initially by the United Kingdom Aviation Fuels Committee (AFC) during the approval of the Sasol iso-paraffinic kerosene (IPK) for use in blending semi-synthetic jet fuel in Johannesburg, South Africa. The definition of the tests has been reviewed and updated as a set of properties and characteristics that are both necessary and sufficient to demonstrate that a synthetic kerosene is fit-for-purpose as jet fuel. The protocol then defines appropriate tests for each issue and provides a range of values that are considered typical for conventional jet fuels in the market today in-so-far as data is available.

If the provider of the fuel demonstrates that the candidate F-T kerosene meets the prescribed conditions, it will be considered fit-for-purpose as jet fuel under an aviation turbine fuel specification and will be approved for use by the engine manufacturers. At this point it can be marketed under the fuel specification, and the fit-for-purpose demonstration need not be conducted again unless the manufacturing process is changed. Such changes will be considered on a case-by-case basis.

If the fuel does not meet some of the requirements, the provider has the option of demonstrating that the fuel is fit-for-purpose by conducting a test or tests that would be defined by the engine manufacturers specifically to address the issue. These may be tests on fuel system components, combustor tests, or full-scale engine tests depending upon the issue. Obviously, it is to the benefit of the provider to develop a candidate F-T kerosene that satisfies the prescribed fit-for-purpose tests.

It is intended that this protocol will be included in, or referenced by a major aviation-fuel specification such as ASTM D 1655 so that once a fuel is accepted as fit-for-purpose by the aircraft engine original equipment manufacturers (OEMs) and written into their fuel specifications/service bulletins, it will automatically be an approved fuel under that specification, and no further action will be required.

The benefit of this approach is that a refiner will know what is expected, how to meet those expectations, and what the cost will be. Furthermore, the refiner will know that upon meeting those expectations, the fuel will be accepted and can be marketed.

The engine manufacturers consider that the option of using paraffinic F-T kerosene as a blending stream for semi-synthetic jet fuel may be ready for general approval under ASTM D 1655 based upon the successful experience with the Sasol semi-synthetic fuel that has been in continuous use in Johannesburg since 1999. They have requested a demonstration that (1) other F-T kerosene candidates are chemically similar to the Sasol IPK, and (2) 50/50 blends of these F-T kerosenes with petroleum-derived jet fuel will have properties and characteristics that are similar to the Sasol semi-synthetic jet fuel.

Four F-T kerosenes have been identified and offered for this purpose. All are gas-to-liquid (GTL) products – one each from Syntroleum, Shell, Sasol, and Rentech. Of these, the Syntroleum fuel, designated S-8, has been analyzed and successfully flight-tested in a 50/50 blend with JP-8 by the U.S. Air Force. This CRC project, AV-02-02, was supplemented with funds from the U.S. Army to conduct certain of the fit-for-purpose tests that the Air Force did not conduct and to include in this report a comparison of a 50/50 blend of the Syntroleum fuel with JP-8 to the 50/50 blend of the Sasol IPK with Jet A-1.

From this comparison, it is concluded that even though the two synthetic kerosenes came from different resources and processes, they are both comprised solely of iso- and normal paraffins and, when blended up to 50%(v) with petroleum-derived jet fuel, produce semi-synthetic jet fuels that have all the properties and characteristics considered important for jet fuel with none of the characteristics that could be considered detrimental to use as aviation fuel. Semi-synthetic kerosenes blended from these two synthetic kerosenes are considered to be fit-for-purpose as jet fuel. Flight-testing and experience in ground support systems have validated this conclusion.

These results form a sufficient basis for comparing the other candidate F-T kerosenes when they become available. If the trend continues, the results will support the inclusion of paraffinic F-T kerosenes into the major specifications for aviation fuel as blending streams up to 50%(v) subject to a minimum aromatic content of 8%(v).

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# 1.0 BACKGROUND

Prior to the introduction of Sasol's semi-synthetic jet fuel (SSJF) at Johannesburg International Airport in July 1999, all commercial aviation fuel had been derived solely from petroleum sources. The specifications controlling the quality of those fuels had evolved around the characteristics and properties of those fuels, assuming a relatively constant, or slowly evolving, range of crude resource and refining techniques. The Sasol request for the use of synthetic hydrocarbons derived from coal through their Fischer-Tropsch (F-T) processing was a significant departure from experience. Since many of the inherent properties of kerosenes that make them "fit-for-purpose" as jet fuels are not a part of the specification and quality control system and are rarely measured, the United Kingdom Aviation Fuels Committee (AFC), which guides the Defence Standard (DEF STAN) 91-91 [1] fuel specification for Jet A-1, developed a new set of guidelines for fuels containing synthetic products as blending stocks.

If accepted under DEF STAN 91-91, specific synthetic kerosenes can now be used in concentrations up to 50%(v) providing there are at least 8%(v) aromatics in the final blend, all of which must come from the petroleum-derived blending streams.

Sasol iso-paraffinic kerosene (IPK) is the only synthetic kerosene that has been approved at the time of this writing. The blend with petroleum-derived jet fuel is termed semi-synthetic jet fuel. The blend has been recognized by ASTM D 1655 [2] as an acceptable fuel for commercial aviation to maintain compatibility with DEF STAN 91-91.

As currently written, any synthetic kerosene must be approved on an individual, site-specific basis. This puts the AFC in the position of having to approve every synthetic kerosene that is developed and offered for consideration, a time-consuming effort for members of the Committee.

The Aviation Fuels Subcommittee of ASTM International is the cognizant body for the commercial jet fuel specification in the United States. The specification designating the jet fuel to be used in civil aviation is ASTM D 1655, *Standard Specification for Aviation Turbine Fuels*. [2] However, ASTM has a policy that it does not approve products under its specifications. Instead, it provides the requirements that a fuel must meet to be certified for use.

Recognizing the growing interest in the United States and elsewhere in synthetic jet fuels from F-T processes, ASTM requested that the Aviation Committee of the Coordinating Research Council (CRC) develop a process to accept F-T kerosenes for use in jet fuel for civil aviation so that ASTM would not be in the position of having to approve individual candidate fuels.

This report defines the acceptance protocol along with the rationale behind its development. The report also identifies the acceptance process that a provider must expect to follow to gain the approval of a candidate fuel.

During the conduct of this project, it became apparent that the class of F-T kerosenes that contain no aromatic hydrocarbons may be sufficiently similar to the Sasol IPK that a general acceptance of these kerosenes might be considered. The aircraft engine original equipment manufacturers (OEMs) requested a demonstration of the similarity of semi-synthetic fuels containing paraffinic

F-T kerosenes. The Syntroleum fuel designated S-8 has been analyzed and successfully flight-tested in a 50/50 blend with JP-8 by the U.S. Air Force. The CRC project was then supplemented with funds from the U.S. Army to conduct certain of the "fit-for-purpose" tests that the Air Force did not conduct and to include in this report a comparison of a 50/50 blend of the Syntroleum fuel with JP-8 to the 50/50 blend of the Sasol IPK with Jet A-1.

## 2.0 PROJECT OBJECTIVES

The original overall objective of this project was to identify and document a process to successfully gain approval of hydrocarbon streams from F-T processes for use as fuel for civil aviation, either as a refinery stream to be blended with petroleum-derived jet fuel or as wholly synthetic jet fuel.

Two tasks were identified to meet this objective:

- The objective of the first task was to determine the information that is both necessary and sufficient to demonstrate that a candidate F-T kerosene is "fit-for-purpose" as an aviation fuel, by itself, or as a refinery blending stream for increasing jet fuel production.

- The objective of the second task was to identify and document the process for taking the information demonstrating that an F-T kerosene, or class of kerosenes, is "fit-for-purpose" and officially having that fuel approved or accepted for use in civil aviation.

The first task defines what is needed, and the second task defines what to do with the information in order to gain official approval for use.

During the conduct of this effort, a second objective was identified. The decision was made to compare the properties and characteristics of the F-T kerosene produced by Syntroleum for the U.S. Air Force to those of the Sasol IPK to show the similarities as a prelude to a general acceptance of F-T kerosenes without aromatics for the blending of semi-synthetic jet fuel.

## 3.0 PROJECT SCOPE

While synthetic kerosenes can be, and have been, produced by a number of methods from several different non-petroleum sources, the scope of this project was limited to a protocol for acceptance of synthetic kerosenes derived from F-T processes from synthesis gas, i.e., hydrogen and carbon monoxide. The source of the synthesis gas was not limited, but most likely would be from natural gas, coal, or biomass.

The two tasks were conducted assuming four possibilities of fuel-use combinations. First of all, there are two fuel possibilities:

- Synthetic hydrocarbon streams in the kerosene boiling range which are essentially paraffinic, i.e., consisting only of normal and iso-paraffins with no aromatics; these will be termed “paraffinic F-T kerosene”
- Synthetic hydrocarbon streams which do contain synthetic aromatics; these will be termed “aromatic F-T kerosene”

Either of these two fuel concepts could then be used in one of the following ways to produce jet fuel:

- As a blending component with conventional jet fuel to make a semi-synthetic jet fuel
- As a fully synthetic jet fuel

The basic distinction of these four elements is based on the concern about the need for aromatics and the lack of knowledge about the detailed chemistry of synthetic fuels containing aromatics as compared to that of conventional jet fuel from petroleum; this includes identifying the presence of trace materials, or the lack thereof, as well as bulk chemistry.

A common general protocol was developed to cover all four fuel-use concepts.

# 4.0 APPROACH

## 4.1 General Considerations

In order to be considered “fit-for-purpose” as aviation fuel or a blending stream, the fuel must have no adverse effects on aircraft performance, durability, or safety and must be transparent to all elements of the aviation industry. Fuel specifications are meant to ensure fuel of a specified quality, but they do not define or control all of the properties and characteristics of fuels that the designers, manufacturers, and users depend upon. Therefore, it was necessary to go beyond the fuel specification tests, i.e., Table 1 of ASTM D 1655, to ensure these needs are met.

Three basic needs were identified as necessary to meet the objectives of this project:

- Identify all of the *concerns and issues* from the various stakeholders in the civil aviation industry with regard to using synthetic hydrocarbons.

- Define a necessary and sufficient combination of tests that will provide data and information to satisfy the *concerns and issues*.

- Define the acceptance criteria for the tests identified above.

The primary stakeholders in the aviation industry for fuel issues are the engine and airframe OEMs because they design the aircraft to have certain performance, durability, and safety standards based upon a fuel quality defined by the fuel specification. Other members of the aviation industry that also have an interest in ensuring fuel quality include those responsible for the transport and handling of the fuel, the OEMs of fuel systems and controls, as well as the user, i.e., the airlines, and the regulatory authorities such as the FAA. Direct consultation was held with the OEMs while the other stakeholders were briefed at several meetings of the ASTM Aviation Fuels Subcommittee and CRC Aviation Fuels Committee during the conduct of this project, and their comments were frequently requested.

### 4.2 Defining the Issues and Concerns

The initial list of *issues and concerns* used in this project was based on the criteria defined in DEF STAN 91-91/Issue 5, Annex D entitled "Additional Requirements Applicable to Fuels Containing Synthetic Compounds." These requirements were first defined by the AFC to ensure that Sasol's semi-synthetic jet fuel (SSJF) using a synthetic iso-paraffinic kerosene (IPK) was "fit-for-purpose". For reference, Table 1 provides a list of these critical issues from DEF STAN 91-91 Issue 4 dated 14 June 2002. After it was demonstrated that SSJF met these requirements, the AFC was able to rule that Sasol SSJF was "fit-for-purpose" as a Jet A-1. All of the elements of Table 1 except the Chemistry apply to the final fuel.

**Table 1. General Areas of *Issues and Concerns***

| |
|---|
| Chemistry of synthetic components |
| Hydrocarbons |
| Organics |
| Metals |
| Bulk physical properties vs temperature |
| Boiling point distribution |
| Lubricity |
| Water separation |
| Compatibility |
| Fuels |
| Additives |
| Materials |
| Stability |
| Thermal |
| Storage |

In 2003, during the review process for Sasol's proposed fully synthetic fuel, these same criteria were reviewed by the AFC as well as the U.S. engine and airframe manufacturers to determine if they were still considered necessary and sufficient. The only new question raised was whether the smoke point test would be valid for these fuels in light of the fact that the aromatics were synthetic and might somehow be different from those in conventional fuels. The smoke point test results for the Sasol fully synthetic fuel were similar to conventional fuels. Thus the criteria have stood at least an initial test of time.

The use of the DEF STAN 91-91 criteria as a strawman was, therefore, considered to be a valid and efficient approach. As will be seen, a few new *issues and concerns* have been added to develop a more general list of requirements for the fully synthetic fuels.

# 5.0 APPROVAL PROCESS

## 5.1 Demonstrating Fit-For-Purpose

Figure 1 presents a flow chart of the process to determine if a candidate fuel is fit-for-purpose as a commercial jet fuel. There are five major considerations that are keyed to elements of Figure 1:

1. Fuel specification requirements
2. Fit-for-purpose tests
3. Component tests
4. Engine tests
5. Resolving remaining issues or anomalies

Figure 1a contains the first two elements that can lead to approval without further component testing or engine testing. Figure 1b contains the other three elements to be used if component and/or engine testing are necessary to satisfy issues in case the candidate fuel does not fall within the realm of experience with conventional, petroleum-derived jet fuels. Note that all testing is done at the expense of the provider of the candidate fuel.

### 5.1.1 Fuel Specification Requirements – Element 1 on Figure 1a

Any candidate fuel must first meet the performance requirements found in major specifications of aviation fuel such as Table 1 of ASTM D 1655, which is reproduced in the Appendix.

### 5.1.2 Fit-For-Purpose Tests – Element 2 on Figure 1a

As previously stated, candidate fuels must also have other properties and characteristics that fall within the experience of petroleum-derived jet fuel but are not a part of the fuel specification. If a candidate falls within the norm of experience for these properties or is an improvement, it will be accepted as fit-for-purpose and can be marketed. If the fuel falls below or out of the norm, component and/or engine tests may have to be conducted to demonstrate that the fuel is fit-for-purpose as jet fuel. The details of the specific tests, test methods, and acceptable limits will be explained in Section 6.

The first set of tests for chemistry applies to the synthetic components. If the synthetic is to contain no aromatics, that must be demonstrated. If the fuel contains synthetic aromatics, they are to be identified. The remainder of the tests apply to the complete fuel whether semi-synthetic blend or fully synthetic fuel.

It is expected that the complete fuel containing synthetic components will exhibit properties and characteristics that are similar in value, and temperature function if appropriate, to that of typical petroleum-derived fuels. Where possible, the standards are the CRC World Fuel Sampling Program [3] or the CRC Handbook of Aviation Fuel Properties [4] because they contain information on properties and characteristics other than specification properties. It is recognized that even petroleum-derived fuels have properties and characteristics that vary over a wide range. The guidelines are set to represent the majority of fuels. Every effort should be made to produce a fuel that is typical and not at the edge or outside the range of typical variations for each property.

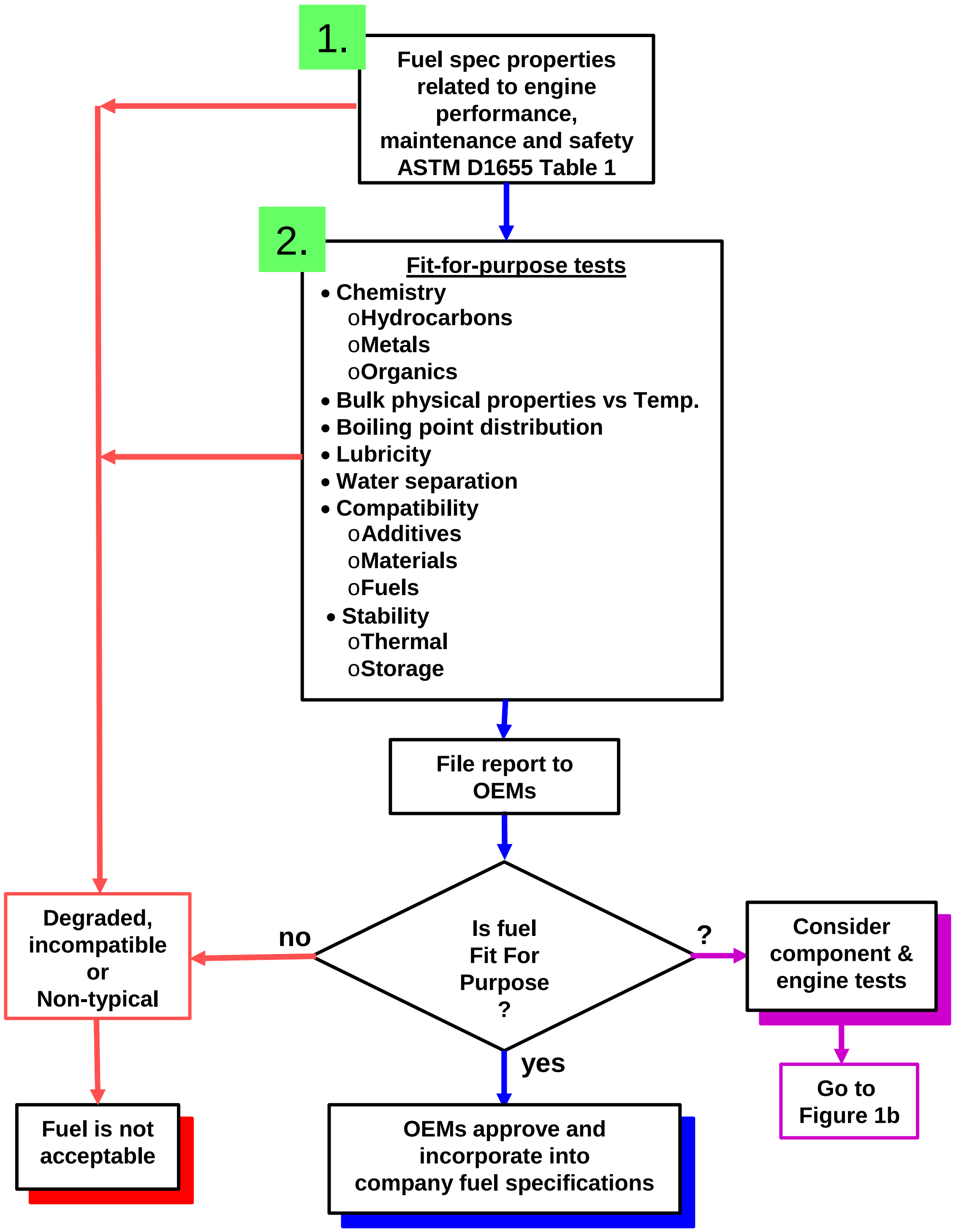


**Figure 1a. Approval Process for F-T Kerosenes as Jet Fuel**
**Part 1: Fit-For-Purpose Test Evaluation**

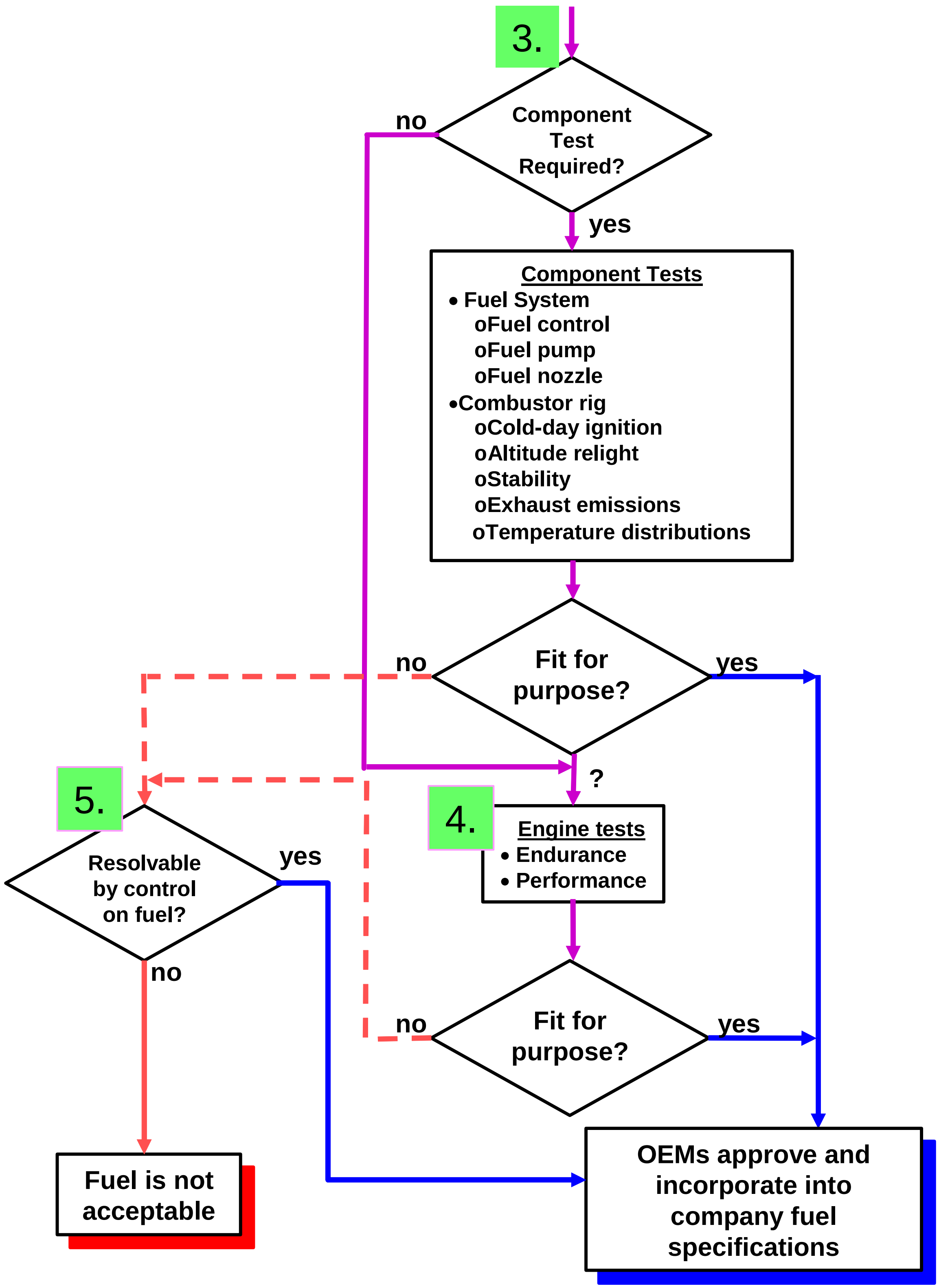


**Figure 1b. Approval Process for F-T Kerosenes as Jet Fuel**
**Part 2: Supplemental Component/Engine Tests**

Little data exist for some of the fit-for-purpose tests, e.g., trace organics and metals; the provider should make an effort to minimize/eliminate the presence of these materials. For some tests, such as thermal conductivity, bulk modulus, and materials compatibility, there are no defined limits; for these, every effort should be made to produce a fuel that is similar to the data or guidance provided.

A written report on the results of the fit-for-purpose tests will be submitted to the engine OEMs for review. If there is consensus among the engine OEMs that the fuel fits well within the expected range of fuel properties and characteristics, it will be considered fit-for-purpose under. The engine companies will acknowledge this in their respective company fuel specifications, and service bulletins will be issued to the airlines and field representatives. At this point, the fuel can be marketed.

It is possible that an issue exists for which no data or test exists to resolve. In such a case, a special restriction may be placed on the fuel as a buffer to ensure fit-for-purpose. A case in point was the minimum aromatic content of 8%(v) placed on the Sasol semi-synthetic jet fuel when it was accepted under DEF STAN 91-91. This was done to ensure there would be no problems of compatibility related to elastomeric materials as, at that time, there was no documented experience or data on fuels of very low aromatic contents.

If the candidate fuel does not have typical properties, it will be up to the provider to demonstrate there will be no ill effects of the questionable property or characteristic on aircraft safety, performance, and operability as well as storage and handling. Such a demonstration could involve component and/or engine tests as discussed below.

#### 5.1.3 Component Tests – Element 3 on Figure 1b

If the fuel is marginal, and there is some question about its suitability, the engine manufacturers may request a series of component tests to demonstrate that the fuel will not affect performance or durability. These will be conducted at the expense of the provider. If there is consensus among the engine OEMs that there are no anomalies or unresolved issues, the fuel may then be considered acceptable and acknowledged as previously described.

#### 5.1.4 Engine Tests – Element 4 on Figure 1b

If further issues exist, and the provider wishes to continue, an engine test may be required to demonstrate the questionable issue. The engine test will be at the expense of the provider. Again, if there is consensus that the issue(s) is resolved and there are no anomalies, the fuel may be considered acceptable and acknowledged as described above.

#### 5.1.5 Resolving Remaining Issues or Anomalies – Element 5 on Figure 1b

After the component and/or engine tests, an issue may still exists or an unexpected anomaly identified. It may be possible that the issue can be resolved with a special restriction on the fuel. A case in point was the restriction on maximum flash point and minimum slope of the boiling point distribution that is being placed on the Sasol fully synthetic fuel. [5] If this is possible, the fuel could still be considered acceptable with restriction. Such a restriction could then become a part of the fit-for-purpose tests for further considerations.

## 5.2 Acceptance of Candidate Fuels

The engine OEMs are the final arbiters of fit-for-purpose for jet fuels, although other stakeholders such as the airframe OEMs, pipeline companies, and airlines, have interests in selected properties such as dielectric and water shedding. After the prescribed tests have been conducted on the candidate F-T kerosene, a report summarizing all of the results will be written and submitted to the fuel technologist of each of the four aircraft engine companies, and will be available upon request:

- General Electric
- Honeywell
- Pratt & Whitney
- Rolls-Royce

Usually, the fuel technologist will be the company representative to the ASTM and CRC aviation fuel committee meetings.

As previously stated, if the fuel passes the first two elements of the protocol as presented in Figure 1a and described in Sections 5.1.1 and 5.1.2, the fuel will be accepted as fit-for-purpose as jet fuel. Each of the engine companies will acknowledge this fact in their respective fuel specifications and service bulletins. The fuel can then be produced and delivered to airports for use. While no further effort on the part of the provider will be necessary, the engine OEMs may request periodic reviews of the fuel performance characteristics to assure manufacturing integrity.

It cannot be stressed too highly that the provider should make every attempt to produce a fuel that meets the criteria set out in Sections 5.1.1 and 5.1.2, thus saving everyone time and expense. If, however, the fuel is somewhat marginal and the provider wishes to continue without modification to the fuel, the OEMs will review the results and define appropriate component tests to resolve the issue and demonstrate the fuel is fit-for-purpose. These may include components of the fuel system, combustor, hot section, or complete engine. There must be consensus among the OEMs in the definition of the tests and acceptance criteria for passing. But, again, if the fuel passes the tests, it may be accepted and may be produced and marketed.

It is intended that this protocol will be included in, or referenced by major specification-writng bodies, such as ASTM, so that once a fuel is accepted as fit-for-purpose by the engine OEMs and written into their fuel specifications, it will automatically be an approved fuel in the specifications and no further action will be required.

## 6.0 FIT-FOR-PURPOSE TEST MATRIX

Table 2 lists the tests that have been defined as both necessary and sufficient to demonstrate that an F-T kerosene is fit-for-purpose as jet fuel. Also provided are appropriate tests and range of values or criteria that are considered typical for conventional jet fuels in the market today. It is possible that there are fuels being used today that have properties and characteristics that are outside the stated limits. However, the limits and criteria are based on the majority of fuels not fringe fuels or outliers. Based on experience with the Sasol and Syntroleum F-T kerosenes, it is believed that, in general, F-T fuels can be produced that will easily meet the laboratory tests defined.

Line 1.0, "hydrocarbon fuel chemistry" applies only to the F-T kerosene itself and is split into Line 1.1 for paraffinic F-T kerosenes and Line 1.2 for F-T kerosenes with aromatics. For paraffinic F-T kerosenes, the test is simply to demonstrate that the fuel is essentially free of synthetic aromatics. A more complete hydrocarbon analysis is required of F-T kerosenes containing aromatics to identify the possible presence of unusual families. Line 2.0 applies to the F-T kerosene regardless of whether they contain aromatics or not. All other tests are to be conducted on the finished fuel, i.e., semi-synthetic blend or fully synthetic fuel.

Figures 2 through 10 provide supporting data to define the limits or characteristics that the candidate fuel must have to be considered fit-for-purpose. These figures are called out in Table 2 where they are applicable. Where possible, the reference data for these figures have been taken from the CRC World Fuels Survey [3] or the CRC Handbook of Aviation Fuel Properties [4]. In a couple cases, data for individual fuels have been used to supplement these sources.

**Table 2. Test Matrix to Demonstrate an F-T Kerosene is Fit-For-Purpose for Aviation Jet Fuel**

| Line | Fuel Property/Characteristic | | Test Method | Units | Min | Max | Comments |
|---|---|---|---|---|---|---|---|
| 1.0 | Hydrocarbon fuel chemistry | | | | | | |
| 1.1 | Paraffinic F-T kerosenes | | D 5292 | mol% | Report | | |
| 1.2 | F-T kerosenes with aromatics | | D 2425 | v% | Report | | Normal and iso-paraffins, cyclo-paraffins, mono-aromatics, indans, indanes, tetralins, naphthalenes, acenaphthenes, acenaphthalenes, tricyclic aromatics |
| 2.0 | Trace materials in F-T kerosene | | | | | | |
| 2.1 | Organics | Carbonyls | E 411 | mg/kg | Report | | No limits established. |
| 2.2 | | Alcohols | UOP 656 | m% | Report | | |
| 2.3 | | Esters | To be determined | mg KOH/g | Report | | |
| 2.4 | | Phenols | To be determined | mg/kg | Report | | |
| 2.5 | | Acid number | D 3242 | mg KOH/g | Report | | |
| 2.6 | Inorganics: N, O, … | | | ppm | Report | | |
| 2.7 | Metals | | ICP | ppb | | | |
| 2.8 | Al, As, B, Ca, Co, Cu, F, Fe, I K, Mn, Na, Ni, P, Pb, V, Zn | | ICP | ppb | Report | | Eliminate/minimize; based on request by OEMs. |
| 3.0 | Boiling point distribution | | | | | | Based on composite of CRC World survey and DESC Petroleum Quality Information System survey. |
| 3.1 | Initial Boiling Point | | D 86 | °C | 140 | 200 | |
| 3.2 | 10% Recovery, T10 | | D 86 | °C | 150 | 205 | |
| 3.3 | 20% Recovery, T20 | | D 86 | °C | 160 | 220 | |
| 3.4 | 50% Recovery, T50 | | D 86 | °C | 170 | 230 | |
| 3.5 | 90% Recovery, T90 | | D 86 | °C | 205 | 260 | |
| 3.6 | Final Boiling Point | | D 86 | °C | 240 | 300 | |
| 3.7 | T50 - T10 | | D 86 | °C | 24 | — | |
| 3.8 | T90 - T10 | | D 86 | °C | 48 | — | |
| 3.9 | Vapor-Liquid Ratio @ 38 deg C | | D 6378 | | — | 4.5 | Based on request by OEMs. |
| 4.0 | Thermal stability, JFTOT Breakpoint | | D 3241/App X.2 | °C | 275 | — | |
| 4.1 | Deposit thickness at breakpoint | | Method pending | nm | — | 85 | |

**Table 2. Test Matrix to Demonstrate an F-T Kerosene is Fit-For-Purpose for Aviation Jet Fuel (continued)**

| Line | Fuel Property/Characteristic | Test Method | Units | Min | Max | Comments |
|---|---|---|---|---|---|---|
| 5.0 | Viscosity vs Temperature (T) | D 445 | $mm^2/s$ | — | — | 3 temperatures from -40°C to +40°C plus viscosity at 5°C above the freezing point. See Figure 2 for typical values and temperature variation. |
| 6.0 | Lubricity | D 5001 | mm WSD | | 0.85 | Based on DEF STAN 91-91 requirements. |
| 6.1 | Response to CI/LI additive | | | Report | | See Figure 3 for typical response. |
| 7.0 | Specific heat vs T | E 1269 | kJ/kg/K | Report | | See Figure 4 for temperature ranges, typical values, and temperature variations. |
| 8.0 | Density vs T | D 4052 | $kg/m^3$ | Report | | See Figure 5 for temperature ranges, typical values, and temperature variations. |
| 9.0 | Surface Tension vs T | D 1331 | mN/m | Report | | See Figure 6 for minimum values and typical variation. |
| 10.0 | Bulk modulus vs T & P | D 6793 | MPa | Report | | Limits not known; see Figure 7 for typical values and variation. |
| 11.0 | Thermal conductivity vs T | D 2717 | watts/m/K | Report | | Limits not known; see Figure 8 for typical values and variation. |
| 12.0 | Storage stability | | | | | |
| 12.1 | Peroxides | D 3703 | ppm | — | 8.0 | Store for 6 weeks @ 65°C. |
| 12.2 | Potential gums | D 5304 | mg/100mL | — | 7.0 | Store for 16 hours @ 100°C. |
| 13.0 | Fuel compatibility | mod to D 4054/B | | Report | | No visible separation, cloudiness, solids, or darkening of color. |
| 14.0 | Additive solubility & compatibility | D 4054/B | | Report | | Anti-oxidant, CI/LI, FSII, SDA; no visible cloudiness, solids, or darkening of color. |
| 15.0 | Materials compatibility | | | | | |
| 15.1 | Volume swell | D 471 | | Report | | Definite limits not established. Compare to conventional fuel of similar aromatic content. |
| 15.2 | Tensile strength | D 412 | | Report | | |
| 15.3 | Hardness | D 2240 | | Report | | |
| 15.4 | Modulus of elasticity | D 412 | | Report | | |
| 16.0 | Electrical properties | | | | | |
| 16.1 | Di-electric vs density | D 924 | | | | See Figure 9 for typical values. |
| 16.2 | Conductivity & response to SDA | D 2624 | | | | See Figure 10 for typical response. |

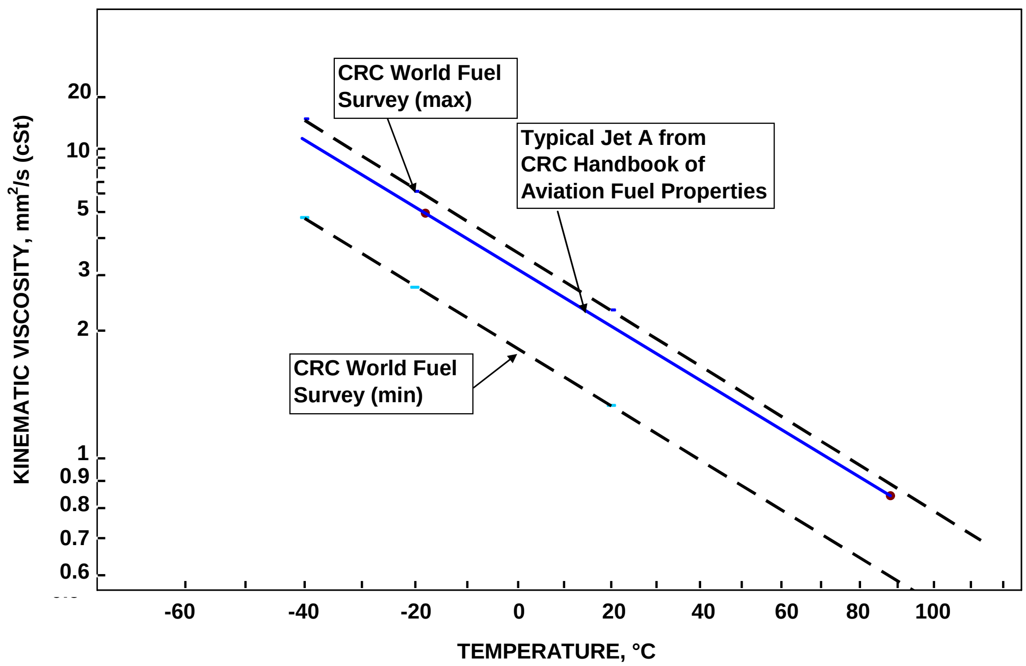


**Figure 2. Typical Viscosity Characteristics of Jet Fuel**

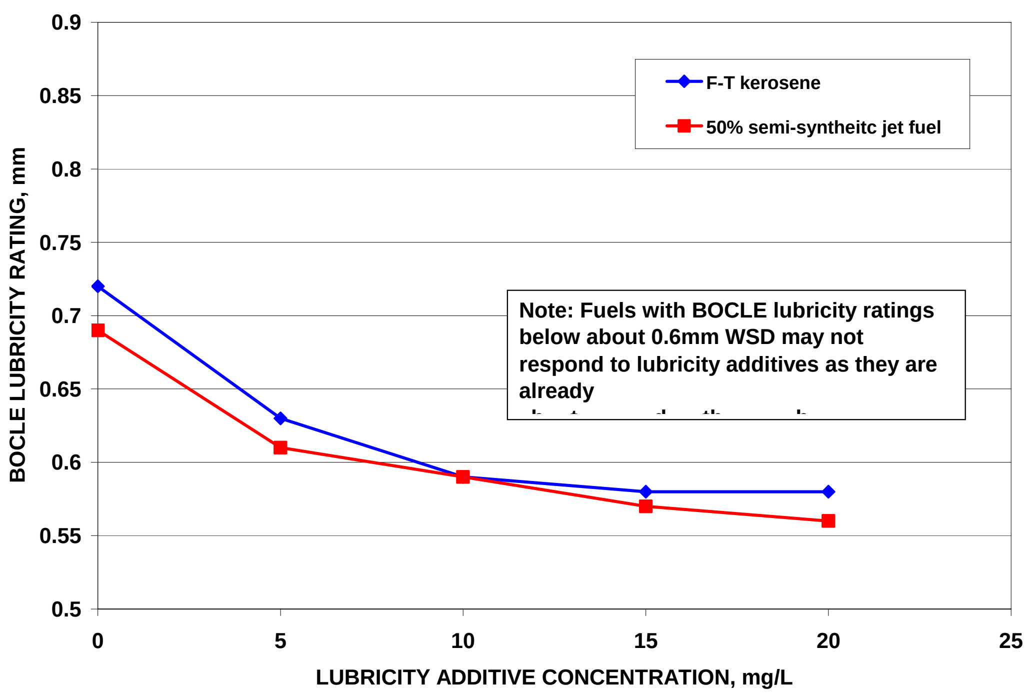


**Figure 3. Typical Response to Corrosion Inhibitor/Lubricity Improver (CI/LI) Additive**

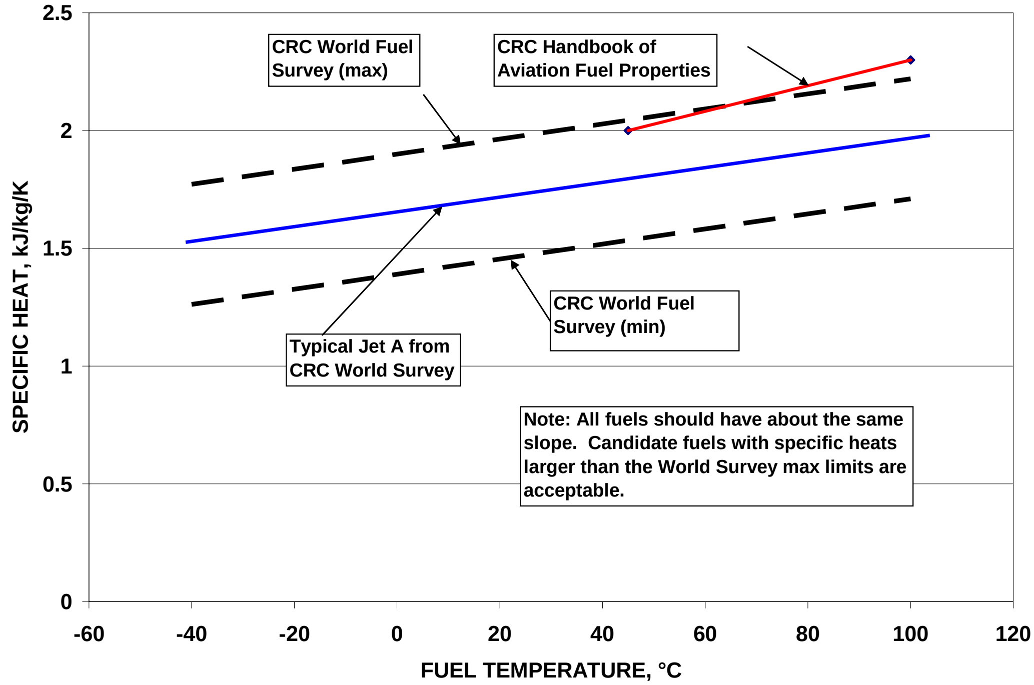


**Figure 4. Typical Specific Heat Characteristics of Jet Fuel**

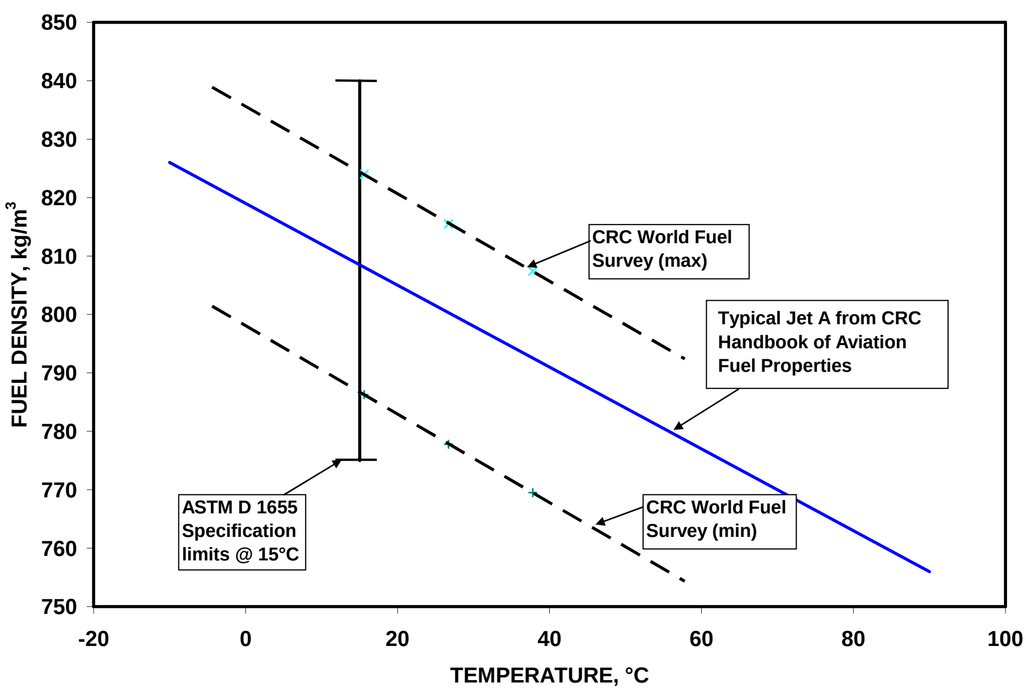


**Figure 5. Typical Density Characteristics of Jet Fuel**

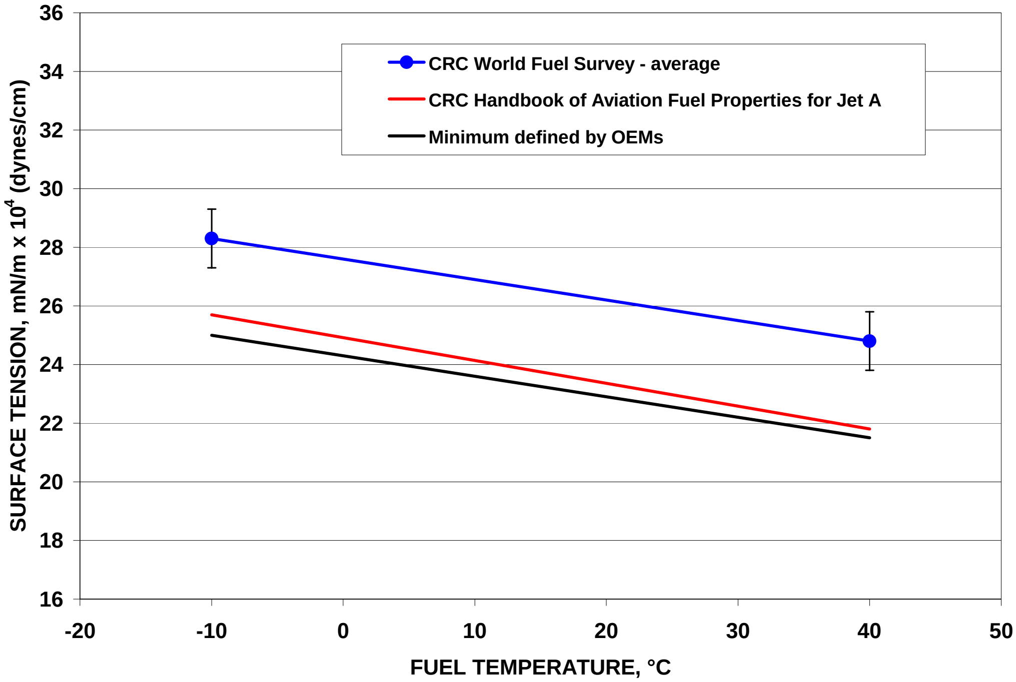


**Figure 6. Typical Surface Tension Characteristics of Jet Fuel**

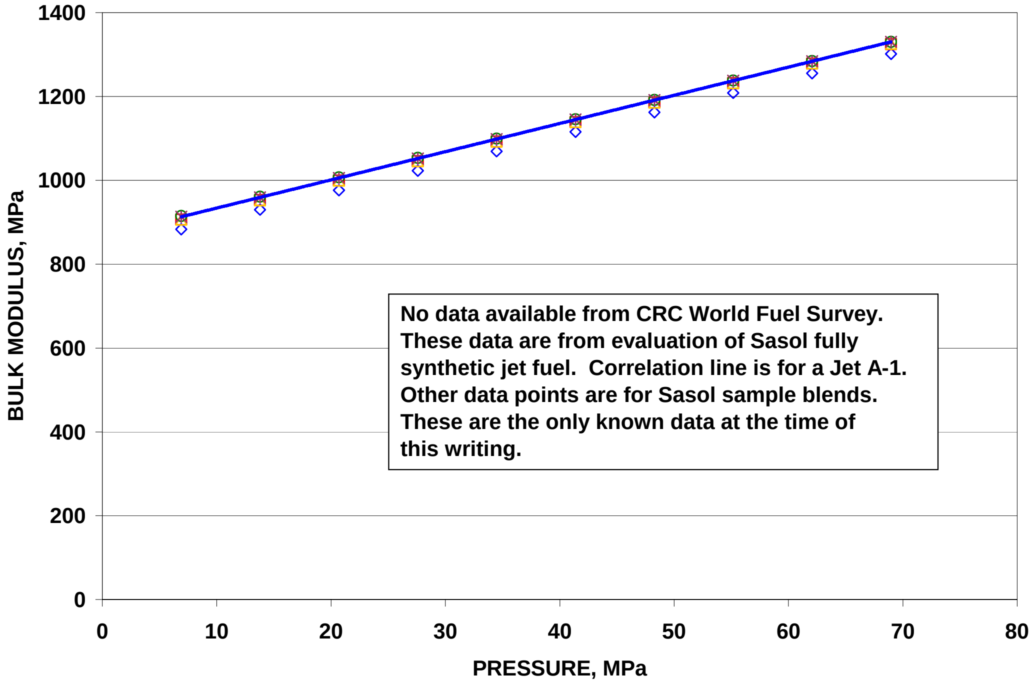


**Figure 7. Bulk Modulus Characteristics**

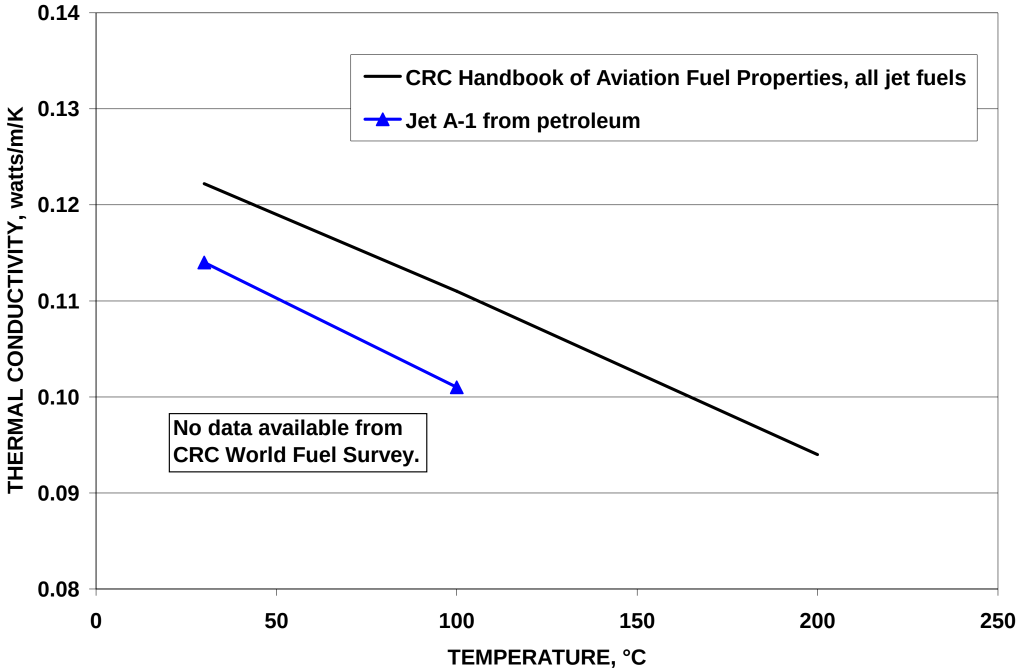


**Figure 8. Typical Thermal Conductivity Characteristics of Jet Fuel**

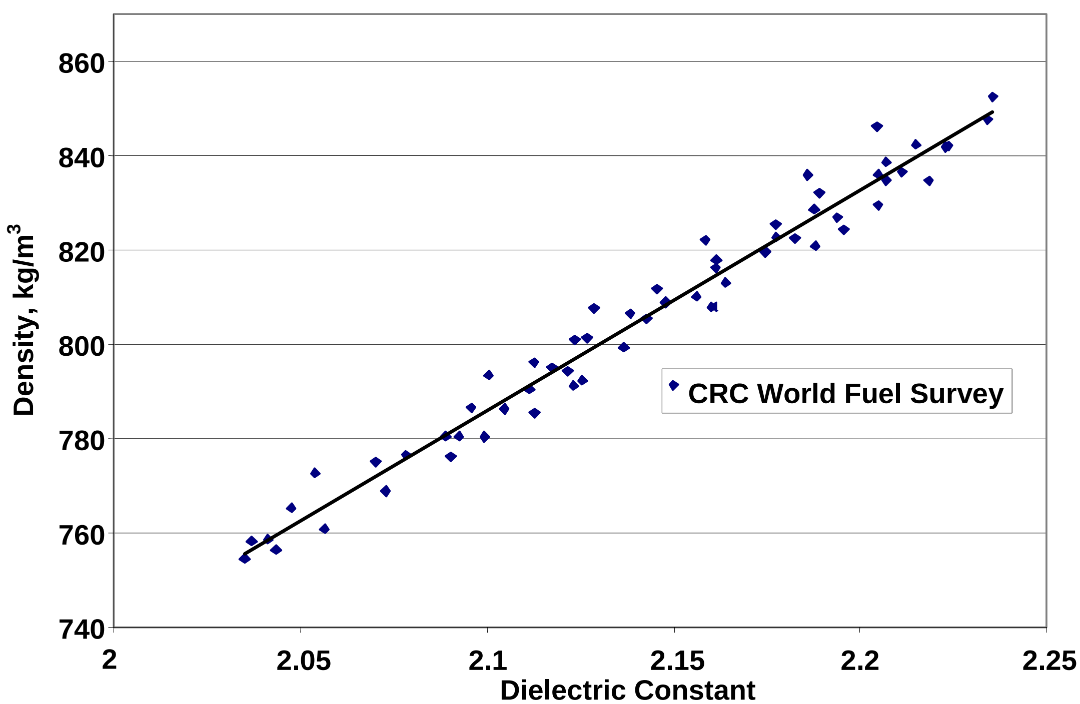


**Figure 9. Typical Dielectric-Density Characteristics for Jet Fuel**

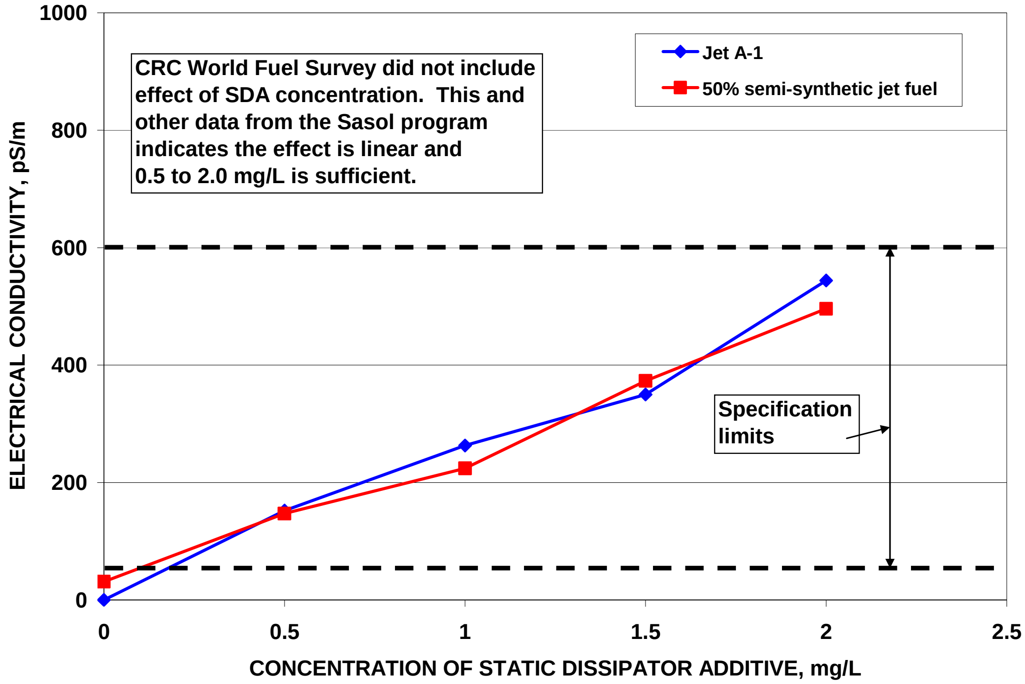


**Figure 10. Typical Response to Static Dissipater Additive**

# 7.0 WAY FORWARD

## 7.1 Introduction

The four possibilities for using F-T kerosenes in jet fuel identified in Section 3.0 are restated below:

- F-T kerosene without aromatics; used for blending semi-synthetic jet fuel
- F-T kerosene without aromatics; used for 100% synthetic jet fuel
- F-T kerosene containing aromatics; used for blending semi-synthetic jet fuel
- F-T kerosene containing aromatics; used for 100% synthetic jet fuel

Based on the successful 8-year experience with the Sasol semi-synthetic jet fuel, the OEMs consider that it may be possible to address the first option by including F-T kerosenes with zero aromatics as acceptable blending materials in producing Jet A/Jet A-1 under major fuel specifications such as ASTM D 1655 regardless of the process resource, i.e., coal, natural gas, or biomass, using the same restrictions as imposed on the Sasol fuel under DEF STAN 91-91. If this approach is successful, all paraffinic F-T kerosenes could be used up to 50%(v), with a minimum of 8%(v) aromatics that come from the petroleum stream, without having to be subjected to the approval protocol outlined in this report.

Fuels meeting the other three options would be required to follow the approval protocol. Despite the pending acceptance of the Sasol fully synthetic jet fuel with synthetic aromatics, there is not enough experience with synthetic aromatics to accept such streams without demonstrating fit-for-purpose. Questions exist at this time about the need for aromatics in the fuel that prevent the general approval of paraffinic F-T kerosenes for fully synthetic jet fuel.

### 7.2 General Approval of Semi-Synthetic Jet Fuel

To proceed with this consideration, the OEMs have asked that several other F-T kerosenes be evaluated and compared to the Sasol semi-synthetic fuel. If they are sufficiently similar, then the process for modifying fuel specifications, such as D 1655, to include these streams will be initiated.

At the time of this writing, only one other such kerosene has been available for evaluation – S-8 produced from natural gas by Syntroleum for the U.S. Air Force. Three other kerosenes have been offered for evaluation – all from natural gas. The evaluation of these fuels against the Sasol and S-8 blends is slated for Fall 2007. The following is an evaluation of a 50/50 blend of S-8 with JP-8 against the 50/50 blend of the Sasol iso-paraffinic kerosene with Jet A-1 as provided in the evaluation report of the Sasol semi-synthetic jet fuel. [6]

#### 7.2.1 Evaluation of S-8/JP-8 Blend (50/50) Versus Sasol IPK/Jet A-1 Blend (50/50)

The Syntroleum S-8 has been blended with JP-8 to create a semi-synthetic fuel which was then successfully flown by the U.S. Air Force in a B-52 aircraft. The U.S. Air Force has provided test data to compare with the Sasol evaluation. [7] Not all the property tests of the Sasol evaluation were conducted by the Air Force, and the remaining have been conducted by Southwest Research Institute for inclusion in this report.

Table 3 summarizes the property tests of the Sasol evaluation that are used for comparison. Data are provided in figures and tables that follow. The first three properties of the comparison focus on the two F-T kerosenes while the remainder address the 50/50 blends.

Figure 11 shows that both F-T kerosenes are comprised of iso- and normal paraffins, and contain no measurable aromatics. There is, however, a difference in both the composition and the distribution of hydrocarbons between the two. The Sasol IPK is comprised of molecules with carbon numbers between C10 and C14 and contains only about 3% normal paraffins, hence its name. In comparison, S-8 is about 22% normal paraffins, and the molecules are spread from C8 to C19. Thus, S-8 has a much broader distribution, which would be more typical of a jet fuel. However, it will be shown that these differences have little impact on the properties and characteristics of the 50/50 blends.

It can be seen from the data presented in Figures 12 through 21 and Tables 4 through 7 that the 50/50 blends of these F-T kerosenes with conventional, petroleum-derived fuels have very similar bulk properties and characteristics. More importantly, the values and temperature functions are seen to agree very well with the CRC World Fuel Survey and/or the CRC Handbook of Aviation Fuel Properties, as appropriate. Also, the alternate methods for determining specific energy are seen to be valid as they yield almost identical results.

**Table 3. Summary of Comparison of S-8/JP-8 Blends and IPK/Jet A-1 Blends**

| Property | IPK & Jet A-1 | S-8 & JP-8 | Comment |
|---|---|---|---|
| Hydrocarbon Composition of F-T Kerosene | See Figure 11 | | No aromatics in either F-T kerosene. Different ratio of iso- to normal paraffins S-8 has a broader distribution. |
| Trace Organics | See Table 4 | | Not detectable in S-8. |
| Trace Metals | See Table 5 | | Only done on 4 metals for IPK blends; all are <100ppb on S-8 blends. |
| Thermal Stability | >300°C | >325°C | Both have excellent thermal stability. |
| Viscosity vs T | See Figure 12 | | Similar values; same T function. |
| Lubricity | 0.69 mm | 0.56 mm | S-8 blend contained CI/LI*. |
| | See Figure 13 for CI/LI effect on S-8 & IPK | | Both respond equally well to CI/LI*. |
| Density vs T | See Figure 14 | | Same temperature functions and compare well with data from the CRC Handbook of Aviation Fuel Properties. |
| Specific Heat vs T | See Figure 15 | | Same temperature functions. |
| Surface Tension vs T | See Figure 16 | | Similar values and temperature functions as surveys; both are higher than CRC Handbook, but in range of CRC World Fuel Survey. |
| Thermal Conductivity vs T | See Figure 17 | | Similar values and T functions. |
| Bulk Modulus | No data for either blend | | No test apparatus available during project. |
| Boiling Point Distribution | See Figure 18 | | Fuels are similar and within the CRC World Fuel Survey results. |
| Dielectric vs Density | See Figure 19 | | Similar values as CRC World Fuel Survey. |
| Storage Stability – Peroxides | See Figure 20 | | Both fuels form peroxides in accelerated storage, but less than limit for existing peroxides. |
| Storage Stability – Gums | See Table 6 | | S-8/Jet A blend had higher potential gums in accelerated storage. |
| Electrical Conductivity | See Figure 21 | | Both fuels respond to SDA like Jet A-1. |
| Additive Compatibility | No data to present; see summary at right. | | All additives soluble at 2x; no visible cloudiness, solids, or coloration after 24 hours at both -17.8°C and 38°C. |
| Alternate Test Methods | See Table 7 | | Alternate methods of calculating specific energy are valid for both blends. |
| Materials Compatibility | See Figures 22 and 23 | | Different tests conducted for the most part, and different test conditions for similar tests. |

* CI/LI – Corrosion Inhibitor / Lubricity Improver additive

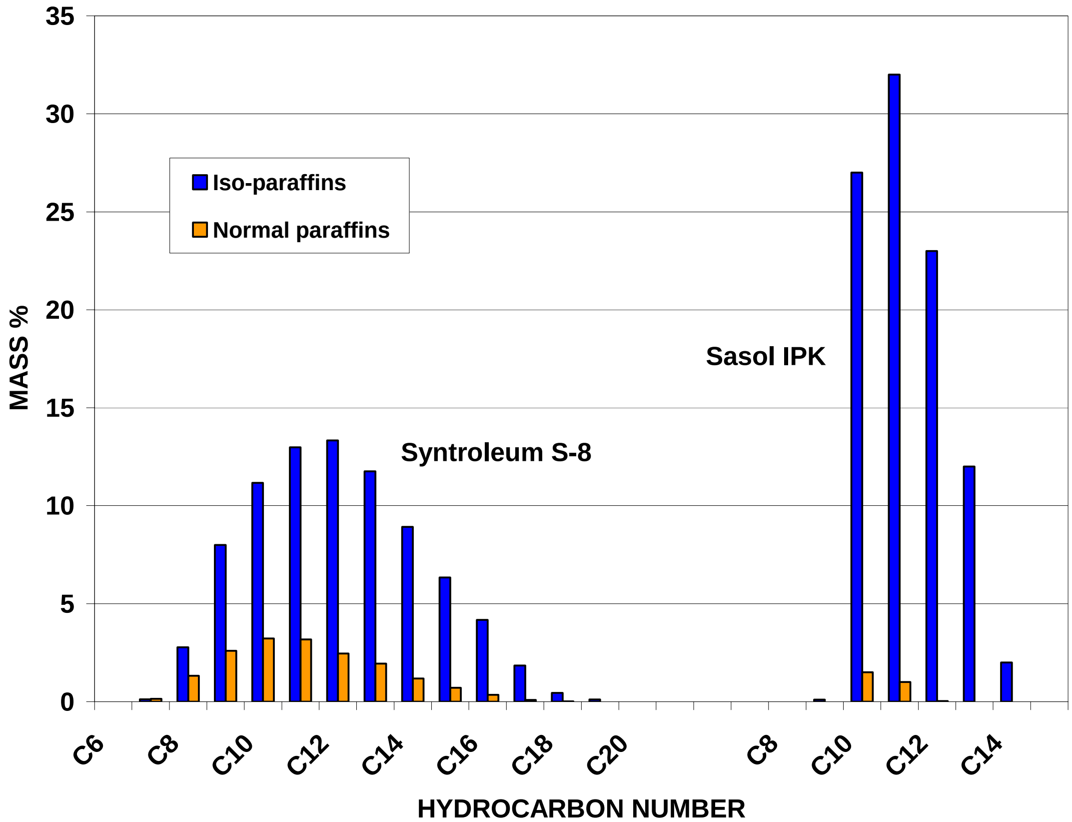


**Figure 11. Hydrocarbon Composition of S-8 and IPK**

**Table 4. Trace Organics and Non-metals in S-8 and IPK**

| Trace Material | IPK | S-8 |
|---|---|---|
| Carbonyls as MEK, mg/kg | <25 | ND* |
| Alcohols as EtOH, wt% | <0.01 | ND |
| Esters, mg KOH/g | <0.001 | ND |
| Phenols, mg/kg | 1 | ND |
| Acid Number, mg KOH/g | 0.001 | 0.004 |
| Sulfur, wt% | 0.0001 | 0.0002 |
| Nitrogen, mg/L | 1 | ND |

* Not detectable

**Table 5. Trace Metals in S-8 and IPK**

| Metal | S-8 | IPK | CRC World Fuel Survey |
|---|---|---|---|
| Ag | <100ppb | na* | na |
| Al | <100ppb | na | na |
| Ba | <100ppb | na | na |
| Ca | <100ppb | na | 0 – 42 ppb |
| Cr | <100ppb | na | na |
| Cu | 14 ppb | <10 ppb | 0 – 195 ppb |
| Fe | <100ppb | 10 – 50 ppb | 0 – 3 ppb |
| K | <500ppb | na | na |
| Mg | <100ppb | na | na |
| Mn | <100ppb | na | 0 – 103 ppb |
| Mo | <100ppb | na | na |
| Na | <1ppm | na | na |
| Ni | <100ppb | na | na |
| Pb | <100ppb | < 50 ppb | na |
| Si | <100ppb | na | na |
| Ti | <100ppb | na | na |
| V | <100ppb | na | na |
| Zn | 118 – 266 ppb | na | 0 – 32 ppb |

* na – Fuel was not analyzed for this metal

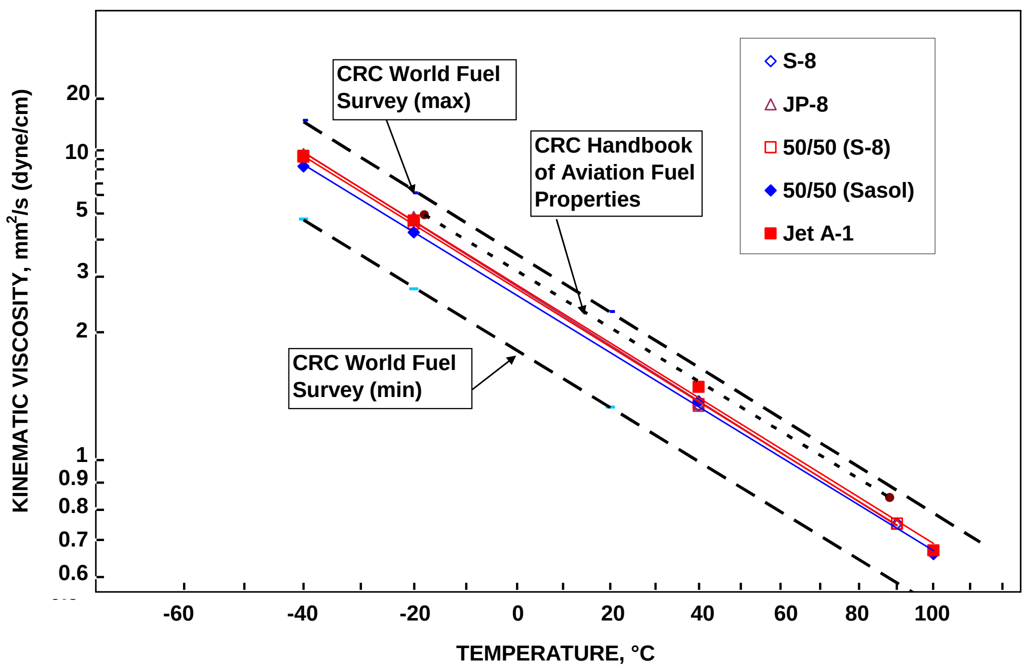


**Figure 12. Comparison of Viscosity**

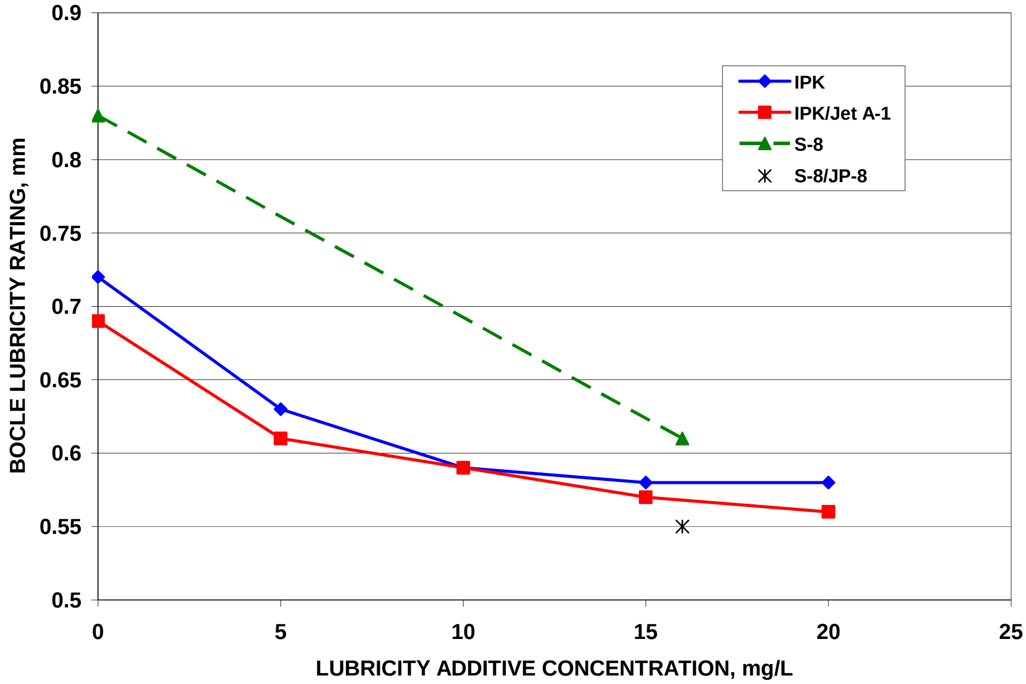


**Figure 13. Effectiveness of CI/LI Additives in S-8 and IPK Blends**

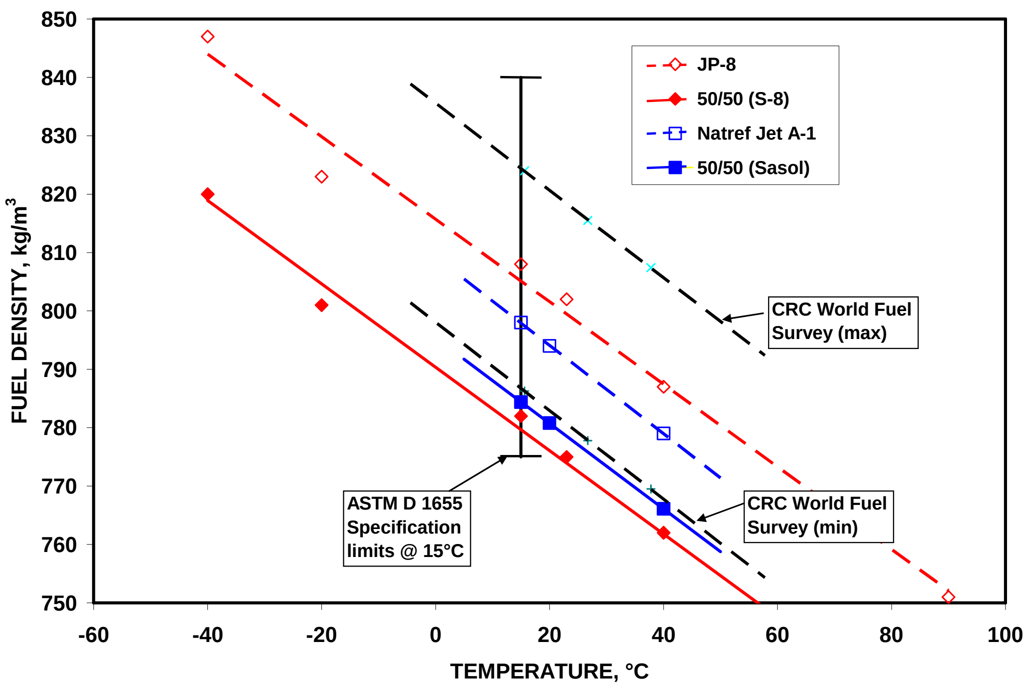


**Figure 14. Comparison of Density**

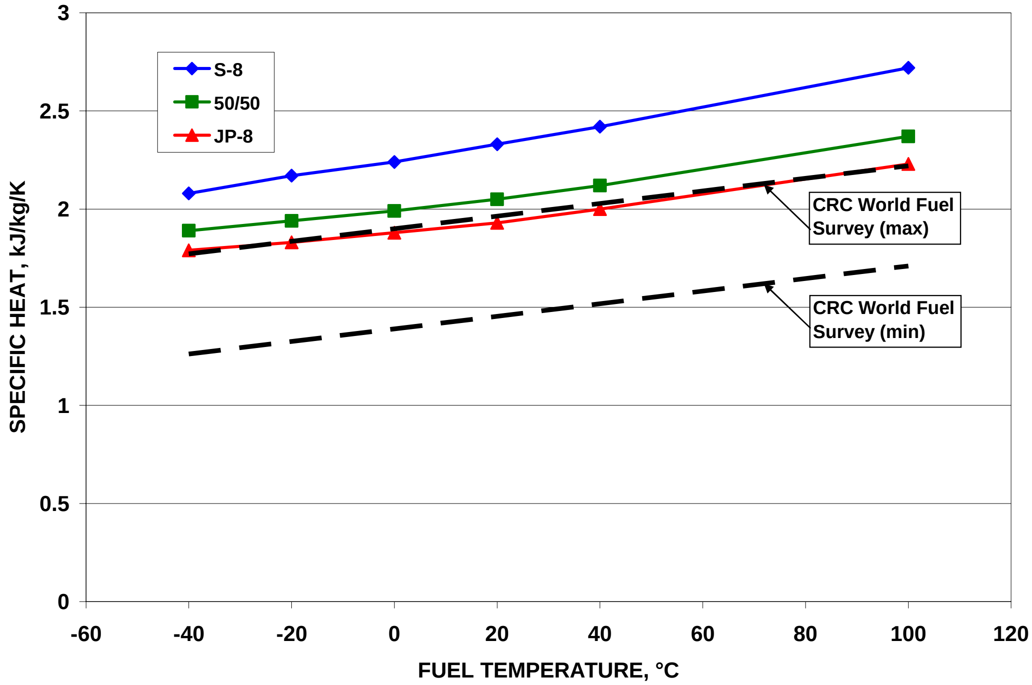


**Figure 15. Comparison of Specific Heat**

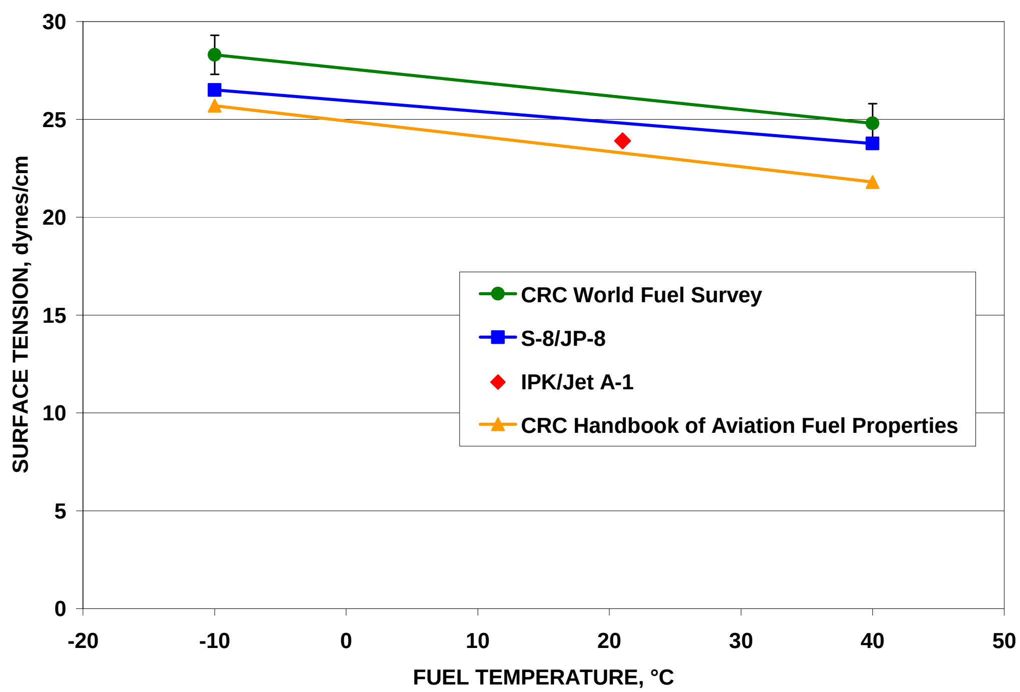


**Figure 16. Comparison of Surface Tension**

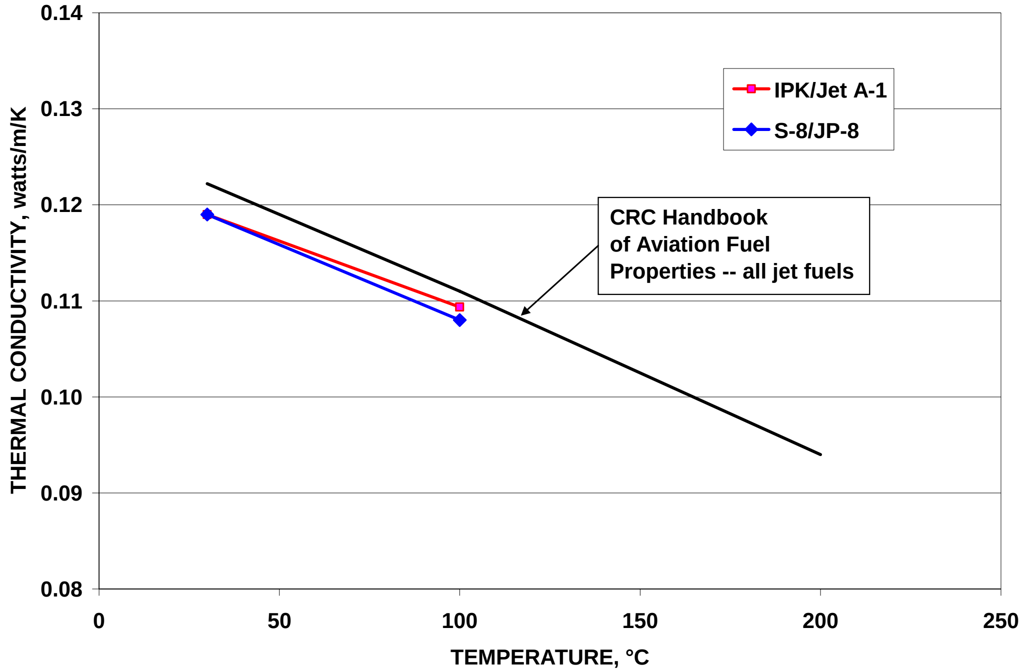


**Figure 17. Comparison of Thermal Conductivity**

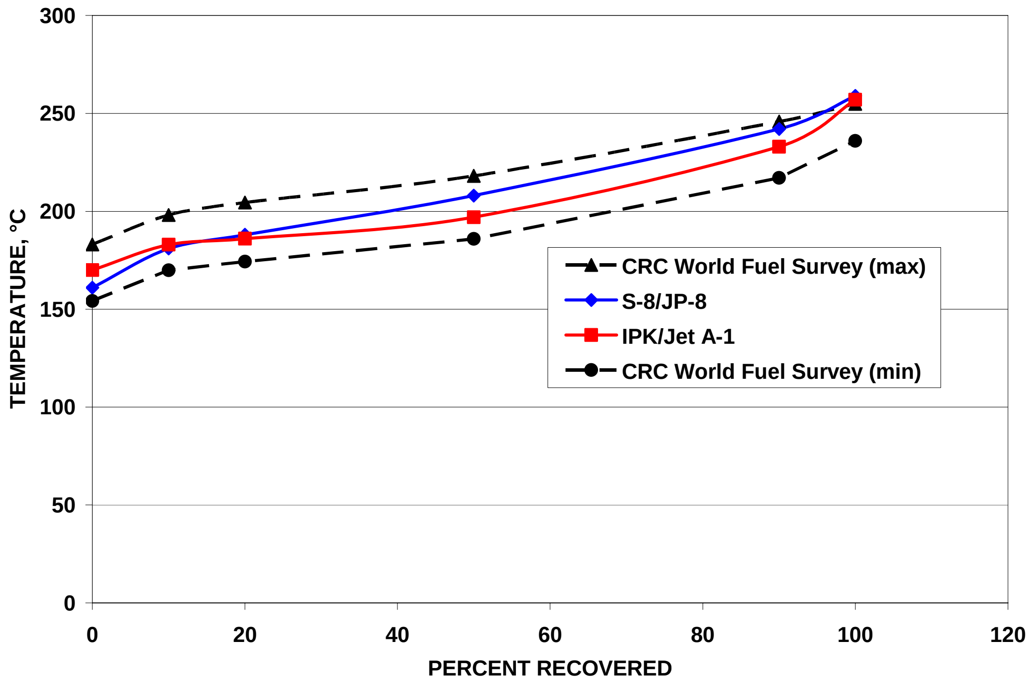


**Figure 18. Comparison of Boiling Point Distribution (ASTM D 86)**

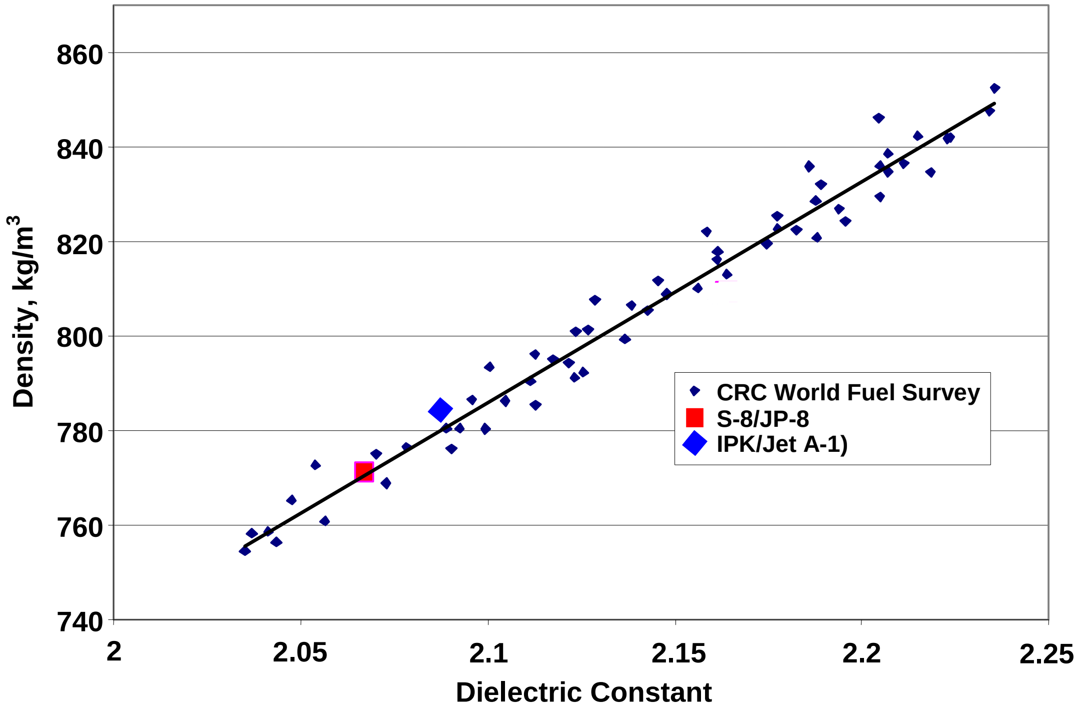


**Figure 19. Comparison of Dielectric-Density Characteristics of 50/50 Blends with CRC World Fuel Survey**

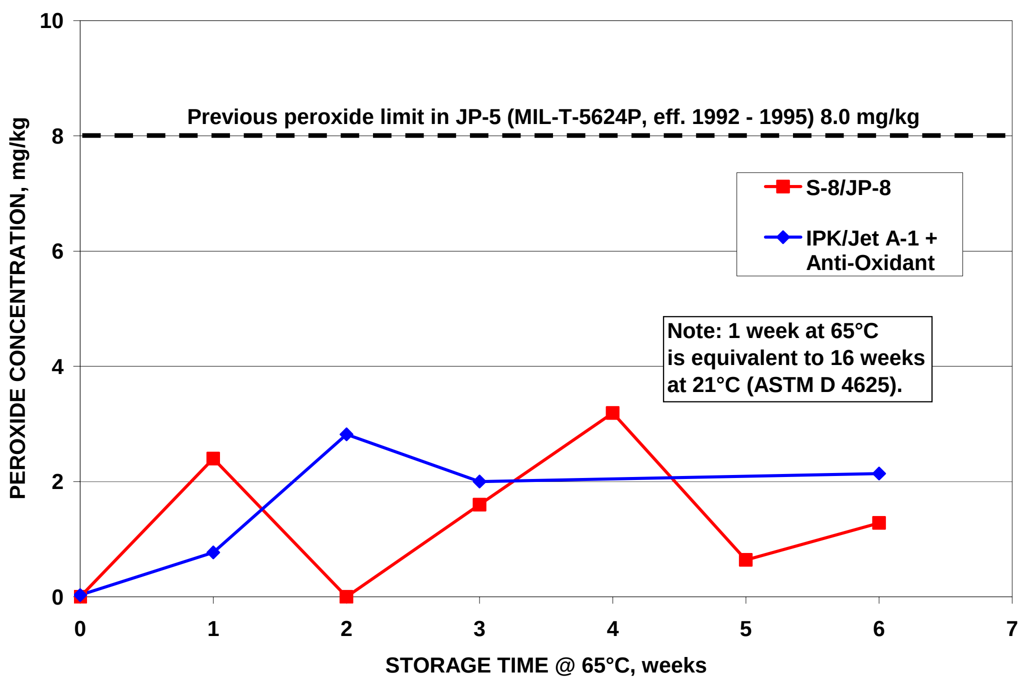


**Figure 20. Peroxide Formation During Accelerated Storage (ASTM D 3703)**

**Table 6. Gum Formation During Accelerated Storage**

| Fuel | Gum Concentration mg/100 mL |
|---|---|
| Jet A-1 | 0.6, 1.3 |
| IPK/Jet A-1 | 1.9, 1.9 |
| S-8 (S-5)* | No data for S-8 (0.3 to 0.4)* |
| S-8/JP-8 (S-5/JP-5) | 13.1 (0.7 to 0.9) |

* S-5 data provided by US Navy; similar fuel except for flash point.

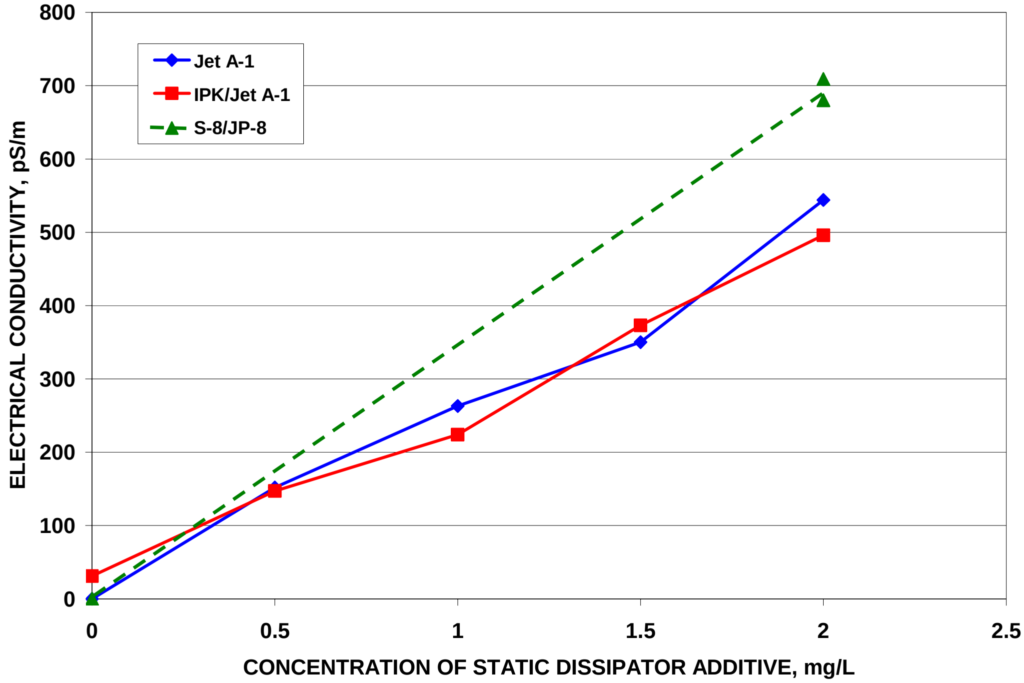


**Figure 21. Effectiveness of Static Dissipator Additive**

**Table 7. Comparison of Alternate Methods for Determining Specific Energy**

| ASTM Method | Specific Energy, MJ/kg | | | | |
|---|---|---|---|---|---|
| | SYNTROLEUM S-8 | | | Sasol IPK | |
| | S-8 | 50/50 blend | JP-8 | 50/50 blend | Jet A-1 |
| D 3338 | 44.06 | 43.52 | — | 43.58 | 43.28 |
| D 4809 | 43.81 | 43.32 | 43.21 | 43.60 | 43.20 |
| D 4529 | — | — | — | 43.56 | 43.35 |

The comparison of materials compatibility for the two fuels is the weakest comparison because the testing was not the same for the two fuels and there are apparently no definitive pass/fail criteria. Figures 22 and 23 present results of material-compatibility tests on o-rings for the S-8 and IPK blends, respectively. These tests were conducted by different organizations for different purposes. The IPK tests were conducted by SwRI for the purpose of demonstrating that IPK blends were suitable for civil aviation. The S-8 blends were tested by the U.S. Air Force to demonstrate suitability for use in military aircraft, specifically the B52 aircraft. Hence, the Air Force chose to use temperatures and soak times they believed were appropriate for their use. The IPK blend tests were for 14 days at 75°C for all materials. The S-8 blend tests were for 28 days at 165°C for nitrile, 225°C for fluorosilicone, and 325°C for fluorocarbon. To further complicate issues, the same material property tests were not conducted; the only test in common was for tensile strength. It was thought that comparing the property data after the soaks in the synthetic blends with that for the soak in the petroleum reference fuel would be the best evaluation possible. However, the Air Force did not use the same JP-8 for making the blends as they did for the reference fuel.

Despite the lack of an “apples-to-apples” comparison of materials compatibility, the data trends reasonably support that the 50/50 blend of S-8 and JP-8 produced greater changes in material properties than the Sasol SSJF, which had very little effect on the properties evaluated. The greater impact of the S-8 blend is probably due to the higher temperatures and longer soak times. The Air Force concluded that the S-8 blend was acceptable because in the majority of tests the impact on material properties was less than that of the JP-8 reference fuel.

### 7.2.2 Conclusions on Comparison of S-8/JP-8 and IPK/Jet A-1

From these multiple comparisons of properties and characteristics, it is concluded that even though the two synthetic kerosenes came from different resources and processes, they are comprised solely of iso- and normal paraffins, and when blended up to 50%(v) with conventional jet fuel, produce a semi-synthetic jet fuel that has all the properties and characteristics considered important for jet fuel. Semi-synthetic kerosenes blended from these two synthetic kerosenes, and containing at least 8%(v) aromatics are considered to be fit-for-purpose as jet fuel. Flight testing and experience in ground support systems have validated this conclusion.

These results form a sufficient basis for comparing the other candidate paraffinic F-T kerosenes when they become available. If the trend continues, the results may support the inclusion of paraffinic F-T kerosenes into the major fuel specifications as blending streams up to 50%(v) subject to a minimum aromatic content of 8%(v).

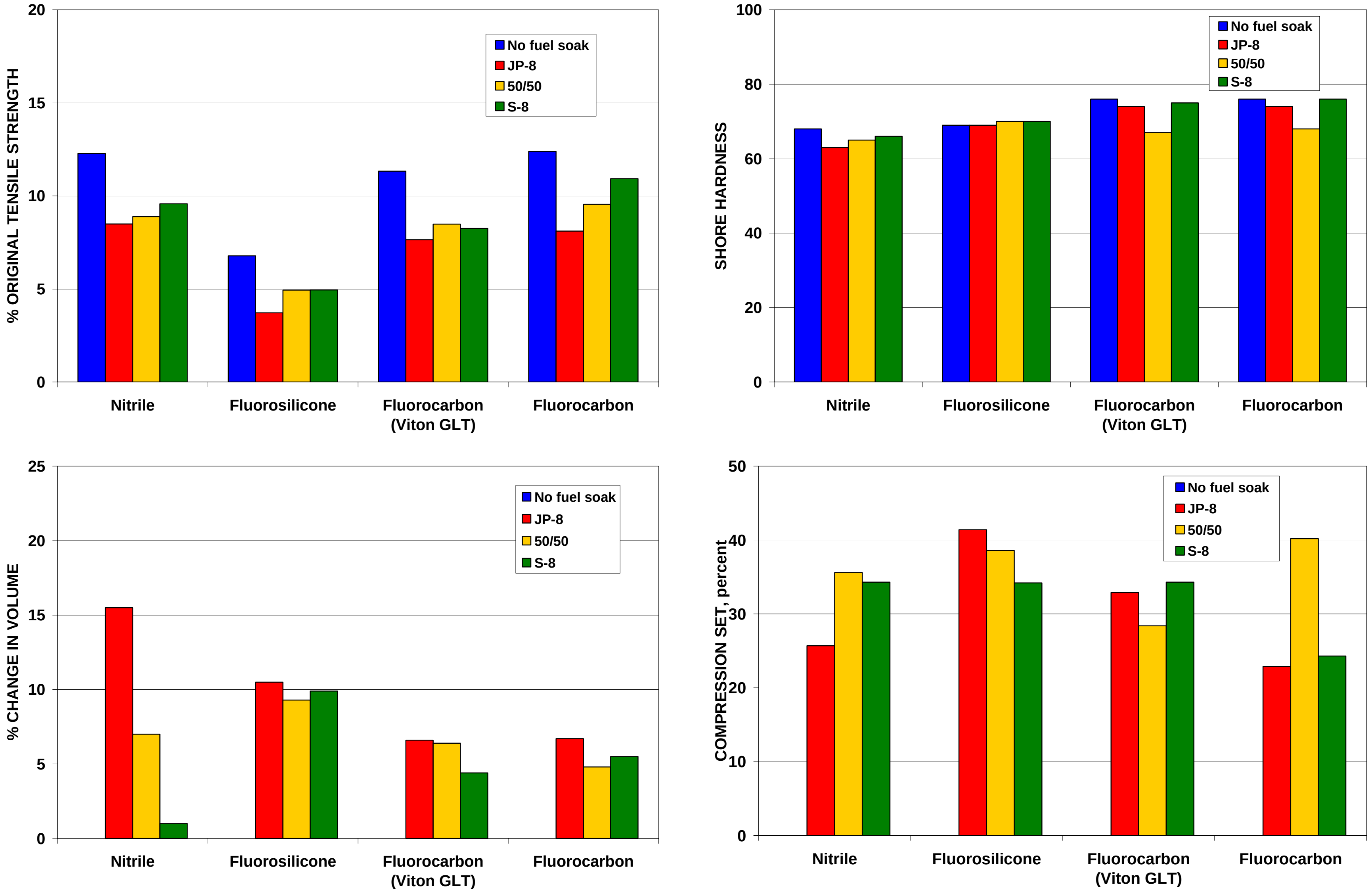


**Figure 22. Effect of S-8 on O-Ring Material Properties**

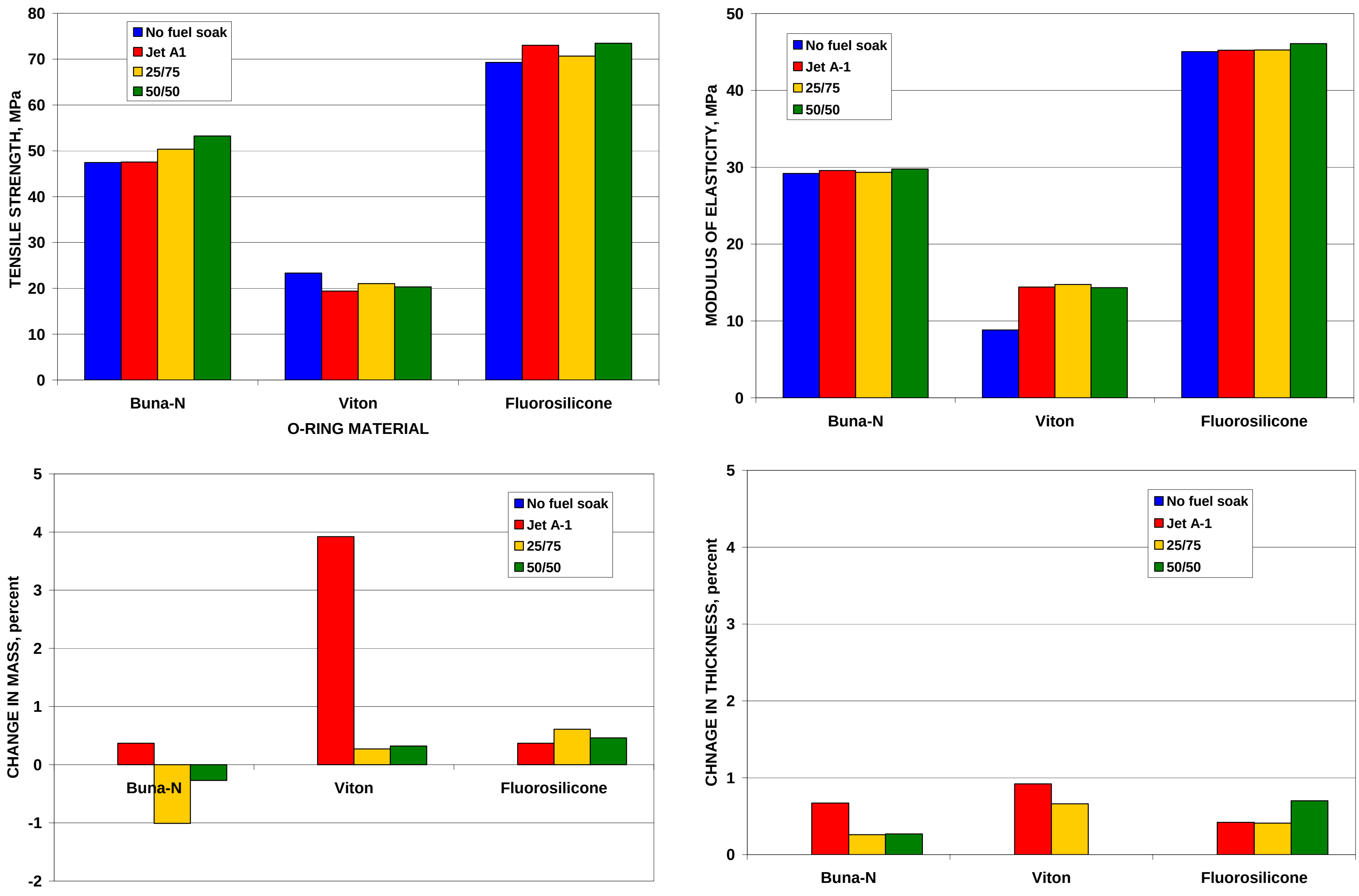


**Figure 23. Effect of Sasol IPK on O-Ring Material Properties**

## 8.0 SUMMARY AND CONCLUSIONS

A protocol has been defined for the approval of F-T kerosenes for use in jet fuels for civil aviation. The protocol is based on a series of laboratory tests that the aircraft engine and airframe manufacturers believe necessary and sufficient to demonstrate that a candidate fuel has properties and characteristics just like conventional, petroleum-derived jet fuels and will perform without compromise to aircraft performance, durability, or safety.

The series of tests was based on the issues and concerns defined by the UK Aviation Fuels Committee (AFC) for the approval of the Sasol semi-synthetic jet fuel, which has now been in use for 8 years in Johannesburg, South Africa, without incident or issue. More recently, the same guidelines were used in the approval process of the Sasol fully synthetic fuel, which, at the time of this writing, has passed all the required tests and has been submitted for approval under DEF STAN 91-91.

This approval protocol goes further than the AFC approach in that it defines suitable tests for each property/characteristic and provides acceptable limits based on jet fuels currently in use.

The benefit of this approach is that a refiner will know what is expected, how to meet those expectations, and what the cost will be. Furthermore, the refiner knows that upon meeting those expectations, the fuel will be accepted and can be marketed.

There is a benefit to the engine manufacturers also, who are the final arbiters for fuel approval. When a fuel is offered for consideration, the engine manufacturers will know that the data presented fall within the norm of existing fuels that are acceptable, thus saving their time as well as providing confidence in their acceptance.

Since this protocol may become either a part of a major aviation fuel specification or referenced by the same, the approval of the fuel by the engine manufacturers is the only necessary hurdle. No changes to the relevant specification are required.

As a supplement to the original scope of this project, a comparison was made of the fit-for-purpose properties and characteristics of a semi-synthetic blend made from the Syntroleum S-8 F-T kerosene made from natural gas with that of the original Sasol semi-synthetic fuel using iso-paraffinic kerosene made from coal using F-T processes.

From this comparison, it was concluded that even though the two synthetic kerosenes came from different resources and processes, when blended up to 50%(v) with conventional jet fuel and having a minimum of 8%(v) aromatics content, they produce semi-synthetic jet fuels that have all the properties and characteristics considered important for jet fuel. Semi-synthetic kerosenes blended from these two synthetic kerosenes are considered to be fit-for-purpose as jet fuel. This conclusion has been validated by flight-testing and experience in ground support systems.

These results form a sufficient basis for comparing the other candidate F-T kerosenes without aromatics when they become available. If the trend continues, the results may support the inclusion of paraffinic F-T kerosenes into major fuel specifications for commercial aviation as blending streams up to 50%(v) subject to a minimum aromatic content of 8%(v).

## 9.0 RESEARCH NEEDS

There is a fundamental lack of understanding about aromatics in jet fuel – whether they are necessary and, if so, at what minimum level. Answering these questions is necessary for the use of paraffinic kerosenes as fully synthetic fuels.

The most urgent need is an understanding of the role of jet fuel and its aromatic content in the design and performance of seals, o-rings, self-sealing bladders, adhesives, etc. It is known that nitrile elastomers are affected by aromatics in the fuel. For example, nitrile o-rings swell in the presence of aromatics and the amount of swell is linear with the aromatic content. It is known that designers of fuel systems do not require any swell. The seal systems are designed to seal when initially assembled. It is thought that the presence of aromatics may be required to prevent shrinkage of older seals that may have taken some plastic set and which would leak upon shrinkage. Much of the evidence seems anecdotal and most of the existing data are on new materials. As difficult as it may be, test data are needed on aged materials that may have taken some plastic set.

One relatively minor issue is that iso-paraffins and normal paraffins have relatively low densities. Kerosenes comprised solely of these families of hydrocarbons will not meet the minimum density requirements specified for jet fuel. About 8%(v) aromatics would be required; cyclo-paraffins would also increase density, but they are not found in the paraffinic F-T kerosenes. Studies should be conducted to establish whether the minimum density requirement is relevant with modern aircraft and routing or if it could be lowered without affecting missions and flight profiles.

Aromatics also increase the solvency of fuels, and may be necessary for the solubility of some additives. This does not appear necessary with the common additives that have been tested, but could be simply verified.

## 10.0 RECOMMENDATIONS

It is recommended that the approval protocol presented in Figure 1 and described in Section 5.0 be approved and adopted as the methodology for approving kerosenes from Fischer-Tropsch processes for use in jet fuel for civil aviation.

It is further recommended that the aviation fuels community continue with the project to compare the fit-for-purpose properties and characteristics of other available paraffinic F-T kerosenes in 50/50 blends with conventional jet fuel for the purpose of developing a general acceptance of all paraffinic F-T kerosenes for use as blending streams for making semi-synthetic jet fuel under civil fuel specifications such as ASTM D 1655.

Finally, it is recommended that relevant research be conducted to answer the questions about the need for aromatics in jet fuel.

## 11.0 REFERENCES


1. Defense Standard 91-91, Turbine Fuel, Aviation Kerosene Type, Jet A-1 NATO Code: F-35 Joint Service Designation: AVTUR, available at www.dstan.mod.uk.

2. D 1655, Standard Specification for Aviation Turbine Fuels, Annual Book of ASTM Standards, Section 05, Petroleum Products, Lubricants, and Fossil Fuels, American Society of Testing and Materials, www.astm.org.

3. Hadaller, O.J. and Johnson, J.M., "World Fuel Sampling Program," CRC Report No. 647, Coordinating Research Council, Inc., Alpharetta, GA 30022, June 2006.

4. "Handbook of Aviation Fuel Properties—2004 Third Edition," CRC Report No. 635, Coordinating Research Council, Inc., Alpharetta, GA 30022.

5. Moses, C., "Evaluation of Sasol Synthetic Kerosene for Suitability as Jet Fuel – Phase II: Engine and Combustor Tests," Report No. 04438-2, Southwest Research Institute, San Antonio, TX, September 2007.

6. Moses, C.A, Stavinoha, L.L., and Roets, P., "Qualification of Sasol Semi-Synthetic Jet A-1 as Commercial Jet Fuel," Report No. SwRI-8531, Southwest Research Institute, San Antonio, TX, November 1997.

7. DeWitt, Mathew J., et al, "Evaluation of Fuel Produced via the Fischer-'tropsch Process for Use in Aviation Applications," Paper No. 58b, AIChE Spring National Meeting, in Houston TX, April 2007.

# APPENDIX

## Table 1 of ASTM D 1655
## "Standard Specification for Aviation Turbine Fuels"

TABLE 1 Detailed Requirements of Aviation Turbine Fuels[A]

| Property | | Jet A or Jet A-1 | ASTM Test Method[B] |
|---|---|---|---|
| COMPOSITION | | | |
| Acidity, total mg KOH/g | max | 0.10 | D 3242 |
| 1. Aromatics, vol % | max | 25 | D 1319 |
| 2. Aromatics, vol % | max | 26.5 | D 6379 |
| Sulfur, mercaptan,[C] mass % | max | 0.003 | D 3227 |
| Sulfur, total mass % | max | 0.30 | D 1266, D 2622, D 4294, or D 5453 |
| VOLATILITY | | | |
| Distillation: one of the following requirements shall be met. | | | |
| 1. Physical Distillation | | | D 86 |
| Distillation temperature, °C: | | | |
| 10 % recovered, temperature | max | 205 | |
| 50 % recovered, temperature | | report | |
| 90 % recovered, temperature | | report | |
| Final boiling point, temperature | max | 300 | |
| Distillation residue, % | max | 1.5 | |
| Distillation loss, % | max | 1.5 | |
| 2. Simulated Distillation | | | D 2887 |
| Distillation temperature, °C | | | |
| 10% recovered, temperature | max | 185 | |
| 50 % recovered, temperature | | report | |
| 90 % recovered, temperature | | report | |
| Final boiling point, temperature | max | 340 | |
| Flash point, °C | min | 38[D] | D 56 or D 3828[E] |
| Density at 15°C, kg/m$^3$ | | 775 to 840 | D 1298 or D 4052 |
| FLUIDITY | | | |
| Freezing point, °C | max | –40 Jet A[F]<br>–47 Jet A-1[F] | D 5972, D 7153, D 7154, or D 2386 |
| Viscosity –20°C, mm$^2$/s[G] | max | 8.0 | D 445 |
| COMBUSTION | | | |
| Net heat of combustion, MJ/kg | min | 42.8[H] | D 4529, D 3338, or D 4809 |
| One of the following requirements shall be met: | | | |
| (*1*) Smoke point, mm, or | min | 25 | D 1322 |
| (*2*) Smoke point, mm, and | min | 18 | D 1322 |
| Naphthalenes, vol, % | max | 3.0 | D 1840 |
| CORROSION | | | |
| Copper strip, 2 h at 100°C | max | No. 1 | D 130 |
| THERMAL STABILITY | | | |
| JFTOT (2.5 h at control temperature of 260°C min) | | | |
| Filter pressure drop, mm Hg | max | 25[I] | D 3241 |
| Tube deposits less than | | 3[J]<br>No *Peacock* or *Abnormal* Color Deposits | |
| CONTAMINANTS | | | |
| Existent gum, mg/100 mL | max | 7 | D 381, IP 540 |
| Microseparometer,[K] Rating | | | D 3948 |
| Without electrical conductivity additive | min | 85 | |
| With electrical conductivity additive | min | 70 | |
| ADDITIVES | | See 5.2 | |
| Electrical conductivity, pS/m | | [L] | D 2624 |

[A] For compliance of test results against the requirements of Table 1, see 6.2.
[B] The test methods indicated in this table are referred to in Section 10.
[C] The mercaptan sulfur determination may be waived if the fuel is considered *sweet* by the doctor test described in Test Method D 4952.
[D] A higher minimum flash point specification may be agreed upon between purchaser and supplier.
[E] Results obtained by Test Methods D 3828 may be up to 2°C lower than those obtained by Test Method D 56, which is the preferred method. In case of dispute, Test Method D 56 will apply.
[F] Other freezing points may be agreed upon between supplier and purchaser.
[G] 1 mm$^2$/s = 1 cSt.
[H] For all grades use either Eq 1 or Table 1 in Test Method D 4529 or Eq 2 in Test Method D 3338. Test Method D 4809 may be used as an alternative. In case of dispute, Test Method D 4809 shall be used.
[I] Preferred SI units are 3.3 kPa, max.
[J] Tube deposit ratings shall always be reported by the Visual Method; a rating by the Tube Deposit Rating (TDR) optical density method is desirable but not mandatory.
[K] At point of manufacture.
[L] If electrical conductivity additive is used, the conductivity shall not exceed 600 pS/m at the point of use of the fuel. When electrical conductivity additive is specified by the purchaser, the conductivity shall be 50 to 600 pS/m under the conditions at point of delivery.

$$1 \text{ pS/m} = 1 \times 10^{-12} \, \Omega^{-1} \, m^{-1}$$