

Properties of Fischer-Tropsch (FT) Blends for Use in Military Equipment

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ABSTRACT

Clean, very low sulfur fuels produced from domestic resources are of interest to the U.S. Military to enhance supply security and reliability versus continuing to rely on the supply of fuels that are either manufactured from an increasing percentage of imported oil or imported in increasing amounts as finished products. [1]* Synthetic Fischer-Tropsch (FT) fuel is one type of fuel that can be produced from domestic resources. FT fuels can be produced from a variety of non-petroleum feed stocks, such as natural gas, coal, petroleum coke, or even biomass and various wastes. Starting with reforming or gasification processes, the FT technology first produces synthesis gas (syngas) which is subsequently processed to high-boiling hydrocarbons. These hydrocarbons are then hydrocracked, hydroisomerized, and/or hydroprocessed to produce the desired liquid fuels. The military has a Single Battlefield Fuel Policy which mandates use of the JP-8/JP-5/Jet A-1 aviation turbine fuels. These are currently derived from conventional resources such as petroleum (crude oil). FT aviation turbine fuels have been produced and are being evaluated for use in military equipment by a Joint Agency Department of Defense (DoD) and Department of Energy (DoE) Team. The military will most likely utilize blends of FT fuels with petroleum JP-8/JP-5/Jet A-1 as a first step in evolving towards the use of cleaner fuels that can be produced from domestic resources. Properties of these "FT/petroleum fuel blends" are shown to be similar to those of petroleum JP-8/JP-5/Jet A-1.

INTRODUCTION

The Office of the Secretary of Defense (OSD), Advanced Systems & Concepts, has established a Clean Fuels Initiative. [2] The intent of this initiative is to catalyze commercial industry to produce clean fuels for use by the U.S. Military from secure domestic resources. Several concerns underlie the reason for this initiative:

- *The growing dependence of the U.S. on foreign oil.* Much of the transportation fuels used by DoD are refined in the U.S. from imported oil. Our dependence on imported oil will continue to grow if we stay the current course. This growing dependence threatens not only America's fuel supply, but our security and economic vitality, and causes our military's resources to be directed towards protecting our energy interests worldwide.
- *The vulnerability of the mega-refineries.* Most of the fuel used by DoD is supplied from large refining complexes situated along the coastal U.S., and also in other places worldwide. These mega-refineries present a limited fuel supply diversity that is susceptible to supply-demand imbalances; this is especially true in a tight oil market, such as we now have globally, when unplanned shutdowns happen. More so, such large sites present significant targets to terrorists. The vulnerability in the U.S. supply chain, in both our refining capacity and pipeline distribution system, was certainly illustrated with the disruptions caused by Hurricanes Katrina and Rita.
- *The divergence in the sulfur content of jet fuel and diesel fuel.* The sulfur content of the diesel fuel, that modern diesel engines are required and designed to use, is diverging from the sulfur content of the jet fuel used in a large share of DoD diesel engines due to Single Battlefield Fuel Policy. Because of this

* Numbers in brackets refer to references.

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divergence, DoD must apply for exemptions from the EPA for the tactical/combat fleet and support equipment. In addition, since the military's procurement of new engines draws from what is available commercially, a number of technical issues may result from using a fuel of higher sulfur content than that of the fuel the engine and its control system are designed to use. The availability and use of cleaner fuel, such as jet fuel with sulfur content similar to that of today's diesel fuel, would help to address this area of concern.

- *Potential limits on operations.* In the U.S., the military's ability to conduct large scale operations, such as training exercises, may be curtailed in areas where regulated air pollutants do not meet EPA targets. Likewise, Europeans are moving forward with more stringent environmental rules that could impact our military's operations there.
- *The rising cost of fuel.* DoD is concerned about the increasing costs of fuel, just as are citizens throughout our nation. The FY06 Defense Working Capital Funds had to be increased by 92% above the FY05 level to account for this increased cost.

The use of clean fuels by the military will help DoD reduce their dependence on foreign oil and supply chain vulnerabilities, and meet U.S. Environmental Protection Agency (EPA) regulations for exhaust emissions. Domestic manufacturing of transportation fuels from unconventional energy resources, such as FT fuels from coal, is needed to meet our military's, as well as our nation's, security of supply. Liquid hydrocarbon fuels, similar to today's jet fuel, will be needed for many years due to the long service lives of military aircraft, ships and ground vehicles that must operate on such a fuel. Much effort is underway to develop improved means of propulsion and power generation, such as systems incorporating diesel-electric engines and fuel cells. However, even for these systems, clean hydrocarbon fuels in the jet-diesel boiling range will be in demand.

Several DoD and DoE evaluations of FT fuels have determined that these fuels are viable for use by the military. [3,4,5,6,7,8]. Not only can FT fuels be utilized in today's military fleets, but a highly Iso-Paraffinic Kerosene (IPK) FT fuel is an attractive candidate as the 'Joint Battlespace Use Fuel of the Future' (JBUFF). [1] Since FT IPK is essentially free of heteroatoms, such as sulfur, and also aromatics, its use in current ground, air, and marine fleets propelled with aviation turbine and diesel engines will immediately translate to reduced exhaust pollutants. Furthermore, its composition results in a fuel with high thermal stability and one that can act as a high-heat-sink coolant in aircraft engines and subsystems. Such a fuel is paramount to development of advanced aviation turbine engines with increased fuel efficiency, and especially the next generation of advanced rockets, scramjets and combined cycle propulsion systems.

The near-term use of FT fuels in existing military fleets is not without some challenges, but none that cannot be overcome. The utmost technical challenge is ensuring that FT fuel can be used interchangeably with the petroleum JP-8/JP-5/Jet A-1 fuel that is in use today. In the instance where FT fuels are manufactured such that they contain no or very low amounts of aromatics, such as with FT IPK, introduction of such a fuel into current fleets presents the possibility of fuel leakage in some equipment. This is because some elastomers used for seals in the fuel distribution systems of current equipment are sensitive to changes in fuel aromatic content; most notably but not exclusively, many nitrile compounds. Aromatics, such as those found in typical petroleum-derived fuels like JP-8/JP-5, are known to cause these sensitive elastomers to swell. Introducing a fuel containing no or very low aromatics may cause these petroleum fuel-wetted elastomers to actually shrink, thus presenting the possibility of fuel leakage at the affected seals. Particularly vulnerable are any of the seals, made of sensitive elastomers, which also have a significant degree of compression set (permanent deformation), such as is often the case with seals that have been in service a long time. If these seals were to also undergo shrinkage, the risk of leakage is increased. This phenomenon, fuel leakage due to changes in fuel aromatic content (higher to lower aromatic content), was observed during the introduction of low sulfur diesel fuel into the California market in 1993. [9] Similarly, changes in jet fuel aromatic content have also been linked to fuel leakage observed in aircraft fuel systems. [10]

A reasonable strategy for near-term use of FT fuels by the military is to introduce them into existing fleets as blends – that is, blends of FT fuel with petroleum fuel. More specifically, this would mean introducing blends of FT kerosene with JP-8/JP-5/Jet A-1. An important precedent for the approval and use of these blends in aircraft already exists. In 1999, under the British Aviation Turbine Fuel Defence Standard 91-91 (DEF STAN 91-91), a blend of FT kerosene with Jet A-1 was approved as a Jet A-1 fuel for use at the Johannesburg International Airport. [11] This initial approval was granted for a blend of FT IPK (containing no aromatics) as produced at Sasol's plant in Secunda, South Africa, with petroleum kerosene (Jet A-1) produced at the National Petroleum Refinery (Natref) in Sasolburg, South Africa's only inland refinery. Among the limitations on the final blend were that the FT IPK could be no more than 50% of the final blend, and that the final blend had to contain a minimum of 8.0 vol. % (eight volume percent) aromatics as supplied by the petroleum kerosene. This latter limitation was placed on the final blend to ensure adequate elastomer compatibility. Testing was completed on new and used o-rings made of various elastomers to show that their responses (such as swelling/shrinkage) were similar between the Natref Jet A-1 alone and test blends of the Sasol FT IPK with the Jet A-1. [12] Since the initial approval, a request was made to allow blends of the Sasol FT IPK with any kerosene from conventional sources and not only with kerosene produced at Natref. [13] This request was

granted and such blends were approved with publication of Issue 5 DEF STAN 91-91 in February 2005. [14]

In addition to the precedent for use of an FT/petroleum fuel blend as a jet fuel, using such a blended fuel in the near-term is more realistic from the standpoint of FT fuel availability. The OSD Clean Fuels Initiative is focused on the commercial production of clean fuels from domestic resources, and then on implementing the use of these fuels by the military after they are evaluated, demonstrated, and approved for use. The use of these fuels, such as FT fuel, will then depend on their availability. As it stands today, only one facility in the Continental U.S. is capable of producing more than just laboratory-scale reactor quantities of FT fuel. This is the 70 barrel-per-day (bpd) Gas-to-Liquids (GTL) Demonstration Plant at the Port of Catoosa, near Tulsa, OK, built jointly by Syntroleum Corporation, Marathon Oil Company, and the Department of Energy. Building commercial-scale plants in the U.S. to produce FT fuels will take several years. So, availability of domestically-produced FT fuels will build gradually and, as such, FT fuel volumes only realistically support an implementation strategy of using FT/petroleum blends in the near-term.

The potential for production of clean fuels from domestic resources is very viable; particularly in as far as the U.S. is rich in resources, most notably oil shale and coal. The large-scale production of FT fuels from coal will likely occur before production of clean fuels from oil shale, so the focus here is on the coal resource. The coal found in the Continental United States (CONUS) is distributed across nearly all regions of the country as shown in Figure 1. [15] The only region that appears not to have significant deposits of coal are states on and near the U.S. West Coast, namely CA, NV, OR and WA.

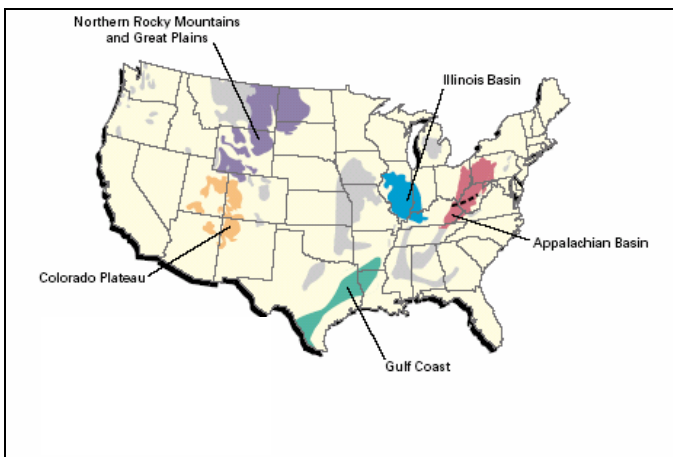


Figure 1. Map of U.S. Coal Deposits According to the U.S. Geological Survey (USGS)

FT plants will likely be constructed close to the resource base due to the high costs associated with transport of coal. This means, then, that FT fuels from coal will most likely be manufactured in states with abundant coal resources such as those in the Western Central U.S. (including states like MT, UT, and WY), those in the

Eastern Central U.S. (including states such as IL, IN, KY, and OH), and some on or near the U.S. East Coast (such as PA, VA and WV). However, ready access to petroleum fuels, such as from local refineries or pipeline distribution, is needed to support a strategy for using FT/petroleum fuel blends. In addition, since CO₂, a greenhouse gas, is a by-product of the coal gasification process, CO₂ capture and storage will be an important part of environmentally-acceptable production of FT fuels. Fortunately, the capture of CO₂ can be accommodated by today's coal gasification processes. Furthermore, CO₂ storage has been used for years in the practice known as Enhanced Oil Recovery (EOR), wherein CO₂ injected into depleting oil fields aids in recovery of more oil. DoE initiated 14 new projects in late 2004 aimed at further improving EOR techniques. In addition, the FutureGen Project, launched in December of 2005 by the FutureGen Industrial Alliance in conjunction with the DoE Office of Fossil Energy, will construct a prototype plant to establish the economic and technical feasibility of capturing and sequestering the carbon dioxide generated while producing electricity and hydrogen from coal.

Another point to note about the use of FT/petroleum fuel blends is the improvements possible in some of the properties of these blends versus petroleum fuels. As previously mentioned, FT IPK contains no sulfur and no aromatics. Blending FT IPK with petroleum kerosene, then, will result in a final fuel that will burn cleaner, meaning reductions in exhaust emissions will be realized. Another benefit is that FT fuels have very high cetane numbers due to their highly paraffinic composition. When FT fuels are blended with petroleum fuels, improvements in cetane numbers will be realized. Diesel engines found in today's military fleets should run better with fuels with high cetane numbers (>50).

A particularly noteworthy example wherein blending of FT fuels could be of great benefit in improving fuel quality is in blends with fuels produced from Alberta oil-sands. The Canadian oil sands are an enormous North American resource which has already produced 4 Billion barrels (1967-2003) of oil. [16] Recoverable reserves are tagged at 174 Billion barrels, ranking second only to Saudi Arabia. Nearly an additional 1.6 Trillion barrels is possible with technology developments. Crude oils derived from oil sands tend to have higher cycloparaffin and aromatic content than conventional crude oils. [17] This means that fuels manufactured from oil sands-derived crude tend to be lower in quality; for instance, jet fuel smoke points trend lower and diesel fuel cetane trends lower. [18] Blending these oil sands-derived fuels of lower paraffinic content with highly-paraffinic FT fuels would improve the quality of those fuels.

As a further step in considering the use of FT/petroleum blends by the military, this paper documents research completed to evaluate blends of FT IPK with petroleum JP-8 fuels. First, 2004 JP-8 fuels procured from

refineries in CONUS were studied to better understand the statistical set of properties (the property 'box') among these fuels. Next, evaluations of FT IPK, primarily as supplied by Syntroleum Corporation to the DoD-DoE Team investigating these fuels, have been ongoing since 2003. Finally, both real blends and 'virtual blends' of the FT IPK with petroleum JP-8 were evaluated to compare them to the 'box' of current JP-8.

A final note here regarding FT IPK; there can be compositional differences between FT IPKs depending on exactly how the FT IPK is produced. The type of FT IPK produced by Sasol and approved for use in blends with Jet A-1 per DEF STAN 91-91 as previously explained in this paper, is made by the conversion of FT olefins (C_3 and C_4 , specifically) to distillate boiling range products such as jet and diesel fuel. The type Syntroleum produces is made by hydroisomerization of FT wax. Due to these differences in manufacturing, these two FT IPKs are different, at least in isoparaffin structure. This results in differences in some of the properties, for instance cetane number.

PROPERTIES OF JP-8 FUELS

The bulk fuel most used by DoD is JP-8, over 70% by volume, due to the high consumption rates of jet engines and the Single Battlefield Fuel Policy. [19] Fuels for DoD are procured by the Defense Energy Support Center (DESC). DESC maintains a useful database known as the Petroleum Quality Information System (PQIS). This database contains critical chemical and physical properties for bulk fuels procured by DESC. In addition to the test data for batches of JP-8 procured, the database also contains volumes for each batch. A PQIS Report is published annually and is available online at www.desc.dla.mil/; a CD-ROM is available containing the database in MS-Access® format. This was the source of the raw data used to define the property 'box' of CONUS JP-8 fuels procured in 2004. A similar exercise could be performed for JP-5.

DESC procures fuel worldwide; for purposes of reporting, nine global Defense Regions are defined. Of these, Regions 1 through 5¹ are in CONUS, with several states belonging to each Region as shown in Figure 2.

Table 1 is a summary of the data collected in 2004 for all the batches of JP-8 procured in CONUS (Regions 1 - 5), giving minimum and maximum values for each property by Region. Specification limits for these properties are also given, along with the number of batches in each Region, the associated regional volumes, and the total CONUS volume. These data begin to define the property 'box' of JP-8 fuels used in CONUS.

JP-8 properties vary on a batch-by-batch basis. So, to get a better understanding of the property 'box' of JP-8

fuels, a detailed statistical analysis was developed using the JP-8 batch data from the PQIS 2004 Report. The mean and weighted means, and associated standard deviations ($\pm 2\sigma$) for regional data sets, and for CONUS as a whole, were determined for selected properties (density, aromatic content, sulfur content, cetane index, net heat of combustion, viscosity, freeze point, and final boiling point). During review of the batch data in PQIS, a few data values were significantly outside specification limits; those values were conjectured to be data entry errors. In addition, a few batches had no values for some property tests. In such cases, values were set to the mean as determined for that region minus the questionable/missing data values. Weighted means were then determined using the revised data sets. Charts (Figures 3 – 8) of these data were created by plotting property values versus percent of regional fuel volumes (one plot for each region separately, Regions 1-5), or, in the case of all CONUS data together, plotting property values versus percent of CONUS (total) fuel volume. Additional charts were created to plot property values versus cumulative percent of regional volumes and cumulative percent of total volume. Only some of these charts are presented here; test methods for properties are noted on each chart.

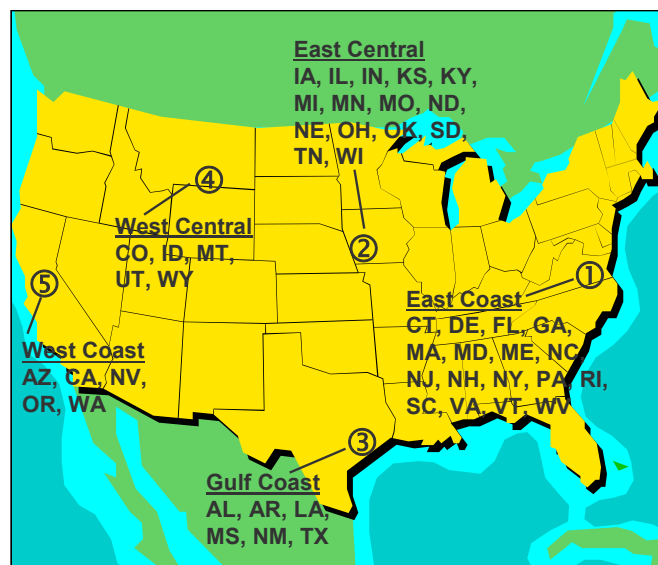


Figure 2. CONUS Defense Regions

Some additional notes about the charts (Figures 3 – 8) will help in understanding the data they represent. The first three charts show density, aromatic content, and sulfur content, while the last three charts show freeze point, viscosity at -20°C , and cetane index. There are some differences between these two groups of charts. For the first group of charts, the property values are plotted versus the cumulative percent of total fuel volume, while as for the last three charts the property values are plotted versus the percent of total volume. Also, fewer data points appear on the first three versus the last three charts, although they still represent data for every individual batch of fuel. This difference is due to the values themselves and the degree to which they were rounded to a certain number of places to the right

¹ Defense Regions 1-5 correspond to Petroleum Administration for Defense Districts (PADDs) I-V.

of the decimal point. Particularly for the analysis and discussions presented herein regarding density and aromatic content, representing density values out to two places and aromatic content values to the nearest integer consolidates data so that conclusions are more

readily apparent. These consolidated density values and aromatic content values are referred to as 'density levels' and 'aromatic content levels' later in this paper, respectively.

Table 1. Summary of JP-8 Data Procured in 2004, Regions 1-5

Property	Volume (MM Gal)		3240.31		1.66		249.1		1193.93		87.22		473.03	
	No. of Batches		2061		96		457		983		152		373	
	Spec Limits		CONUS total		Region 1		Region 2		Region 3		Region 4		Region 5	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Acidity, Total (mg KOH/g)	---	0.015	0.000	0.140	0.001	0.006	0.000	0.014	0.000	0.140	0.000	0.015	0.000	0.019
Aromatics (vol. %)	---	25.0	1.8	25.0	10.1	25.0	4.6	25.0	1.8	25.0	11.1	25.0	9.7	22.8
Sulfur, Mercaptan (wt %)	---	0.002	0	0.100	0.000	0.002	0.000	0.100	0.000	0.002	0.000	0.008	0.000	0.260
Sulfur, Total (mass %)	---	0.30	0	0.39	0.00	0.17*	0.00	0.22*	0.00	0.39*	0.00	0.12	0.00	0.26
Distillation, Initial BP (°C)	---	---	64	201	154	197	130	201	112	187	79	190	64	191
10% recovered (°C)	---	205	142	205	161	204	164	203	142	204	160	205	142	202
20% recovered (°C)	---	---	159	210	172	208	175	206	159	210	166	202	164	208
50% recovered (°C)	Report	Report	173	286	181	221	197	220	178	286	187	218	188	224
90% recovered (°C)	Report	Report	136	283	206	283	214	274	136	256	217	258	219	278
Final Boiling Point (°C)	---	300	221	330	221*	278	243	299	256*	303	231	288	238	330
Residue (vol. %)	---	1.5	0.0	1.6	0.0	1.4	0.0	1.6	0.0	1.6	0.3	1.5	0.2	1.5
Loss (vol. %)	---	1.5	0.0	1.5	0.0	1.0	0.0	1.5	0.0	1.5	0.0	1.5	0.0	1.5
Flash Point (°C)	38	---	38	72	40	98	42	67	38	72	40	61	42	69
Density, API @ 60 °F	37	51	37.2	48.6	38.3	48.6	38.6	45.9	41.4	48.0	44.2	46.3	37.2	43.8
Density, kg/L	0.775	0.840	0.782	0.839	0.786	0.833	0.797	0.832	0.782	0.818	0.787	0.827	0.804	0.839
Freeze Point (°C)	---	-47	-81	-47	-60	-48	-79	-47	-64	-47	-63	-47	-81	-47
Viscosity at -20°C (mm ² /s)	---	8.0	1.2	9.9	2.4	9.7	3.4	10.0	1.2	8.0	3.5	7.5	3.8	7.2
Heat of Combustion (MJ/kg)	42.8	---	41.0	49.5	41.0	49.5	43.0	43.5	42.6	46.3	43.0	44.0	42.2	44.3
Cetane Index (calculated)	Report	Report	29.2	50.9	29.2*	46.4	36.2*	47.5	32.9	50.9	38.1	47.1	30.1	46.7
Hydrogen Content (wt %)	13.4	---	13.0	15.4	13.2	20.0	13.4	14.1	13.4	15.1	13.4	14.3	13	14.1
Smoke Point (mm)	19	---	18	31	19	30	18	29	19	31	20	30	19	24
Thermal Stability, ΔP(mmHg)	---	25	0	26	0	1	0	26	0	9	0	25	0	5
Existent Gum (mg/100 mL)	---	7	0	25	0	4	0	6	0	25	0	7	0	5
Particulates Matter (mg/L)	---	1.0	0	1.8	0.0	0.9	0.0	1.0	0.0	1.0	0.0	1.8	0.0	1.0
Filtration Time (min)	---	15	0	15	1	11	0	15	1	15	5	14	3	15
Micro Separometer (rating)	70	---	40	100	80	99	40	100	70	100	74	100	77	100
Naphthalene (vol. %)	---	3.0	0	4.3	0.5	2.9	0.1	3.0	0.0	4.3	0.0	3	0.1	2.9
Fuel Syst. Icing Inhibitor (vol. %)	0.10	0.15	0	0.15	NR	NR	0	0.15	0	0.15	0.10	0.14	0.11	0.15

*Adjustments to raw data addressing questionable/missing values.

As seen in Figure 3, the weighted mean density of JP-8 procured in CONUS in 2004 is 0.807 kg/L. The associated -2σ value is 0.781 kg/L, while the +2σ value is 0.834 kg/L. The JP-8 specification calls out limits for density of 0.775 kg/L at the lower end and 0.840 kg/L at the upper end.

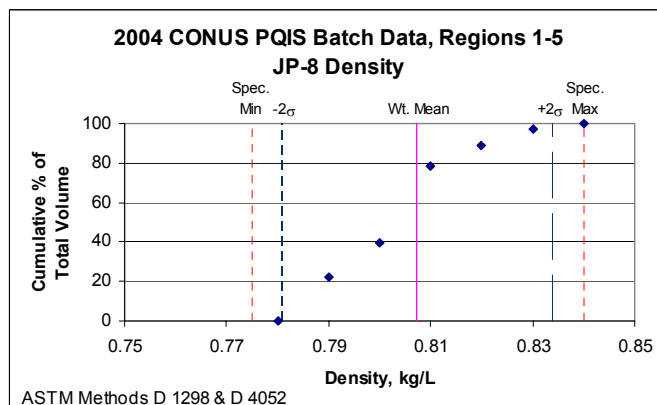


Figure 3. JP-8 Density, CONUS, 2004

Shown in Figure 4 are the statistics regarding aromatic content. The weighted mean aromatic content is 17.7% by volume, and the associated 2σ values are 10.6% by volume on the negative side and 24.8% by volume on the positive side.

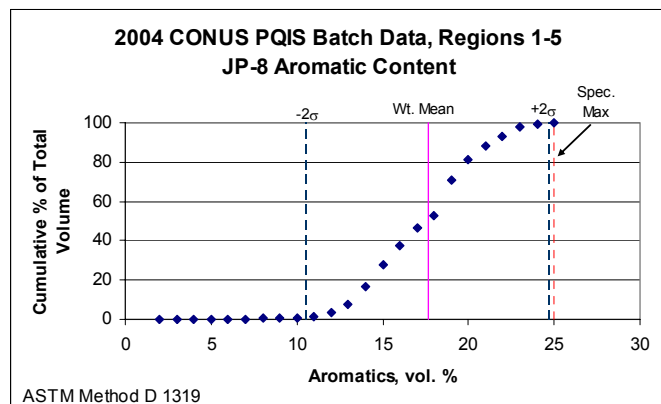


Figure 4. JP-8 Aromatic Content, CONUS, 2004

Regarding sulfur content, the weighted mean is at 0.06% by mass as shown in Figure 5. The 2σ band for this property ranged from a low of -0.04% to a high of 0.16%, by mass. Clearly, a negative content cannot be possible, so the practical lower limit is 0.00%. At least one batch had a reported sulfur content outside of the approved specification maximum of 0.30% by mass.

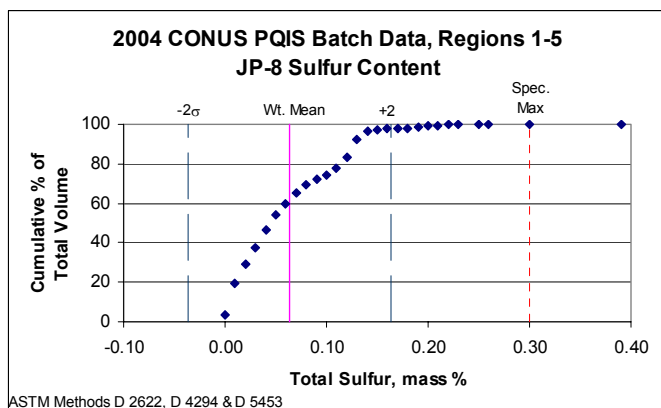


Figure 5. JP-8 Sulfur Content, CONUS, 2004

Freeze point data is shown in Figure 6; however, unlike the previous charts which plotted property values versus cumulative percent total volume, this chart plots property values versus percent total volume. The weighted mean freeze point is -51.5°C. The associated $\pm 2\sigma$ values are -62.7°C and -40.3°C.

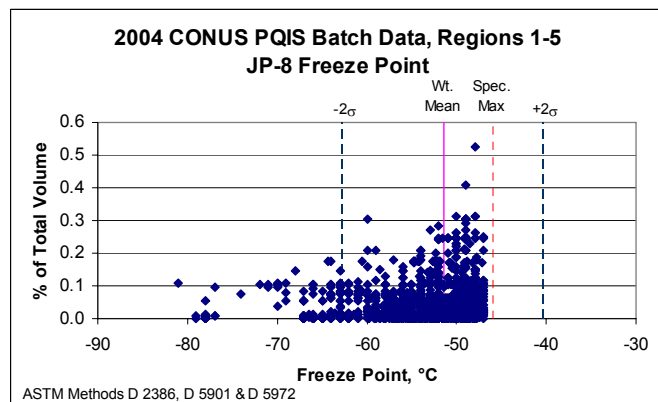


Figure 6. JP-8 Freeze Point, CONUS, 2004

Figure 7 shows viscosity at -20°C. The weighted mean viscosity at -20°C is 4.7 mm²/s. The associated $\pm 2\sigma$ values are 2.8 mm²/s and 6.7 mm²/s. A few batches had reported values outside of the specification maximum of 8.0 mm²/s.

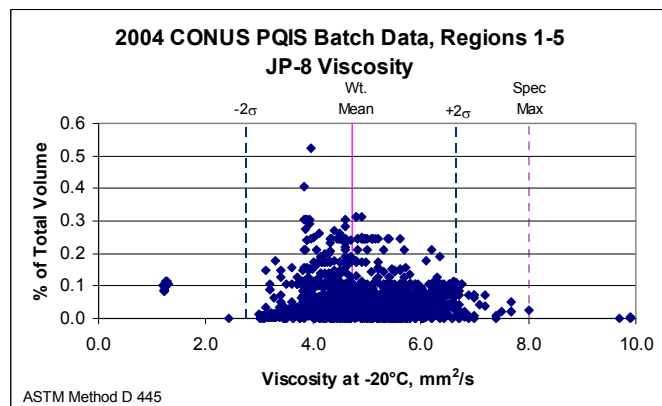


Figure 7. JP-8 Viscosity at -20 °C, CONUS, 2004

Finally, cetane index data is presented in Figure 8. The weighted mean cetane index is 43.9. The associated $\pm 2\sigma$ values are 36.5 and 51.3. The JP-8 specification does not contain any requirement for cetane.

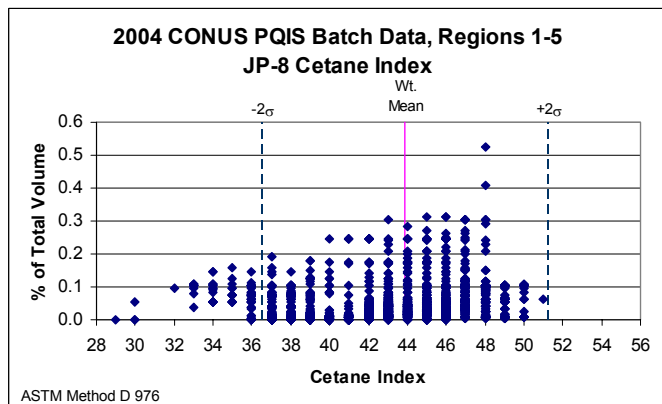


Figure 8. JP-8 Cetane Index, CONUS, 2004

MATHEMATICAL PREDICTION OF S-8/JP-8 (PETROLEUM /FT) BLEND PROPERTIES

The PQIS database of DoD JP-8 procurement provides an opportunity to forecast the effect of blending S-8, an FT IPK fuel meeting the JP-8 specification (with the exception of density) into the JP-8 bulk fuel supply. Mathematical predictions of S-8/JP-8 blend properties can be determined for certain fuel properties that can be calculated linearly based on the fraction of JP-8 or S-8 used to make the blend. Fuel properties mathematically predicted within the scope of this work include density, aromatic content, sulfur content, and cetane index.

A typical S-8 (designated as 'B' in Table A-3), with a density of 0.751 kg/L, zero aromatics and sulfur, and cetane index of 67, was "virtually" blended with JP-8 fuels represented in PQIS. The maximum concentration of S-8, required in an S-8/JP-8 blend to result in blend properties meeting the minimum acceptable density of 0.775 kg/L per the JP-8 specification and the minimum allowable aromatic content of 8.0% by volume for FT/petroleum fuel blends per DEF STAN 91-91 Issue 5, was mathematically calculated.

MINIMUM DENSITY FOR S-8/JP-8 FUEL BLEND

Per the 2004 PQIS database, the minimum and maximum density of JP-8 procured in Regions 1-5 was 0.782 and 0.839 kg/L, respectively. All JP-8 density values in Regions 1-5 can be rounded to density values with two places to the right of the decimal point (i.e., 0.78, 0.79...0.83, and 0.84 kg/L), referred to as 'density levels' (Table A-1 in Appendix). The weighted mean aromatic content, average sulfur content, and average cetane index for each density level were calculated to provide a description of the fuel properties in each density division. Similarly, the percentage of total volume of JP-8 procured was calculated for each density level to understand the overall exposure of the military fleet to the fuel.

The maximum concentration of S-8 that can be blended to reach the minimum density allowable for the S-8/JP-8 blend was calculated using the density of JP-8 at each density level and the density of S-8 (0.751 kg/L). For this example, at the JP-8 density level of 0.80 kg/L, the calculation determines that 51 vol. % of S-8 can be blended to the JP-8 to reach the minimum allowable density of the blend. The calculation was made as follows:

$$51 \text{ vol. \%} = 1 - \frac{(0.775 - 0.751) \frac{\text{kg}}{\text{L}}}{(0.80 - 0.751) \frac{\text{kg}}{\text{L}}} * 100$$

The S-8/JP-8 blend contains a 49 vol. % of JP-8 and a 51 vol. % of S-8. Originally, the JP-8 fuel at this density level (0.80 kg/L) contained a weighted mean aromatic content of 17.1 vol. %. However, when 51 vol. % of zero aromatic fuel is added, the resultant S-8/JP-8 blend aromatic content is diluted to 8.4 vol. %. Similarly, the

average sulfur content and average cetane index in this JP-8 density level change from the 0.036% sulfur by mass and 44.9 cetane index to 0.018% sulfur by mass and 56.2 cetane index when S-8 is added.

The aforementioned calculations were based on maximizing the concentration of S-8 in an S-8/JP-8 blend while still meeting the minimum allowable density for the blend. For comparison purposes, the weighted mean aromatic content for the density level (0.80 kg/L) can be used to determine the maximum concentration of S-8 needed to reach the minimum aromatic content allowable for S-8/JP-8 blends. For example, the weighted mean aromatic content in the 0.80 kg/L density level is 17.1 vol. %; a calculation based on this reveals that it takes 53.2 vol. % of S-8 to reach the 8.0 vol. % aromatic content requirement for blends. As discussed, the maximum concentration of S-8 needed to result in a blend meeting the minimum allowable density (51 vol. % in this example) may not be the same as the maximum concentration of S-8 needed to result in a blend meeting the minimum allowable aromatic content (53.2 vol. % at the 0.80 kg/L JP-8 density level). This minimum allowable density data (Table A-1) is summarized in Figure 9.

From the perspective of JP-8 density levels, the information conveyed by the shaded area and bars in Figure 9 is:

- A shaded area showing the cumulative volume % (left-hand y-axis) of JP-8 density levels (x-axis).
- A bar containing a shaded section plus an unshaded section that when taken in total represent the maximum S-8 concentration in volume % (left-hand y-axis) that is possible at each JP-8 density level (x-axis), to meet the minimum allowable density of 0.775 kg/L per the JP-8 spec.
- A shaded bar representing the maximum S-8 concentration in volume % (left-hand y-axis) that is possible at each JP-8 density level (x-axis), to meet the minimum allowable density of 0.775 kg/L and the minimum allowable aromatic content of 8.0 vol. %.

while the information conveyed by the lines is:

- A dotted line connecting data points designating the weighted mean aromatic content, vol. % (right-hand y-axis) for each JP-8 density level (x-axis).
- A solid line connecting data points designating the calculated aromatic content, vol. % (right-hand y-axis), determined for each JP-8 density level (x-axis), using the weighted mean density for each JP-8 density level and the density of S-8 to reach the minimum allowable density of the S-8/JP-8 blend.
- A dashed horizontal line at a constant 8.0 vol. % aromatic content (right-hand y-axis) designating the minimum allowable aromatic content for FT IPK/conventional jet fuel blends per DEF STAN 91-91 Issue 5.

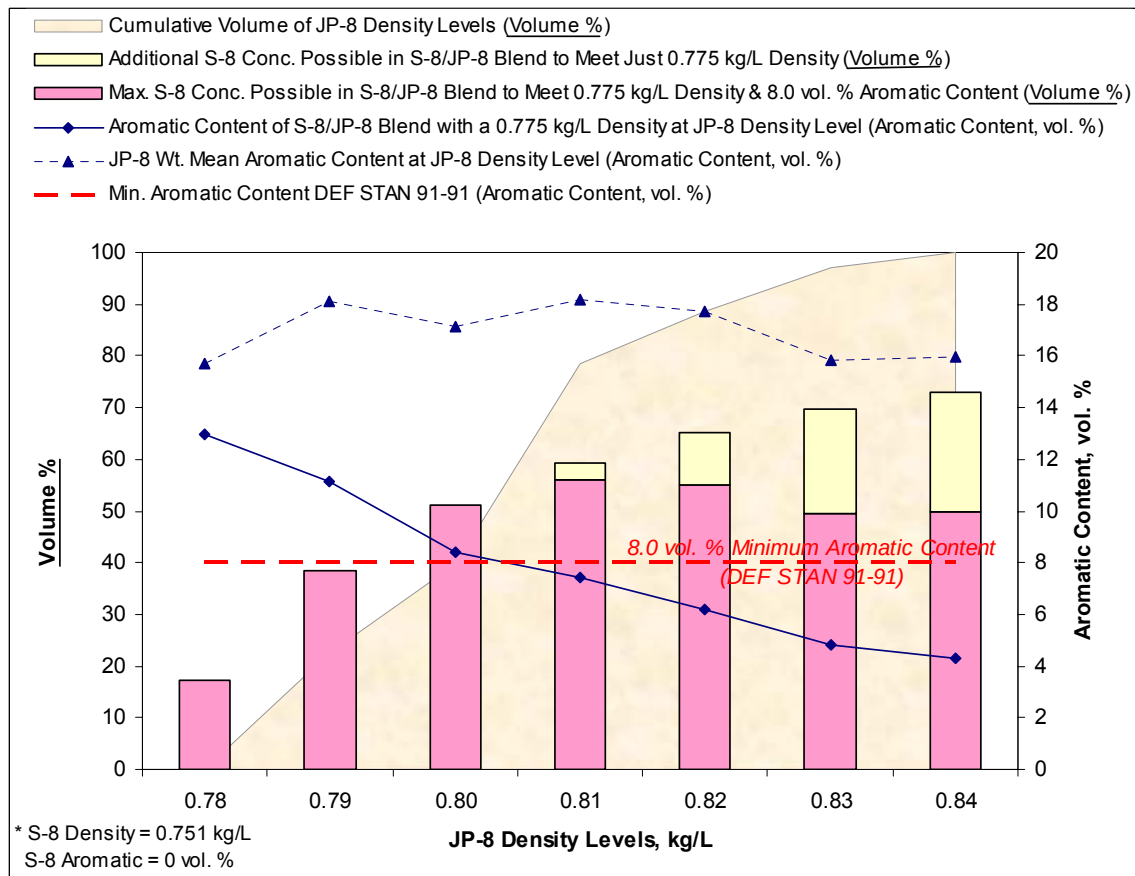


Figure 9. From Perspective of JP-8 Density Levels: Effect of Blending Max. Concentration of S-8 to Achieve Min. Density (JP-8 Spec) and Min. Aromatic Content of 8.0 vol. % (DEF STAN 91-91)

MINIMUM AROMATIC CONTENT FOR S-8/JP-8 FUEL BLEND

Following the DEF STAN 91-91 precedent for minimum aromatic concentration allowable for a conventional and synthetic jet fuel blend, the minimum aromatic content for S-8/JP-8 blend will be assumed to be 8.0 vol. % aromatics for calculation purposes. According to the 2004 PQIS database, the minimum and maximum aromatic content of JP-8 procured in Regions 1-5 (CONUS regions) was 1.8 and 25.0 vol. %, respectively. Again, JP-8 aromatic contents in Regions 1-5 can be rounded to aromatic contents to the nearest integer (i.e., 2, 3, 4...23, 24, and 25 vol. %), referred to as 'aromatic content levels' (Table A-2 in Appendix). The weighted mean density, average sulfur content, and average cetane index for each aromatic content level were calculated to provide a description of the fuel properties for each aromatic content level. Similarly, the percentage of total volume of JP-8 procured was calculated for each aromatic content level to understand the overall exposure of the military fleet to the fuel.

The maximum concentration of S-8 that can be blended to reach the minimum aromatic content allowable for the S-8/JP-8 blend was calculated using the aromatic content for each aromatic content level and the aromatic

content of S-8. For example, for the JP-8 aromatic level with a 14 vol. % aromatic content, 42.9 vol. % of S-8 can be blended into the JP-8 to reach the minimum allowable aromatic content allowed for blends. The calculation was made as follows:

If the JP-8 aromatic volume percent is less than the minimum allowable volume percent of a blend, i.e., less than 8.0 vol. % aromatic content, then S-8 cannot be added to JP-8. If it is greater than 8.0 vol. %, then:

$$42.9 \text{ vol. \%} = 1 - \frac{(8.0 - 0.0) \text{ vol. \% aromatics}}{(14.0 - 0.0) \text{ vol. \% aromatics}} * 100$$

The S-8/JP-8 blend contains 57.1 vol. % of JP-8 and 42.9 vol. % of S-8. Originally, the JP-8 fuel at the 14.0 vol. % aromatic content level contained a weighted mean density of 0.815 kg/L. However, when 42.9 vol. % of S-8, which has a density of 0.751 kg/L, is blended with JP-8 the resultant S-8/JP-8 blend has a density of 0.787 kg/L. Similarly, the average sulfur content and average cetane index in this JP-8 aromatic content level changed from 0.051% sulfur by mass and 43 cetane index to 0.029% sulfur by mass and 53.3 cetane index when S-8 is added.

The aforementioned calculations were based on maximizing the concentration of S-8 in a S-8/JP-8 blend by obtaining the minimum allowable aromatic content. For comparison purposes, the weighted mean density for the aromatic content level can be used to determine the maximum concentration of S-8 needed to reach the minimum density content allowable for the S-8/JP-8 blend. For example, the weighted mean density for the 14 vol. % aromatic level is 0.815 kg/L; a calculation based on this determines that it takes 62.4 vol. % of S-8 to reach the minimum allowable density of 0.775 kg/L allowed for the blend. Again, the maximum volume percent of S-8 determined by calculations to reach the minimum density allowed for blends may not correspond with the maximum volume percent of S-8 determined by calculations to reach the minimum allowed aromatic content for blends. This minimum allowable aromatic content data (Table A-2) is summarized in Figure 10.

From the perspective of JP-8 aromatic content levels, information conveyed by the shaded area and bars in Figure 10 is:

- A shaded area showing the cumulative volume % (left-hand y-axis) of JP-8 aromatic content levels (x-axis).
- A bar containing a shaded section, and also un-shaded section, that when taken in total

represent the maximum S-8 concentration in volume % (left-hand y-axis) that is possible at each JP-8 aromatic content level (x-axis), to meet the minimum allowable aromatic content of 8.0 vol. %.

- A shaded bar representing the maximum S-8 concentration in volume % (left-hand y-axis) that is possible at each JP-8 aromatic content level (x-axis), to meet the minimum allowable aromatic content level of 8.0 vol. % and the minimum allowable density of 0.775 kg/L.

while the information conveyed by the lines is:

- A dotted line connecting data points designating the weighted mean density, kg/L (right-hand y-axis) for each JP-8 aromatic content level (x-axis).
- A solid line connecting data points designating the calculated density, kg/L (right-hand y-axis), determined for each JP-8 aromatic content level (x-axis), using the weighted mean aromatic content for each JP-8 aromatic content level and the aromatic content of S-8 to reach the minimum allowable aromatic content of the S-8/JP-8 blend.
- A dashed horizontal line at a constant 0.775 kg/L density (right-hand y-axis) designating the minimum allowable density for per the JP-8 specification.

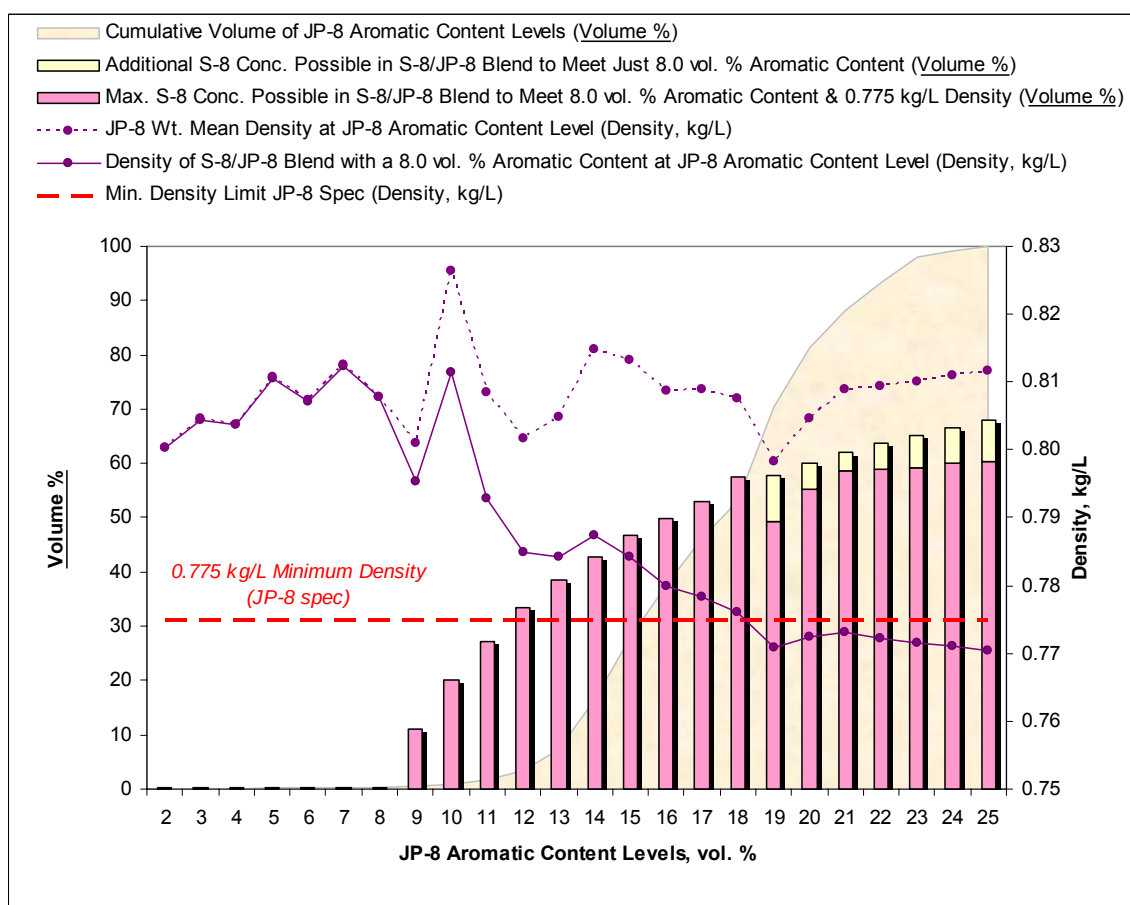


Figure 10. From Perspective of JP-8 Aromatic Content Levels: Effect of Blending Max. Concentration of S-8 to Achieve Min. Density (JP-8 Spec) and Min. Aromatic Content of 8.0 vol. % (DEF STAN 91-91)

PROPERTIES OF REAL S-8/JP-8 BLENDS

Real S-8/JP-8 fuel blends were prepared and property tests were performed. A complete list of property test results, before and after blending, is provided in Tables A-3 (fuels) and A-4 (blended fuels) of the Appendix. At the bottom of each of these tables is a separate section showing the change in property values from those of each of the six test fuel to those of the fuel blend with the addition of the S-8.

Five unidentified JP-8 fuels and one unidentified S-8 fuel were supplied by Air Force Research Laboratory (AFRL/PRTG) to Syntroleum Corporation for blends testing. Syntroleum blended each of the six fuel samples provided by AFRL with two S-8 blend stocks at 25% and 50%. The S-8 blend stocks had similar density, aromatic, sulfur, and viscosity properties, but contrasting flash point, distillation, and freezing point. The five JP-8 fuels had densities ranging from 0.794 to 0.810 kg/L; about 78% of the JP-8 fuels in the PQIS database fall into this density range. Their aromatic content ranged from 14.0 to 19.7 vol. %. This range accounts for about 74% of the JP-8 in the PQIS database. The unidentified S-8 fuel provided by AFRL was submitted as a control fuel. The S-8 sample contained 0 vol. % aromatics and had a density of 0.753 kg/L.

DENSITY AND AROMATIC TRENDS

Of the six fuel samples provided by AFRL, five of the fuels were greater than the minimum allowable density per JP-8 specification and minimum allowable aromatic content of FT/petroleum fuel blends per DEF STAN 91-91; the exception being the unidentified S-8 sample. The six unidentified samples were blended with 25% and 50% (by volume) S-8 using two blend stocks producing 24 total blended samples. Thus, 20 of the 24 samples were S-8/JP-8 blends and four were S-8/S-8 blends. Of the 20 S-8/JP-8 blends, none of the samples fell below the minimum density requirement or the minimum allowable aromatic content when 25 vol. % of S-8 was added to the JP-8 samples. However, when 50 vol. % of S-8 was added to the JP-8 samples, five of the 20 fuels fell below the minimum density requirement (actually measured density; six fell below when density was mathematically predicted) and two of the 20 fell below the minimum aromatic content requirement. The density (measured and calculated) and aromatic content (calculated) of the neat fuels (all values measured) and the fuel blends, are plotted in Figures 11 and 12.

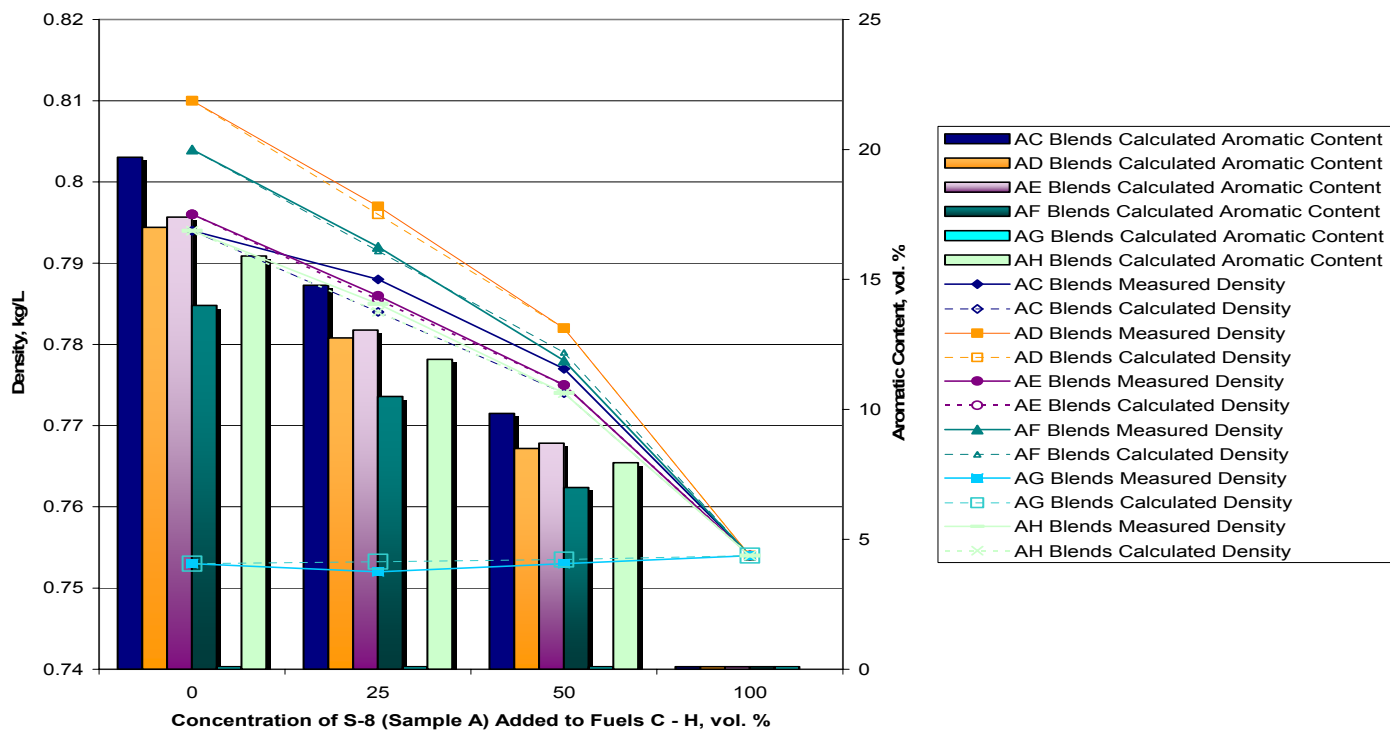


Figure 11. Real S-8/JP-8 Fuel Blend: Density (Measured vs. Predicted) and Aromatics Effect When Less Volatile S-8 Blend Stock is Added to JP-8

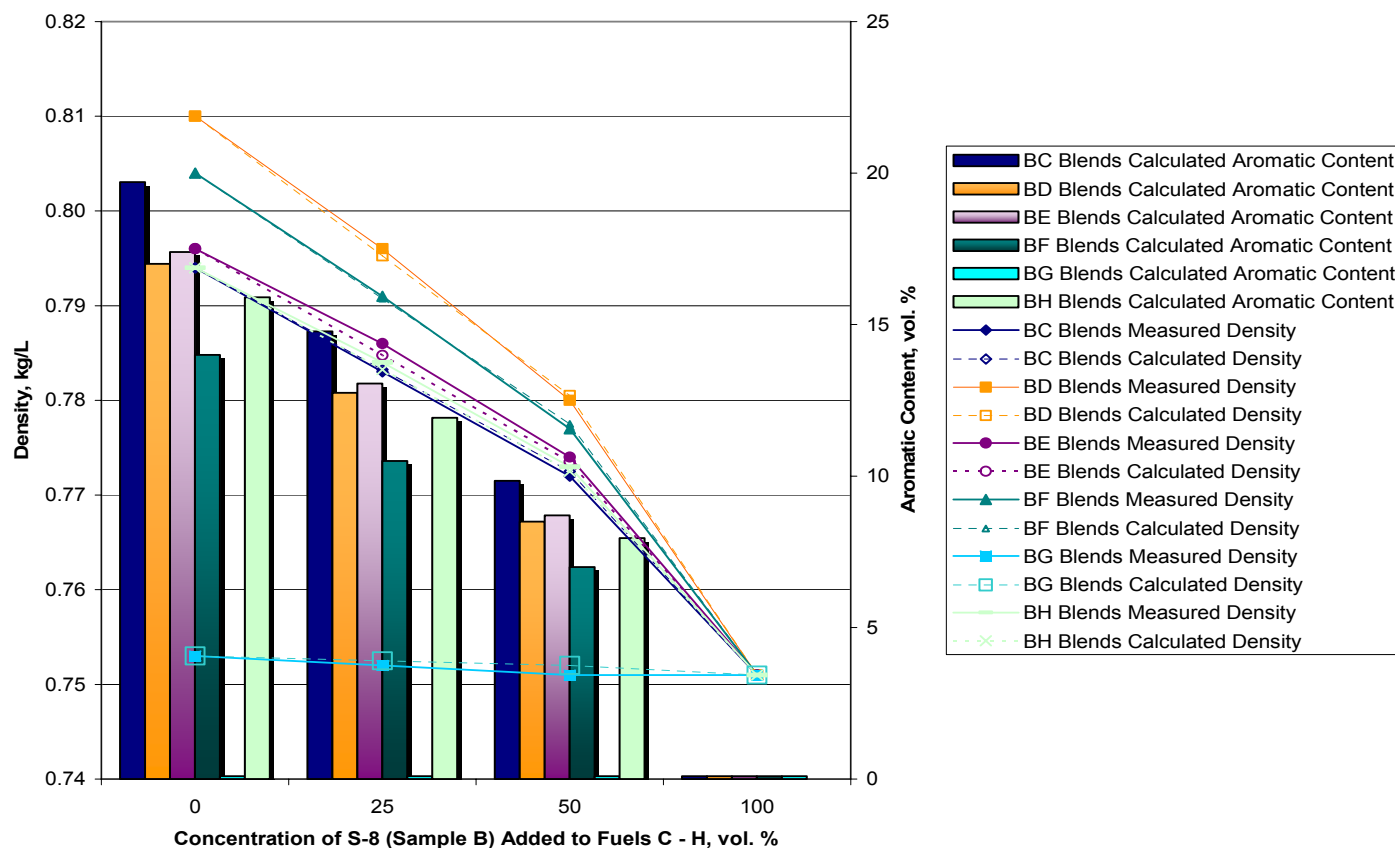


Figure 12. Real S-8/JP-8 Fuel Blend: Density (Measured vs. Predicted) and Aromatics Effect When More Volatile S-8 Blend Stock is Added to JP-8 Conclusion

DENSITY: MEASURED VS. PREDICTED

S-8 blend stocks possess lower densities, 0.751 and 0.754 kg/L, than what is allowed for JP-8. The five JP-8 fuels ranged in density values from 0.794 to 0.810 kg/L. Density measurements were performed on the S-8/JP-8 and S-8/S-8 fuel blends according to ASTM D 4052.

Additionally, a mathematical prediction of density was performed on these fuel blends (Table A-4 'Math' values). Both methods show a directional trend that lowers fuel density when the concentration of S-8 is increased. The average standard deviation between samples calculated by ASTM D 4052 and mathematical prediction was 5.89e-4 kg/L. The standard deviation suggests the mathematical prediction, 'virtual' blending, is representative of real fuel blend densities.

AROMATIC AND SULFUR CONTENTS

Aromatic content of S-8/JP-8 fuel blends was not actually measured; however, a mathematical calculation was used to predict the resultant aromatic content of the blend. The 'virtual' blending, as described in a previous section, blended JP-8 fuels ranging in aromatic content from 14.0 to 19.7 vol. %, with S-8 which contains no

aromatic compounds. The mathematical prediction reveals a directional trend that decreases blend aromatic content as the concentration of S-8 is increased.

Sulfur content was also predicted for the 'virtual' blends. Similar to the aromatic content, the concentration of sulfur decreases as the concentration of S-8, which contains zero sulfur, is increased.

VOLATILITY

The two S-8 blend stocks had flash points of 54°C and 48°C. These fuels were blended into JP-8 fuels with flash points ranging from 48 to 53°C. The higher volatility S-8 displayed greater initial, middle, and final boiling points than the lower volatility S-8, which possessed higher boiling points than the JP-8.

As expected, the higher flash point S-8 blend stock raised the flash point of JP-8 that possessed a lower flash point, and had little or no effect on the JP-8 fuels with similar flash points. In contrast, the lower flash point S-8 decreased the flash point of JP-8 that possessed a greater flash point.

The initial, middle, and final boiling points were also improved when the higher volatility S-8 blend stock was blended into JP-8. The lower volatility S-8 slightly decreased the initial boiling point of JP-8 in some cases, but improved its middle and final boiling points.

Both of these trends suggest that volatility changes directionally in fuel blends and is independent of the fuel's origin (conventional or FT).

CETANE INDEX: MEASURED VS. PREDICTED

Cetane index (CI) was calculated using ASTM D 976 and mathematically predicted using the previously described ratio-based method. The average standard deviation between samples calculated by ASTM D 976 and mathematical prediction was 0.50 CI units. The standard deviation suggests the mathematical prediction, 'virtual' blending, is representative of real fuel blend Cetane Index. Both cetane index methods showed cetane index of the blend was improved when S-8 was added. The extent of improvement was directly related to the magnitude of the blend ratio. As the concentration of S-8 is increased, the cetane number proportionally increases. Both S-8 blend stocks possess greater cetane index, 70 and 67 respectively, than the JP-8, which ranged from 43 to 48.

FREEZE POINT

The two S-8 blend stocks had freezing points of -52 and -57°C. The five JP-8 freezing points ranged from -44 to -57°C. When S-8 was blended with JP-8 that possessed a higher freezing point, the cold temperature properties of the fuel blend improved. When S-8 is blended with lower freezing points, cold temperature properties decreased. These trends suggest that a freezing point change directionally in fuel blend and is independent of the fuel's origin.

VISCOSITY

S-8 blend stocks had viscosities at 40°C of 1.3 and 1.4 mm²/s according to ASTM D 445. JP-8 fuel tested ranged from 1.3 to 1.5 mm²/s. The S-8/JP-8 fuel blends changed modestly when S-8 was added to JP-8. When low viscosity S-8 is blended to a higher viscosity JP-8, the resultant blend possesses a slightly lower viscosity than JP-8 had originally. These trends suggest that a viscosity changes directionally in fuel blends and is independent of the fuel's origin.

S-8/JP-8 FUEL BLENDS VERSUS JP-8 PROCURED IN CONUS DURING 2004

For the properties of the real S-8/JP-8 blends tested (Table A-4), the test results generally fit within the property 'box' as defined by the PQIS data for JP-8 procured in CONUS during 2004. There were some exceptions, including but not exclusively, the following:

- Nearly all of the S-8/JP-8 blend densities were less than the minimum JP-8 density of batches procured in CONUS during 2004 when the concentration of S-8 was at 50% of the blend; however, at a concentration of 25% S-8, all blend densities were higher than that minimum. At 50% concentration of S-8 in the blend, some of the densities were equal to or higher than the 0.775 kg/L minimum allowable density per the JP-8 specification, while others were less than 0.775 kg/L. At 25% concentration of S-8 in the blend, all densities were higher than 0.775 kg/L.
- In each instance of blending a 25% concentration of S-8 (both 'A' and 'B' samples) with the JP-8 Fuel 'F', the freeze point of the blend came in at -46°C which is 1°C higher than the maximum freeze point found for JP-8 batches procured in CONUS during 2004 and also 1°C higher than allowed for JP-8 in the specification (however, a -46°C freeze point does meet the JP-5 specification). As an explanation of this, Fuel 'F' had the highest freeze point, -44°C, of all five JP-8 samples used in the blends study; adding S-8 fuel to this fuel lowered the freeze point by 2°C.
- In each instance of blending a 50% concentration of S-8 (both 'A' and 'B' samples) with all JP-8 fuel samples, the cetane index of the blends came in higher than the maximum cetane index of 51 found for any batch of JP-8 fuel procured in CONUS during 2004. For these blends at 50% concentration of S-8, the cetane indexes ranged from 53 to 59. Furthermore, several of the cetane indexes of the blends containing just 25% concentration of S-8 improved enough that they were also higher than the 51 cetane index that was the maximum seen all JP-8 fuel batches in 2004.

CONCLUSION

Clean, very low sulfur fuels produced from United States domestic resources are of interest to the U.S. Military to enhance supply security and reliability versus increasing reliance on fuels manufactured from a growing percentage of imported oil and/or imports of refined petroleum products. Synthetic Fischer-Tropsch (FT) fuel can be produced from a variety of non-petroleum feed stocks, such as natural gas, coal, petroleum coke, or even biomass and various wastes.

Blending of Fischer-Tropsch Iso-Paraffinic Kerosene (FT IPK) and petroleum-derived JP-8 is the basis of a strategy by which the U.S. Military could begin to use FT fuel in the near-term until:

1. large-scale FT plants are built and are producing enough FT fuel to sustain its use as a neat (100%) fuel, and
2. the seal swelling/shrinkage challenges to the introduction and use of a neat FT IPK fuel interchangeably with JP-8 in the existing DoD fleet are fully addressed and resolved.

The blending requirements (of a minimum of 8.0 vol. % aromatic hydrocarbons and a maximum of 50% by volume FT IPK) established in DEF STAN 91-91 Issue 5 for the approval of Sasol FT IPK in conventional petroleum jet fuel blends, provides a strong precedent for establishing similar requirements for the military's use of FT IPK in blends with JP-8/JP-5/Jet A-1. As is already the case for highly hydroprocessed aviation turbine fuels or blend stocks per both U.S. Military specifications (JP-8 and JP-5) and DEF STAN 91-91 Issue 5, the use of antioxidant would be required in FT IPK. Similarly, the use of a lubricity improver additive should be required in FT IPK for blends.

The results of research and testing presented in this paper have shown that blends of DoD-procured FT IPK (S-8) and JP-8 are a viable approach for use now by the military in the Continental United States (CONUS). This has been shown by:

- Examining and presenting the property 'box' of JP-8 fuel (CONUS Defense Regions 1-5) using the Defense Energy Support Center "Petroleum Quality Information System" (PQIS) database for JP-8 fuel procured during 2004.
- Employing key criteria for creating blends of FT IPK and JP-8:
 1. that meet the minimum acceptable density of 0.775 kg/L in the current JP-8 specification, and
 2. that meet the minimum acceptable aromatic content of 8.0 vol. % as published in DEF STAN 91-91 Issue 5.
 3. to develop and present data for 'virtual' blends of FT IPK and JP-8 (CONUS Defense Regions 1-5) illustrating that significant volumes of FT IPK could be used in blends with JP-8 while still meeting the key blending criteria.
- Presenting measured properties of real blends of FT IPK and JP-8, along with a few calculated properties, showing that:
 1. good agreement between property values for those properties which were both calculated and measured,
 2. properties of the real blends support conclusions developed with the 'virtual' blends, and
 3. properties of these blends fit within the property 'box' for JP-8 developed from PQIS 2004 data.

One of the next critical steps in moving forward with a strategy for the U.S. Military to begin to use blends of FT IPK and JP-8 fuels in CONUS is with ground equipment demonstrations.

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APPENDIX

Table A-1. Data for 'Virtual Blends' at Each JP-8 Density Level

<i>JP-8 DENSITY LEVEL:</i>	<i>0.78</i>	<i>0.79</i>	<i>0.80</i>	<i>0.81</i>	<i>0.82</i>	<i>0.83</i>	<i>0.84</i>
Avg. Aromatic Content (vol. %)	15.6	16.5	16.1	17.2	17.0	17.0	15.8
Wt. Mean Aromatic Content (vol. %)	15.7	18.1	17.1	18.2	17.7	15.8	15.9
Avg. Sulfur Content (mass %)	0.012	0.050	0.036	0.066	0.066	0.037	0.015
Cetane Index	42.1	44.9	44.9	44.1	40.5	38.1	35.9
Cumulative % of Total Volume	0.017	22.4	39.8	78.6	88.7	97.0	100.0
% of Total Volume	0.017	22.4	17.4	38.9	10.1	8.2	3.0
Concentration of S-8 Needed to Reach Minimum Allowable Density (Volume %)	17.2	38.5	51.0	59.3	65.2	69.6	73.0
Concentration of S-8 Blended Using Avg. Aromatic Content to Reach Min. Aromatic Content (Volume %)	48.7	51.6	50.4	53.5	53.0	52.9	49.5
Concentration of S-8 Blended Using Wt. Mean Aromatic Content to Reach Minimum Aromatic Content (Volume %)	49.0	55.9	53.2	56.0	54.9	49.4	49.8
Aromatic Content of Blend Using Avg. Aromatic Content and Concentration of S-8 Needed to Reach Min. Density (vol. %)	12.9	10.2	7.9	7.0	5.9	5.2	4.3
Aromatic Content of Blend Using Wt. Mean Aromatic Content and Concentration of S-8 Needed to Reach Min. Density (vol. %)	13.0	11.2	8.4	7.4	6.2	4.8	4.3
Sulfur Content of Blend Using Avg. Sulfur Content and Concentration of S-8 Needed to Reach Min. Density (mass %)	0.010	0.030	0.018	0.027	0.023	0.011	0.004
Cetane Index of Blend Using Concentration of S-8 Needed to Reach Min. Density (CI Units)	46.4	53.4	56.2	57.7	57.8	58.2	58.6

Table A-2. Data for 'Virtual' Blends at Each JP-8 Aromatic Content Level (1 of 3 pages)

JP-8 AROMATIC LEVEL:	2	3	4	5	6	7	8	9
Avg. Density (kg/L)	0.800	0.804	0.804	0.812	0.807	0.815	0.811	0.808
Wt. Mean Density (kg/L)	0.800	0.805	0.804	0.811	0.807	0.812	0.808	0.801
Avg. Sulfur Content (mass %)	0.000	0.001	0.002	0.002	0.001	0.004	0.023	0.006
Cetane Index	45.3	42.9	42.1	41.6	41.3	40.0	41.0	41.1
Cumulative % of Total Volume	0.01	0.04	0.12	0.17	0.23	0.28	0.38	0.57
% of Total Volume	0.01	0.03	0.08	0.05	0.05	0.05	0.10	0.19
Concentration of S-8 Blended to Reach Minimum Aromatics (Volume %)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.1
Concentration of S-8 Blended Using Avg. Density to Reach Minimum Density (Volume %)	51.4	55.1	54.5	60.4	57.4	62.4	59.7	57.9
Concentration of S-8 Blended Using Wt. Mean Density to Reach Minimum Density (Volume %)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	51.9
Density of Blend Using Avg. Density and Concentration of S-8 Needed to Reach Min. Aromatic Vol. % (kg/L)	0.800	0.804	0.804	0.812	0.807	0.815	0.810	0.802
Density of Blend Using Wt. Mean Density and Concentration of S-8 Needed to Reach Min. Aromatic Vol. % (kg/L)	0.800	0.804	0.804	0.811	0.807	0.812	0.808	0.795
Sulfur Content of Blend Using Avg. Sulfur Content and Concentration of S-8 Needed to Reach Min. Aromatic Vol. % (mass %)	0.000	0.001	0.002	0.002	0.001	0.004	0.023	0.005
Cetane Index of Blend Using Avg. Cetane Index and Concentration of S-8 Needed to Reach Min. Aromatic Vol. % (CI Units)	45.3	43.0	42.1	41.6	41.4	40.1	41.0	43.9

Table A-2. Data for 'Virtual' Blends at Each JP-8 Aromatic Content Levels (2 of 3 pages)

JP-8 AROMATIC LEVEL:	10	11	12	13	14	15	16	17
Avg. Density (kg/L)	0.820	0.810	0.802	0.802	0.814	0.812	0.804	0.802
Wt. Mean Density (kg/L)	0.826	0.808	0.802	0.805	0.815	0.813	0.809	0.809
Avg. Sulfur Content (mass %)	0.012	0.012	0.032	0.031	0.051	0.067	0.049	0.039
Cetane Index	38.7	43.0	44.3	45.0	43.0	43.2	42.9	41.8
Cumulative % of Total Volume	0.98	1.64	3.39	7.41	16.51	27.69	37.63	46.31
% of Total Volume	0.41	0.66	1.75	4.03	9.10	11.18	9.94	8.68
Concentration of S-8 Blended to Reach Minimum Aromatics (Volume %)	20.0	27.3	33.3	38.5	42.9	46.7	50.0	52.9
Concentration of S-8 Blended Using Avg. Density to Reach Minimum Density (Volume %)	65.3	59.0	52.9	53.3	61.9	60.5	54.6	53.0
Concentration of S-8 Blended Using Wt. Mean Density to Reach Minimum Density (Volume %)	68.2	58.2	52.7	55.4	62.4	61.4	58.4	58.5
Density of Blend Using Avg. Density and Concentration of S-8 Needed to Reach Min. Aromatic Vol. % (kg/L)	0.806	0.794	0.785	0.783	0.787	0.783	0.777	0.775
Density of Blend Using Wt. Mean Density and Concentration of S-8 Needed to Reach Min. Aromatic Vol. % (kg/L)	0.811	0.793	0.785	0.784	0.787	0.784	0.780	0.778
Sulfur Content of Blend Using Avg. Sulfur Content and Concentration of S-8 Needed to Reach Min. Aromatic Vol. % (mass %)	0.010	0.008	0.021	0.019	0.029	0.036	0.024	0.018
Cetane Index of Blend Using Avg. Cetane Index of JP-8 and Concentration of S-8 Needed to Reach Min. Aromatic Vol. % (CI Units)	44.4	49.5	51.9	53.4	53.3	54.3	55.0	55.1

Table A-2. Data for 'Virtual' Blends at Each JP-8 Aromatic Content Level (3 of 3 pages)

JP-8 AROMATIC LEVEL:	18	19	20	21	22	23	24	25
Avg. Density (kg/L)	0.807	0.803	0.808	0.814	0.812	0.813	0.817	0.814
Wt. Mean Density (kg/L)	0.807	0.798	0.805	0.809	0.809	0.810	0.811	0.812
Avg. Sulfur Content (mass %)	0.065	0.097	0.073	0.054	0.040	0.038	0.040	0.035
Cetane Index	42.3	44.7	43.6	42.7	42.3	42.3	40.1	42.2
Cumulative % of Total Volume	52.92	70.54	81.33	88.14	93.07	98.00	99.11	100.00
% of Total Volume	6.61	17.62	10.80	6.81	4.92	4.93	1.11	0.89
Concentration of S-8 Blended to Reach Minimum Aromatics (Volume %)	55.6	57.9	60.0	61.9	63.6	65.2	66.7	68.0
Concentration of S-8 Blended Using Avg. Density to Reach Minimum Density (Volume %)	57.5	53.8	58.2	61.8	60.9	61.5	63.4	62.1
Concentration of S-8 Blended Using Wt. Mean Density Reach Minimum Density (Volume %)	57.5	49.2	55.3	58.5	58.8	59.3	60.0	60.5
Density of Blend Using Avg. Density and Concentration of S-8 Needed to Reach Min. Aromatic Vol. % (kg/L)	0.776	0.773	0.774	0.775	0.773	0.773	0.773	0.771
Density of Blend Using Wt. Mean Density and Concentration of S-8 Needed to Reach Min. Aromatic Vol. % (kg/L)	0.776	0.771	0.772	0.773	0.772	0.772	0.771	0.770
Sulfur Content of Blend Using Avg. Sulfur Content and Concentration of S-8 Needed to Reach Min. Aromatic Vol. % (mass %)	0.029	0.041	0.029	0.021	0.014	0.013	0.013	0.011
Cetane Index of Blend Using Avg. Cetane Index and Concentration of S-8 Needed to Reach Min. Aromatic Vol. % (CI Units)	56.0	57.6	57.6	57.7	58.0	58.4	58.0	59.1

Table A-3. Properties of S-8 and JP-8 Fuels Used in Real S-8/JP-8 Blends

		S-8		JP-8					
Fuel Type		S-8	S-8	JP-8	JP-8	JP-8	JP-8	S-8	JP-8
Designation		A	B	C	D	E	F	G	H
Property, Units	Method								
Flash Pt., °C	D 93	54	48	48	51	48	53	---	---
Density, kg/L	D 4052	0.754	0.751	0.794	0.810	0.796	0.804	0.753	0.794
Aromatics, vol. %	D 1319	<1	<1	19.7	17.0	17.4	14.0	0.0	15.9
Sulfur, mass %	D 2622	<0.002	<0.002	0.08	0.14	0.08	0.12	0.00	0.07
Net Heat of Combustion				18604	18541	18594	---	18965	18625
Freeze Pt., °C	D 5972	-52	-57	-49	-57	-50	-44	-57	-50
Visc., 40°C	D 445	1.4	1.3	1.3	1.4	1.4	1.4	1.5	1.5
SimDist., °C	D 2887								
IBP		131	116	109	105	102	109	116	104
5%		143	139	149	147	143	151	139	142
10%		156	143	159	163	154	164	144	154
20%		174	164	174	180	168	181	166	167
30%		188	178	182	192	179	196	178	178
40%		201	189	193	201	190	204	190	189
50%		216	204	202	209	201	217	204	198
60%		227	217	213	218	214	226	217	211
70%		239	230	223	226	226	237	230	222
80%		255	246	236	236	237	249	246	237
90%		272	265	251	249	254	262	265	254
95%		282	280	259	261	266	272	279	265
FBP		332	316	282	303	289	301	310	288
Cetane Index	D 976	70	67	47	43	46	48	66	46

Table A-4. Properties of Real S-8/JP-8 Blends for 'A' Blends (page 1 of 2)

Blend Ratios S-8:JP-8		'A' Blends											
		25:75	50:50	25:75	50:50	25:75	50:50	25:75	50:50	25:75	50:50	25:75	50:50
Designation		AC25	AC50	AD25	AD50	AE25	AE50	AF25	AF50	AG25	AG50	AH25	AH50
Property, Units	Method												
Flash Pt., °C	D 93	49	51	51	53	49	51	54	53	46	49	49	51
Density, kg/L	D 4052	0.788	0.777	0.797	0.782	0.786	0.775	0.792	0.778	0.752	0.753	0.785	0.774
Density, kg/L	Math	0.784	0.774	0.796	0.782	0.786	0.775	0.792	0.779	0.753	0.754	0.784	0.774
Aromatics, vol. %	Math	14.8	9.9	12.8	8.5	13.1	8.7	10.5	7.0	0.0	0.0	11.9	8.0
Sulfur, mass %	Math	0.06	0.04	0.11	0.07	0.06	0.04	0.09	0.06	0.00	0.00	0.05	0.04
Freeze Pt., °C	D 5972	-49	-50	-56	-54	-50	-51	-46	-47	-56	-55	-50	-51
Visc., 40°C	D 445	1.3	1.4	1.4	1.5	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.3
SimDist., °C	D 2887												
IBP		113	116	111	116	107	113	113	117	116	118	109	114
5%		146	143	145	143	142	142	149	145	141	141	142	142
10%		158	158	161	159	155	155	162	160	149	151	154	154
20%		173	174	178	176	168	169	179	176	166	167	167	168
30%		183	186	191	189	180	182	194	191	180	183	179	182
40%		196	197	201	201	193	196	203	202	196	197	191	196
50%		204	208	210	211	204	208	216	216	207	209	202	206
60%		217	218	218	221	217	219	226	227	219	221	215	217
70%		227	231	228	231	229	232	236	237	234	236	227	231
80%		239	246	238	245	243	247	249	251	248	251	240	246
90%		255	262	255	263	259	264	264	267	267	269	257	263
95%		267	273	271	277	272	275	274	278	281	281	271	274
FBP		293	294	321	341	324	297	302	300	321	314	293	294
Cetane Index	D 976	50	56	49	55	51	57	53	59	68	68	51	57
Cetane Index	Math	52	58	50	56	52	58	54	59	67	68	52	58

Designation		'A' Blends Change (Δ): Δ = Blend Fuel Property - JP-8 Fuel Property											
		Δ AC25	Δ AC50	Δ AD25	Δ AD50	Δ AE25	Δ AE50	Δ AF25	Δ AF50	Δ AG25	Δ AG50	Δ AH25	Δ AH50
Property, Units	Method												
Flash Pt., °C	D 93	1	3	0	2	1	3	1	0	n/a	n/a	n/a	n/a
Density, kg/L	D 4052	-0.006	-0.017	-0.013	-0.028	-0.010	-0.021	-0.012	-0.026	-0.001	0.000	-0.009	-0.020
Aromatics, vol. %	D 1319	-5	-10	-4	-9	-4	-9	-4	-7	0	0	-4	-8
Sulfur, mass %	D 2622	-0.02	-0.04	-0.04	-0.07	-0.02	-0.04	-0.03	-0.06	0.00	0.00	-0.02	-0.04
Freeze Pt., °C	D 5972	0	-2	2	3	-1	-1	-2	-3	1	3	-1	-1
Visc., 40°C	D 445	-0.02	0.08	-0.01	0.08	-0.05	-0.01	0.01	0.00	-0.06	-0.06	-0.06	-0.13
SimDist., °C	D 2887	0	0	0	0	0	0	0	0	0	0	0	0
IBP		3	7	6	11	5	11	4	7	0	2	6	11
5%		-4	-6	-2	-3	-1	-1	-2	-6	1	2	0	0
10%		-1	-2	-2	-3	1	1	-2	-4	6	7	0	1
20%		-1	0	-2	-4	0	1	-2	-5	0	1	0	1
30%		1	3	-1	-2	1	3	-2	-4	2	5	2	4
40%		2	3	0	0	3	6	-1	-2	6	7	2	7
50%		2	6	1	1	3	7	-1	-1	3	5	3	8
60%		3	5	1	3	3	5	0	1	2	4	4	7
70%		4	8	2	5	3	7	-1	1	4	6	4	8
80%		3	9	3	9	6	9	1	2	2	4	3	9
90%		4	11	6	14	4	9	2	4	2	4	3	9
95%		8	14	9	16	6	9	2	6	2	2	6	9
FBP		11	13	18	38	34	7	2	-1	11	4	6	7
Cetane Index	D 976	3	10	5	12	5	11	5	10	2	2	5	12

Table A-4. Properties of S-8/JP-8 Blends for 'B' Blends (page 2 of 2)

Blend Ratios S-8:JP-8		'B' Blends											
		25:75	50:50	25:75	50:50	25:75	50:50	25:75	50:50	25:75	50:50	25:75	50:50
Designation		BC25	BC50	BD25	BD50	BE25	BE50	BF25	BF50	BG25	BG50	BH25	BH50
Property, Units	Method												
Flash Pt., °C	D 93	56	49	49	49	47	46	49	49	43	44	?	?
Density, kg/L	D 4052	0.783	0.772	0.796	0.780	0.786	0.774	0.791	0.777	0.752	0.751	0.784	0.773
Density, kg/L	Math	0.783	0.773	0.795	0.781	0.785	0.774	0.791	0.778	0.753	0.752	0.783	0.773
Aromatics, vol. %	Math	14.8	9.9	12.8	8.5	13.1	8.7	10.5	7.0	0.0	0.0	11.9	8.0
Sulfur, mass %	Math	0.06	0.04	0.11	0.07	0.06	0.04	0.09	0.06	0.00	0.00	0.05	0.04
Freeze Pt., °C	D 5972	-50	-52	-58	-58	-52	-53	-46	-49	-53	-58	-51	-53
Visc., 40°C	D 445	1.3	1.4	1.4	1.4	1.4	1.3	1.4	1.5	1.4	1.4	1.4	1.3
SimDist., °C	D 2887												
IBP		112	114	111	114	107	113	113	114	115	115	109	113
5%		142	141	142	141	141	140	143	141	139	139	141	140
10%		156	151	158	153	152	151	159	154	143	143	151	151
20%		169	167	175	172	167	166	176	173	164	164	166	166
30%		181	180	188	186	178	178	190	187	178	178	178	178
40%		192	192	198	197	190	190	201	198	190	189	189	189
50%		202	202	208	207	201	202	213	210	204	204	199	201
60%		214	216	217	217	215	216	224	221	217	217	212	214
70%		226	227	227	227	227	228	236	234	229	229	224	227
80%		237	239	237	239	239	242	248	248	246	246	238	241
90%		254	257	254	257	256	261	264	264	265	265	255	259
95%		265	271	269	272	271	274	274	276	279	279	269	272
FBP		296	304	326	310	315	335	327	313	314	314	302	306
Cetane Index	D 976	51	57	48	55	50	56	52	57	66	67	50	56
Cetane Index	Math	52	57	49	55	51	56	53	58	66	66	51	56

Designation		'B' Blends Change (Δ): Δ = Blend Fuel Property - JP-8 Fuel Property											
		Δ BC25	Δ BC50	Δ BD25	Δ BD50	Δ BE25	Δ BE50	Δ BF25	Δ BF50	Δ BG25	Δ BG50	Δ BH25	Δ BH50
Property, Units	Method												
Flash Pt., °C	D 93	8	1	-2	-2	-1	-2	-4	-4	n/a	n/a	n/a	n/a
Density, kg/L	D 4052	-0.011	-0.022	-0.014	-0.030	-0.010	-0.022	-0.013	-0.027	-0.001	-0.002	-0.010	-0.021
Aromatics, vol. %	D 1319	-5	-10	-4	-9	-4	-9	-4	-7	0	0	-4	-8
Sulfur, mass %	D 2622	-0.02	-0.04	-0.04	-0.07	-0.02	-0.04	-0.03	-0.06	0.00	0.00	-0.02	-0.04
Freeze Pt., °C	D 5972	-2	-4	-1	-1	-2	-3	-2	-5	4	-1	-2	-4
Visc., 40°C	D 445	-0.01	0.15	-0.03	-0.05	-0.07	-0.14	-0.01	0.06	-0.07	-0.09	-0.10	-0.11
SimDist., °C	D 2887	0	0	0	0	0	0	0	0	0	0	0	0
IBP		3	5	6	9	5	11	3	5	-1	-1	6	9
5%		-7	-9	-5	-6	-2	-3	-8	-10	-1	-1	-2	-2
10%		-3	-8	-4	-10	-3	-4	-6	-11	-1	-1	-3	-3
20%		-5	-7	-5	-8	-1	-2	-6	-8	-1	-1	-1	-2
30%		-2	-2	-3	-6	-1	-1	-6	-9	-1	-1	0	0
40%		-1	-2	-2	-4	0	0	-3	-7	0	-1	0	1
50%		0	1	-1	-2	0	1	-3	-7	0	0	1	3
60%		1	2	-1	-1	1	2	-2	-6	-1	-1	1	3
70%		2	4	1	1	1	2	-1	-2	-1	-1	2	4
80%		1	3	1	3	2	5	-1	-1	0	0	1	4
90%		3	6	4	7	2	6	2	2	0	0	1	5
95%		6	12	8	11	5	8	3	4	0	0	4	7
FBP		14	22	23	7	26	46	27	13	4	4	14	18
Cetane Index	D 976	5	10	5	12	4	10	4	9	0	1	5	10