

The Ignition Behavior of a Coal to Liquid Fischer-Tropsch Jet Fuel in a Military Relevant Single Cylinder Diesel Engine

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ABSTRACT

The U.S. Army currently uses JP-8 for global operations according to the 'one fuel forward policy' that was enacted almost twenty years ago in order to help reduce the logistics burden of supplying a variety of fuels for given Department of Defense vehicle and base applications. One particular challenge with using global JP-8 is the lack of or too broad a range of specified combustion and fuel system affecting properties including ignition quality, high temperature viscosity, and lubricity. In addition to these challenges, the JP-8 fuel specification currently allows the use of blending with certain types of synthetic jet fuels up to 50% by volume. This blended fuel also doesn't include an ignition quality or high temperature viscosity specification, but does include a lubricity specification that is much less restrictive than DF-2. One particular currently available synthetic fuel that could be used as a blending agent with JP-8 is produced by Sasol for use in South Africa and is a Fischer-Tropsch's (FT) coal-to-liquid (CTL) aviation fuel that has poor ignition quality (25 cetane number and 52 cetane index) and is more volatile than JP-8. A series of single cylinder experiments were conducted using the Sasol jet fuel in order to study its ignition behavior over a range of relevant military diesel engine operating conditions. In particular, mean ignition combustion chamber densities of 18, 24, and 30 kg/m³ were explored over a mean ignition temperature range of 780 to 1000 K. Additional evaluation of this fuel and a 50-50 blend of this fuel with JP-8 was conducted by performing modal testing at high, medium, and low load conditions representative of a military medium-duty truck engine. A comparison of the ignition behavior of this fuel to higher ignition quality fuels showed that the Sasol jet fuel behaved similar (within 20%) to a higher cetane number fuel over a considerable portion of the mean ignition density and temperature range, but also exhibited poor ignition quality behavior in various lower mean ignition temperature and density regimes. Additionally, blending the Sasol jet fuel in a 50-50 volumetric proportion with a typical JP-8 significantly impacted the ignition and heat release profile behavior at medium and light load operating conditions alleviating part of the poor ignition quality concern of using unblended Sasol jet fuel. These results are highly sensitive to the initial injection rate and thus are a strong function of the fuel system which was a hydraulically actuated electronically controlled unit system in this study that inherently has a more gradual initial injection rate in comparison to high pressure common rail systems.

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INTRODUCTION

Reducing fuel consumption is a challenge for the Army that is being addressed with a multi-faceted approach. One particular thrust area focuses on the utilization of alternative fuels for both aviation and ground vehicle applications [1] that do not significantly alter the current 'one fuel forward fuel policy'. Ideally, these alternative fuels should meet current JP-8 fuel specifications while not leading to any practical piston engine performance degradation issues. In particular, maintaining mean volumetric energy density, ignition quality, evaporation, viscosity, and lubricity near mean JP-8 values is a challenge. In order to address this issue, the JP-8 fuel specification was recently modified to

allow for the use of up to 50% Fischer-Tropsch's process derived synthesized paraffinic kerosene (SPK) as a blend agent with JP-8 [2]. SPK is allowed to contain n-paraffins, iso-paraffins, and cycloparaffins and currently does not include an ignition quality specification though it is anticipated that this requirement is likely during the ensuing fuel specification revisions [3].

Such blend fuels typically have lower volumetric energy density in comparison to JP-8, but conversely, have improved ignition quality in comparison to JP-8. Though this latter observation is true in most cases, there is one potential SPK blend agent fuel candidate derived from coal currently produced in South Africa by Sasol for commercial aviation [4] that has very poor ignition quality. This type of fuel when

used as a straight replacement fuel for JP-8 likely would lead to cold start issues and significant part-load pressure rise rate and peak firing pressure limit issues which ultimately could lead to significant engine reliability and durability issues. To date, there exists little published combustion data for this particular fuel at military relevant diesel engine boundary conditions. Ciatti et al. [5] did include this fuel in a study that successfully highlighted the possibility of using low ignition quality and high volatility fuel in a light duty diesel with exhaust gas recirculation for achieving highly homogeneous combustion behavior at part-load operating points which produced both low nitrous oxides and particulate matter emissions. Hoogterp-Decker and Schihl [6] included this fuel as part of a test matrix of thirteen various military compression ignition fuels and showed that the ignition delay was 10% to 50% longer than higher ignition quality fuels such as JP-8, DF-2, and S-8 (Syntroleum JP-8) at high load operating conditions where the variance decreased with increasing bulk ignition temperature. Last, Henein et al. [7] evaluated this fuel in a multi-cylinder generator set engine in addition to a North American DF-2 and a high ignition quality bio-diesel fuel, and showed that the ignition delay was significantly longer and excessive ignition delays were observed below a bulk mean pressure and temperature of 50 bar and 800 K.

Additionally, blending this fuel with JP-8 would aid in addressing the ignition quality issue though the effectiveness of this strategy is highly contingent on the particular JP-8. For example, the petroleum quality information system (PQIS) has shown that the cetane index of JP-8 on a global basis can vary between 30 and 60 in a given year though the mean value has fallen in the range of 43 to 45 as given by the 2001 through 2009 annual reports. Figures 1 and 2 illustrate this trend by showing a typical cetane index distribution during a given procurement year and also how the minimum value has typically been near 30 and maximum value is typically greater than 54. It is important to note that the derived cetane index (ASTM 976 and 4737) tends not to correlate well with fuels that have cetane numbers below 35 or values above 50 [8]. Therefore other ignition quality methods such as the cetane number test (ASTM 613) or the ignition quality test (ASMT 6890) methods are more applicable in these ignition quality regimes though the latter has still not been proven to correlate well below cetane numbers of 40 [8]. One particular recent single cylinder engine research effort that included a 50-50 blend of the Sasol jet fuel with Jet A was conducted by Murphy and Rothamer [9]. These researchers noted that at high load conditions there wasn't a significant ignition delay difference between the former case and a typical North American diesel fuel with standard intake valve timing. Additionally, they reported a 10% increase of the 50-50 blend ignition delay in comparison to diesel fuel upon retardation of the intake valve timing from -143° to -85° which effectively reduced the bulk ignition temperature and pressure by 20 K and 10 bar for each test point.

The worst case 50-50 blend scenario for military piston engines would include a blend of the Sasol JP-8 and a 30 cetane index JP-8 that theoretically will produce a fuel with an ignition quality near a cetane number of 28. The purpose of this submission is to explore the overall worst case limit of using the Sasol JP-8 as a blend fuel with JP-8 which ultimately includes performing unblended Sasol JP-8 experiments over a range of light to high load operating conditions; this type of approach closely approximates the aforementioned worst 50-50 blend case.

EXPERIMENTAL SET-UP

The combustion device utilized in this study was an AVL 521 single cylinder, high output diesel engine as shown in [table 1](#) that was modified from its original configuration with a more flexible combustion system and externally controlled lubrication and coolant systems. The original base engine included a Bosch PLN (pump-line-nozzle) injection system that had a maximum peak injection pressure of 700 bar and variable start of injection capability. This PLN system was replaced with an Indiana Research Institute (IRI) hydraulically actuated electronically controlled unit injection (HEUI) system. The injector was modified to allow for peak injection pressures near 1900 bar at a peak injection quantity of 240 mm³ per stroke, and a prototype driver was developed to provide multiple injection capability with minimum dwell times near 0.5 milliseconds and minimum injection quantities of 10 mm³ per stroke. A linear displacement, ring-type AECTTM gap transducer was integrated into the injector needle button in order to provide direct real-time needle lift behavior and oil rail pressure was measured using a piezoresistive transducer. Fuel system control was provided by a custom built combination low and high speed Southwest Research Institute Rapid Prototype Electronic Control System (RPECSTM) engine control cart.

Table 1. AVL 521 Single Engine Characteristics

Bore x Stroke (mm)	120 x 120
Displacement (cc)	1357
Compression Ratio	13.7 or 16.0
Boost System	Shop air
Injection System	HEUI
Nozzle Geometry (number of holes x size, mm)	7 x 0.190
Operating Speed Range (rpm)	800 - 3000

A test stand was developed to directly measure injection pressure in a simulated engine environment in order to indirectly determine on-engine injection pressure and rate. Nozzle test specimens were modified to interface with a fuel pressure measurement cavity that included necessary sealing, drainage, and a piezo-resistive transducer. This test stand was employed to assess nozzle flow rate, peak injection pressure, and average injection pressure for both properly matching nozzles to the engine and also for ensuring safe on-engine

operation given the 1900 bar peak injection pressure limitation on the injector assembly. Two production type nozzles were included in this study for investigating the impact of nozzle geometry on the fuel injection rate profile and the relationship between oil rail pressure, injection command signal duration, peak injection pressure, and mean injection pressures is given in [figures 3 & 4](#) for a larger flow nozzle with similar geometry to the injector nozzle used in the experimental work reported in this submission.

The original aluminum piston was machined below the second compression ring and retrofitted with a bolt-on steel crown that was attached to the base piston with titanium bolts. As a result of this change in reciprocating mass, the crankshaft was rebalanced to address any vibration issues over the engine's operating speed range. Both the coolant and lubrication systems were externally controlled to provide desired flow rate and supply temperature through necessary heat exchangers and valves. The engine induction system included a closed loop control shop air system and triple pass electrical heater for controlling the intake manifold thermodynamic state. The former air system included a precise pneumatic air valve and a Micro Motion coriolis flow meter for controlling the air consumption rate within 1% and the latter air heating system included a proportional-integrative-derivative (PID) controller for maintaining a fairly constant intake manifold temperature at a given air consumption rate.

A LabVIEW™ (Laboratory Virtual Instrument Engineering Workshop) low speed data acquisition system application was utilized to collect and process numerous low speed temperature and pressure measurements, analog output from various flow meters associated with fuel and air consumption, coolant flow rate, and lube oil flow rate. High-speed instrumentation included injector needle lift, oil rail pressure, injection command pulse, driver current, and in-cylinder pressure. Each of these signals was acquired using a HiTechniques™ sixteen (16) channel high speed data acquisition system through crankshaft triggering from a BEI 1440 count optical encoder.

COMBUSTION ANALYSIS

In-cylinder pressure data was analyzed using in-house combustion analysis software. Essentially, the first law of thermodynamics was applied to a control volume that included the entire combustion chamber throughout the compression and expansion strokes as shown below:

$$\frac{dQ}{d\theta} = \frac{k}{k-1} P \frac{dV}{d\theta} + \frac{1}{k-1} V \frac{dP}{d\theta} \quad (1)$$

where Q is the net heat release rate (combustion rate less the wall heat transfer rate), k is the specific heat ratio, P is the combustion chamber pressure, V is the combustion chamber volume, and θ is the crankshaft rotation angle. In order to more accurately estimate the bulk specific heat ratio, a

compressibility correction was utilized to correct the bulk temperature [10] as given by:

$$\nu = \frac{RT}{P} + 1.09059 \times 10^{-3} - \frac{8.50053 \times 10^{-3}}{(T/100)^{1.64}} + \frac{4.34248 \times 10^{-10}}{(T/100)^{2.49}} P - \frac{6.52579 \times 10^{-18}}{(T/100)^{2.92}} P^2 + \frac{2.95689 \times 10^{-26}}{(T/100)^{3.17}} P^3 \quad (2)$$

where R is the gas constant. A single step global C_nH_m equilibrium equation was utilized to determine perturbations in the specie mole fractions upon initiation of the injection process and each combustion chamber specie mole fraction was initialized at a chosen time following intake valve closure in order to better estimate the specific heat ratio. Since the net apparent heat release rate does not differentiate between heat transfer and gross burning rate, and typical combustion efficiencies for standard combustion mode operation in diesel engines are 99%, a speed up factor was incorporated within the equilibrium equation to ensure a complete burn and thus a more accurate calculation of the charge specific heat ratio. All experimental pressure traces were conditioned with a digital low pass filter that had a cutoff frequency of typically one and a half to two and half times the engine speed preceding heat release analysis.

An illustrative example of measured needle lift and net heat release rate profiles is given in [figure 5](#). It is important to note that this HEUI system had a slow initial injection rate which in this case had almost a 1 millisecond time delay before reaching the peak injection rate. Such a delay has significant implications on the initial jet break-up, evaporation and mixing rates, and thus the physical delay portion of the overall ignition delay event. For example, one fundamental turbulent mixing layer study showed that a 20% increase in the mean injection rate during the ignition delay period lead to a 16% decrease in the ignition delay [11]. Last, the ignition delay was determined by the difference between the zero cross-over point of the latter and the 15% opening point of the needle based on experience with the nozzle test stand.

EXPERIMENTAL PROCEDURE

In order to compare ignition delay data for the Sasol JP-8 with other compression ignition fuels, a series of experiments were performed to match the mean ignition delay period temperature and density of these other fuels. The first set of experiments (referred to as TC-9) covered a test matrix including six high load points, six medium load points, and three light load points using a single injection strategy where injection timing was judiciously chosen according to best fuel consumption using diesel fuel at a targeted crankshaft torque [6] - see [table 2](#) and [figure 6](#). The intake to exhaust manifold pressure ratio was held at unity whenever possible though the two lower speed high load conditions had a ratio of

approximately 1.25 due to issues with the exhaust system back pressure control valve.

Table 2. TC-9 Test Conditions

RPM	PIM* (bar)	SOI *(BTDC)	TIM* (°C)	OIL RAIL PRESSURE (BAR)
1250	H : 2.19 M : 1.70 L : 1.32	H : 18.75 M : 11.75 L : -2.75	H: 63 M: 54 L: 46	H: 241 M: 262 L: 207
1400	H : 2.88 M : 2.32 L : 1.74	H : 18.5 M : 16.0 L : 4.25	H: 81 M: 60 L: 46	H: 310 M: 262 L: 207
1600	H : 2.88 M : 2.32 L : 1.77	H : 18.5 M : 18.25 L : 6	H: 91 M: 66 L: 46	H: 276 M: 262 L: 207
1800	H : 2.94 M : 1.88	H : 19.75 M : 15.75	H: 99 M: 71	H: 276 M: 290
2000	H : 2.94 M : 2.05	H : 18.25 M : 18.5	H: 99 M: 74	H: 331 M: 310
2200	H : 3.15 M : 1.98	H : 21 M : 13.25	H: 99 M: 74	H: 331 M: 310

*PIM: intake manifold pressure; TIM: intake manifold temperature; SOI: start of injection; H- high load; M - medium load; L - light load

The second set of experiments focused on covering a broad range of ignition period temperatures at three mean ignition charge densities by taking advantage of the induction system control strategy. The closed loop control air induction system was operated at three mass flow rates that targeted mean charge densities of 18, 24, and 30 kg/m³ covering a mean ignition temperature range of 700 to 1000 K at an oil rail pressure of 207 bar. This was accomplished by holding the start of injection timing constant for a single injection event and subsequently increasing the intake temperature in increments of 10 K while acquiring cylinder pressure data upon stabilization of the engine after each 10 K increment - see [table 3](#) for more detail. Due to the decrease in the ignition delay as the intake manifold temperature increased during the experiment, the mean charge density during the ignition delay period did vary from $\pm 2\%$ to $\pm 12\%$. All but one test case was performed at an engine speed of 1400 RPM.

RESULTS

The fuels included in this study are given below - see [table 4](#). Please note that the Sasol JP-8 fuel exhibited poor ignition quality relative to the other test fuels using the cetane number and ignition quality testing methods as the basis in comparison to the cetane index which tends not to correlate well to ignition quality below an index of 35 [8].

MEDIUM DUTY TRUCK ENGINE EXPERIMENTS (TC-9)

A combination of fifteen high, medium, and light load operating conditions were chosen to compare the engine performance and combustion characteristics between the four test fuels. The base engine timing strategy was derived using DF-2 by reaching a given prescribed torque with a single injection event control strategy while subsequently varying both the start and end of injection until the engine demonstrated its best brake specific fuel consumption (BSFC). The three remaining test fuels were then subjected to the same injection timing strategy while holding boost pressure and temperature constant.

High Load Performance

The ignition delay of the Sasol JP-8 varied from 5% to 20% longer than the other three test fuels as shown in [figure 7](#). Each test condition excluding the 1250 RPM case exhibited mean bulk ignition temperatures and pressures greater than 800 K and 70 bar while the former case had a slightly lower mean ignition temperature (770 to 790 K) and significantly lower mean ignition pressure (50 to 53 bar). Also, the 1800 RPM case did show a slightly longer ignition delay relative to the other four higher speed cases (1250, 1400, 2000, and 2200 RPM) due to the earlier start of injection (see [figure 8](#)) for the Sasol case which lead to a lower mean ignition temperature and pressure in comparison to the other test fuels. It is interesting to note that the 50-50 blend fuel, DF-2, and JP-8 exhibited similar ignition delay period and general heat release characteristics (see [figures 9,10,11](#) high load sheet) at all high load operating points showing a variance of up to 0.05 milliseconds for five out of the six test cases which is roughly one to two crankshaft encoder counts and therefore is arguably within the uncertainty of this measurement. Also recall that the ignition quality or cetane number was 38.7, 42.8, and 44.9 for the 50-50 blend fuel, the DF-2, and the JP-8 with the first and third fuels having similar T₉₀ boiling points and thus the variance in ignition delay between these fuels is anticipated to fall within 10 to 15% based on ignition quality [12, 13, 14]. Therefore, blending the Sasol JP-8 with JP-8 in a 50% volume proportion provided similar ignition and heat release behavior in comparison to a typical JP-8 and North American DF-2.

Table 3. Constant Density Experiments

Test Case	TIM Range (°C)	Air Consumption (kg/hr)	SOI (ATDC)	Targeted Density (kg/m ³)	Actual Density Range (kg/m ³)
L1	160 - 211	70	5	18	19 – 19.2
L2	60 - 204	77	12	18	18.6 – 19.6
L3	29 - 66	77	17	18	17.9 – 20.3
M1	174 – 212	93	5	24	25.2 – 25.4
M2	51 – 208	105	15	24	23.7 – 25.4
M3	29 – 63	105	17	24	23.7 – 23.9
M4	58 – 209	105	12	24	24.9 – 26
H1	177 – 210	115	5	30	31.4 – 31.6
H2	57 – 207	130	12.5	30	30.3 – 32
H3	29 – 62	130	20	30	29.7 – 30.7
H4	29 – 62	130	17	30	28.1 – 29.3

*TIM: intake manifold temperature

Medium Load Performance

All test cases exhibited typical conventional diffusion controlled combustion as shown in [figures 12,13,14,15](#) though the ignition delay was 10% to 30% longer for the Sasol JP-8 in comparison to the other three test fuels - see [figure 15](#). In particular, the ignition delay was 30% longer at 1250 RPM where the mean ignition temperature was less than 800 K and the mean ignition pressure was below 52 bar for each fuel. All other test cases had mean ignition temperatures ranging from 800 K to 890 K and mean ignition pressures exceeding 60 bar. The 50-50 blend fuel exhibited similar ignition characteristics to DF-2 and JP-8 at all cases except the 1800 RPM point where the start of injection behavior for JP-8 was 'sluggish' and likely lead to lower initial injection rate than either DF-2 or the 50-50 fuel thus leading to a longer ignition delay - see [figure 16](#).

Light Load Performance

The 1250 RPM point exhibited low temperature chemistry characteristics in the cases of the Sasol JP-8 and DF-2 as shown in [figure 17](#). The bulk start of injection temperature was less than 750 K in all cases except for the 50-50 blend which was roughly 764 K and the bulk start of injection pressure was 43 to 46 bar for all test cases. Additionally, the start of injection for JP-8 was a slightly retarded in comparison to the other fuels and thus included slightly lower bulk start of injection temperature. It is apparent that the operating condition at 1250 RPM presents a combustion control issue for the Sasol JP-8 using a single injection event strategy which was on the verge of misfire. In all cases, the ignition delay was excessive and warrants use of a pilot

injection strategy to overcome potential misfire and pressure rise rate issues - see [figure 18](#).

Table 4. Test Fuel Properties

Fuel	Cetane Number	Density	Viscosity	Lubricity HFRR	T90	Lower Heating Value	Sulfur Content
	[]	[kg/L] @ 15 C	[mm ² /s] @ 40 C	[mm]	[C]	[MJ/kg]	PPM
DF-2	42.8 CN 42.6 CI	0.8655	2.688	0.22	317.1	42.6	390
JP-8	44.9 CN 46.8 CI	0.8026	1.390	NA	234.4	43.4	23
Sasol JP-8	25.2 CN 31.2 DCN 52.1 CI	0.7612	1.1322	0.73	205.3	44	0
50-50 Sasol/JP-8	38.7 CN 41.8 DCN	0.7840	1.289	0.789	228.7	43.6	512

Note: CI - cetane index (ASTM 976); CN - cetane number (ASTM D613); DCN - derived cetane number (ASTM 6890)

At 1400 RPM, both JP-8 and DF-2 exhibited retarded timing which subsequently led to lower start of injection temperatures of roughly 20 K in comparison to the 50-50 blend fuel case - see [figure 19](#) - given that start of injection was after TDC. This variance is significant given that the bulk cylinder temperatures were below 780 K in all test cases similar to the lower speed, high and medium load cases which tended to lead to longer ignition delays and more variance in the ignition delay period between the Sasol JP-8 and the other three test fuels. The same sort of scenario arose for the 1600 RPM test case though the 50-50 blend fuel temperature was approximately 15 K higher than the DF-2 and JP-8 cases, but the 50-50 blend fuel bulk temperature was nearly 800 K resulting in less variance in the ignition delay relative to the 1400 RPM test case.

Overall, the Sasol JP-8 exhibited ignition behavior variance in comparison to the other three test fuels that was more dramatic (greater than 20%) at bulk ignition temperatures less than 800 K and bulk ignition pressures less than 60 bar. Those operating conditions that exceeded these boundary conditions tended to exhibit ignition delays that were 10% to 20% longer than JP-8, DF-2, and the 50-50 blend and thus had somewhat higher premixed phase combustion peak rates that didn't appear to dramatically impact peak firing pressure or pressure rise rate. Nevertheless, the TC-9 experiments provided a general comparison between the various fuels though start of injection and ignition cylinder conditions did vary among the various fuel experiments at a given operating condition. Thus, in order to address this observed behavior in a more precise manner a set of experiments were conducted to study the impact of temperature and density on the ignition behavior of the Sasol JP-8 relative to other fuels of interest to the Army. These experiments were outlined above and essentially attempt to maintain a constant trapped mass in the cylinder while slowly increasing the start of injection temperature while keeping start of injection constant.

CONSTANT DENSITY EXPERIMENTS

The targeted mean ignition densities were chosen as 18, 24, and 30 kg/m³ due to the availability of data from constant volume bomb and shock tube experiments [15] as shown in [table 3](#). Unfortunately, significant portions of the data set exhibited mean ignition densities greater than 10% of the targeted charge density and thus to minimize the variance, charge densities of 19, 25, and 31 kg/m³ were chosen for comparison purposes. The resulting variance was ± 2 kg/m³ at a given test point which correlates to a maximum variance of less than 10% though most test cases did have a variance of less than 4%.

The resulting iso-density ignition lines are given in [figures 20,21,22](#) which include both an ideal gas law pressure line on the secondary y-axis and the same Arrhenius-type correlation superimposed on each data set, i.e. ignition delay $\sim A \cdot \exp(E_a/T)$ where A and E_a are constants. It is interesting to note that the 19 and 25 kg/m³ cases have similar Arrhenius-type behavior as seen by the decreasing rate of the ignition delay as a function of mean ignition temperature. Also, the TC-9 test cases that had these same mean ignition densities are also shown in each figure and agree fairly well with the iso-density experimental data especially in the case M2 where the mean injection pressures are more similar in comparison to the other iso-density test cases - please see [tables 2](#) and [3](#). Additionally, the 50-50 fuel blend is shown in [figure 20](#) for the 25 kg/m³ case and it has a very similar ignition delay (within 15% - see error bars) to the Sasol JP-8 at mean ignition temperatures and pressures greater than 800 K and 55 bar.

The 31 kg/m³ case as shown in [figure 22](#) has a much steeper slope than the two corresponding lower mean ignition density cases of 19 and 25 kg/m³ near 800 K. Again, the TC-9 data agrees fairly well ($\sim 15\%$) with the iso-density data and this variance in part is due to the lower mean ignition density of this data set in comparison to the iso-density data, i.e. the TC-9 data had mean ignition densities less than 30 kg/m³ while the iso-density data sets tended to have mean charge densities greater than 30 kg/m³. A superposition of each of three iso-density cases is shown in [figure 23](#) that further accentuates the differences in the slope between the highest density and two lower density cases. It is interesting to note that the ignition delay for the 25 and 31 kg/m³ cases are very similar at mean ignition temperatures greater than 925 K and that the ignition delay for the 19 kg/m³ cases is rapidly approaching values of the two higher density cases at what appear to be a mean ignition temperature higher than 950 K. This trend implies that the ignition pressure dependency becomes weaker at mean ignition temperatures above 950 K given that the mean ignition pressure for each of three iso-density cases is approximately 50, 70, and 85 bar at 950 K.

At the opposite end of the spectrum, the ignition delay becomes large and arguably excessive at mean ignition temperatures from 700 K to 750 K as function of the iso-density case. This excessive region is shown in gray on [figure 23](#) and it appears that all three iso-density cases are rapidly heading upward into this gray region near 700 K though the 19 kg/m³ reaches this area first at mean ignition temperatures below 800 K. Quantitatively and qualitatively this trend implies potential cold start and light load operating condition issues with the Sasol JP-8 in the absence of a pilot injection and possibly charge air heater strategy. This point is further solidified according to the previous discussion of the 1250 RPM part-load TC-9 operating condition which exhibited a 'sluggish' heat release that was on the verge of misfire. Further experimentation is necessary to fully quantify these possible issues.

Comparison with Higher Ignition Quality Fuels

Ignition data from previous work that utilized the same single cylinder engine, but at a lower compression ratio [14], along with data from a small bore diesel engine (DIATA - Direct Injection Aluminum Through-bolt Assembly), a multi-cylinder heavy-duty truck engine (Detroit Diesel Corporation Series 60), a multi-cylinder HMMWV engine (GEP - General Engine Products) and a two-cylinder military engine (Cummins VTA-903) was carefully compared with data from the iso-density experiments. Three slightly different mean ignition densities of 18, 24, and 30 kg/m³ were chosen for this exercise in order to maintain a mean ignition density variance of less than ± 2 kg/m³. The resulting ignition trends are shown in [figure 24, 25, 26](#). Collectively, the Sasol JP-8 ignition trends for each of the three iso-density cases is very similar to JP-8 and DF-2 data collected from the various engine sources at mean ignition temperatures greater than 850 K.

As shown in [figure 24](#), the 18 kg/m³ iso-density Sasol JP-8 data exhibited a magnitude and overall trend similar to JP-8 and DF-2 with 43 CN from the AVL 521 single cylinder engine (13.7 compression ratio), JP-8 with a 47 CI from a V-2 diesel engine, and shock tube data derived from Jet A with a 45.3 CN, i.e. within 20%. This observation is strictly limited to the temperature range included in this figure, i.e. greater than 850 K. Similarly, as shown in [figure 25](#), the 24 kg/m³ iso-density data also agreed well with AVL 521 JP-8 and DF-2 data at mean ignition temperatures greater than 800 K and when extrapolated beyond 1000 K appears to have the possibility of trending well with DIATA and GEP data. Conversely, at temperatures less than 800 K the iso-density data appears to diverge from TC-9 JP-8 data which is similar to the trend discussed in the TC-9 results section that pointed toward large ignition variance between the Sasol JP-8 and the other three higher ignition quality fuels at similar mean ignition temperatures. Last, the higher iso-density case shown in [figure 26](#) agreed well (i.e. within 20%) with the various engine data sets at mean ignition temperatures greater than