

The Combustion and Ignition Characteristics of Varying Blend Ratios of JP-8 and 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' in order to reduce the logistics burden of supplying a variety of fuels for given Department of Defense ground vehicle applications. One particular challenge with using global JP-8 is the lack of or too broad a range of specified combustion affecting properties including ignition quality, high temperature viscosity, and density. In particular, the ignition quality of JP-8 has dramatically varied throughout the past decade on a global basis covering a range of 29 to 70 cetane index. This key combustion affecting parameter was explored in this study by evaluating a synthesized low ignition quality jet fuel blended in 25% volumetric proportions with JP-8 to effectively cover a cetane number range of 25 to 45 in a single cylinder diesel engine operated at various light, medium, and high load operating conditions. The low ignition quality fuel was a Fischer-Tropsch Synthesized, coal-to-liquid (CTL) paraffinic kerosene (FT-SPK) which exhibited low temperature chemistry behavior at light load operating conditions including unstable combustion at lower engine speeds. To better understand this latter combustion behavior, supplemental single cylinder experiments were conducted to explore the impact of cylinder charge density on the ignition delay of the CTL FT-SPK covering mean charge densities of 19, 25, and 30 kg/m³ and a temperature range of 750 K to 950 K. Such experiments revealed a peninsula of excessive ignition delay at mean ignition pressures of less than 55 bar and mean ignition temperatures less than 800 K that were representative of the unstable lower load operating points. Blending the CTL FT-SPK with an 'average' JP-8 increased the low temperature activity and yielded stable combustion at lower, light load engine speeds. In particular, the 50-50 blend ratio alleviated any ignition concerns with the CTL FT-SPK at the test conditions included in this study while the 25-75 blend ratio (JP-8/CTL FT-SPK) addressed a major portion of such ignition concerns at full, medium, and certain light load operating conditions. These results are highly sensitive to the initial injection rate. The main purpose of this submission is to explore the effect of blending JP-8 with a known poor ignition quality SPK to assess any potential performance impacts on military relevant diesel engines.

CITATION: Schihl, P., Gingrich, E., and Decker, L., "The Combustion and Ignition Characteristics of Varying Blend Ratios of JP-8 and a Coal to Liquid Fischer-Tropsch Jet Fuel in a Military Relevant Single Cylinder Diesel Engine," *SAE Int. J. Fuels Lubr.* 8(2):2015, doi:10.4271/2015-01-9073.

INTRODUCTION

Reducing the logistics footprint of the fuel supply 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 that do not significantly alter the current 'one fuel forward fuel policy' and might be readily available within the region of operation [1]. Ideally, these alternative fuels should meet current JP-8 fuel specifications while not leading to any practical piston engine performance degradation issues by ensuring mean volumetric energy density, ignition quality, and lubricity near mean JP-8 values. The JP-8 fuel specification was recently modified to address this issue by allowing 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 cyclo-paraffins and currently does not include an ignition quality specification [3] though the resultant blend with JP-8 must meet a minimum derived cetane number (DCN) of 40 [4].

Nevertheless, 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 [5] that has very poor ignition quality. This particular fuel represents a worst case JP-8 blend from an ignition quality point-of-view and likely could lead to cold start and

combustion instability issues at part load operating conditions that collectively can result in engine reliability and durability issues. Furthermore, most military engines were and are originally designed and calibrated to operate on North American diesel fuel (DF-2). The variance in combustion and injection system affecting properties can lead to lower power levels in such engines when exposed to alternative jet fuels, but typically such differences are less than 5% at North American type operating conditions [6]. It is therefore important to understand the combustion characteristics of synthetic fuels in order to properly assess their impact on military engine performance. To date, there exists little published combustion data for this particular CTL FT-SPK fuel at military relevant diesel engine boundary conditions as outlined below.

Ciatti, Nathan, Aggarwal, and Adhikary [7] did include this CTL fuel in a study that successfully highlighted the possibility of using a 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 [8] and Schihl, Hoogterp-Decker, and Gingrich [9] 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 and that at light load the CTL fuel exhibited excessive ignition delay at cylinder thermodynamic conditions below 770 K and 50 bar. Henein, Rofail, Schihl, Hoogterp et al. [10] evaluated this CTL 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 for the CTL than the other two test fuels and excessive ignition delays were observed below a bulk mean pressure and temperature of 50 bar and 800 K. Zha, Yu, Lai, and Jansons [11] explored the impact of main injection timing with a fixed and very early pilot injection at a light load operating condition and showed that retarded timing was limited by 'sluggish' combustion and possible misfire. McNeilly [12] used a non-optical constant volume combustion vessel to evaluate the ignition variances between DF-2 and the CTL fuel over a range of three chamber densities and various bulk temperatures showing a 20% to 40% percent increase in the ignition delay in the case of the CTL. Murphy and Rothamer [13] and Rothamer [14] conducted single cylinder engine experiments using the CTL and also a 50-50 blend and a 75-25 blend with Jet-A and showed that both blends had comparable ignition delays over a bulk temperature range of 900 to 1050 K and mean charge densities of 15, 20, 25, and 35 kg/m³ in comparison to Jet-A and DF-2. Last, Schihl, Hoogterp-Decker, and Gingrich [9] also demonstrated that a 50-50 blend of CTL with JP-8 noticeably reduced the ignition delay of SPK at part load operation to levels that would allow for single injection combustion at various load conditions.

Overall, blending the CTL with JP-8 will aid in addressing the ignition quality issue of the CTL 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 2011 annual reports [15]. 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 [16]. Therefore other ignition quality methods such as the cetane number test (ASTM 613) or the ignition quality test (ASTM 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 [16]. Nevertheless, the overall blend must meet the ignition quality specification of 40 DCN [4] which is one key parameter for controlling the blend ratio of the CTL or any other SPK with JP-8.

One purpose of this submission is to explore the overall worst case limit of both using the CTL as representative for the lowest ignition quality JP-8 and also as a blending agent to explore the impact of jet fuel ignition quality on the combustion characteristics of a military relevant single cylinder diesel engine.

EXPERIMENTAL SET-UP

An AVL 521 single cylinder, high output diesel engine was used throughout this study as shown in table 1. It 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 AECTM gap transducer was integrated into the injector needle button in order to provide direct real-time needle lift behavior and the 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 (RPECSM) engine control cart.

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. A production type nozzle with similar geometry to the nozzle used for this study was evaluated on the test stand to determine the impact of nozzle geometry on the fuel injection rate profile and the relationship between oil rail pressure and injection

command signal duration, peak injection pressure, and mean injection pressures is given in [figures 3 and 4](#). These measurements provide a reasonable estimate of the mean injection system behavior for the conditions included in this study.

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 nearly 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.

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

Combustion Analysis

In-cylinder pressure data was analyzed using in-house combustion analysis software based on the averaging of fifty consecutive cycles. 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 calculate the bulk temperature [17] 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 once and a half to two and a half times the engine speed preceding heat release analysis. An illustrative example of measured needle lift and fuel injection pressure is given in [figure 5](#). It is important to note that this HEUI system had a slow initial injection rate which in this particular operating condition had almost a 1 millisecond time delay before reaching the peak injection rate which later will be shown to have an impact on any conclusions generated by this study. Last, the ignition delay was determined by the difference between the zero cross-over point of the net heat release rate profile and the 15% opening point of the needle based on experience with the nozzle test stand [9]. Finally, the bulk ignition temperature was calculated based on the mean bulk temperature between the start of injection and start of combustion points.

Experimental Procedure

In order to compare ignition delay data for the CTL with the various blend ratios of CTL and JP-8, a series of experiments were performed at representative light, medium, and high load conditions. The first set of experiments 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 and duration was judiciously chosen according to best fuel consumption using diesel fuel at a targeted crankshaft torque - see [table 2](#). The start of injection timing and injection duration was held constant based on the DF-2 case for all subsequent test fuels. Additionally, 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. These experiments were conducted using the 13.7:1 compression ratio piston.

The second set of experiments focused on covering a broad range of CTL ignition period temperatures at three mean ignition charge densities. 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 at each operating point- 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 varied from $\pm 2\%$ to $\pm 12\%$. All but one test case was performed at an engine speed of 1400 RPM and these experiments utilized the 16:1 compression ratio piston; condition H3 was performed at 1250 RPM.

Table 2. TC-9 Test Conditions

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

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

RESULTS

The various fuels included in this study are given in table 4. The DF-2 and JP-8 properties were representative of typical samples found in the United States though the former was an off-road variant with higher sulfur than seen in today's fuel supply. Additionally, the JP-8 included in table 3 was not the exact same JP-8 sample used in the CTL-JP-8 blends though was a representative JP-8 found in the United States. Please note that the volumetric energy density was lower for the blend fuels in comparison to DF-2 and JP-8 and thus will impact the engine power level at each operating point dependent on the fuel system and the combustion characteristics. Also note that

other data sets referenced in the introduction did not overlap the datasets presented in this paper and thus are not included in the subsequent discussions.

Single Cylinder 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 test fuels. The base engine timing strategy was derived using DF-2 by reaching a given prescribed torque at a given boost level 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 remaining test fuels were then subjected to the same injection timing strategy while holding boost pressure and temperature constant.

Table 3. Constant Density Experiments

Test Case	TIM Range* (°C)	Air Consumption (kg/hr)	SOI (BTDC)	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

High Load Performance

As shown in figure 6, there was very little variance in the ignition delay between all test fuels though all test fuels yielded lower net indicated mean effective pressure (NIMEP) in comparison the baseline DF-2 sample as given by figure 7. For illustrative purposes, a 10% 'variance bar' for the CTL was included in this figure to readily compare the performance of the various fuels included in this study. Conversely, the various blend fuel samples generated similar NIMEPs across the speed range in comparison to JP-8.

At 1400 RPM, the injection timing for the DF-2 case yielded a higher NIMEP by 10% in comparison to the JP-8 blend fuels and the CTL - see figure 7. This difference is partially explained by the lower volumetric energy density of these fuels which varied from 6% to 9%. The other main factor impacting the NIMEP was the shorter injection event for each of the JP-8 blend fuels in comparison to the CTL as given in figure 8. In the case of the CTL, there was a slightly

shorter injection event in comparison to DF-2 though the mixing controlled combustion phasing was slight retarded compared to the JP-8 blend fuel cases which collectively was the other more minor factor impacting the observed lower NIMEP in comparison to DF-2.

At 1600 RPM it appears that the injection duration was essentially the same for all fuels excluding JP-8 which had a slighter longer duration - see [figure 9](#). The heat release phasing was very similar for the JP-8 blend fuels leading to almost an indistinguishable difference in NIMEP among these fuels as given in [figure 7](#). For this particular test case the JP-8 high speed pressure data was found to be corrupt after the experiment was disassembled and thus a comparison of cylinder pressure to other fuels is not possible at this time. The CTL case was the worst performing of all the fuels at 1600 RPM mostly due to the aforementioned reduction in volumetric energy density; the CTL was approximately 2% lower than the 50-50 JP-8 blend fuel. Last, JP-8 had higher energy content than the blend fuels and the CTL by almost 4%, but its 'sluggish' heat release rate profile lead to a reduction in NIMEP that outweighed the fuel energy density advantage. It is suspected that the sluggish behavior might have been due to a fuel system dynamic control issue that ultimately led to a reduced injection rate as manifested in an apparent reduction in mixing rate during the onset of the mixing controlled phase of combustion.

Table 4. Test Fuel Properties

Fuel	Ignition Quality*	Density (kg/L) at 40 °C	T90 (°C)	Lower Heating Value (MJ/kg)
CTL	25.2 CN 52.1 CI 31.2 DCN	0.7612	205.3	44.0
75-25 (CTL-JP-8)	49.1 CI 37.7 DCN	0.773	216.3	43.8
50-50 (CTL-JP-8)	38.7 CN 48.7 CI 41.8 DCN	0.784	228.7	43.6
25-75 (CTL-JP-8)	47.2 CI 44.7 DCN	0.795	233.7	43.5
JP-8	44.9 CN 46.8 CI	0.8026	234.4	43.4
DF-2	42.8 CN 42.6 CI	0.8655	317.1	42.6

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

The 1250 RPM case is another example of combustion phasing optimization discussed in the previous section. In the cases of the JP-8 blend fuels, the earlier heat release phasing as shown in [figure 10](#) had an inherent improvement in thermal efficiency in comparison to the DF-2 case even though each of these cases had a 6% to 8% decrease in volumetric energy in comparison to DF-2. These cases demonstrated that an earlier phasing with a more volatile fuel could lead toward an improvement in NIMEP with a more aggressive onset of the mixing controlled phase of combustion as shown in [figure 10](#). Conversely, a retarded start of combustion as manifested by the CTL could also lead toward an improvement in thermal efficiency though the impact on NIMEP isn't as noticeable as the JP-8 blend cases due to the 9% reduction in volumetric energy density. Last, JP-8 had a more sluggish heat release profile compared to the JP-8 blend fuels

and DF-2 due to a more sluggish initial injection rate alluded to in the needle lift profile shown in [figure 10](#) that ultimately negatively impacted NIMEP.

For the 1800 RPM, 2000 RPM, and 2200 RPM test cases, the heat release profiles are very similar as shown in [figures 11, 12, 13](#). The resulting NIMEPs for the DF-2 and JP-8 blend cases are essentially non-variant as given in [figure 7](#). The JP-8 and CTL heat release profiles are lagging the DF-2 case throughout this engine speed range resulting in a slightly lower NIMEP due to the retarded mixing associated with these particular fuels. Use of a pilot injection could 'pull' the main portion of the heat release profile to an early part in the compression stroke and thus potentially improve thermal efficiency under the limitation of the fuel injection system injection pressure profile that has a sluggish start as shown by the illustrative operating case in [figure 5](#).

Medium Load Performance

The ignition delay variance between the various JP-8 blend ratio fuels was small (within approximately 10%) from 1400 RPM to 2200 RPM as given in [figure 14](#). Therefore, given that these three fuels have similar volumetric energy density (within 2% variance) there wasn't much difference in the heat release profiles among these candidate fuels - see [figures 15, 16, 17, 18, 19](#). The phasing in these cases was barely distinguishable and thus the NIMEP variance was very small - see [figure 20](#). At 1250 RPM, the 50% and 75% JP-8 blend ratio cases had almost exactly the same heat release profile while the 25% JP-8 blend ratio case exhibited a couple degrees retarded phasing and had a noticeably higher peak premixed phase burn rate. Though the later fuel was slightly retarded in comparison to the other two cases, the higher peak phase burn rate was advantageous for increasing the peak pressure to a level similar to the 25% and 50% JP-8 blend ratio cases resulting in similar NIMEP - see [figure 20](#). Similar to the high load cases, a 10% variance bar was added to this figure for comparison purposes.

The CTL fuel cases exhibited longer ignition delay compared to the other test fuels (see [figure 14](#)) and between 1250 RPM and 1600 RPM provided a more optimal combustion phasing than the DF-2 yielding a higher indicated mean effective pressure as shown in [figure 20](#). For engine speeds between 1800 RPM and 2200 RPM, the later combustion timing did not provide a phasing advantage in comparison to the DF-2 cases and thus there was little difference in NIMEP. Though this observation is correct it is important to note that the CTL cases had approximately 9% less injected fuel mass per stroke than the DF-2 cases. The implication is that the SPK cases had a higher thermal efficiency than the DF-2 cases.

Last, each JP-8 case had a retarded start-of-injection timing compared to the other test fuels which lead to later combustion timing. The resulting heat release rate profiles were retarded compared to the other test fuel cases and NIMEP was nominally 3% to 5% lower than the DF-2 baseline case as shown in [figure 14](#). Much of this degradation can be attributed to the lower volumetric energy density of JP-8 in comparison to DF-2 which was approximately 5% in this study. Careful inspection of the heat release profiles for 11 and