Annual Report for the Ultra-Clean Fischer-Tropsch Fuels Production and
Demonstration Project
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Report Structure

The Report Abstract provides summaries of the past year's activities relating to each of the main project objectives. Some of the objectives will be expanded on in greater detail further down in the report. The following objectives have their own addition sections in the report: SFP Construction and Fuel Production, Impact of SFP Fuel on Engine Performance, Fleet Testing at WMATA and Denali National Park, Demonstration of Clean Diesel Fuels in Diesel Electric Generators in Alaska, and Economic Analysis.

Abstract

Program Management

ICRC provided overall project organization and budget management for the project. ICRC held meetings with various project participants. ICRC presented at the Department of Energy's annual project review meeting.

SFP Construction and Fuel Production

The plant began producing fuel in October 2004. The first delivery of finished fuel was made in March of 2004 after the initial start-up period

Evaluation of SFP Fuels in Current Diesel Engines

Cold Start Testing

ICRC has completed cold start testing of the Syntroleum fuel. The same tests were run with number one and number two diesel fuels. All cold start tests were completed using a Detroit Diesel Model 50 engine. The test results have been compiled and will be included in the final report at the end of the project. The Syntroleum fuel shows excellent cold start properties. Use of the Syntroleum fuel enabled the engine to start at more the ten degrees lower than traditional fuels. This makes the fuel a good candidate for truck fleets operating in very cold areas.

Dynamometer Durability Tests

The DDC Series 50 WMATA engine has accumulated 1300 of the scheduled 1500 hours on the CTA cycle. After completion of the 1500 hours, an emissions comparison will be performed on two fuels: Syntroleum and low sulfur diesel used by the WMATA fleet. Following the emissions evaluations, the fuel system components will be subjectively evaluated for wear.

The Caterpillar C-7 Denali National Park bus engine is being run on conventional diesel fuel to break-in its new fuel-system components. Testing of the Denali engine was delayed because the Engine Control Module was programmed to limit engine speed. Hardware and software to gain access to the Cat engine control program had to be obtained, and this problem required that fundamental changes be made in the automation program in order to run the engine on the CTA cycle. These changes have been completed and the CAT engine is being switched from conventional fuel to S-2 Syntroleum fuel.

SFP Fuel Assessment with Advanced Prototype Diesel Engines

Although ICRC is still attempting to manufacturers to participate in this part of the project, industry enthusiasm seems to be waning as the project goes on. ICRC has approached engine manufacturers including Ford, GM, Caterpillar, and Cummins, and emission control system manufacturers including Johnson-Matthey and Englehard. All have declined participation in the project.

The reason for decline by the manufacturers is quite possibly the result of the current great rush by the manufacturers to find engines and aftertreatment systems that meet the 2007 EPA emissions regulations. The developers prefer to deal with fuel that is closest to the cutoff point for emissions requirements, rather than the cleanest fuel possible.

Impact of SFP Fuel on Engine Performance

Part of the project is the study of how gas-to-liquid fuel formulations may affect engine performance and emission characteristics. The project will complement the fuel production, engine, and emission control system testing programs by parallel investigations on what and how key fuel variables affect engine emissions, and in what ways, by illustrating the fundamental relationships. The project aims at exploring advanced engine design changes from potential future engine-fuel systems that will benefit from the new fuels.

Specific tasks in this subcontract project include:

- (1) To assess how gas-to-liquid fuels impact engine performance and emissions, directly and in blends; to evaluate tradeoffs among fuel properties and blending ratios; to evaluate engine modifications in further improving engine emissions; and to determine combustion and emission characteristics.
- (2) To explore opportunities of injection strategy control and exhaust-gas-recirculation (EGR) in pushing limits of NO_x/particulates reduction using Syntroleum Fischer Tropsch (FT) fuels produced from small footprint plant (SFP). The engine will be modified for various injection control and EGR systems. Since particulates are expected to be substantially lower with the GTL fuel, limits of NO_x reduction via EGR and injection variables will be explored using the specific fuels.
- (3) To evaluate exhaust after-treatment systems performance and design tradeoffs available using gas-to-liquid fuels. Optimize the fuel/engine/emission-control system.

Goals for this reporting period, the second year, were to (i) extend the test conditions in Task (2) to ascertain the previous findings, (ii) evaluate whether blending produces proportional or disproportional benefits, and (iii) start investigating interactive effects of different fuel properties and an exhaust after-treatment system. Tasks (1) and (2), except for the fuel blends, have essentially been covered in the first year and previously reported. In this period, similar results have been obtained with the extended tests, which included

fuel blends. The goals in this period have thus been accomplished, although work on the after-treatment system, a particulate trap, has just been started.

The experiments were performed on a Cummins model year 2002 ISB 300, 5.9 liter, 6-cylinder, turbocharged, heavy-duty direct injection diesel engine, rated at 224 kW (300 hp) at 2500 RPM. Emission characteristics showed the same trends as those measured previously. Combustion rates and emission formation mechanisms were studied earlier using an analytical model based on heat release rates and published conceptual models of diesel combustion.

Specifically, compared to regular diesel, FT fuel reduces particulate emission substantially (25-75%). We concluded in the first year that most of this reduction came from sulfur in the 400 ppm sulfur diesel fuel, as the reduction was consistent with the expected sulfates contribution from the high sulfur fuel. However, the recent data using 15 ppm sulfur fuel also produced similar particulate reductions. It can be inferred from the additional data that FT fuel consistently reduces particulates in ways other than from having zero sulfur alone. Essentially, the faster burn rate of the FT fuel than the diesel at retarded injection timings did not produce the particulates increase that normally accompanied retarded injection timings for NO_x control using the regular diesel fuel. Therefore, late injection timings can be utilized more effectively with the FT fuel in controlling both particulates and NO_x. Also, conventional diesel fuel normally produces more particulates as EGR increases. Results show that FT fuel removes the sensitive dependence of PM production on EGR rate, allowing significant NO_x reductions through the use of higher EGR rates before PM levels become unacceptably high. Current results are consistent with earlier findings that NO_x decreases by up to 20% with the FT fuel. It is possible that further optimization of the engine to take advantage of the large particulates reduction can reduce NO_x even further.

The issue of fuel blending was investigated to determine whether the benefits of FT fuel are proportional to its content in the fuel blend. A blend of 25% (by volume) FT fuel with 75% 15 ppm sulfur fuel, as well as a blend of 25% FT with 75% 400 ppm sulfur fuel were studied. The particulates data show that the 25% FT fuel in either blend produced about half of the particulate reduction of using neat FT fuel (slightly more than half - 60% - for the blend with the higher sulfur fuel and slightly less than half - 40% - for blend with the lower sulfur fuel). This non-linear benefit is consistent with independent results reported elsewhere.

MIT has started investigating the impact of and opportunities in using the FT fuel on emission control via exhaust after-treatment. A diesel particulate trap system, consisting of four parallel units of 6" in diameter each, has been designed and procured and provisions made for its installation in the exhaust system. The experiments will address differences in trap regeneration characteristics, if any, of using FT fuel and opportunities made available, such as enhanced catalytic reactions, in a sulfur-free exhaust stream. A substantial part of the research in the next reporting period will focus on this area.

MIT has observed modest NO_x reductions but 25-75% particulates reductions from using FT fuel over both 400 ppm and 15 ppm sulfur diesel fuels. Benefits arise not just from

the zero sulfur but also from a faster burn rate at retarded timings. Blending of FT fuel produces more than a proportional gain in benefit. Exhaust after-treatment work has started. Overall, FT fuel gives greater freedom to engine designers when trying to optimize the engine/emission-control/fuel system in modern engines, since it provides the fuel properties as another flexible set of variables that affect the combustion and emission processes.

Fleet Testing at WMATA and Denali National Park

Fuel tests on buses at Denali National Park and the Washington Metropolitan Area have begun and will be completed by the end of 2004. Preliminary emissions test results are provided in this report.

Demonstration of Clean Diesel Fuels in Diesel Electric Generators in Alaska

The primary goal of the Diesel Electric Generator clean fuels demonstration is to assure the potential users of these fuels that no adverse affects are encountered, while significant advantages are gained. The possible adverse effects to be measured include possible increased wear in the fuel delivery system leading to higher maintenance costs, and to difficulties associated with handling the fuel in arctic conditions. The significant advantages include reduced emissions of criteria pollutants, the ability to recover significantly more heat from the combustion exhaust, and the reduced environmental impacts of possible spills. Based on our literature reviews, we expect that the Syntroleum fuel will give excellent performance in our tests.

Results to date indicate that the clean diesel fuel is performing as expected, with no apparent negative impacts on the diesel engine. More detailed conclusions will be possible after completion of the testing, which is set for November 15, 2004.

Feasibility Study of SFPs for Rural Alaska.

During the year study sites were selected for the analysis, and information was gathered on local resource potential and regional energy distribution patterns. The selected sites will include potential gas, coal and biomass supply to the plants. The study is to be complete by February, 2005.

Demonstration of Clean Diesel Fuels in Fuel Cells

This goal of this project is to demonstrate a fuel cell operating on the naphtha fraction of the clean fuels. This naphtha fraction is lighter than the synthetic diesel product, and so should vaporize easily, thus enabling the reaction to proceed without the formation of solid carbon (coking). Proof of this may establish a market for the naphtha fraction of the fuels. Fuel cell testing has not begun, but is expected to begin within the next six months.

Cold Weather Testing of Ultra-Clean Fuel

Denali National Park has expressed interest in continuing to use arctic-grade SFP fuel in its vehicles throughout the winter. ICRC is working with Denali to determine whether this is feasible.

Economic Analysis

Preliminary results suggest that a small GTL plant (1000 bpd) would be able to generate profit (10% internal rate of return) under circumstances of sufficiently cheap feedstock (\$0.00 to \$0.40 per million btu) if located sufficiently remotely (>300 miles) from a conventional source of fuel (wholesale price of \$0.74/gal). While the results depend sensitively on scale of operation, cost of gas, location and market price of the fuel it is fair to infer that remote locations, for example in Alaska, may benefit the most from this technology. Tiax is in the process of refining that analysis to take into account Alaska-specific market information, construction factors and resource locations.

In the current reporting period Tiax revised its existing estimates of the costs of constructing and operating a small footprint plant and has compared the results to those provided by Syntroleum for a much more detailed analysis of two sizes of plants (100 and 1700 barrels per day). The agreement between the overall costs obtained from the two sets of estimates was excellent. Thus, going forward, we can apply the revised values of energy efficiency, costs and operating assumptions to refine the well-to-tank analysis that serves to identify the technically and economically viable resources. The revised model also permits estimating the environmental and greenhouse emissions associated with generating the GTL fuel. We will combine those emissions with those associated with using the fuel through the tank-to-wheels scenarios that will be constructed in the next reporting period.

Part A: Plant Construction and Fuel Production

The dedication of the GTL plant at the Port of Catoosa, Tulsa, Oklahoma, was held at the plant on October 3, 2003. Subsequently, start-up and commissioning of the GTL demonstration plant was completed during the first quarter of 2004.

The GTL plant reached mechanical completion in October of 2003 and first delivery of finished fuel was made in March of 2004 after the initial start-up period. To date, fuel shipments under the Ultra-Clean Fuels Program have been:

Participant	Shipped Approximate Volume (gals)	Produced / Available Approximate Volume (gals)	Fuel Type
AVL #1	6,073		No. 2 Diesel (S-2)
AVL #2	6,110		No. 2 Diesel (S-2)
AVL #3	6,039		No. 2 Diesel (S-2)
AVL #4		6,000	No. 2 Diesel (S-2)
AVL #5		6,010	No. 2 Diesel (S-2)
AVL #6		6,008	No. 2 Diesel (S-2)
MIT #1	110		No. 2 Diesel (S-2)
MIT #2	220		No. 1 Diesel (S-1)
MIT #3		1,815	No. 2 Diesel (S-2)
WMATA #1	5,332		No. 2 Diesel (S-2)
WMATA #2	6,014		No. 2 Diesel (S-2)
WMATA #3		6,190	No. 2 Diesel (S-2)
Denali National Park #1	5,950		No. 2 Diesel (S-2)

Denali National Park #2	4,600		No. 1 Diesel (S-1)
U.S. Army #1	5,020		JP-8 (S-8)
U.S. Army #2	5,200		JP-8 (S-8)
Participant	Shipped Approximate Volume (gals)	Produced / Available Approximate Volume (gals)	Fuel Type
Univ. of Alaska Fairbanks #1	5,894		No. 1 Diesel (S-1)
Univ. of Alaska Fairbanks #2	6,058		No. 2 Diesel (S-2)
Univ. of Alaska Fairbanks #3	6,050		No. 1 Diesel (S-1)
Univ. of Alaska Fairbanks #4		300	FT Naphtha
Additional Program Volumes		12,200	No. 2 Diesel (S-2)
Reserve Fuel		4,375	No. 2 Diesel (S-2)
Total	68,670		

Emission testing of GTL fuels is being performed by The National Research Center for Alternative Fuels, Engines and Emissions at West Virginia University (WVU) and reports of the initial results have been provided in separate documents.

In addition to the fuel testing by WVU, the U.S. Army and U.S. Air Force have been active participants in testing GTL fuels for military applications. With respect to preliminary engine emission tests results are highlighted in the following slides presented by Ms. Patsy Muzzell of the U.S. Army (National Automotive Center) and Mr. William Harrison III of the U.S. Air Force (Wright-Patterson Air Force Base - National Aerospace Fuels Research Complex).

The U.S. military continues to evaluate GTL fuels as a potential source of supply of ultra-clean transportation fuels and the ability to produce these fuels from domestic coal resources.

On September 22nd, 2004 a press conference was held at the Rayburn House Office Building in Washington, DC to highlight the Department of Energy's Ultra-Clean Fuels Program in conjunction with the demonstration plant. The event was hosted by Congressman John Sullivan, Oklahoma. In addition, Congressman Don Young of Alaska spoke about the potential of GTL fuels and the role these ultra-clean fuels could play in our country's pursuit of reducing our dependence on foreign supplies of energy. Acting Assistant Secretary for Fossil Energy, Mark Maddox, spoke on behalf of the DOE.

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COMBUSTION AND EMISSIONS IN AN ADVANCED DI ENGINE

1.0 SCOPE OF WORK FOR THIS REPORTING PERIOD

The role of MIT in the project team is to complement other production, testing, and assessment efforts in the overall Ultra-Clean Fuels Program by exploring how advanced engine and emission control systems may benefit from the use of the Syntroleum gas-to-liquid fuel.

Specific project tasks are:

- (1) To assess how gas-to-liquid fuels impact engine performance and emissions, directly and in blends; to evaluate tradeoffs among fuel properties and blending ratios; to evaluate engine modifications in further improving engine emissions; and to determine combustion and emission characteristics.
- (2) To explore opportunities of injection strategy control and exhaust-gas-recirculation (EGR) in pushing limits of NO_x/particulates reduction using Syntroleum Fischer Tropsch (FT) fuels produced from small footprint plant (SFP). The engine will be modified for various injection control and EGR systems. Since particulates are expected to be substantially lower with the GTL fuel, limits of NO_x reduction via EGR and injection variables will be explored using the specific fuels.
- (3) To evaluate exhaust after-treatment systems performance and design tradeoffs available using gas-to-liquid fuels. Optimize the fuel/engine/emission-control system.

If future resources become available, fundamental models and experiments to verify the effects of fuel characteristics on diesel processes most critical to effective engine performance and low emissions will also be developed. These advanced models will focus on fuel chemical composition effects.

Tasks (1) and (2), except for the fuel blends, have essentially been covered in the first year and previously reported. Goals for this reporting period, the second year, were to (i) extend the test conditions in Task (2) to ascertain the previous findings, (ii) evaluate whether blending produces proportional or disproportional benefits, and (iii) start investigating interactive effects of different fuel properties and an exhaust after-treatment system.

2.0 SUMMARY OF PREVIOUS LITERATURE SURVEY

Results of ten typical studies [1-10] on FT fuels reported during 1997-2002 have been presented in the first annual report and are briefly summarized here. The current work in this program distinguishes from previous studies in two respects: The current study is done on a modern advance engine that has incorporated much of the latest engine technology Model year 2002 heavy duty engine). Secondly, a wide injection timing sweep and EGR rates were tested and combustion characteristics analyzed via in-cylinder pressure measurements.

The reports in the aggregate compared FT fuels with regular diesel fuels in combination of engine and vehicle tests, including steady-state and Transient Cycle results. These studies covered different engines and test conditions and were done at a variety of locations including Southwest Research Institute, West Virginia University, UC Berkeley, Sasaol Oil, and in Sweden. The aggregate results showed consistently lower NO_x and particulate emissions of using FT fuel over conventional diesel fuel. However, most results showed NO_x reductions to be less than 20% while particulate reductions ranged from 10-40%. All of the previous studies indicated that further engine optimization of the engine, fuel, and emission control systems would yield more advantages in the future.

3.0 CUMULATIVE ACCOMPLISHMENTS

MIT has measured and correlated the NO_x and particulate emission trends with combustion characteristics for a modern diesel engine (Cummins MY 2002 ISB 5.9 liters). Different injection timing strategies as well as EGR rates were explored. Initial results using limited quantities of the FT fuel and 400 ppm sulfur fuel showed NO_x reductions of 6-13% and particulate reductions of FT fuel up to 75% compared to the 400 ppm sulfur diesel fuel.

Subsequent tests expanded the test matrix. MIT explored substantial changes in fuel injection timings and EGR rates from the standard factory settings and included 15 ppm and 400 ppm sulfur diesel fuel, as well as FT/diesel blends (25% FT/75% diesel by volume). While NO_x reductions were still limited to 20% or less, the bulk of the data showed particulate reductions between 25-50%. Particulate reductions of up to 75% by FT fuel compared to diesel were observed at extremely retarded timing and light load conditions, primarily due to the increase of particulates of the regular diesel fuel at those extreme conditions.

Comparison with the ultra low sulfur fuel indicates that the particulate reduction benefit of FT fuel originates beyond the zero sulfur content of the FT fuel. In fact, the analyses suggest that the FT fuel maintains its combustion rates, even as injection timings are severely retarded and EGR rates heavily increased to reducing NO_x. This is in contrast to conventional diesel fuel, where these conditions result in an increase in particulates.

Hence, we have shown that FT fuel offers another extra flexibility to the engine designer in optimizing the combined fuel/engine/emission-control system.

MIT has started investigating the impact of using the FT fuel on emission control via exhaust after-treatment. A diesel particulate trap system, consisting of four parallel units of 6" in diameter each, has been design and procured and provisions made for its installation in the exhaust system. The experiments will address differences in trap regeneration characteristics, if any, of using FT fuel and opportunities made available, such as enhanced

catalytic reactions, in a sulfur-free exhaust stream. The next phase of the current project will focus on this area.

4.0 REPORT ORGANIZATION AND DISCUSSION OF RESULTS

Following a summary of the Experimental Set-Up in Section 5, the Fuels tested in Section 6, and the Test Matrices in Section 7, the Results of the effects of FT fuel versus conventional diesels, as well as blends will be discussed in Section 8. Section 9 summarizes the progress to-date on the study of the impact of FT fuel use on the Exhaust After-treatment System.

5.0 EXPERIMENTAL SET-UP

5.1 Engine

Cummins supplied a close-to-production development engine based on the model year 2002 (MY02) ISB 300. The ISB 300 is a turbocharged, 6-cylinder, 5.9-liter direct injection diesel engine. The engine is rated at 224 kW (300 hp) at 2500 RPM and 890 N-m (660 lb-ft) torque at 1600 RPM. In order to meet 2002 EPA standards, the engine has advanced subsystems like a Bosch common-rail fuel injection system, Holset variable geometry turbocharger, and cooled-EGR system. To control these devices, the ISB 300 has an electronic control module (ECM) (version CM 850) that has been calibrated to meet emissions when operating with an EPA No. 2 diesel fuel. Table 5.1 contains further detailed information of engine specifications and geometry.

Model	Cummins ISB 300
Number Of Cylinders	6
Combustion System	Direct Injection
Aspiration	Turbocharged
Stroke (Displaced) Volume [liters]	5.9
Bore [mm]	102
Stroke [mm]	120
Connecting Rod Length [mm]	192
Crank Radius [mm]	60
Compression Ratio	17.2
Valve Timing	IVO = 9.5° bTDC IVC = 23.5° aBDC
	EVO = 142.0 °aTDC EVC = 18.0° aTDC
Injection Nozzle	O.D. = 158 μ m, L = 1.00 mm
	8 Sac-less (VCO) Nozzles Per Injector

Table 5.1 Pre-production ISB 300 engine details.

5.2 Engine Control Software

The pre-production ISB 300 engine came equipped with an unlocked ECM, allowing for engine calibration changes and real-time monitoring and modification of engine parameters. To communicate and link to the engine's ECM, Cummins provided their in-house software, CalTerm (Calibration Terminal) version 7.63. Once the engine was installed, the stock 300-horsepower calibration, based on No. 2 diesel and provided by Cummins was uploaded into the ECM. This was done to ensure the engine would run on the 2002 EPA-emission-certified performance maps.

CalTerm allows for the monitoring and modification of hundreds of engine parameters. The important parameters modified in the experiments include the start of main injection and EGR fraction. The response time after commanding an injection timing change is trivial, since the electronic control of fuel injection with the common-rail system provides a response time dependent only upon the speed of the signal from the ECM. For adjustments to the EGR fraction, changes take a few seconds to settle since the ECM tries to find the best path to move to a different state. The coupling of engine load, turbine inlet pressure, turbine exhaust backpressure, intake manifold boost pressure, and EGR valve position required the ECM to optimize changes to prevent the system from reaching an unstable state. One last commanded parameter that was changed enabled cylinder cut out. During engine shakedown and TDC determination, the engine parameter FSI_x_ExtCylMask_c was set to 001F (hexadecimal representation of cylinder 6) in order to cut fueling to the cylinder so that motoring pressure traces could be recorded.

Various other parameters were monitored and logged, including charge flow, pilot injection quantity and timing, post injection quantity and timing, and common-rail accumulator pressure.

5.3 Dynamometer Setup and Dynamometer Controller

A Digalog AE 250 eddy current dynamometer, able to absorb up to 250 kW, was used to load the engine. A Maywood Instruments U4000, 500 kg load cell measures torque by resisting the rotation of the outer casing. A differential pressure switch on the cooling-water outlet protects the dynamometer from failing if the cooling water supply happens to shut off.

Connecting the engine to the dynamometer is a drive shaft assembly made with two Spicer 1710 Series flange yokes attached to a 10.16 cm (4") O.D. tube. The flange yokes are rated to withstand up to 1220 N-m at steady state or spikes of up to 6500 N-m. The drive-shaft is installed at about an 8° to relieve stresses in the flange yokes as they rotate.

A Digalog Model 1022A-STD dynamometer controller was used to control engine speed while reading out the load from the Maywood Instruments load cell. The PID settings in the dynamometer controller were also adjusted to reduce load fluctuations when the commanded throttle setting changes. Before any tests were run, the controller and dynamometer were calibrated at two points, the 50% and 100% loads of the engine.

5.4 Data Acquisition System

A full complement of National Instruments data acquisition (DAQ) hardware and software was used to measure and record various temperatures, pressures, and flows. The heart of the system is the high-speed DAQ board, a National Instruments PCI-6024E. This board can read up to 200,000 samples per second. The high-speed DAQ board is limited to 16 single-ended channels (signals with a common ground) or 8 differential channels (signals with separate grounds). In order to get around this limitation, an SCXI-1000 multiplexing chassis was also used. The SCXI-1000 chassis can house up to 4 special modules, containing various signal amplification, isolation, and noise suppression circuitry. The multiplexing chassis works by quickly scanning, one after another, all the channels of each module installed streaming the data into one differential channel of the DAQ board.

A special 32-channel module for thermocouples (SCXI-1102B) containing a fixed low-pass filter of 200 Hz was installed into the multiplexing chassis. The SCXI-1102B allows for gain and filter settings to be programmed on a per-channel basis. Most slow-speed signals were connected to this module. Attached to the SCXI-1102B is a TBX-1303 terminal block. The TBX-1303 provides a convenient location for the sensors to wire into while also containing a cold-junction-compensation sensor to provide a reference voltage to correctly scale any thermocouples plugged into the terminal block. A general 32-channel module (SCXI-1100) was used for mixed measurements. This module has user-selectable low-pass filter settings (4 Hz, 10 kHz, and no filter) that apply to all channels. Since high-speed cylinder measurements (see Section 0) were recorded through this module along with various slow-speed signals, the 10 kHz filter setting was used to provide some noise filtering while preventing the possibility of introducing phase errors into the high-speed signals due to poor low-pass filter response. Another TBX-1303 terminal block is attached to the SCXI-1100 module to facilitate sensor wiring.

5.4.1 Crank-Angle-Resolved (High Sampling Rate) Measurements

High-speed measurements taken during the experiments consisted of in-cylinder pressure, intake manifold pressure, and engine-position-indexing signals. Since in-cylinder pressures in a diesel engine can rise very rapidly after the auto-ignition event, a high-resolution crank-angle encoder was installed onto the tone wheel to act as an external clock to the DAQ system. An 1800-pulse-per-revolution BEI encoder provides a 0.2° resolution for the high-speed data. The BEI encoder also has another channel that gives out one digital pulse per revolution. This once-per-revolution signal was used to trigger the high-speed DAQ measurements, ensuring the data recording started at the same point of an engine revolution, although not always on the same stroke. This removed the need to superimpose a reference signal to the cylinder pressure data.

The pre-production ISB 300 engine installed at MIT was actually used at Cummins to perform development work on the engine currently available on the market. When the engine was shipped to MIT, an AVL QC33C heavy-duty pressure transducer was already installed in cylinder number 6 (cylinder closest to flywheel). The QC33C is a quartz, piezo-electric pressure transducer that is actively liquid-cooled to reduce the effects of thermal shock. A Bernard Model 2500SS MIG welder cooler is plumbed into the pressure transducer

and circulates and cools a 50:50 mixture of distilled water and ethylene glycol. The transducer's small current output is converted to a voltage using a Kistler Model 5010B charge amplifier. The charge amplifier's output is fed into the DAQ system.

Since piezo-electric pressure transducers only measure changes in pressure, a method of referencing the pressure is required. The intake manifold pressures recorded along with the in-cylinder pressure provide a value to peg the cylinder pressure. The in-cylinder pressure signal is usually averaged around BDC and then scaled to equal the intake manifold pressure.

In order to provide precise fueling, the engine's ECM not only must know where the pistons are in relation to TDC, it also needs to differentiate which aspect of the four-stroke cycle each piston is going through. To provide engine-position data, the engine has Hall-effect sensors on both the camshaft and tone wheel. The tone wheel is a 60 (-1) design, originally containing 60 equally spaced teeth with one removed to provide a point of reference. The signal from the tone-wheel sensor was also fed into the DAQ system to check the phasing of the in-cylinder pressure signal.

5.5 Fueling System

Prior to this reporting period, work on this project used two Exact Flow Model EFM84 single-rotor turbine flow meters to measure volumetric fuel flow to and from the engine. This system was replaced due to a failure of one of the Exact Flow meters and a gravimetric system of fuel flow measurement was installed in its place. This system consisted of an Ohaus Scout II Pro balance and a four-liter beaker containing some quantity of fuel. The balance was connected to the serial port of the data acquisition computer and continuously polled to display the updated fuel mass every second. Because only about one gallon of fuel could be contained in the beaker, fuel flow data was only taken when gaseous emissions data was recorded. The counter flow heat exchangers installed for the previous system were retained, though they were superfluous as the new system measures the mass flow directly without the need to correct for temperature. To control the fuel supply and return, two three-way ball valves were installed to select either the beaker or tank as fuel source, and likewise for return. The beaker was generally refilled by selecting the tank as a source and the beaker for the return.

In order to prevent cross contamination of sulfur and aromatics between the two fuels used in the experiments, two 81.4-liter (22-gallon) ATL Inc. SP122B racing fuel cells were installed on the engine test bed. Two bulkhead connections near the engine allow switching between the individual fuel tanks. Another bulkhead allows for fuel to bypass the return system in order to drain the entire system or purge standing fuel in various fuel galleries in the engine when changing fuels. The entire fuel system uses Teflon lines since diesel fuel is a strong solvent, while stainless-steel over-braids over the Teflon protect them from physical wear and tear.

5.6 Intake Air Measurement and Preparation

An Eldridge Products, Inc. Series 8732 thermal mass flow meter measures airflow into the turbocharger's compressor inlet. The inline-style flow meter consists of a sensing element,

installed into a flow section. The flow section has a laminar flow element to ensure fully developed flow by the time the air reaches the sensing element. The sensing element uses two RTDs (resistance temperature detector) to measure airflow. One RTD measures the temperature of the incoming. The second RTD is forced through self-heating to maintain a constant temperature above the incoming gas. The sensing element's signal processor takes both the required current to heat the second sensor and the initial temperature read by the first RTD to calculate the mass of air flowing through the flow section. A K&N paper filter fitted upstream of the thermal mass flow meter filters the ambient air in the test cell before it flows into the engine.

After being compressed by the turbocharger, the pressurized air leaving the turbocharger is extremely hot. To reduce peak pressures in the engine, the compressed air is cooled once it leaves the compressor. A Spearco Universal Air/Liquid Intercooler was used to cool the fresh charge leaving the turbocharger. The amount of charge-air cooling is controlled by a gate valve on the liquid side of the charge-air cooler that controls the flow of water through the core of the charge-air cooler. Connections between the engine and aftercooler are made with 7.54 cm (3") I.D. silicone rubber hose, capable of withstanding temperatures up to 450 K.

5.7 Gaseous Emissions Analyzers

Figure 5.1 Emission sampling system schematic

Figure 5.1 shows a schematic of the emission sampling system. To measure hydrocarbon emissions, a California Analytical Instruments (CAI) Model 300-HFID was installed. The Model 300-HFID was calibrated with 300 PPM propane (C_3H_8), so the effective range was 0 – 900 PPM of C_1 . During experiments, the Model 300-HFID was left on the 0 – 30 PPM range since HC emissions from diesel engines are low. To measure HC, a flame ionizes the sample stream and electrodes in the instrument measure the particles. The flame in the Model 300-HFID is fueled by HC-free air and a fuel mixture of 40%/60% H_2/He .

A California Analytical Instruments Model 400 HCLD Heated chemiluminescence NO_x analyzer was used to measure NO_x concentration in the raw exhaust. For engine-out NO_x, a sample point about 10 pipe diameters away from the nearest elbow was used, ensuring fully developed flow at the sample point. To calibrate the Model 400, a calibration gas of 296 PPM of NO_x and zero gas of high grade compressed air was used to create a linear voltage output between the two concentrations. This output of is fed into the DAQ system, and the voltage read is converted back to a PPM concentration and recorded.

The sample for both CAI instruments was carried from the sample point through a 25' heated line to a Universal Analyzers Model 270S heated stack filter that removes any large particulate matter that can also clog sample and capillary tubes within the gas analyzers.

For CO₂ measurements, a Horiba MEXA 554 JU was used. CO₂ measurements were taken from three sample streams: raw exhaust, intake air and dilution tunnel air. These figures were used to do consistency checks of the fuel and air flow measurements and to calculate EGR and dilution ratios. For intake-mixture CO₂ (for EGR fraction calculations), a sample point 0.1016 m (4") downstream from the closest elbow (0.3048 m (12") from EGR valve) was installed. The intake sample point was installed in the middle of the intake air heater, the heating elements within the flow stream acting as guide vanes, helping to distribute the flow uniformly. For dilution ratio measurements, a sample point was installed about 0.762 m (30") away from the transfer tube, again ensuring fully developed flow at the sampling point.

All engine and dilution sample points for CO₂ measurements are connected to a bulkhead holding various 3-way valves to switch between various sample points. The engine-out gas stream is transferred to the bulkhead using a one-meter Teflon tubes. All samples from the bulkhead are drawn through a 0.5 micron filter by a Gast diaphragm pump. A check valve is installed upstream of the filter and pump to avoid over-pressurizing the pump when intake manifold samples are collected. The sample is then passed through a canister containing Drierite desiccant to prepare the sample for the CO₂ analyzer.

5.8 Mini-Dilution Tunnel

The EPA defines particulate matter as all solid matter and condensable species that can be collected on a paper filter from a diluted exhaust sample held at no higher than 52°C [12]. The EPA defines particulate matter in such a way since it forces the sampling system to employ some form of a dilution tunnel that helps simulate particle transformations (i.e. agglomeration, adsorption, and nucleation) that would normally occur outside of the laboratory. Dilution tunnels can be designed to condition the entire exhaust flow or can be arranged in such a way as to only take and dilute a small sample of the exhaust.

The mini dilution tunnel used with the experimental setup is based on the dilution of a fraction of the exhaust stream. The dilution tunnel is predominantly made of 75.4 cm (3") O.D. stainless steel 304 tubing. The exhaust gas sample is transferred, due to a positive pressure differential, through a 1.88 cm (3/4") O.D. tube with a high-temperature resistant ball valve in place to regulate exhaust gas flow. The transfer tube introduces raw exhaust into the dilution tunnel 0.762 m (30") away from the sample point, allowing the dilution air and raw exhaust to mix and become fully developed before being sampled. The pressure in the dilution tunnel is held below atmospheric conditions by connecting the exit of the dilution

tunnel to the intake of a Spencer Model 1001-1/2SS blower. As air is drawn through the mini dilution tunnel, the pressure drops due to losses within the tubing. A Solberg FS-31P-250 air filter holder with a HEPA filter element is installed at the inlet of the dilution tunnel system, providing an additional pressure drop within the tunnel. The dilution ratio is measured by comparing the CO₂ readings in the tunnel to the CO₂ readings in the raw exhaust.

5.9 Gravimetric Particulate Matter Sampling System

The gravimetric particulate matter sampling system used to sample raw and dilute gas samples employs a Pall Corporation stainless steel 47mm filter holder that housed Pall Corporation Pallflex® Fiberfilm glass filters (Model T60A20-47 MM). Made with borosilicate glass fibers and a moisture-resistant fluorocarbon (TFE) coating, the Pallflex Model T60A20 brand of filters resist moisture uptake and prevent moisture-gas reactions, eliminating the need for lengthy drying times when using normal hygroscopic glass fiber filters. As such, the EPA recommends the Model T60A20 brand of filters for use in gravimetric filter measurements [13]. The Model T60A20 filters can also withstand very high temperatures, up to 315.5°C, making it ideal for raw exhaust gas sampling as well.

To measure sample flow through the filter, an Omega FVL-1611 volumetric flow meter was installed downstream of the filter/filter holder assembly. The Omega FVL-1611 sensor body houses a differential pressure transducers, a thermocouple, and a laminar flow element that the flow computer uses to measure flow rates up to 250 SLPM. The flow computer output is fed into the National Instruments DAQ system, so flow rates over time can be recorded, then averaged. This helps account for the variation in flow rates as the filter paper is loaded. A Gast Model 0823 rotary vane vacuum pump was used to draw the raw or dilute sample through the sampling lines, filter paper, and mass flow meter. To prevent condensation of particles on the walls with raw exhaust samples, the stainless steel lines from the raw exhaust sample point were insulated with silicon-rubber based tubing insulation. Also, a rope heater was installed from the sample point to a position 1.524 m (5 feet) downstream.

6.0 EXPERIMENTAL FUELS

6.1 Number 2 Diesel Fuel

The No. 2 diesel fuels used to create a performance and emission baseline were supplied by Fleetline, distributed by Dennis K. Burke Inc. Based on the product information brochure, these fuel are formulated with anti-oxidants to reduce volatility and prevent fuel degradation, inhibitors to fight gum and deposit formations in the fuel system, viscosity improvers for fuel injector lubrication and correct spray pattern, and additives for low-temperature operation.

6.1.1 Low Sulfur Diesel Fuel

Initial work on this project used Fleetline's "Low Sulfur Diesel Fuel." Although this diesel fuel has a fuel-sulfur content of 400 PPM (see Table 6.1), it still meets the EPA Low-Sulfur Fuel requirement (<500 PPM). Also, since it meets the ASTM D 975 specifications for No. 2 diesel fuel, it should contain a high aromatic content, although no more than 35% as required by law (see Table 6.2). As this is a typical worst-case fuel currently allowed and

available to on-road heavy-duty diesel engines, it was used to provide a good baseline to compare the improvements seen when running with FT fuel.

6.1.2 Ultra-Low Sulfur Diesel Fuel

To provide a more realistic baseline for comparison for FT fuel, baseline tests were also performed with Fleetline's "Ultra-Low Sulfur Diesel Fuel," which meets the 2006 standard of 15 PPM sulfur by volume. The purpose of using this fuel is twofold: first, to allow for evaluation of fuel sulfur effect on emissions and second to compare FT fuel to a fuel that will be widely available.

The lower heating value of the No. 2 diesel fuel is not listed in the table provided by Fleetline. In order to compare the lower heating value of the No. 2 diesel fuel to the Syntroleum Fischer-Tropsch fuel used in the experiments, the lower heating value for an EPA No. 2 diesel fuel given by Syntroleum's S-2 brochure was used [15]. The value reported in the brochure is: $Q_{LHV, No.2} = 129,400$ Btu/gal. Converting this to SI units on a mass basis requires the density of the fuel. Table 6.1 lists the API (American Petroleum Institute) gravity obtained using the ASTM D 287 method. The ASTM D 287 method lists API gravity at 16°C as:

$$\text{Equation 6.1} \quad API @ 16^{\circ}C = \frac{141.5}{s.g. @ 16^{\circ}C} - 131.5$$

Using the above equation and an average API gravity of 35, we get a fuel density of $\rho_{No.2} = 840$ kg/m³. Finally, converting the lower heating value appropriately leads to a lower heating value of $Q_{LHV, No.2} = 42.9$ MJ/kg. This checks closely to data about general light diesel fuels listed as $Q_{LHV, No.2} = 43.2$ MJ/kg in [16].

In order to make combustion-characteristic comparisons between No. 2 diesel and Syntroleum S-2 FT diesel, a simplified chemical composition of $CH_{1.8}$ and molecular weight of 170 g/mol [16] was used in order to write the ideal combustion equation (using the simplified chemical composition) for No. 2 diesel as follows:

$$\text{Equation 6.2} \quad 12.3CH_{1.8} + \frac{17.835}{f}(O_2 + 3.773N_2) \rightarrow 12.3CO_2 + 11.07H_2O + 17.835\left(\frac{1}{f} - 1\right)O_2 + \frac{67.29}{f}N_2$$

Using Equation 6.2, the air/fuel ratio of No. 2 diesel fuel is 14.50:1. This equation was used in the analysis of both the 400 PPM and 15 PPM fuel

ULTRA LOW SULFUR DIESEL

TEST DESCRIPTION	ASTM METHOD	ASTM NO. 2-D STANDARD (D 975)	TYPICAL ANALYSIS
Cetane Index (Calculated)	D 976	40 min.	42.7
Cetane Number	D 613	40 min.	50
API Gravity at 16°C (60°F)	D 4053	30 min.	40.3
Density, lbs./gallon	Table 8	–	6.858
Pour Point, °C (°F)	D 97	–6 (20) max.	–30 (–22)
Cloud Point, °C (°F)	D 2500	–	–30 (–22)
Flash Point (Pensky-Martens), °C (°F)	D 93A	52 (125) min.	63 (146)
Heat of Combustion, BTU/gallon	D 240	–	135,514
Viscosity, Saybolt, SUS at 38°C (100°F)	D 2161	32.6-40.1	31.47
Viscosity, Kinematic, cSt at 40°C (104°F)	D 445	1.9-4.1	1.67
Sulfur, parts per million	D 5453	30 max.	15
Nitrogen, parts per million	D 5762	–	5
Corrosion, Copper Strip	D 130	1 max.	1
Alkali or Mineral Acids	D 974	–	neutral
Distillation (Evap.), °C (°F)	D 86		
10% Recovered		–	199 (390)
50% Recovered		–	218 (425)
90% Recovered		282-338 (540-640)	248 (478)
End Point		–	269 (517)
Recovery %		–	98.0
Residue %		–	1.4
Loss %		–	0.6
Carbon Residue, Wt. % (10% Bottoms)	D 524	0.35 max.	0.15
Water and Sediment, Vol. %	D 1796	0.05 max.	0.00
Ash, Weight %	D 482	0.01 max.	0.00
Color (Visual)	D 1500	(Clear to Amber)	< 0.5
Date Approved: 2/15/04 (Specification valid only if dated)			

Table 6.1 Manufacturer's specifications for the baseline No. 2 diesel used in experiments

6.2 Syntroleum Fischer-Tropsch Fuel

The Syntroleum Corporation provided the Fischer-Tropsch fuel (Syntroleum S-2) used in the experiments. Syntroleum S-2 fuel is synthesized using the Syntroleum Process™, which consists of a special reformer (auto-thermal-reformer, ATR) that produces synthesis gas using untreated air. This reduces the overall production costs, making S-2 fuel economically marketable.

Due to the zero-sulfur content (not listed in preliminary specifications, but found in [15]) of the S-2 fuel, the lubricity properties of the fuel are low, increasing the likelihood of wear and tear in the fuel injection system. To pass lubricity tests, 300 PPM of a lubricity additive from Lubrizol was added to the fuel before shipping to MIT. The Lubrizol additive should not affect the combustion characteristics of the S-2 fuel. Lubricity additives contain polar groups that attracts to metal forming a thin surface film on the injector surfaces that are subject to wear [15].

ASTM D 975 Requirements for Diesel Fuel Oils

Property	Test Method*	Low Sulfur No. 1-D	No. 1-D	Low Sulfur No. 2-D	No. 2-D	No. 4-D
Flash point, °C, min	D 93	38	38	52	52	55
Water and sediment, % vol, max	D 2709 D 1796	0.05	0.05	0.05	0.05	0.50
Distillation temperature, °C, 90% vol recovered	D 86					
min				282	282	
max		288	288	338	338	
Kinematic viscosity, 40°C, cSt	D 445					
min		1.3	1.3	1.9	1.9	5.5
max		2.4	2.4	4.1	4.1	24.0
Ash, % mass, max	D 482	0.01	0.01	0.01	0.01	0.1
Sulfur, % mass, max	D 2622	0.05	0.50	0.05	0.50	2.00
Copper strip corrosion, 3 hr at 50°C, max rating	D 130	No. 3	No. 3	No. 3	No. 3	
Cetane number, min	D 613	40	40	40	40	30
One of the following: 1) Cetane index, min 2) Aromaticity, % vol, max	D 976 D 1319	40 35		40 35		
Ramsbottom carbon residue on 10% distillation residue,	D 524	0.15	0.15	0.35	0.35	

* All "Dxx" methods are ASTM standards.

Table 6.2 ASTM D 975 requirements for diesel fuel oils

Like many other FT diesel fuels available, the S-2 fuel has a combination of advantageous properties. The S-2 fuel has a very high cetane index (CNI = 74.4), zero aromatic content, and zero olefin content. Furthermore, it has a viscosity similar to that of No. 2 diesel, eliminating the need any modifications to the fuel injection system to properly handle the fuel.

The lower heating value of Syntroleum S-2 was calculated using information from Syntroleum Corporation's product brochure and values listed in Table 6.3. The product brochure lists a lower heating value of $Q_{LHV,S-2} = 121,500 \text{ Btu/gal}$. Converting this to a mass basis with the S-2 density listed in Table 6.2 as $\rho_{S-2} = 775 \text{ kg/m}^3$ results in a value of $Q_{LHV,S-2} = 43.7 \text{ MJ/kg}$.

Correspondence with Syntroleum provided further S-2 properties, necessary to do combustion calculations. The molecular weight of the FT fuel is 205 g/mol with a chemical composition of 84.9% carbon and 15.1% hydrogen, with no other impurities detectable (i.e. oxygen and nitrogen). This composition gives a reduced chemical C:H ratio of $\text{CH}_{2.12}$ for the S-2 diesel fuel. Using this simplified composition, the ideal combustion formula for Syntroleum S-2 is:

$$\text{Equation 6.3} \quad 14.49\text{CH}_{2.12} + \frac{22.17}{f}(O_2 + 3.773N_2) \rightarrow 14.49CO_2 + 15.36H_2O + 22.17\left(\frac{1}{f} - 1\right)O_2 + \frac{83.65}{f}N_2$$

Using the above equation nets an air/fuel ratio of 14.95:1 for Syntroleum S-2 diesel.

Sample Data & Preliminary Product Specification

Syntroleum®

S-2

RDIL 4047

S-2 is an additized, highly paraffinic, high-cetane distillate product suitable for use as a fuel cell fuel and in compression ignition engines. S-2 combustion emission characteristics are superior to petroleum-based diesel fuels.

SYNTHETIC DIESEL FUEL (CONTAINS ADDITIVES)

PHYSICAL PROPERTIES	TEST METHOD	UNITS	SPECIFICATION VALUE	TYPICAL VALUE	SAMPLE PROPERTIES
Specific Gravity, 15°C	ASTM D-4052	°C		0.771	0.775
API	ASTM D-4052	°		52.0	51.1
Flash Point	ASTM D-93	°F, (°C)		148, (64)	142, (61)
Cloud Point	ASTM D-5771	°F, (°C)		<0, (<-18)	-13, (-25)
Color	ASTM D-1500			L0.5	L0.5
Viscosity	ASTM D-445	cSt @ 40°C		2.1	2.2
		cSt @ 100°C		1.0	1.0
Copper Strip	ASTM D-130			1a	1a
Bromine Index	ASTM D-2710	mg/100g			179
Cetane Index	ASTM D-976			>74	74.4
Distillation, IBP, vol%	ASTM D-86	°F(°C)		320 (160)	347 (175)
10		°F(°C)		390 (199)	395 (202)
50		°F(°C)		493 (256)	487 (253)
90		°F(°C)		601 (316)	601 (316)
FBP		°F(°C)		662 (350)	648 (342)
Ash	ASTM D-482	wt%		<0.001	
Aromatics	ASTM D-1319	vol%		nd*	
Olefins	ASTM D-1319	vol%		nd*	
Saturates	ASTM D-1319	vol%			
Carbon Res.	ASTM D-524	wt%		nd*	
Total Insolubles		mg/100ml		0.0	
Lubricity	ASTM D-6079	mm		<0.37	

*nd indicates Not Detectable by the prescribed test method. Result is either below method detection limit or outside of method range.

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Table 6.3 S-2 fuel properties. Fuel used in experiments was from a preliminary run in Syntroleum's pilot plant

6.3 Fuel Blends

To examine how varying fuel properties contribute to emissions reductions, fuel blends were studied. This allowed assessment of the effect of fuel sulfur level on particulate emissions.

6.3.1 25% FT/75% D2 Blend

This blend was used to show whether the advantages of FT fuel could be realized if it's only a portion of the engine's fuel. Other studies have found that the effect on emissions does not go linearly with the portion of FT in the blend, rather that most of the benefit can be had with less than 50% FT in the blend. Given our setup, it was convenient to choose a 3:1 by volume D2 to FT fuel ratio. Derived from the above figures for standard and FT fuel, the following properties were used in the analysis. Converting 25% by volume FT fuel to a mass basis yields a fuel density of 824 kg/m³ and 23.5% FT fuel by mass. Based on a 25% molar fraction of FT, the simplified composition of the blend is CH_{1.9}. Assuming complete combustion, this yields the ideal combustion:

From this, the stoichiometric air-fuel ratio is 14.61:1

7.0 EXPERIMENTAL TEST MATRIX AND PROCEDURE

7.1 Engine Operation

Since the test engine is a close-to-production design incorporating advanced subsystems to control emissions, a proper test matrix was designed to include the effects of engine technology on fuel properties. The start of main injection and EGR fraction parameters was varied. The electronic control module, ECM, was left alone in every other respect, letting it command the values for such parameters as charge flow, pilot and post injection quantities, and pilot and post injection timings and execute the correct algorithms to move between states that are contained in the original No. 2 diesel calibration. This provides the worst-case scenario for a modern engine that switches to FT fuel without properly calibrating the ECM to account for the change in fuel properties.

7.1.1 Experimental Test Matrix

As part of engine development, Cummins uses the European Stationary Cycle (ESC) outlined by the Euro-III directive that came into effect in October 2000 [17]. The test modes are found in Table 7.1. In general, high average load factors and very high exhaust gas temperatures, simulating actual on-road driving conditions quite well, characterize the ESC test. The engine speeds A, B, and C are defined by the following: 1) the high speed RPM, RPM_{high}, is defined by calculating the highest engine speed (above the rated speed) where 70% of the declared maximum net power occurs, 2) the low speed RPM, RPM_{low}, is defined by calculating the lowest engine speed (below the rated speed) where 50% of the declared

maximum net power occurs, 3) the following formulas are then used to calculate each mode speed:

Equation 7.1
$$A = RPM_{low} + 0.25 * (RPM_{high} - RPM_{low})$$

Equation 7.2
$$B = RPM_{low} + 0.50 * (RPM_{high} - RPM_{low})$$

Equation 7.3
$$C = RPM_{low} + 0.75 * (RPM_{high} - RPM_{low})$$

Using the above equations with the torque and power curves of the test engine gives the following values for the above mode speeds: A = 1682 RPM, B = 2013 RPM, and C = 2345 RPM.

Condition	RPM	BMEP	EGR	Timing Sweep				
A25	1682	470	-10%	-7	-3	Stock	+3	+7
			Stock	-7	-3	Stock	+3	+7
			+20%	-7	-3	Stock	+3	+7
A50*	1682	1000	-10%	-7	-3	Stock	+3	+7
			Stock	-7	-3	Stock	+3	+7
			+10%	-7	-3	Stock	+3	+7

*This point is actually 53% load

Table 7.1 Test matrix used in previous work

7.1.2 Expanded Test Matrix

While last year's test matrix was constrained by fuel availability, such problems were not predicted for this reporting period, and as such, the test matrix was modified to represent a larger portion of the engine's operating range.

Condition	RPM	BMEP	EGR	Timing Sweep				
A25	1682	470	Stock	-7	-3	Stock	+3	+7
			+10%	-7	-3	Stock	+3	+7
			+20%	-7	-3	Stock	+3	+7
B50	2011	950	Stock	-7	-3	Stock	+3	+7
			+10%	-7	-3	Stock	+3	+7
B75	2011	1400	Stock	-7	-3	Stock	+3	+7

Table 7.2 Test matrix for current reporting period

This test matrix was designed to complement the data previously collected in several ways. As can be seen in Tables 1 and 2, there is significant overlap in the A25 condition. The purpose of this is two-fold: to provide an opportunity to correlate current results with old data and to allow a direct comparison of 400ppm and 15ppm sulfur fuel to FT fuel. To complement the A50 data previously taken, the 50% load was retained, but the engine speed was increased to 2011 RPM. Finally, with a larger supply of FT fuel available, it was possible to take 75% load data at 2011. This extends the scope of the work to cover a representative sample of engine operating conditions.

As noted in the 2003 report, FT fuel reduces PM output significantly, thereby avoiding the so-called PM-NO_x tradeoff typical in emissions control strategies. Essentially, FT should allow EGR to be pushed to the practical limit, allowing for significant reduction in NO_x with little (or no, in an optimized system) NO_x increase. As such, the EGR sweep for the A25 points was adjusted to include stock+20% absolute EGR rate in lieu of the –10% point.

A25-	Timing				
EGR	Stock	-3	-7	+3	+7
Stock (20%)	01	02	03	04	05
30%	06	07	08	09	10
40%	11	12	13	14	15
B50-	Timing				
EGR	Stock	-3	-7	+3	+7
Stock (18%)	01	02	03	04	05
23%	06	07	08	09	10
B75-	Timing				
EGR	Stock	-3	-7	+3	+7
Stock (18%)	01	02	03	04	05

Table 7.3 Definitions of operating conditions and data set labeling convention

Data sets recorded in experiments and presented here adhere to a prescribed naming convention that indicates fuel used and engine operating parameters. Excepting data for 15 PPM baseline fuel, a 2 to 3 letter prefix indicates the type of fuel for the data set. FT, BL and HS represent Fischer-Tropsch, FT/15 PPM blend and 400 PPM fuel, respectively. There is no prefix for the baseline fuel and ancillary blends used in one experiment also get a digit (e.g., BL2). Following the fuel specification, the general operating condition is indicated by the letter corresponding to the speed and two digits representing the percent load for that speed, as outlined in table 7.2. Following the load/speed information is a hyphen and another pair of digits indicating the timing and EGR rates, relative to stock. For example, BLA25-03 is for

25% load (224 N-m) at the A speed (1682 RPM) with FT/15 PPM blended fuel, stock EGR rate and timing retarded 7 degrees.

7.2 Particulate Matter Sampling Conditions

Unlike prior work reported, this study included particulate data from gravimetric sampling of both dilute and raw exhaust. Before each test, the Pallflex filter papers were placed in individual plastic petri dishes and allowed to condition for at least 8 – 56 hours as recommended by the EPA [13]. All filter preparation, conditioning, and settling were done in an air-conditioned room where the temperature was between the EPA mandated range of 68° – 86° and relative humidity of 30% – 70%. However, it was found that daily variation in room conditions had a substantial effect on filter mass, in some cases on the order of the entire particulate mass sampled. To correct for this, a set of “control” filters were kept in the sample room at all times so that a correction could be calculated based on the variation of the control filters in the period between filter weighing.

7.2.1 Dilute Exhaust Sampling

Though raw sampling was relied upon heavily last year, with the greater availability of fuel, it was possible to perform dilute particulate sampling. Dilution ratios were generally kept between 7 and 12. The goal was to dilute the exhaust just enough to reduce the temperature below the mandated 52C, and not too much more. This was to keep sample time reasonable. With the Gast rotary vane pump installed, sample times were typically around 15 to 30 minutes to collect at least 2 mg of sample. It was observed that filters sitting idle in the climate controlled conditioning room could vary in weight by 0.5 to 1.0 mg. Even though measures were taken to correct for this, the best way to improve data quality was to collect as much sample as possible.

Unused filter papers were allowed to condition in a climate controlled room for at least 24 hours prior to use. After the conditioning period, four PM samples were taken consecutively to have a large enough sample to average. After the filter papers were loaded, they were again allowed to sit for at least 24 hours in order to dry the paper and settle the particulates.

7.2.2 Raw Exhaust Sampling

Though it typically shows lower PM output than dilute sampling, some raw sampling was performed due to time constraints. Since the raw exhaust is sampled hot and undiluted, the driving forces for nucleation and adsorption of condensable gas species is severely reduced. Therefore, the raw PM emission levels are much less than a comparable sampling run with a dilute sample for the same operating point.

Generally, the dilute sampling produced more consistent results, though both methods are extremely prone to error and leave much room for improvement. Of primary concern is the filter conditioning pre- and post- weighing.

7.3 Engine Operation During Experiments

Before beginning each round of experiments, the CAI Models 300-HFID and 400 HCLD gas analyzers were calibrated with zero and span gases. After the instrumentation was properly calibrated, the engine was then started and allowed to idle for a few minutes as the National Instruments and CalTerm software programs were started and the dynamometer idle torque offset would settle. After all the computers and gas analyzers were ready for use, the ECM settings were left in stock form while the voltage output from the Watlow controller was increased until the appropriate load condition was reached. In the case of raw particulate sampling, warm-up was then run to bring the filter holders and sampling apparatus to operating temperature.

Once the engine reached a steady-state condition, a 60-second scan of all slow-speed engine data was taken. After this, a 30-second scan of the gas analyzers was run and CO₂ was recorded in a lab book. During these runs, the engine's fuel was drawn from the fuel beaker instead of the tank, which provided fuel flow figures for the condition. Once the emissions scans had finished, the first filter sample was begun. During the particulate sampling, the data acquisition system recorded the flow through the filter for calculation of actual engine out data. Between the four particulate samples, another round of emissions data was taken and the particulate sampling process repeated. All in all, four particulate samples were taken in between five sets of emissions and fuel consumption data. Finally, after all PM samples were taken, a final scan of all data was taken, along with a 100-cycle high-speed scan. The 100-cycle scan was taken at the end of all tests (about 20 minutes after the start of the first low-speed scan) since this ensured ample time for all operating parameters to reach a steady state.

7.4 Data Processing and Reduction

The emission data reported by Cummins is given on a wet basis. The values recorded by the Models 300-HFID and 400 HCLD are already on a wet basis, while the Horiba MEXA 554 JU reports data on a dry basis due to the desiccant upstream. Therefore, to convert everything to a wet basis to compare to the ESC data, the water content of the intake and exhaust had to be estimated. The following equation was used to estimate the mole fraction of species in an intake mixture with EGR. The unburned mixture per mole of O₂ is:

$$\text{Equation 7.7} \quad (1 - x_b) \left[\frac{4}{M_f} (1 + 2\epsilon) f (CH_y)_a + O_2 + y N_2 \right] + x_b (n_{CO_2} + n_{H_2O} + n_{CO} + n_{H_2} + n_{N_2})$$

where x_b is the burned gas fraction (equal to the EGR rate in the case of no residuals), M_f is the molecular weight of the fuel, y is the molar H/C ratio of the fuel, ϵ is $4/(4+y)$, ϕ is the fuel/air equivalence ratio, n_i is the mole fraction of species i per mole of O₂ reactant, α is the coefficient to multiply the molecular weight of the simplified chemical composition to equal M_f , and ψ is the molar N/O ratio (3.773 for air). The mole fractions of each species are obtained by dividing by the total number of moles of unburned mixture [13].

$$\text{Equation 7.8} \quad n_u = (1 - x_b) \left[\frac{4(1 + 2\epsilon)f}{M_f} + 1 + y \right] + x_b n_b$$

where n_b , the total number of moles of burned mixture is given by (for a lean mixture) [13]:

Equation 7.9
$$n_b = (1 - e)f + 1 + y$$

An assumption made in the above equations is the residual gas fraction is negligible since the engine is turbocharged. Therefore, x_b is initially equal to the EGR rate determined from the dry-basis CO_2 ratio from scans in the intake and exhaust system. After finding the corrected water vapor mole fraction in the intake, and estimating the water vapor mole fraction from the ideal combustion of the above reactants, the dry-basis CO_2 readings can be corrected to a wet basis, and the actual EGR rate can be determined. The above equations are iterated with the newly determined EGR until a steady-state value is found.

The PM sample flow rate data recorded from the Omega FVL-1611 volumetric flow meter was averaged during the PM sampling period. Any offsets during filter loading were recorded and appropriately applied to get a properly scaled and average sample flow rate across the filter.

7.5 Heat Release Analysis

The heat release analysis used to process the pressure data applies the First Law of Thermodynamics assuming the closed system between intake valve closing (IVC) and exhaust valve opening (EVO) is a single-zone of uniform products. The gas properties are predicted using ideal-gas relationships, with a gas constant for air. The First Law expanded to include various heat sources (neglecting heat loss through crevice effects) is:

Equation 7.10
$$dU_{internal} = dQ_{chemical} - dQ_{HT} - dW$$

where $\delta Q_{chemical}$ is the calculated energy of the fuel, δQ_{HT} is the energy lost through heat transfer and δW is the work term. To apply the First Law to in-cylinder pressure data, the following form of the First Law is used:

Equation 7.11
$$\frac{dQ_{chemical}}{dq} = \frac{1}{g-1} V \frac{dP}{dq} + \frac{g}{g-1} P \frac{dV}{dq} + \frac{dQ_{HT}}{dq}$$

where V is the cylinder volume, P is the cylinder pressure, and γ is the ratio of specific heats. The differential forms of some of the terms are written on a crank-angle basis, since pressure and volume data are normally recorded with a crank-angle encoder as an external clock to the DAQ system. The heat transfer term was determined from a Nusselt-Reynolds number correlation analogous to that used for steady turbulent pipe flow. See Reference [19] for further information on the heat transfer model for its implementation in the heat-release analysis code.

8.0 RESULTS AND DISCUSSION

8.1 Emissions Characteristics

Due to the overall-lean operation of diesel engines, carbon monoxide (CO) levels are negligible. The compression of only air during the compression stroke prevents several major sources of unburned hydrocarbons (UHC) common in pre-mixed engines, thus UHC from diesels are usually within acceptable levels. Therefore, the following discussion focuses primarily on oxides of nitrogen (NO_x) and particulate matter (PM) emission behavior in the experiments.

8.1.1 NO_x Emission Trends

It is well understood that the principal factor driving NO_x formation is in-cylinder temperature during combustion. The extended Zeldovich mechanism is very sensitive to temperature and NO_x control techniques typically attempt to lower peak cylinder temperatures.

Figure 8.1 Summary of BSNO_x results for several conditions

Figure 8.1 summarizes typical results obtained in NO_x experiments in this study. Generally, FT fuel showed a greater positive effect on NO_x output at lower loads, and virtually no effect, or a slight increase, at higher loads.

8.1.1.1 Fuel effects

FT fuel showed around a 19% improvement in NO_x output for the low load, low speed (A25) condition as shown in Figure 8.2. Prior work showed that NO_x output in this low load condition was relatively free from fuel effects. However, it appears that the inaccuracy of the fuel flow measurement system contributed to an over-correction when converting the dry-

basis NO_x concentration to a wet basis. Thus, NO_x output for this condition should have been lower than reported.

Figure 8.2 BSNO_x vs. timing for the low-speed, low load condition with FT and 15 PPM D2 fuels

Figure 8.3 shows the peak cylinder temperature calculated from a first-law heat release analysis of the cylinder pressure data from the stock, 3 degrees advanced and 3 degrees retarded timing points. FT fuel lowers peak cylinder temperature in all cases. Given the strong dependence of NO_x formation on cylinder temperature, the results shown in Figure 8.2 are consistent with the heat release analysis.

Figure 8.3 Cylinder temperature vs. crank angle for two fuels and three timings

High load NO_x data did not show a clear improvement for FT fuel. In fact, in a back-to-back comparison of 3 neat fuels and 3 blends at the low speed, mid load condition, FT fuel and the FT/D2 blends had the highest output. In terms of data analysis, this can be explained by the fact that while the NO_x concentration by volume was typically lower with FT fuel, it requires a higher intake air mass-flow rate for a given condition. Thus, the mass flow out of the engine is higher, yielding a higher NO_x output in g/hp-hr.

Figure 8.4 Fuel effect on NO_x production: BSNO_x output for six fuels

Comparisons of NO_x data collected during high load operation on different days show that environmental conditions can impact results significantly. NO_x data can be corrected for temperature, humidity and atmospheric pressure, however these corrections did not account for the results seen in Figure 8.5. Looking at the heat release analysis, Figure 8.6, for the 15 PPM fuel and the FT/15 blend for the results shown in Figure 8.4 (FT fuel pressure data from this test was unavailable) it is clear that the peak temperature is higher with the blended fuel.

Figure 8.5 BSNO_x for four fuels and five timing points

There are some peculiarities in this graph that are a result of noise in the cylinder pressure signal. This seems to be more of a problem at higher loads.

Figure 8.6 Cylinder temperature vs. crank angle for 15 PPM D2 and FT/15 blend

Figure 8.7 shows the results for the high-speed, high load test of NO_x output. Similar to the mid-load condition, fuel had little effect on NO_x formation and the output from either fuel was essentially the same. However, retarding timing had a significant effect, as expected. Again, this is due to reduced peak cylinder temperatures.

Figure 8.7 BSNO_x vs. injection timing at high speed, high load

The results of this study indicate that FT fuel has little direct effect on NO_x output at high loads, whereas it has a pronounced effect at low loads. Heat release analysis confirms that NO_x output is primarily dependent on cylinder temperature.

8.1.1.2 EGR and Timing Effect on NO_x Emissions

As shown in Figures 8.5, NO_x output is a strong function of injection timing. This well-known trend is a function of the peak gas temperatures during combustion. Peak cylinder pressure and temperature increase appreciably as injection timing is advanced from the stock timing point while noticeable temperature reductions occur as timing is retarded. As mentioned, the predominant NO_x-formation mechanism in diesel engines is thermally driven; as such, NO_x emissions should scale with peak cylinder temperatures. Interestingly, the gas temperatures in the exhaust manifold show the opposite trend with timing, lower temperatures in advanced timing with higher temperatures in retarded timing, beyond TDC. As combustion occurs later in the expansion stroke, less work is extracted per crank angle due to the thermodynamic reduction in efficiency with cooler working fluids, resulting in elevated exhaust gas temperatures.

Very little NO_x data was taken at elevated EGR rates due to an equipment failure. However, the small amount available confirms previous findings and indicates that increasing EGR rate reduces NO_x output regardless of fuel. This is illustrated in Figure 8.8. These results show that FT fuel gives a greater improvement when EGR rate is increased. Of particular interest is the disproportional improvement the blended fuel yields. Consistent with prior results, NO_x outputs dropped from about 15% to 44% when increasing EGR rate from 18% to 23% for the low-speed, mid-load condition, depending on fuel.

Figure 8.8 Change in BSNO_x output with increased EGR rate for four fuels

EGR effectively reduces NO_x in two distinct ways. Similarly to SI engines, EGR acts as a dilutant with added heat capacity, helping reduce peak gas temperatures. More importantly for diesel engines, especially at high loads, EGR reduces the amount of oxygen available. As the fuel-air equivalence ratio increases towards the stoichiometric value, the mole fraction of oxygen steadily decreases while the mole fractions of both carbon dioxide (CO₂) and water vapor (H₂O) steadily increase in the exhaust-gas composition. Furthermore, as the exhaust gas is composed of more polyatomic species, the heat capacity increases (based on the Kinetic Theory of Gases), shown by a related decrease in γ_{exhaust} as the fuel-air equivalence ratio becomes richer. This likely accounts for the larger improvement of FT fuel over D2 at increased EGR rates.

An explanation of this behavior is suggested by Lee et. al [28]. It was reported that the H/C ratio of a fuel could also impact NO_x emissions by influencing another aspect of the kinetic pathway through reductions of the concentration of species required by the rate-limiting step in the extended Zeldovich mechanism. The mole fraction of water in the exhaust gas of FT fuel is slightly higher than No. 2 diesel fuel due to its higher H/C ratio. It was proposed that since water has a lower tendency to dissociate at high temperatures compared to carbon dioxide, fuels with higher H/C ratios would have lower concentrations of $\dot{\text{O}}$ radicals, reducing the kinetic production of NO_x as it relies on radical-oxygen concentration. Furthermore, the concentration of nitrogen is lower for the high-H/C ratio FT fuel. Again, a reduction in nitrogen concentration should reduce the production rate of NO_x. Although the above arguments should also apply to the low-load tests, the difference in H₂O and N₂ mole fractions between FT fuel and No. 2 diesel fuel decreases as the overall fuel-air equivalence ratio decreases, while the mole fraction of oxygen rises substantially as conditions become more lean. As such, the importance of H₂O dissociation decreases as the radical-oxygen contribution from molecular oxygen takes precedence.

8.1.2 Particulate Matter Emission Trends

The particulate matter that exits the engine is based on two competing processes, the extent of particulate formation and oxidation. Many models for soot formation and oxidation exist [29], ranging in scope from empirical, semi-empirical, and detailed-chemistry formulations. Empirical models are relatively crude, as they do not separate formation and oxidation in their prediction of soot while detailed-chemistry models can become overly complex.

Figure 8.9 Summary of BSNOx results for several conditions

Figure 8.9 shows a summary of the particulate sampling results reported. The x-axis corresponds to the PM output generated by the 15 PPM sulfur baseline fuel and the y-axis shows the FT fuel results. The heavy line on the plot has a slope of unity; any data point on this line is one for which there is no difference in emissions between FT and D2 fuels. Any points below this line indicate an improvement in emissions. For reference, the lines representing 25, 50 and 75 percent improvements are also shown. From this figure, it is clear that FT fuel reduces PM output between about 25 and 50 percent for most every operating condition for which there is data, which is consistent with prior work. By experimenting with different fuel combinations and varied engine operating parameters, an overall strategy for emissions control can be developed.

8.1.2.1 Fuel Effects

The inclusion of FT/D2 fuel blends in this study allowed us to examine the possibility of obtaining the positive effects of using FT without the cost of using pure FT fuel. As discussed earlier FT was blended with the baseline 15 PPM sulfur fuel, as well as last year's baseline 400 PPM sulfur fuel. This would help show what portion of particulate reduction was due to the fact that FT fuel has essentially zero sulfur and what might be due to the combustion characteristics of FT fuel.

Figure 8.10 shows the results of low-speed, mid load dilute PM sampling tests with four fuels: neat FT, 15 PPM D2, 400 PPM D2 and the 25%/75% by volume blend of FT and 15

PPM fuels. It can be seen that FT fuel reduces PM output for all timing points and that the blended fuel can produce a varying amount of reduction, depending on timing.

Figure 8.10 BSPM output for four fuels over five injection timings

The sulfur content obviously a major source of the reduction in the total particulate emissions measured among fuels of varying sulfur levels. According to Kittelson et al [32], typical diesel exhaust (without any after-treatment devices) has sulfuric acid concentrations ranging from 5 – 20 PPM when using fuel with a sulfur content of 0.04%, or 400 PPM. Estimations were made as to the sulfate contribution to PM for this fuel. Using this sulfate-exhaust concentration, the exhaust of the test engine should have sulfate levels between 0.002 – 0.009 g/hp-hr at the stock timing, stock EGR, low load condition. For stock timing, Figure 8.10 shows a difference in PM output of about 0.005 g/hp-hr between the 400 PPM and 15 PPM fuel. As such, if the difference in fuel sulfur content were the principal contributor to reduced PM output with FT fuel, there should be little difference between particulate output with FT and 15 PPM fuel. However, it can be seen that FT fuel reduces PM levels even further than 15 PPM fuel. Thus, the reduction must be due to more than just reduced fuel sulfur.

Results from raw sampling experiments with fuel blends reinforce this conclusion. As shown in Figure 8.11, the fuel blend that contains 25% FT fuel and 75% 400 PPM fuel reduces PM emissions approximately 24%, compared to 49% for neat FT fuel. Additionally, Figure 8.12 shows results for the blend of FT and 15 PPM fuel. The relative reduction is even greater in this case, again affirming that fuel sulfur reduction only contributes partially to the overall PM reduction. As shown, the FT/D2 blends produce 69% and 50% of the particulate reductions of neat FT versus 15 PPM and 400 PPM fuel, respectively.

Figure 8.11 Relative reduction in PM emissions for 400 PPM, FT fuel and their blend

Figure 8.12 Relative reduction in PM emissions for 15 PPM, FT fuel and their blend

Figure 8.12 shows a comparison of PM results from raw sampling of 15 PPM fuel, FT fuel and the blend of the two. The relative reduction of neat FT and the blend is greater than in the case of the 400 PPM fuel and blend. It should be noted that these particular experiments were conducted with raw exhaust sampling to reduce the effect of daily temperature and humidity variation. Based on the raw sampling method, the PM collected in the experiments is most likely carbonaceous agglomerates. Therefore, the PM reductions must be related to the soot particles themselves, and not to the species that usually contribute to surface growth such as volatile species and sulfates. The reason for the reduction in soot particles due to fuel properties is most likely the chemical structure of the fuels themselves. This may explain why there is little difference between the PM collected from the 400 and 15 PPM fuel, compared to the dilute sampling.

Frenklach and Wang [30] and Richter et al [31] suggest that the initial inception of the smaller polycyclic aromatic hydrocarbons (PAHs) that eventually combine to form soot is dependent upon the availability of aromatic molecules after the initial breakdown of the fuel molecules. If aromatic molecules are present, the hydrogen-abstraction carbon-addition (HACA) mechanism can proceed directly on a simple aromatic to form the second aromatic rings. If, however, no aromatic molecules are present, acetylene must react to form the first ring, such that the above HACA mechanism can act upon this first ring to grow larger and larger particles. Therefore, based on the fact that the FT fuel from the Syntroleum Corporation has less than 0.001% by weight aromatics (see fuel specifications), more time is spent forming the first rings than growing larger PAHs, leading to a reduction in PM when using FT fuel.

8.1.2.2 Engine Operating Parameter Effect

Both raw and dilute particulate data were taken for the low speed, low load condition. Prior data from MIT showed that the stock timing point was actually a local maximum for PM output, and the current data confirms this. Dilute exhaust sampling data was taken for a number of timing points and the result is shown in Figure 8.13.

Figure 8.13 BSPM vs. timing for FT, 15 PPM and 400 PPM fuels

As combustion is phased after TDC, the overall cylinder conditions become cooler as the piston expands the cylinder contents. With the drop in temperatures during fuel injection after TDC, the rate of formation of soot is most likely decreasing. Furthermore, the amount of air entrainment before the standing premixed flame seems play a role in the overall soot formation process. Flynn et al showed [25] that as more oxygen is mixed with the fuel-rich vapor feeding the premixed flame, less carbon went into soot precursor formation and more went into forming carbon monoxide. Air entrainment increases as the unburned gases in the cylinder cool. Therefore, as timing is retarded away from TDC, the PM levels should drop as the data show since less soot is initially formed.

Based on the fact that higher peak cylinder pressures and temperatures lead to increasing NO_x as injection timing is advanced, the overall PM output is most likely a difference of two large numbers as formation and oxidation rates are likely elevated. Since PM drops as the cylinder gets hotter, the oxidation rate is most likely dominating as injection timing advances, leading to the drop in PM shown in the data. Combine this with the fact that the combustion duration grows with injection timing advance, and the time for PM oxidation increases helping to lower the overall engine-out PM level.

The A50 particulate matter results are shown in Figure 8.10. For all but the most retarded timing point, the PM dependence on timing is fairly small, yet the same trends appear independent of fuel. As timing is advanced 3 degrees from stock, PM output increases for all fuels; with further timing advances, PM output decreases as peak cylinder temperatures increase. With 3 degrees retard in timing, three of the four fuels show a decrease in PM, with the fourth holding about steady. Addition retard shows a significant increase in PM output. It is likely that the stock timing point exists where the competing effects of soot formation and oxidation rates are well balanced. It seems that deviating significantly from this point would have the expected effect of increasing PM output as timing is phased after TDC and vice versa. Conversely, the low-speed, low-load stock timing condition is around a local maximum and deviating more than a few degrees in either direction reduces PM output.

Figure 8.14 Relative increase in PM output with EGR increase for different fuels

Another trend common to both fuels shown in the aforementioned brake specific particulate matter results is the increase of PM as EGR rates increase. In general, EGR reduces the overall flame temperature through the increase in heat capacity of the recycled exhaust gases and reduces the oxygen concentration of the fresh air by diluting it with burned-gas products. The combination of the reduced temperature and oxygen concentration lowers the soot oxidation rate.

Figure 8.14 shows the relative increase in PM output with varying EGR rate increase for different fuels. Compared to 400 PPM, the FT shows a smaller increase in PM out put with a

10% (absolute) increase in EGR rate in mid-load tests. Likewise, in a low-load test, FT showed a smaller increase in PM when EGR rate was increased by 20% absolute in a low-load test. This is indicative of tendency of FT fuel to reduce dependency of emissions on engine operating parameters. As such, it was predicted that the blended fuel would show some of the improvement of straight FT fuel, as it does in stock EGR test. However, this behavior is not seen. Unfortunately, there is no data comparing FT fuel to 15 PPM and blended fuel for the mid-load condition. It is suspected that this result may actually be due to experimental error.

8.1.3 Tradeoffs

Typically, NO_x reduction strategies increase PM output and vice versa. This is known as a ‘ NO_x – PM tradeoff’ and makes it difficult to meet ever-more stringent emissions requirements for both pollutants. Considering that, it is useful to plot NO_x output against PM output to examine the potential of a certain emissions control scheme in real-world use. Furthermore, this serves to put the presented data into perspective. Figure 8.14 shows the NO_x -PM tradeoff for FT fuel and 15 PPM fuel for the low-speed, mid-load condition. The typical tradeoff behavior can essentially be seen in the 15 PPM fuel curve, though in this case, it appears that advancing timing beyond the stock point increases both PM and NO_x output. Additionally, the stock timing point is nearly optimal.

Figure 8.15 BSPM – BSNO_x tradeoff for the low speed, mid load data

The FT fuel curve shows much less of the typical tradeoff when injection timing is retarded. From Figure 8.15, it is clear that FT fuel allows timing to be further retarded for NO_x control without significant impact on PM output.

8.2 Fuel Consumption Measurements

As discussed previously, the fuel flow measurement system had been replaced since previous work done at MIT. The new gravimetric system reduces error in that there is no correction

necessary to account for variation in fuel temperature unlike the prior system, which measured volumetric flow rate, and thus was incorrect when the fuel density changed. In addition, the fuel flow meters had to be calibrated for the specific fuel being used. The gravimetric system was completely mass based, so no correction or calibration was necessary.

As discussed previously, FT fuel's lower heating value (LHV) is approximately 1.8% higher than that of standard diesel fuel. As shown in Figure 8.16, FT fuel showed at least a 2% improvement in BSFC for all conditions, and up to 6% for some conditions.

Figure 8.16 Summary of BSFC results for several conditions

Figure 8.17 Relative improvement in BSFC for FT fuel compared to 15 PPM D2

8.2.1 Timing and Fuel Effects on Fuel Consumption

Figure 8.17 shows the percent reduction in BSFC for FT fuel compared to 15 PPM D2. For the stock timing condition, the improvement is approximately the same as the difference in LHV of the two fuels. However, as timing is retarded or advanced, FT fuel shows a larger improvement in fuel consumption. This is possibly because the stock timing has been selected to provide optimal fuel given the other competing effects (e.g., EGR, etc.). However, when the timing is modified, the system as a whole is no longer optimized; as such it stands to reason that the benefit of FT fuel can be amplified in such cases.

Figure 8.18 Gross heat release rate for the low-speed, mid load condition

Figure 8.19 BSFC vs. timing for the low-speed, mid-load condition

Examining the heat release curve for the stock and 3 degrees retarded FT and 15 PPM data from the low-speed, mid-load condition (Figure 8.18) shows the reduced ignition delay associated with FT fuel. Furthermore, comparing the retarded to stock timing (A50-02 and A50-01, respectively) shows what advancing the timing “looks like” in terms of heat release. Advancing timing before TDC tends to decrease BSFC, as shown in Figure 8.19. Examining the FT heat release curve and the corresponding D2 curve shows that FT fuel behaves like D2 fuel with *slightly* advanced timing, thereby contributing to the improvement in BSFC.

9.0 EXHAUST AFTER-TREATMENT SYSTEM

With new emission standards in place in 2007, heavy-duty diesel engines will have exhaust after-treatment systems, in particular particulate traps. Particulate traps have been studied for many years; however many of the technical issues such as regeneration initiation and control, excessive oxidation of sulfur in catalytic, ash accumulation, in addition to durability issues still remain. The absence of sulfur in FT fuels removes constraints on some catalysts in lowering the temperatures required to initiate regeneration. The deposition of particulates from FT fuels on the trap substrates and regenerating the trap with FT particulates and FT fuel have not been adequately addressed. These issues remain the topic of the current phase of the program.

The goals of this task are:

- To evaluate exhaust after-treatment systems performance and design tradeoffs available using gas-to-liquid fuels. Optimize the fuel/engine/emission-control system.

Active regeneration strategies such as burners, heaters, throttling, bypasses/waste-gates, microwave devices, late fuel injection, exhaust fuel injection, valve timing, etc. all interfere with engine operation and incur fuel penalty. Passive systems do not necessarily guarantee on-demand regeneration but offer high probabilities that, under most user routes and operating cycles, regeneration occurs continuously or with sufficient frequency that no active ignition of the particulates is required. These passive systems often require either fuel-borne catalysts or catalytic washcoats on the trap substrates. We will examine the strategies for initiating and controlling the regeneration process.

Bench and engine experiments have shown that particulate regeneration is a function of particulate loading density, oxygen partial pressure, temperature in the trap, as well as trace species such as nitrogen dioxide. Control of the regeneration process requires a thorough understanding of the regeneration map. Some bench tests have developed these maps while maintaining steady inlet conditions (steady-state maps). However, changes in the operating conditions during regeneration, for example the oxygen concentration, as occurring when the engine switches to idle during regeneration, can have catastrophic effects. Run-away, uncontrolled temperatures can occur that could result in the melting or cracking of the trap substrate. This project area will address these transient regeneration characteristics both in the control and in the initiation of trap regeneration.

Advances in fuel technology offer potential to optimize the engine/fuel/emission-control system. One area is in catalysis or catalytic regeneration of particulate traps. It has been

shown that the catalytic particulate regeneration process involves the oxidation of hydrocarbons, either in the ambient or in the adsorbed organic matter. Unfortunately, fuel sulfur conversion rates to sulfates, even at the low fuel sulfur levels, are concomitantly high. The presence of synthetic zero-sulfur fuel, namely the Fischer-Tropsch gas-to-liquid fuel, removes the sulfur and sulfate constraint. The synthetic fuel can be tailored to provide the optimum combination of HC, particulate composition, and catalysts for low-temperature particulate oxidation and trap regeneration, in the absence of fuel sulfur.

Hence to study the impact of FT gas-to-liquid fuel and particulate characteristics on trap regeneration, the following are the major initial subtasks:

- a) Design, fabricate and install an uncatalyzed and a catalytic particulate trap system for the Cummins ISB 300 engine for use with both #2 diesel and Syntroleum fuels.
- b) Fully instrument the filter to measure pressure and temperatures throughout the trap.
- c) Measure and characterize the characteristics of particulates from using synthetic zero-sulfur fuel versus regular low-sulfur diesel fuel
- d) Design and implement means of regeneration that fully investigate the emissions and regeneration characteristics of each fuel. Optimize engine/trap system as appropriate.

9.1 Current System Design:

Figure 9.1 Front and side views of initial trap design for preliminary tests

Figure 9.1 shows an initial trap design. The substrate is made of four pieces of ceramic honeycomb substrate blocks made of cordierite material. The substrates are 14.37 cm (5.66”) in diameter and the cell density is 100 cells per square inch. The trap is intentionally designed with separate substrate pieces so that each piece can be removed to a separate installation for bench regeneration studies if necessary. The four separate channels also allow for independent control of the different flow rates into each channel (for regeneration).

The particulate trap is designed to be installed in the engine and exhaust system as shown in the schematic below:

Figure 9.2 Schematic of particulate trap as exhaust after-treatment system in Cummins ISB engine using Syntroleum and No. 2 diesel fuels

We have identified and procured the materials required for the trap fabrication and already have essential parts on hand. The next stage will be the actual installation and instrumentation of the trap and control systems for detailed studies of the effects of FT fuel on trap performance and regeneration. We will also explore the opportunities to further optimize such a particulate after-treatment system given the special properties of the FT fuel.

10.0 CONCLUSIONS

Current results confirm the earlier finding that the Fischer-Tropsch (FT) gas-to-liquid diesel fuel from the Syntroleum small footprint plant performs better and with lower emissions than regular diesel fuel on a late vintage (MY 2002) direct injection diesel engine. Further improvements in performance and emissions can be realized by configuring the engine to take advantage of FT diesel fuel's properties. A small fraction of FT fuel blended with diesel can offer emission reductions more than shown by its proportion in the blended fuel. Investigations on the effects of FT fuel on a particulate after-treatment system (a trap) are continuing.

The cetane number (CN) of a fuel is commonly believed to control NO_x output by dictating the amount of fuel that auto-ignites in the initial premixed burn fraction. However, the modern engine tested is designed to have small premixed burn fractions, such as those with high injection pressures to promote good mixing along with late injection in hot cylinder conditions around TDC. Thus, NO_x emissions are less sensitive to the value of a fuel's CN.

On the other hand, combustion data show that the FT fuel burns faster during the latter part of combustion, in back-to-back comparisons with No. 2 diesel. This improves particulates, and when combined with retarded injection timing past TDC provides an optimal combination of both NO_x and particulate reduction.

The additional tests performed since the last report include comparisons of FT fuel with ultra-low sulfur fuel (15 ppm), with low sulfur regular diesel fuel (400 ppm), as well as fuel blends of FT with regular diesel. The test conditions have also been expanded. With the additional data, the following are the updated conclusions:

- For a modern MY 02 heavy-duty diesel engine, FT fuel reduces particulate emissions substantially, mostly in the range of 25-50% for a variety of steady-state conditions tested. Under light load, low speed conditions typical of urban driving, particulate reductions can reach up to 75%. The absence of sulfur in the FT fuel is only part of the reason. Favorable combustion effects for the FT fuel for late injection timings contributed significant particulate reduction.
- For the same modern engine, FT diesel fuel reduces NO_x emissions consistently from 6-20% versus No. 2 diesel fuel. The more recent results are consistent with previous results of 6-13% reduction and with overall results reported in the literature. FT fuel's higher cetane number and a shorter ignition delay allow fuel injection to be further retarded for emission control.
- A blend of 25% (by volume) FT fuel with 75% 15 ppm sulfur fuel, as well as a blend of 25% FT/75% 400 ppm sulfur fuel both showed that the 25% FT fuel in either blend produced about half of the particulate reduction of using neat FT fuel (slightly more than half - 60% - for the blend with the higher sulfur fuel and slightly less than half - 40% - for blend with the lower sulfur fuel).
- FT fuel burns faster during the latter part of combustion, especially when combustion occurs predominantly during the expansion stroke. Therefore, late injection timing retard at or after TDC can be employed for large NO_x reduction in modern engines.
- Conventional diesel fuel normally produces more particulate matter as EGR increases. FT fuel removes the sensitive dependence of PM production on EGR rate, allowing significant NO_x reductions through the use of higher EGR rates before PM levels become unacceptably large.
- Increases in PM output from increased EGR rates can be controlled by after-treatment systems without concern of system performance deterioration from fuel sulfur, as FT diesel fuel is virtually sulfur free. A particulate trap system has been designed and is being set up to investigate the fuel impact on the relative ease to both initiate and control regeneration. This is being addressed in the current work and will be documented in the next report. In addition, as established elsewhere but not presently on the test plan, sulfur-free fuel does not poison catalysts in NO_x after-

treatment systems with sulfur originating from the fuel. Sulfur in the lubricant presents a different problem.

In summary, FT fuel gives greater freedom to engine designers when trying to optimize the engine/emission-control/fuel system in modern engines, since it provides the fuel properties as another flexible set of variables that affect the combustion and emission processes.

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Test Methodology

The West Virginia University Transportable Heavy-Duty Vehicle Emissions Testing Laboratories were constructed to gather emissions data from in-use heavy-duty vehicles. The Laboratory used in this research, consisted of two trailers. One trailer embodied rollers, flywheels and power absorbers for the dynamometer function, and a second trailer housed the controls and emissions measurement equipment. The vehicle to be tested was driven onto the chassis dynamometer and positioned on two sets of rollers (Figure 1). The outer wheel of the dual wheel set on each side of the vehicle was removed and replaced with hub adapters that couple the drive axle directly to the dynamometer units on each side of the vehicle (Figure 2). Vehicle inertia was mimicked using a flywheel set. Various flywheels could be engaged to mimic a desired vehicle inertia weight. Road load drag on the vehicle was mimicked partially by the irreversible (frictional) losses in the laboratory, and was adjusted to the correct value at each speed using eddy current power absorbers with closed-loop torque control. A human driver operated the vehicle through a driving schedule that was selected to represent the typical duty cycle encountered by WMATA transit buses during normal service.

Figure 1: The vehicle under test is positioned on the dynamometer rollers.

Figure 2: Hub adapters connect the vehicle's drive axle to the power absorber units.

The full exhaust from the tail pipe of the test vehicle was ducted to a full-flow exhaust dilution tunnel where it was mixed with HEPA filtered dilution air. The quantity of diluted exhaust was measured precisely by a critical flow venturi system (CVS). Samples of the diluted exhaust were analyzed using NDIR for carbon monoxide (CO) and carbon dioxide (CO₂), and chemiluminescent detection for oxides of nitrogen (NO_x). Hydrocarbons (HC) were analyzed using a heated flame ionization detector. Total particulate matter (PM) was collected using 70-mm fluorocarbon coated glass fiber filter media and PM emissions were determined gravimetrically.

For each run, background bags were gathered, analyzed and used to correct gaseous emissions. Dilute gas bags were also collected during a run, but continuous data, integrated over the run, were used for reporting purposes. Separate runs were used to gather background PM levels for

PM filter weight correction. Even though the tunnel had HEPA filtered dilution air, PM backgrounds were essential because the tunnel itself may shed PM particles or outgas heavy hydrocarbons that condense onto the PM.

Dynamometer Driving Schedule

The Washington Metropolitan Transit Authority Cycle (WMATA) was derived from vehicle speed data logged from transit buses during normal operation in Washington D.C. and surrounding areas. It has been employed in prior studies conducted for the U.S. Department of Energy National Renewable Energy Laboratory [4] and Cummins Engine Company [5] to evaluate emissions reduction strategies for transit buses operated in the Washington DC area. WVU and Cummins Engine Company logged vehicle activity data from several WMATA transit buses during normal passenger service on multiple routes within the WMATA system. Vehicle speed data was recorded from a Global Positioning System. These data comprised a database of vehicle activity, which was analyzed to characterize the duty cycle of a typical WMATA transit bus. The WMATA Cycle is shown in Figure 3

Figure 3: WMATA Cycle target speed versus time schedule.

Test Vehicle Configurations

The test vehicle was a 2000 model year Orion 40-foot municipal transit bus equipped with a 1999 model year Detroit Diesel Corporation (DDC) Series 50 diesel engine. The transit bus (Number 2027) was owned by the Washington Metropolitan Area Transit Authority (WMATA) and was operated in municipal transit service in the Washington D.C., Northern Virginia and Southern Maryland area. The transit bus had a gross vehicle weight rating of 42,540 lbs and an unloaded curb weight of 27,800 lbs. It could accommodate 39 seated passengers and 20 standing passengers. The bus emissions were characterized at a simulated weight of 33,125 lbs

representing approximately one-half of the maximum passenger capacity (150 lbs/person approximate weight) including the driver.

The DDC Series 50 engine was a 4-stroke cycle, turbocharged, in-line 4-cylinder, lean-burn, compression ignition engine with a displacement of 8.5 liters. The engine had a power rating of 275 hp at 2100 rpm. In its original equipment (OEM) configuration, the bus was equipped with a diesel oxidation catalyst (DOC) but had been retrofitted with an Engelhard DPX passive catalyzed particulate filter. The Engelhard DPX was a catalyzed ceramic wall-flow filter. It utilized a dual-function platinum precious-metal catalyst in combination with a base-metal-oxide catalyst. The catalyst coating was impregnated into the walls of the filter element. Particulate matter was trapped as exhaust gas flowed through the porous walls of the filter element. The catalyst coating promoted oxidation of the collected PM, HC and CO when exhaust temperatures were 375 F or above for at least 25% of the time. Nitrogen dioxide (NO₂) produced from nitric oxide (NO) in the exhaust stream by the catalyst enhanced low temperature oxidation of PM.

WMATA bus 2027 was tested first in the as received configuration with the EngelhardDPX particulate filter installed using in-tank ULSD1 fuel. The particulate filter was then removed and replaced with an OEM-style diesel oxidation catalyst (DOC) and the tests were repeated using the ULSD1 fuel. The fuel was then changed to the Syntroleum GTL fuel supplied in 55-gallon drums and tests were performed with the DOC in place. Prior to beginning these tests the engine fuel filter was changed and the fuel system was flushed with the Syntroleum fuel. Finally the DOC was removed and the Engelhard DPX was re-installed and tested with the Syntroleum GTL fuel.

Table 2 shows the test matrix and the corresponding WVU test sequence numbers.

Table 2: WMATA bus 2027 test matrix for ICRC testing.

WVU test sequence Number	Fuel	Exhaust Aftertreatment
4178	ULSD1	Engelhard DPX
4181	ULSD1	OEM DOC
4184	Syntroleum GTL	OEM DOC
4187	Syntroleum GTL	Engelhard DPX

Emissions Results

Oxides of Nitrogen Emissions

Measured NO_x emissions are plotted in Figure 4. Each bar represents the average of at least three separate repeat test runs and the error bars indicate the spread of the data by showing the maximum and minimum individual test results. NO_x formation in the combustion chamber is a temperature and pressure driven process. Higher in-cylinder temperatures and pressures increase the formation of NO_x. Fischer-Tropsch fuels generally produce moderate reductions in NO_x emissions. The benefit arises from the lower aromatic content, higher cetane number and shorter ignition delay period associated with combustion of Fischer-Tropsch fuels compared to typical petroleum derived diesel fuel [6]. An increase in the cetane number results in a reduction in the ignition delay period, causing a reduced volume of fuel to undergo premixed combustion and a larger portion undergo diffusion-controlled combustion. This results in lower in-cylinder temperatures and lower rates of NO_x formation. The lower aromatic content of the Fischer-

Tropsch fuel also leads to lower in-cylinder combustion temperatures and lower NO_x emissions [6]. Measured NO_x emissions, shown in Figure 4, were reduced by 28 percent when changing from ULSD1 to Syntroleum GTL fuel with a DOC and 23 percent with the DPX.

Figure 4: Oxides of nitrogen (NO_x) emissions.

A slight decrease in NO_x emissions of approximately 6% was observed with the DPX and the ULSD1. In general, the DPX catalyst formulation is not expected to reduce total NO_x (NO+NO₂) emissions although it does alter the ratio of NO₂ to NO in the exhaust stream. Oxides of nitrogen emission from diesel engines without aftertreatment devices may include 3% to 15% NO₂ depending on engine design and operating conditions and are typically 3% to 5% averaged over a transient test cycle. Emissions from vehicles equipped with catalyzed particulate filters and other aftertreatment devices may consist of 30% to 40% NO₂. It is possible that installation of the DPX increased the exhaust backpressure on the engine thereby increasing slightly the internal exhaust gas recirculation (EGR). Increasing the amount of burned exhaust gases in the cylinder also reduces in-cylinder temperatures leading to lower NO_x formation. It is also noted that if the NO₂ concentration in the exhaust is higher and the NO₂-NO conversion efficiency of the chemiluminescent analyzer is less than 100% (EPA requires that the efficiency must be above 90%), then an error of one to two percent would be induced in the measurement causing the total NO_x to be under reported by a couple of percent. This apparent reduction may or may not be significant when experimental variability is considered.

Particulate Matter Emissions

Particulate emissions are plotted in Figure 5. Use of the Syntroleum GTL fuel resulted in significant reductions in PM emissions with both the DOC and DPX after-treatment devices. With the OEM oxidation catalyst installed, PM was reduced by 35% compared to the ULSD1 fuel. Installation of the Engelhard DPX reduced PM emissions by 93% from 0.31 g/mile to 0.02 g/mile when operating with ULSD1 fuel. The percent reduction in the case of the DPX is difficult to characterize because the very low levels of PM mass are close to the measurement limit of the

laboratory. Use of the Syntroleum GTL fuel in combination with the DPX further reduced the PM emissions from 0.02 g/mile average to 0.003 g/mile representing a reduction of over 99% compared to the OEM oxidation catalyst with ULSD1 fuel. The reader is cautioned that the very low particulate levels emitted by catalyzed particulate filter equipped buses are at or near the detection limits of the measurement methodology.

Figure 5: Particulate matter emissions (PM) emissions.

Increased cetane number, lower aromatic content and near zero sulfur content of the Syntroleum fuel contribute to reductions in PM emissions. The effect of cetane number on particulate emissions is less clear with some studies indicating decreased PM, others the opposite trend and some others showing no effect [6]. A number of studies have found that the soluble organic fraction (SOF) of the PM was significantly reduced when the cetane number increased, but that the benefit was offset by an increase in the insoluble portion of the PM [6]. Reduced aromatic content particularly polycyclic aromatics (PAH) may also contribute to lower particulate emissions. Some studies have shown that at low engine speeds and loads, particulate emissions are largely composed of unburned fuel PAH. Studies have found that reducing fuel PAH resulted in reduction in HC, NO_x and PM emissions [6]. Fuel sulfur is converted to SO₂ and sulfates which, along with bound water manifest themselves as PM emissions. There is generally a linear relationship between fuel sulfur consumption and the sulfate portion of PM emissions with a conversion rate of between 1 to 2 percent for engines without aftertreatment. The contribution of sulphates to the total particulate mass is only a few percent so that the reduction of PM through reduction of fuel sulfur content is limited. However, the high precious metal and platinum loading in passive catalyzed particulate filters such as the Engelhard DPX substantially increase the formation of sulfates. The near zero sulfur content of Syntroleum GTL fuel may offer a marginal advantage over ultra-low sulfur petroleum derived diesel for vehicles equipped with catalyzed particulate filters. It is difficult to validate or quantify this potential emissions benefit given the accuracy of currently accepted PM measurement methodology and practice.

Hydrocarbon and Carbon Monoxide Emissions

Hydrocarbon results are plotted in Figure 6. In the OEM configuration with the DOC installed, hydrocarbon emissions increased by 14 percent when comparing Syntroleum GTL to ULSD1. With the Engelhard DPX installed, hydrocarbon emissions from both fuels were reduced to levels that were at or below the detection limit of the laboratory methods and were essentially indistinguishable from ambient background hydrocarbon levels.

Figure 6: Hydrocarbon emissions (HC) emissions.

In the OEM configuration with the DOC installed, use of the Syntroleum GTL fuel produced a reduction in CO emissions of 7.1 percent compared to the USLD1 fuel. As expected the Engelhard DPX produced substantial reductions in CO emissions with both fuels as shown in Figure 7. These results are in agreement with those of previous emissions studies conducted by WVU involving the Engelhard DPX catalyzed diesel particulate filters [7]. This type of exhaust after-treatment system has proven very effective in reducing HC and CO emissions when used in conjunction with very low sulfur fuels.

Figure 7: Carbon Monoxide emissions (CO) emissions.

Fuel Economy Results

Fuel economy results, shown in Figure 8 indicate a slight improvement in fuel economy as a result of the Syntroleum GTL fuel. The error bars shown on the plot are between duplicate runs. Fuel consumption is influenced by the energy content of the fuel (its lower heating value) and the thermal efficiency of the engine, which is influenced by the fuel through its effect on combustion efficiency. These may be affected by the cetane number, density and chemical composition of the fuel. It is also noted that CO₂ emissions could vary from test to test and the fuel economy differences shown may not be statistically significant.

Figure 8: Fuel economy.

Conclusions

The exhaust emissions of a 40-foot transit bus equipped with a 1999 model year DDC Series 50 engine and fueled with a Syntroleum GTL fuel were measured and compared to emissions from the same transit bus fueled with ultra-low sulfur petroleum derived diesel fuel. Tests were conducted with two different types of exhaust after-treatment systems; an OEM-style diesel oxidation catalyst and an Engelhard DPX catalyzed particulate filter. Results indicated that use of Syntroleum GTL fuel produced reductions in NO_x emissions of 23-28%. With the OEM diesel oxidation catalyst installed particulate matter emissions were reduced by approximately 35% when Syntroleum fuel was used. Results also indicated that with the Engelhard DPX installed, PM emissions were lower with the Syntroleum fuel compared to the ULSD1. However, it must be noted that the PM levels emitted from the Engelhard DPX are at or below the detectable limits of the current PM measurement methodology and practice. With the Engelhard DPX particulate filter installed, the effect of the fuel formulation on PM emissions cannot be accurately quantified. The Syntroleum GTL fuel produced a slight increase in hydrocarbon emissions and a slight decrease in carbon monoxide emissions compared to the USLD1 fuel in the DOC configuration. The Engelhard DPX reduced both HC and CO emissions to near ambient background levels regardless of fuel formulation. Results seem to indicate a slight improvement in fuel economy associated with the Syntroleum GTL fuel. However, it should be noted that due to the very limited number of test runs it is difficult to determine whether the fuel economy improvement is statistically significant.

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Appendix for Part C: WVU Data Sheets

Test Sequence Number: 4178

WVU Test Reference Number: WMATA-2027-ULSD1-2WMATA

Fleet Owner Full Name Washington Metropolitan Area Transit Authority
Fleet Address 3500 Pennsy Drive
Fleet Address (City, State, Zip) Landover, MD 20784

Vehicle Type Transit Bus
Vehicle ID Number (VIN) 1VH6H2A23Y6600264
Vehicle Manufacturer Orion
Vehicle Model Year 2000
Gross Vehicle Weight (GVW) (lb.) 42540
Vehicle Total Curb Weight (lb.) Not Available
Vehicle Tested Weight (lb.) 33125
Odometer Reading (mile) 218466
Transmission Type Automatic
Transmission Configuration 3
Number of Axles 2

Engine Type Detroit Diesel Series 50
Engine ID Number 04R0031355
Engine Model Year 1999

Engine Displacement (Liter) 8.5
Number of Cylinders 4
Engine Rated Power (hp) 275

Primary Fuel ULSD1
Particulate Trap Manufacturer Engelhard
Test Cycle 2WMATA
Test Date 4/23/04

Engineer R. Barnett
Driver G. England

Emissions Results (g/mile)

Fuel Economy

Run Seq. No.	CO	NO _x ¹	NO _x ²	FIDHC	PM	CO ₂	mile/gal	BTU/mile	Miles
4178-1	0.26	25.8	25.8	e	0.024	3624	2.66	48004	8.37
4178-2	0.09	25.2	20.2 ^{NO}	e	0.021	3607	2.68	47776	8.42
4178-3	e	25.4	20.0 ^{NO}	e	0.023	3575	2.70	47340	8.39
4178 Average	0.18	25.5	c	c	0.023	3602	2.68	47707	8.39
Std. Dev.	0.12	0.3	c	c	0.002	25	0.02	337	0.02
CV%	68.7	1.3		d	8.2	0.7	0.7	0.7	0.3

x-Not Reportable, a-Outlier, b-HC Not Reportable(Residual HC), c-missing component, d-Coefficient of Variation Too Large, e-below detectable limit

Test Purpose:

WMATA Transit Bus 2027

Special Procedures:

Run 1 is in NO_x mode, runs 2 and 3 are NO_x/NO split

Observations: WMATA fuel with Particulate Trap

Test Sequence Number: 4181**WVU Test Reference Number: WMATA-2027-ULSD1-WMATA**

Fleet Owner Full Name Washington Metropolitan Area Transit Authority
 Fleet Address 3500 Pennsy Drive
 Fleet Address (City, State, Zip) Landover, MD 20784

Vehicle Type Transit Bus
 Vehicle ID Number (VIN) 1VH6H2A23Y6600264
 Vehicle Manufacturer Orion
 Vehicle Model Year 2000
 Gross Vehicle Weight (GVW) (lb.) 42540
 Vehicle Total Curb Weight (lb.) Not Available
 Vehicle Tested Weight (lb.) 33125
 Odometer Reading (mile) 218466
 Transmission Type Automatic
 Transmission Configuration 3
 Number of Axles 2

Engine Type Detroit Diesel Series 50
 Engine ID Number 04R0031355
 Engine Model Year 1999

Engine Displacement (Liter) 8.5
 Number of Cylinders 4
 Engine Rated Power (hp) 275

Primary Fuel ULSD1
 Catalytic Converter Manufacturer Nelson
 Test Cycle WMATA
 Test Date 4/24/04

Engineer R. Barnett
 Driver G. England

Emissions Results (g/mile)**Fuel Economy**

Run Seq. No.	CO	NO _x ¹	NO _x ²	FIDHC	PM	CO ₂	mile/gal	BTU/mile	Miles
4181-1	3.98	28.0	28.0	0.22	0.33	3557	2.71	47203	4.22
4181-2	4.03	27.3	26.4 ^{NO}	0.22	0.29	3517	2.74	46675	4.21
4181-3	4.04	26.7	25.6 ^{NO}	0.25	0.29	3512	2.74	46619	4.22
4181 Average	4.01	27.4	c	0.23	0.31	3529	2.73	46833	4.21
Std. Dev.	0.03	0.6	c	0.02	0.02	24	0.02	322	0.01
CV%	0.7	2.2		7.8	6.6	0.7	0.7	0.7	0.2

x-Not Reportable, a-Outlier, b-HC Not Reportable(Residual HC), c-missing component, d-Coefficient of Variation Too Large, e-below detectable limit

Test Purpose:

WMATA Transit Bus 2027

Special Procedures:

Run 1 is with both NO_x analyzers in NO_x mode, runs 2 and 3 are NO/NO_x split.

Observations:

WMATA fuel with Oxidation Catalyst

Test Sequence Number: 4184**WVU Test Reference Number: WMATA-2027-ULSD1-WMATA**

Fleet Owner Full Name	Washington Metropolitan Area Transit Authority
Fleet Address	3500 Pennsy Drive
Fleet Address (City, State, Zip)	Landover, MD 20784
Vehicle Type	Transit Bus
Vehicle ID Number (VIN)	1VH6H2A23Y6600264
Vehicle Manufacturer	Orion
Vehicle Model Year	2000
Gross Vehicle Weight (GVW) (lb.)	42540
Vehicle Total Curb Weight (lb.)	Not Available
Vehicle Tested Weight (lb.)	33125
Odometer Reading (mile)	218466
Transmission Type	Automatic
Transmission Configuration	3
Number of Axles	2
Engine Type	Detroit Diesel Series 50
Engine ID Number	04R0031355
Engine Model Year	1999
Engine Displacement (Liter)	8.5
Number of Cylinders	4
Engine Rated Power (hp)	275
Primary Fuel	ULSD1
Catalytic Converter Manufacturer	Nelson
Test Cycle	WMATA
Test Date	4/26/04
Engineer	R. Barnett
Driver	G. England

Emissions Results (g/mile)**Fuel Economy**

Run Seq. No.	CO	NO _x ¹	NO _x ²	FIDHC	PM	CO ₂	mile/gal	BTU/mile	Miles
4184-2	3.38	19.7	19.2 ^{NO}	0.29	0.23	3376	2.73	45724	4.17
4184-3	3.78	19.5	18.9 ^{NO}	0.27	0.19	3404	2.71	46106	4.28
4184-4	4.08	19.6	19.6	0.24	0.19	3425	2.69	46396	4.24
4184 Average	3.75	19.6	c	0.27	0.20	3402	2.71	46075	4.23
Std. Dev.	0.35	0.1	c	0.03	0.02	24	0.02	337	0.05
CV%	9.3	0.5		10.6	11.3	0.7	0.7	0.7	1.3

x-Not Reportable, a-Outlier, b-HC Not Reportable(Residual HC), c-missing component, d-Coefficient of Variation Too Large, e-below detectable limit

Test Purpose:

WMATA Transit Bus 2027

Special Procedures:

Runs 2 and 3 are in Split Mode. Run 4 has both analyzers in NO_x mode.

Observations:

Syntroleum fuel with Oxidation Catalyst

Test Sequence Number: 4187**WVU Test Reference Number: WMATA-2027-ULSD1-2WMATA**

Fleet Owner Full Name Washington Metropolitan Area Transit Authority
 Fleet Address 3500 Pennsy Drive
 Fleet Address (City, State, Zip) Landover, MD 20784

Vehicle Type Transit Bus
 Vehicle ID Number (VIN) 1VH6H2A23Y6600264
 Vehicle Manufacturer Orion
 Vehicle Model Year 2000
 Gross Vehicle Weight (GVW) (lb.) 42540
 Vehicle Total Curb Weight (lb.) Not Available
 Vehicle Tested Weight (lb.) 33125
 Odometer Reading (mile) 218466
 Transmission Type Automatic
 Transmission Configuration 3
 Number of Axles 2

Engine Type Detroit Diesel Series 50
 Engine ID Number 04R0031355
 Engine Model Year 1999

Engine Displacement (Liter) 8.5
 Number of Cylinders 4
 Engine Rated Power (hp) 275

Primary Fuel ULSD1
 Particulate Trap Manufacturer Engelhard
 Test Cycle 2WMATA
 Test Date 4/27/04

Engineer R. Barnett
 Driver G. England

Emissions Results (g/mile)**Fuel Economy**

Run Seq. No.	CO	NO _x ¹	NO _x ²	FIDHC	PM	CO ₂	mile/gal	BTU/mile	Miles
4187-1	e	19.5	19.5	e	0.0034	3212	2.88	43405	8.64
4187-2	0.051	19.6	15.0 ^{NO}	e	e	3246	2.85	43884	8.36
4187-3	0.075	19.8	15.1 ^{NO}	e	e	3115	2.97	42101	8.53
4187 Average	0.063	19.6	c	c	0.0034	3191	2.90	43130	8.51
Std. Dev.	0.017	0.1	c	c	c	68	0.06	923	0.15
CV%	26.5	0.6		d	d	2.1	2.2	2.1	1.7

x-Not Reportable, a-Outlier, b-HC Not Reportable(Residual HC), c-missing component, d-Coefficient of Variation Too Large, e-below detectable limit

Test Purpose:

WMATA Transit Bus 2027

Special Procedures:

Run 1 has both NO_x analyzers in NO_x mode. Runs 2 and 3 are in split mode.

Observations:

Syntroleum fuel with Particulate Trap

BYRON RAPP
WEST VIRGINIA UNIVERSITY
MAE DEPT \ PO BOX 6106
MORGANTOWN, WV 26505

Date Reported: 5/25/04
Date Received: 5/10/04

Analytical Report

Test	Result	Units	Method	Date	Anal
Sample Number: 140585-001		Sample ID: WMATA BUS			
2047/Syntroleum		Description:			
Sample Date:					
API Gravity @ 60 Deg. F	52.9	deg.API	ASTM D-1298	5/18/04	RMT
BTU, Gross	20453	BTU/lb	ASTM D-240	5/20/04	OE
BTU, Net	19026	BTU/lb	ASTM D-240	5/20/04	OE
Carbon/Hydrogen/Nitrogen/Oxygen Content					
Carbon Content	84.75	wt%	ASTM D-5291M	5/13/04	QTI*
Hydrogen Content	15.19	wt%			
Nitrogen Content	< 0.05	wt%			
Oxygen Content	< 0.10	wt%		5/19/04	
Cetane Number	70.7		ASTM D-613	5/18/04	FB
Distillation					
IBP	329.3	deg.F	ASTM D-86	5/17/04	OE
5% Rec	367.1	deg.F			
10% Rec	376.8	deg.F			
20% Rec	390.1	deg.F			
30% Rec	407.6	deg.F			
40% Rec	426.7	deg.F			
50% Rec	447.7	deg.F			
60% Rec	468.6	deg.F			
70% Rec	491.6	deg.F			
80% Rec	516.8	deg.F			
90% Rec	548.5	deg.F			
95% Rec	574.2	deg.F			
FBP	585.4	deg.F			
Recovery	97.0	%			
Residue	1.5	%			
Loss	1.5	%			
Kinematic Viscosity @ 40 deg.F	1.705	cSt	ASTM D-445	5/19/04	OE
Kinematic Viscosity @ 100 deg.F	1.760	cSt	ASTM D-445	5/19/04	OE

Page

BYRON RAPP
WEST VIRGINIA UNIVERSITY
MAE DEPT \ PO BOX 6106
MORGANTOWN, WV 26505

Date Received: 5/10/04

Date Recp

Analytical Report

Test	Result	Units	Method	Date	Anal
Sample Number: 140585-001		Sample ID: WMATA BUS			
2047/Syntroleum		Description:			
Sample Date: Nitrogen, Total	< 1.0	ppm wt	ASTM D-4629	5/18/04	RMT
Specific Gravity	0.7674	@ 60 deg.F	ASTM D-1298	5/18/04	RMT
Sulfur, Total by X-Ray Spec	< 0.0010	wt%	ASTM D-2622	5/12/04	CLH

Approved By: GREG L. COOK, ASSISTANT MANAGER

Issuer warrants that it has exercised due diligence and care with respect to the information and professional judgments embodied in this report. This report reflects only the findings at the time and place of the inspection and testing. Issuer expressly disclaims any further indemnity of any kind. This report is not a guarantee or policy of insurance with respect to the goods or the contractual performance of any party. Any person relying upon this report should be aware that issuer's activities are carried out under their general terms and conditions. Precision parameters apply in the evaluation of the test results specified above. Please also refer to ASTM D-3244 (except for analysis of RFG), IP 367 and Appendix E of IP Standard Methods for Analysis & Testing with respect to the utilization of test data to determine conformance specifications.

Part D. Fleet Tests, Denali National Park

Test Methodology

The West Virginia University Transportable Heavy-Duty Vehicle Emissions Testing Laboratories were constructed to gather emissions data from in-use heavy-duty vehicles. Detailed information pertaining to the design and operation of the laboratories can be found in technical papers [1, 2, 3]. The dynamometer unit consisted of power absorbers and a set of selectable flywheels, which allowed simulation of tire rolling losses, aerodynamic drag and inertial load equivalent to a gross vehicle weight of up to 60,000 pounds. The vehicle to be tested was driven onto the chassis dynamometer and positioned on two sets of rollers (Figure 1). The outer wheel of the dual wheel set on each side of the vehicle was removed and replaced with hub adapters that couple the drive axle directly to the dynamometer units on each side of the vehicle (Figure 2). Torque cells and speed transducers continuously measured drive axle torque and speed. Road load drag on the vehicle was mimicked partially by the irreversible (frictional) losses in the laboratory, and was adjusted to the correct value at each speed using eddy current power absorbers with closed-loop torque control. A human driver operated the vehicle according to a driving schedule.

Figure 9: The vehicle being tested is positioned on the dynamometer rollers.

Figure 10: Hub adapters connect the vehicle's drive axle to the power absorber units. Emissions are known to be dependent on the duty cycle of the vehicle and thus the dynamometer test schedule used. The Ultra-Clean Transportation Project included emissions testing of urban transit buses in Washington DC and testing of national park tour buses in Denali Alaska. In the interest of consistency and in order to allow comparison between the two bus fleets the Washington Metropolitan Transit Authority Cycle (WMATA) was selected as the dynamometer test schedule for the project. This cycle, though not necessarily representative of the actual Denali tour bus duty cycle, was chosen for comparative purposes between the Doyon/Aramark (Aramark) testing results and data collected from the buses tested at WMATA in Washington DC. The WMATA Cycle was derived from vehicle speed data logged from transit buses during normal operation in Washington DC and surrounding areas. Vehicle activity data was logged from several WMATA transit buses during normal passenger service on multiple routes within the WMATA system. Vehicle speed data were recorded from a Global Positioning System. These data comprised a database of vehicle activity, which was analyzed to characterize the duty cycle of a typical WMATA transit bus. The WMATA Cycle is shown in Figure 3.

Chassis dynamometer testing is the most accurate and repeatable method of characterizing emissions from in-use heavy-duty vehicles and provides the most useful data for prediction of atmospheric emissions inventories, evaluation of clean-vehicle programs at transit agencies and truck fleets, and accessing the success of retrofit programs. Chassis dynamometer systems have been developed and used for many years and it has been demonstrated that they are reliable tools for studying vehicle emissions.

Figure 11: WMATA Cycle target speed versus time schedule.

The emissions measurement system used a full-scale dilution tunnel measuring 18 inches (45 cm) in diameter and 20 feet (6.1 m) in length. The exhaust was mixed with HEPA filtered ambient air and the quantity of diluted exhaust was measured precisely by a critical flow venturi system (CVS). The diluted exhaust was analyzed using NDIR for carbon monoxide (CO) and carbon dioxide (CO₂), and using chemiluminescent detection for oxides of nitrogen (NO_x). NO_x emissions were corrected for standard humidity. Hydrocarbons (HC) were analyzed using flame ionization detection (FID). Simultaneous pre-tunnel bag samples were taken during each test to establish ambient background gas concentrations. The gaseous emissions measurements were performed in accordance with the CFR Title 40, Part 86 Subpart N (CFR40) [1] to the extent possible. A carbon balance using fuel properties and exhaust emissions data was used to determine fuel economy. Particulate matter (PM) was collected using 70-mm fluorocarbon coated glass fiber filter media and PM mass emissions were determined gravimetrically. Dilution tunnel background samples were collected for establishing particulate matter background levels. Even though the tunnel has HEPA filtered dilution air, PM backgrounds are essential because the dilution tunnel walls may shed particles that are re-entrained into the sample stream or outgas heavy hydrocarbons that condense onto the PM. Triplicate runs were performed for each emissions test.

Test Vehicle Configurations

The test vehicles were 2004 model-year Thomas 40-foot transit buses equipped with 2004 model-year Caterpillar C7 ACERT diesel engines. The buses evaluated in this study were owned by Aramark and used as tour buses in Denali Park, Alaska. These buses had a gross vehicle weight rating of 36,200 lbs and an unloaded curb weight of 21,830 lbs. They could accommodate 49 seated passengers including the driver. All buses tested were equipped with

Telma eddy current retarders, but they were disabled during testing to eliminate any additional and unquantified load placed on the engine by the retarder system. The buses were tested at simulated weights of 29,180 lbs representing the full capacity of the buses while touring Denali Park (150 lbs/person approximate weight).

The Caterpillar C7 ACERT engines were 4-stroke cycle, turbocharged/aftercooled, in-line 6-cylinder compression ignition engines with displacements of 7.2 liters each. The engines had power ratings of 230 hp at 2400 rpm and 660 lb-ft of torque at 1440 rpm. Each test vehicle was equipped with an Allison MD3060 5-speed automatic transmission and a Dana Corporation rear axle. Exhaust from the Caterpillar C7 engine passed through a diesel oxidation catalyst (DOC) before exiting the four-inch exhaust system. The first three buses (531, 532, 536) were the baseline group and were tested with the JET A diesel fuel normally use at Denali National Park. The remaining buses (533, 534, 537A) were tested on the Syntroleum (SYNTRO) fuel. Test vehicle information is summarized in Table 2.

Table 3: Aramark bus test matrix for ICRC testing

Aramark Transit Bus Specifications				
Chassis	MY 2004 Thomas			
Engine Manufacturer/Model	MY 2004 Cat C7 ACERT			
Engine Ratings	230hp @ 2400rpm			
After-treatment System	Diesel Oxidation Catalyst			
Transmission Type	5-speed Automatic			
GVWR/Curb Weight	36200 / 21830 lb			
Bus Number	VIN	Engine Serial Number	Odometer Reading	Fuel Type
531	1T88U2C2751149858	KAL23694	8602	JETA
532	1T88U2C2951149859	KAL23696	7645	JETA
536	1T88U2C2X51149970	KAL24268	8144	JETA
533	1T88U2C2351149860	KAL24396	8086	SYNTRO
534	1T88U2C2551149861	KAL24760	6068	SYNTRO
537A	1T88U2C2151149971	KAL24425	6507	SYNTRO

Emissions Results

Oxides of Nitrogen Emissions

Measured NO_x emissions are plotted in Figure 4. Each bar represents the average of at least three separate repeat test runs and the error bars indicate the spread of the data by showing the maximum and minimum individual test results. NO_x formation in the combustion chamber is a temperature and pressure driven process. Higher in-cylinder temperatures and pressures increase the formation of NO_x. Fischer-Tropsch fuels are generally expected to produce moderate reductions in NO_x emissions. The benefit arises from the lower aromatic content, higher cetane number and shorter ignition delay period associated with combustion of Fischer-Tropsch fuels compared to typical petroleum derived diesel fuel [6]. An increase in the cetane number results in a reduction in the ignition delay period, causing a reduced volume of fuel to undergo premixed combustion and a larger portion undergo diffusion controlled combustion. This results in lower maximum in-cylinder temperatures and lower rates of NO_x formation. The lower aromatic content of the Fischer-Tropsch fuel is usually associated with a high cetane number and so lower aromatic content is also associated with lo NO_x [6]. Previous emissions measurements from Detroit Diesel Corporation (DDC) Series 50 powered transit buses at the Washington DC Metropolitan Transit Authority (WMATA)

demonstrated a reduction in NO_x emissions of approximately 20% when operated on Syntroleum Fischer-Tropsch fuel compared to petroleum derived ultra low sulfur diesel fuel [5].

Measured NO_x emissions from the Denali Park buses are shown in Figure 4. The Denali Park buses, powered by Caterpillar C7 ACERT engines, exhibited the opposite trend from the WMATA buses. NO_x emissions from the Syntroleum fueled buses were higher than buses fueled with Denali Park's standard JET A fuel. NO_x emissions from the three buses fueled with JET A fuel averaged 12.78 g/mile and were highly consistent from vehicle to vehicle. NO_x emissions from the buses fueled with Syntroleum fuel averaged 15.73 g/mile ranging from 14.55 g/mile to 16.83 g/mile. In order to verify that the higher NO_x results were not due to a malfunction or calibration problem with the measurement systems, WVU retested bus Number 532, fueled with JET A, at the end of the program. The results from the retest were consistent with the previous results for that same bus indicating that the higher NO_x emissions were indeed a fuel related or vehicle related phenomenon. They could not be attributed to any change or drift in laboratory function.

NO_x emissions from diesel, compression ignition engines are primarily composed of nitric oxide (NO) and nitrogen dioxide (NO₂). Generally NO comprises 85-97% of the total NO_x emissions depending on engine design and operating conditions and NO₂ are typically 2% to 5% averaged over a transient test cycle. For vehicles equipped with certain types of catalyzed diesel particulate filters NO₂ may comprise as much as 30% to 40% of the total NO_x emissions. The Denali Park buses were not equipped with catalyzed diesel particulate filters and the NO fractions shown in Figure 4 are consistent with the levels that would be expected for buses not equipped with such filters. The NO results also follow the same trend with regards to fuel as the total NO_x results.

Samples of the Syntroleum and JET A fuels are presently being analyzed. Fuel composition and properties may offer some insight into the NO_x emissions trend. The effect of fuel properties will be discussed in the final version of this report.

Figure 12: Oxides of nitrogen (NO_x) emissions.

Particulate Matter Emissions

Particulate emissions are plotted in Figure 5. There was some vehicle-to-vehicle variability in the particulate emissions. PM emissions from the JET A fueled buses, averaged over the group was 0.188 g/mile. The Syntroleum fueled buses averaged 0.144 g/mile which constituted a reduction of approximately 25%.

Increased cetane number, lower aromatic content and near zero sulfur content of the Syntroleum fuel contribute to reductions in PM emissions. The effect of cetane number on particulate emissions is less clear with some studies indicating decreased PM, others the opposite trend and some others showing no effect [6]. A number of studies have found that the soluble organic fraction (SOF) of the PM was significantly reduced when the cetane number increased, but that the benefit was offset by an increase in the insoluble portion of the PM [6]. Reduced aromatic content particularly polycyclic aromatics (PAH) may also contribute to lower particulate emissions. Some studies have shown that at low engine speeds and loads, particulate emissions are largely composed of unburned fuel PAH. Studies have found that reducing PAH resulted in reduction in HC, NO_x and PM emissions [6]. Fuel sulfur is converted to SO₂ and sulfates which, along with bound water manifest themselves as PM emissions. There is generally a linear relationship between fuel sulfur consumption and the sulfate portion of PM emissions with a conversion rate of between 1 and 3 percent. The contribution of sulfates to the total particulate mass is only a few percent so that the reduction of PM through reduction of fuel sulfur content is limited.

Figure 13: Particulate matter emissions (PM) emissions.

The Denali Park buses were equipped with diesel oxidation catalysts rather than catalyzed diesel particulate filters. It is important to note, however, that due to its near zero sulfur content, the Syntroleum fuel is highly compatible with catalyzed particulate filter technology. The high precious metal and platinum loading in passive catalyzed particulate filters such as the Engelhard DPX and Johnson-Matthey CRT substantially increase the formation of sulfates. The near zero sulfur content of Syntroleum GTL fuel may offer an advantage over ultra-low sulfur petroleum derived diesel for vehicles equipped with catalyzed particulate filters.

Hydrocarbon and Carbon Monoxide Emissions

Hydrocarbon results are plotted in Figure 6. HC emissions were very low for both fuels. The JET A fueled buses averaged 1.05 g/mile while the Syntroleum fueled buses averaged 0.197 g/mile an apparent reduction of 81%. It is noted however that the JET A results exhibited substantial bus-to-bus variability.

Carbon monoxide results are plotted in Figure 7. The buses fueled with JET A fuel averaged 11.20 g/mile ranging from 8.74 g/mile to 13.72 g/mile. The Syntroleum fueled buses averaged 3.55 g/mile, which is a reduction of 68% compared to the JET A fueled bus group.

Figure 14: Hydrocarbon emissions (HC) emissions.

Figure 15: Carbon Monoxide emissions (CO) emissions.

Fuel Economy Results

Fuel economy results are shown in Figure 8. Fuel consumption during the chassis dynamometer testing was very similar between the two fuels. The JET A bus group averaged 3.65 miles/gallon over the WMATA driving cycle while the Syntroleum buses averaged 3.61 miles/gallon. It is noted however that Doyon/Aramark report observing a slight increase in fuel economy from the Syntroleum fueled buses based on fleet fueling records.

Figure 16: Fuel economy.

Conclusions

Emissions measurements were conducted on six identical Thomas Transit Liner buses equipped with 2004 Caterpillar C7 ACERT engines at Denali National Park Alaska. The exhaust emissions from buses fueled Syntroleum Fischer-Tropsch fuel were compared to emissions from buses fueled with low sulfur petroleum derived JET A fuel. All of the buses were equipped with diesel oxidation catalysts. Results indicated that use of Syntroleum reduced particulate emissions by approximately 25% and carbon monoxide by approximately 68%. Averaged over the two groups Syntroleum fuel also resulted in a reduction in HC emissions of 81% but it is noted that HC emissions were low from both fuels and that there was substantial variation within the JET A bus group. There did not appear to be any significant difference in fuel economy between the two fuels. Use of the Syntroleum Fischer-Tropsch fuel with the Caterpillar C7 ACERT engines produced an increase in NO_x emissions of approximately 2.9 g/mile compared to the buses fueled with JET A fuel. This trend is contrary to the results observed from the Detroit Diesel powered buses at the Washington DC Metropolitan Transit Authority. WVU did verify that this was indeed a fuel related or vehicle related phenomenon by retesting one of the JET A fueled buses at the end of the program. This retest verified that there had not been a shift of the laboratory equipment of calibration.

The Caterpillar C7 ACERT engines appeared to respond differently in terms of NO_x emissions than did the DDS Series 50 engines. It is also noted that the baseline fuels used at Denali Park and WMATA are different. WMATA uses an ultra-low sulfur type 1 diesel fuel and Denali Park uses a low sulfur JET A fuel. Sample of the Syntroleum and JET A fuels used at Denali have been sent for analysis and will be reported in the final draft of this report. Fuel properties may offer some insight in to the NO_x emissions results observed with the Denali Park buses.

References for Part D

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3. Clark, N.N., Gautam, M., Bata, R.M., Loth, J., Palmer, G.M., Wang, W.G., and Lyons, D.W., "Design and Operation of a New Transportable Laboratory for Emissions Testing of Heavy-duty Trucks and buses," International Jour. Of Vehicle Design (Heavy Vehicle Systems) 1995, Vol. 2, Nos. 3/4, pp. 285-299.
4. Schaberg, P.W., Myburgh, I.S., Botha, J.J., Roets, P.N., Viljoen, C.L., Dancuart, L.P., and Starr, M.E., "Diesel Exhaust Emissions Using Sasol Slurry Phase Distillate Process Fuels," Society of Automotive Engineers Paper No. 972898, 1997.
5. Wayne, W.S., Lyons, D.W., Clark, N.N., and Nine, R.D., "Ultra-Clean Transportation Fuels Project - Interim Report No. 1, Submitted to Integrated Concepts and Research Corporation by West Virginia University, P.O. Box 6106 Morgantown WV, 26506, June 2004.
6. Letavec, C., Uilein, J., Vertin, K., Chatterjee, S., Hallstrom, K., Wayne, S., Clark, N., Gautam, M., Thompson, G., Lyons, D., Chandler, K., and Coburn, T., "Year-Long evaluation of Trucks and Buses Equipped with Passive Diesel Particulate Filters," Society of Automotive Engineers Paper No. 2002-01-0433, 2002.

Appendix for Part D

Test Sequence Number: 4235

WVU Test Reference Number: ARAMARK-531-JETA-2WMATA

Fleet Owner Full Name Doyon/Aramark
Fleet Address 241 W. Ship Creek Ave.
Fleet Address (City, State, Zip) Anchorage, AK 99501

Vehicle Type Transit Bus
Vehicle ID Number (VIN) 1T88U2C2751149858
Vehicle Manufacturer Thomas
Vehicle Model Year 2004
Gross Vehicle Weight (GVW) (lb.) 36200
Vehicle Total Curb Weight (lb.) 21830
Vehicle Tested Weight (lb.) 29180
Odometer Reading (mile) 8602
Transmission Type Auto
Transmission Configuration 5 speed
Number of Axles 2

Engine Type Caterpillar C7 ACERT
Engine ID Number KAL23694
Engine Model Year 2004

Engine Displacement (Liter) 7.2
Number of Cylinders 6
Engine Rated Power (hp) 230

Primary Fuel JETA
Catalytic Converter Manufacturer Diesel Oxidation Catalyst
Test Cycle 2WMATA
Test Date 7/18/04

Engineer R. Barnett
Driver J. England

Emissions Results (g/mile)

Fuel Economy

Run Seq. No.	CO	NO _x ¹	NO _x ²	FIDHC	PM	CO ₂	mile/gal	BTU/mile	Mile
4235-1	12.6	12.4	12.3	1.75	0.18	2579	3.70	34033	8.6
4235-2	12.1	12.5	12.3 ^{NO}	1.64	0.19	2560	3.73	33776	8.6
4235-3	11.5	13.5	13.4	1.38	0.20	2653	3.60	34961	8.4
4235 Average	12.0	12.8	c	1.59	0.19	2597	3.68	34257	8.5
Std. Dev.	0.6	0.6	c	0.19	0.01	49	0.07	623	0.1
CV%	4.7	4.7		11.9	5.5	1.9	1.8	1.8	1.4

x-Not Reportable, a-Outlier, b-HC Not Reportable(Residual HC), c-missing component, d-Coefficient of Variation Too Large, e-below detectable limit

Test Purpose:

Aramark bus #531 running with muffler.

Special Procedures:

runs 1 and 3 in NO_x mode, run 2 NO/NO_x split

Test Sequence Number: 4239**WVU Test Reference Number: ARAMARK-532-JETA-2WMATA**

Fleet Owner Full Name Doyon/Aramark
 Fleet Address 241 W. Ship Creek Ave.
 Fleet Address (City, State, Zip) Anchorage, AK 99501

Vehicle Type Transit Bus
 Vehicle ID Number (VIN) 1T88U2C2951149859
 Vehicle Manufacturer Thomas
 Vehicle Model Year 2004
 Gross Vehicle Weight (GVW) (lb.) 36200
 Vehicle Total Curb Weight (lb.) 21830
 Vehicle Tested Weight (lb.) 29180
 Odometer Reading (mile) 7645
 Transmission Type Auto
 Transmission Configuration 5 speed
 Number of Axles 2

Engine Type Caterpillar C7 ACERT
 Engine ID Number KAL23696
 Engine Model Year 2004

Engine Displacement (Liter) 7.2
 Number of Cylinders 6
 Engine Rated Power (hp) 230

Primary Fuel JETA
 Catalytic Converter Manufacturer Diesel Oxidation Catalyst
 Test Cycle 2WMATA
 Test Date 7/19/04

Engineer R. Barnett
 Driver J. England

Emissions Results (g/mile)**Fuel Economy**

Run Seq. No.	CO	NO _x ¹	NO _x ²	FIDHC	PM	CO ₂	mile/gal	BTU/mile	Mile
4239-1	12.1	12.7	12.5 ^{NO}	0.64	0.17	2535	3.77	33408	8.7
4239-2	9.0	13.0	12.8	0.64	0.18	2540	3.77	33411	8.6
4239-3	9.8	13.3	13.1 ^{NO}	0.67	0.18	2585	3.70	34013	8.4
4239 Average	10.3	13.0	c	0.65	0.18	2554	3.75	33611	8.6
Std. Dev.	1.6	0.3	c	0.02	0.00	27	0.04	348	0.1
CV%	15.5	2.5		2.9	2.4	1.1	1.0	1.0	1.7

x-Not Reportable, a-Outlier, b-HC Not Reportable(Residual HC), c-missing component, d-Coefficient of Variation Too Large, e-below detectable limit

Test Purpose:

Aramark bus #531 running with muffler.

Special Procedures:

Run 2 is in NO_x mode, runs 1 and 3 are NO/NO_x split

Test Sequence Number: 4243**WVU Test Reference Number: ARAMARK-536-JETA-2WMATA**

Fleet Owner Full Name Doyon/Aramark
 Fleet Address 241 W. Ship Creek Ave.
 Fleet Address (City, State, Zip) Anchorage, AK 99501

Vehicle Type Transit Bus
 Vehicle ID Number (VIN) 1T88U2C2X51149970
 Vehicle Manufacturer Thomas
 Vehicle Model Year 2004
 Gross Vehicle Weight (GVW) (lb.) 36200
 Vehicle Total Curb Weight (lb.) 21830
 Vehicle Tested Weight (lb.) 29180
 Odometer Reading (mile) 8144
 Transmission Type Auto
 Transmission Configuration 5 speed
 Number of Axles 2

Engine Type Caterpillar C7 ACERT
 Engine ID Number KAL24268
 Engine Model Year 2004

Engine Displacement (Liter) 7.2
 Number of Cylinders 6
 Engine Rated Power (hp) 230

Primary Fuel JETA
 Catalytic Converter Manufacturer Diesel Oxidation Catalyst
 Test Cycle 2WMATA
 Test Date 7/20/04

Engineer R. Barnett
 Driver J. England

Emissions Results (g/mile)**Fuel Economy**

Run Seq. No.	CO	NO _x ¹	NO _x ²	FIDHC	PM	CO ₂	mile/gal	BTU/mile	Mile
4243-1	8.43	12.3	12.2	0.52	0.20	2655	3.61	34899	8.5
4243-2	7.80	13.0	12.9 ^{NO}	0.45	0.22	2667	3.60	35037	8.5
4243-4	9.98	12.9	12.6	0.72	0.21	2704	3.54	35570	8.4
4243 Average	8.74	12.7	c	0.56	0.21	2675	3.58	35169	8.5
Std. Dev.	1.12	0.4	c	0.14	0.01	25	0.04	354	0.0
CV%	12.8	3.1		24.7	4.1	0.9	1.0	1.0	0.7

x-Not Reportable, a-Outlier, b-HC Not Reportable(Residual HC), c-missing component, d-Coefficient of Variation Too Large, e-below detectable limit

Test Purpose:

Aramark bus #536 running with muffler.

Special Procedures:

Run 1 and 4 in NO_x mode, rest NO/NO_x split

Observations:

run 3 bad due to HC analyzer pump failure. WMATA warm-up run in next sequence number, then came back and completed run 4.

Test Sequence Number: 4248**WVU Test Reference Number: ARAMARK-533-SYNTRO-2WMATA**

Fleet Owner Full Name Doyon/Aramark
 Fleet Address 241 W. Ship Creek Ave.
 Fleet Address (City, State, Zip) Anchorage, AK 99501

Vehicle Type Transit Bus
 Vehicle ID Number (VIN) 1T88U2C2351149860
 Vehicle Manufacturer Thomas
 Vehicle Model Year 2004
 Gross Vehicle Weight (GVW) (lb.) 36200
 Vehicle Total Curb Weight (lb.) 21830
 Vehicle Tested Weight (lb.) 29180
 Odometer Reading (mile) 8086
 Transmission Type Auto
 Transmission Configuration 5 speed
 Number of Axles 2

Engine Type Caterpillar C7 ACERT
 Engine ID Number KAL24396
 Engine Model Year 2004

Engine Displacement (Liter) 7.2
 Number of Cylinders 6
 Engine Rated Power (hp) 230

Primary Fuel SYNTRO
 Catalytic Converter Manufacturer Diesel Oxidation Catalyst
 Test Cycle 2WMATA
 Test Date 7/21/04

Engineer R. Barnett
 Driver J. England

Emissions Results (g/mile)**Fuel Economy**

Run Seq. No.	CO	NO _x ¹	NO _x ²	FIDHC	PM	CO ₂	mile/gal	BTU/mile	Mile
4248-1	4.22	15.6	15.4	0.27	0.14	2524	3.65	34214	8.6
4248-2	5.30	15.5	15.1 ^{NO}	0.29	0.14	2520	3.65	34186	8.4
4248-3	4.12	16.3	15.9 ^{NO}	0.25	0.14	2532	3.64	34323	8.4
4248 Average	4.55	15.8	c	0.27	0.14	2525	3.65	34241	8.5
Std. Dev.	0.65	0.4	c	0.02	0.00	6	0.01	72	0.0
CV%	14.4	2.7		8.1	1.5	0.2	0.2	0.2	0.9

x-Not Reportable, a-Outlier, b-HC Not Reportable(Residual HC), c-missing component, d-Coefficient of Variation Too Large, e-below detectable limit

Test Purpose:

Aramark bus #533 running with muffler.

Special Procedures:

Run 1 in NO_x mode, runs 2 and 3 NO/NO_x split

Test Sequence Number: 4252**WVU Test Reference Number: ARAMARK-537A-SYNTRO-2WMATA**

Fleet Owner Full Name Doyon/Aramark
 Fleet Address 241 W. Ship Creek Ave.
 Fleet Address (City, State, Zip) Anchorage, AK 99501

Vehicle Type Transit Bus
 Vehicle ID Number (VIN) 1T88U2C2151149971
 Vehicle Manufacturer Thomas
 Vehicle Model Year 2004
 Gross Vehicle Weight (GVW) (lb.) 36200
 Vehicle Total Curb Weight (lb.) 21830
 Vehicle Tested Weight (lb.) 29180
 Odometer Reading (mile) 6507
 Transmission Type Auto
 Transmission Configuration 5 speed
 Number of Axles 2

Engine Type Caterpillar C7 ACERT
 Engine ID Number KAL24425
 Engine Model Year 2004

Engine Displacement (Liter) 7.2
 Number of Cylinders 6
 Engine Rated Power (hp) 230

Primary Fuel SYNTRO
 Catalytic Converter Manufacturer Diesel Oxidation Catalyst
 Test Cycle 2WMATA
 Test Date 7/22/04

Engineer R. Barnett
 Driver J. England

Emissions Results (g/mile)**Fuel Economy**

Run Seq. No.	CO	NO _x ¹	NO _x ²	FIDHC	PM	CO ₂	mile/gal	BTU/mile	Mile
4252-1	2.99	16.6	16.5	0.20	0.16	2608	3.53	35332	8.4
4252-2	3.05	17.1	16.9 ^{NO}	0.19	0.15	2621	3.52	35504	8.3
4252-3	3.02	16.7	16.5 ^{NO}	0.16	0.15	2583	3.57	34983	8.4
4252 Average	3.02	16.8	c	0.18	0.15	2604	3.54	35273	8.4
Std. Dev.	0.03	0.3	c	0.02	0.00	20	0.03	266	0.0
CV%	1.0	1.5		9.3	1.8	0.8	0.8	0.8	0.4

x-Not Reportable, a-Outlier, b-HC Not Reportable(Residual HC), c-missing component, d-Coefficient of Variation Too Large, e-below detectable limit

Test Purpose:

Aramark bus #537A running with muffler.

Special Procedures:

run 1 is NO_x mode, runs 2 and 3 are NO/NO_x split.

Test Sequence Number: 4254**WVU Test Reference Number: ARAMARK-532-JETA-WMATA**

Fleet Owner Full Name Doyon/Aramark
 Fleet Address 241 W. Ship Creek Ave.
 Fleet Address (City, State, Zip) Anchorage, AK 99501

Vehicle Type Transit Bus
 Vehicle ID Number (VIN) 1T88U2C2951149859
 Vehicle Manufacturer Thomas
 Vehicle Model Year 2004
 Gross Vehicle Weight (GVW) (lb.) 36200
 Vehicle Total Curb Weight (lb.) 21830
 Vehicle Tested Weight (lb.) 29180
 Odometer Reading (mile) 7953
 Transmission Type Auto
 Transmission Configuration 5 speed
 Number of Axles 2

Engine Type Caterpillar C7 ACERT
 Engine ID Number KAL23696
 Engine Model Year 2004

Engine Displacement (Liter) 7.2
 Number of Cylinders 6
 Engine Rated Power (hp) 230

Primary Fuel JETA
 Catalytic Converter Manufacturer Diesel Oxidation Catalyst
 Test Cycle WMATA
 Test Date 7/22/04

Engineer R. Barnett
 Driver J. England

Emissions Results (g/mile)**Fuel Economy**

Run Seq. No.	CO	NO _x ¹	NO _x ²	FIDHC	PM	CO ₂	mile/gal	BTU/mile	Mile
4254-3	13.7	12.6	12.5	1.22	0.17	2652	3.60	34996	4.2
4254 Average	13.7	12.6	c	1.22	0.17	2652	3.60	34996	4.2
Std. Dev.	c	c	c	c	c	c	c	c	c
CV%	d	d	d	d	d	d	d	d	d

x-Not Reportable, a-Outlier, b-HC Not Reportable(Residual HC), c-missing component, d-Coefficient of Variation Too Large, e-below detectable limit

Test Purpose:

Retest of Aramark bus #532

Special Procedures:

run 2 is invalid due to the computer locking up.

Test Sequence Number: 4257**WVU Test Reference Number: ARAMARK-534-SYNTRO-2WMATA**

Fleet Owner Full Name Doyon/Aramark
 Fleet Address 241 W. Ship Creek Ave.
 Fleet Address (City, State, Zip) Anchorage, AK 99501

Vehicle Type Transit Bus
 Vehicle ID Number (VIN) 1T88U2C2551149861
 Vehicle Manufacturer Thomas
 Vehicle Model Year 2004
 Gross Vehicle Weight (GVW) (lb.) 36200
 Vehicle Total Curb Weight (lb.) 21830
 Vehicle Tested Weight (lb.) 29180
 Odometer Reading (mile) 6068
 Transmission Type Auto
 Transmission Configuration 5 speed
 Number of Axles 2

Engine Type Caterpillar C7 ACERT
 Engine ID Number KAL24760
 Engine Model Year 2004

Engine Displacement (Liter) 7.2
 Number of Cylinders 6
 Engine Rated Power (hp) 230

Primary Fuel SYNTRO
 Catalytic Converter Manufacturer Diesel Oxidation Catalyst
 Test Cycle 2WMATA
 Test Date 7/24/04

Engineer R. Barnett
 Driver J. England

Emissions Results (g/mile)**Fuel Economy**

Run Seq. No.	CO	NO _x ¹	NO _x ²	FIDHC	PM	CO ₂	mile/gal	BTU/mile	Mile
4257-1	3.12	14.3	14.3	0.15	0.14	2525	3.65	34198	8.6
4257-2	3.47	14.0	13.8	0.19	0.14	2516	3.66	34092	8.5
4257-3	2.64	15.3	15.2	0.09	0.15	2546	3.62	34474	8.5
4257 Average	3.08	14.5	c	0.14	0.14	2529	3.65	34255	8.5
Std. Dev.	0.42	0.7	c	0.05	0.01	15	0.02	197	0.0
CV%	13.6	4.8		37.7	4.4	0.6	0.6	0.6	0.7

x-Not Reportable, a-Outlier, b-HC Not Reportable(Residual HC), c-missing component, d-Coefficient of Variation Too Large, e-below detectable limit

Part E. Demonstration of Clean Diesel Fuels in Diesel Electric Generators in Alaska

Introduction

The primary goals of the Diesel Electric Generator clean fuels demonstration is to assure the potential users of these fuels that no adverse affects are encountered, while significant advantages are gained. The possible adverse effects to be measured include possible increased wear in the fuel delivery system leading to higher maintenance costs, and to difficulties associated with handling the fuel in arctic conditions. The significant advantages include reduced emissions of criteria pollutants, the ability to recover significantly more heat from the combustion exhaust, and the reduced environmental impacts of possible spills. The University of Alaska-Fairbanks expects that the Syntroleum fuel will give excellent performance in its tests.

Experimental plan

The experimental plan is based on a 2000 hour demonstration of the Syntroleum fuel operating in a high efficiency diesel electric generator setup similar to those being used in remote Alaskan power systems. Efficiency, emissions, engine wear, injection timing, heat recovery, and fuel handling issues will be monitored during this testing.

Description of experimental apparatus

After conversations with several rural electrical utility operators, this program decided to use a Detroit Diesel Series 50 generator for the clean fuels testing. This generator was selected because it exhibits the high efficiency associated with the new generation electronic injection engines, including the high compression ratios from turbochargers, but is small enough to allow the maximum number of testing hours to be conducted with the fuel provided under the program.

Procurement of the diesel engine has been an interesting exercise due to the funding issues associated with the delayed funding in 2002. We initially contacted the Alaska Village Electric Cooperative (AVEC) to see if a used diesel engine could be found for use in our program. The response was negative, so in late fall of 2002, a purchase request was begun to purchase a new generator. However, the stop work order in December of 2002 prevented the university from completing the purchase, and the request was canceled. During the funding blackout, AVEC contacted us to indicate that a generator would be available that would meet our needs, and that this generator would be available late in the summer of 2002. Because of the concerns raised about switching fuels on existing engines, we preferred obtain a used engine, and planned on obtaining this generator for our project. In August of 2003, we were informed that the new generator was in place in the village where the used DEG was, but that the generator could not be moved from its location until the ground froze. Unfortunately, this would not be likely until sometime in January 2004. Given the fact that our plan calls for doing the 2000 hour demonstration as quickly as possible after the arrival of the fuel (storage costs for the fuel will be significant), and the need for the generator to be instrumented prior to the start of testing, we elected to return to the plan of purchasing a new generator.

The purchase order for the generator was started at the University in mid-September, 2003, with an expected delivery date of November, 2003. In October, 2003, discussions with the University fire marshal led to the decision to house the generator in a connex box outside an existing building, as this building has no sprinkler system, and would need three hour fire walls for code compliance in installing a generator. Installation of the generator in the connex box was contracted to the generator supplier, but this installation resulted in additional delays in the delivery of the unit. The installation was finally delivered to the university on May 15, 2004.

The on site fuel storage issue was of some concern, as it was not clear if double walled tanks or secondary containment was required for a temporary project. Our initial plan was to use the ISO containers as the primary dispensing container, and to build a gravel pit with a liner for secondary containment. However, the Denali National Park service has allowed UAF to borrow a tank they purchased several years ago, with the university agreeing to pay for the transportation and cleaning of the tank (it has been sitting empty for several years, and has accumulated some surface rust and dirt). This tank is now in place, and is ready to receive the clean fuel when delivered.

The other major question is what to do with the electricity generated in the project. Electrical switching equipment to connect the generator to the university grid is more expensive than the generator, and our initial budget did not provide sufficient funds for a sophisticated switch. Also, the environmental testing requires adjusting the load, and this can be most easily accomplished by use of a controllable load bank. Therefore, we have elected to purchase a computer controllable load bank for this work. This item had a lead time of several months, and was ordered in May of 2003, and is currently being shipped to the university.

The experiments will be controlled and the data collected through a data acquisition and control system based on National Instruments Labview hardware and software.

The demonstration will require baseline emissions and efficiency data on conventional diesel fuel, to be conducted prior to the arrival of the clean diesel fuel. It is expected that the injection timing will need to be adjusted to optimize the performance of the clean fuels. Changing the injection timing is controlled by software, and Detroit Diesel has agreed to provide the necessary “maps” and train our researchers in how to load these into the generator.

As of this writing, the diesel engine has operated for a total of 731 hours, with 272 being on conventional fuel for a break in period, and 459 being on clean diesel fuel. A total of 3680 gallons of clean fuel have been consumed in this testing. No significant operational issues have been identified with the operation of the engine.

One important issue is the lubricity of the fuel. The university had the equipment for doing the scuffing ball test ASTM D6078 (SLBOCLE), but after looking at the standardized testing method, a decision was made to send the fuel out to an external testing laboratory for evaluation. The first sample sent to this laboratory indicated that the lubricity value (2850g) was slightly under the recommended value of 3100 g.

However, this test is somewhat difficult to conduct, and there is often high variance in the results, so we have drawn no conclusions as yet.

A collection system has been devised to condense water from the exhaust system in order to evaluate the chemistry of the condensate. This system is working and condensate from clean diesel fuel has been collected, but evaluation of the water has not been completed. However, the condensate appears relatively clear (except for a slight green color most likely imparted from the copper tubing), has a faint odor of soot.

The Detroit Diesel engine also has a data interface using CAN bus. We have managed to collect a lot of engine performance data from this system and are comparing these values to ones measured externally. For example, the CAN bus provides both instantaneous values for fuel consumption, as well as total fuel consumed in the history of the engine. While we have not yet established complete confidence in our own instantaneous fuel flow measurements, we have compared the engine total value with the total gallons of fuel consumed by the engine, and found that the two numbers differ by about 3.25%, the higher number being from the pumping records we have kept. This may indicate a difference between the expected fuel consumed based on the heating value of conventional diesel fuel as compared to the somewhat reduced energy per volume of the clean fuel. However, this discrepancy is not large, and may simply be within the error bounds of the performance mapping of the engine.

Some emissions data have been collected, but additional calibrations need to be completed before these data can be evaluated.

Conclusions

Results to date indicate that the clean diesel fuel is performing as expected, with no apparent negative impacts on the diesel engine. More detailed conclusions will be possible after completion of the experimental program outlined above. The testing is expected to be completed by November 15, 2004.

Part F, Economic Analysis

TIAX is assessing the impact of the introduction of ultraclean fuels produced by Gas-to-Liquid (GTL) processes on air emissions, cost and energy use. During the previous reporting period we completed the first round of an analysis that involves selecting viable fuel chains, determining feedstock availability and estimating the feasibility of producing the selected fuels from the available feedstocks by means of a small footprint GTL plant. In subsequent work the preliminary well-to-tank analyses should be refined and extended to include well-to-wheels considerations once emissions and fuel economy data become available from the other team members. In addition, the analyses should be focused on the conditions and needs specific to fuel production and use in Alaska.

The feedstocks that TIAX is considering include both conventional and unconventional natural gas resources (the latter comprising coal-bed methane, tight gas, shale gas, coal gas and biomass). The conversion process is the small footprint Fischer-Tropsch process of Syntroleum, sized to make 500 to 10000 barrels per day (bpd) of fuel. The SFP products include ultraclean diesel fuel, naphtha and electricity. A reference case of conventional Diesel fuel is being used to anchor the economic analysis. Market potential is being estimated based on distillate usage in transportation, residential customers, industrial customers, commercial customers and electricity generation. The results reported here are based on a very approximate characterization of the economics of the GTL technology and must be viewed circumspectly. More refined analyses and sensitivity analyses (to identify significant parameters and assumptions) should be the focus of future work.

In our preliminary screen, we identified 171 gas resources of a suitable size and location for small footprint GTL plants sized for 1000 bpd of production and a 15-year lifetime. All of these proven reserves are located within 150 miles of a wholesale Diesel outlet, suggesting that conventional fuel suppliers could serve the potential markets for GTL products. However, 41 of these reserves have high concentrations of hydrogen sulfide (>10 ppm), nitrogen (>4%) and/or carbon dioxide (>2%) which may make them less attractive because of the additional clean up that may be required to employ them.

To estimate the economics of a small footprint GTL plant TIAX extrapolated the results of a techno-economic analysis carried for a much large scale plant (>50,000 bpd), using standard allometric relations (power-law scaling). The analysis estimated the capital cost each of the important components required in the GTL process (heat exchangers, reactors, separation units, compressors), each sized according to the desired scale of the plant. Operating expenses combined the costs of the feedstock, expendables and labor. It was assumed that the plants were built with 100% equity.

With the assumptions used, the preliminary results suggest that a small GTL plant (1000 bpd) would be able to generate profit (10% internal rate of return) under circumstances of sufficiently cheap feedstock (\$0.00 to \$0.40 per million btu) if located sufficiently remotely (>300 miles) from a conventional source of fuel (wholesale price of \$0.74/gal). While the results depend sensitively on scale of operation, cost of gas, location and market price of the fuel it is fair to infer that remote locations, for example in Alaska, may benefit the most from

this technology. Tiax is in the process of refining that analysis to take into account Alaska-specific market information, construction factors and resource locations.

In the current reporting period we revised our existing estimates of the costs of constructing and operating a small footprint plant and we have compared the results to those provided by Syntroleum for a much more detailed analysis of two sizes of plants (100 and 1700 barrels per day). The agreement between the overall costs obtained from the two sets of estimates was excellent. Thus, going forward, we can apply the revised values of energy efficiency, costs and operating assumptions to refine the well-to-tank analysis that serves to identify the technically and economically viable resources. The revised model also permits estimating the environmental and greenhouse emissions associated with generating the GTL fuel. We will combine those emissions with those associated with using the fuel through the tank-to-wheels scenarios that will be constructed in the next reporting period.

Conversion factors

A given quantity of gas can be converted into an amount of liquid fuel that contains some fraction of the energy content (heat of combustion) of the starting material, the difference in energy content going to the conversion process. For the preliminary analysis reported here we have employed an energy conversion efficiency of 40%, which is a conservative first estimate of the efficiency of a small scale plant. The overall energy efficiency of the plant could be considerably higher with appropriate heat integration or if the waste heat were used to produce electricity. That extension will be considered in the more detailed analyses in the future. The calculations below use an overall energy efficiency of 50% to estimate the amount of liquid products that can be obtained from 1 million cubic feet (MMCF) of gas with a nominal heating value of 1050 BTU/scf:

For Diesel (36.4 MJ/liter [1])

$$1050 \frac{BTU}{scf} \times 10^6 scf \times 0.50 \frac{BTU_{products}}{BTU_{gas}} \times 1055 \frac{J}{BTU} \times \frac{1}{36.4 \times 10^6} \frac{liter}{J} \times \frac{1}{159} \frac{bbl}{liter} = 95 bbl$$

For Gasoline (32 MJ/liter [1])

$$1050 \frac{BTU}{scf} \times 10^6 scf \times 0.50 \frac{BTU_{products}}{BTU_{gas}} \times 1055 \frac{J}{BTU} \times \frac{1}{32 \times 10^6} \frac{liter}{J} \times \frac{1}{159} \frac{bbl}{liter} = 109 bbl$$

With these assumptions about energy content and energy conversion efficiency, a SFP sized to make 500 BPD of a product stream, consisting of 25% naphtha and 75% Diesel fuel, for 10 years would require a gas field containing about 20 bcf of gas:

$$0.25 \times \frac{109 bbl_{gasoline}}{10^6 scf} + 0.75 \times \frac{95 bbl_{Diesel}}{10^6 scf} = 99 \frac{bbl_{product}}{10^6 scf}$$

$$500 bpd \times 365 d \times 10 = 1,800,000 bbl$$

$$1,800,000 bbl \times \frac{10^6 scf}{99 bbl_{product}} = 18 bcf$$

METHODS

Resource Identification

In the previous reporting period, to identify suitable starting resources TIAX employed the GASIS database [2], which includes data on small and unconventional resources in the lower 48 states. Release 2 of the GASIS Reservoir Data System is a national database of geological, engineering, production, and ultimate recovery data for U.S. oil and gas reservoirs. The reservoir data system contains 19,220 reservoir records with 185 data fields per record. These reservoirs represent most of the historical gas production in the areas covered. Included reservoirs are those either meeting minimum cumulative gas production levels (through 1996) or those that were included in the Department of Energy/Gas Research Institute Gas Atlas projects. In general, GASIS reservoirs are those with at least 10 Bcf of cumulative gas production (5 Bcf in Rocky Mountain region).

Data sources for the Reservoir Data System include the regional DOE/GRI Gas Atlas data sets, new information from Dwights TOTL (field and reservoir) database, Dwights DOGR (well completion) database, GRI tight gas identification data and gas composition data, and other public domain data. Some data elements included in GASIS are calculated values, such as gas well productive area, recovery per well statistics, and estimated ultimate recovery.

TIAX used the query functions in GASIS to characterize and count gas resources of four types (Table 1). On the upper end, the search was limited to fields that were not currently “in play”, since gas that is being delivered to the grid was deemed to have a value higher than could be attained by converting it to liquid fuel. On the lower end, the search was bounded at 25 bcf, the minimum amount of gas required to keep a 500 BPD SFP in production for 10 years.

Table 4. Gas resources considered as possible feedstocks

Resource	Description
Conventional	Reservoirs of associated natural gas (dissolved in or lying above oil reservoirs) or non-associated gas
Coal bed methane	Natural gas associated with coal beds
Tight gas	Natural gas from low-permeability (tight) reservoirs, having permeabilities less than 0.1 millidarcies [3]
Shale gas	Natural gas derived from shale deposits

In the next reporting period TIAX will search for resources that meet a less stringent size requirement since we will be using a more accurate, and higher, energy efficiency and since we will consider, as our base case, the possibility of relocating the small footprint plant after 5 years of operation.

Estimate of Location-dependent economics

To estimate the effect of geographic remoteness on the perceived value of SFP products we attempted to determine the added cost of delivering fuel from a central depot to outlying locations where one might site an SFP (whose products were assumed to be delivered without cost). Our simple model took into account the costs of storage and transportation:

$$Cost_{overall} = Cost_{transport} + Cost_{storage}$$

$$Cost_{transport} = Cost_{fixed} + Cost_{variable}$$

The storage costs were assumed to be 2 cents/gal; the fixed cost for transportation (driver, vehicle) was assumed to be \$700 per day, prorated by the number of deliveries; and the variable cost was assumed to be 38 cents/mile.

Techno-economic analysis of a Small Footprint Plant.

We have based on our preliminary analysis of the technical and economic performance of an SFP by extrapolating our previous work on Gas-to-Liquid technology [4]. In the previous reporting period we constructed a spreadsheet model that included the costs of the unit operations, the nature of the gas and project financing (Figure 1). In that work, we scaled the sizes and costs of the equipment using standard allometric techniques [5] (power law relations between scale and cost).

Figure 17. Schematic of the economic analysis.

The model was then exercised to determine the sensitivity of the results (capital costs, operating costs, internal rate of return, etc). to the values of the input parameters (e.g, plant scale, cost and quality of gas, price of products). The base case (Table 2) was an air-blown GTL plant designed to resemble the technology employed by Syntroleum but, given that the input values and technical performance are only initial estimates, the results should be viewed as placeholders.

Table 5. Base case parameters used to estimate the economics of an SFP.

Parameter	Value
Feedstock	Gaseous with a heating value of 1005 BTU/scf
Plant capacity	6000 BPD, air-blown generation of synthesis gas
Location factor	1
Energy conversion efficiency	40%
Crude oil price	\$24/bbl
Products	80% Diesel, 20% naphtha, no credit for electricity or steam

RESULTS AND DISCUSSION

Resources

The data in the GASIS database suggest that the resources for feeding an SFP will come most readily from small reservoirs of conventional gas (associated and non-associated), tight gas and coal bed methane (Figure 2). The database contained only a single record for a suitable shale gas reservoir, when screened according to the criteria described in the Methods section and described more fully in the Appendix. Altogether there were 180 resources that fit the screening criteria (Appendix 1).

Whether a particular resource is, in fact, usable will depend on its location proximity to infrastructure and markets, its quality (energy content of the gas, presence of impurities that require extensive cleanup or removal) and whether the resource can be used in other, more profitable ways. The increasing price of natural gas has a direct bearing on the latter criterion.

Figure 18. Results of the screening exercise. Left: Median recoverable ultimate reserves reported in GASIS. Right: Median higher heating value of reserves of each type.

The number of resources of each type suitable for feeding an SFP depends on the desired lifetime of the SFP (Figures 3-5). Small, conventional resources are by far the most numerous, followed by tight gas and coalbed methane. To read a plot, first choose the desired lifetime

(curves for 15, 20 and 25 years are shown) then choose the size of the desired plant on the x-axis. The corresponding coordinate on the y-axis tells the number of such plants that might be constructed. For example, roughly 45 SFPs with a production rate of 2000 bpd could be supported on the available conventional resources (Figure 3) if the plants were to last for 15 years.

Figure 19. Number of SFPs that can be supported using the screened, conventional resources of natural gas identified in the GASIS database

Figure 20. Number of SFPs that can be supported using the screened, tight resources of natural gas identified in the GASIS database

Figure 21. Number of SFPs that can be supported using the screened, resources of coalbed methane identified in the GASIS database

Summary Economic Analysis

We present three analyses below to account for the effects of plant size, plant location, price of natural gas and the price of crude oil on the overall operating economics. Each of these analyses should be considered as a placeholder since we will be revising them in the next reporting period to agree with the more accurate estimates obtained from our revised economics model. Moreover, the values may change markedly with the cost of feedstocks and products and the availability of credits for co-products (electricity, steam, water). Directionally, however the plots shown below are valid and serve to indicate the variables that have the most significant effects on the resulting economics.

To estimate the effect of plant size on profitability (Figure 6) we calculated the internal rate of return for a given feedstock price (\$0.40/million BTU) and a given average price of the products (\$0.84/gal). To construct this graph we made the assumptions listed in Table 2. The graph shows that, with our particular set of estimates a 2000 bpd plant achieves an IRR of 10%. Again, we hasten to point out that the actual values are only approximately correct. However, it is likely to be the case that the overall economics will be most sensitive to plant size at the small end of the curve since capital expenses are the major contributor to the cost of producing a unit of fuel.

To estimate the effect of remoteness on the overall economics we have constructed “iso-IRR” graphs for the two cases of varying the price of the feedstock and the price of the competing products, which are of course based on petroleum. The curves in Figures 7 and 8 show the minimum capacity of an SFP required to achieve an IRR of 10% as a function of distance from a Diesel rack (depot). For a given sized plant there is roughly a linear relation between the price of gas and distance from the rack (Figure 7). As gas gets more expensive, the plant

must be serve a more remote market in order for SFP products to compete with conventional Diesel and gasoline fuels. Similarly, as crude oil gets more expensive for a fixed price of natural gas, the SFP products become comparatively cheaper. However, while there once was a weak interdependence between the prices of crude oil and natural gas, the current relationship is much closer to energy content parity (\$4 per million BTU gas is about the same as \$24 per barrel of oil).

Figure 22. Effect of plant size on profitability

Figure 23. The interaction between the remoteness of the SFP and the minimum plant size required to achieve an IRR of 10% as a function of natural gas price

Figure 24. The interaction between the remoteness of the SFP and the minimum plant size required to achieve an IRR of 10% as a function of the price of crude oil

Revised Economic Analysis

In the current reporting period, TIAX updated its previous GTL model with costing and scaling factors to estimate the capital costs of the major components of the SFP. TIAX also rewrote the model in a form that permits much easier maintenance and revision. The previous model was an Excel spreadsheet. The current model (Figure 9) is based on

Simulink®, a general purpose modeling tool in which the functionality of each unit operation in the small footprint plant can be encapsulated in an independent module. We believe that this is the first such use of Simulink® for techno-economic modeling. An important benefit of this new approach is that the models can be packaged in a way that permits them to be distributed without revealing confidential information.

Our approach uses a multifactor method that has proved successful in work we have done for much larger GTL plants. The cost of a system is constructed from the costs of the individual components, which are divided into equipment costs, construction costs and installation costs. The latter two are estimated by multiplying the equipment costs by factors (hence the name, “multifactor”) derived from field experience for the different types of equipment (synthesis gas generator, Fischer-Tropsch reactor, balance of plant) and for the ancillary services that lie outside the “battery limits” of the core process (e.g., roads, housing, safety services).

TIAX has constructed models for plants sized between 100 and 6000 barrels per day capacity, operating with an air-blown synthesis gas generator and an operating pressure of 170 psi. A major assumption is the overall energy efficiency of the plant, defined to be the heating value of the products divided by the heating value of the input feed gas. We used a value of 50% for the energy efficiency, a number that has been validated by Syntroleum as being appropriate for this size range of plants.

Figure 25. Top level of the Simulink® model that incorporates the revised economics for the small footprint plants.

To validate the new model we compared its output to information provided by Syntroleum for two sizes of plants (Figure 10). The overall agreement between our cost estimates is very good. We hasten to point out, however, that the costs of the individual components were not estimated on the same basis since we have allocated utilities like heat exchangers and compressors in a manner different from that used by Syntroleum.

A sensitivity analysis on the model (Figure 11) indicate that the most expensive aspects of constructing a small footprint plant are associated with the infrastructure (services and equipment outside the battery limits), the synthesis gas generator and the Fischer-Tropsch reactor. Consideration of those factors have led us to consider ways to significantly decrease the cost of the plant by combining unit operations into a single module. We call that approach GTL-in-a-Can™ and will discuss it briefly in the later section of this report.

Figure 26. Comparison of capital costs for small footprint plants based on a conventional, “stick-built” architecture across a range of plant sizes. The costs of the individual components are not directly comparable because TIAX has used a different method of allocating utilities than that employed by Syntroleum.

Figure 27. Sensitivity analysis on the capital cost factors for constructing a small footprint plant.

TIAX also revised its estimates for operating the small footprint plant (Figure 12) and performed a sensitivity analysis (Figure 13) to identify the major costs. According to our estimates, a conventional plant incurs very significant costs for personnel at the smallest sizes of operation; at larger scales, the cost of the feedstock dominates. As will be seen below, modularization can help decrease labor costs by reducing the number of unit operations that need to be monitored.

Figure 28. TIAX estimates of operating costs for stick-built small footprint plants.

Figure 29. Sensitivity analysis on the operating expenses of a stick-built small footprint plant.

A possible alternative: GTL-in-a-Can™

The revised economic analysis presented above suggests that a small footprint plant would become significantly more profitable and possibly more robust if a way could be found to decrease capital costs and operating costs in the smaller size range (<1000 bpd). To address those issues, in prior work at the predecessor to TIAX, our staff had investigated ways to integrate the synthesis gas generation reactor and the Fischer-Tropsch reactor in one pressure vessel. The combined unit, which we call GTL-in-a-Can™ appears to be well positioned to become part of a fieldable, modular plant that promises better decreased capital and operating costs as well as increased transportability and reliability than a “stick-built” plant. Our preliminary costing suggests that fuel products could be synthesized for less than \$1/gal with a capital cost of \$25 million for a 500-1000 bpd plant, about half the costs associated with a stick-built plant. The savings arise from the decreased need for personnel, since we envisage the modular plant being highly automated, and the decreased construction costs, since we envisage the modular plant being produced at high enough volume that it benefits from economies of scale. Such a plant might be used in a number of ways, for example:

- Monetization/utilization of small, remote resources—the topic of this project
- Upgrading/interconversion of fuels—of possible interest to the military
- Alternative to flaring—to enable the drilling of exploration wells or monetization of associated gas
- Conversion of gaseous or liquid fuels to hydrogen or methanol, or other alternative transportation fuels—again, of possible interest to the military or remote communities.

We present the concept below as an adjunct to our analysis of the conventional plant and will include it in the final analyses to be completed in the next reporting period.

The modular plant incorporates the heart of the GTL plant (Figure 14) in one reactor unit (Figure 15). The reactor unit must be designed to ensure heat integration and the proper flow of species. By arranging the operations concentrically the hottest zone can be located deep inside the can, obviating the need for materials of construction that must withstand both high temperature and high pressure.

Figure 30. Schematic of a GTL-in-a-Can™ process showing the components included in the can.

Figure 31. Schematic of the Integrated Modular GTL Technology (Fischer-Tropsch application). The aspect ratio is distorted to show detail.

In our economic analysis we estimate that a plant that consumes 10 million scf/day of gas (equivalent to about 750 bpd of liquid products) can be built for about \$25 million and operated at a cost of about \$2.5 million/year. Automating the operation of the plant both decreases the number of operators required to run it and, potentially, makes the plant safer and more robust.

Figure 32. Estimated economics of GTL-in-a-Can™ at a size of 10 million scf/day (750 bpd products).

We have carried out sufficient analysis to identify the strengths of GTL-in-a-Can™ as commercial offering and to identify the needs for additional data. We offer it here as a concept in which a small footprint plant might be implemented in a way that could benefit both civilian and military applications.

CONCLUSION

The picture that emerges is that there are resources and conditions under which a SFP can be operated profitably. In particular, high cost of oil, long distances from conventional sources and underutilized resources all contribute to the economic viability of the plant. The addition of credits for electricity, steam and water only serve to improve the economic outlook.

In the next reporting period, the identification of particular resources will be updated to reflect the more accurate economics for constructing and operating small footprint plants. Evidently, the conditions favorable to the economic viability of SFPs prevail in Alaska and it will be interesting to refine the parameters for specific resources and markets there.

The complete picture, however, requires consideration of the full, well-to-wheels analysis to estimate the overall economic and environmental impact of the production and use of SFP-produced fuels. We also note that modularization of a small footprint plant could increase its appeal for both civilian and military applications.

References for Part F

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