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# Evaluation of Ultra-Clean Fischer-Tropsch Diesel Fuel in Transit Bus Applications

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16. Abstract


This document reports on one particular FTA-sponsored, Fischer-Tropsch (F-T) diesel fuel evaluation program, and it incorporates directly related findings (and the current, ongoing status) of other programs in the same series of FTA programs that have been, or are being, conducted by ICRC/VSE. The type of F-T fuel evaluated can be produced form a variety of US domestic energy resources other than petroleum. The overall technical priorities of these F-T fuel evaluations have been to:

1. Determine whether or not operational problems are likely to occur with F-T diesel fuel over the full spectrum of transit-relevant conditions;
2. Compare directly the fuel consumption of F-T and conventional diesel fuels under well controlled but still realistic on-road conditions in the more severe (than typical transit service) region of the spectrum of heavy-duty, diesel-engine service;
3. Compare the potential environmental impacts, in terms of both engine exhaust emissions and fuel biodegradability, of F-T and conventional diesel fuels under transit-relevant conditions.


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## EXECUTIVE SUMMARY

This document reports on one particular Federal Transit Administration-sponsored, Fischer-Tropsch (F-T) diesel fuel evaluation program, and it incorporates directly related findings (and the current, ongoing status) of other programs in the same series of Federal Transit Administration programs that have been, or are being, conducted by Integrated Concepts & Research Corporation/VSE. This type of Fischer-Tropsch fuel evaluated can be produced from a variety of United States domestic energy resources other than petroleum. The term Fischer-Tropsch refers both to fuels and to the process used to produce them. Synthesis gas, which consists of hydrogen and carbon monoxide, is produced first, either by reforming natural gas or by gasifying coal and/or biomass. The synthesis gas is cleaned-up and pre-treated appropriately, then fed to a synthesis reactor at high temperature and pressure containing Fischer-Tropsch catalyst. Paraffin-wax (a long-chain, hydrogen-saturated hydrocarbon) is synthesized, which would be solid at most ambient temperatures. Therefore, the wax must then be upgraded by hydrocracking and other processing to produce finished diesel fuel.

The overall technical priorities of these Fischer-Tropsch fuel evaluations have been to:

1. Determine whether or not operational problems are likely to occur with Fischer-Tropsch diesel fuel over the full spectrum of transit-relevant conditions;
2. Compare directly the fuel consumption of Fischer-Tropsch and conventional diesel fuels under well controlled but still realistic on-road conditions in the more severe (than typical transit service) region of the spectrum of heavy-duty, diesel-engine service;
3. Compare the potential environmental impacts, in terms of both engine exhaust emissions and fuel biodegradability, of Fischer-Tropsch and conventional diesel fuels under transit-relevant conditions.

The core program covered in this report is the nearly three-year, high-usage-rate evaluation of 24,000 gallons of neat (i.e. unblended) Syntroleum S-2 Fischer-Tropsch diesel fuel in revenue service in a new transit bus owned and operated by the Metropolitan Tulsa Transit Authority (MTTA). This program included the periodic removal, and electron-microscope inspection, of fuel-injector nozzles during the project. Inspections showed that nozzle-fouling deposits (that can originate from non-combustible materials in the engine oil additive package, not from the fuel, and which did occur in one laboratory engine under severe-service dynamometer testing) did not occur in extended transit-bus service in this program. Additional transit-based evaluations of smaller quantities of Fischer-Tropsch diesel fuel were carried out, both in extreme arctic-cold and in hot-desert conditions, to find out if such extremes might provoke operational problems with Fischer-Tropsch fuel.

The hot desert climate Fischer-Tropsch fuel evaluation program was conducted jointly with the US Air Force, using a military transit-bus at Edwards Air Force Base in California. The cooperative Fischer-Tropsch fuel evaluation has been enhanced and extended, with additional Air Force equipment being used to evaluate both neat and

blended Fischer-Tropsch fuels at another base, Selfridge Air National Guard Base, Michigan. The ongoing Selfridge Fischer-Tropsch fuel evaluation incorporates neat-Fischer-Tropsch fuel operation of a military transit bus similar to that used at Edwards Air Force Base. However, the Selfridge bus presents the opportunity to closely monitor and evaluate neat Fischer-Tropsch fuel in the same type of diesel engine that initially accumulated fuel-injector nozzle fouling deposits (referred to above) in severe-service dynamometer testing. Arctic cold climate transit-bus Fischer-Tropsch fuel evaluations were completed previously, but results are reviewed here to help demonstrate that Fischer-Tropsch diesel fuels can indeed be used over the full range of transit-relevant conditions without causing operational problems in either storage or usage.

Potential differences in fuel consumption are a major consideration when a new diesel fuel such as Fischer-Tropsch is being considered for transit use or for virtually any other heavy-duty diesel application as well. However, transit-service, with relatively light vehicles (compared to heavy trucks), frequent stopping and idling, etc., represents the relatively low-severity, and the relatively low and variable fuel-usage, end of the heavy-duty diesel service spectrum. Therefore, an extremely heavy-duty, on-road trucking application, with extremely consistent operating conditions, was selected to compare Fischer-Tropsch and conventional fuel consumption, and results are included in this report. Fischer-Tropsch fuel consumption was shown in this testing to be higher than for conventional diesel fuel, in proportion to the energy density difference between the two fuels.

The effects of Fischer-Tropsch diesel fuel on engine emissions were measured in several back-to-back tests conducted on Fischer-Tropsch and conventional diesel fuels. Back-to-back tests are required to eliminate differences attributable to different individual engines and vehicles. The diesel emissions of greatest concern are particulate matter (PM) and oxides of nitrogen (NOx), both of which can be immediately and consistently reduced by switching from conventional to Fischer-Tropsch diesel fuel (Reference 1). Furthermore, the effects on emissions with both Fischer-Tropsch and conventional fuels are measured with a retrofit diesel particulate filter, which may be referred to as a catalyzed particulate trap.

In summary, as a result of the combined transient-relevant fuel evaluation studies, which were conducted considering both temperature extreme conditions (hot desert climate in California and cold winter climate in Alaska) and a long-term, high usage rate test (Metropolitan Tulsa Transit Authority fleet test), the findings in this report show that no fuel-related operational problems occurred. To address the differences in fuel consumption between Fischer-Tropsch derived synthetic diesel fuel and conventional diesel fuel, findings from a well controlled, on-road, fuel economy comparison of the two fuels, conducted in association with Auburn University, yielded slightly higher fuel consumption for the synthetic fuel proportionate to the difference in energy density between them. Finally, a comparison of the environmental impacts of the Fischer-Tropsch diesel fuel was conducted by performing back-to-back exhaust emission testing, the results of which can be found in Table 2 of this document, showing reductions in both particulate and NOx emissions that were obtainable by switching to F-T fuel.

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|---|---|
| AFB | Air Force Base |
| APTO | Advanced Power Technology Office |
| ASTM | American Society for Testing Materials |
| ATA | American Trucking Association |
| BDL | Below the Detection Limit |
| BPD | Barrel-Per-Day |
| CO | Carbon Monoxide |
| CTA | Chicago Transit Authority |
| CTC | Concurrent Technologies Corporation |
| DDEC | Detroit Diesel Electronic Control |
| DOC | Diesel Oxidation Catalyst |
| DOD | Department of Defense |
| DOE | Department of Energy |
| DOT | Department of Transportation |
| DPX | Diesel Particulate Filters |
| DRO | Diesel-Range Organics |
| EDS | Energy Dispersive X-Ray Spectroscopy |
| EPA | Environmental Protection Agency |
| ERC | Energy Research Center |
| FNSB | Fairbanks Northstar Borough |
| GCMS | Gas Chromatography-Mass Spectroscopy |
| GTL | Gas-to-Liquids |
| GVW | Gross Vehicle Weight |
| F-T | Fischer-Tropsch |
| FTA | Federal Transit Administration |
| HC | Hydrocarbon |
| HCCI | Homogeneous-Charge Compression-Ignition |
| ICRC | Integrated Concepts & Research Corporation |
| MTTA | Metropolitan Tulsa Transit Authority |
| NCAT | National Center for Asphalt Technology |
| NETL | National Energy Technology Laboratory |
| NO | Nitric Oxide |
| $NO_2$ | Nitrogen Dioxide |
| PM | Particulate Matter |
| RP | Recommended Practice |
| SANG | Selfridge Air National Guard Base |
| SEM | Scanning Electron Microscope |
| Syntro | Syntroleum |
| TMC | Technology and Maintenance Council |
| UAF | University of Alaska Fairbanks |
| ULSD | Ultra-Low Sulfur Diesel fuel |
| WMATA | Washington Metropolitan Area Transit Authority |
| WVU | West Virginia University |

## 1.0 INTRODUCTION

The general purpose of this report is to describe, and provide a summary and overview of several vehicle demonstration activities associated with Ultra-Clean Fischer-Tropsch diesel fuel. VSE Corporation, having recently acquired the Integrated Concepts Research Corporation – ICRC – the original FTA contractor for this project, in association with the Federal Transit Administration (FTA), has been actively demonstrating the operating performance benefits of Ultra-Clean Fischer-Tropsch (F-T), Gas-to-Liquid (GTL) diesel fuel in transit bus applications.

Synthetic fuels can provide a significant volume of the US transportation fuel demand from secure domestic resources. Furthermore, the synthetic product produced via Fischer-Tropsch synthesis can back out imported crude oil directly. Surprisingly, the demand for middle distillate (diesel fuel and jet fuel), not gasoline, determines the total amount of crude oil that must be run through U.S. refineries. F-T fuels can be derived from non-petroleum sources such as coal, petroleum coke, biomass and land fill waste via gasification, Fischer-Tropsch hydrocarbon synthesis, and hydroprocessing into ultra-clean diesel fuel. These fuels can be blended with conventional diesel fuel or used neat. Emissions reductions are essentially proportional to the amount of synthetic component in the blended fuel.

The F-T fuel that was evaluated in both Alaska and Oklahoma was produced at Syntroleum Corporation's demonstration plant using the Fischer-Tropsch process to convert natural gas into liquid synthetic fuels. The ultra-clean Fischer-Tropsch synthetic diesel fuel that was demonstrated during this project was produced at a pilot-plant that was built as part of a multi-year ICRC/ Department of Energy (DOE) – National energy Technology Lab (NETL) project titled "Fischer-Tropsch (F-T) Production and Demonstration Program" (Reference 1). The project included the design, construction, and operation of a 70 barrel-per-day (BPD) fuels-production demonstration plant by project-partners Syntroleum Corporation and Marathon Oil Corporation.

While natural gas was the feedstock for the fuel used in this project, the F-T process is also capable of converting coal and biomass into liquid synthetic fuels.
The demonstrations have covered a range of climates in several locations across the United States, including at military installations, and all have been aimed at determining how the F-T diesel fuel works in conventional heavy duty diesel engines.

The specific purpose of this report is to address three major concerns dealing with the potential introduction of the above mentioned ultra-clean, Fischer-Tropsch, gas-to-liquid diesel fuel, into transit bus applications. The primary areas which needed to be addressed were:

- Engine and vehicle operational issues caused by F-T fuel:
    - Potential fuel-effects on engine and equipment performance and durability in long-term, high-fuel-usage testing
    - Potential for climate extremes to provoke fuel-related operational problems

- F-T fuel consumption comparison to conventional diesel fuel
- Potential impacts of F-T fuel on the environment

The following three explanatory paragraphs expand upon the bullet points above, and all demonstrations referred to will be covered in more detail later in this report.

Operational issues were explored by running the F-T fuel in real-life diesel transit bus applications, in an attempt to determine if the new fuel performed satisfactorily over the long term, and, if not, why not. Revenue Service driving schedules, using the F-T fuel in a new Metropolitan Tulsa Transit Authority (MTTA) city bus, tested the long-term performance and durability aspects of the F-T fuel in rigorous real-world conditions. Furthermore, transit bus tests were conducted in two locations with extreme climates: Fairbanks, Alaska and the California desert at Edwards Air Force Base (AFB), searching for operational issues that might surface in prolonged low or high temperature operations.

The evaluation of F-T diesel fuel in a desert environment at Edwards AFB provided the initial opportunity for the project team to work with and leverage the Air Force's interest in F-T jet fuel, which was also being evaluated in a 50:50 blend with conventional jet fuel in aircraft at Edwards AFB. The Air Force program, known as the Defense Assured Fuels Initiative, was focused on using F-T jet fuel, initially as a blend with conventional jet fuel, in both aircraft and ground support equipment. As such, the Air Force contribution to the FTA demonstration effort was to expand vehicle testing and share and exchange test results, greatly expanding the knowledge base of the program.

On-road comparisons of the fuel efficiency of F-T and conventional diesel fuels were performed under extremely well controlled, long-haul, heavy-load, diesel truck conditions in studies performed at the National Center for Asphalt Technology (NCAT) Test Center at Auburn University in Alabama (Reference 5).

Potential environmental impacts of F-T fuel were also evaluated. Diesel engine exhaust emissions were measured, both in back-to-back tests of dynamometer engines and vehicles using F-T and conventional fuels, and in vehicle-fleet type emission tests in which similar (but not necessarily identical) vehicles used the two fuels. Furthermore, the biodegradability of F-T diesel fuel was compared to conventional diesel fuel under laboratory conditions representative of a fuel-spill in an arctic environment.

The approach taken in this project has been to focus on transit bus demonstrations in a variety of cold, warm and hot climates, and to capture other agency testing related to S-2 F-T diesel fuel. The FTA project team worked closely with the DOE's NETL, and coordinated this program's demonstration testing with the U.S Air Force as part of their Defense Assured Fuels Initiative.

## 1.1. Project Evolution

The intent of the project has always been to demonstrate the operating performance benefits of Ultra-Clean F-T, diesel fuels in transit bus fleet applications covering a range of climates.  The Oklahoma portion of the project was to demonstrate and test a large quantity (24,000 gallons) of Syntroleum's S-2 F-T diesel fuel over a multi-year period in a new city transit bus running in Tulsa, Oklahoma, and in a shorter term demonstration that would have run 10,000 gallons of S-2 F-T fuel in existing campus transit buses at the University of Oklahoma in Norman.  However, it was determined in fall 2006 that conducting the bus fleet demonstration of F-T diesel fuel at the University of Oklahoma would be cost-prohibitive to the project.

After considering several alternative demonstration sites, ICRC/VSE and the FTA decided, in consultation and coordination with the Air Force, to conduct similar bus fleet demonstrations on F-T fuel in a desert location at Edwards AFB in southern California and on a specific Cummins CAT-7 powered diesel engine transit bus at Selfridge Air National Guard Base (SANG) in southeastern Michigan. Covered in this report is the Edwards AFB desert testing, while another follow-on FTA effort will focus on the (currently ongoing) new-technology CAT-7 diesel engine SANG testing.

The replacement project at Edwards AFB (in lieu of the University of Oklahoma) demonstrated and tested Syntroleum's S-2 F-T diesel fuel in the newest and most-used transit bus at the base, a 2004 Thomas 44-passenger bus with a Caterpillar model No. 3126 engine.  The bus fuel economy was approximately 4.4 miles per gallon (Appendix C).  The Air Force Advanced Power Technology Office (APTO) purchased an 8,000-gallon fuel tank for storing the F-T fuel at Edwards AFB, and the Air Force Fuels Research Laboratory at Wright-Patterson AFB analyzed the S-2 diesel fuel.

### 1.2 Benefits of the Evolutionary Changes

The additional Air Force demonstrations have helped the FTA achieve interagency collaboration with the Air Force by providing access to test data from the Department of Defense's (DOD) Assured Fuels Initiative, a large-scale military effort to collaborate with commercial industry to produce clean fuels, including ultra-clean F-T diesel fuel, from secure domestic resources. Similarly, FTA has leveraged its resources with the Air Force by sharing test vehicles, manpower, and subsequent test data.  The Edwards demonstration has provided data on how the S-2 fuel performs in a hot (desert) climate, an originally stated objective for this phase of the overall effort (Appendix C).

## 2.0 LONG-TERM, HIGH USAGE OPERATIONS OF F-T FUEL: TULSA TRANSIT BUS DEMONSTRATION

The Metropolitan Tulsa Transit Authority (MTTA) demonstration represents a major portion of the overall effort by the Federal Transit Administration of the US Department of Transportation (FTA-DOT) project team to demonstrate the utility of advanced F-T fuel in urban transit and general transportation service under a variety conditions.  As described above, other demonstrations involved severe condition operation of F-T fuel in urban buses operated by the Fairbanks (Alaska) Northstar Borough bus system and in an Air Force transit bus in the California desert at Edwards Air Force Base.  Another demonstration, which included an extremely well-controlled on-road comparison of F-T and conventional fuel consumption, involved operation of highway trucks under highly loaded conditions at the NCAT operated by Auburn University in Alabama.

The Fairbanks Northstar Borough bus utilized a Detroit Diesel Series 50 engine, the Edwards AFB bus used a Caterpillar 3126 engine, and the NCAT demonstration used a Detroit Diesel Series 60 engine and 160,000 Gross Vehicle Weight (GVW) operating weight. No operational problems were reported during any of these demonstrations on F-T diesel fuel (Reference 4, Reference 5, Appendix C). Low and high temperature operation of F-T fuels was more than acceptable and there was an expected reduction in fuel economy during the NCAT highway demonstration, which consumed 6,000 gallons of fuel, proportional to the reduced energy density of F-T diesel fuel in comparison to conventional diesel fuel (Reference 5). However, these demonstrations used relatively small total amounts of fuel (only a few thousand gallons), and none included tear-down type inspection of the engine or fuel system before, during or after completion of the demonstration. The Metropolitan Tulsa Transit Authority was a long-term real-world, transit-bus demonstration of 24,000 gallons of S-2 fuel, and it included engine/fuel system inspections. Under a previous program ICRC/VSE conducted for the Department of Energy-National Energy Technology Laboratory, fuel system durability of Ultra-Clean F-T diesel fuel was tested (Reference 1). (See link: http://www.osti.gov/bridge/product.biblio.jsp?query_id=2&page=0&osti_id=920084) The tests included 1500 hours of operation of two diesel bus engines, a DDC Series 50 and a Caterpillar C-7, using the Chicago Transit Authority (CTA) Urban Bus Driving Cycle (http://www.dieselnet.com/standards/cycles/cta.html). Under the CTA Cycle test conditions, these two engines ran 1500 hours each, and used approximately 15,000 and 11,500 gallons of S-2 fuel, respectively.

The testing showed that under laboratory conditions, deposits can form on the external surfaces of injector nozzles leading to partial plugging of the nozzle holes and subsequent power loss (Reference 1). The power loss caused by these deposits was negligible for the DDC Series 50 engine, which had minimal nozzle-orifice deposits even though it had used a greater quantity of S-2 fuel. However, the power loss was more than 20% of peak power output for the Caterpillar C-7 engine, and thus far above and beyond the single-digit percentage power loss attributable to the moderately lower density of F-T fuel compared to conventional diesel fuel. It is not known if these deposits can be formed only under laboratory conditions or are related to only one engine type. Scanning Electron Microscope (SEM) analysis of the injectors showed conclusively that the deposits were formed only on the outside of the injectors and that the source of the deposits was from combustion of metallic (ash) components of the additive package in the engine lubricating oil (Reference 2). Therefore, one of the goals of this project was to inspect fuel injector nozzles from the MTTA demonstration bus engine for deposit formation.

MTTA agreed to demonstrate the utility of F-T diesel fuel in a new Gillig transit bus (see Figure 1) with a Cummins ISL engine beginning August 23, 2005, and continuing until July 3, 2008. The long-term advanced fuel demonstration lasted approximately 3 years and measured the ability of F-T fuels to meet the operational requirements of diesel fueled engines under severe inner-city bus service. Fuel for the demonstration was provided by Syntroleum Corporation and met ASTM D-975 standards for No. 2 diesel fuel. A total of 24,000 gallons of F-T diesel fuel, designated S-2, were used by the bus, and 121,111 miles were accumulated for an average fuel consumption of 5.05 miles per gallon.


*Figure 1: Metropolitan Tulsa Demonstration Bus*

The MTTA demonstration was designed to demonstrate long term operability of neat (or unblended) F-T diesel fuel under urban transit bus driving conditions with inspection of fuel-injector nozzles for any possible fouling. The demonstration also included comparison of nozzle deposits formed during use of F-T fuel with deposits formed during use of conventional petroleum derived diesel fuel in a similar bus and engine.

The fuel used in the MTTA demonstration was derived from natural gas resources using GTL conversion technology and thus was non-petroleum in origin. GTL technology, as well as Coal-to-Liquids and Biomass-to-Liquids, is a combination of three processing steps: Conversion of feedstock to synthesis gas and removal of contaminants, F-T synthesis of hydrocarbons, and upgrading of those hydrocarbons to paraffinic fuels which meet all diesel fuel specifications. As with all F-T fuels, whether derived from coal, petroleum coke, biomass or waste products, the F-T synthetic fuel is free of sulfur and aromatics and is comprised of essentially paraffins, isoparaffins and cycloparaffins.

The MTTA test fuel was treated with additives common to commercial ultra-low sulfur diesel fuels to improve lubricity, conductivity, corrosion resistance, oxidation stability, and reduce foaming. The Syntroleum-proprietary additive system also contained a fuel dispersant, or injector deposit control additive, as prior laboratory fuel system durability testing under the DOE Ultra-clean Fuels program, in which the S-2 fuel did not include the dispersant additive, had indicated that metals derived from combustion of lubricant additives found in the engine lubricating oil, can be deposited on the outside of the injectors and lead to partial plugging of the fuel-injector nozzle orifices under some circumstances.

### 2.1. Summary of Tulsa Transit Bus Operations

Long term engine and fuel-injection system durability is a primary concern when new fuel types are introduced into the transportation sector. This study supported by DOT-FTA funding, documents a demonstration of the utility of neat F-T fuel in urban transit bus applications and addresses some of the concerns about fuel-injection system durability. This report documents an analysis of deposits formed on fuel injector nozzles during long-term urban bus operation on neat F-T fuel and compares these deposits to those formed during operation of a similar reference engine in a comparable bus on conventional diesel fuel.

After approximately one and a half years of operation on February 8, 2007, the first injector (Injector 1) from the Tulsa Transit bus was removed for inspection and replaced with a new injector. At the time of removal, the bus had accumulated 54,758 miles and operated for approximately 3800 hours for an average speed of 14.41 miles/hour. The bus had consumed approximately 9,800 gallons of fuel for an average fuel consumption of 5.6 miles per gallon.

About six months later on July 6, 2007, a second injector (Injector 2), which had been in the engine since it was new, was removed for inspection and replaced with a new injector. The bus had accumulated an additional 35,891 miles for a total of 90,649 miles by that date. It had used approximately an additional 6500 gallons of S-2 fuel for a total of 16,300 gallons, more than had been used in either engine during the dynamometer tests referred to previously. (The actual odometer reading at that point was 38,874 because the original speedometer and odometer had been replaced.)

Optical microscopy indicated that deposits had formed on the tips of both the injector nozzles removed from the Tulsa Transit bus (Reference 2). It appeared that the deposits formed preferentially on one side of the injector and not on the other. None of the injector nozzle holes were plugged and no operational difficulties were noted at any time during the entire test period. Due to the accumulation of deposits on the injector tips shown on the optical microscope images, it was concluded that additional SEM analysis of the injector tips was warranted to try to determine the source and composition of the deposits. A fuel-injector run in a similar engine on conventional diesel fuel was also studied for reference.

### 2.2. Comparison of Fuel-Injector Nozzle Deposits between F-T Synthetic and Conventional Fuels

The analysis concluded that for F-T synthetic diesel fuel, the deposits found on the outside surface of the fuel-injector nozzles were derived from metallic components of the engine oil additive system. Deposits were found only on the outside tip of the injectors. The interior sac areas of the injectors were not coated with deposits (Reference 2)

Figures 2-13 show various optical and SEM photos and results of the SEM elemental analysis and summarize the key findings. Figure 2 shows deposits which accumulated on one side of the injector tip. It is not possible from this image to determine if the deposits came from the fuel or another source within the engine. The nozzle hole visible in Figure 2 is clearly not "covered" or otherwise obviously obstructed by deposits.

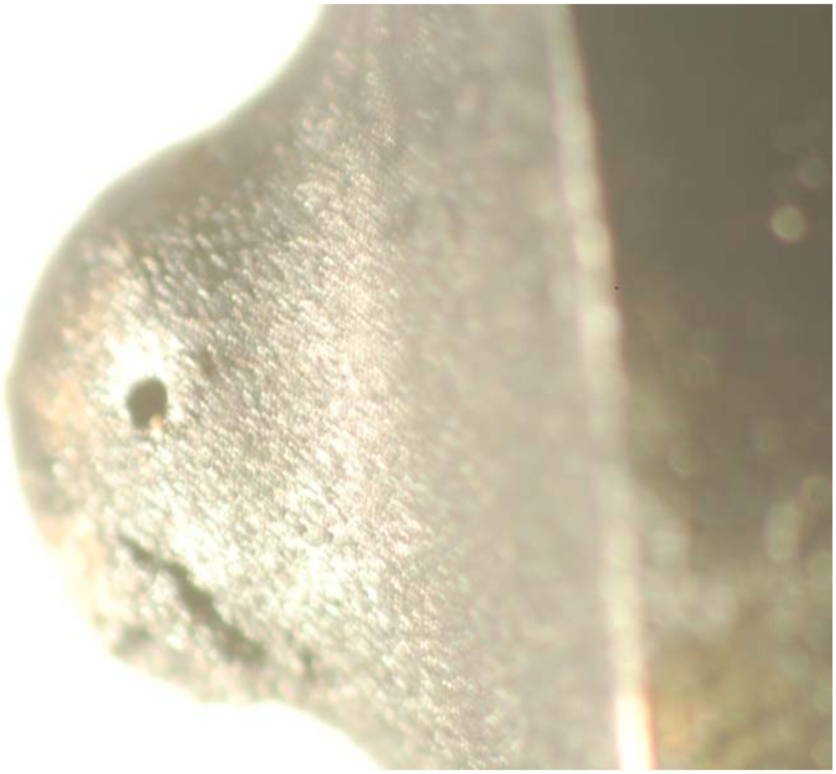


*Figure 2: Optical Microscope view of Injector 1 nozzle tip from a Cummins ISL engine operated on F-T diesel fuel for 54,758 miles*

Figure 3 is a view of the injector nozzle tip on Injector 1 looking straight down on the tip. Note that deposits appear to have formed primarily on one side of the tip. The mottled black background is the electrically conductive mounting surface for the SEM instrument.

The overhead view of Injector 1 gives an indication of the radial dispersion of the deposits. Deposits are found predominantly on only one side of the injector tip (right hand side of the photo in Figure 3.) In this overhead view, vertical distances are distorted. Note that there are some scratches and gouges in the deposit layer due to handling prior to examination of the injectors by optical and scanning electron microscope (SEM) microscopy.

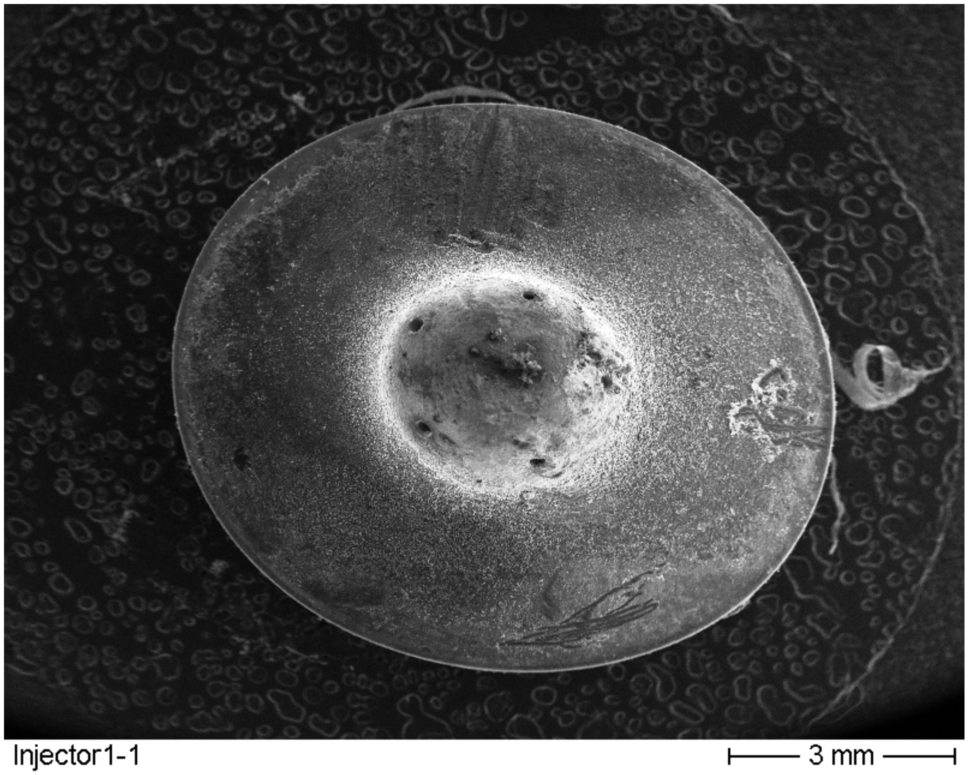


*Figure 3: SEM image of Tulsa Transit bus Injector 1 nozzle looking straight down on tip*

The composition of the deposits was determined from the energy dispersive x-ray spectrum (EDS) which was acquired during SEM imaging (see Figure 4). The presence of calcium, zinc, phosphorus, sulfur and magnesium is consistent with the composition of conventional engine oil lubricant additive metals. None of these metals is present in the fuel or fuel additive package except for sulfur which is only present in one component of the fuel additive package and the total concentration of sulfur in the fuel is much less than 1 ppm. In this large area EDS analysis, the iron in the underlying surface of the injector is seen clearly in the EDS spectrum. This is not so for the EDS spectrum when the focus area is reduced to just the deposit area.

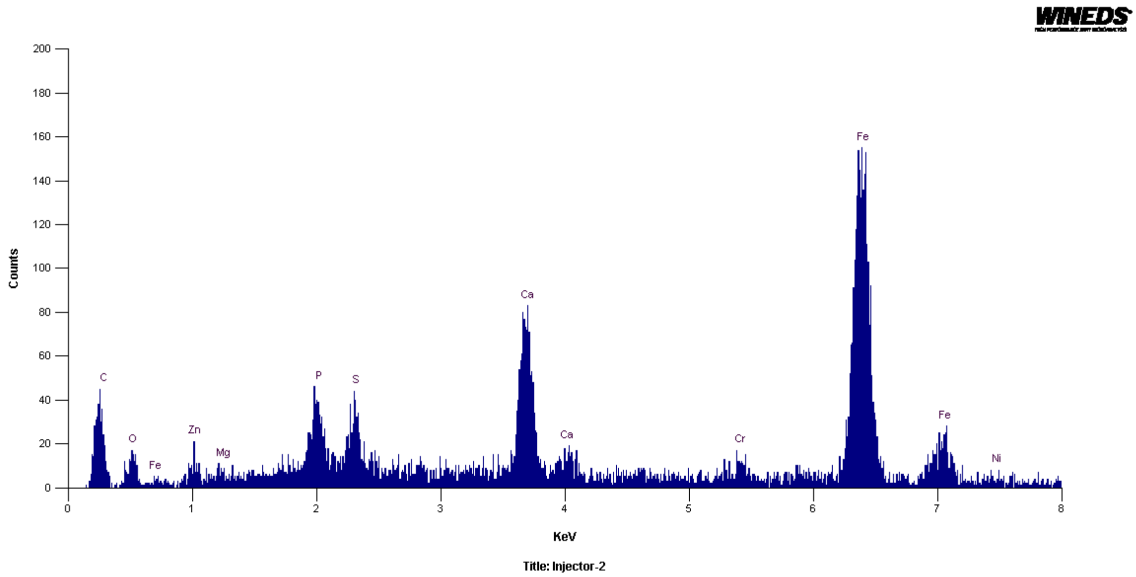


*Figure 4: Elemental composition of injector tip deposits by EDS*

The injector nozzle tip was next flipped over to show the inside sac area (Figure 5). This area is exposed mostly to fuel with the possibility that combustion gases can blow back inside the injector through the holes or orifices into the sac - area. Note that this area is relatively clean although not completely free of deposits. The entrances to the injector holes are clean and no obstruction or restriction to fuel flow appears in this image.

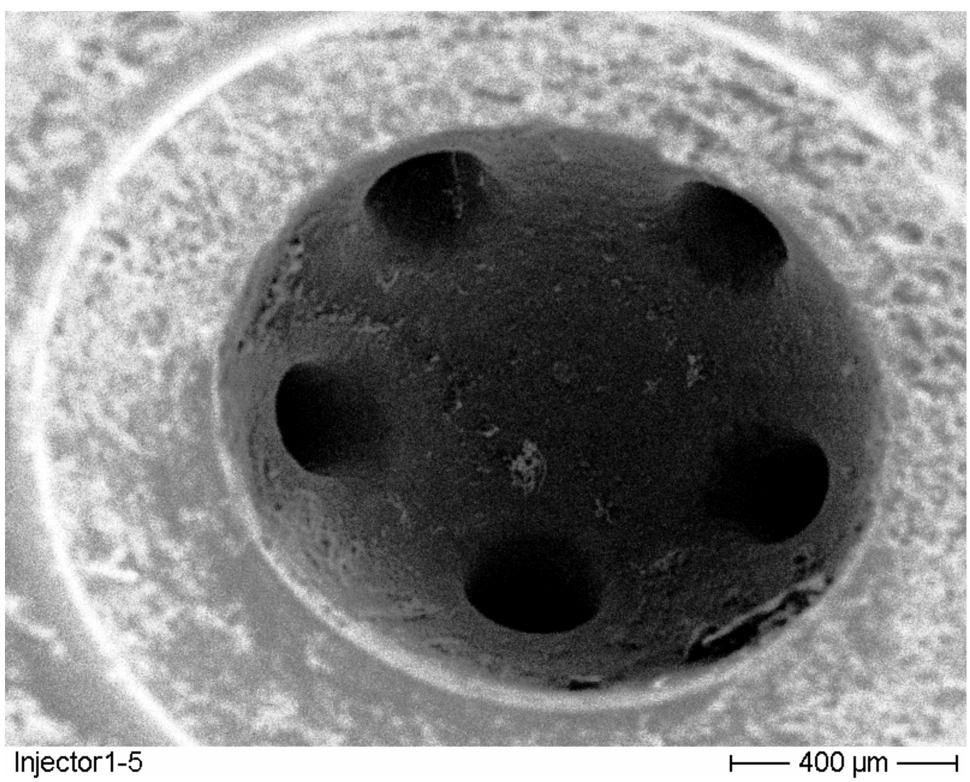


*Figure 5: Inside the sac area of F-T diesel fuel Injector 1*

On July 6, 2007, after 90,649 miles of operation on F-T fuel, the second injector was removed from the bus for inspection. This second injector is identified as Injector 2 in the optical and SEM images. Under the optical microscope, no significant increase in deposits was observed in comparison to Injector 1.

Figure 6 shows a view of the Injector 2 with the major amount of deposits. This injector also appears to have deposits predominantly on one side as well.

*Figure 6: Optical microscope image of Injector 2 nozzle from Tulsa Transit bus after 90,649 miles of operation on F-T diesel fuel.*

A view of the injector showing the entire tip is shown in Figure 7. As with Injector 1, removed at 54,758 miles, most of the deposits appear to be on only one side of the tip.


*Figure 7: Injector from Tulsa Transit bus run on F-T fuel for 90,649 miles. View showing entire tip of injector nozzle.*

As shown in Figure 8, the deposits that have accumulated around the injector hole have the same elemental composition as that of the non-combustible (ash) elements in the additive packages of commercial heavy-duty diesel engine oil, and the composition is the same as deposits found on Injector 1.

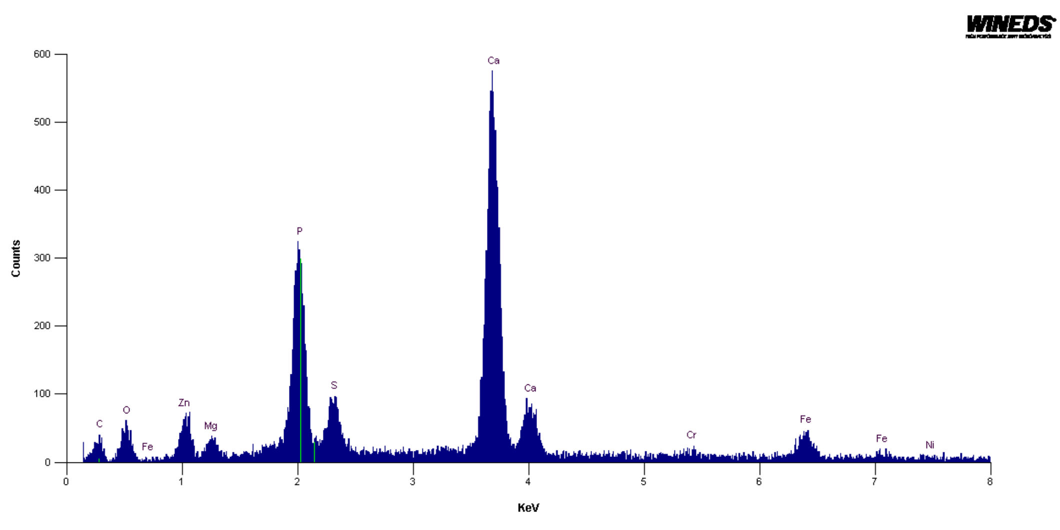



*Figure 8: EDS spectrum of the deposits found around one spray hole from Injector 2 showing elemental composition similar to that of the metals found in heavy-duty diesel engine oil.*

Additional images of the injector sac show that the holes are clean (Figure 9).

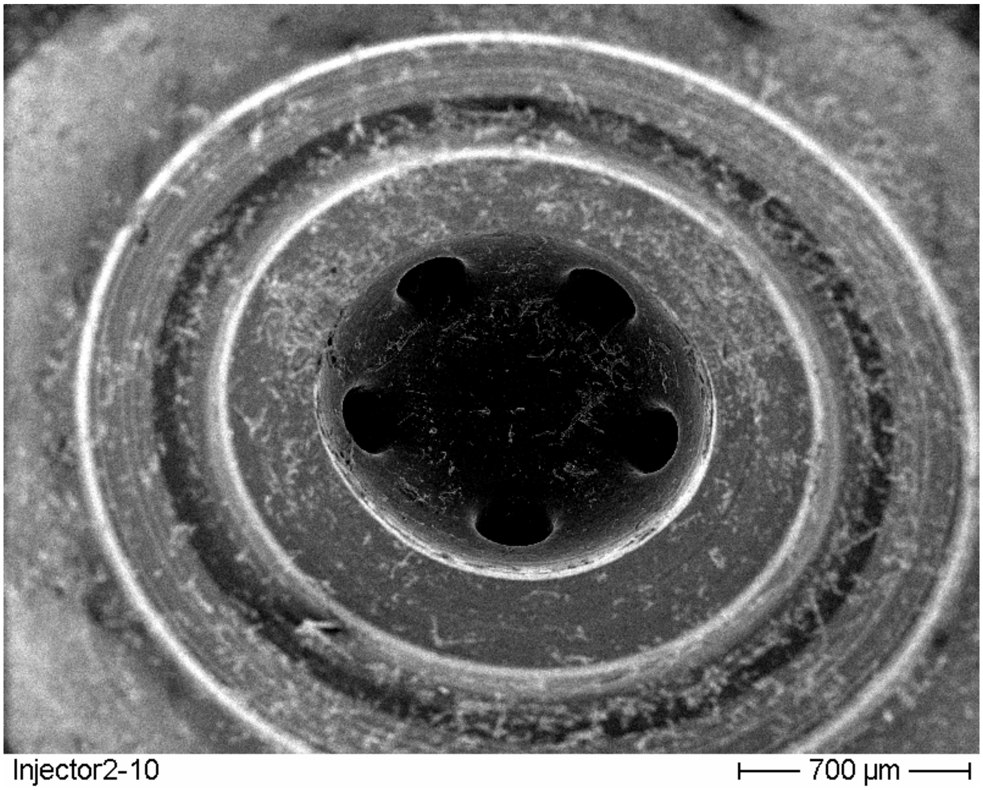


*Figure 9: SEM image of injector sac (inside) of Injector 2 showing no deposits.*

To obtain reference information on injector nozzle condition, an injector was removed from a Tulsa Transit bus with a Cummins ISL engine running on standard ultra-low sulfur conventional diesel (ULSD) No. 2 fuel used by the fleet. The injector had 51,825 miles of operation prior to removal.

Upon removal, the injector was photographed using an optical microscope to give an overall impression of the deposit level and location. Much of the injector nozzle was covered with a layer of flaky deposits. However, one section of approximately ¼ of the total tip surface area was free of deposits (see Figure 10). This may have been due to thermal shock or humidity changes which caused debonding of the deposited material. This does indicate that the deposits are not strongly adhered to the metal surface of the injector nozzle.

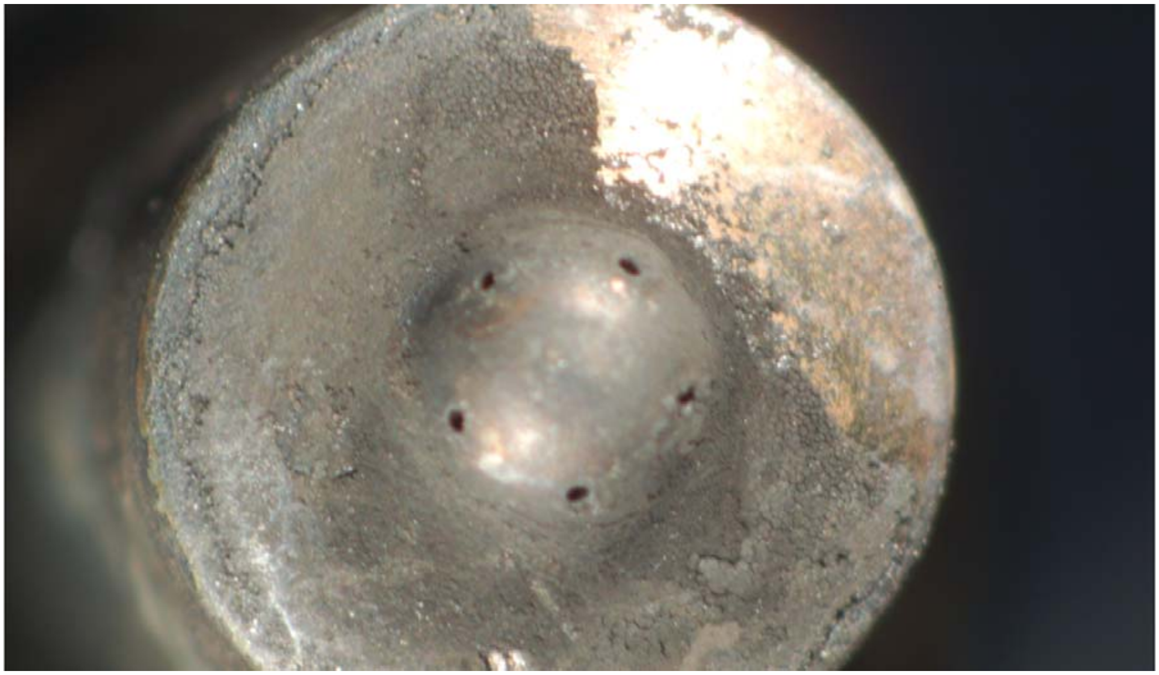


*Figure 10: Top view of Cummins diesel injector nozzle operated on conventional ULSD fuel with optical microscope*

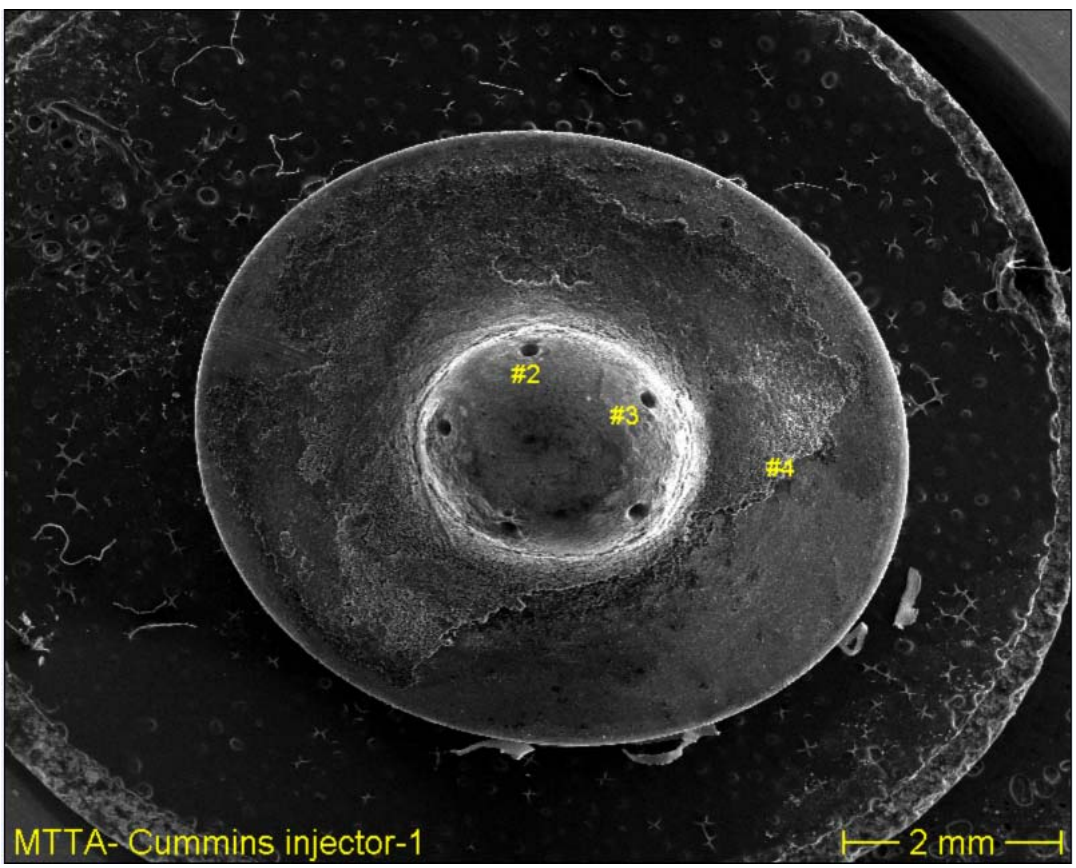



*Figure 11: SEM Micrograph of ULSD Cummins injector viewed from top with orientation mark at 10 o'clock*

Under the SEM microscope, more detail can be seen of the deposits. Figure 11 is the electron microscope image of the injector nozzle tip. Holes labeled #2 and #3 were examined more closely as was the edge of the deposits on the flank of the injector nozzle labeled #4. This view also shows that the sectioned injector nozzle tip is mounted on a conductive graphite surface which is mounted to a brass (copper and zinc) surface. Both Cu and Zn show up in the EDS analysis although some of the Zn may actually be from the deposits themselves.

As shown in Figure 12, in addition to iron (Fe), carbon (C), and oxygen (O), the EDS spectrum shows the presence of phosphorus (P), sulfur (S), calcium (Ca), and zinc (Zn). These latter elements are common components of engine oil additive systems used in the crankcase lubricating oil and are not found in fuel additives.

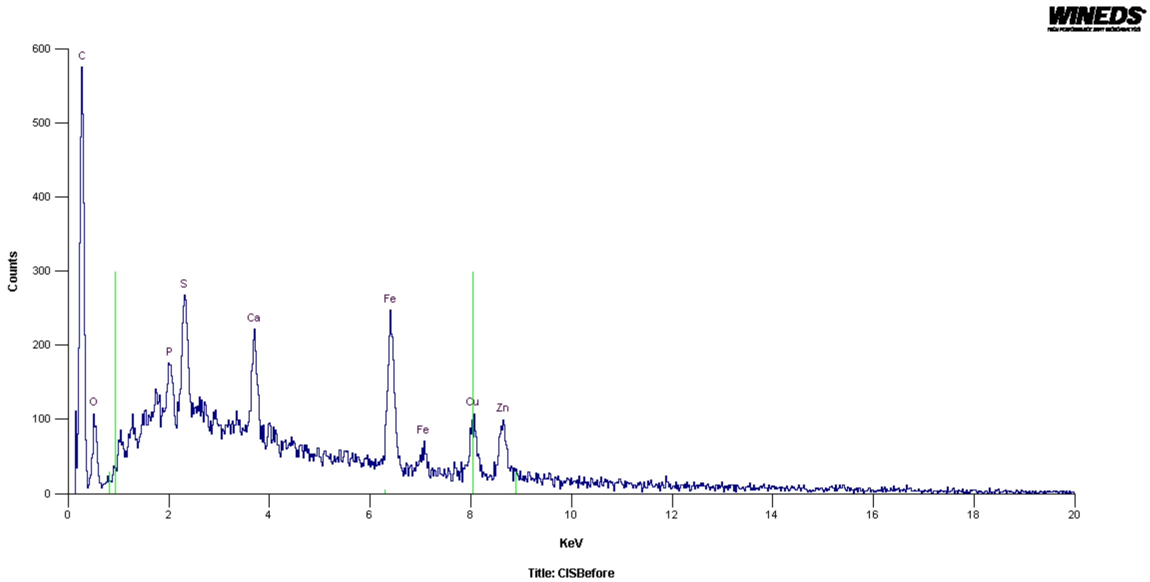



*Figure 12: EDS spectrum of MTTA Cummins injector-3*

The interior of the injector nozzle from this engine run on conventional diesel fuel is not as clean as was observed with F-T fuel. Figure 13 shows the sac region of the injector with significant deposits shown in the area outside the injector-nozzle pintle seat diameter. The EDS spectrum has indicated that the bulk of the deposits in this region are again from engine oil additives, but there is a significant amount of chlorine in these deposits as well. Chlorine is not found in engine oil additive or fuel additives, so the origin of this element is not clear.

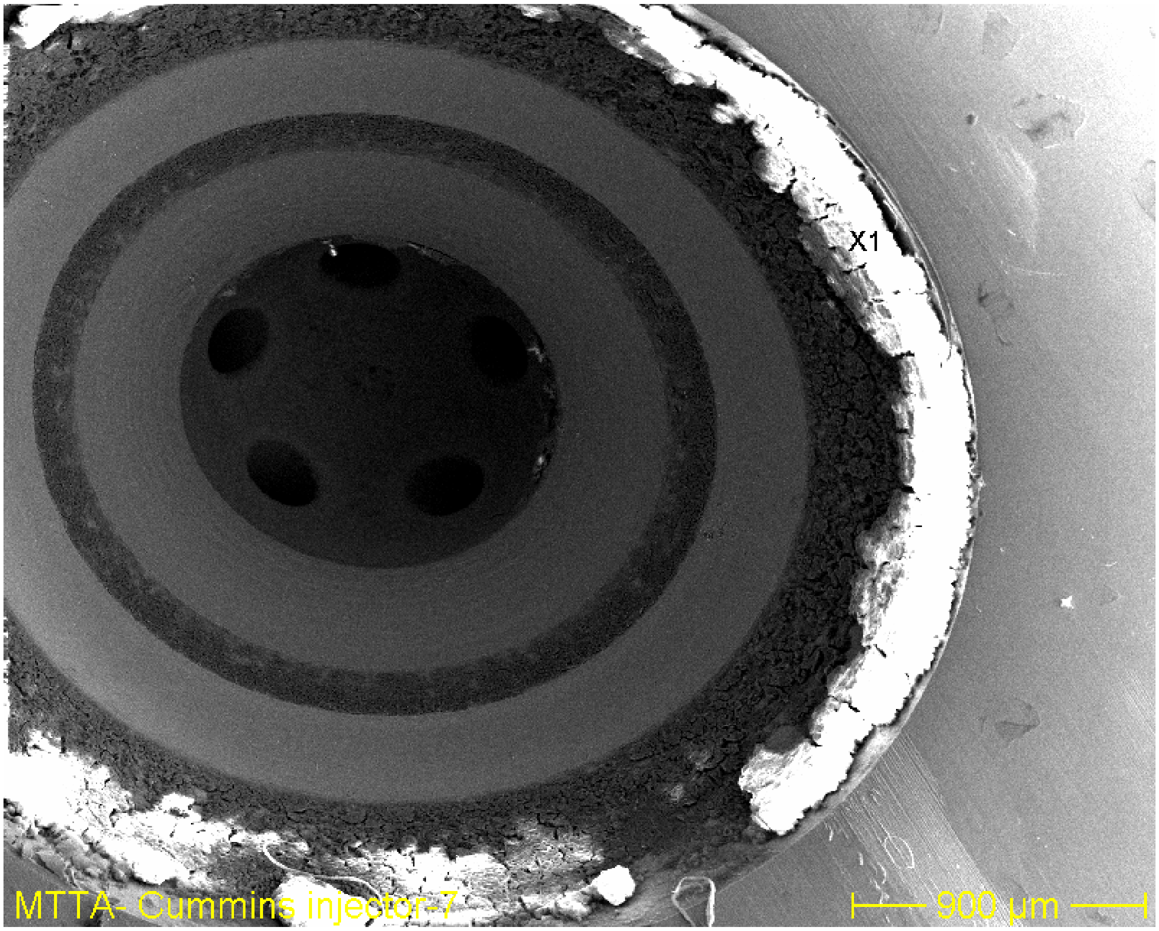


*Figure 13: View of injector sac (back side) of injector showing deposits formation with location of EDS spectrum outside the pintle-seat diameter shown as X1.*

There was a significant difference in the appearance of the deposits between the injector nozzles from the engine which ran on F-T synthetic fuel and the injector nozzle from the engine which ran on conventional diesel fuel. For example, a comparison of Figures 2 and 6 to Figure 10 shows that the F-T synthetic fuel injector nozzles have deposits on the tips around the injector holes, but the conventional fuel injector nozzle optical image (Figure 10) shows heavy flaky deposits around the flank of the injector nozzle with less deposits on the tip. Furthermore, a significant amount of the conventional-fuel deposits have flaked off revealing the bare metal surface of the injector nozzle.

The same general observation can be made by comparing the SEM photos in Figures 3 and 7 to Figure 11. There is relatively uniform distribution of the injector nozzle surface deposits from the F-T synthetic fuel compared to the flaky deposits found on the injector nozzle from the conventional fueled bus.

For conventional diesel fuel, the deposits contain significant amounts of carbon relative to the engine oil additive metals, whereas the nozzle-surface deposits observed with F-T synthetic diesel fuel contain a much higher fraction of engine oil additive metals.

Similar comparisons between the deposit composition for F-T synthetic and conventional diesel fuel can be made at the exterior tips of the injector nozzles and for the very thin layer of deposits “on the wall” inside some of the injector nozzle-orifices or spray holes. However, the internal portion of the injector nozzles operated on F-T synthetic diesel fuel appeared to be significantly cleaner than the internal portion of the injector nozzle operated on conventional diesel fuel. Figures 5 and 9 show the sac area and internal portions of the injectors from the bus which operated on F-T synthetic diesel fuel. The injector sac areas showed minimal deposits and the debris visible in the SEM images are mainly left behind by the diamond sectioning saw used to prepare the injector for SEM analysis.

Although the SEM image in Figure 5 does not show the full area seen in Figures 9 and 13, there were essentially no deposits with F-T fuel on the internal portions of the injector nozzles. However, with conventional diesel fuel there was a deposit near the seating surface of the pintle as shown in Figure 13 on the outside ring.

### 2.3. Results of Fuel Injector Nozzle Inspections/Analyses

- Based upon a relatively small sample of three fuel-injection nozzles from two different Cummins ISL engines, the morphology of deposits formed on the exterior surfaces of fuel-injector nozzles when using conventional No. 2D diesel fuel are different from the deposits formed when using synthetic F-T diesel fuel. Optical and electron microscopic analysis of injector nozzle from the engine operated on No. 2D fuel show thick flaky deposits. EDS analysis of these deposits indicates that the deposits contain predominantly carbon and elements that are commonly found in heavy-duty diesel engine oils—Sulfur, Phosphorus, Zinc, Calcium and Magnesium.

- Deposits formed on the exterior nozzle surfaces when a similar engine was operated on synthetic F-T diesel fuel are distributed differently (primarily on the nozzle tips) and do not show a tendency to flake off as was seen with the deposits from conventional No. 2D fuel. EDS analysis of these deposits with F-T fuel show substantially less carbon and relatively higher amounts of elements found in engine oil additives.

Despite differences in morphology of the deposits, there is no indication that there were any operational problems with either engine or any of their injectors.

## 3.0 SUMMARY OF DESERT CLIMATE DEMONSTRATIONS

The desert transit bus project at Edwards AFB demonstrated and tested Syntroleum's S-2 F-T diesel fuel in the newest and most-used transit bus at the base, a 2004 Thomas 44-passenger bus with a Caterpillar model No. 3126 engine (Figure 14).

*Figure 14: VSE Program Manger, Steve Bergin & Chief of the Transportation System, Murray Westley with FTA Transit Demonstration bus at Edwards AFB.*

The neat S-2 diesel fuel used by the bus was analyzed by the Air Force Fuels Laboratory at Wright Patterson AFB on two occasions, and the data obtained is included in Appendix A and B of this report. Even though this product was a diesel fuel, not a jet fuel, the Air Force lab compared the measured values for the S-2 to the normal JP-8 military jet-fuel specification, MIL-DTL-83133, which can be obtained at the following link: http://www.everyspec.com/MIL-SPECS/MIL+SPECS+(MIL-DTL)/MIL-DTL-83133F_11933/. The S-2 diesel fuel successfully met all diesel fuel specifications.

The Edwards demonstration bus began running on neat (unblended) S-2 F-T diesel fuel, September 19th, 2006. This same bus was used to transport people to and from the first Air Force test flight of blended F-T jet fuel. During the test flight, the B-52 bomber successfully used, in two of its eight engines, a 50:50 blend of Syntroleum F-T jet fuel and conventional petroleum-derived jet fuel.


*Figure 15: Similar R-11 Refueler used to initially store fuel for the desert tests.*

### 3.1 Desert Storage of Neat S-2 F-T Diesel Fuel

The Air Force Advanced Power Technology Office purchased a new 8,000-gallon stationary fuel tank for storing and dispensing the neat F-T diesel fuel at Edwards AFB. No desert storage problems were encountered with the new tank. However, when the neat S-2 diesel fuel arrived at Edwards, it was stored temporarily in an R-11 fuel truck similar to that seen in Figure 15, The R-11 that was used for the temporary storage had been previously taken out of service at Edwards because it had developed leaks, even when handling conventional petroleum-derived jet fuel. The leaks were judged to be worse by Edwards fuel personnel when the "old" truck was used to store and handle the neat S-2 diesel fuel.

### 3.2 Operational Testing In the Desert

The desert bus demonstration of neat F-T S-2 diesel fuel at Edwards continued through the 2009 calendar year, for a total duration of just over 3 years. A total of 1997 gallons of F-T S-2 diesel fuel were consumed and 8,828 miles were accumulated, for an overall bus fuel consumption rate of 4.4 miles per gallon. The bus was used to transport visitors and military personnel for many Air Force events, both on base and in the surrounding desert environment communities. No operational problems attributable to the F-T S-2 fuel were encountered, as described in the brief report on the demonstration included in the Appendix C. The brief report was written by Mr. Murray Westley, the Chief of the Edwards AFB Transportation System and the primary individual responsible for operating the stationary S-2 fuel dispensing tank, as well as for maintaining the demonstration bus and virtually all other on-road vehicles on the base, including the R-11 fuel trucks.

### 3.3 On-Board Data Acquisition

ICRC/VSE installed an on-board data acquisition system on the bus to record engine operational data available from the normal (i.e. stock) engine electronic control system. This is a small-size but high-capacity dedicated, single-purpose computer system designed by ICRC/VSE using commercially available electronic components. The system has the capacity to store up to several hundred hours of engine operational data before it begins to over-write the “first” data stored. The primary advantage of this system is that it provides a very cost effective method for obtaining virtually all engine operational data without the need for an expensive, dedicated, high-capacity, mobile phone line on-board the vehicle for transmission of data from the vehicle.

The accumulated on-board data was automatically downloaded periodically to an ICRC/VSE dedicated server provided to Edwards AFB, through an economical, automatic, short-range (nominally 50 feet) antenna system that operated whenever the bus was brought within range of the receiving antenna. The receiving antenna was positioned within a few yards of the stationary S-2 fuel dispensing tank within the base Transportation System Compound. Therefore, the accumulated on-board engine operational data was downloaded to the server, clearing the on-board memory capacity for accumulation of more data, at least each time the bus was fueled.

The server was a single-purpose, stand-alone computer, not connected to any of the other computers or military networks on the base. The server was connected only to a dedicated, high-speed, “land-line” commercial telephone line installed by the local phone company and paid for by ICRC/VSE so that the bus engine operational data could be retrieved by ICRC/VSE over the internet.

The entire system, including operating frequencies of the short-range, wireless data downloading antenna system from the bus on-board unit to the dedicated server, server connection to the phone line, etc, was checked-out thoroughly by base security personnel before the go-ahead approval was given for ICRC/VSE to install and operate the system.

The engine operational data could have proven invaluable for analysis, diagnosis, etc., in the event that any operational problems with the bus, whether they proved to be fuel-related or not, might have occurred during the bus demonstration of S-2 fuel in this desert climate. However, since no operational problems did occur, the data obtained is simply a large quantity of normal operational data for a bus engine running in a desert climate.
In summary, throughout the desert testing no operational problems were encountered.

## 4.0 SUMMARY OF COLD CLIMATE DEMONSTRATIONS

The primary purpose of a related FTA-sponsored project was to study the potential use of ultra-clean F-T synthetic diesel fuel in cold-climate transit applications. Alaska's cold arctic climate represented the cold end of the spectrum, while the project ran in parallel with the "warmer weather" demonstration of F-T fuel in Tulsa, Oklahoma. The cold climate project activities included a 24,000-mile, 5,000-gallon winter demonstration of Syntroleum arctic-grade F-T fuel in two urban transit buses in Fairbanks, Alaska. Additionally, the University of Alaska (UAF) Fairbanks ran a soil biodegradability analysis to determine the environmental effects of potential F-T fuel leaks. The Alaska-centered project focused primarily on running and storing F-T fuel in cold climates, both major issues. The following few pages summarize the major elements and findings of this effort which can be viewed in more detail at http://www.fta.dot.gov/documents/Fischer_Tropsch_Synthetic_Diesel_Demonstration_Project.pdf.

### 4.1 Arctic Transit Bus Demonstrations in Fairbanks

The objective of the Fairbanks transit bus demonstration was to show that highly isomerized arctic-grade F-T diesel fuel can be routinely stored, dispensed, and run successfully in buses at the coldest temperatures likely to ever be encountered in any urban area in the U.S. Data collected included transit personnel observations, fuel usage/fuel economy, and of on-road gaseous emissions using a portable analyzer on-board a bus operating on both F-T and conventional No. 2 diesel fuels. Ultra-low sulfur diesel was not yet required for on-road use when this demonstration took place in 2005.

The cold-weather phase of demonstration ran from mid-December 2004 to late April 2005 on an urban transit route in Fairbanks, Alaska, with temperatures ranging from below -40°F up to about +50°F. The two buses running exclusively on F-T fuel covered a total of 23,720 miles during the cold-weather phase, and consumed 5,451 gallons of arctic grade F-T fuel. When the weather warmed up in late April 2005, the same buses continued to use the arctic grade F-T fuel for some fill-ups, but No. 2 diesel fuel use was interspersed because the transit agency had concerns about continuing the exclusive use of the very light arctic grade fuel at (what they considered to be) very warm temperatures. The concern was apparently based upon the perception by the agency that the lubricity of arctic grade F-T fuel, if used exclusively, might not be sufficient to protect the engine's fuel injection system at warm temperatures. However, several previous evaluations of the lubricity of the Syntroleum F-T fuel during the NETL Project (Reference 1) have shown that the commercially proven lubricity additive treatment applied to all Syntroleum diesel fuels, including arctic-grade, is fully capable of protecting diesel fuel systems under the full range of real-world operating conditions. With the exception of changing fuel filters and draining tanks to segregate the F-T fuel from the No. 2 diesel, operations were conducted as though the F-T was the agency's "regular" winter fuel.

### 4.1.1 Fuel Storage and Dispensing

The 6,970 total gallons of F-T fuel that were demonstrated were stored in an 8,000-gallon, dual-walled and fire-rated bulk dispensing tank (Figure 16). Fortunately, contamination was not an issue, as the tank had previously contained only F-T fuel, as part of the diesel-generator testing portion of the NETL project described above. The Fairbanks Northstar Bureau (FNSB) maintenance personnel filled the tanks of the buses at the end of each day so that buses could begin operations the next morning with full tanks. Fuel dispensing was carefully tracked and recorded. Since the F-T fuel for the two demonstration buses was stored in its own separate tank and clearly segregated from the conventional fueling area, misfueling was effectively prevented.

*Figure 16: Dispensing tank at the Fairbanks Northstar Borough Department of Transportation*

### 4.1.2 Transit Buses

The two buses used to demonstrate the F-T fuel were very similar. Both were 1994 Phantom models, manufactured by the Gillig Corporation (Figure 17). The engines in both buses were turbocharged Detroit Diesel Series 50 engines, incorporating the Detroit Diesel Electronic Control (DDEC) electronic fuel injection system. Both buses were nearing the end of their service life at the time of the demonstration, with approximately 500,000 miles on each of their odometers at the start.

The buses operated normally on their scheduled urban transit routes while using the F-T fuel. After April 22, 2005, the two buses used for the demonstration project operated on both conventional No 2. diesel and F-T fuel.


*Figure 17: Transit Bus used in Arctic Demonstrations in Fairbanks, Alaska*

### 4.1.3 Fairbanks Transit-Bus Demonstration Conclusion

The most significant conclusion to the demonstration is that FNSB staff observed no fuel-related problems, and no maintenance issues were attributable to the use of F-T over the approximately 2,000 hour, 30,000 mile test (Reference 4). The operation demonstrated that F-T fuel can directly replace conventional diesel fuel without modification to engines or significant changes in performance, since switching between F-T and No. 2 diesel fuel remained uneventful. The use of F-T fuel did not have an adverse effect on emissions.

Cold weather characteristics are an important consideration in any Arctic endeavor and the F-T fuel performed well during cold weather operations in temperatures as low as -40 F. This project showed that F-T fuel can be stored, dispensed, and successfully run in transit buses at extremely low temperatures, without any modifications to the bus engines (Reference 4).

### 4.2 Arctic Environmental Fuel Impacts

The UAF evaluated the biodegradability of F-T fuel by comparing it to conventional No. 2 diesel fuel and fish biodiesel fuel, a cheaply available waste product from Alaskan fish processing plants. Over a period of several months, UAF conducted microcosm experiments to investigate the effect of temperature (6°C vs. 20°C), moisture content (2%-12%), and nitrogen-fertilizer nutrient addition (0 vs. 300 mg N/kg soil) on the biodegradation of the different fuels in two types of soil (sand vs. gravel). Biodegradation was characterized by measuring $CO_2$ production by naturally occurring microbes during the course of the experiment and by gas chromatography-mass spectrometry (GCMS) analysis of diesel-range hydrocarbons remaining in the soil at the end of the experiment. Because $CO_2$ is the main product in aerobic breakdown of organic molecules, $CO_2$ production indicates the level of microbial activity. One set of experiments examined the adaptation period (lag times) of the microorganisms to the different types of fuels under optimum conditions.

For each experiment, 1kg of soil (sand or gravel) was placed in an airtight 2.5-liter container. Quantified amounts of the chosen contaminant (i.e. the fuel to be evaluated) were added to the previously uncontaminated soil. Additionally, a small amount of previously contaminated soil was added to provide an inoculum of microbes.

Data was collected over different time periods. F-T and No. 2 diesel fuel were investigated for five months while fish biodiesel was added later to the experiment.

### 4.2.1 Biodegradability Results

F-T fuel and No. 2 diesel fuel showed similar trends for hydrocarbon removal from the soil by microbial respiration. However, in almost every experiment, the F-T fuel had a significantly higher rate of biodegradation than No. 2 diesel fuel, meaning that the F-T fuel was being removed from the soil faster by bacterial action (Reference 4). In the extended five-month experiment at 20°C, a 36% higher cumulative amount of $CO_2$ was produced for the F-T fuel compared to the diesel and an approximately 60% higher amount at 6°C (Figure 18). The results indicate that F-T fuel was biodegraded faster than conventional diesel fuel because F-T was favored over diesel fuel by the naturally occurring microorganisms that are already present in the soil.

Temperature mainly influenced the adaptation times, or the times required for the bacteria to adapt to the fuel and begin degrading the fuel at a high rate, as indicated by the rate of $CO_2$ production. Although the bioremediation process started much earlier for higher temperatures compared to lower ones, microbes adjusted to the lower temperature and degraded the hydrocarbons to a significant extent.

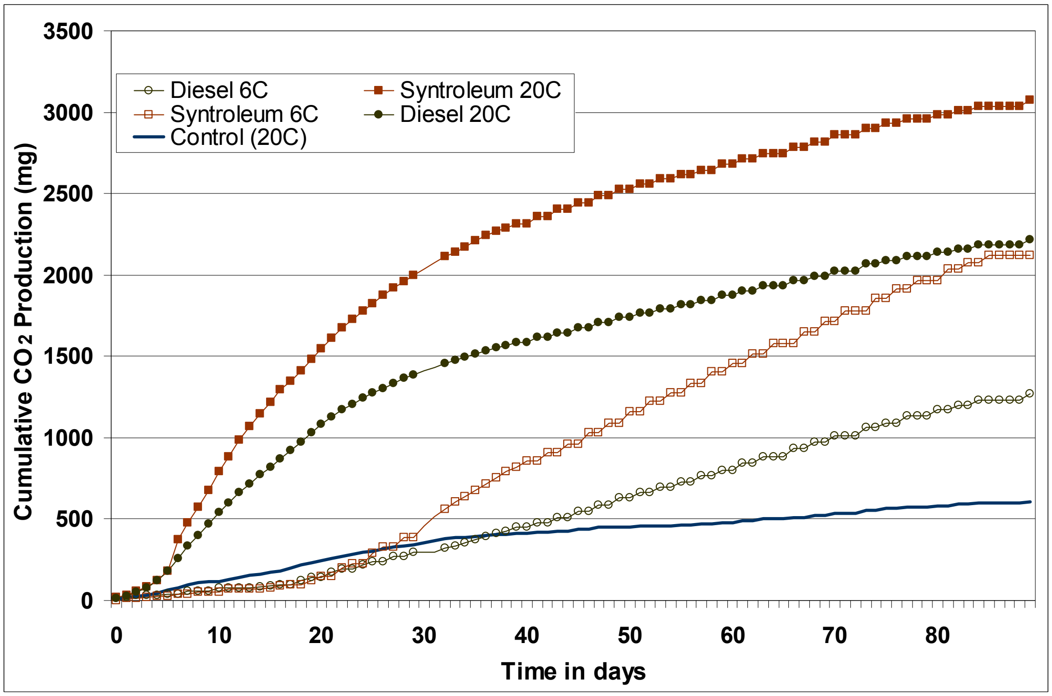



*Figure 18: Effect of Temperature on Respiration of Syntroleum F-T v. Diesel, Reported as Cumulative Amount of $CO_2$ (mg). Conditions: 2g/kg of fuel, 300 mg N/kg, sand. The control line represents soil without fuel and 300 mg N/kg.*

In nutrient deficient soils such as those used in this experiment, the addition of nitrogen and phosphate was necessary to achieve high degradation results. Fertilizer addition increased the amount of $CO_2$ produced by a factor 2.6 in the case of the F-T fuel, compared to the soil with a very low natural nutrient content. Moisture content proved to be a negligible factor between 2% and 12% as volumetric water content. Intensive agitation was shown to be irrelevant as a biodegradation enhancement factor, indicating that mass transfer in the bulk soil did not appear to be a rate limiting factor.

In order to determine how much carbon actually remained in the soil as a function of time, the soil was analyzed by GCMS after different time periods. During the first week, the $CO_2$ production is minimal, and the contamination in the soil is very high. As time progresses, the amount of carbon dioxide produced increases strongly and the amount of contamination remaining in the soil (determined by GCMS) decreases significantly.

### 4.2.2 Biodegradability Conclusion

Experimental data generated over a period of several months show that the two main types of fuel, F-T and No. 2 diesel, have similar biodegradation profiles (Reference 4). However, in almost every experiment, the F-T fuel had a significantly higher rate of biodegradation than No. 2 diesel fuel, meaning that the F-T fuel was being removed from the soil faster by bacterial action. Longer lag phases were observed for fish biodiesel, meaning that more time was required for the soil bacteria to adapt to the fuel and begin degrading the fuel at a high rate, as indicated by the rate of $CO_2$ production. The moisture content in sand proved to be only a minor factor. Although the bioremediation process started much earlier for higher temperatures compared to lower ones, microbes adjusted to the lower temperature and degraded the hydrocarbons to a significant extent. After a period of three months, the cumulative $CO_2$ production at 6°C reached about 2/3 of that observed for 20°C. After the first month, during which respiration rates at 20°C peaked and then declined, actual rates at 6°C were even slightly higher than those for 20°C. In summary, F-T biodegrades faster than conventional diesel fuels, which reduces potential environmental damage in the event of a spill or leak.

## 4.3 Fairbanks, Alaska Transit-Bus Emission Check

Near the end of the demonstration on March 29, 2006, UAF researchers performed an emissions check on bus X941 of the Fairbanks Northstar Borough's Metropolitan Area Commuter System. This comparison did employ back-to-back runs of the same bus on the two fuels. However, the other five items listed in Appendix D as requisites for meaningful comparisons of fuel-property effects on engine emissions could not be fully attained during these on-road checks of gaseous emissions using a portable analyzer. Nonetheless, this emissions check was a valuable exercise for the information it ultimately provided on the condition of the bus engine, even if it was not likely to be able to quantify precisely the relatively small differences in engine emission levels attributable to differences in fuel properties.

A NOVA Model 7465 DNN exhaust analyzer was used to check the exhaust emissions. The primary intended use for this device was to "check" emissions and thus quickly identify those engines (i.e. in a large fleet) that have such unusually high emissions which may be precursors that other "engine problems" may be starting to occur, even if the overall performance of the engine still seems to be acceptable.

Table 1 presents the results of six emissions samples taken. The emissions monitor provides readings for both Nitric Oxide (NO) and Nitrogen Dioxide ($NO_2$). The literature usually refers to oxides of nitrogen, NOx, a term that includes both NO and $NO_2$.

*Table 1: Fairbanks Demonstration NOVA Analyzer Emission Results*

| | Sample 1 *No. 2 diesel under load at 45 mph* | Sample 2 *No. 2 diesel under load at 45 mph* | Sample 3 *No. 2 diesel idle* | Sample 4 *Syntroleum S-1 F-T under load at 45 mph* | Sample 5 *Syntroleum S-1 F-T under load at 45 mph* | *Sample 6 Syntroleum S-1 F-T idle* |
|---|---|---|---|---|---|---|
| *$O_2$ (%)* | *14.9* | *14* | *18.5* | *15.6* | *15.5* | *18.3* |
| *CO (%)* | *0.01* | *0* | *0* | *0* | *0.01* | *0* |
| *$CO_2$ (%)* | *4.4* | *5* | *2* | *5.1* | *4.7* | *1.9* |
| *HC (ppm)* | *6* | *9* | *5* | *4* | *6* | *5* |
| *NO (ppm)* | *300* | *315* | *353* | *193* | *359* | *242* |
| *$NO_2$ (ppm)* | *48* | *45* | *53* | *32* | *53* | *66* |

### 4.3.1 Emission Check Summary

Considering the relatively crude methods employed, the emission-check results are quite consistent from run to run. However, it would be a “stretch” to attempt to attribute the differences in emission levels to fuel properties. For example, this analyzer has relatively low sensitivities to both CO and hydrocarbons. Consistent with the idea of using this portable analyzer as a screening tool for potential early-stage engine problems, engines that are operating properly should have low levels of both CO and hydrocarbons when measured on these scales. However, the early stages of the common diesel engine problem of fuel-injector nozzle-leakage, for example, would produce much higher levels of CO and hydrocarbons that this analyzer would be able to detect.

The results from a Series 50 Detroit Diesel engine, virtually identical to the engines in the demonstration buses, operated as a stationary power plant at the University of Alaska Fairbanks Energy Research Center (ERC) as part of the NETL project referred to previously (Reference 1), are consistent with the results of the emissions sampling with the portable exhaust analyzer (Reference 4). On the basis of simple averaging of all values for a given pollutant on each fuel, the bus exhaust contained less NOx ($NO_2$ and NO) and unburned hydrocarbons (HC) when operating with F-T fuel than with No. 2

diesel. The emissions tests at the UAF ERC indicated that operation on the S-2 F-T fuel resulted in 18% lower unburned hydrocarbons than when operating on No. 2 conventional diesel, and that NOx emissions decreased by 12% when using the F-T fuel (Reference 4). The test at the UAF ERC on the Series 50 Detroit Diesel ran for 2,000 hours and the emissions test followed Environmental Protection Agency (EPA) protocols for stationary sources.

## 5.0 SUMMARY OF HEAVY LOAD FUEL CONSUMPTION COMPARISONS OF S-2 AND CONVENTIONAL DIESEL

The purpose of using the NCAT Pavement Test Track in Auburn, Alabama was to conduct a well controlled, on-road, fuel economy comparison of Syntroleum S-2 and conventional diesel fuel, over many thousands of miles in heavy-duty diesel powered trucks. In addition to documenting fuel economy using accepted methods, any operational issues that were experienced (i.e., equipment problems, performance problems, etc.) were also tracked. This section summarizes the major elements of this controlled fuel economy comparison as well as summary findings.

The NCAT Pavement Test Track, shown in Figure 19, is a 1.7-mile oval test facility on which a fleet of 5 heavy triple trucks each run over 3,000 miles a week in order to damage experimental pavements. A design lifetime of truck traffic (1.7 million total miles) is applied to pavement test sections within a 2-year period of time in an accelerated manner. Funding for experimental pavements is provided by state departments of transportation, who rely on results to determine which methods and materials produce pavements with lower life cycle costs. Fleet operations also provided an excellent opportunity to conduct S-2 and conventional diesel fuel comparisons in a highly controlled manner.

*Figure 19: Aerial View of NCAT Pavement Test Track*

The target speed of the entire 5-truck fleet was between 45 and 50 mph, which is generally considered to be the speed where the horsepower requirements for aerodynamic drag and rolling resistance are nearly equal and fuel efficiency is optimized. Both the AM and PM shifts ran in 2 ½ hour segments that were separated by 30-minute breaks All 5 trucks were sequential serial number 2004 Columbia series Freightliners equipped with 435 hp 60 series Detroit Diesel engines. In order to optimize damage to experimental pavements, the GVW of each rig was approximately 160,000 pounds.

At the end of each shift, the amount of fuel necessary to fill each vehicle's tank and the total amount of miles driven was logged into a computer database. Data from the morning and evening shifts were added together to produce gallons burned and miles driven for the entire day of operation. A single fuel economy value that represented a day of operation for each truck was computed as the total number of miles driven divided by the total number of gallons burned. The target length of each day "trip" was approximately 680 miles.

Truck number 4 was selected as the treatment vehicle for the S-2 F-T diesel fuel. At the beginning of the first full day of fleet operations with the synthetic diesel fuel treatment in use (10/18/05), truck number 4 rolled out with a starting odometer reading of 324,622 miles. The operating fleet is shown in Figure 20. By the time the last full tank of research fuel was pumped out of the ISO container on 12/7/05, the odometer in truck number 4 read 346,801 miles. This provided for a total traveled distance of 22,179 miles running nothing but synthetic fuel. At the conclusion of testing, the pump meter indicated that 5,876 (calibrated) gallons of fuel had been dispensed, with 5,700 gallons run in an unbiased manner that would accommodate the fuel economy analysis described next.

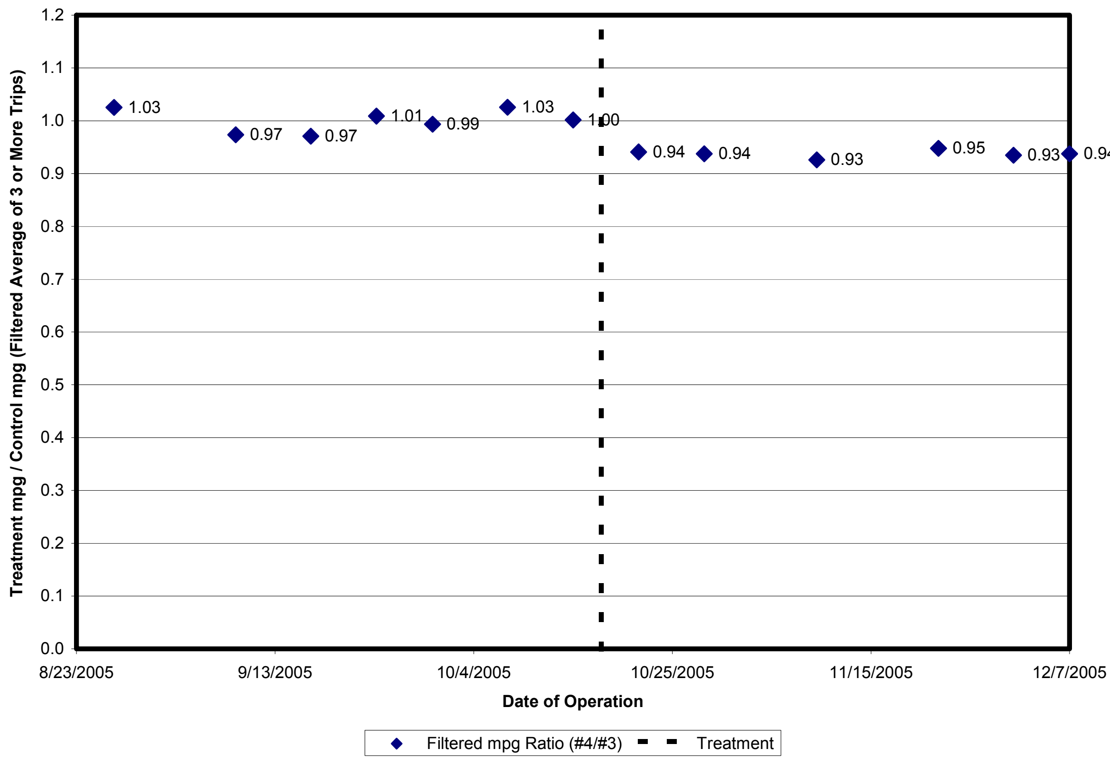
*Figure 20: Operational Fleet Seen on the Track's North Tangent (GVW ≈ 160,000 lbs)*

## 5.1 Summary of Fuel Efficiency Findings

Based on the total miles driven and the total amount of fuel pumped, an average fuel economy of 4.24 mpg was experienced with the synthetic fuel (Reference 5). In order to assess the significance of this number, it was necessary to normalize the data to account for any change in fuel economy that would have been experienced by the entire fleet (e.g., slight changes in speed, weather conditions, etc.). The American Trucking Association's (ATA) Technology and Maintenance Council (TMC) has developed a standardized method for relating fuel economy in a treatment vehicle to fuel economy in a designated control economy in Recommended Practice (RP) number 1102 entitled "TMC/SAE In-Service Fuel Consumption Test Procedure – Type II."

To facilitate Type II testing, truck number 3 was designated as the Track's control vehicle. Regardless of what treatments were evaluated in the other four trucks, truck number 3 was never altered in any way. Because it never changed, fuel economy in the other trucks could be divided by the fuel economy in number 3 to produce a fuel economy ratio as specified in RP 1102. Resulting fuel economy ratios were then passed through a 2% filtering band in order to be included in the analysis. In accordance with the Type II procedure, all groups of 3 or more trips that fall within this band in each work week (5 calendar days) are averaged to produce a single number that has statistical significance. Qualifying Type II data for the synthetic fuel experiment is shown in Figure 21.

*Figure 21: Average Fuel Economy Ratios for Truck #4 Filtered Using the American Trucking*




*Association's RP 1102 Type II Methodology*

It was found that filtered fuel economy ratios averaged 1.000 before the treatment, then averaged 0.937 during the treatment period. This amounts to a 6.3 percent increase in fuel consumption as a result of the use of synthetic diesel fuel in truck number 4 (Reference 5). An increase in fuel consumption was expected since lighter synthetic diesel fuel contains less energy per gallon than heavier petroleum-derived diesel fuels.

The Track's trucking coordinator reported no difference in starting difficulty with truck number 4; however, drivers reported that power was reduced until the engine had been running long enough to become heated. With the engine hot, drivers reported excellent power. It appeared the synthetic fuel produced less visible smoke as number 4 pulled through the slight grade in the West curve, although this observation was not objectively quantified.

## 6.0 EFFECTS OF F-T FUEL ON TRANSIT-BUS DIESEL ENGINE EXHAUST EMISSIONS

One of the goals of this FTA project is to provide a summary of the transit-relevant emissions testing that had been completed on Syntroleum F-T fuel thus far. ICRC/VSE collected emission data during the two major bus demonstrations that were part of the NETL F-T fuels project referred to previously (Reference 1). These included: an urban transit-bus demonstration at the Washington Metropolitan Area Transit Authority (WMATA) in Washington, DC, and in wilderness tour buses at Denali National Park in Denali, Alaska. Emission data was also collected from dynamometer emission tests that were conducted on bus engines identical to those used in the WMATA and Denali demonstrations.

### 6.1 F-T Fuel Emissions Background

The primary advantage of using F-T diesel fuel for transit bus applications is that an immediate reduction in diesel exhaust emissions can be obtained without making any changes to the buses or their engines. Furthermore, the general type of supporting infrastructure (fuel-tank, fuel-lines, pumps, etc.) and procedures required for fueling the buses with F-T are no different than those required for conventional diesel fuel.

Many bus fleets elected to use the lowest-emission conventional-diesel fuel available to reduce exhaust emissions, even before ULSD was required on-road in late 2006. A notable example was the WMATA which has used ultra-low sulfur No. 1 diesel fuel for several years, starting well before 2006. Since city transit buses typically operate in close proximity to large numbers of people, the additional cost associated with lower-emission fuel paid-off in reduced exposure of citizens to diesel exhaust emissions. As will be shown, F-T fuel can reduce diesel exhaust emissions to levels significantly below those obtainable with even the lowest-emission conventional diesel fuels.

In addition to using low-emission fuels, WMATA (and several other transit fleets) sought to reduce diesel exhaust emissions even further by retrofitting some of their older model year buses with catalyzed diesel particulate filters, which are sometimes referred to as diesel particulate traps. As will be described, particulate-filter technology can greatly reduce some diesel exhaust emissions, but the trap's control-system must be integrated into the engine's overall control system to obtain long-term reliability. Fortunately, such integration of control has now been incorporated into 2007 and later model-year diesel vehicles sold in the US and fitted with original-equipment diesel particulate filters.

Comparisons of fuel-effects on diesel exhaust emissions are most meaningful when the same engines, or the same diesel vehicles, are run back-to-back on the fuels to be compared. In fact, back-to-back testing is virtually essential when the engines and vehicles used have been in service for relatively long periods of time. Potential vehicle-to-vehicle differences tend to increase over long service lives, and emission variations between vehicles can often be greater than the "fuel-effect" being studied.

### 6.2 Back-to-Back Emission Data for F-T and Conventional Fuels

Measurement of the difference in diesel engine exhaust emissions attributable to as subtle an influence as differences in fuel properties, requires an excellent degree of control over all other potential variables, as described in Appendix D of this report. This demands, in addition to excellent control of operating conditions, exhaust sampling, instrument calibration, etc., back-to-back emission testing on the test-fuels to be compared to minimize engine and vehicle variations. Figures 22 and 23 show, respectively, particulate matter (PM) and NOx emissions from a WMATA bus operated back-to-back on ultra-low sulfur No. 1 diesel fuel and on Syntroleum F-T diesel fuel as measured by West Virginia University (WVU) (Data included in Reference 1). Another aspect of this back-to-back comparison is the exhaust aftertreatment equipment installed on the bus.

The original equipment installed on this bus was a diesel oxidation catalyst (DOC). The DOC is similar to the early catalytic converters used on gasoline-fueled cars. The DOC is intended to reduce carbon monoxide (CO) and hydrocarbon (HC) emissions, but it has very little if any effect on PM or NOx emissions. Diesel engines were typically equipped with DOCs starting in the late 1990s, but from the 2007 model year onward, on-road diesels in the US are equipped with diesel particulate filters, abbreviated as DPX in Figures 22 and 23.

Figure 22 shows that Syntroleum F-T diesel fuel reduces particulate matter emissions for the stock-DOC bus by more than 30% compared to the lowest emission conventional diesel fuel, ULSD1. The retrofitted catalyzed DPX greatly reduces PM emissions for both fuels, and indicates that the F-T diesel fuel is, at the very least, compatible with particulate filter technology. In fact, the lower engine-out PM emission rate obtained with F-T fuel means that the DPX filter needs regeneration, or burn-off of accumulated particulate matter, is required less often. This slower accumulation of particulate matter in the diesel particulate filter was indeed verified by laboratory tests conducted at MIT (Reference 1) which is expected to result in a longer service-life for the diesel particulate filter.

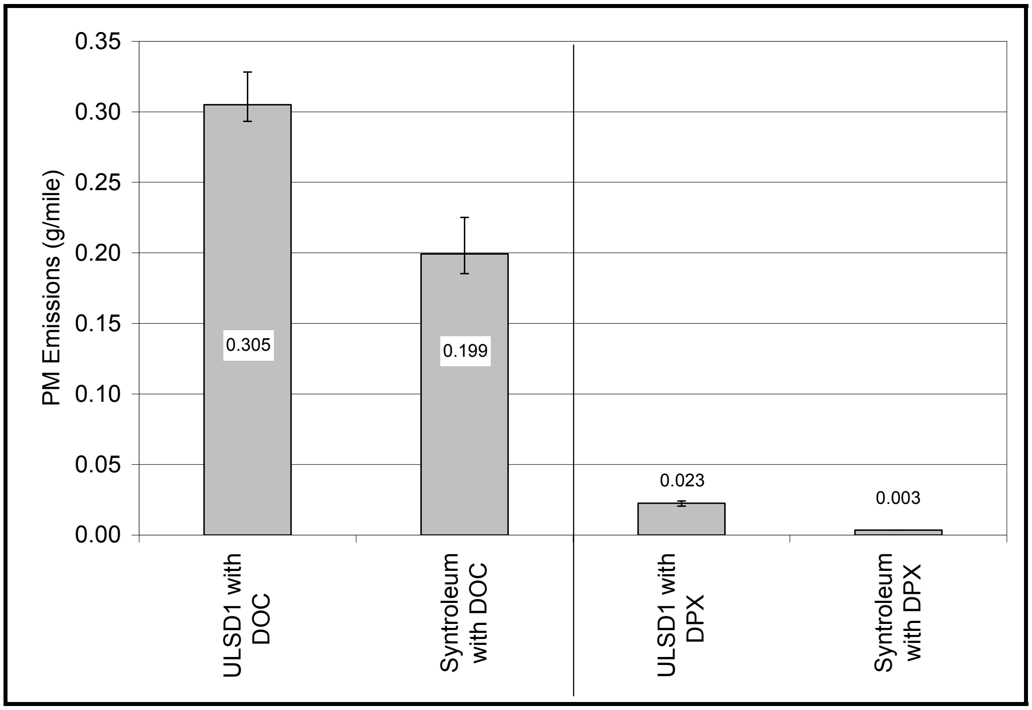



*Figure 22: Particulate Matter (PM) emissions from a single WMATA bus operated on Ultra-Low Sulfur No. 1 Diesel (ULSD1) and on Syntroleum S-2 F-T diesel fuels, with two different exhaust-aftertreatment configurations; the original-equipment Diesel Oxidation Catalyst (DOC), and a retrofitted Diesel Particulate Filter (DPX)*

Figure 23 shows that Syntroleum F-T diesel fuel reduces NOx emissions for the stock-DOC bus by more than 20% compared to the lowest emission conventional diesel fuel, ULSD1. Figure 23 also shows that the DPX has virtually no effect on NOx emissions for either fuel, as expected. However, the catalyzed diesel particulate filter does appear to oxidize some of the NO originally in the exhaust to $NO_2$. This reduces the amount of NO measured in the exhaust, but has no significant effect on total NOx emissions.

Particulate and NOx emissions are the most difficult diesel exhaust emissions to control from legacy diesel vehicles. Without the use of relatively expensive exhaust aftertreatment systems, and their control systems that must be integrated with the engine's control system, there are few workable approaches other than switching to lower-emission fuels. In fact, WMATA found that plugging of retrofitted particulate filters was such a problem that the program originally intended to apply retrofit particulate filters to most of the WMATA fleet was cancelled.

Particulate and NOx emissions are usually considered together for another reason as well; the well known particulate/NOx emission tradeoff. Many approaches that could reduce emissions of one of these species produce a corresponding increase in the other.

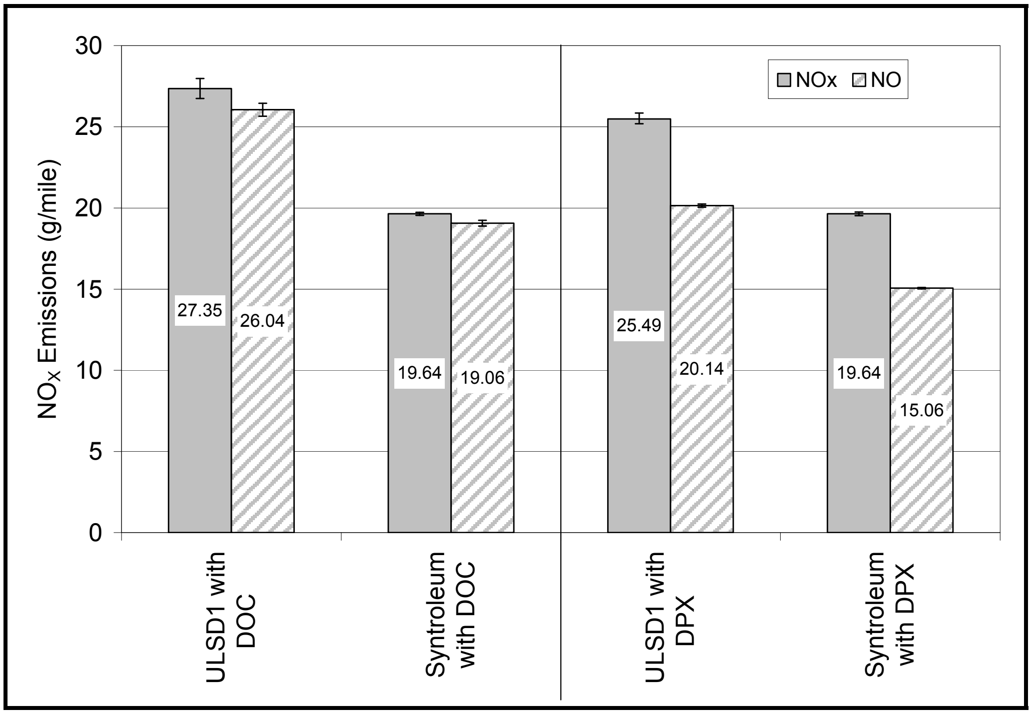



*Figure 23: Oxides of Nitrogen (NOx and NO) emissions from a single WMATA bus operated on Ultra-Low Sulfur No. 1 Diesel (ULSD1) and on Syntroleum S-2 F-T diesel fuels, with two different exhaust-aftertreatment configurations; the original-equipment Diesel Oxidation Catalyst (DOC), and a retrofitted Diesel Particulate Filter (DPX)*

Figures 24 and 25 show that CO and HC emissions are about the same for F-T and ULSD1 fuels for the stock-DOC vehicle configuration. However, Figures 24 and 25 also show that the diesel particulate filter (DPX) is far more effective in reducing CO and HC emissions than the DOC for both fuels. In fact, Figure 25 shows that HC are below the detection limit (BDL), or virtually zero, for both fuels with the DPX.

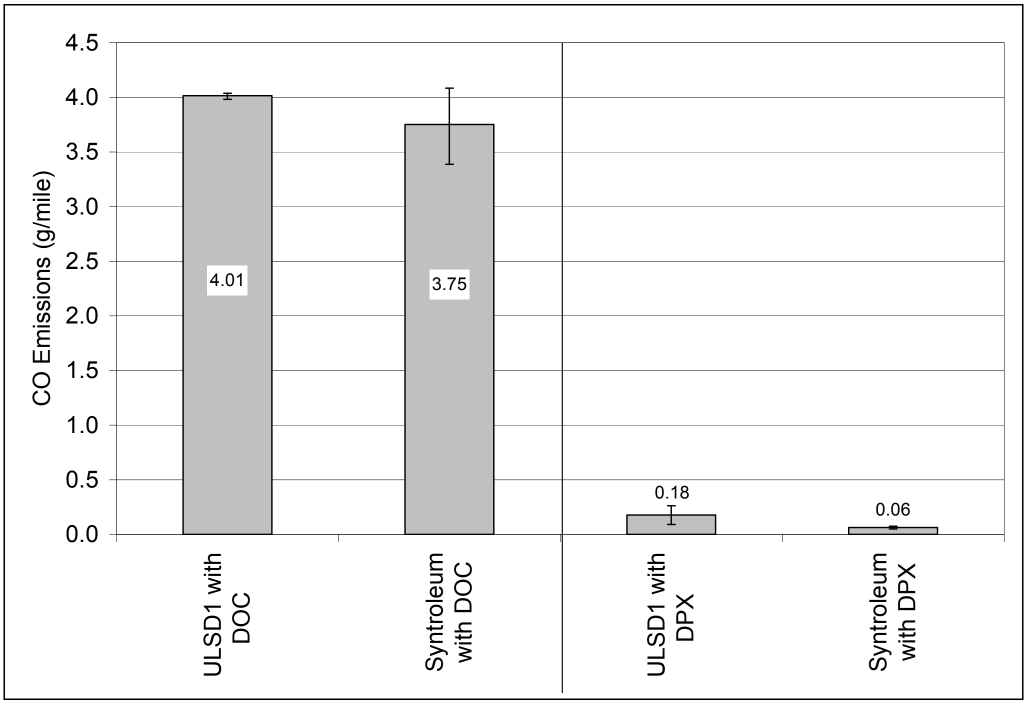



*Figure 24: Carbon Monoxide (CO) emissions from a single WMATA bus operated on Ultra-Low Sulfur No. 1 Diesel (ULSD1) and on Syntroleum S-2 F-T diesel fuels, with two different exhaust aftertreatment configurations; The original-equipment Diesel Oxidation Catalyst (DOC), and a retrofitted Diesel Particulate Filter (DPX)*

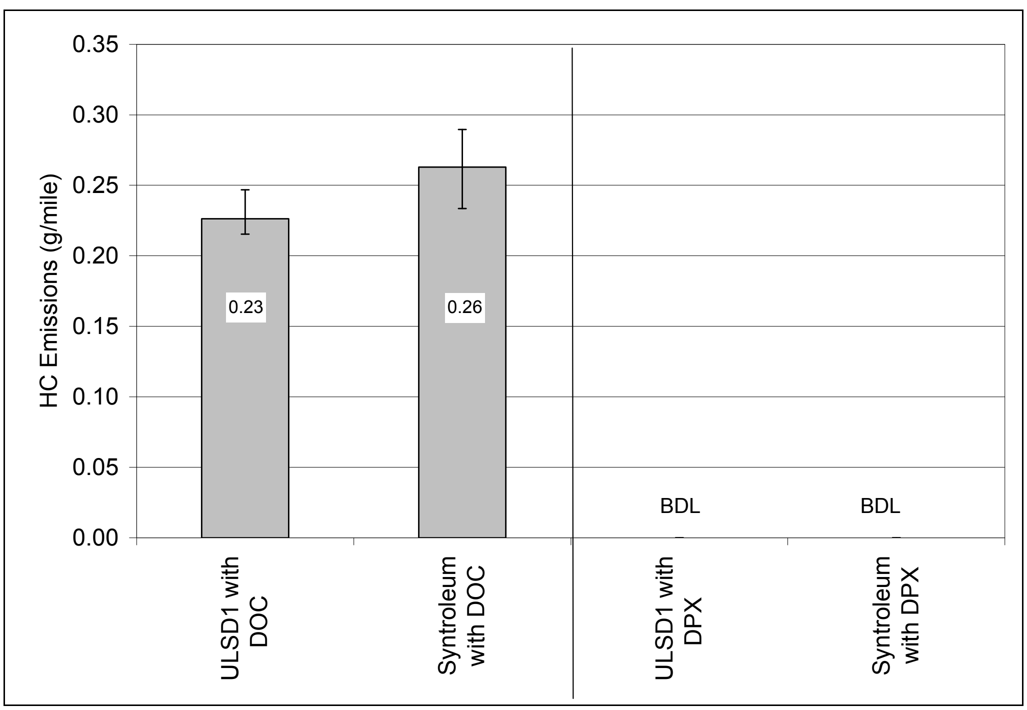



*Figure 25: Hydrocarbon (HC) emissions from a single WMATA bus operated on Ultra-Low Sulfur No. 1 Diesel (ULSD1) and on Syntroleum S-2 F-T diesel fuels, with two different exhaust aftertreatment configurations; The original-equipment Diesel Oxidation Catalyst (DOC), and a retrofitted Diesel Particulate Filter (DPX). BDL stands for an emission level Below the Detection Limit, or virtually zero.*

Table 2 is a summary of back-to-back particulate and NOx emission measurement results comparing Syntroleum S-2 F-T diesel fuel to the same conventional low-emission fuel, ULSD1, for three separate data sets. The first column of results summarizes the results in Figures 22 and 23 for the single WMATA bus in its stock configuration with the diesel oxidation catalyst. The second column of results gives the average reductions in PM and NOx for three similar WMATA buses measured under the same conditions at a later time.

*Table 2: Summarized Emission Reduction Percentages in Particulate Matter and Oxides of Nitrogen attributable to switching to Syntroleum S-2 F-T fuel from conventional Ultra-Low Sulfur No. 1 Diesel Fuel (ULSD1) in Back-to-Back Tests*

| Back-to-Back Data Source | 1 WMATA Bus (Figures 22 and 23) | 3 Bus Average (WMATA buses) | Dynamometer Emission Test |
|---|---|---|---|
| Engine | DDC Series 50 | DDC Series 50 | Caterpillar C-7 |
| Exhaust Aftertreatment | Diesel Oxidation Catalyst | Diesel Oxidation Catalyst | Diesel Oxidation Catalyst |
| Test Cycle | WMATA Cycle | WMATA Cycle | AVL 8-Mode |
| Reference Fuel | ULSD1 | ULSD1 | ULSD1 |
| S-2% Reduction in Particulate | 35 | 35 | 42 |
| S-2% Reduction in Oxides of Nitrogen | 28 | 16 | 19 |

The third column of results in Table 2 is for a Caterpillar C-7 engine run on a laboratory dynamometer using the AVL 8-Mode emission measurement cycle. The AVL 8-Mode test is an eight-mode steady-state engine test procedure designed to correlate with exhaust emission results of the US FTP Heavy-Duty Transient Cycle. Relative weights of particular modes and additional data are given in Appendix E of this report.

Table 2 shows that the reductions in both particulate and NOx emissions obtainable by switching to F-T fuel, even from the lowest-emission conventional diesel fuel ULSD1, are significant and fairly consistent from test to test. Data from other testing (not back-to-back), while not as definitive, provides additional support for the data in Table 2, as is discussed in Appendix E of this report.

## 7.0 CONCLUSIONS

In summary, VSE/ICRC has conducted demonstrations and tests of Syntroleum Corporation's S-2 F-T diesel fuel in: a new transit bus that ran a large total volume of F-T over a period of almost 3 years in Tulsa, Oklahoma; in a recently completed desert-climate demonstration of S-2 F-T diesel fuel in an Air Force passenger bus at Edwards AFB in Southern California; in a cold-weather transit bus demonstration in Fairbanks, Alaska; and in a Class 8 truck run at the National Center for Asphalt Technology at Auburn University in Auburn, Alabama.

Additionally, VSE has worked to compile and provide summary documentation on the emission testing programs and results to date for Syntroleum's S-2 and S-1 (arctic grade) ultra-clean diesel fuel tested under several related projects, including the Department of Energy's (DOE) National Energy Technology Laboratory's (NETL) Ultra-Clean Fuels Program, the FTA, and other organizations (including the University of Alaska-Fairbanks (UAF), Massachusetts Institute of Technology (MIT), West Virginia University (WVU), and AVL Powertrain Engineering). This final project report document provides a single point of reference for all transit-relevant emission measurements and comparisons associated with Syntroleum's ultra-clean diesel fuel as tested, including those done prior to the demonstration program with the Federal Transit Administration.

Long-term testing of neat F-T diesel fuel in transit bus service over the full range of climatic conditions has concluded that:

- No fuel-related operational problems occurred;
- The environmental impacts of F-T diesel fuel are even less severe than those associated with conventional ultra low sulfur diesel (ULSD) fuel; and
- Fuel consumption of F-T and ULSD are comparable.

**References**


1. Bergin, Stephen P. "Final Report: Ultra-Clean Fischer-Tropsch (F-T) Fuel Production and Demonstration Project." Final Project Report for Department of Energy Award Number DE-FC26-01NT41099. June 2007. http://www.osti.gov/bridge/product.biblio.jsp?query_id=2&page=0&osti_id=920084

2. Freerks, Robert L., John Cox & David Sowards "Analysis of Fuel-Injector Nozzle Deposits in a Cummins ISL Diesel Engine Operating Exclusively on Ultra-Clean Fischer-Tropsch Diesel Fuel with Comparison to Injector Nozzle Deposits Formed with Conventional Fuel" Technical Report for Federal Transit Administration Contract Number OK-26-7016-00. March 2009.

3. MIL-DTL-83133F, Detail Specification, Turbine Fuel, Aviation, Kerosene Type, JP-8 (NATO F-34), NATO F-35, and JP-8+100 (NATO F-37) (11 APR 2008) http://www.everyspec.com/MIL-SPECS/MIL+SPECS+(MIL-DTL)/MIL-DTL-83133F_11933/

4. Bergin, Stephen P. "Demonstration of Fischer-Tropsch Diesel Fuel in Cold Climates". Final Report for Federal Transit Administration Contract Number AK-26-7005.2007.01. November 2007. http://www.fta.dot.gov/documents/Fischer_Tropsch_Synthetic_Diesel_Demonstration_Project.pdf

5. Powell, R.B. "Conventional and Synthetic Fuel Efficiency Comparison on the NCAT Pavement Test Track". Topical Report for Federal Transit Administration Contract Number OK-26-7005-00. November 2006.

# APPENDICIES

## APPENDIX A – Analysis of S2 Fuel at Edwards AFB, September 2006

DEPARTMENT OF THE AIR FORCE
DET 3, WR-ALC/AFTLA
2430 C St, Bldg 70 Area B
Wright-Patterson AFB, OH 45433-7632

LABORATORY TEST REPORT

Submitter's Sample No: 06POSF5031
Date Sampled: 09/18/2006

Lab Report No: F-2006LA07388
Date Reported: 10/03/2006
Date Received: 09/27/2006
Product/Manufacturer/Contractor:

Sample Submitter:
AKIMA CORP
114 S. WOLF AVE.
EDWARDS AFB, CA 93524-6570

Reason for Submission: Fisher-Tropsch Testing
Product: Aviation Turbine Fuel, Kerosene
Specification: MIL-T-83133 JP-8
Sample Origin: S-2
Quantity Represented: 6000

NSN:
Contract No:
Batch/Lot:
Date Manufactured:

| | | LIMITS | | LAB |
|---|---|---|---|---|
| METHOD | TEST | MIN | MAX | RESULTS |
| SPEC\W | Workmanship | | PASS | Pass |
| D3242 | Total Acid Number, mg KOH/g | | 0.015 | 0.058## |
| D1319 | Aromatics, % vol | | 25.0 | 0.0 |
| D3227 | Mercaptan Sulfur, % mass | | 0.002 | 0.000 |
| D4294-03 | Total Sulfur, % mass | | 0.30 | See Below |
| D86 | Distillation | | | |
| | IBP, °C | | REPORT | 166 |
| | 10% Recovered, °C | | 205 | 188 |
| | 20% Recovered, °C | | REPORT | 203 |
| | 50% Recovered, °C | | REPORT | 249 |
| | 90% Recovered, °C | | REPORT | 313 |
| | EP, °C | | 300 | 330## |
| | Residue, % vol | | 1.5 | 1.3 |
| | Loss, % vol | | 1.5 | 1.1 |
| D93 | Flash Point, °C | 38 | | 60 |
| D5972 | Freezing Point, °C | | -47 | -22## |
| D445 | Viscosity @ -20°C, cSt | | 8.0 | 9.1## |
| D4809 | Heat of Combustion, BTU/lb | 18400 | | 18934 |
| D3343 | Hydrogen Content, % mass | 13.4 | | 15.3 |
| D1322 | Smoke Point, mm | 19.0 | | >40.0 |
| D1840 | Naphthalenes, % vol | | 3.0 | Not Req. |
| D130 | Copper Strip Corrosion | | 1 | 1a |
| D3241 | Thermal Stability @ 260°C | | | |
| | Tube Deposit Rating, Visual | | <3 | 1 |
| | Change in Pressure, mm Hg | | 25 | 0 |
| D381 | Existent Gum, mg/100mL | | 7.0 | 5.6 |
| D1094 | Water Reaction | | 1B | 3## |
| D5006 | FSII (DiEGME), % vol | 0.10 | 0.15 | 0.00## |
| D2624 | Conductivity, pS/m | 150 | 600 | 235 |
| D4052 | API Gravity @ 60°F | 37.0 | 51.0 | 52.5## |
| D5001 | Lubricity Test (BOCLE), wear scar mm | | REPORT | 0.45 |
| GC | Gas Chromatography Scan | | REPORT | See Below |
| D6217 | Particulates, mg/L | | REPORT | 0.8 |
| D445 | Viscosity @ -40°C, cSt | | REPORT | See Below |

Submitter's Sample No: 06POSF5031
Lab Report No: F-2006LA07388
As of : 10/03/2006 16:07:00
Page 2

| METHOD | TEST | LIMITS MIN | LIMITS MAX | LAB RESULTS |
|---|---|---|---|---|
| D445 | Viscosity @ 40°C, cSt | | REPORT | 2.0 |
| D5773 | Cloud Point,°C | | REPORT | -22 |
| D5949 | Pour Point, °C | | REPORT | -27 |
| D524 | Carbon Residue, 10% Bottoms, % mass | | REPORT | 0.15 |
| D6079 | HFRR Lubricity @ 60°C, wear scar mm | | REPORT | 0.370 |

REMARKS:
Product is S-2 synthetic diesel fuel representing 6000 gallons. Value obtained for D2622 sulfur was 0.0009 % mass. Gas chromatography scan appears to be an F-T version of a diesel fuel with the n-paraffin signal being 59.8% of the total signal.

Value obtained for D3338 Heat of Combustion was 18971 BTU/lb. Viscosity at -40°C was not performed due to the high freezing point value.

Copy To: AFTT

Reported By:

CHERYL M. MCCORMICK
Chemist

Approved By:

MIGUEL A. ACEVEDO
Chief, Aerospace Fuels Laboratory

# APPENDIX B - Analysis of S2 Fuel at Edwards AFB, January 2007

DEPARTMENT OF THE AIR FORCE
HQ AFPET/AFTLA
2430 C Street, Bldg 70 Area B
Wright-Patterson AFB, OH 45433-7632

LABORATORY TEST REPORT

Submitter's Sample No: 06POSF5047
Date Sampled: 01/22/2007

Lab Report No: F-2007LA02277
Date Reported: 02/01/2007
Date Received: 01/25/2007
Product/Manufacturer/Contractor:

Sample Submitter:
AKIMA CORP
114 S. WOLF AVE.
EDWARDS AFB, CA 93524-6570

Reason for Submission: Fisher-Tropsch Testing
Product: Aviation Turbine Fuel, Kerosene
Specification: MIL-T-83133 JP-8
Sample Origin: 91L069
Quantity Represented: 5335

NSN: /
Contract No:
Batch/Lot:
Date Manufactured:

| METHOD | TEST | LIMITS MIN | LIMITS MAX | LAB RESULTS |
|---|---|---|---|---|
| SPEC\W | Workmanship | | PASS | Pass |
| D3242 | Total Acid Number, mg KOH/g | | 0.015 | 0.064## |
| D1319 | Aromatics, % vol | | 25.0 | 0.0 |
| D3227 | Mercaptan Sulfur, % mass | | 0.002 | 0.000 |
| D4294-03 | Total Sulfur, % mass | | 0.30 | See Below |
| D86 | Distillation | | | |
| | IBP, °C | | REPORT | 165 |
| | 10% Recovered, °C | | 205 | 187 |
| | 20% Recovered, °C | | REPORT | 200 |
| | 50% Recovered, °C | | REPORT | 245 |
| | 90% Recovered, °C | | REPORT | 309 |
| | EP, °C | | 300 | 329## |
| | Residue, % vol | | 1.5 | 1.4 |
| | Loss, % vol | | 1.5 | 0.3 |
| D93 | Flash Point, °C | 38 | | 60 |
| D5972 | Freezing Point, °C | | -47 | -22## |
| D445 | Viscosity @ -20°C, cSt | | 8.0 | 8.7## |
| D4809 | Heat of Combustion, BTU/lb | 18400 | | 18960 |
| D3343 | Hydrogen Content, % mass | 13.4 | | 15.3 |
| D1322 | Smoke Point, mm | 19.0 | | 40.0 |
| D1840 | Naphthalenes, % vol | | 3.0 | Not Req. |
| D130 | Copper Strip Corrosion | | 1 | 1a |
| D3241 | Thermal Stability @ 260°C | | | |
| | Tube Deposit Rating, Visual | | <3 | 1 |
| | Change in Pressure, mm Hg | | 25 | 1 |
| D381 | Existent Gum, mg/100mL | | 7.0 | 6.0 |
| D1094 | Water Reaction | | 1B | 4 |
| D5006 | FSII (DiEGME), % vol | 0.10 | 0.15 | 0.00## |
| D2624 | Conductivity, pS/m | 150 | 600 | 79## |
| D4052 | API Gravity @ 60°F | 37.0 | 51.0 | 52.5## |
| D5001 | Lubricity Test (BOCLE), wear scar mm | | REPORT | 0.54 |
| GC | Gas Chromatography Scan | | REPORT | See Below |
| D6217 | Particulates, mg/L | | REPORT | 0.3 |
| D445 | Viscosity @ -40°C, cSt | | REPORT | See Below |

Submitter's Sample No: 06POSF5047
Lab Report No: F-2007LA02277
As of : 02/01/2007 14:53:59
Page 2

| METHOD | TEST | LIMITS MIN | MAX | LAB RESULTS |
|---|---|---|---|---|
| D445 | Viscosity @ 40°C, cST | | REPORT | 1.9 |
| D5773 | Cloud Point,°C | | REPORT | -23 |
| D5949 | Pour Point, °C | | REPORT | -30 |
| D524 | Carbon Residue, 10% Bottoms, % mass | | REPORT | 0.07 |
| D6079 | Lubricity by HFRR @ 60°C, mm | | REPORT | 0.375 |

REMARKS:
Value obtained for D2622 sulfur was 0.0015 % mass. Gas chromatography scan appears to be that of a mixture of summer diesel and F-T fuels with the n-paraffin signal being 55.0% of the total signal. Viscosity at -40°C not performed due to the high freezing point value.

Additional comments from AFTT (E. Alfaro): Syntroleum Corp S-2 FT diesel fuel taken on 22 Jan 2007 from R-11 MRV 91L-069. S-2 FT diesel fuel has been stored in the R-11 since Sep 2006. Original S-2 sample was taken on 18 Sep 2008 (test report # F-2006LA07388/06POSF5031).

Copy To: AFTT

Reported By:

CHERYL M. MCCORMICK
Chemist

Approved By:

MIGUEL A. ACEVEDO
Chief, Aerospace Fuels Laboratory

## APPENDIX C - Edwards AFB California S-2 Fuel report

Reported by Mr. Murray J. Westley
Chief of Transportation System
Edwards Air Force Base

The Fischer Tropsch S-2 fuel test began using a Thomas 44 passenger bus in September 2006 and was finalized on December 31, 2009. During this three year period, the bus traveled over 8,800 miles and supported numerous high visibility events, such as The 2006 Air Force Ball. It also transported many other dignitaries who visited Edwards. In addition, the bus performed flawlessly during the 2009 Open House and Air Show where Edwards hosted over 250,000 people. The bus was also used to conduct over 300 Base Public Affairs Tours during this period without fail and when used to travel around the local community, the bus performed well.

The bus engine injectors and/or injector pump did not require modification or retrofitting to accept the synthetic fuel. The bus did not misfire and there was no obvious odor or fuel leaks of any kind; however, when traveling under load, the bus displayed a lack of engine power. That was the only known problem or drawback during the testing phase. When the test began, the bus mileage was 13,730 and when it ended, the mileage was 22,558 for a total of 8,828 miles driven. The total gallons of S-2 consumed during this test period were 1,997 gallons. We returned the 44 passenger bus to regular diesel fuel on January 8, 2010 without modification and any maintenance related repairs. To date, the vehicle is operating normally. Overall, the test was a complete success.

## APPENDIX D - Requisites for Measuring Effects of Changes in Fuel Properties on Emissions

Making meaningful measurements of an effect on engine emissions as small as that attributable to the influence of fuel properties requires, at a minimum:

1. The ability to monitor and precisely control engine conditions to obtain test-to-test operational consistency;
2. Exhaust sampling equipment and procedures that have been demonstrated to preclude sample contamination (notably from atmospheric air, which may otherwise be present in differing amounts from test-to test);
3. Technically sophisticated analytical methods and instruments (with demonstrated high sensitivity to the concentration range of interest for the chemical species to be measured and with virtually no interference from other chemical species that may, or may not, be present);
4. In-use instrument and overall-system calibration, verified frequently by using both “zero” and “span” reference gases;
5. Simultaneous measurement of all relevant emissions, especially inclusion of particulates along with NOx gaseous emissions, since these two are known to “trade-off” in diesel combustion;
6. Back-to-back testing to eliminate variables associated with different engines and vehicles.

## APPENDIX E - Other (Not Back-to-Back) Emission Data for F-T and Conventional Fuels

The dynamometer-based emission measurements referred to in the last column of Table 2 (in the main body of this report) were conducted as a direct result of the emission measurements made on 6 new buses at Denali National Park during the summer of 2004. All six Denali buses were brand-new, having just been put in service in the spring of 2004. At the time they were tested, all six buses had accumulated odometer mileages ranging from (only) 6000 to 8600 miles. Three buses were tested on Syntroleum S-2 diesel fuel and three were tested on the conventional No. 1 diesel fuel used at Denali National Park, which is actually jet-A fuel. These six Denali buses were equipped with original-equipment diesel oxidation catalysts, not with diesel particulate filters.

The Denali S-2 fuel-evaluation and emission-measurement programs had been structured, including within the language of the DOE Cooperative Agreement covering the work, such that 3 buses would run on S-2 "test fuel," and 3 more virtually identical buses would be run on conventional "control fuel."

Determination of whether or not Fischer-Tropsch (F-T) fuel would be acceptable for operating bus fleets was one of the questions that the project was intended to answer. Therefore, the use of three "control" buses running on conventional fuel during the bus fleet demonstrations of F-T fuel in three other test buses in each fleet, provided a valuable reference in the event of any operating difficulties that could, potentially, have occurred with the then "new and unproven" F-T fuel. This same approach to emission measurements flowed rather naturally from the program's overall approach.

However, the primary question to be answered ultimately was the effect of F-T fuel on emissions. Attempting to determine the fuel-effect using other than back-to-back testing implicitly makes the assumption that vehicle to vehicle differences will be relatively small and insignificant.

Figure E-1 shows NOx emissions for the six buses, numbered 531 through 534, 536 and 537A, along with the fuel they were tested on, Syntro (for Syntroleum) or Jet-A. The results are quite consistent within each group of three buses running on each fuel. This consistency tends to support the implicit assumption that the bus-to-bus variation is relatively small. On this basis, the apparent increase in NOx emissions with F-T fuel is approximately 23%. This is in contrast to the results in Table 2 in Section 6.2. of this report, which show reductions of approximately 20% in NOx emissions with F-T fuel.

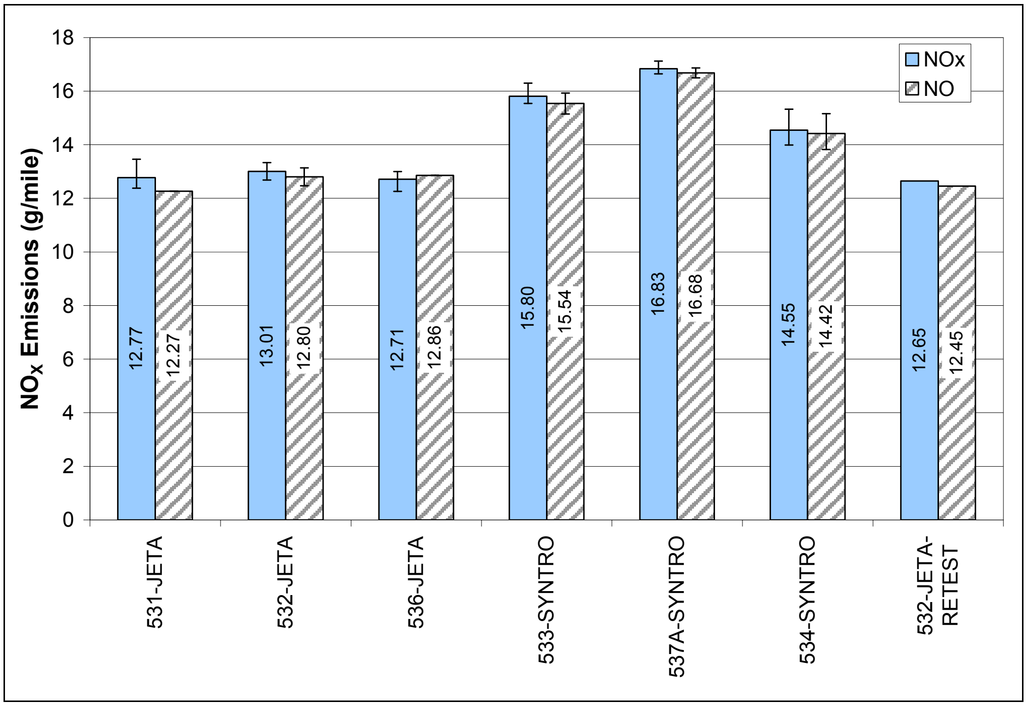



Figure E-1. Oxides of Nitrogen (NOx and NO) Emissions from six Denali National Park buses (with bus-numbers shown) operating on conventional Jet-A (which is used as No. 1 diesel fuel in Alaska), and on Syntroleum S-2 F-T diesel fuel

As an initial attempt to understand this discrepancy in the direction of the change in NOx emissions with F-T fuel, bus 532 was retested. Results were very similar to the initial test on bus 532, indicating that emission-measurement instrument “drift” was unlikely to be the cause of the unexpected results.

Figure E-2 shows particulate matter emissions for the same series of tests on the six Denali buses. The apparent decrease in particulate emissions with F-T fuel was approximately 25%. This is somewhat less than the values indicated in Table 2 for particulate emissions, but at least it is in the same direction.

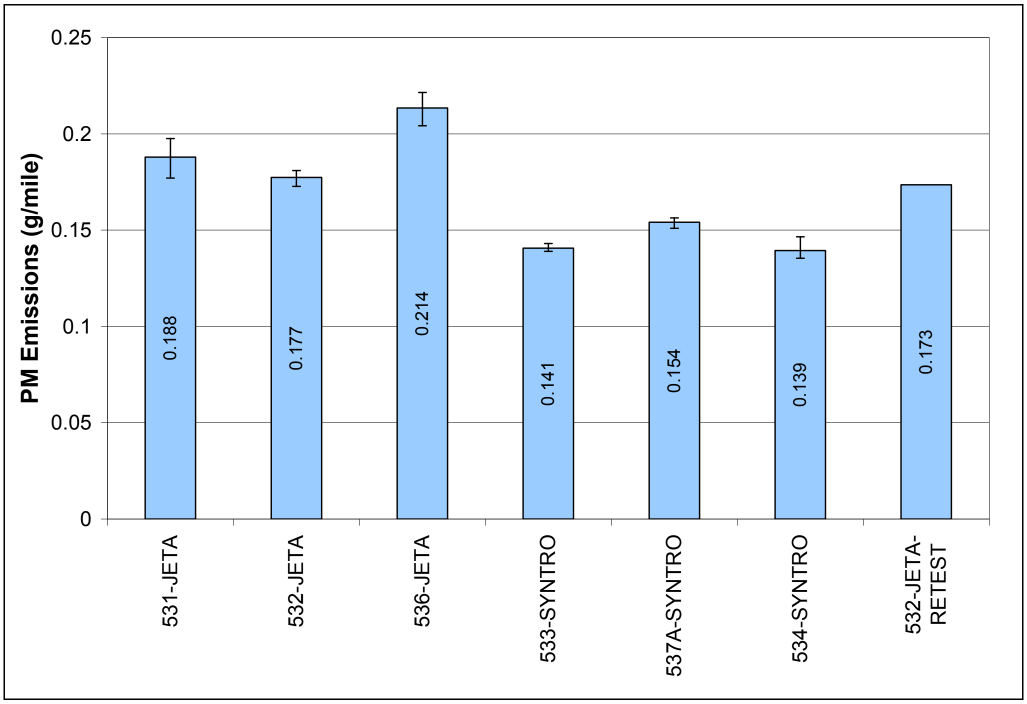


Figure E-2. Particulate Matter (PM) Emissions from six Denali National Park buses (with bus-numbers shown) operating on conventional Jet-A (which is used as No. 1 diesel fuel in Alaska), and on Syntroleum S-2 F-T diesel fuel

Follow-up investigation, including the dynamometer-based emission tests summarized in Table 2 in Section 6.2. of this report, revealed several interesting facts about the 2004 model-year Caterpillar C-7 engine. Although not publicly admitted by Caterpillar, this engine uses a homogeneous-charge compression-ignition (HCCI) strategy under some low-load conditions. This strategy can be effective for reducing both diesel particulate and NOx emissions, but it is difficult to control and its use is limited to the low-load regime with current technology.

Figure E-5 and the three tables at the end of this Appendix show the complete set of dynamometer-based emission data for the Caterpillar C-7 engine; three runs on each of three fuels at all 8 of the conditions shown in these tables below. At the lowest load conditions, Modes 1 and 2, this data-set shows high run-to-run variability in NOx, with correspondingly high, but opposite-direction variability, in both CO and hydrocarbon emissions. This is exactly the type of variability that would be expected for an engine control system that is “hunting” for opportunities to apply HCCI-type operation.

In retrospect, the choice of the WMATA operating cycle for the Denali National Park bus emission testing (for the sake of consistency), was a poor choice. The WMATA cycle is indeed representative of congested urban-traffic transit-bus operation, with a significant percentage of relatively low-speed and low-load operation. However, the Denali National Park buses, which must climb steep grades on rough roads, actually operate under much heavier average loads than urban buses. Furthermore, the relatively low-load

WMATA cycle chosen for emission testing apparently provided multiple "opportunities" for the Caterpillar C-7 engines in the Denali buses to run in HCCI-type operation.

The problem for F-T fuels with HCCI-type technology is that to achieve minimum emissions, the engine control system must be calibrated for the Cetane Number range of the fuels that the engine will be using. Typical conventional diesel fuels in the US have Cetane Numbers in the range of 40 to 45. However, hydrogen-saturated F-T diesel fuel has a much higher (literally "off the chart") Cetane Number of at least 70.

In HCCI operation, the fuel is injected "early and often" in an attempt to obtain a lean, but nearly homogeneous, charge of fuel-air mixture which will then autoignite, ideally producing low emissions of NOx and particulate, but relatively high emissions of CO and hydrocarbons. Exhaust aftertreatment technology, including the diesel oxidation catalyst, but especially the diesel particulate filter, can subsequently "clean-up" the CO and hydrocarbon emissions.

Extremely high Cetane-Number F-T fuel ignites much earlier than conventional diesel fuel in HCCI-type operation. Presumably, the HCCI engine's control system could have been calibrated to take advantage of F-T fuel's inherent lower emission characteristics, rather than inadvertently causing an increase in NOx emissions with F-T fuel. The early ignition caused by F-T fuel's high Cetane Number in HCCI-type operation (when not calibrated for high-Cetane fuel) has the same net effect on increasing NOx emissions as advancing the fuel-injection timing in a more traditional diesel engine.

In an emission measurement program with an identical design to that used for the Denali National Park buses just described (i.e. not using back-to-back testing), emissions were measured from six WMATA buses, three using Syntroleum S-2 F-T fuel, and three using ULSD1. However, these WMATA buses were much older (with "traditional" diesel technology), had been in transit-service operation for over 4 years and had all accumulated between 180,000 and 220,000 odometer miles, far more than the new Denali buses at the time they were tested.

Nonetheless, NOx emissions for these older WMATA buses, as shown in Figure E-3, were remarkably consistent within the two fuel-groups, with an apparent reduction of 22% in NOx attributable to S-2 fuel, which is well in-line with the summarized back-to-back NOx reduction values in Table 2 in Section 6.2 of this report. For particulate emissions, however, as shown in Figure E-4, bus-to-bus variations for these high-mileage buses were very large, obscuring any fuel-effect. This is the reason that in subsequent emission testing at WMATA, as summarized in Table 2, the back-to-back testing approach was used; the same three buses were tested back-to-back on the two fuels to be compared.

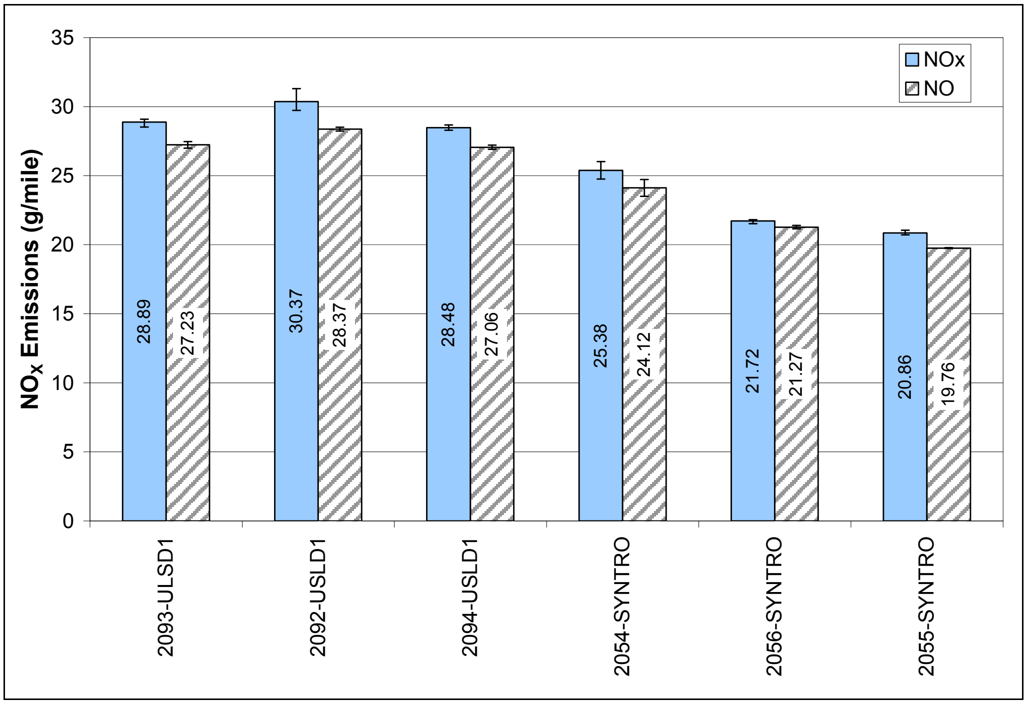



Figure E-3. Oxides of Nitrogen (NOx and NO) Emissions from six WMATA buses (with bus-numbers shown) operating on conventional ULSD1, and on Syntroleum S-2 F-T diesel fuel

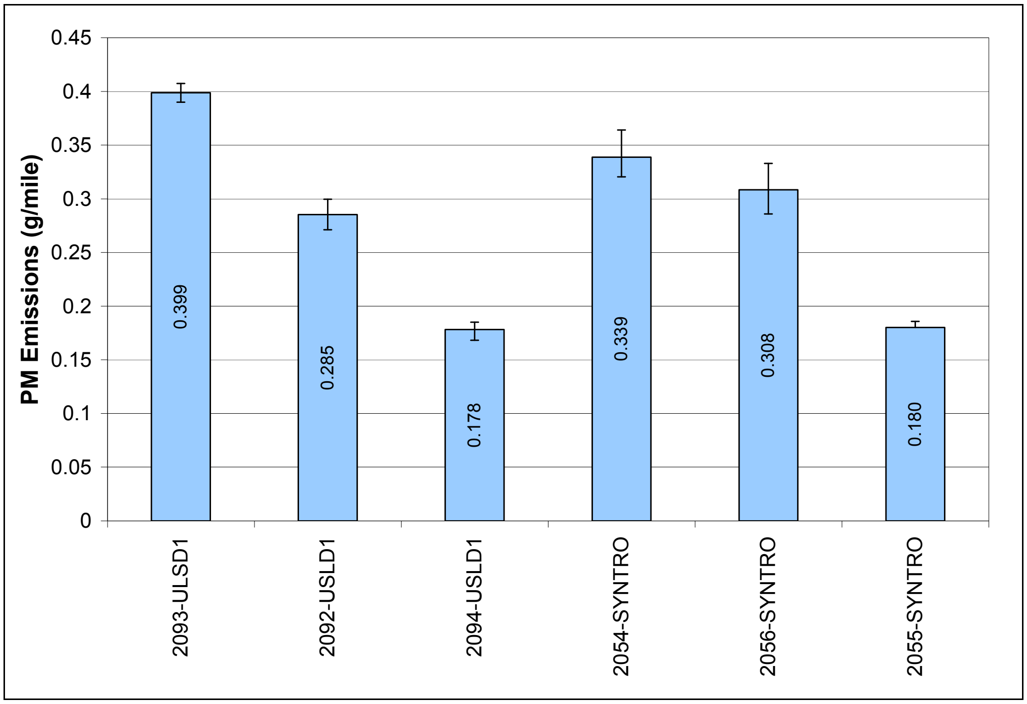



Figure E-4. Particulate Matter (PM) Emissions from six WMATA buses (with bus-numbers shown) operating on conventional ULSD1, and on Syntroleum S-2 F-T diesel fuel

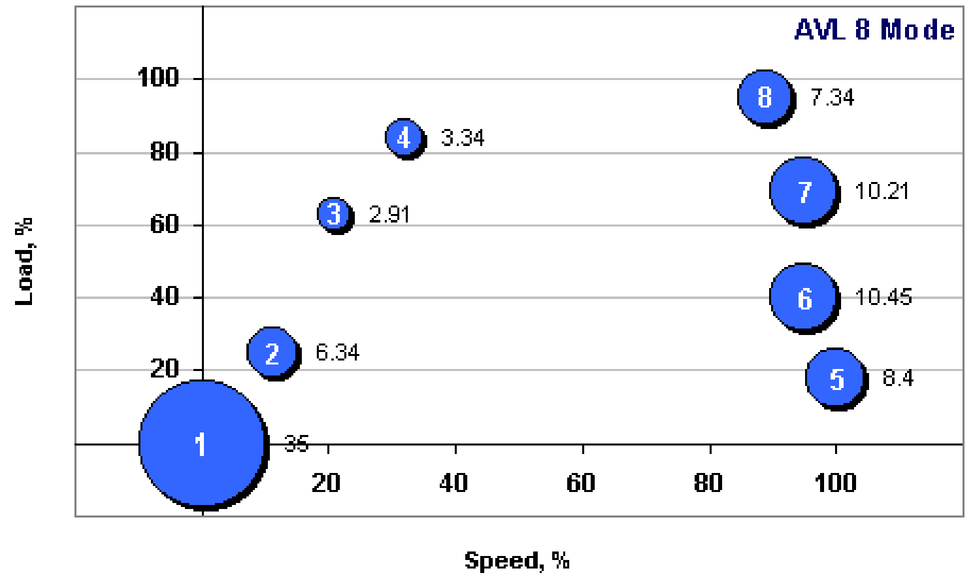



Figure E-5. AVL 8-Mode Emission Test Cycle-Visual Weight Factors Apply to following tables

## AVL 8 Mode: Average Weighted Brake Specific Emissions

**Engine:** CAT C7 2004 | **Rated Speed:** 2400 | **Rated Power:** 230 HP | **Disp. (L)** 7.2 | **Fuel Type** Syntroleum

**PUMA File** 5758_synt_19Apr05 | 2319

**SPC File** 1012

| Mode | Weight Factor | Speed | Load | Power | NOx | CO2 | CO | THC | Wt Power | Wt NOx | Wt CO2 | Wt CO | Wt THC | PM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | percent | rpm | (Nm) | (kw) | (g/hr) | (g/hr) | (g/hr) | (g/hr) | (kw) | (g/hr) | (g/hr) | (g/hr) | (g/hr) | |
| 1 | 35 | 799 | -5.08 | -0.43 | 45.69 | 3857 | 14.68 | 10.68 | -0.15 | 15.99 | 1350 | 5.14 | 3.74 | |
| 2 | 6.34 | 887 | 138.67 | 12.88 | 90.96 | 11651 | 36.28 | 13.58 | 0.82 | 5.77 | 739 | 2.30 | 0.86 | |
| 3 | 2.91 | 1057 | 407.28 | 45.08 | 212.46 | 32936 | 156.72 | 19.52 | 1.31 | 6.18 | 958 | 4.56 | 0.57 | |
| 4 | 3.34 | 1244 | 614.46 | 80.05 | 307.23 | 59771 | 176.26 | 27.46 | 2.67 | 10.26 | 1996 | 5.89 | 0.92 | |
| 5 | 8.4 | 2399.6 | 94.79 | 23.82 | 111.67 | 36998 | 96.14 | 73.54 | 2.00 | 9.38 | 3108 | 8.08 | 6.18 | |
| 6 | 10.45 | 2315 | 234.08 | 56.75 | 181.94 | 56862 | 109.51 | 76.47 | 5.93 | 19.01 | 5942 | 11.44 | 7.99 | |
| 7 | 10.21 | 2315 | 402.43 | 97.56 | 250.3 | 85128 | 1122.7 | 98.76 | 9.96 | 25.56 | 8692 | 114.63 | 10.08 | |
| 8 | 7.34 | 2213.1 | 587.04 | 136.05 | 474.75 | 102940 | 848.88 | 76.87 | 9.99 | 34.85 | 7556 | 62.31 | 5.64 | |
| Weighted Power and Weighted Mass Emission Sums →→→→→→→→ | | | | | | | | | 32.53 | 127.00 | 30341 | 214.34 | 35.98 | |
| **Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→** | | | | | | | | | | **3.90** | **933** | **6.59** | **1.11** | **0.030** |

**PUMA File** 5776_synt_19Apr05 | 2322

**SPC File** 1013

| Mode | Weight Factor | Speed | Load | Power | NOx | CO2 | CO | THC | Wt Power | Wt NOx | Wt CO2 | Wt CO | Wt THC | PM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | percent | rpm | (Nm) | (kw) | (g/hr) | (g/hr) | (g/hr) | (g/hr) | (kw) | (g/hr) | (g/hr) | (g/hr) | (g/hr) | |
| 1 | 35 | 800.1 | -6.63 | -0.56 | 23.6 | 3861 | 329.34 | 30.67 | -0.20 | 8.26 | 1351 | 115.27 | 10.73 | |
| 2 | 6.34 | 887 | 138.49 | 12.86 | 75.27 | 11649 | 213.61 | 22.24 | 0.82 | 4.77 | 739 | 13.54 | 1.41 | |
| 3 | 2.91 | 1057 | 408.31 | 45.19 | 214.78 | 33157 | 145.07 | 17.75 | 1.32 | 6.25 | 965 | 4.22 | 0.52 | |
| 4 | 3.34 | 1244 | 612.92 | 79.85 | 313.92 | 59655 | 167.19 | 24.05 | 2.67 | 10.48 | 1992 | 5.58 | 0.80 | |
| 5 | 8.4 | 2400.2 | 100.17 | 25.18 | 113.78 | 37027 | 96.52 | 72.84 | 2.12 | 9.56 | 3110 | 8.11 | 6.12 | |
| 6 | 10.45 | 2315 | 232.76 | 56.43 | 183.01 | 56133 | 108.11 | 76.06 | 5.90 | 19.12 | 5866 | 11.30 | 7.95 | |
| 7 | 10.21 | 2314.9 | 402.12 | 97.48 | 255.04 | 85166 | 1119.6 | 95.81 | 9.95 | 26.04 | 8695 | 114.31 | 9.78 | |
| 8 | 7.34 | 2213 | 586.74 | 135.98 | 466.52 | 102416 | 849.89 | 77.42 | 9.98 | 34.24 | 7517 | 62.38 | 5.68 | |
| Weighted Power and Weighted Mass Emission Sums →→→→→→→→ | | | | | | | | | 32.55 | 118.73 | 30236 | 334.72 | 43.00 | |
| **Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→** | | | | | | | | | | **3.65** | **929** | **10.28** | **1.32** | **0.030** |

**PUMA File** 5780_synt_19Apr05 | 2328

**SPC File** 1014

| Mode | Weight Factor | Speed | Load | Power | NOx | CO2 | CO | THC | Wt Power | Wt NOx | Wt CO2 | Wt CO | Wt THC | PM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | percent | rpm | (Nm) | (kw) | (g/hr) | (g/hr) | (g/hr) | (g/hr) | (kw) | (g/hr) | (g/hr) | (g/hr) | (g/hr) | |
| 1 | 35 | 800 | -0.79 | -0.07 | 22.21 | 3619 | 370.26 | 32.55 | -0.02 | 7.77 | 1267 | 129.59 | 11.39 | |
| 2 | 6.34 | 887 | 138.07 | 12.82 | 66.3 | 11687 | 226.9 | 23.4 | 0.81 | 4.20 | 741 | 14.39 | 1.48 | |
| 3 | 2.91 | 1057 | 405.54 | 44.89 | 199.48 | 33035 | 153.75 | 19.38 | 1.31 | 5.80 | 961 | 4.47 | 0.56 | |
| 4 | 3.34 | 1244 | 613.8 | 79.96 | 293.75 | 59954 | 179.97 | 27.68 | 2.67 | 9.81 | 2002 | 6.01 | 0.92 | |
| 5 | 8.4 | 2399.7 | 95.56 | 24.01 | 107.3 | 37256 | 101.29 | 74.33 | 2.02 | 9.01 | 3130 | 8.51 | 6.24 | |
| 6 | 10.45 | 2314.9 | 232.29 | 56.31 | 171.09 | 56223 | 110.39 | 76.35 | 5.88 | 17.88 | 5875 | 11.54 | 7.98 | |
| 7 | 10.21 | 2315.1 | 402.45 | 97.57 | 245.63 | 84632 | 1161.91 | 97.8 | 9.96 | 25.08 | 8641 | 118.63 | 9.99 | |
| 8 | 7.34 | 2213 | 586.65 | 135.95 | 449.18 | 103196 | 872.24 | 81 | 9.98 | 32.97 | 7575 | 64.02 | 5.95 | |
| Weighted Power and Weighted Mass Emission Sums →→→→→→→→ | | | | | | | | | 32.61 | 112.53 | 30192 | 357.16 | 44.52 | |
| **Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→** | | | | | | | | | | **3.45** | **926** | **10.95** | **1.37** | **0.030** |

**Average Weighted Brake Specific Emissions for all 8Mode Tests Above (g/kw-hr) →→→→ 3.67 929 9.28 1.26 0.030**

## AVL 8 Mode: Average Weighted Brake Specific Emissions

| Engine: CAT C7 2004 | Rated Speed: 2400 | Rated Power: 230 HP | Disp. (L) 7.2 | Fuel Type Denali |
|---|---|---|---|---|

**PUMA File** 5781_Denali_21Apr05 | 2343

**SPC File** 2343

| Mode | Weight Factor | Speed | Load | Power | NOx | CO2 | CO | THC | Wt Power | Wt NOx | Wt CO2 | Wt CO | Wt THC | PM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | percent | rpm | (Nm) | (kw) | (g/hr) | (g/hr) | (g/hr) | (g/hr) | (kw) | (g/hr) | (g/hr) | (g/hr) | (g/hr) | g/kw-hr |
| 1 | 35 | 799.7 | 7.17 | 0.6 | 34.36 | 3310 | 528.08 | 76.23 | 0.21 | 12.03 | 1158 | 184.83 | 26.68 | |
| 2 | 6.34 | 887 | 156.02 | 14.49 | 83.51 | 12570 | 322.69 | 34.95 | 0.92 | 5.29 | 797 | 20.46 | 2.22 | |
| 3 | 2.91 | 1057 | 427.24 | 47.29 | 251.2 | 35532 | 194.03 | 28.16 | 1.38 | 7.31 | 1034 | 5.65 | 0.82 | |
| 4 | 3.34 | 1244 | 628.55 | 81.88 | 369.42 | 63054 | 225.74 | 41.06 | 2.73 | 12.34 | 2106 | 7.54 | 1.37 | |
| 5 | 8.4 | 2399.7 | 100.69 | 25.3 | 143.05 | 39587 | 169.8 | 145.64 | 2.13 | 12.02 | 3325 | 14.26 | 12.23 | |
| 6 | 10.45 | 2215 | 239.1 | 55.46 | 200.09 | 55202 | 146.38 | 119.5 | 5.80 | 20.91 | 5769 | 15.30 | 12.49 | |
| 7 | 10.21 | 2215 | 410.1 | 95.13 | 274.02 | 83096 | 1346.6 | 147.32 | 9.71 | 27.98 | 8484 | 137.49 | 15.04 | |
| 8 | 7.34 | 2212.9 | 600.02 | 139.05 | 555.74 | 108281 | 1003.91 | 115.91 | 10.21 | 40.79 | 7948 | 73.69 | 8.51 | |
| Weighted Power and Weighted Mass Emission Sums →→→→→→→→ | | | | | | | | | 33.08 | 138.66 | 30621 | 459.21 | 79.36 | |
| **Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→** | | | | | | | | | | **4.19** | **926** | **13.88** | **2.40** | **0.059** |

**PUMA File** 5774_Denali_22Apr05 | 2349

**SPC File** 2349

| Mode | Weight Factor | Speed | Load | Power | NOx | CO2 | CO | THC | Wt Power | Wt NOx | Wt CO2 | Wt CO | Wt THC | PM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | percent | rpm | (Nm) | (kw) | (g/hr) | (g/hr) | (g/hr) | (g/hr) | (kw) | (g/hr) | (g/hr) | (g/hr) | (g/hr) | g/kw-hr |
| 1 | 35 | 799.7 | 5.9 | 0.49 | 96.1 | 3828 | 37.2 | 16.92 | 0.17 | 33.64 | 1340 | 13.02 | 5.92 | |
| 2 | 6.34 | 887 | 157.13 | 14.6 | 184.65 | 12840 | 187.79 | 24.52 | 0.93 | 11.71 | 814 | 11.91 | 1.55 | |
| 3 | 2.91 | 1057 | 428.38 | 47.42 | 251.8 | 35489 | 178.23 | 24.5 | 1.38 | 7.33 | 1033 | 5.19 | 0.71 | |
| 4 | 3.34 | 1244 | 626.03 | 81.55 | 362.78 | 63147 | 217.94 | 35.81 | 2.72 | 12.12 | 2109 | 7.28 | 1.20 | |
| 5 | 8.4 | 2399.6 | 97.46 | 24.49 | 139.34 | 38469 | 180.81 | 154.07 | 2.06 | 11.70 | 3231 | 15.19 | 12.94 | |
| 6 | 10.45 | 2315 | 238.15 | 57.73 | 213.31 | 59454 | 149.34 | 123.59 | 6.03 | 22.29 | 6213 | 15.61 | 12.92 | |
| 7 | 10.21 | 2315 | 411.01 | 99.64 | 305.32 | 89354 | 1355.52 | 145.31 | 10.17 | 31.17 | 9123 | 138.40 | 14.84 | |
| 8 | 7.34 | 2213.1 | 600.09 | 139.07 | 546.04 | 108001 | 1023.5 | 111.28 | 10.21 | 40.08 | 7927 | 75.12 | 8.17 | |
| Weighted Power and Weighted Mass Emission Sums →→→→→→→→ | | | | | | | | | 33.67 | 170.03 | 31790 | 281.71 | 58.25 | |
| **Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→** | | | | | | | | | | **5.05** | **944** | **8.37** | **1.73** | **0.051** |

**PUMA File** 5701_Denali_22Apr05 | 2353

**SPC File** 2353

| Mode | Weight Factor | Speed | Load | Power | NOx | CO2 | CO | THC | Wt Power | Wt NOx | Wt CO2 | Wt CO | Wt THC | PM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | percent | rpm | (Nm) | (kw) | (g/hr) | (g/hr) | (g/hr) | (g/hr) | (kw) | (g/hr) | (g/hr) | (g/hr) | (g/hr) | g/kw-hr |
| 1 | 35 | 800.1 | 3.23 | 0.27 | 90.25 | 3942 | 51.58 | 18.24 | 0.09 | 31.59 | 1380 | 18.05 | 6.38 | |
| 2 | 6.34 | 887 | 158.22 | 14.7 | 198.6 | 13215 | 37.17 | 16.34 | 0.93 | 12.59 | 838 | 2.36 | 1.04 | |
| 3 | 2.91 | 1057 | 430.48 | 47.65 | 251.06 | 35858 | 192.66 | 24.5 | 1.39 | 7.31 | 1043 | 5.61 | 0.71 | |
| 4 | 3.34 | 1244 | 627.46 | 81.74 | 358.96 | 63384 | 221.43 | 35.84 | 2.73 | 11.99 | 2117 | 7.40 | 1.20 | |
| 5 | 8.4 | 2400.1 | 103.55 | 26.03 | 139.19 | 39523 | 180.5 | 150.34 | 2.19 | 11.69 | 3320 | 15.16 | 12.63 | |
| 6 | 10.45 | 2314.9 | 238.4 | 57.79 | 209.82 | 60245 | 150.68 | 123.81 | 6.04 | 21.93 | 6296 | 15.75 | 12.94 | |
| 7 | 10.21 | 2314.9 | 411.28 | 99.7 | 288.44 | 89273 | 1348.39 | 145.29 | 10.18 | 29.45 | 9115 | 137.67 | 14.83 | |
| 8 | 7.34 | 2213.1 | 600.76 | 139.23 | 555.21 | 108832 | 999.84 | 111.03 | 10.22 | 40.75 | 7988 | 73.39 | 8.15 | |
| Weighted Power and Weighted Mass Emission Sums →→→→→→→→ | | | | | | | | | 33.77 | 167.29 | 32096 | 275.38 | 57.88 | |
| **Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→** | | | | | | | | | | **4.95** | **951** | **8.16** | **1.71** | **0.052** |

**Average Weighted Brake Specific Emissions for all 8Mode Tests Above (g/kw-hr) →→→→ 4.73 940 10.13 1.95 0.054**

## AVL 8 Mode: Average Weighted Brake Specific Emissions

**Engine:** CAT C7 2004 | **Rated Speed:** 2400 | **Rated Power:** 230 HP | **Disp. (L)** 7.2 | **Fuel Type** WMATA

**PUMA File** 5703_WMATA_1_28Apr05 | 2383

**SPC File** 1019

| Mode | Weight Factor | Speed | Load | Power | NOx | CO2 | CO | THC | Wt Power | Wt NOx | Wt CO2 | Wt CO | Wt THC | PM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | percent | rpm | (Nm) | (kw) | (g/hr) | (g/hr) | (g/hr) | (g/hr) | (kw) | (g/hr) | (g/hr) | (g/hr) | (g/hr) | |
| 1 | 35 | 800.6 | 3.55 | 0.3 | 36.36 | 3527 | 584.03 | 81.59 | 0.11 | 12.73 | 1235 | 204.41 | 28.56 | |
| 2 | 6.34 | 887 | 155.12 | 14.41 | 80.55 | 12472 | 342.53 | 38.63 | 0.91 | 5.11 | 791 | 21.72 | 2.45 | |
| 3 | 2.91 | 1057 | 445.89 | 49.35 | 251.62 | 36239 | 193.49 | 30.63 | 1.44 | 7.32 | 1055 | 5.63 | 0.89 | |
| 4 | 3.34 | 1244 | 714.92 | 93.13 | 393.53 | 69780 | 240.17 | 43.23 | 3.11 | 13.14 | 2331 | 8.02 | 1.44 | |
| 5 | 8.4 | 2400.2 | 112.63 | 28.31 | 146.68 | 39229 | 173.09 | 136.01 | 2.38 | 12.32 | 3295 | 14.54 | 11.42 | |
| 6 | 10.45 | 2315 | 252.17 | 61.13 | 224.18 | 61229 | 150.3 | 118.03 | 6.39 | 23.43 | 6398 | 15.71 | 12.33 | |
| 7 | 10.21 | 2315 | 433.99 | 105.21 | 299.48 | 90564 | 1509.73 | 151.25 | 10.74 | 30.58 | 9247 | 154.14 | 15.44 | |
| 8 | 7.34 | 2213 | 637.01 | 147.63 | 564.12 | 111225 | 1099.32 | 109.94 | 10.84 | 41.41 | 8164 | 80.69 | 8.07 | |
| Weighted Power and Weighted Mass Emission Sums →→→→→→→→→ | | | | | | | | | 35.91 | 146.03 | 32515 | 504.86 | 80.61 | |
| **Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→** | | | | | | | | | | **4.07** | **905** | **14.06** | **2.24** | **0.057** |

**PUMA File** 5704_WMATA_2_28Apr05 | 2385

**SPC File** 1020

| Mode | Weight Factor | Speed | Load | Power | NOx | CO2 | CO | THC | Wt Power | Wt NOx | Wt CO2 | Wt CO | Wt THC | PM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | percent | rpm | (Nm) | (kw) | (g/hr) | (g/hr) | (g/hr) | (g/hr) | (kw) | (g/hr) | (g/hr) | (g/hr) | (g/hr) | |
| 1 | 35 | 699.5 | 0.56 | 0.04 | 85.77 | 3360 | 40.07 | 15.45 | 0.01 | 30.02 | 1176 | 14.02 | 5.41 | |
| 2 | 6.34 | 887 | 156.21 | 14.51 | 179.21 | 12696 | 193.24 | 29.47 | 0.92 | 11.36 | 805 | 12.25 | 1.87 | |
| 3 | 2.91 | 1057 | 447.84 | 49.57 | 258.51 | 36157 | 184.39 | 26.95 | 1.44 | 7.52 | 1052 | 5.37 | 0.78 | |
| 4 | 3.34 | 1244.1 | 716.03 | 93.29 | 408.52 | 68856 | 238.94 | 39.34 | 3.12 | 13.64 | 2300 | 7.98 | 1.31 | |
| 5 | 8.4 | 2400.3 | 112.55 | 28.29 | 145.76 | 39917 | 166.87 | 136.27 | 2.38 | 12.24 | 3353 | 14.02 | 11.45 | |
| 6 | 10.45 | 2314.9 | 252.71 | 61.26 | 223.48 | 61505 | 142.46 | 118.95 | 6.40 | 23.35 | 6427 | 14.89 | 12.43 | |
| 7 | 10.21 | 2314.9 | 435.43 | 105.56 | 305.12 | 90995 | 1484.9 | 149.64 | 10.78 | 31.15 | 9291 | 151.61 | 15.28 | |
| 8 | 7.34 | 2213 | 638.02 | 147.86 | 567.31 | 111296 | 1094.62 | 113.71 | 10.85 | 41.64 | 8169 | 80.35 | 8.35 | |
| Weighted Power and Weighted Mass Emission Sums →→→→→→→→→ | | | | | | | | | 35.90 | 170.94 | 32573 | 300.48 | 56.88 | |
| **Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→** | | | | | | | | | | **4.76** | **907** | **8.37** | **1.58** | **0.045** |

**PUMA File** 5777_WMATA_4_29Apr05 | 2390

**SPC File** 1022

| Mode | Weight Factor | Speed | Load | Power | NOx | CO2 | CO | THC | Wt Power | Wt NOx | Wt CO2 | Wt CO | Wt THC | PM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | percent | rpm | (Nm) | (kw) | (g/hr) | (g/hr) | (g/hr) | (g/hr) | (kw) | (g/hr) | (g/hr) | (g/hr) | (g/hr) | |
| 1 | 35 | 801.1 | 2.31 | 0.19 | 91.54 | 4255 | 71.67 | 20.27 | 0.07 | 32.04 | 1489 | 25.08 | 7.09 | |
| 2 | 6.34 | 887 | 156.06 | 14.5 | 222.71 | 13120 | 37.44 | 18.25 | 0.92 | 14.12 | 832 | 2.37 | 1.16 | |
| 3 | 2.91 | 1057 | 446.46 | 49.42 | 251.13 | 36193 | 203.77 | 25.01 | 1.44 | 7.31 | 1053 | 5.93 | 0.73 | |
| 4 | 3.34 | 1244.1 | 718.03 | 93.55 | 404.77 | 69441 | 251.7 | 36 | 3.12 | 13.52 | 2319 | 8.41 | 1.20 | |
| 5 | 8.4 | 2399.8 | 108.61 | 27.3 | 141.59 | 39701 | 167.54 | 141.01 | 2.29 | 11.89 | 3335 | 14.07 | 11.84 | |
| 6 | 10.45 | 2315 | 252.38 | 61.18 | 216.67 | 60853 | 144.67 | 122.86 | 6.39 | 22.64 | 6359 | 15.12 | 12.84 | |
| 7 | 10.21 | 2315 | 435.14 | 105.49 | 293.97 | 90806 | 1561.61 | 156.39 | 10.77 | 30.01 | 9271 | 159.44 | 15.97 | |
| 8 | 7.34 | 2213.1 | 638.19 | 147.9 | 551.96 | 111549 | 1120.03 | 116.08 | 10.86 | 40.51 | 8188 | 82.21 | 8.52 | |
| Weighted Power and Weighted Mass Emission Sums →→→→→→→→→ | | | | | | | | | 35.86 | 172.05 | 32847 | 312.64 | 59.35 | |
| **Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→** | | | | | | | | | | **4.80** | **916** | **8.72** | **1.66** | **0.053** |

**Average Weighted Brake Specific Emissions for all 8Mode Tests Above (g/kw-hr) →→→– 4.54 | 910 | 10.38 | 1.83 | 0.052**