Final Technical Report
on

Dimethyl Ether (DME)-Fueled Shuttle Bus Demonstration Project

For the Period
July 1, 1999 – November 30, 2002

by
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ABSTRACT

The objectives of this research and demonstration program are to convert a campus shuttle bus to operation on dimethyl ether, a potential ultra-clean alternative diesel fuel. To accomplish this objective, this project includes laboratory evaluation of a fuel conversion strategy, as well as, field demonstration of the DME-fueled shuttle bus. Since DME is a fuel with no lubricity (i.e., it does not possess the lubricating quality of diesel fuel), conventional fuel delivery and fuel injection systems are not compatible with dimethyl ether. Therefore, to operate a diesel engine on DME one must develop a fuel-tolerant injection system, or find a way to provide the necessary lubricity to the DME. In this project, we have chosen the latter strategy in order to achieve the objective with minimal need to modify the engine. Our strategy is to blend DME with diesel fuel, to obtain the necessary lubricity to protect the fuel injection system and to achieve low emissions. The bulk of our efforts over the past year were focused on the conversion of the campus shuttle bus. This process, started in August 2001, took until April 2002 to complete. The process culminated in an "event" to celebrate the launching of the shuttle bus on DME-diesel operation on April 19, 2002. The design of the system on the shuttle bus was patterned after the system developed in the engine laboratory, but also was subjected to a rigorous failure modes effects analysis (FMEA, referred to by Air Products as a "HAZOP" analysis) with help from Dr. James Hansel of Air Products. The result of this FMEA was the addition of layers of redundancy and over-pressure protection to the system on the shuttle bus. The system became operational in February 2002. Preliminary emissions tests and basic operation of the shuttle bus took place at the Pennsylvania Transportation Institute's test track facility near the University Park airport. After modification and optimization of the system on the bus, operation on the campus shuttle route began in early June 2002. However, the work and challenges continued as it was been difficult to maintain operability of the shuttle bus due to fuel and component difficulties. In late June 2002, the pump head itself developed operational problems (loss of smooth function) leading to excessive stress on the magnetic coupling and excessive current draw to operate. A new pump head was installed on the system to alleviate this problem and the shuttle bus operated successfully on DME blends from 10 – 25 vol% on the shuttle bus loop until September 30, 2002. During the period of operation on the campus loop, the bus was pulled from service, operated at the PTI test track and real-time emissions measurements were obtained using an on-board emissions analyzer from Clean Air Technologies International, Inc. Particulate emissions reductions of 60% and 80% were observed at DME blend ratios of 12 vol.% and 25 vol.%, respectively, as the bus was operated over the Orange County driving cycle. Increases in NOx, CO and HC emissions were observed, however. In summary, the conversion of the shuttle bus was successfully accomplished, particulate emissions reductions were observed, but there were operational challenges in the field. Nonetheless, we were able to demonstrate reliable operation of the shuttle bus on DME-diesel blends.

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EXECUTIVE SUMMARY

The objectives of this research and demonstration program are to convert a campus shuttle bus to operation on dimethyl ether, a potential ultra-clean alternative diesel fuel. To accomplish this objective, this project includes laboratory evaluation of a fuel conversion strategy, as well as, field demonstration of the DME-fueled shuttle bus. Since DME is a fuel with no lubricity (i.e., it does not possess the lubricating quality of diesel fuel), conventional fuel delivery and fuel injection systems are not compatible with dimethyl ether. Therefore, to operate a diesel engine on DME one must develop a fuel-tolerant injection system, or find a way to provide the necessary lubricity to the DME. In this project, we have chosen the latter strategy in order to achieve the objective with minimal need to modify the engine. Our strategy is to blend DME with diesel fuel, to obtain the necessary lubricity to protect the fuel injection system and to achieve low emissions. Sponsorship comes from the National Energy Technology Laboratory (Project Manager Shelby Roger, and Program Manager John Winslow), the Pennsylvania Department of Environmental Protection Alternative Fuel Incentive Grant Program (Program Manager Susan Summers) and Air Products and Chemicals, Inc. (Program Manager Ed Heydorn).

To date, our activities have covered two areas: laboratory investigations and field investigations. The laboratory studies have included work with a Navistar V-8 turbodiesel engine, demonstration of engine operation on DME-diesel blends and instrumentation for evaluating fuel properties. The field studies have involved performance, efficiency and emissions measurements with the Champion Motorcoach "Defender" shuttle bus and conversion of the shuttle bus operation on DME-diesel blends.

Within the Diesel Combustion and Emissions Laboratory in the Penn State Energy Institute, we have installed and equipped a Navistar V-8 direct-injection turbodiesel engine for measurement of gaseous and particulate emissions and examination of the impact of fuel composition on diesel combustion. We have also reconfigured a high-pressure viscometer for studies of the viscosity, bulk modulus (compressibility) and miscibility of blends of diesel fuel, dimethyl ether and lubricity additives. Our results include baseline emissions, performance and combustion measurements on the Navistar engine for operation on a federal low sulfur diesel fuel (300 ppm S). During the course of this project, we constructed an entire engine test facility which ultimately led to tests of DME-diesel blends up to 30 vol.% (25 wt.%) DME in the Navistar engine. The engine results included detailed analysis of cylinder pressure trace data, injection parameters reported by the ECM on the engine and emissions data. The results from the laboratory studies have been summarized in two a Society of Automotive Engineers technical papers, an American Chemical Society preprint and were summarized in detail in the MS Theses of Elana Chapman and Shirish Bhide.

We have also performed viscosity measurements on diesel fuel, DME and blends of DME in diesel. These tests have verified that DME has a much lower viscosity than the diesel fuel and that the viscosity of the blended fuel is also much lower than the diesel base fuel. This has implications for the injection and atomization of the DME/diesel blends. The test results on fuel viscosity were summarized in an ACS Preprint presented at the 2001 ACS National Meeting in Chicago.

The ultimate goal of this project is the conversion of the campus shuttle bus. This process, started in August 2001, took until April 2002 to complete. The process culminated in an "event" to celebrate the launching of the shuttle bus on DME-diesel operation on April 19, 2002. The design of the system on the shuttle bus was patterned after the system developed in the engine laboratory, but also was subjected to a rigorous failure modes effects analysis (FMEA, referred to by Air Products as a "HAZOP" analysis) with help from Dr. James Hansel of Air Products. The result of this FMEA was the addition of layers of redundancy and over-pressure protection to the system on the shuttle bus. The system became operational in February 2002. Preliminary emissions tests and basic operation of the shuttle bus took place at the Pennsylvania Transportation Institute's test track facility near the University Park airport.

After another month's worth of modification and optimization of the system on the bus, operation on the campus shuttle route began in early June 2002. However, the work and challenges have continued as it has been difficult to maintain operability of the shuttle bus due to fuel and component difficulties. The difficulties with the converted fuel system have arisen in two areas: operation of the converted fueling system, which circulates fuel to the engine; and operation of the engine, which has run very rough at times and is emitting a significant amount of "blow by" that indicates the engine may need an overhaul.

The difficulties with the fuel circulation system were primarily with the gear pump which draws DME-diesel fuel blend from the onboard mixture tank. The pump developed operational problems that appeared to either be cavitation (possible if DME vaporized in our fueling system) or loss of magnetic coupling between the pump head and electric motor. The latter turns out to be the main problem, although this magnetic coupling has been replaced on the vehicle once already. In late June 2002, it was determined that the pump head itself developed operational problems (loss of smooth function) leading to excessive stress on the magnetic coupling and excessive current draw to operate. A new pump head was installed on the system to alleviate this problem and the shuttle bus operated successfully on DME blends from 10 – 25 vol% on the shuttle bus loop until September 30, 2002. During the period of operation on the campus loop, the bus was pulled from service, operated at the PTI test track and real-time emissions measurements were obtained using an on-board emissions analyzer from Clean Air Technologies International, Inc. Particulate emissions reductions of 60% and 80% were observed at DME blend ratios of 12 vol.% and 25 vol.%, respectively, as the bus was operated over the Orange County driving cycle. Increases in NOx, CO and HC emissions were observed, however.

In summary, the conversion of the shuttle bus was successfully accomplished, particulate emissions reductions were observed, but there were operational challenges in the field. Nonetheless, we were able to demonstrate reliable operation of the shuttle bus on DME-diesel blends.

EXPERIMENTAL

This project is driven by Air Products' interest in the development of markets for the Liquid Phase Dimethyl Ether process technology, the state's interest in development of transportation fuel usage from Pennsylvania resources (e.g., coal) and the Department of Energy's interest in ultra-clean transportation fuels. In this project we (Penn State Energy Institute and Air Products and Chemicals, Inc.) have determined how to effect the conversion of a shuttle bus equipped with a Navistar DI turbo-diesel engine to operation on Dimethyl Ether (DME). To accomplish this goal, we have been examining the co-firing of the engine on diesel fuel and dimethyl ether, using the diesel fuel as a lubricating agent to protect the fuel pump and fuel injection system from excessive wear. Dimethyl ether has no natural lubricity, making it antagonistic to fuel system components.

The work consists of two parallel efforts. One is the development of a conversion process to operate a diesel engine on dimethyl ether using conventional fuel injection equipment. The other is an evaluation of the performance, emissions and efficiency of a shuttle bus equipped with a diesel engine and operated on dimethyl ether.

Development of the conversion strategy required first the construction of an engine test facility, and then a methodology for fueling the engine on DME. A pressurized fuel delivery system was developed and successfully implemented on the laboratory engine. With the engine and test facility, we have demonstrated that the laboratory engine can be operated effectively on the blended fuel.

The shuttle bus conversion relied on an adaptation of the laboratory conversion strategy for use in the field. While the conversion strategy was under development, the shuttle bus (Champion "Defender" model) that serves as a faculty/staff shuttle on the University Park campus operated for a period of three and one half years on diesel fuel, accumulating roughly 90,000 miles prior to conversion. Performance and efficiency tests were performed after the break-in of the vehicle during operation on diesel fuel, and emissions tests were performed after the conversion to dimethyl ether operation.

To accomplish the operation of the campus shuttle bus on DME-diesel blends, we designed a large scale, dedicated DME fueling station for delivery of DME-diesel blends. The cost of the initial design, however, was well beyond the level of funding available for the fueling station. Instead, we turned to a simpler plan that involved a two-stage fueling process. The person refueling the shuttle bus would use the existing diesel fuel pumps for University service vehicles to fill the bus' main tank with diesel fuel. Then, the driver will back up to an adjacent storage location for the DME. Diesel fuel was then transferred to the DME-diesel mixture tank from the main diesel tank, and finally, DME was added to the DME-diesel mixture tank to complete the refueling of the shuttle bus. Once filled, the mixture tank is pressurized with a blanket of helium gas to keep the DME in the liquid phase and maintain the blend ratio of the two fuels.

The objectives of the laboratory testing have been to determine the compositions of fuel and additive blends that will permit long term operation of the T444E engine on dimethyl ether. We have successfully operated the laboratory engine on blends with up to 30 wt.% DME. Based on these tests, we determined that the optimal blend ratio for the field vehicle is 25 wt.% DME in diesel fuel.

Through collaboration with the Tribology Laboratory in Penn State's Chemical Engineering Department, we have characterized the viscosity, compressibility and miscibility of blends of DME, diesel fuel and the additives under pressures and temperatures relevant to the fuel injection system. These tests have used a high pressure viscometer adapted to these specific experiments. In addition a closely related project with support from NETL, we are constructing an injector durability experiment to determine the time to failure and boundary of the of fuel composition which can lead to injector failure. Also, we have modified an existing pin-on-ring apparatus to investigate the lubricity of DME blends with diesel fuel and lubricity additives.

On the outset of this project, we believed that the most significant technical challenge in this project would be accounting for the lubricating quality of the fuel and additive mixtures. This challenge of working with DME involves two considerations of the mixtures: (1) the lubricating quality of the mixtures; and (2) the phase behavior of the mixtures, given that advanced diesel fuel injection systems use injection pressures that exceed the critical pressure of DME. At higher DME blend ratios, we observed some instability in the laboratory engine, perhaps due to generation of excessive amounts of DME vapor. This aspect of engine operation on DME-diesel blends was confirmed during the field evaluation of the campus shuttle bus. At a shift of sustained load to idling, the engine would idle roughly, surging and sagging in speed, typically when the vehicle was fueled at the higher concentrations of DME, 25 wt.% and on warm days.

However, it became clear during the field work with the shuttle bus, that the greatest challenge was instead getting the supporting components within the pressurized fueling system to perform properly over extended periods of time. System integrity and durability became far more significant challenges than management of the volatility and lubricity of the DME-diesel blends.

The rest of this report consists of a section for each of the major activities (tasks) under the project.

- Laboratory Engine Results
- Viscometer Results
- Fuel Station Construction and Shuttle Bus Conversion

Finally, there are extensive appendices included with this report (in electronic format) that document the technical progress on the project through the preparation of technical papers and theses.

RESULTS AND DISCUSSION
Laboratory Engine Results

The laboratory engine, a Navistar T444E 190hp V-8 Turbodiesel has been operational since October 1999 in our engine test cell. The engine is outfitted with numerous thermocouple sensors, an in-cylinder pressure sensor (in Cylinder #1) and the exhaust system has a number of ports for sampling particulate emissions, gaseous emissions (including total hydrocarbons) and particulate composition (via thermal analysis). The figure below shows a digital photo of the engine in the test cell prior to the fuel system conversion.

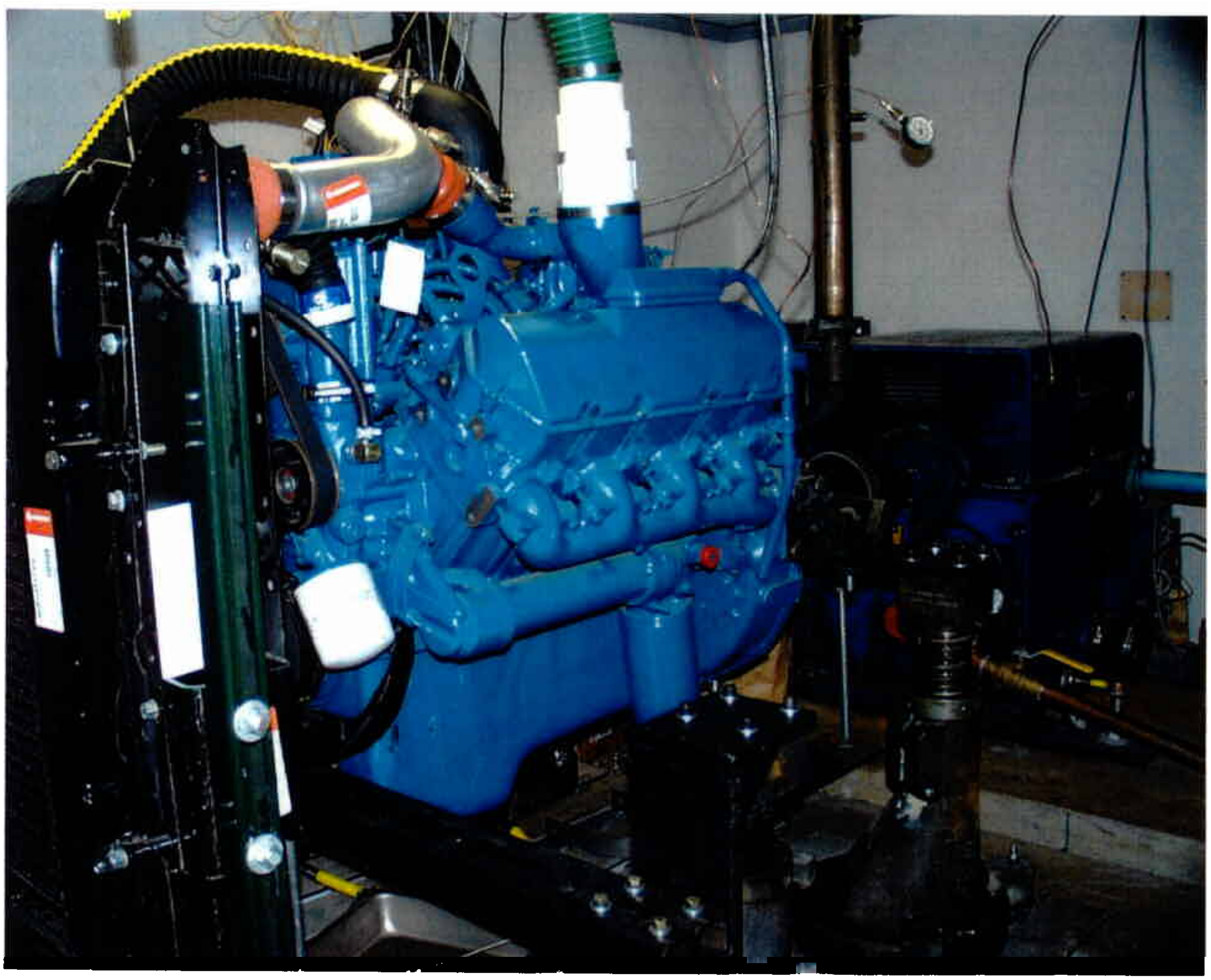

Figure 1. Photo of the Navistar T444E Turbodiesel Engine in the 450 hp Engine Test Cell Prior to Conversion to DME-Diesel Blends

The AVL steady state 8 mode test had been selected to do the emissions comparison studies for different fuel additives and blend ratios of DME to diesel. During previous tests, a comparison of exhaust emissions was made with two different oxygenates, the CETANER™ fuel additive and

Dimethyl ether (DME). These were blended with a federal low sulfur diesel fuel that will also serve as the baseline fuel. The oxygenates were blended such that the oxygen content of the mixture was 2% by mass (reported in SAE Technical Paper NO. 2000-01-2887). More recently, tests were completed at 5 and 10 wt.% oxygen addition by blending DME and diesel fuel, which is equivalent to 15 vol.% (12.5 wt.%) and 30 vol.% (25 wt.%) DME addition, respectively. The Appendix includes a copy of a Society of Automotive Engineers technical paper that was written on the results from the DME-diesel blend studies.

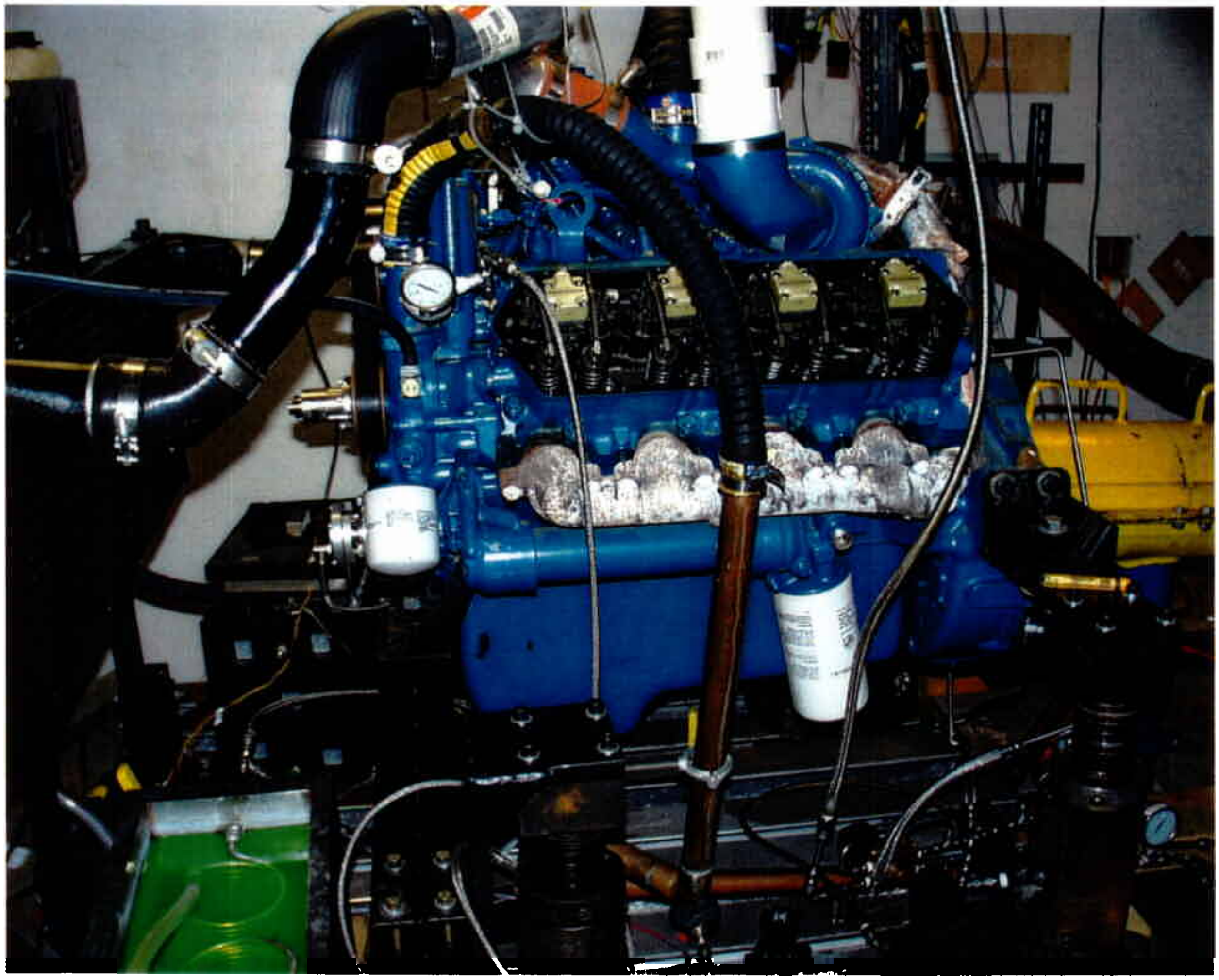

Figure 2. Navistar T444E showing conversion to DME-diesel operation.

Emissions Evaluation- Low DME/Diesel Concentration Tests

Engine tests had been completed with conservative blends of Dimethyl Ether (DME) blended in diesel fuel. The objective of these tests was to determine the effect of the fuel blends on emissions. As with most all oxygenated fuel blends, there was a particulate matter reduction observed as the oxygen concentration was increased, for most all of the 8 modes tested (variations of speed and load). However, the other emissions showed scattered results across the modes. This data was prepared and presented in two papers in 2000 and 2001 [1, 2], which are included with this report in the Appendix.

As the engine load was increased and regardless of engine speed, the particulate emission was lowered, except for mode 7. To further understand the variations in the emissions data, the data from the engine electronics was reviewed. Of specific interest was the actions of the fuel injectors, as shown in Figures 3,4 and 5, since the electronic controls of the engine had not been changed from the production calibration, yet the fuel density was different.

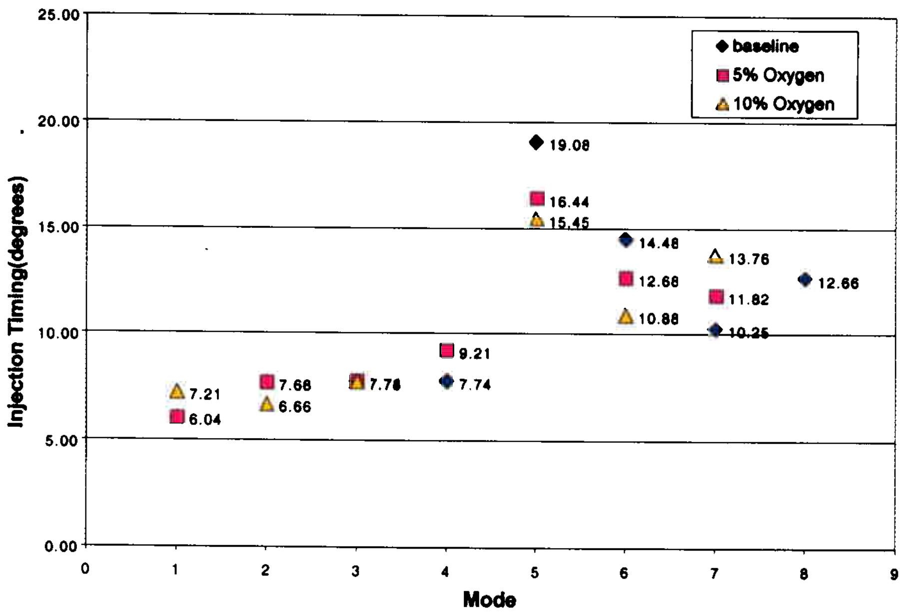

Figure 3. Engine Injection Timing
(* Injection timing is relative to the number of degrees before 0 degrees: TDC (Top Dead Center))

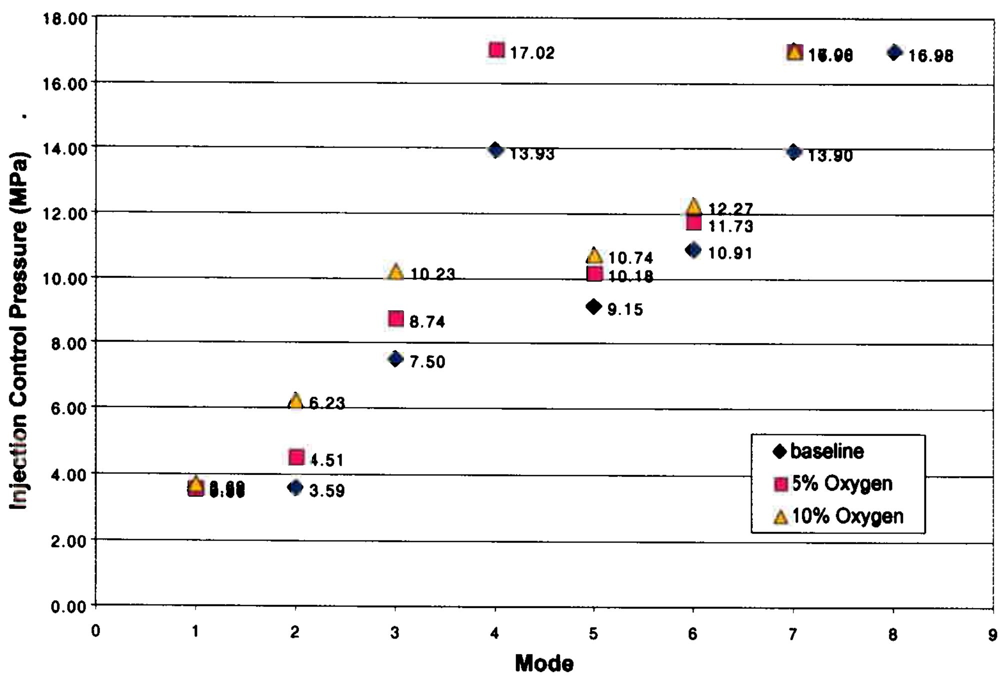

Figure 4. Engine Injection Pressure

The effect seen in Mode 7 may be due to a change in the injection timing. As shown in Figure 3 and Figure 4, the injection timing and injection pressure were changing as commanded by the engine control for changing speed and load. This is true for the low as well as the high engine speeds. The trends follow what would be expected based on the work by Kajitani and coworkers [3]. Their work showed that as the mean effective pressure increases, which correlates with increasing load, for an engine speed of 960 RPM, so does soot emissions based on the Bosch Smoke Number with diesel fuel. In their work, the DME emissions were close to zero. In this work, with increasing content of DME, the soot emissions decreased.

As has been shown in previous work by Liotta and co-workers, this particulate reduction is due to a reduction in the soot portion of the emission, and would result in a percentage increase in the soluble organic faction (SOF) portion [4]. This has also been confirmed more recently by Sidhu and coworkers [5], with DME giving the highest SOF.

As can be seen in Figure 3, the injection timing of the engine was changing so as to increase the amount of fuel to meet the speed and load condition. Mode 3 was the only mode where the injection timing did not change, and shows that the NO_x does increase with DME addition. However, injection pressure was increasing so that the required fuel energy could be injected into the cylinder over the same crank angle timing. This may explain the increase in NO_x.

Because of DME's vapor pressure, as the fuel is injected into the engine, the DME may be acting to atomize the diesel fuel into a finer spray. The blended fuel has a lower density than the diesel fuel, and the compressibility of the fuel blend has also changed. This may be reducing the premixed phase of combustion, causing more of the combustion process to be diffusion-controlled because the fuel is vaporizing and igniting so quickly. Additionally, more fuel by volume is being injected to maintain the same energy density and thus the same speed and load conditions. So, there could be some small increase in NO_x emissions for this reason. In Figure 6, the brake specific energy consumption shows that the same amount of fuel on an energy basis is used for each mode, except for mode 1. Since the fuel is less dense and has higher compressibility, this may be affecting the fuel leaving the injector port and modifying the air entrainment into the fuel jet. Kajitani and coworkers data supports the increase in NO_x emissions [3].

As described before, the engine was commanding more fuel, which caused the fuel injection pressure, as well as, the fuel injection timing to shift. The fuel volume required is also confirmed by the engine control signals, shown in Figure 5. From a fuel consumption standpoint, as DME content increased the volume of fuel being commanded from the engine control increased, but reached the maximum limit. This could be the result of the maximum limit, the fuel injection pressure limit and possibly the injection timing limit, within the engine control program.

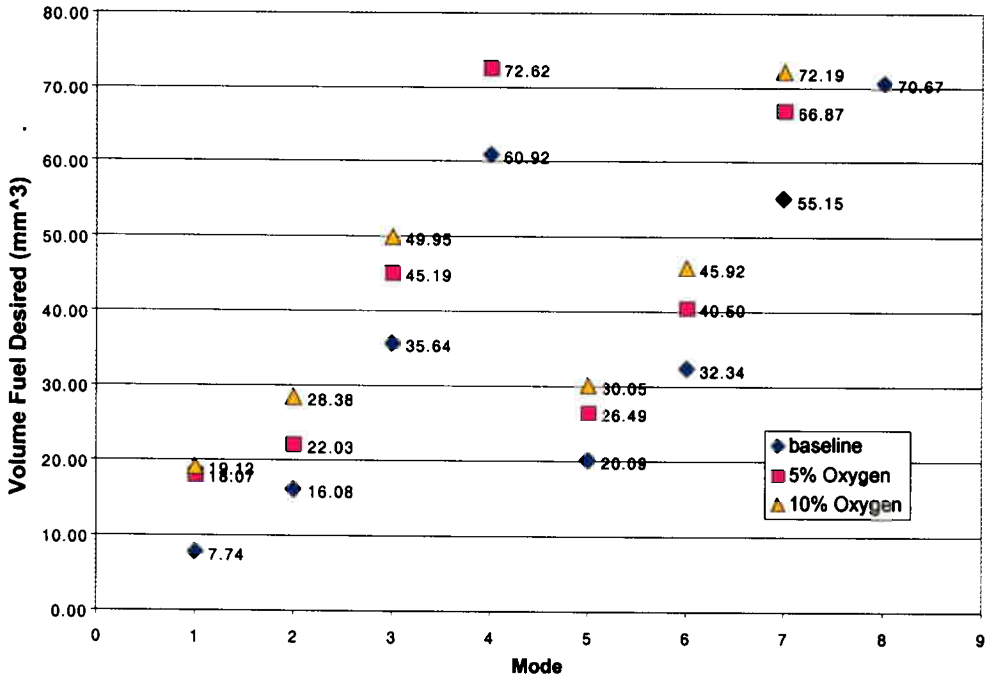

Figure 5. Engine control commanded fuel volume desired

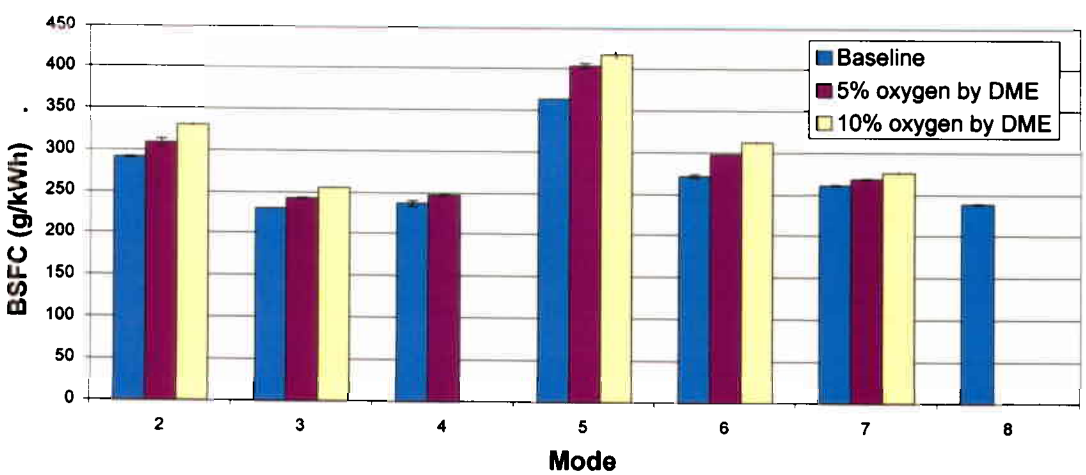

Figure 6. Fuel Consumption

Laboratory Engine Operational Challenges

During the data analysis phase, the engine was operated occasionally to prepare the fuel system for the Bus Project. There were several issues to address, with the major one being the gear swell of the fuel pump.

After discussion with the pump manufacturer (Tuthill) that was chosen, a compromise design was concluded to be the best approach based on the pressure, temperature, and flow rate envelope of the fuel system. Since the swell rate of the gears was not known, and the bus fuel systems would be designed to leave the fuel on the fuel system upon shutdown, it was critical to find a solution. In the engine lab, experience was gained with gear swell from DME/diesel blends. The initial material selection was PPS (Polyphenylene Sulfide, Carbon Fiber reinforced), which was believed to be the best with regard to the materials the manufacturer could offer. So, to accommodate the pump for the situation with the bus, it was decided to increase the tolerance in the gears so that the pump would not shut down after immersion in the fuel over an extended period of time. By doing this, the flow rate from the pump was reduced. It should be noted that the ability of the pressurized fuel system to keep the fuel in a liquid form is a function of pressure, temperature, and flow rate.

Additionally, when preparing the engine to test the modified fuel pump, starting problems were encountered. It was initially thought that this failure was due to possible early wear in the injectors. However, this issue was resolved by enabling the electronics that control the glow plugs, which ensure adequate charge temperature for ignition when the engine is started. Further work determined that the electrical system of the engine is sensitive to battery voltage. After placing a deep charge on the battery, the engine started without any problems. This was a significant step, in that after not operating the engine for several months, engine wear due to the fuel blends had not been the cause of the failure, and did not present concern for the bus project.

Laboratory Engine Evaluation for Bus Project Fuel System Design

Based on the finalized Failure Modes and Effects Analysis (FMEA) of the bus fuel system design, a number of engine tests were proposed to validate the robustness of the system. These tests included the following:

1. Repeatedly start the engine to confirm the starting problem has been corrected.
2. Test Bus Heat exchangers to confirm that the thermal capacity on the steady state lab engine test is greater than what the bus would experience. Use a thermal couple in the system to determine the time it takes for the system to heat up and stabilized.
3. Test flammable gas monitors
4. Perform Injector test with electronic service tool
5. Test Evaporative canisters for system vapor capture on shutdown.

As the bus system development and testing moved forward, decisions were made to go without the Evaporative Canister system, as a vapor test on the bus system proved this was not an issue. Also, engine lab evaluations on the heat exchangers showed that the initial system was undersized and greater exchange capability was need, including the addition of a fan. Finally, as the bus system developed and failures were experienced, the lab engine was used to test out theories of operation, in order to demonstrate a failure mode and provide corrective action for the bus system. It proved to be a valuable tool for this purpose.

At this time, utilizing the service tool to test the injectors was not possible due to several of the external components of the engine electronics not being available. The service tool performs a series of system checks before testing the injectors, and the electronic inputs necessary were not available so that one could step through in the service tool software. This test will be valuable to perform in the future injector study, so some time will be spent in determining the necessary inputs and software safety stops, so that it can be used as a diagnostic approach in the injector studies.

Viscometer Progress Report.

High Pressure Viscometer Setup

To optimize the performance of a fuel injection system for a particular fuel or fuel blend, it is very important to have a good estimate of the physical properties of those fuels. It is equally important to know the change in properties with change in pressure and temperature. An experiment was configured to measure the viscosity of diesel, DME and their blends at various pressures. The high pressure viscometer apparatus used for this work was designed and built at The Pennsylvania State University in 1962-63. This apparatus was modified to allow for charging of a pressurized liquid sample, as is necessary when dealing with compressed liquids. Robert Johnson in his Master's thesis, gives a detailed description of the design and use of the apparatus. The thesis presents an excellent overview and a summary of the work done in the field of high pressure viscometry up to 1962. The equipment very simple in design, is nevertheless extremely accurate in viscosity measurement up to a pressure of 10,000 psig.

Description of High Pressure Viscometer

A schematic diagram of the apparatus setup is shown in Figure 7. The setup consists of a pressure intensifying system, a pressure measurement system, a constant temperature bath and the viscometer pressure vessel.

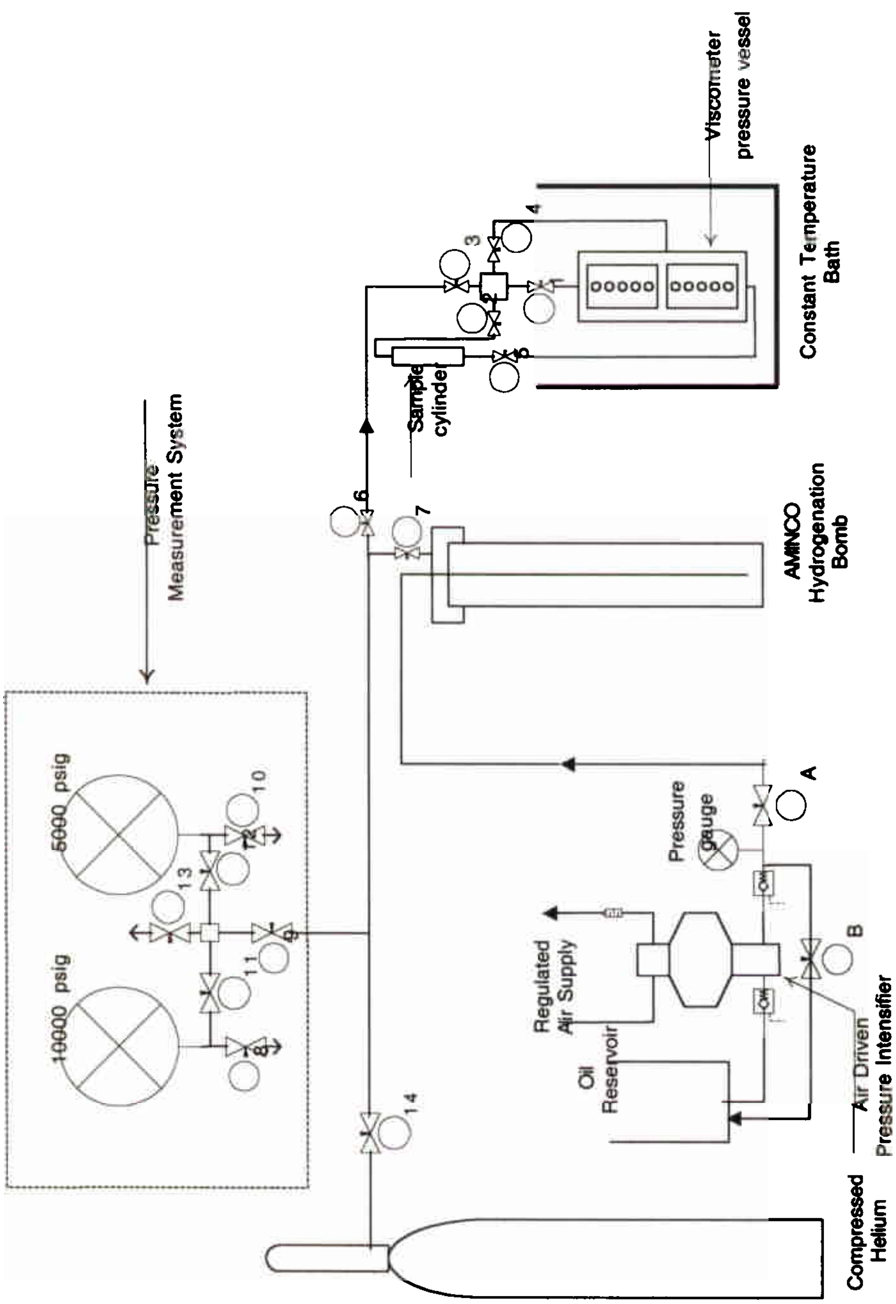

Figure 7. High Pressure Viscometer Setup

Viscosity of Diesel – DME Blends

The high pressure viscometer capillary was calibrated using a CANNON Certified Viscosity Standard N 1.0. Mass was used as the controlled variable in determining the composition of the samples.

Table 1 shows the samples used for viscosity measurement.

Table 1. Samples for Viscosity Measurement

Sample number	Percent of DME by Mass
1	100
2	74
3	50
4	26
5	0

The remaining portion of the sample was made up by Emissions Certification Diesel – Low Sulfur (ECD-LS) from Specified Fuels of Channelview, TX. Figure 8 shows the effect of ambient pressure on the viscosity of the various liquid samples. The kinematic viscosity is plotted on a logarithmic scale. R.H. Johnson notes that a plot of the logarithm of the kinematic viscosity versus the pressure results in a straight line. The slope of this line can be used to extrapolate to higher pressures with a fair amount of accuracy.

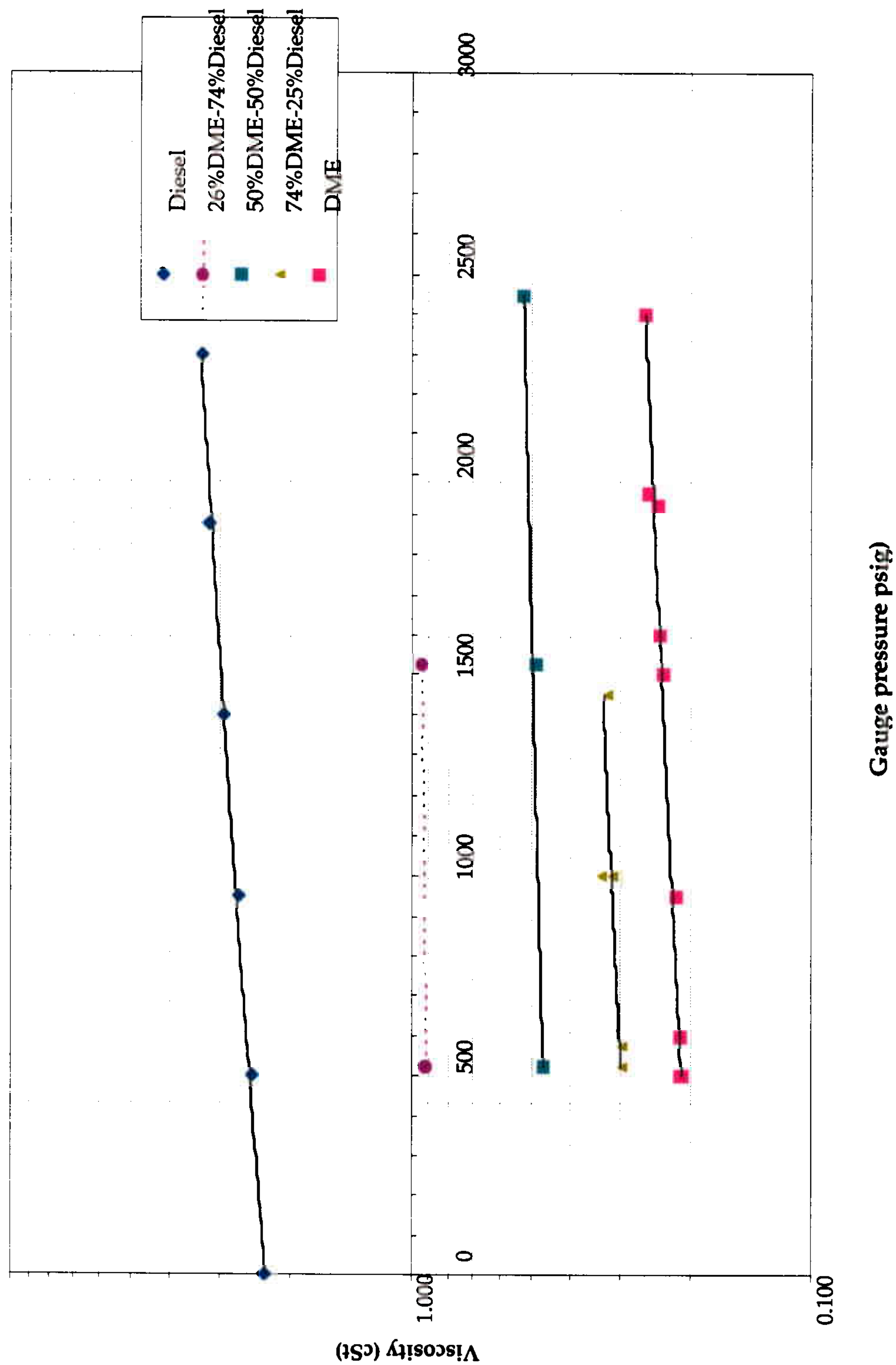

Figure 8. Pressure-Viscosity Relationship for Diesel-DME Samples @ 100 F

The line representing the 49 State Reference Diesel fuel starts from ambient pressure. For the remaining samples with DME as a constituent, the starting point was 500 psig to ensure that the samples remain in a liquid state. The pressure range, in which the viscosity measurements are made, is typical of the low pressure circuit of a diesel engine. Previous studies, done with pure DME as the fuel, state that lower injection pressures can be used for DME as the condition in the cylinder just before the firing TDC allows a very rapid vaporization of DME.

Another use of the viscosity versus pressure relations for the various blends is to choose or design a fuel injection system for the optimized blend ratio. There are two ways in which the fuel system can be designed for an engine running on a Diesel-DME blend. The first one is to examine the capability of an existing fuel systems. The deciding factor in this case will be the minimum viscosity than an existing fuel injection system can handle. The other way would be to optimize a blend ratio for a particular engine considering the exhaust emissions benefits and the energy density tradeoffs, and to use the viscosity data of this particular blend to design a fuel injection system.

Figure 9 shows the response of the kinematic viscosity to the ratio of DME in the blend. This graph shows the effect of pressure on the viscosity of a particular blend. This data was used to select the target concentration for operation of the campus shuttle bus on DME-diesel fuel blends. At 25 wt.% DME addition, the viscosity of the blend is already below the ASTM diesel fuel specification. So, 25 wt.% is the maximum DME content on which the engine should operate.

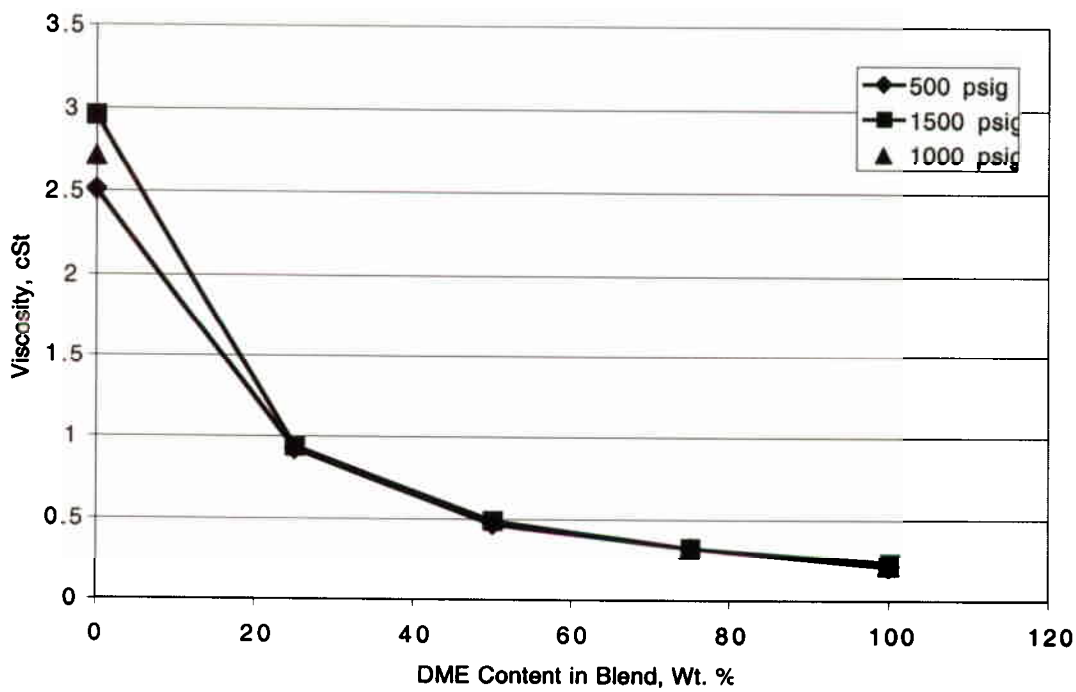

Figure 9. Viscosity – DME Content Relationship at Different Pressures @100 F

Fuel Station Construction And Bus Conversion

Fuel Station Construction

Initially an in depth research and design project was undertaken for a large-scale permanent DME fueling station. The fueling station consisted of two DME storage tanks, one diesel tank, and one tank for the mixed fuel. The station was designed to utilize two transfer pumps: the DME/mixed fuel pump to perform at 10 gallons per minute (GPM) and the diesel transfer pump to perform at 100GPM. Extreme attention was given to the material of the inner seals/O-rings in the DME/mixed transfer pump. The system was designed to utilized helium as the gas to provide the necessary over pressure in the DME/mixed tanks.

The final and much less expensive design of the fueling station required only that we make the refueling process more elaborate. By switching to a two step process, we eliminated the need to have a dedicated fueling station. Instead, refueling relies on the existing diesel fuel pumps for University service vehicles to fill the bus' main tank with diesel fuel. Then, the driver backs up to an adjacent storage location for the DME tank to transfer diesel fuel to the mixture tank containing DME and diesel fuel. The final step is to add the DME to the mixture tank and provide the helium over-pressure to keep the DME in the liquid phase. Figure 10 shows a schematic diagram of the refueling site.

In conjunction with the construction of the fueling station, a "Preparedness, Prevention and Contingency" (PPC) Plan was developed and executed in collaboration with Penn State's office of Environmental Health and Safety.

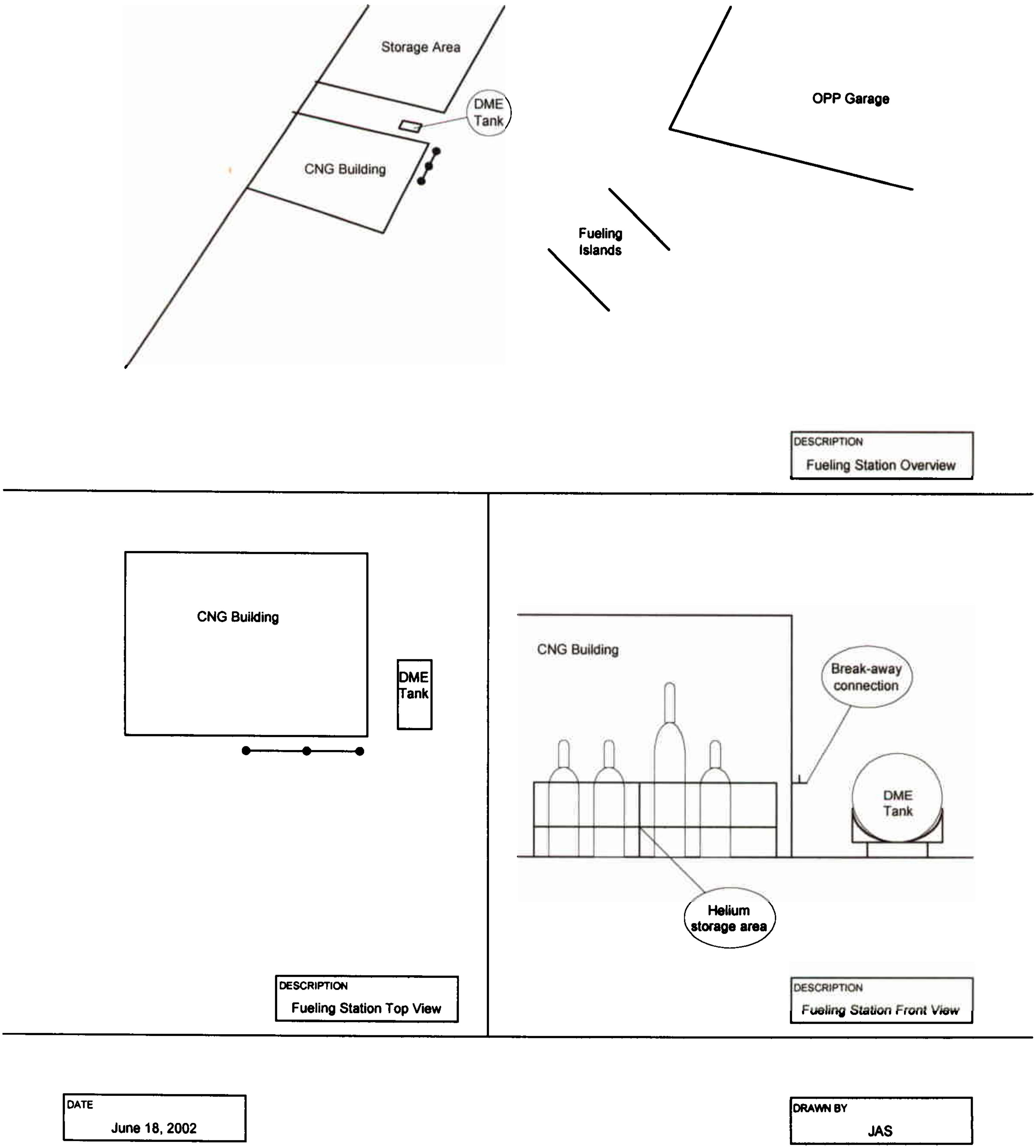

Figure 10. Schematic diagram of DME fueling station

Shuttle Bus Conversion

For the past two years a fleet vehicle on the campus of The Pennsylvania State University has been undergoing a conversion process to run on an alternative fuel mixture. This fuel, a mixture of diesel fuel and dimethyl ether, requires the use of a pressurized fuel tank and fueling system. The initial design of this system was completed in the laboratories of The Energy Institute at Penn State on an identical engine in an engine test cell. This design was then used as the basis for the system to be implemented on the fleet vehicle. The system on the fleet vehicle started with a schematic of the laboratory setup and evolved into the present day onboard system through a complicated development process which is outlined below.

Phase 1:

This phase starts with the initial system design from the laboratory setup and adapts the design to the necessary operational changes required for use on a fleet vehicle. These issues are mainly limited to fueling procedure and consideration of the interaction between the driver and the fueling system. The system must be designed so that the fueling procedure after the conversion process is relatively easy and efficient.

Phase 2:

This phase starts after a functional design has been achieved. It includes environmental considerations, material compatibility issues, and public safety issues. The conclusion of this phase is the completion of a detailed HAZOP analysis on the final system design layout and determination of any necessary changes to the design before construction begins.

This phase increased the complexity of the design by adding numerous fail safe components such as bypass valves, emergency shutoff valves, pressure relief valves, fill stop valves, pressure gauges, and check valves. In addition these changes and considerations also led to the development of a complicated electrical system to monitor pressure, temperature and fuel level.

Phase 3:

This phase involved individual component selection, sizing, pricing and purchasing. Due to availability issues and material compatibility issues this phase took the better part of 6 months to complete.

Phase 4:

This phase consisted of the actual system construction on the bus. The system was constructed on the vehicle in two blocks:

> Block 1: All components under the bus and in the passenger compartment are installed. No changes were made to the existing fueling system or engine compartment. This allowed the bus to be operated during times of high demand for fleet vehicles.
>
> Block 2: The bus is removed from service and the factory fueling system was disconnected and the new fueling system connection was made.

This phase also included constant re-evaluation of design changes as needed.

Phase 5:

This phase is an actual safety inspection of the completed system on the bus. The inspection was performed by both outside and inside personnel. This phase also served to check the status of open line items in the Hazop analysis and sign off on those items if they were now a non-issue due to design changes or there were completed.

Phase 6:

This phase is the debugging process and functionality test for the system. It is divided into two sections which are in turn each divided into two blocks.

Section 1: This section involves running the bus on diesel fuel while utilizing the new fueling system. This test is separated into two blocks:

Block 1: The bus is driven at the Pennsylvania Transportation Institute test track facility located in State College Pennsylvania for a distance of no less than 50 miles. This serves to evaluate the structural integrity of the system and its functionality.

Block 2: The bus is operated on the Penn State campus while under supervision from Energy Institute staff. The purpose of which is to orient the fleet drivers and passengers to the on-board changes. This block also serves to evaluate the systems performance in the buses normal environment.

The completion of this section is a leak check of the system by both a visual and physical inspection.

Section 2: This section is similar in structure to section 1 with the addition of the DiMethyl ether into the system. Again the section is separated into two blocks:

Block 1: The bus is driven at the Pennsylvania Transportation Institute test track facility located in State College Pennsylvania for a distance of no less than 50 miles. This serves to evaluate the structural integrity of the system and its functionality.

Block 2: The bus is operated on the Penn State campus while under supervision from Energy Institute staff. The purpose of which is to orient the fleet drivers and passengers to the on-board changes. This block also serves to evaluate the systems performance in the buses normal environment.

The completion of this section and this phase is a final leak check of the system by both a visual and physical inspection.

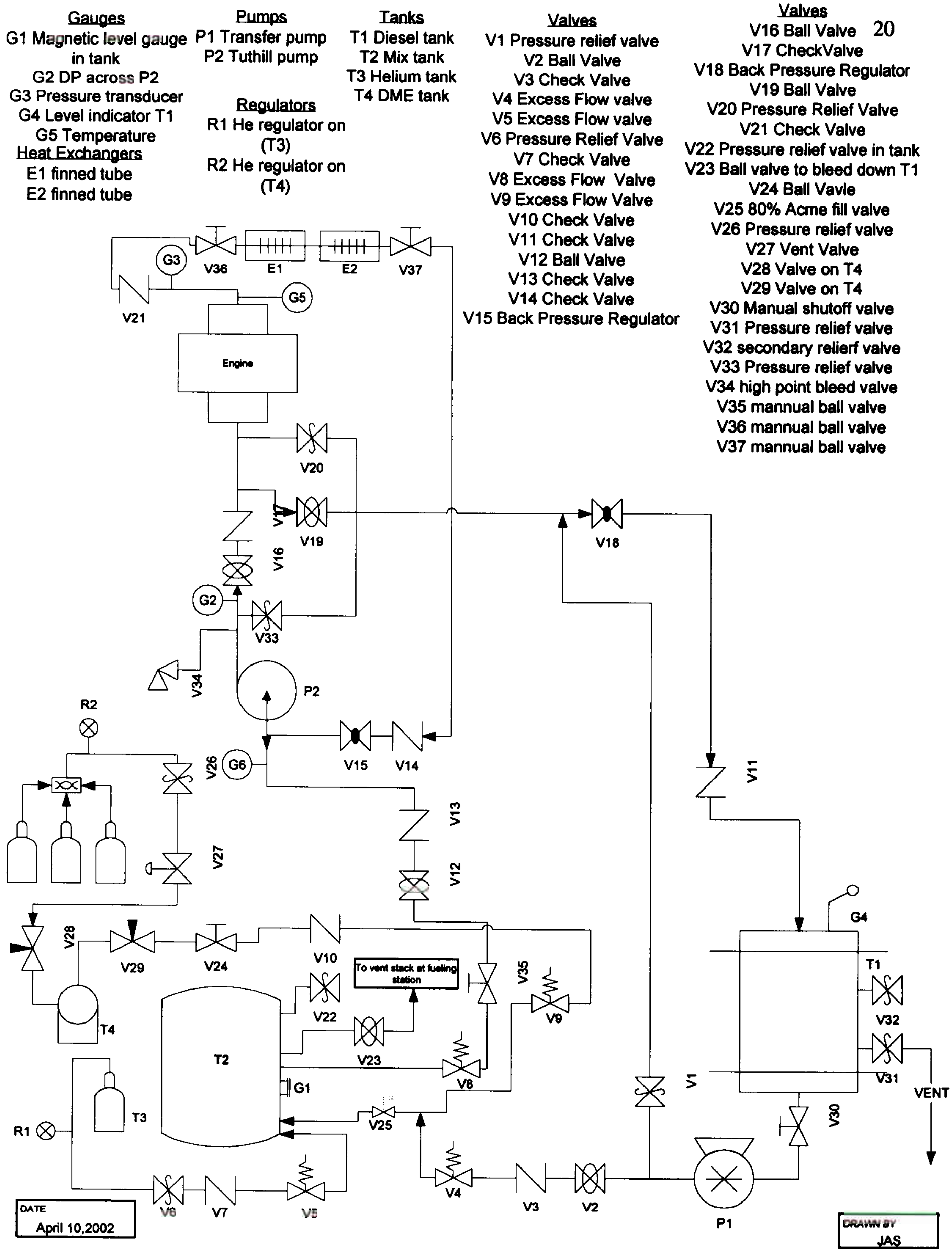

Figure 11. Schematic diagram of DME-diesel fueling system on the shuttle bus

Figures 12 and 13 show digital photos of the shuttle bus after the conversion. These pictures were taken at the event hosted on April 19, 2002 to celebrate the launch of the bus on DME-diesel blends.

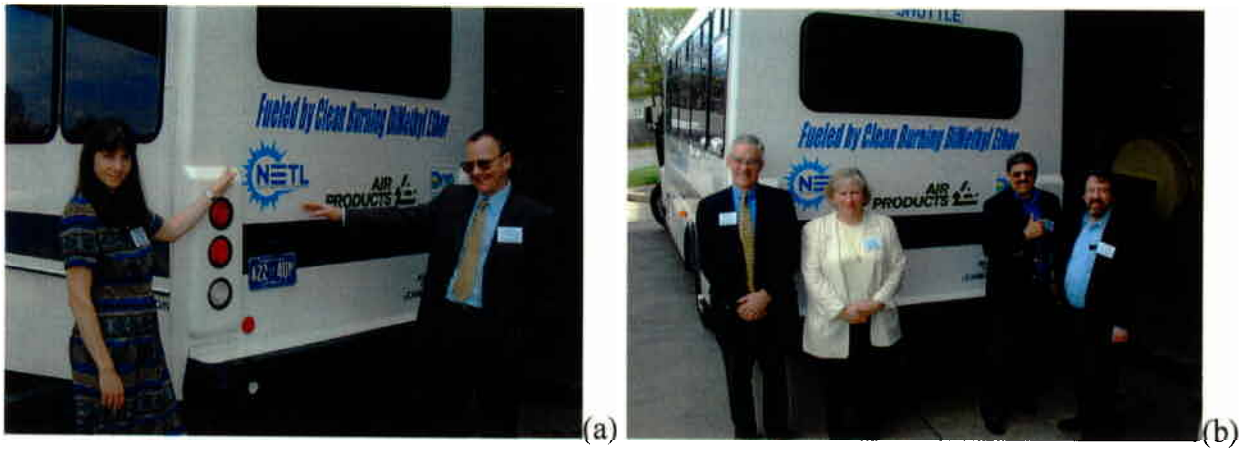

Figure 12. **(a) Jenny Tennant and John Winslow of NETL and (b) Jim Sorensen, Jo Ann Franks, Bob Miller and Barry Halper of Air Products and Chemicals, Inc.**

Figure 13. **DME-Diesel Fueled Campus Shuttle Bus pulling away during its maiden voyage at the event to celebrate the launch of the bus, April 19, 2002 held at the Penn State Energy Institute.**

Finalization of the Converted Fueling System

The standard configuration of the T444E engine is for fuel to enter from the backside of the cylinder head (side closest to the firewall) and remain in the fuel rail until needed by the injectors. This configuration, referred to as a "dead heading," causes the fuel to be heated to engine coolant temperatures. When the engine is fueled on diesel fuel this is not a problem. However, when running on a blend of DME and diesel fuel, this heat soak becomes an issue. To combat the heating of the fuel in the rail, the fuel flow path is changed from a "dead heading" arrangement to a circulation loop. Fuel enters the engine at the same place as in the original configuration and exits at the front of the engine. The fuel from each side of the engine is then combined and routed through four transmission oil coolers (referred to as "fuel coolers") that are mounted just in front of the factory radiator and charge air cooler. This configuration allows the fuel to be cooled and fresh makeup fuel added to the loop before the mixture is re-circulated to the engine. Figure 14 shows a photograph of the final configuration of the fuel handling system installed under the hood of the shuttle bus.

Figure 14. **Photograph of the fuel handling system on the converted shuttle bus**

Test Firing

Once construction of the fuel handling system was complete, the vehicle was test fired on diesel fuel. This allowed for a full operational check of the new system and a fully pressurized leak check. The vehicle was then operated at the Pennsylvania Transportation Institute Test Track facility to verify vehicle performance, operation of the vehicle with the converted fueling system and refueling procedures. The vehicle was fueled on a conservative mixture of 10 vol.% DME in diesel fuel for initial testing after operation problems had been addressed.

Operational Issues

With the complexity of the design, several operational issues became evident once construction was completed. These problems involved formation of two-phase flow in the fuel handling system that caused rough engine operation and re-fueling difficulties.

Circulation Pump

A magnetically coupled gear pump is used to circulate fuel through the cylinder heads through fuel coolers and back to the engine. Since DME is a vapor at room temperature and pressure, the fuel must be kept pressurized to avoid formation of two-phase flow within the system. When the fuel is exposed to engine temperatures, the amount of pressure needed to keep the DME in the liquid phase increases. The vapor pressure of DME as a function of temperature is shown in Figure 15 for reference, provided by Dupont Technical Bulletin for Dymel A [6]. Since the system pressure is set, the fuel temperature must be lowered via heat exchange through the fuel coolers. Thus, if for some reason the circulation pump does not work, fuel is not moved through the head to provide sufficient cooling and the resulting two-phase flow causes rough engine operation.

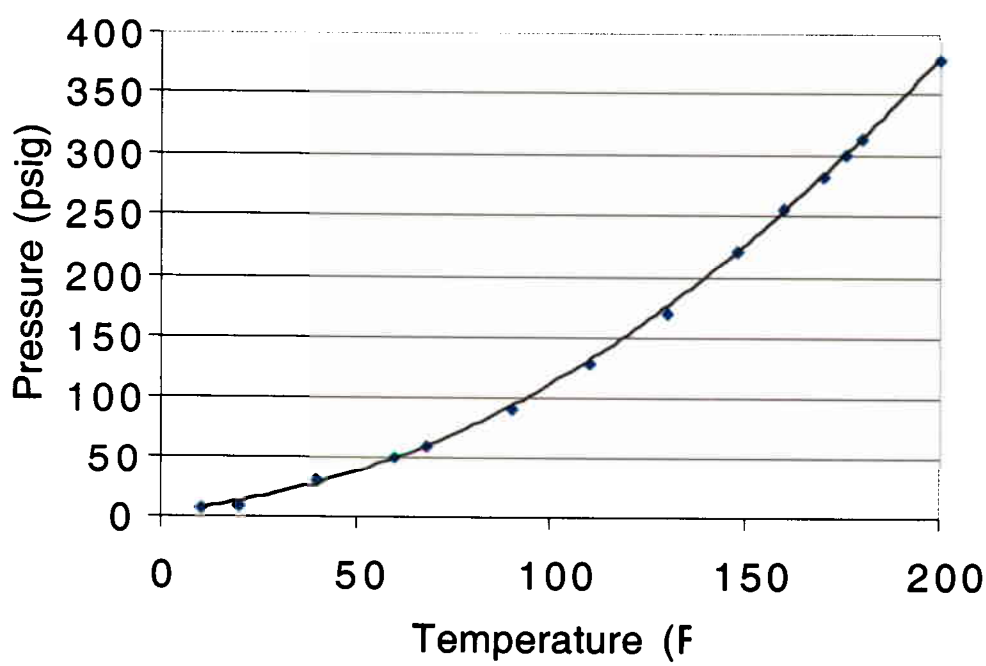

Figure 15. Vapor pressure of DME as a function of temperature [6].

Several scenarios for pump failure were encountered. The pump, which runs off 110 AC power provided by a DC-to-AC inverter, was demanding increasing amounts of power due to: inadequate power supply, inadequate flow of fluid through the system due to blockage, jamming of the gears due to debris, thermal shutoff, and swelling of the gears.

Initially, after construction was complete, the bus was fueled on diesel fuel. During this time no problems with the pump were noticed. However, after long periods of operation, the engine ran roughly and the amount of blow-by increased. When the bus was fueled on DME, the current draw by the electric motor that drives the circulation pump gradually increased over time. The current demand by the pump motor would increase to the maximum rated current for the motor and trip an internal protection circuit in the motor. Hence, the pump would shut off.

The manufacturer was contacted and a larger motor and a motor adapter were purchased and installed. After installation the operation of the pump seemed to become worse and the motor and motor adapter were removed. It was found that the magnetic coupler from the motor shaft to the cap of the pump was destroyed, as can be seen in Figure 16. The pump, motor mate, and coupler were taken to the attention of the regional sales representative who replaced the destroyed coupler and correctly installed a new one. The pump was then reincorporated into the system.

Figure 16. Damaged magnetic coupling from Tuthill gear pump.

With the motor now working correctly, it became evident that a larger power source was required. Since the pump runs on 110 AC but only 12V DC is available on the vehicle an inverter is used. To obtain the size inverter needed a recreational vehicle dealer was contacted. Once the inverter was in place the pump performed flawlessly on diesel fuel for 8 days. When the vehicle was switched to DME-diesel blends, problems again became evident.

A flow meter was installed to determine if the pump was getting adequate fluid or if it was running dry. The meter was installed in the system with as little changes as necessary to ensure a true reading. The flow was found to be in the acceptable range for the motor rating. This ruled out insufficient flow due to blockage in the system. It was postulated that the flow restriction could be on the outlet side of the pump so the filter element was examined.

The filter was found to have disintegrated at the top and bottom of the element where rubber caps were used in the manufacturing. A new filter element with a completely metal housing and a more resilient rubber was chosen and installed. The pump was then removed and the gears checked for any debris that could be preventing their rotation. Very little material was found in the gears and the pump was reassembled and reinstalled.

By the manufacturer's suggestion, a surface temperature thermal coupler was installed on the skin of the pump. It was found that there was inadequate airflow to the motor of the pump so a 12V DC accessory fan was installed to direct air toward the pump. After the installation of the fan, the skin temperature was found to be in the acceptable range, thus ruling out thermal shutoff. With all of these test and modifications, problems were still evident after fueling with DME.

It was thus apparent that gear swell due to prolonged exposure to DME was the source of the problem. The manufacturer was again contacted and a new pump was obtained. Pump shutoff and rough engine operation ceased to be a problem from this point forward.

Fuel Level Gauge

A float gauge inside the tank monitors the level of fuel in the mix tank. The signal is then sent to two individual readouts. One readout is mounted above the driver's seat and the other is attached to a five-pin connector on the side of the bus during fueling.

Vehicle Emissions Testing

Emission testing is done by use of on board analysis equipment owned and operated by Clean Air Inc. The equipment consists of two units, which are approx. 24 inches wide by 22 inches deep, and several laptop computers that provide interface and control ability. The equipment measures CO, CO_2, NO_x, particulate matter, as a function of vehicle speed and load. Fuel consumption is calculated from the CO and CO2 measurements.

Driving Cycles

For the purpose of ensuring and verifying repeatability, a specific testing procedure was adhered to for all testing runs. All testing was performed at The Pennsylvania State Transportation Institute Test Track facility on a one-mile oval track. Four different driving cycles were used for the testing: P20, P40, Orange County, and Manhattan Cycles.

A P20 consists of starting at a specific point on the track and accelerating to 20 mph. The vehicle is held at 20 mph until the first stopping point is reached. The vehicle is then brought to a stop for seven seconds and the driver then accelerates back to 20 mph. There are 8 stops performed in one loop. A complete P20 consists of 2 loops.

A P40 consists of starting again at a specific point on the track and accelerating to 40 mph. The vehicle's speed is then held at 40 mph until the first stopping point is reached. Then vehicle is then brought to a stop for seven seconds and the driver accelerates back to 40 mph. The first stop is at half-track the second is at the original starting point. A complete P40 consists of 2 loops.

An Orange County cycle is a reproduction of a typical bus cycle in Orange County California. The cycle is displayed on a laptop computer running Driver's Aid software® provided by Clean Air Technologies International, Inc. The software also displays the vehicle's speed and the driver matches the speed trace to the prescribed cycle being displayed. The Orange County cycle is broken into two parts to minimize data file length and can be seen in Figures 17 and 18. A complete Orange County set consists of four complete cycles.

A Manhattan cycle is a reproduction of a typical bus cycle in Manhattan, New York. Again the cycle is displayed by the Driver's Aid ® software and the driver matches the vehicle speed trace to the prescribed cycle. A complete Manhattan set consists of four cycles. The Manhattan cycle is shown in Figure 19.

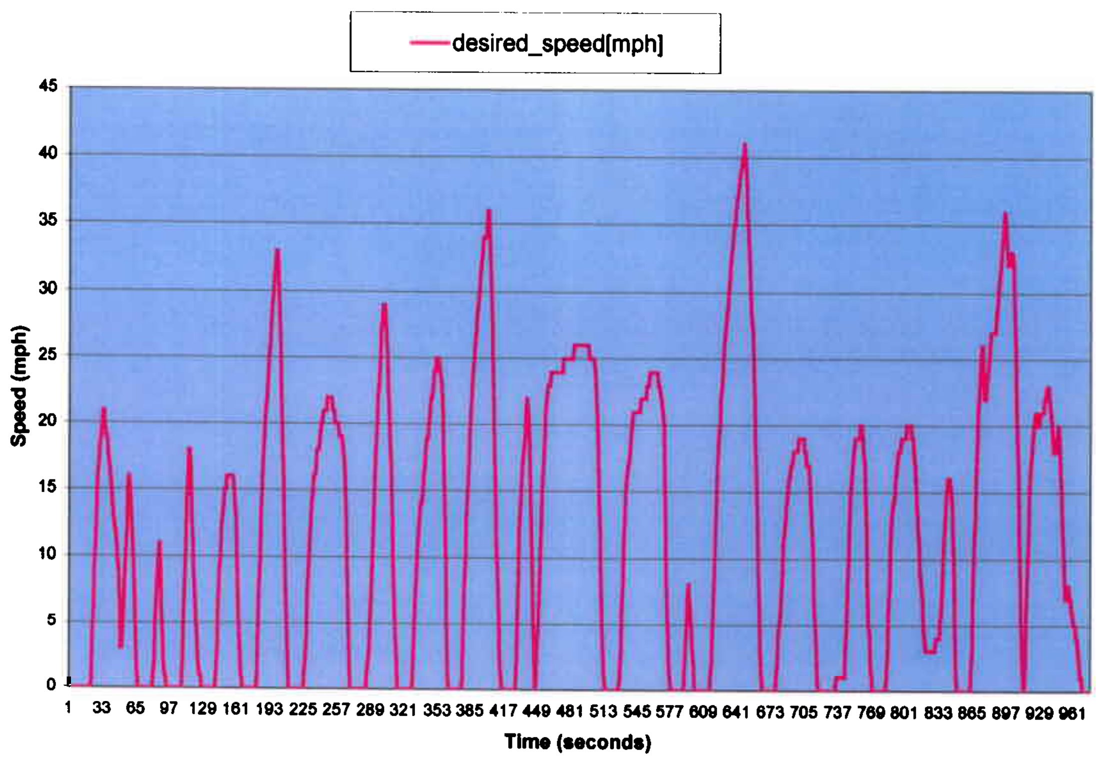

Figure 17. Part One of the Orange County Cycle – Driving Cycle to Represent Transit Bus Operation in Orange County, CA.

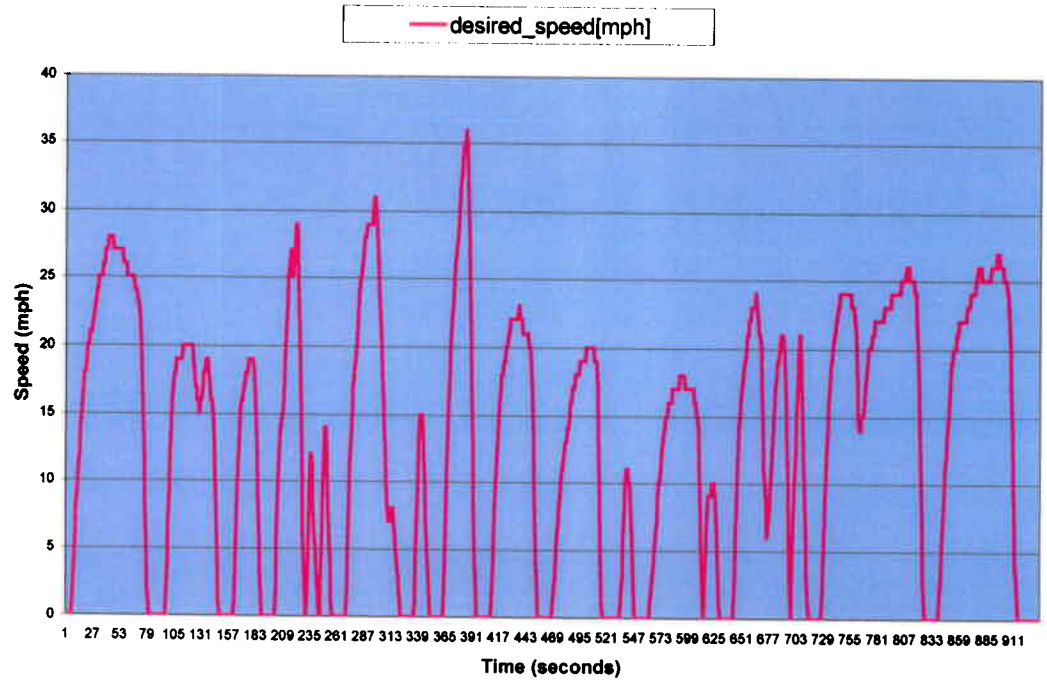

Figure 18. Part Two of the Orange County Cycle.

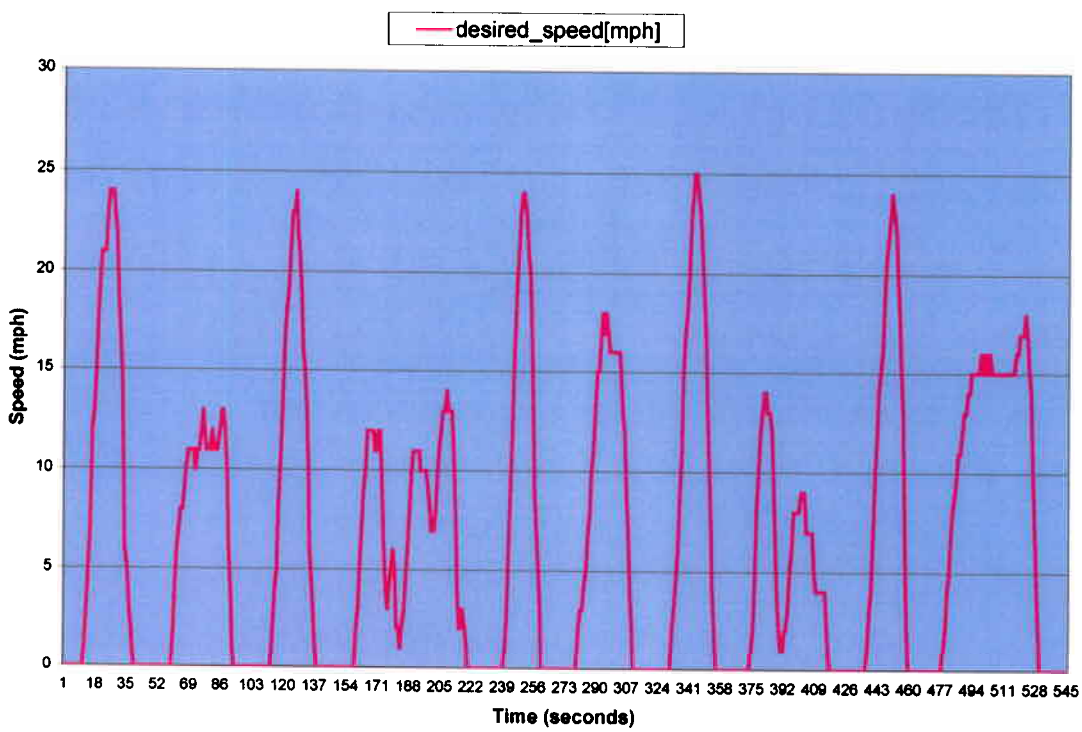

Figure 19. Manhattan Cycle – Driving Cycle to Represent Transit Bus Operation in Manhattan, NY.

Vehicle Testing Procedures

Since the Driver's Aid® software display is difficult to see during the day the Orange County and Manhattan cycles are run at night and the P20 and P40 cycles are run during the day.

A typical day of testing begins with warming up the equipment. This process takes about one hour to complete during which the vehicle is at idle. At the completion of this time period, several test laps are made to check the equipment status. If redundant instruments indicate conflicting measurements the laps are aborted and the equipment checked. Once consistent results are obtained, actual testing begins.

Using the onboard equipment as a live monitoring system, three laps at 30 mph are made to burn off particulates that may have accumulated during the warm-up time. If particulate levels continue to trend downward in the last lap, additional laps are done until stable readings are seen.

At the completion of these "burn off" laps, the vehicle is brought to a stop at the P20 starting point. A period of 90 seconds is allowed to transpire allowing for the equipment to be reset. A complete P20 is then run fallowed by a complete P40, this pattern is then continued alternating back and forthwith 90 seconds between each complete set.

An identical pattern is fallowed for the Orange County and Manhattan cycles. After equipment warm up "burn off" laps are run pausing 90 seconds then beginning the desired cycle. The testing pattern consists of running blocks of Manhattan cycles before switching to Orange County cycles.

Vehicle Testing Results

Testing was performed for 3 different fuel mixtures. The first test served as a baseline run and the vehicle was fueled on pure diesel. The second test was a fuel mixture of 14% by volume DME and diesel; the third test was 25% by volume DME and diesel. While emissions data were monitored for the P20, P40, Orange County and Manhattan test cycles, only data from the Manhattan cycle is presented here.

Total particulate results for all three-fuel compositions for the Manhattan cycle can be seen in Figure 20. As is expected with the addition of an oxygenate as the amount of DME in the fuel mixture increases the measured particulate level drops. For 14 vol.% DME, the PM emissions drop by 60%. For 25 vol.% DME, the PM emissions drop by 80%.

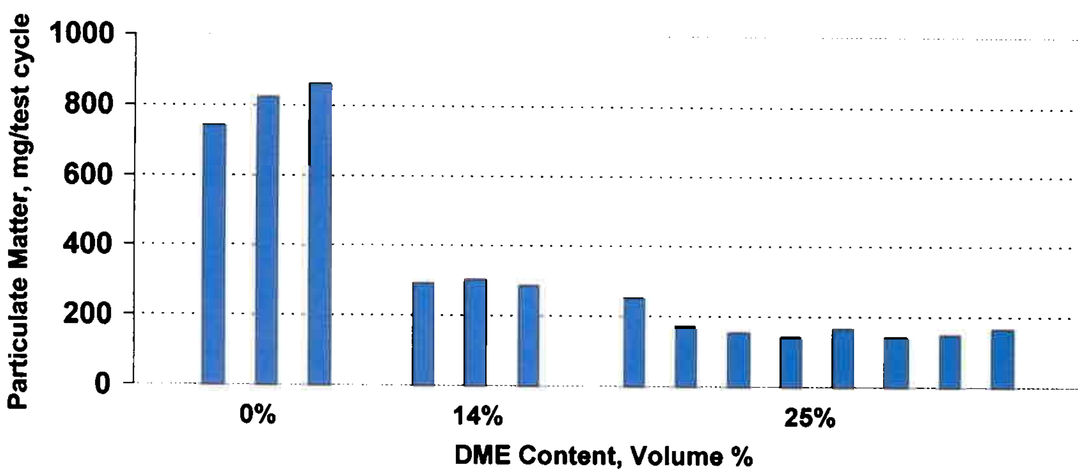

Figure 20. Particulate Matter Emissions During the Manhattan Cycle (cumulative mass emissions per test cycle) for 0, 14 and 25 vol.% DME in Diesel Fuel.

Similar results to those seen by Chapman et al. [1] were seen for hydrocarbons, NO_x, and CO. For a Manhattan cycle, the emissions of hydrocarbons, NO_x, and CO are shown in Figures 21,22, and 23, respectively.

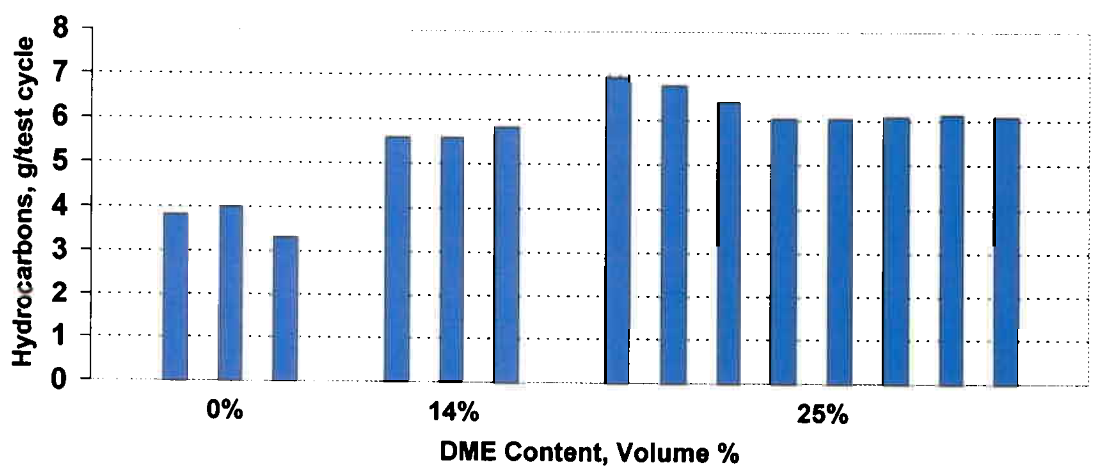

Figure 21. Hydrocarbon Emissions During the Manhattan Cycle (cumulative mass emissions per test cycle) for 0, 14 and 25 vol.% DME in Diesel Fuel.

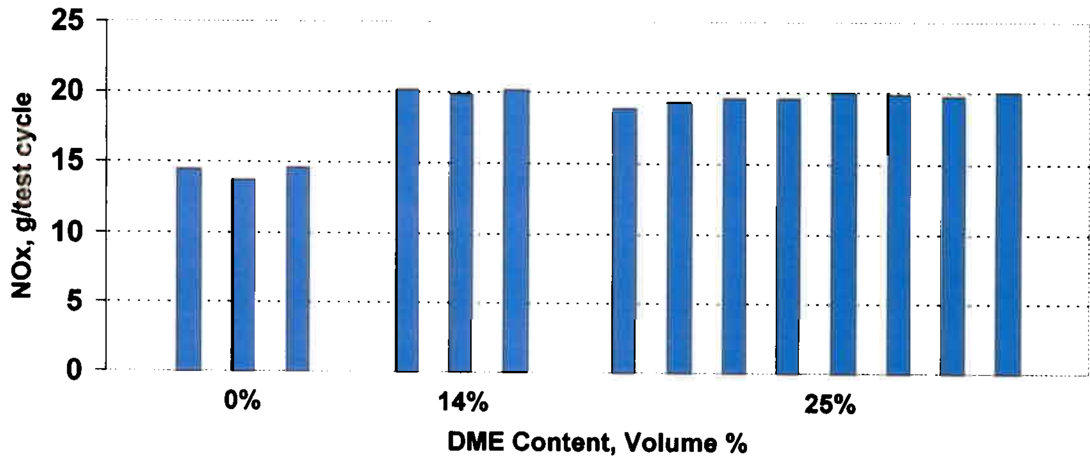

Figure 22. **NOx Emissions During the Manhattan Cycle (cumulative mass emissions per test cycle) for 0, 14 and 25 vol.% DME in Diesel Fuel.**

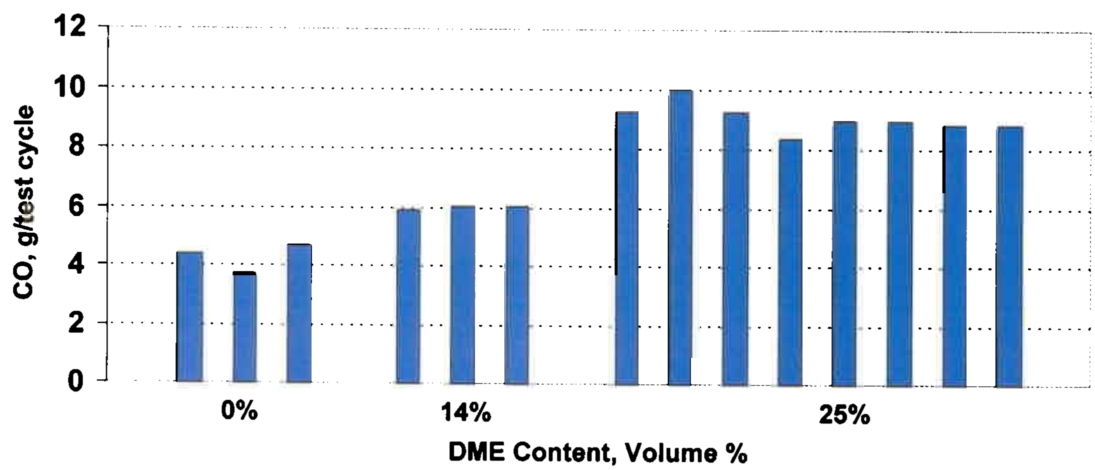

Figure 23. **Carbon Monoxide Emissions During the Manhattan Cycle (cumulative mass emissions per test cycle) for 0, 14 and 25 vol.% DME in Diesel Fuel.**

While the emissions of particulate were substantially reduced, emissions of hydrocarbons, NOx, and CO were significantly increased with DME addition. While these trends were also observed in the laboratory engine, they point to a need to optimize the injection characteristics of the fuel blend and to the need to add an oxidation catalyst to a vehicle fueled in this manner. A similar observation was made in the Volvo bus demonstration, that addition of an oxidation catalyst to a DME-fueled vehicle provided very low emissions [7].

Technical Issues With The Utilization Of Dme As A Fuel

Much of the early work with DME utilization has been done at the AVL labs in Graz, Austria. The testing showed that DME reduces particulate emissions to zero, and also showed that the typical diesel fuel injection system does not tolerate DME [8]. The present work shows that with DME-diesel blends, substantial particulate emissions reduction can be obtained while preserving the integrity of the fuel injection system. Figure 24 shows a picture of the DME-Fueled Shuttle bus in operation at Penn State.

Figure 13. DME-Fueled Shuttle Bus Operating on the Faculty/Staff Loop at the University Park campus of the Pennsylvania State University, August 2002.

Overall, this demonstration project has shown that a vehicle can be successfully operated on DME, but at restricted DME blend levels below 25 wt.% (30 vol.%). There are remaining concerns and challenges, particularly because of the low viscosity of DME. Below is a combined list of concerns not only from the present work, but also from other groups who are now working through the fuel property, design and technology issues for utilization of DME:

- DME was leaking past clearances on the injectors and seals. This caused the need for the camshaft housing and crankcase of the engine to be vented [8].
- At high vapor pressure, the DME was cavitating, which caused difficulties in maintaining stable fuel injection [8].
- While DME is more compressible than diesel fuel, it was found that the compressibility changed with temperature and pressure. Therefore, this made it difficult to inject the

maximum fuel quantity at high temperatures and during full load operation using traditional diesel equipment [8].

- DME chemically attacked some seals [8].
- Not much effort has been put towards understanding the environmental impacts of the compound itself or the emissions from the fuel combustion, as compared to other fuels [8].
- A larger fuel tank will be required, as compared to diesel fuel, because of the lower density and heating value of DME [9].
- Since the vapor pressure of DME is low, the fuel vaporizes immediately upon injection into the cylinder. This may or may not be an issue, but further study may confirm how the combustion reaction takes place after the vaporization occurs [9].
- Injection via some fuel pumps causes uncontrollable pressure waves in the entire system [10]
- Predictability of spray behavior and characteristics is important in repeatability of combustion [11].
- Turbulence within the cylinder is important for mixing of the fuel, which in turn reduces emissions [12].

CONCLUSIONS

This work has demonstrated that a conventional diesel vehicle can be converted to operate on blends of DME and diesel fuel. Significant reductions in particulate emissions were observed when the converted shuttle bus was operated on DME – diesel blends, while there were increases in unburned hydrocarbons, NOx and CO. By blending DME with diesel fuel, an acceptable viscosity and lubricity could be obtained in the fuel mixture to provide reliable operation of the fuel injection system. Nonetheless, operation of the vehicle was not without challenges during the conversion and debugging phases, as is documented in this paper.

DME holds great promise as a fuel for the future. But, many technical challenges remain to be overcome before neat DME-fueled vehicles can be a commercially viable option. Among them are the low viscosity, low lubricity and material incompatibilities.

REFERENCES

1. Chapman, E.M., Boehman, A.L., Tijm, P.J.A., and Waller, F.J. "*Emissions Characteristics of a Navistar 7.3L Turbodiesel Fueled with Blends of Dimethyl Ether and Diesel Fuel*". *Society of Automotive Engineers*, 2001(2001-01-3626).

2. Chapman, E., Bhide, S., Boehman, A.L., Tijm, P.J.A., and Waller, F.J. "*Engine Performance and Emissions from fuel blends of Dimethyl Ether (DME) and diesel fuel*". in *AIChE Spring National Meeting, Session 141- Oxygenated Fuels*. 2001. New Orleans, LA, March 10-14, 2002.

3. Kajitani, S., Chen, Z., Konno M, "*Engine performance and Exhaust Characteristics of DI Diesel Engine operated with DME*". *Society of Automotive Engineers*, 1997 (972973).

4. Liotta, F.J., and Montalvo,D.M., "*The Effects of Oxygenated Fuels on Emissions from a Modern Heavy-Duty Diesel Engine*". *Society of Automotive Engineers*, 1993 (932734).

5. Sidhu, S., et.al., "*Semi-volatile and particulate emissions from the combustion of alternative diesel fuels*". *Chemosphere*, 2001. **42**: p. 681-690.

6. DuPont, *Dymel Aerosol Propellants: Dymel A*, in *Technical Information ATB-25*. 1992, Fluorochemicals Laboratory, E.I. duPont de Nemours and Company.

7. Hansen, K., Nielsen, L., Hanses, J., Mikkelsen, S., Landalv, H., Ristola, T., Vielwerth, K., "*Demonstration of a DME (Dimethyl Ether) Fuelled City Bus.*" *Society of Automotive Engineers*, 2000 (2000-01-2005).

8. Ofner, H., Gill, D.W., Krotscheck, C., "*DME as Fuel for CI engines - A New Technology and its Environmental Potential.*" *Society of Automotive Engineers*, 1998 (981158).

9. Glensvig, M., Sorenson, S.C., Abata, D. L., "*An Investigation of the Injection Characteristics of Dimethyl Ether.*" *ASME Fall Technical Conference*, 1997. 29-3 (97-ICE-67): p. 77-84.

10. Sorenson, S.C., Glensvig M., Abata Duane L, "*Dimethyl Ether in Diesel Fuel Injection Systems.*" *Society of Automotive Engineers*, 1998 (981159).

11. Wakai, K., Yoshizaki, T., "*Numerical and Experimental Analyses of the Injection Characteristics of Dimethyl Ether with a DI Diesel Injection System.*" *Society of Automotive Engineers*, 1999 (1999-01-1122).

12. Konno, M., Kajitani, S., Oguma, M., Iwase, T., Shima, K., "*NO Emission Characteristics of a CI Engine Fueled with Neat Dimethyl Ether.*" *Society of Automotive Engineers*, 1999 (1999-01-1116).

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A variety of companies provided support and hardware to the project, particularly during the shuttle bus conversion. Chief among the industrial sponsors has been Navistar (now International Truck) and Dr. Pranab Das, who donated funds for the laboratory engine for this project. In addition, the project received support and technical guidance from: Allegheny Truck, Caterpillar, Clean Air Technologies, Columbia Propane, DuPont Fluorochemicals, DuPont-Dow Elastomers, F&L Fluid Components, Manchester Tank, Master Flow Pumps, National Instruments, Sierra Monitor Corporation, Parker - Racor Filtration, and Tuthill Pump.

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The original Principal Investigator for this project was Prof. Don Streit, who passed away tragically in August 2001. He played a critical role in getting this project underway and we are forever grateful for his guidance.

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This material was prepared with the support of the Pennsylvania Department of Environmental Protection. Any opinions, findings, conclusions, or recommendations expressed herein are those of the author(s) and do not necessarily reflect the views of the DEP.

APPENDICES

The appendices include papers and theses written during the course of this project. These documents are included on the CD that accompanies this document.

Society of Automotive Engineers Technical Paper No. 2000-01-2887

ACS Preprint from 2001 ACS National Meeting

Society of Automotive Engineers Technical Paper No. 2001-01-3626

ACS Preprint from 2002 ACS National Meeting

Society of Automotive Engineers Technical Paper No. 2003-01-0756

MS Thesis in Fuel Science, E. M. Chapman, 2002

MS Thesis in Mechanical Engineering, S. V. Bhide, 2003

2000-01-2887

Emission Characteristics of a Navistar 7.3L Turbodiesel Fueled with Blends of Oxygenates and Diesel

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Peter J.A. Tijm and Francis J. Waller
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ABSTRACT

Several oxygenates have been proposed and tested for use with or as diesel fuel. This paper examines two such oxygenates, CETANER™ and dimethyl ether (DME), partially or wholly produced by Air Products and Chemicals, Inc's Liquid Phase Technology. In previous studies on a single cylinder compression ignition engine and a Volkswagen TDI four cylinder engine, significant reductions in particulate matter emissions were observed with blends of CETANER™ in diesel fuel. In this study, experiments were performed on a multi-cylinder Navistar 7.3L Turbodiesel engine confirmed and extended the observations from the earlier studies. This is an important step in not only showing that the fuel does perform on each type of engine in similar fashion, but also in showing that DME and its derivatives can give consistent, significant results in lowering emissions. The oxygenated fuels were blended to achieve a net addition of 2 wt.% oxygen in the blended fuel. A pressurized fueling system was developed to deliver mixtures of DME-diesel at up to 1 MPa (150 psi). With the DME-diesel blend, less consistent emissions results were obtained owing to an inability to sufficiently the fuel in the rail.

INTRODUCTION

Demand for cleaner burning diesel fuels is growing worldwide, as governmental regulations make emissions reductions necessary. In the U.S., future regulations that take effect in 2004 and 2007 will require diesel engine and vehicle manufacturers to review all aspects of the vehicle system design. To achieve substantial reductions in emissions, it is thought that reformulated diesel fuels will play an important role. The reformulation of diesel fuels could include lowering the sulfur content, lowering the aromatic content, or potentially the addition of oxygen within the fuel.

A solution to affect emissions reductions for future and current diesel vehicles on the road is to modify the fuel without the need for modifying the engine hardware. It has been shown that many oxygenates are effective at reducing particulate emissions from diesel engines [1-20]. Therefore, much research has focused on screening of oxygenated fuel additives, including alcohols, esters, and ethers. Of particular interest are the glycol ethers, which have been shown to be very effective as blends and as neat fuel.

Over the last ten years, many researchers have begun to evaluate the performance of blends of glycol ethers with diesel fuel, and have observed decreases in particulate matter emissions. Liotta and Montalvo [5] measured the effects of several different oxygenated fuel additives, including several glycol ethers. From the tests performed in a DDC Series 60 diesel engine, their results indicated that particulate matter reductions of 4-10% could be achieved for each 1% of oxygen blended into diesel fuel, through incorporation as a glycol ether. Specifically, the results indicated that oxygen addition via glycol ether addition was more effective than oxygen addition via alcohol. Ullman and coworkers [6,7] also evaluated the addition of several glycol ethers to diesel fuel, specifically, monoglyme (1,2-dimethoxyethane) and diglyme (diethylene glycol dimethyl ether), at 2 wt.% and 4 wt.% oxygen. A DDC Series 60 engine and a Navistar DTA-466 engine were used for the testing. Their results indicated that particulate matter reductions of 6-7% were reached for each 1% of oxygen blended into diesel fuel.

Higher molecular weight glycol ethers blended with diesel fuel have also been effectively used to reduce particulate matter emissions. Tsurutani and coworkers [8] blended several glymes , including monoglyme, diglyme, triglyme and tetraglyme, at levels up to 12 wt.% oxygen in diesel fuel. They observed that combustion of the glycol ether blends in an IDI engine yielded a particulate matter emission reduction of 3-5% for each percent of oxygen blended. Additional studies completed by Hess et al. [9] as well as by Litzinger and coworkers [10,11] have shown that higher molecular weight glycol ethers are also effective in reducing particulate matter emissions, although to a lesser extent than monoglyme or diglyme.

Beatrice and coworkers [12-15] as well as Miyamoto and coworkers [16,17] have evaluated the use of diglyme as both an oxygenated blend component and as a neat fuel. Both research groups have reported that smokeless combustion is possible with pure diglyme. Heat release rates have shown that combustion of diglyme results in shorter combustion duration, with a shift towards the diffusion phase of the combustion process.

Although it has been shown that glycol ethers effectively reduce particulate emissions, the fundamental mechanisms of the reduction have not been clearly identified. There has been some work in simulating the ignition and rate mechanism behavior of dimethyl ether in comparison to dimethoxy methane [18]. Also, oxidation mechanisms have been proposed for gaseous forms of DME [21-23]. Limited data is available for many of the liquid oxygenates under consideration.

Hence, the objectives of the experimental work reported here are to further evaluate the effects of glycol ethers, specifically CETANER™ on the diesel combustion process, as well as to compare this data to another oxygenate, dimethyl ether (DME), utilizing the same engine condition. In different engine configurations, CETANER™ has been shown to reduce particulate emissions over a range of blend ratios in diesel fuel [24]. CETANER™ is an oxygenated diesel fuel additive developed as a coal-derived syngas product by Air Products and Chemicals, Inc., and is a mix of glycol ethers, namely monoglyme and diglyme. As a diesel fuel additive, CETANER™ has been shown to exhibit high cetane number, roughly 125 [25]. This work is also intended to demonstrate fueling of a commercial turbodiesel engine on DME-diesel blends through the use of a pressurized fueling system. The long term objective is to apply this fueling strategy to a shuttle bus on the Penn State University Park campus.

For this experimental work, blends of a Federal Certification diesel fuel with CETANER™ and dimethyl ether were evaluated in a multi-cylinder direct injection (DI) engine. A simplified mixture of 20% monoglyme and 80% diglyme was chosen for the experimental work, to represent a potential CETANER™ formulation. In-cylinder pressure measurements provided information about the impact of the oxygenated fuel on the combustion process. In addition, fuel property tests were performed on the base fuels as well as the fuel blends. These measurements included calorific value, flash point, and viscosity, and were used to understand and describe the combustion behavior. Since dimethyl ether is a vapor at 1 atm., the fuel property tests for the fuel blends were performed under pressure so that the dimethyl ether and diesel remained in the liquid state. Therefore, the fuel system of the engine was redesigned to accommodate the pressurized fuel delivery.

EXPERIMENTAL

TEST ENGINE

For the purpose of studying the effects of fuel additives on light-medium duty diesel combustion, a Navistar T444E 7.3L Turbodiesel engine was coupled to a 450 horsepower Eaton (Model AD-1802) eddy-current dynamometer for testing. The specifications for the engine are given in Table 1. Pentium PCs with Kiethly Metrabyte DAS-1800 data acquisition cards were connected to the engine to log real-time engine parameters. These parameters included engine speed, torque, and power from the engine. A Modicon PLC was used to record temperatures from the engine, as well as, for the entire experimental system monitoring. Intake airflow rates were determined via an electronic flow sensor, which was calibrated from a laminar flow element. Fuel consumption was monitored using a precision Sartorius Industrial Scale (Model EA60EDE-1) , with an accuracy of ± 2 grams. Figure 1 shows the test cell set up, and additional equipment used for emissions monitoring.

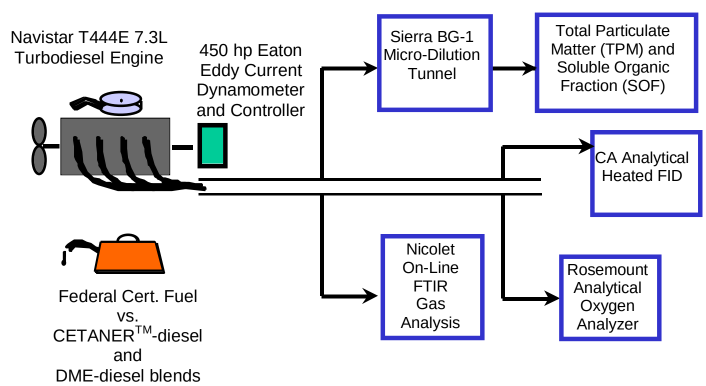

Figure 1. Multicylinder Engine Test Cell Navistar T444E 7.3L Turbodiesel

TEST PROCEDURE

In this work, an AVL 8-mode test procedure has been utilized as a model for diesel emissions tests. The AVL 8-mode tests was designed to correlate to the U.S. Federal Heavy- Duty Transient Test procedure through a weighted 8- mode steady state test procedure. The 8 modes are a combination of speeds and loads, to produce the same emissions output as would be recorded for a transient cycle [26]. For our engine, the test procedure included the speed and load settings, shown in Table 2.

Table 1. Characteristics of the 1998 Navistar T444E 7.3L Turbodiesel Engine

Displacement	7.3 Liter (444 cu.in.)
Bore	104.39mm (4.11 inch)
Stroke	106.20mm (4.18 inch)
Rated Power	143kW (190 HP)@2300 RPM
Peak Torque	640Nm(485lbf-ft)@1500 RPM
Configuration	Turbo charged, Intercolled (Air-to-Air), Direct Injection
Injection Scheme	HEUI- Hydraulically actuated, electronically controlled unit injectors
Low Idle Speed	700 RPM
Features	Split- shot injection
Compression Ratio	17.5:1

Table 2. AVL 8-Mode Test for the Navistar T444E Turbodiesel engine

Mode	Speed (rpm)	Load (Nm)
1	700	0
2	876	111
3	1036	296
4	1212	472
5	2300	102
6	2220	235
7	2220	405
8	2124	540

EMISSIONS ANALYSIS

An extended warm-up period was used to prepare the engine for testing. The sampling and measurements during each mode commenced when the exhaust temperatures reached a steady state. During this time, RPM and torque were maintained within 1-2% of the target test conditions. Once steady-state operation was achieved, a portion of the exhaust gas was passed through a Sierra Instruments BG-1 micro-dilution test stand with a constant dilution air / sample flow ratio of 8:1 and a total flow of 150 liters/min. These settings were chosen in order to maintain the filter temperature below the EPA specification of 52°C. Particulate collection occurred on Pallflex 90mm filters (Type EMFAB TX40HI20-WW), conditioned in an environmental chamber at 25°C and 45% relative humidity before and after sampling. Five particulate samples were taken for each fuel at each test mode, except for the DME-diesel tests where only one sample was obtained.

Exhaust gas analyses were completed using a Nicolet Magna 550 Fourier Transform Infrared (FTIR) Spectrometer. For each mode, five gas samples were analyzed for CO_2, CO, NO and NO_2 . Also, a Rosemont Analytical O_2 sensor was used to monitor the percent oxygen in the exhaust gas. The oxygen readings were used in conjunction with the mass flow sensor to determine and verify the air / fuel ratio. Additionally, total hydrocarbon emissions were monitored using a California Analytical Instruments Model 300 HFID Heated Total Hydrocarbon Gas Analyzer. For the total hydrocarbon measurements, undiluted exhaust gas was collected via a heated sample line, which was maintained to 190°C. Calibration of all equipment was completed prior to each day of testing. Gaseous emissions data are only presented for the CETANER^{TM}-diesel blend, as the gaseous sampling system was not functioning correctly during the testing of the DME-diesel blends.

PRESSURE TRACE ANALYSIS

In order to observe the impact of the oxygenated blends on combustion and heat release, the combustion chamber of cylinder 1 of the engine was fitted with a Kistler 6125A pressure probe. The pressure sensor was used with a Kistler 2612 optical crank angle encoder to provide time resolved in-cylinder pressure traces of the combustion event. Pressure, crank angle, and TDC trigger signals were acquired with a Kiethley DAS-1800 data acquisition card operating in a "burst " mode. The pressure traces were analyzed with PTrAn V.02, a software product designed by Optimum Power.

TEST FUELS

Previous work has been completed comparing the increasing percentage of oxygenate mixed with diesel fuels within several types of engines [8-17,24]. For this testing, comparisons are made between a 2 wt.% addition oxygen of two different additives. The baseline diesel fuel properties, as well as test fuel properties are given below in Table 3. A Federal Certfication Fuel (Specified Fuels, Emissions Certification Diesel – Low Sulfur, ECD-LS) was used in these experiments. Because of the difficulty of obtaining the fuel blend properties for DME as a liquid, the properties available in the literature for neat DME are presented.

PRESSURIZED FUEL DELIVERY SYSTEM FOR DIESEL-DME BLENDS

DME is a liquefied gas. At STP, it is a gas, but liquefies under a moderate pressure. The fuel delivery system was designed keeping in mind the following important points:

The vapor pressure of DME.
Material compatibility of the various components in the fuel system with DME
Lack of lubricity of pure DME.

A schematic of the fuel delivery system is shown in Figure 2. The working of the fuel delivery system can be explained as follows:

1. The fuel comes out of the fuel tank at a pressure of about 0.6 MPag (90 psig). This overpressure is necessary to keep the DME in a liquid state. Any inert gas is suitable for this purpose. Helium was used as it has a lower solubility in DME than nitrogen.
2. The pressure is then boosted by a gear pump to about 0.82 or 1.0 MPag (120 or 150 psig), depending on the pressure rating of the fuel rail. The rail pressure is maintained at 0.48 MPag (70 psig) in the original fuel system of the engine.
3. The fuel return line pressure is held at about 0.82 MPag (120 psig) by the backpressure regulator. The regulator is a simple spring loaded valve that regulates the flow to keep the backpressure at 0.82 MPag (120 psig).
4. This fuel then passes through a heat exchanger, where it is cooled down to a predetermined level.
5. After cooling, the fuel is then fed to the inlet of the pump

Table 3. Fuel Properties

Fuel Property	ASTM Method	ASTM Spec.	Base Diesel	5wt.% CETANER	DME
Viscosity, 40°C, cSt	D 445	1.39-4.20	2.2	1.27	.25 [30]
API Gravity	D 287	API 30	35.3	42.5	
Cloud Point (°C)	D 2500	<-18	-16		
Pour Point (°C)	D2500	<-18	<-18		
Flash Point (°C)	D 93	52	74		-41
Calorific Value (MJ/kg)	D2015	46	45	44	28

PRESSURE AND FLOW REQUIREMENTS

At 20°C the vapor pressure of DME is about 0.52 MPa (75 psia). Keeping DME in a liquefied state calls for pressurizing the entire fuel system from the fuel tank up to the fuel injectors. The vapor pressure also changes rapidly with temperature. The pressure of the fuel system is hence dictated by the fuel temperature. The pressure, however, is limited by the pressure rating of the fuel rail. The engine used in the study has a common rail injection system. Each cylinder head has a fuel rail running along its length, which is the source of fuel for the pressure intensifier in the fuel injectors. In the original fuel system of the engine, the pressure in the rail is maintained at 0.48 MPa (70 psig). This facilitates proper filling of the pressure intensifiers. The fuel rails in the cylinder head form a dead head system. This means that there is no fuel return once the fuel enters the fuel rail. It is because of this that the fuel temperature in the rail approaches the engine coolant temperature in the head. This layout of the fuel system was modified to accommodate a fuel return from the cylinder heads.

A study was performed in which the temperature of the fuel in the fuel rail was recorded in conjunction with the fuel consumption of the engine, for the 8 modes of the AVL test. Assuming certain values for heat capacities for diesel and DME, a minimum flow rate value was calculated so as to keep the temperature of the fuel in the rail below 50°C. The vapor pressure of DME at this temperature is about 1.0 MPa (150 psi). This pressure, more or less, dictated the temperature rise allowed. The fuel delivery pump was sized based on the above calculations. In addition to excess flow rate, cooling of the returned fuel was necessary to maintain the required fuel temperature. In these tests, a 500 W chiller was used to chill a bath through which the fuel was passed within stainless steel coils. This fuel cooling was insufficient to maintain the fuel temperature below 50°C under some operating conditions, particularly during Mode 8.

<u>Design Considerations for the Pressurized Fuel System</u>

DME is known to be incompatible with the common gasket materials such as Viton and buna-N, used in diesel service. Data provided by DuPont Inc. indicated Kalrez to be the best material for DME. For economic considerations however, this material was used sparingly. Other materials such as butyl rubber, Teflon and neoprene have also been found to be compatible, though not to the same degree as Kalrez. Stainless steel was used for the fuel lines as a safeguard against corrosion. All the other components such as valves and regulators were also made of stainless steel.

Selecting a pump for pumping DME was challenging due to the properties of DME such as its low lubricity and low viscosity. Due to the vapor pressure of DME, the pump

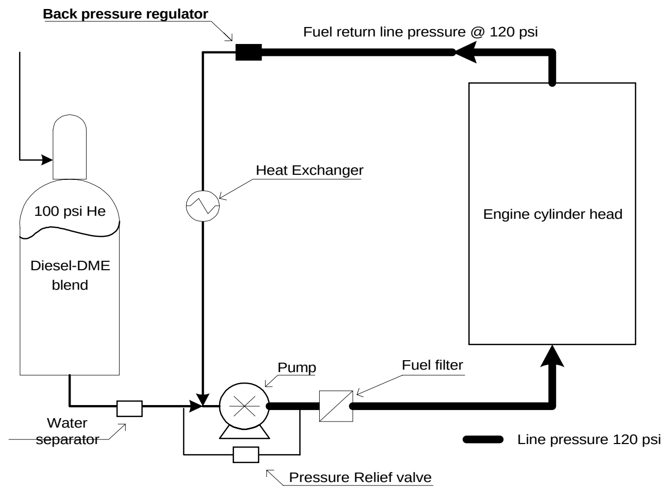

Figure 2. Pressurized Fuel System Diagram for the Navistar T444E Turbodiesel Engine.

housing was required to handle pressures up to 1.7 MPag (250 psig). Positive displacement pumps such as vane pumps, diaphragm pumps and gear pumps were considered. Gear pumps were found to be economical as well as convenient to operate. With these considerations, a gear pump made by Tuthill Pump CO, California (model #TXS2.6PPPT3WN00000) was selected. This pump has a magnetically coupled AC motor. This configuration does not have the driveshaft going through the pump housing, which in turn obviates the need for seals, a potential source of leakage. The gear material is Ryton (Polyphenylene sulphide), which was found to be compatible with diesel and DME as per the data by provided DuPont Inc. The pump body seals are made of Teflon.

The fuel filters on the engine could not be used because of the high pressure of the fuel. The minimum pressure in the fuel lines was 0.62 MPag (90 psig). This required the use of special filters, which would withstand higher pressure. A diesel water separator was used as a primary filter. This is rated at 0.69 MPag (100 psig). The final filter was a LPG filter rated at 3.4 MPag (500psig). The mesh size of the filter was 2 micron, very near to the engine specification.

The fuel tank was made out of a modified 45 kg (100 lb) capacity LPG cylinder which was pressure tested prior to use. This tank was fitted with a 1/2" NPT fitting at the bottom for liquid exchange.

RESULTS AND DISCUSSION

This section presents results from combustion studies of the effect of the CETANER™ additive on emissions compared to the base fuel composition (prior to the fuel system conversion), and the effect of the DME-diesel mixture on emission compared to the base fuel composition (after the fuel system conversion). Fuel property tests were completed to permit comparisons of the combustion data. Through an uncertainty analysis, based on methods described by Moffat, error bars showing the 95% confidence intervals are presented in each figure [27].

PARTICULATES

As noted previously in the discussion, oxygenates traditionally reduce particulate emissions. Shown in Figure 3, the brake specific particulate matter (BSPM) emissions for the 2 wt. % oxygen (5.59wt.% CETANER™ and 5.75wt.% DME) show a decrease in particulate matter emissions for CETANER™ addition, but a mixed result for DME addition. As seen in Figure 4, on a basis of particulate emissions per unit fuel consumed, greater variability in the results is evident. These numbers for the impact of CETANER™ addition correlate well with the particulate emissions observed previously by Hess and coworkers [24], as well as, Ullman and coworkers [6,7]. In their work, particulate emissions decreased as a function of increasing load. This is also seen in the results in Figure 3. For mode 4, even though there is a particulate reduction through using CETANER™ vs. the baseline diesel, the interesting trend is in the engine particulate output for the engine conditions. Mode 4 operates the engine near the peak torque, and the overall emissions conditions change, possibly due to a change in the injection timing.

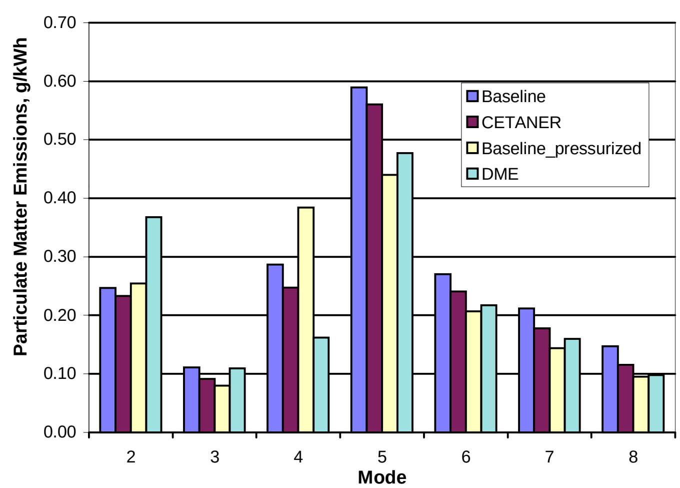

Figure 3. Particulate Matter Emissions, Brake Specific Basis.

Considering the work here and elsewhere on CETANER™, there seems to be some consistency in the results between different engine configurations, which would lead one to believe that the particulate reductions are more a function of the presence of the oxygen in the fuel, and less a function of number of cylinders and fuel injection type (DI or IDI) [24]. As has been shown in previous work, this particulate reduction is due to a reduction in the soot portion of the emission, and would result in a percentage increase in the soluble organic faction (SOF) portion [5].

It is evident from Figure 4 (in particular, Mode 4), there is substantially greater variability introduced by the pressurized fueling system with regard to particulate emissions measurements. The variation from the original baseline emissions (before the fuel system conversion) is quite large, and may in part be due to difficulties in maintaining sufficiently low temperatures in the fuel rail. As shown in Figure 2, the pressurized fuel system relies on a heat exchanger to cool the fuel that is rejected from the rail so that this fuel can be recirculated to the rail. However, during these tests it was observed that the heat exchanger capacity was insufficient to maintain fuel rail temperatures below 50°C under some of the operating modes, particularly Mode 8.

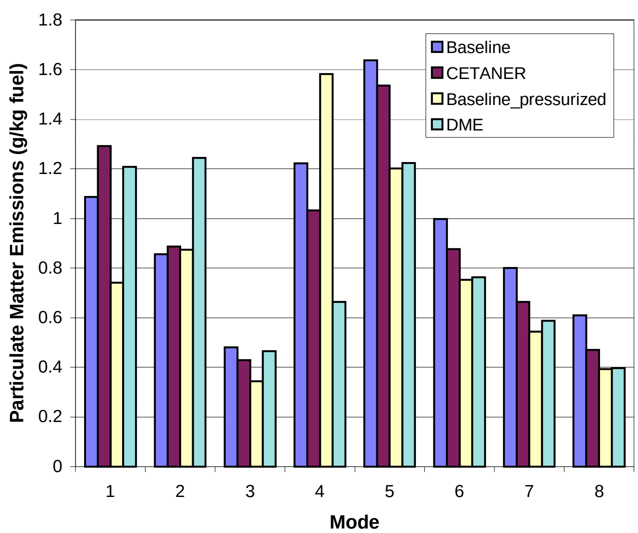

Figure 4. Particulate Matter Emissions, g/kg Fuel Basis.

NITROGEN OXIDES

Table 4 reports the weighted brake specific NO_x ($BSNO_x$) emissions for the CETANER™-diesel blend. Using the AVL 8-mode weight factors, the net NO_x emission reduction was 5.35%. Shown in Figure 5, for modes 4 through 8 a reduction of NO_x per unit fuel consumed was observed. In general, the data follows an expected trend, in that at higher engine speeds, NO_x is lower, and as the load increased, NO_x increased. For the other three modes, the data does not show significant conclusions. There are conflicting reports in the literature as to whether oxygenates do indeed reduce NO_x[2,4,5,11,15]. The data from this engine, however, shows a reduction in NO_x emissions on a brake specific basis, for most modes. Choi and Reitz [4] observed that there is a small penalty on the NO_x emissions when using a split injection strategy (two fuel pulses) with an oxygenated fuel, which could be affecting the results for mode 1 and 2 for this particular engine. Because the unique multiple fuel injection strategy of the Navistar T444E especially is more pronounced at lower speeds, the NO_x reduction could occur due to greater mixing effect in the cylinder during the combustion event.

Figure 6 presents the particulate matter vs. NO_x tradeoff per mode for the CETANER™-diesel blend. As can be seen for modes 2 though 8 on a brake specific basis, a slight decrease in particulate matter and NO_x occurs for each mode. In each case, the PM-NO_x emissions point shifts toward the origin, which further demonstrates the viability of reducing diesel engine emissions via oxygen addition.

CARBON MONOXIDE

Table 4 reports the weighted brake specific CO (BSCO) emissions. There is no clear trend in this data, although there is an increase in CO for most of the mode positions. If CO per unit of fuel is reviewed, one can see that for each of the lower speed and load modes, a definite increase in the CO for CETANER™ is observed. This is shown in Figure 7. This may again support the rationale that during the low speed and low load conditions, CO formed during early reactions of the fuel are being halted from final conversion to CO_2. This was postulated by Litzinger and coworkers [11]. As explained by Glassman, the conversion of CO to CO_2 would be a function of the size of the hydroxyl radical pool, which does not grow until after all the original fuel and hydrocarbons have been consumed [31]. Since the concentration of hydroxyl radicals is important in the rate of CO oxidation, the additional molecules of oxygen with the monoglyme and diglyme may be playing a role in providing excess CO and CO_2 which continue the creation of the hydroxyl radical pool. In addition, Flynn and coworkers show through kinetic simulations that the addition of the oxygen in the fuel leads to reduced amounts of soot precursors, and larger amounts of carbon leaving the fuel rich premixed combustion zone as CO [28].

Table 4. AVL 8-mode Weighted Gaseous Emissions Results, CETANER™-Diesel Blend, Brake Specific Basis

WEIGHTED EMISSION	BASELINE DIESEL (g/BHP-hr)	2 wt. % OXYGEN VIA CETANER™ (g/BHP-hr)
NOx	3.31	3.13
CO	1.29	1.30
HC	.252	.238

TOTAL HYDROCARBONS

The weighted brake specific emissions for the CETANER™-diesel blend are reported in Table 4. In general, the HC emissions decrease with higher engine loads, as the engine combustion efficiency increases. In this work for all engine loads, HC emissions remain unchanged as compared to the baseline diesel, as can be seen in Figure 8. These results are consistent with other work by Hess and coworkers [24].

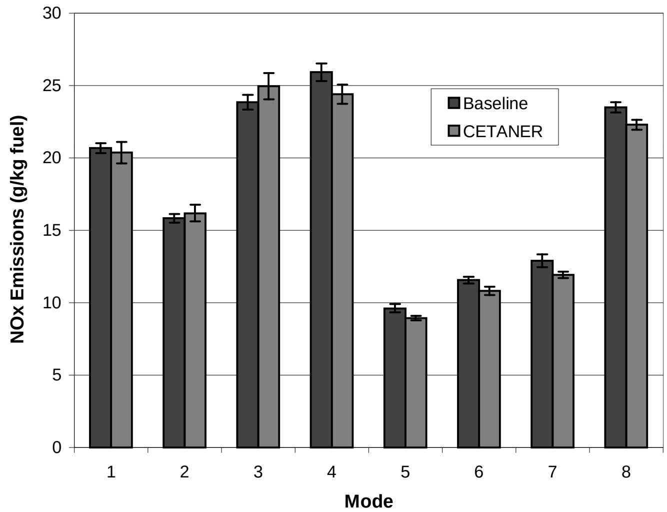

Figure 5. NOx Emsissions per Unit Fuel Consumed for CETANER™ Addition, g/kg Fuel Basis.

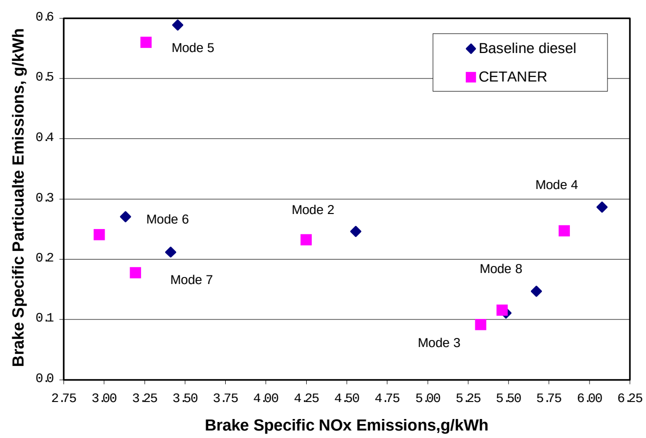

Figure 6. Brake-Specific Particulate Emission vs. NOx Emission Tradeoff.

FUEL CONSUMPTION

Figure 9 reports the brake specific fuel consumption (BSFC) for CETANER™ and DME addition. The general trend shows an increase in the amount of fuel required to maintain the same speed and load. This is due to the slightly lower calorific value of the CETANER™ and DME blends, as shown in the Fuel Properties of Table 3. However, when fuel consumption is calculated on an energy basis, the energy consumption results are not significantly different.

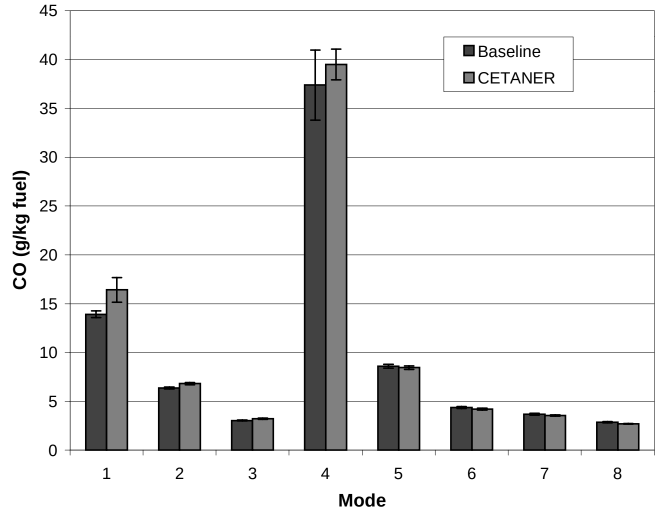

Figure 7. CO Emissions per Unit Fuel Consumed for CETANER™ Addition, g/kg Fuel Basis.

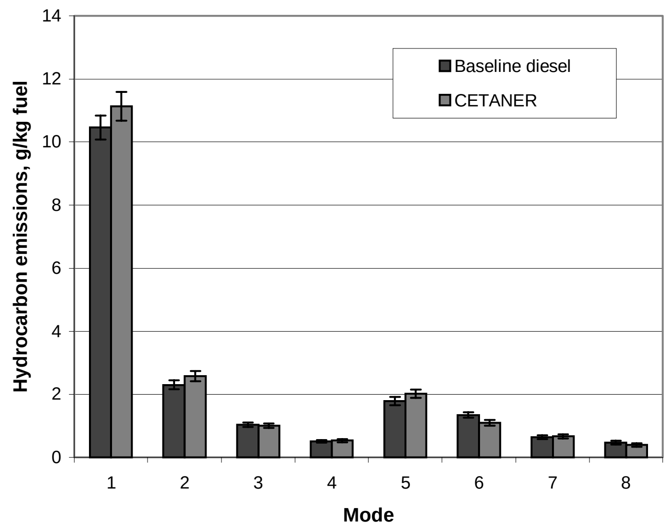

Figure 8. Total Hydrocarbon Emissions per Unit Fuel Consumed for CETANER™ Addition, g/kg fuel

The results from this work are significant in that they confirm previous data for particulate reductions. The reductions correlate well with those of 2 wt.% oxygen addition via diglyme of Liotta and Montalvo [5]. For this data, a NOx reduction was shown for specific modes and as an overall number, which would be contrary to most work found in the literature. The CO emissions seem to follow the trends as reported [11,24,28]. The mode 4 CO data raises questions, but will be reviewed further.

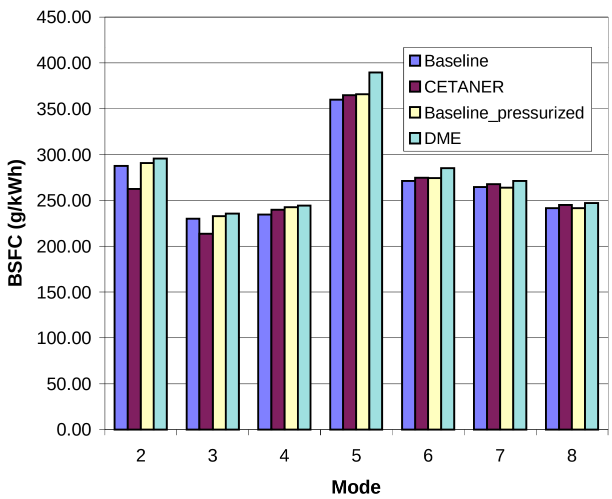

Figure 9. Fuel Consumption, Brake Specific Basis.

CONCLUSION

On-going research continues in testing and reviewing the affects of oxygenates on the composition of emissions from diesel engines. Optimization of the pressurized fuel system for DME-diesel blends is underway. The development of this fueling system is a significant advance toward practical use of DME as a diesel fuel. The results in this paper lead to the following conclusions:

The emissions results with CETANER^{TM} addition are consistent with previous work and shown significant particulate emissions reductions in a DI diesel engine. NOx emissions were moderately lower, while HC emissions were unchanged and CO emissions increased at low load.

Results with the pressurized fueling system yielded scattered emissions results, with and without DME addition to the base diesel fuel. These difficulties may stem from an inability to properly cool the fuel that resides in the rail.

The strategy outlined here for combining DME and diesel fuel under pressure can provide an effective means of fueling an engine with DME without excessive modifications to the engine.

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REFERENCES

1. Neeft, J.P.A., Makkee, M. and Moulijn, J.A. *Fuel Proc. Tech.*, 47:1-69 (1996).
2. McCormick, R.L., Ross, J.D. and Grabowski, M.S., *Environ. Sci. Tech.,* 31:1144-1150 (1997).
3. Grabowski, M.S. and McCormick, R.L. *Prog. Energy and Combust. Sci.* 24:125-164 (1998).
4. Choi, C.Y. and Reitz, R.D. *Fuel*, 78:1303-1317 (1999).
5. Liotta, F.J, and Montalvo, D.M., Society of Automotive Engineers Technical Paper No. 932734, Society of Automotive Engineers, Warrendale, PA (1993).
6. Ullman, T.L., Spreen, K.B. and Mason, R.L., Society of Automotive Engineers Technical Paper No. 941020, Society of Automotive Engineers, Warrendale, PA (1994).
7. Spreen, K.B., Ullman, T.L. and Mason, R.L. Society of Automotive Engineers Technical Paper No. 950250, Society of Automotive Engineers, Warrendale, PA (1995).
8. Tsurutani, K., Takei, Y., Fujimoto, Y., Matsudaira, J. and Kumamoto, M., Society of Automotive Engineers Technical Paper No. 952349, Society of Automotive Engineers, Warrendale, PA (1995).
9. Hess, H.S., Roan, M.A., Bhalla, S., Butnark, S., Zarnescu, V., Boehman, A.L., Tijm, P.J.A. and Waller, F.J., ACS Preprints, Division of Petroleum Chemistry, 43(4):593-596 (1998).
10. Stoner, M. and Litzinger, T., Society of Automotive Engineers Technical Paper No. 1999-01-1475, Society of Automotive Engineers, Warrendale, PA (1999).
11. Litzinger, T., Stoner, M., Hess, H. and Boehman, A., *Int. J. Engine Res.*, accepted for publication (2000).
12. Beatrice, C., Bertoli, C., D'Alessio, J., Del Giacomo, N., Lazzaro, M. and Massoli, P. *Comb. Sci. and Tech.,* 120:335-355 (1996).
13. Bertoli, C., Del Giacomo, N. and Beatrice, C., Society of Automotive Engineers Technical Paper No. 972972, Society of Automotive Engineers, Warrendale, PA (1997).
14. Beatrice, C., Bertoli, C. and Del Giacomo, N. *Comb. Sci. Tech.,* 137:31-50 (1998).
15. Beatrice, C., Bertoli, C., Del Giacomo, N. and Migliaccio, M.na., Society of Automotive Engineers Technical Paper No. 1999-01-3595, Society of Automotive Engineers, Warrendale, PA (1999).

16. Miyamoto, N., Ogawa, H., Nurun, N.M., Obata, K. and Arima, T., Society of Automotive Engineers Technical Paper No. 980506, Society of Automotive Engineers, Warrendale, PA (1998).
17. Nabi, M.N., Minami, M., Ogawa, H. and Miyamoto, N., Society of Automotive Engineers Technical Paper No. 2000-01-0231, Society of Automotive Engineers, Warrendale, PA (2000).
18. Edgar, B.L., Dibble, R.W. and Naegeli, D.W., Society of Automotive Engineers Technical Paper No. 971677, Society of Automotive Engineers, Warrendale, PA (1997).
19. Murayama, T., Zheng, M., Chikahisa, T., Oh, Y.-T., Fujiwara, Y., Tosaka, S., Yamashita, M. and Yoshitake., H., Society of Automotive Engineers Technical Paper No. 952518, Society of Automotive Engineers, Warrendale, PA (1995).
20. Rubino, L. and Thompson, M.J., Society of Automotive Engineers Technical Paper No. 1999-01-3589, Society of Automotive Engineers, Warrendale, PA (1999).
21. Mueller, M., Yetter, R., and Dryer, F., *Twenty-Seventh Symposium (International) on Combustion*, 177-184 (1998).
22. Dagaut, P., Daly, C., Simmie, J., and Cathonnet, M., *Twenty-Seventh Symposium (International) on Combustion*, 361-369 (1998).
23. Amano T., and Dryer, F., *Twenty-Seventh Symposium (International) on Combustion*, 397-404 (1998).
24. Hess, H., Boehman, A., Tijm, P., and Waller, F.J., Society of Automotive Engineers Technical Paper No. 2000-01-2886, Society of Automotive Engineers, Warrendale, PA. (2000).
25. Tijm, P.J.A., Waller, F.J., Toseland, B.A. and Peng, X.D., Energy Frontiers International Conference, Alaska (1997).
26. Fleisch,T., McCarthy, C., Basu, A., Udovich, C., Charbonneau, P., Slodowske, W., Mikkelsen, S., McCandless, J., Society of Automotive Engineers Technical Paper No. 950061, Society of Automotive Engineers, Warrendale, PA (1995).
27. Moffat, R.J., Experimental Thermal and Fluid Science, 1:3-17 (1988).
28. Flynn, P.F., Durrett, R.P., Hunter, G.L., zur Loye, A.O., Akinyemi, O.C., Dec, J.E. and Westbrook, C.K., Society of Automotive Engineers Technical Paper No. 1999-01-0509, Society of Automotive Engineers, Warrendale, PA (1999).
29. Ni, T., Pinson, J.A., Gupta, S. and Santoro, R.J. *Twenty-Fifth Symposium (International) on Combustion,* 585-592 (1994).
30. McCandless, J. and Li,S., Society of Automotive Engineers Technical Paper No. 970220, Society of Automotive Engineers, Warrendale, PA (1997).
31. Glassman, I. Combustion, 2nd edition, Orlando, FL: Academic Press, 1987.

VISCOSITY OF DME-DIESEL FUEL BLENDS

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Introduction

The need to reach ever tightening NOx and particulate emissions standards has placed a tremendous amount of pressure on the fuel, lubricant, engine and vehicle manufacturers. However, in the 1990's studies of direct injection diesel engines fueled by dimethyl ether demonstrated particulate emissions below the ULEV standard and NO_x emissions that approach or achieve ULEV levels, *without exhaust aftertreatment* [1,2]. Until those tests, DME had not been considered as a primary replacement fuel. Previously, DME had been considered as a methanol ignition improver for methanol powered vehicles [3-6]. At present, the predominant use for DME is as an environmentally benign aerosol propellant, since DME is non-toxic and is easily degraded in the troposphere [7]. Recent work on DME has focused on its use in advanced technology, direct-injection (DI) engines as a neat fuel [8-12].

However, DME has significantly different physical properties than diesel fuel including a low critical point, low viscosity, negligible lubricity and a high vapor pressure. In the present work, DME has been blended into diesel fuel to obtain a fuel mixture that retains the desirable physical properties of diesel fuel but includes the cleaner burning capability of DME. The miscibility and viscosity of blends of DME and diesel fuel were characterized using pressurized, optically accessible instrumentation. These physical property measurements are part of a comprehensive study of the operation of a turbodiesel engine on DME-diesel blends which is leading to a field demonstration of this fueling strategy [13].

Experimental

Two different high pressure cells were adapted for studying the miscibility and viscosity of blends of DME and diesel fuel. One permitted the fuel mixtures to be held at pressures up to 200 psi to examine miscibility by visual inspection of blends over extended periods of time. The fuels were deemed to be miscible if no evidence of phase separation was observed. The other instrument is a high pressure viscometer based on a capillary tube held within a pressurized chamber suitable for measurements at pressures up to 3500 psi.

Miscibility Measurements. Qualitative studies of the miscibility of blends of DME and a federal low sulfur (300 ppm) "emissions certification" diesel fuel (Specified Fuels "ECD LS") were performed under pressures above 90 psi. Blends from 25 wt.% DME up to 75 wt.% DME in diesel fuel were examined. Diesel fuel was gravity fed into an optically accessible pressure chamber, while DME was delivered from a cylinder of liquefied DME through an opening in the bottom of the pressure chamber. Pressures in the chamber were raised by feeding nitrogen above the fuel mixture to attain 90 psi or greater in the chamber.

Viscosity Measurements. Quantitative measurements of the viscosity of blends of DME in the federal low sulfur fuel were obtained using a high pressure viscometer, using capillary tubes that provided optimal measurement accuracy depending on the viscosity of the fuel mixture. Figure 1 shows a photograph of the high pressure chamber where the capillary tubes are located.

Figure 1. High pressure viscometer housing.

Figure 2 shows the rest of the viscometer system, which includes a pressure intensifier and pressure gages for generation of pressures up to 3500 psi with the chamber.

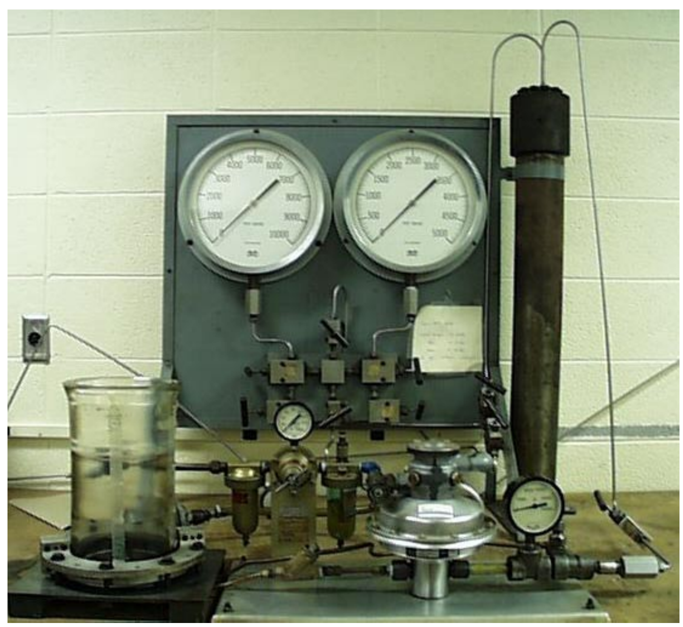

Figure 2. Supporting instrumentation for the high pressure viscometer.

Results and Discussion

Miscibility Measurements. The DME was observed to rapidly mix uniformly with the diesel fuel at all blend ratios. Over time, a blend that was initially not well mixed would become uniform, but injection of the DME from below the pool of diesel fuel was a particularly effective means of rapidly obtaining a uniform mixture.

Viscosity Measurements. Observations of the viscosity of the blends of DME and diesel fuel are summarized in Figure 3. Measurements were obtained over a range of pressures with the viscometer housing immersed in a constant temperature bath at 100°F (38°C). Results obtained at three different levels of chamber pressure are plotted in Figure 4 to show the impact of DME content on viscosity.

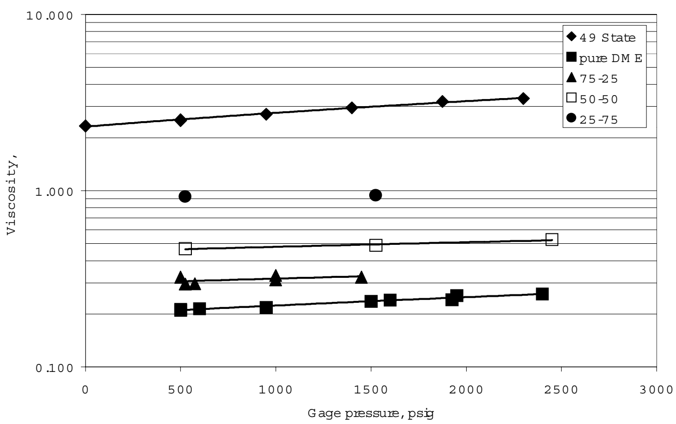

Figure 3. Viscosity of DME-diesel blends at pressures from 500 to 2500 psi.

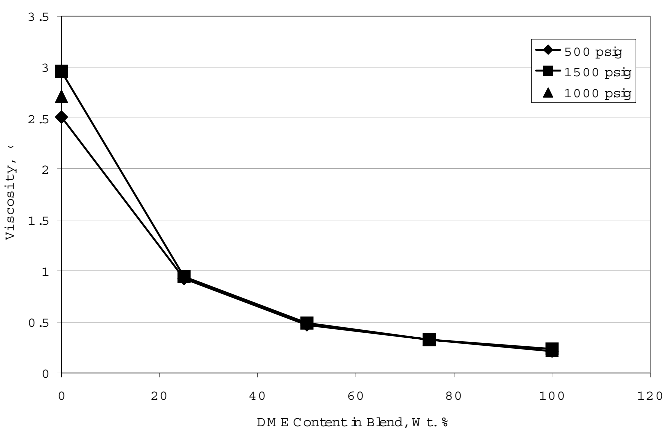

Figure 4. Blend response of viscosity to DME addition at various pressures.

These two figures show that viscosity decreases rapidly at low levels of DME addition. For instance at 25 wt.% DME addition, viscosity falls by more than a factor of 2, from the more than 2.5 cSt value of the neat diesel fuel to roughly 1 cSt. This non-linear blending response demonstrates that even modest addition of DME to diesel fuel brings the fuel blend below the ASTM diesel viscosity specification of 1.39-4.20 cSt at 40°C.

These viscosity measurements are among the first reported for DME under elevated pressures and are the first reported for blends in diesel fuel. Recent work by Sivebaek et al. [14] also considered the viscosity of DME, in particular with addition of lubricity and viscosity enhancing additives. They developed a volatile fuel viscometer (VFVM) that was designed to handle DME, neat or additized. They measured kinematic and dynamic viscosities of pure DME of 0.185 cSt and 0.122 cP at 25 °C, which compares well with the present study. Their measurements were performed at 5 bar pressure, roughly 75 psi. In the present study, no DME blends were examined at a pressure below 500 psi, but at this pressure the viscosity of neat DME was found to be 0.21 cSt. Extrapolating data for neat DME from the present study to a pressure of 75 psi yields an estimate of 0.2 cSt, which is in reasonable agreement with the value of 0.185 cSt obtained by Sivebaek et al. They also concluded that additized DME cannot reach the same viscosity and lubricity as diesel fuel. They suggest that rather than using additives to allow fuel systems to tolerate DME, the solution is to design the pumps so that they can handle pure DME.

Conclusions

Blending DME in diesel fuel is one option to utilize DME in diesel engines without drastic redesign of fuel pumps and fuel injectors. However, even modest addition of DME into diesel fuel significantly reduces the viscosity of the fuel mixture. Addition of as little as 25 wt.% DME into diesel fuel reduces fuel viscosity below the ASTM specification. This suggests that viscosity rather than miscibility is the limiting factor in blending DME with diesel fuel.

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References

(1) Fleisch, T., McCarthy, C., Basu, A., Udovich, C., Charbonneau, P., Slodowske, W., Mikkelson, S.-E., and McCandless, J., **1995**, SAE paper no. 950061.
(2) Kapus, P. E., and Cartellieri, W. P., **1995**, SAE paper no. 952754.
(3) Karpuk, M. E. and Cowley, S. W., **1988**, SAE paper no. 881678.
(4) Green, C. J., Cockshutt, N. A. and King, L., **1990**, SAE paper no. 902155.
(5) Murayama, T., Chikahisa, T., Guo, J., and Miyano, M., **1992**, SAE paper no. 922212.
(6) Guo, J., Chikahisa, T., Murayama, T., and Miyano, M., **1994**, SAE paper no. 941908.
(7) Hansen, J. B., Voss, B., Joensen, F., and Siguroardottir, I. D., **1995**, SAE paper no. 950063.
(8) Wilson, R., *Diesel Progress Engines and Drives*, **1995**, June 1995, pp. 108-109.
(9) Fleisch, T. H., *Diesel Progress Engines and Drives*, **1995**, October 1995, pp. 42-45.
(10) Glensvig, M., S. C. Sorenson and D. L. Abata, ASME Paper No. 97-ICE-67, **1997**, in ICE-Vol. 29-3, pp. 77-84.
(11) McCandless, J. C. and Li, S., **1997**, SAE paper no. 970220.
(12) Alam, M., O. Fujita, K. Ito, S Kajitani, M. Oguma and H. Machida, **1999**, SAE paper no. 1999-01-3599.
(13) Chapman, E. M, Bhide, S. V., Boehman, A. L., Tijm, P. J. A. and Waller, F. J., **2000**, SAE paper no. 2000-01-2887.
(14) Sivebaek, I. M., Sorenson, S. C., and Jakobsen, J., **2001**, SAE paper no. 2001-01-2013.

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Emission Characteristics of a Navistar 7.3L Turbodiesel Fueled with Blends of Dimethyl Ether and Diesel Fuel

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ABSTRACT

Several oxygenates have been proposed and tested for use with diesel fuel as a means of reducing exhaust emissions. This paper examines dimethyl ether (DME), which can be produced in many ways including via Air Products and Chemicals, Inc's Liquid Phase Technology (LPDME ™). Modest additions of DME into diesel fuel (2 wt.% oxygen) showed reductions in particulate matter emissions, but the previous data reported by the author from a multicylinder Navistar 7.3L Turbodiesel engine were scattered. In this study, experiments were performed on a multi-cylinder Navistar 7.3L Turbodiesel engine to repeatably confirm and extend the observations from the earlier studies. This is an important step in not only showing that the fuel does perform well in an engine with minor modifications to the fuel system, but also showing that DME can give consistent, significant results in lowering emissions. The DME and diesel blends tested were to achieve a net addition of 5 and 10 wt. % oxygen in the blended fuel. The data confirms that the addition of DME can reduce the particulate emissions from a compression ignition engine. However, the NO_x emissions were not favorable for all conditions. It is believed that through further modification of injection timing, NO_x emissions can be effectively reduced.

INTRODUCTION

Demand for cleaner burning diesel fuels is growing worldwide, as governmental regulations make emissions reductions necessary. In the U.S., future regulations that take effect in 2004 and 2007 will require diesel engine and vehicle manufacturers to review all aspects of the vehicle system design [1]. To achieve substantial reductions in emissions, it is thought that reformulated diesel fuels will play an important role. The reformulation of diesel fuels could include lowering the sulfur content, lowering the aromatic content, or potentially the addition of oxygen within the fuel.

A solution for reducing emissions from future and current diesel vehicles is to modify the fuel, without the need to modify the engine hardware. It has been shown that many oxygenates are effective at reducing particulate emissions from diesel engines [2-21]. Therefore, much research has focused on screening of oxygenated fuel additives, including alcohols, esters and ethers. Of particular interest are the glycol ethers, which have been shown to be very effective as blends and as neat fuel. This study focuses on the use of dimethyl ether, which has the chemical formula: CH3-O-CH3.

Dimethyl ether is a common chemical used as an aerosol propellant [22]. The properties of DME are given in Table 3, and are compared to the diesel fuel used for the baseline testing for this experiment. DME is a liquid at low pressure and standard temperature, and is relatively easy to handle. Over the past ten years, researchers have begun to consider the use of DME as a fuel. Because the Cetane number and ignition temperature are close to that of diesel fuel, DME was thought to be an excellent substitute for use in compression ignition engines. However, there were some drawbacks to using the fuel, including the reduced viscosity and lubricity of the fuel in neat form, as well as fuel compressibility effects [23,24].

To potentially overcome the fuel property effects of DME, as well as reduce emissions, the experiments for this study focus on mixing dimethyl ether with diesel fuel. The initial goal is to determine the effect of the oxygen concentration on the emissions, with minimal engine modifications. In this part of the work, no changes have been made to the fuel injection timing, fuel injectors, or engine programming. Changes to the fuel system have been made to allow for the fuel to be delivered to the common rail as a liquid by maintaining the DME-diesel blend at over 100 psi.

Over the last ten years, many researches have begun to evaluate the performance and emissions effects of neat dimethyl ether. Sorenson and Mikkelsen [25] found that for a fixed speed and across various loads, the particulate and NO_x emissions from a .273 Liter direct injection single cylinder engine fueled with neat dimethyl ether could be significantly reduced as compared to emissions when fueled with diesel. In the same study, the HC and CO emissions showed little to no change. Later, Sorenson and Mikkelsen [26] further studied the HC emissions from this same engine, and found that there was an increase in the HC emissions when using neat DME, with more methane found than in a typical diesel engine, and less light hydrocarbons. With another engine, Christensen and Sorenson [27] looked at various effects on the suite of emissions when using neat DME. Of particular interest, the NO_x emissions were significantly reduced when the injection timing was retarded towards Top Dead Center (TDC). However, there was an increase in the CO emissions, and little effect on the HC emissions. Other effects tested determined that lower injector opening pressure reduces NO_x, and nozzle types did not seem to influence NO_x emissions. Experiments completed by Kajitani and coworkers [28] also supported effects of injection timing on reducing NO_x, and having little effect on HC emissions, from a single cylinder Yanmar engine fueled with neat DME.

However, in the work completed by Hupperich and coworkers [29] with a 1.75 liter single cylinder engine for the ECE R49 13-mode test, the cumulative emissions show some differing results. With the use of neat DME, HC emissions are reduced. The trends with the other emissions are similar to what had been determined with previous studies. One difference to note is the change in injection nozzle size, which may have effected the emission results in allowing for more complete combustion of all fuels tested in an effort to maintain consistent conditions.

Recently, experiments completed by Ikeda and coworkers [30] with a single cylinder engine using a binary fuel injection method, showed similar NO_x emissions between diesel fuel and 40% DME mixed with diesel fuel, as injection timing was retarded. Also, HC emissions increased and smoke emissions were reduced as injection timing was retarded. In addition, comparisons were made as a function of BMEP. NO_x was reduced, HC remained constant and smoke increased with increasing Brake Mean Effective Pressure (BMEP). The experiments also included % DME fractions, but no comparisons were made to the baseline diesel fuel.

Many researchers have been evaluating the performance of other oxygenates including blends of glycol ethers with diesel fuel, and have observed decreases in particulate matter emissions with increasing oxygenate concentration. Most recently, Hallgren and Heywood [31] prepared a review of the collection of work which showed that as the oxygen content of the fuel increases, the particulate matter is reduced, suggesting that this occurs regardless of chemical structure or molecular weight. However, their actual testing showed that the oxygenate structure did impact particulate emissions. Studies completed by Hess et al. [10] as well as by Litzinger and coworkers [11,12] have shown that higher molecular weight glycol ethers are also effective in reducing particulate matter emissions, although to a lesser extent than monoglyme or diglyme.

Although it has been shown that glycol ethers effectively reduce particulate emissions, the fundamental mechanisms of the reduction have not been clearly identified. There has been some work in simulating the ignition and rate mechanism behavior of dimethyl ether in comparison to dimethoxymethane [19]. Also, oxidation mechanisms have been proposed for gaseous forms of DME [32-34]. Limited data is available for many of the liquid oxygenates under consideration.

For this experimental work, an Emissions Certification Diesel-LS, provided by Specified: Fuels & Chemicals, LLC., used in combination with dimethyl ether, was evaluated in a multi-cylinder direct injection (DI) engine. In-cylinder pressure measurements provided information about the impact of the oxygenated fuel on the combustion process. In addition, fuel property tests were performed on the base fuels, as well as for the blended fuels. These measurements were used to understand and describe the combustion behavior. Since dimethyl ether is a vapor at 1 atm, the fuel property tests for the fuel blends were performed under pressure to maintain the DME in a liquid state. Because not all tests could be performed, data for DME reported in literature is used for most values. Therefore, the fuel system of the engine was redesigned to accommodate the pressurized fuel delivery.

EXPERIMENT

TEST ENGINE- For the purpose of studying the effects of fuel additives on light-medium duty diesel combustion, a Navistar T444E 7.3L Turbodiesel engine was coupled to a 450 horsepower Eaton (Model AD-1802) eddy-current dynamometer. The specifications for the engine are given in Table 1. A Pentium PC with Keithley Metrabyte DAS-1800 data acquisition card was connected to the engine to log real-time engine parameters. These parameters included engine speed, torque, and power from the engine. A Modicon PLC was used to record temperatures from the engine, as well as, for the entire experimental system. Intake airflow rates were determined via an electronic flow sensor, which was calibrated using a laminar flow element. Fuel consumption was monitored using a precision Sartorius scale (Model EA60EDE-1) , with an accuracy of ± 2 grams. Figure 1 shows the test cell set up, and additional equipment used for emissions monitoring.

Table 1. Characteristics of the 1998 Navistar T444E 7.3L Turbodiesel engine

Displacement	444 cu.in. (7.3 Liter)
Bore	4.11 inch (104.39mm)
Stroke	4.18 inch (106.20mm)
Rated Power	190 HP @2300 RPM
Peak Torque	485 lbf-ft @ 1500 RPM
Configuration	Turbo charged, Intercooled (Air-to-Air), Direct Injection
Injection Scheme	HEUI- Hydraulically actuated, electronically controlled unit injectors
Low Idle Speed	700 RPM
Features	Split- shot injection
Compression Ratio	17.5:1

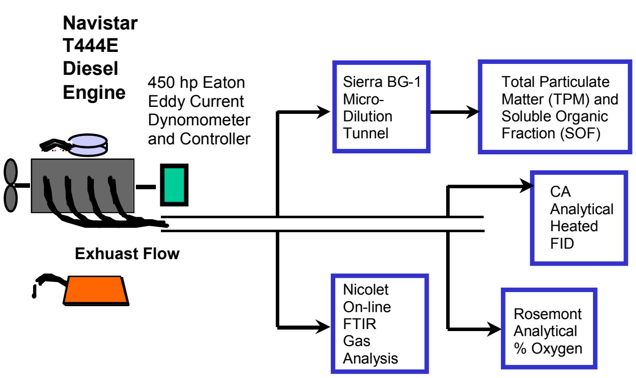

Figure 1. Multicylinder Test Cell, Navistar T444E Turbodiesel

TEST PROCEDURE- In this work, an AVL 8-mode test procedure has been utilized as a model for diesel emissions tests. The AVL 8-mode test was designed to correlate to the U.S. Federal Heavy-Duty Transient Test procedure through a weighted 8- mode steady state test procedure. The 8 modes are a combination of speeds and loads, that produce the same emissions output as would be recorded for a transient cycle [35]. For this engine, the test procedure included the speed and load settings, shown in Table 2.

Table 2. AVL 8-Mode Test for the Navistar T444E 7.3L Turbodiesel engine

Mode	Speed (rpm)	Load (ft-lb)
1	700	0
2	876	84
3	1036	224
4	1212	357
5	2300	77
6	2220	178
7	2220	307
8	2124	409

EMISSIONS EQUIPMENT- An extended warm-up period was used to prepare the engine for testing. The sampling and measurements during each mode commenced when the exhaust temperatures reached steady state. During this time, RPM and torque were maintained within 1-2% of the target test conditions. Once steady-state operation was achieved, a portion of the exhaust gas was passed through a Sierra Instruments BG-1 micro-dilution test stand with a constant dilution air / sample flow ratio of 8:1 and a total flow of 150 liters/min. These settings were chosen in order to maintain the filter temperature below the EPA specification of 52°C. Particulate collection occurred on Pallflex 90mm filters (Type EMFAB TX40HI20-WW), conditioned in an environmental chamber at 25°C and 45% relative humidity before and after sampling. Five particulate samples were taken for each fuel at each test mode.

Exhaust gas analyses were completed using a Nicolet Magna 550 Fourier Transform Infrared (FTIR) Spectrometer. For each mode, five gas samples were analyzed for CO_2, CO, NO and NO_2 . Also, a Rosemont Analytical on-line O_2 analyzer was used to monitor the percent oxygen in the exhaust gas. The oxygen readings were used in conjunction with the mass flow sensor to determine and verify the air / fuel ratio. Additionally, total hydrocarbon emissions were monitored using a California Analytical Instruments Model 300 Heated Flame Ionization Detector (HFID) Total

Hydrocarbon Gas Analyzer. For the total hydrocarbon measurements, undiluted exhaust gas was collected via a heated sample line, which was maintained to 190°C. Calibration of all equipment was completed prior to each day of testing.

PRESSURE TRACE ANALYSIS- In order to observe the impact of the oxygenated blends on combustion and heat release, the combustion chamber of cylinder 1 of the engine was fitted with a Kistler 6125A pressure probe. The pressure sensor was used with a Kistler 2612 optical crank angle encoder to provide time resolved in-cylinder pressure traces of the combustion event. Pressure, crank angle, and TDC trigger signals were acquired with a Kiethley DAS-1800 data acquisition card operating in a "burst " mode. The pressure traces were analyzed with PtrAn V.02, a software product designed by Optimum Power.

TEST FUELS- Previous work has been completed comparing the increasing percentage of oxygenate mixed with diesel fuels within several types of engines [9-18,36]. For this testing, comparisons are made between a 5 wt.% and 10 wt. % oxygen via blending of DME in diesel fuel. The baseline diesel fuel properties, as well as test fuel properties are given below in Table 3. Because of the difficulty in obtaining experimentally the fuel blend properties for DME as a liquid, the properties available in the literature for neat DME are represented, as well as linear calculation of the blends.

PRESSURIZED FUEL DELIVERY SYSTEM FOR DIESEL-DME BLENDS -Dimethyl ether (DME) is a liquefied gas. At room temperature and atmospheric pressure, it is a gas, but changes to a liquid at a moderate pressure. DME is currently manufactured by DuPont Fluorochemicals under the trade name Dymel A. For the purposes of the experimental design, information regarding the vapor pressure and density changes with temperature are available in the Technical Information (ATB-25) bulletin from DuPont.

In tests conducted, DME was found to be miscible with # 2 diesel fuel. Miscibility tests were carried out in a pressurized vessel with a glass observation window. The two fuels were introduced taking care not to mix them. Diesel was introduced first into the bottom of the vessel. DME, which has a specific gravity less than diesel fuel, was then introduced on top of the diesel fuel. Thus, initially there were two distinct layers. The two layers were then observed to mix together without physical agitation after a period of 5 to 6 hours to form a homogeneous mixture. The DME was about 60% by mass in this mixture. Furthermore, no separation was observed after standing undisturbed for about 3 days.
A schematic of the modified fuel system is shown in Figure 2. The fuel system on the T444E engine had to be modified to account for the need to deliver fuel at elevated pressure. The fuel rail in the cylinder head of the engine receives fuel at a pressure of about 70 psi. Fuel from this rail is then fed to the injectors.

A study was performed using #2 diesel fuel to measure the temperature rise of the fuel in the fuel rail. This measurement , coupled with the fuel consumption gave an approximate heat transfer rate between the cylinder head and the fuel in the gallery. A maximum target temperature was chosen for the diesel-DME blend based on the vapor pressure curve of DME and the pressure rating of the fuel rail. The required change in fuel recirculation flow rate was then calculated based on the above observations. This recirculated fuel was then cooled down using a water cooled heat exchanger. The fuel delivery pump was sized based on the above calculations.

Table 3. Fuel Properties

Fuel Property	ASTM Method	ASTM Spec.	Base Diesel	DME	25 wt% DME in Diesel
Viscosity, 40°C, cSt	D 445	1.39-4.20	2.2	.25 [32]	.95[43]
API Gravity	D 287	API 30	35.3		
Cloud Point (°F)	D 2500	<0	4		
Pour Point (°F)	D2500	<0	<0		
Flash Point (°F)	D 93	125	166	-42	
Calorific Value (BTU/lb)	D2015	19700	19483	12228	17669*
Density (kg/m^3)	D4052	.845-.855	.848	.660	.801*
Cetane Number	D613	46-48	47.4	>55	>55*

* Projected

Selecting a pump for DME was challenging due to the properties of DME. Gasket material for the pump had to be modified, as common materials such as Viton and buna-N have been found to be unsatisfactory. A fuel filter with a high filter surface area and high pressure capacity was needed. A modified propane filter was selected for the application. The fuel tank consisted of a modified 60 lb capacity LPG cylinder which was pressure tested at 120 psi prior to use.

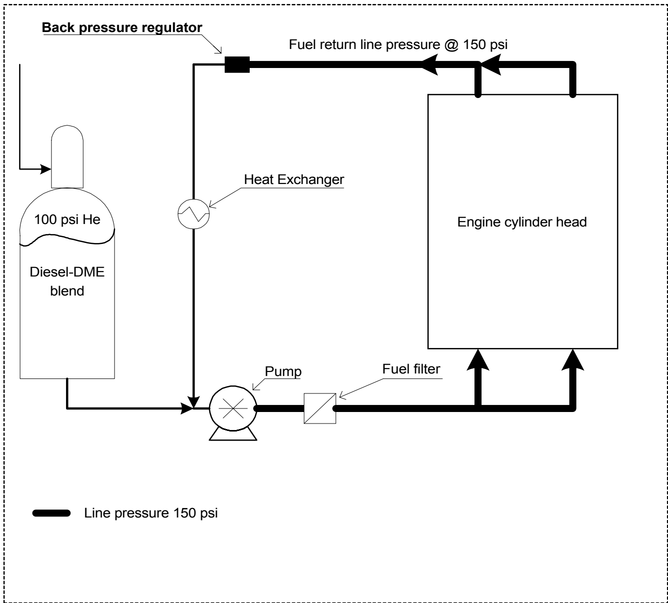

Figure 2. Diagram of Pressurized Fuel System

From the previous studies on this same engine for the 2 wt.% oxygen in diesel, the cooling capacity of the heat exchanger and fuel circuit was determined to be insufficient, based on the fuel temperatures recorded, as well as, observed engine instabilities [37]. Therefore, the system shown in Figure 2 represents the modifications made, which included the addition of a second fuel coil in the cooled bath, and a larger chiller unit for cooling the bath. Additionally, the system was pressurized to 150 psi, which then increases the allowable fuel temperature before the DME becomes vapor.

RESULTS AND DISCUSSION

In this next section, detailed results are provided for the effect of the additive on emissions. Fuel property data is available in Table 3 so that comparisons of the combustion data can be analyzed. Through an uncertainty analysis, based on methods described by Moffat, error bars showing the 95% confidence intervals are presented in each figure [38].

PARTICULATES- As noted previously in the discussion, oxygenates traditionally reduce particulate emissions. The data from this testing indicates that this general trend is for all modes the engine was able to operate, as shown in Figure 3. Using the AVL 8-mode test, the net particulate emission reductions for each mode are found in Table 4. Because the engine was not able to be run for modes 4 and 8 for each additive, the data was presented in a mode by mode comparison. For most modes, shown in Figure 3, particulate reductions were observed on a particulate matter vs. fuel consumed basis. As the engine load is increased, the particulate emission is lowered, except for mode 4. This is true for the low as well as the high engine speeds. The trends follow what would be expected from prior work on oxygenated fuels. Mode 4 operates the engine near the peak torque, and the overall emissions change, possibly due to a change in the injection timing.

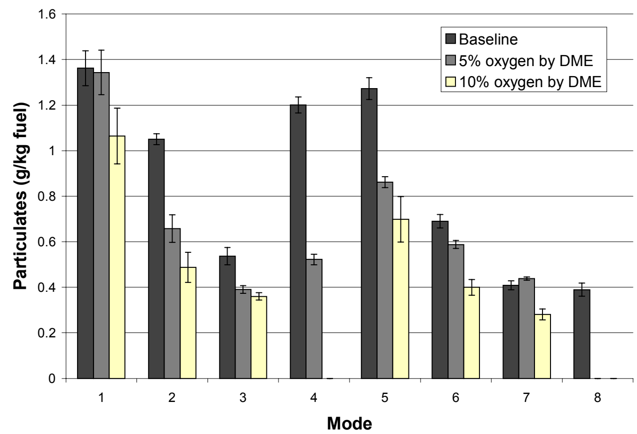

Figure 3. Particulate Matter Results per unit fuel consumed, g/kg fuel

As has been shown in previous work, this particulate reduction is due to a reduction in the soot portion of the emission, which would result in a percentage increase in the soluble organic faction (SOF) portion [6]. This has also been confirmed more recently by Sidhu and coworkers [39], with DME giving the highest SOF.

OXIDES OF NITROGEN (NO_x)-Table 4 reports the brake specific NO_x ($BSNO_x$) emissions. Figure 4 shows that at lower loads NO_x decreases. At higher loads, NO_x increases. The oxygenated additive leads to reduced NO_x at the lower load conditions, possibly due to the injection timing of the engine. The NO_x emission decreases for the 5 wt. % oxygen, and then begins to increase with additional oxygen content, as shown in modes 1 and 2. The Hydraulically actuated Electronically controlled Unit Injector (HEUI) use a split shot injection at the lower engine speeds, which may be providing better mixing to the fuel and air, and thus reducing NO_x. At higher engine speeds, NO_x is lower, and NO_x increases as load increases. There are conflicting reports in the literature as to whether oxygenates increase or decrease NO_x emissions [3,5,6,12,16]. The data from this engine, however, shows a reduction in NO_x emissions on a brake specific basis, for most modes. Choi and Reitz [5] observed that there is a small penalty on the NO_x emissions when using a split injection strategy (two fuel pulses) with an oxygenated fuel, which could be affecting the results for modes 1 and 2 for this particular engine. Because the unique multiple fuel injection strategy of the Navistar T444E is especially predominant at lower speeds, the NO_x reduction could occur due to better improved mixing effect in the cylinder during the combustion event.

Table 4. AVL 8-mode Emissions Results per mode, Brake Specific Basis

a.

Particulate Emissions Per Mode	**Baseline Diesel (g/bhp-hr)**	**5wt. % oxygen via DME (g/bhp-hr)**	**10wt. % oxygen via DME (g/bhp-hr)**
1	3.36	3.44	2.87
2	.224	.149	.118
3	.091	.069	.082
4	.209	.095	NA
5	.339	.255	.214
6	.137	.128	.092
7	.078	.086	.057
8	.068	NA	NA

b.

NOx Per Mode	**Baseline Diesel (g/bhp-hr)**	**5wt. % oxygen via DME (g/bhp-hr)**	**10wt. % oxygen via DME (g/bhp-hr)**
1	43.91	24.74	36.54
2	3.31	3.21	4.14
3	3.52	3.85	4.80
4	3.35	4.01	NA
5	3.18	2.36	2.40
6	2.44	2.05	2.11
7	2.37	2.67	2.99
8	3.42	NA	NA

c.

CO Per Mode	**Baseline Diesel (g/bhp-hr)**	**5wt. % oxygen via DME (g/bhp-hr)**	**10wt. % oxygen via DME (g/bhp-hr)**
1	40.0	51.8	75.93
2	1.60	1.97	2.75
3	.560	.689	.671
4	8.12	7.63	NA
5	2.33	4.16	6.59
6	.913	1.344	2.10
7	.691	.875	.916
8	.493	NA	NA

d.

Hydrocarbon Per Mode	**Baseline Diesel (g/bhp-hr)**	**5wt. % oxygen via DME (g/bhp-hr)**	**10wt. % oxygen via DME (g/bhp-hr)**
1	34.3	51.4	48.5
2	.707	1.78	1.54
3	.211	.953	1.54
4	.137	.561	NA
5	.549	3.07	3.18
6	.216	1.22	1.28
7	.127	.777	.430
8	.094	NA	NA

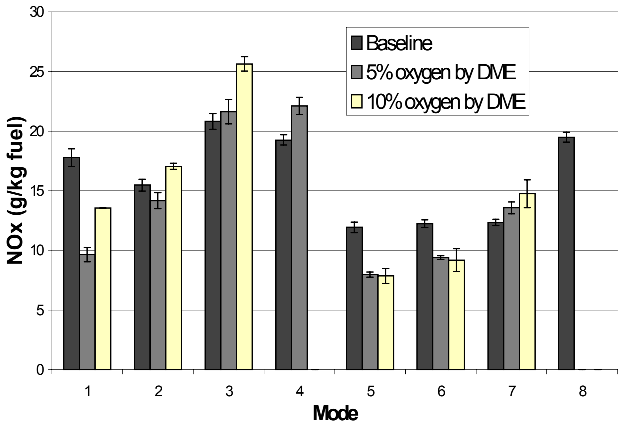

Figure 4. **NOx Emission Results per unit fuel consumed, g/kg fuel**

Figure 5 presents the particulate matter vs. NO_x tradeoff per mode. As can be seen for modes with lower loads, as particulates are reduced, NO_x is reduced. However, for modes 3, 4 and 7, an increase in NO_x with decreasing particulates is observed. In some cases, the PM-NO_x emissions point shifts toward the origin, which demonstrates that oxygen addition is a viable means of reducing diesel engine emissions. However, this is not true for all cases, and could possibly be due to changes in injection timing by the engine controls, and not necessarily a function of the changing fuel properties.

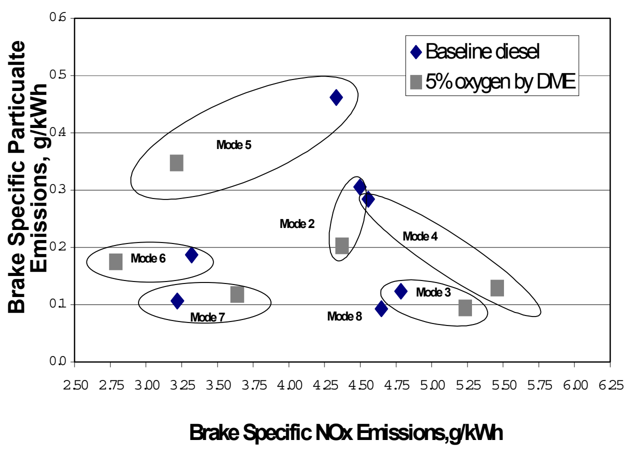

Figure 5. **Brake-Specific Particulate Emission vs. NOx Emission Tradeoff**

CARBON MONOXIDE (CO)- Table 4 reports the brake specific CO (BSCO) emissions. On a CO per unit of fuel basis, CO emissions increase as the wt. % oxygen is increased, with a decreasing effect as the load increases. In general, CO decreases as load increases, as shown in Figure 6. This may again support the idea that during the low speed and low load conditions, CO formed during early reaction of the fuel is impeded from conversion to CO_2. This was postulated by Litzinger and coworkers [12]. As explained by Glassman, the conversion of CO to CO_2 would be a function of the size of the hydroxyl radical pool, which does not grow until most all the original fuel and hydrocarbons have been consumed [40]. Since the concentration of hydroxyl radicals is important in the rate of CO oxidation, the additional molecules of oxygen from DME may be playing a role in providing excess CO and CO_2 which continue the creation of the hydroxyl radical pool. In addition, Flynn and coworkers show through kinetic simulations that the addition of the oxygen in the fuel leads to reduced amounts of soot precursors, and larger amounts of carbon leaving the fuel rich premixed combustion zone as CO [41].

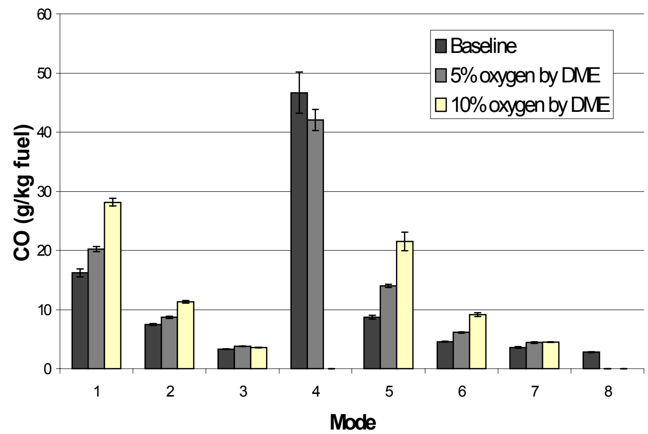

Figure 6. **CO Emission Results per unit fuel consumed, g/ kg fuel**

HC- The brake specific emissions for each mode are reported in Table 4. In general, the HC emissions decrease with higher engine loads, as the engine combustion efficiency increases. For all modes, HC emissions increase with oxygen addition, and decrease as engine load increases, as seen in Figure 7. For the lower engine speeds, as the oxygen addition increases, the HC emissions decrease. However, because very few data points are involved with this figure, it would be important to repeat the study. This data is inconsistent with what has been observed by some previous engine studies.

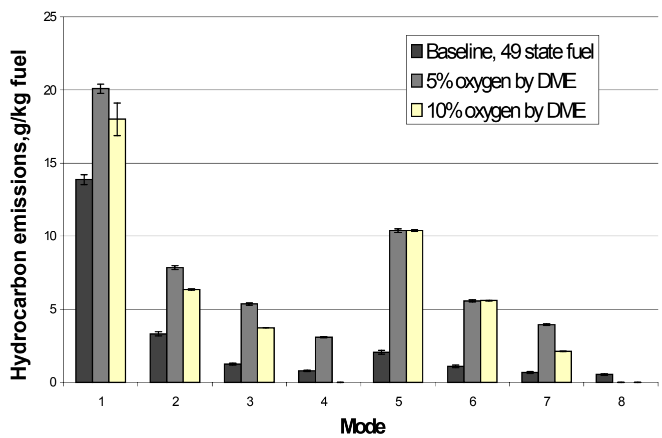

Figure 7. Hydrocarbon Emission Results per unit fuel consumed, g/ kg fuel

FUEL CONSUMPTION- Figure 8 reports the brake specific fuel consumption (BSFC) for the DME addition. The general trend shows an increase in the amount of fuel required to maintain the same speed and load. This is due to the slightly lower calorific value of the fuel blend, as shown in the Fuel Properties of Table 3. However, when fuel consumption is calculated on an energy basis, the energy consumption results are not significantly different.

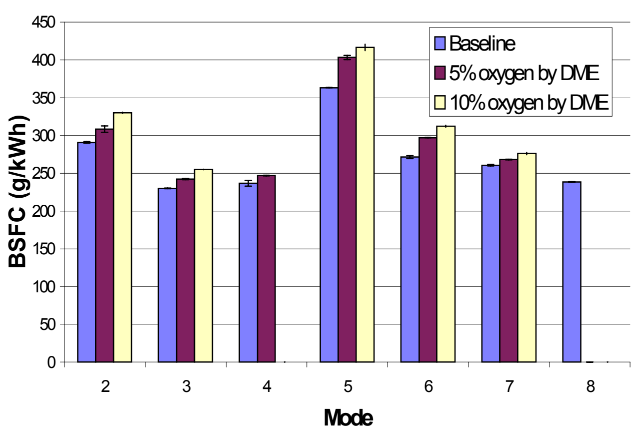

Figure 8. Brake Specific Fuel Consumption (BSFC)

CONCLUSION

On-going research continues in testing and reviewing the effects of oxygenates on the composition of emissions from diesel engines. The results in this paper lead to the following conclusions:

- DME has been shown to reduce particulate emissions from a DI diesel engine. Through the addition of oxygen contained within the hydrocarbon structure of the fuel, additional CO and CO2 are present in the combustion process. This prevents the formation of soot precursors, which reduces the formation of particulates.

- Higher amounts of CO have been observed for each mode. This can be explained by the presence of the fuel born oxygen creating a larger pool of CO and CO_2, which aids in creating hydroxyl radicals, thus quenching the combustion process and leaving CO not oxidized.

- It has also been observed that along with a reduction in particulate emissions per mode, there is a small NO_x reduction for some modes. It is unclear what may be causing this, but several possible reasons are given. Multiple injections at lower loads and speeds may explain the reason for this data. Also, there may be some affect of the increased fueling required by the engine, as the fuel oxygen content changes. The net effect is some change in the ignition timing of the fuel, as a result of the engine control adjusting injection timings differently for each fuel.

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REFERENCES

1. Karim, G.A., “Combustion in Gas Fueled Compression-Ignition Engines”, ICE Paper No. 2000-ICE-299, Vol.35-1, ASME ICE Fall Technical Conference (2000).
2. Neeft, J.P.A., Makkee, M. and Moulijn, J.A. *Fuel Proc. Tech.*, 47:1-69 (1996).
3. McCormick, R.L., Ross, J.D. and Grabowski, M.S., *Environ. Sci. Tech.,* 31:1144-1150 (1997).
4. Grabowski, M.S. and McCormick, R.L. *Prog. Energy and Combust. Sci.* 24:125-164 (1998).
5. Choi, C.Y. and Reitz, R.D. *Fuel*, 78:1303-1317 (1999).
6. Liotta, F.J, and Montalvo, D.M., Society of Automotive Engineers Technical Paper No. 932734, Society of Automotive Engineers, Warrendale, PA (1993).
7. Ullman, T.L., Spreen, K.B. and Mason, R.L., Society of Automotive Engineers Technical Paper No. 941020, Society of Automotive Engineers, Warrendale, PA (1994).
8. Spreen, K.B., Ullman, T.L. and Mason, R.L. Society of Automotive Engineers Technical Paper No. 950250, Society of Automotive Engineers, Warrendale, PA (1995).
9. Tsurutani, K., Takei, Y., Fujimoto, Y., Matsudaira, J. and Kumamoto, M., Society of Automotive Engineers Technical Paper No. 952349, Society of Automotive Engineers, Warrendale, PA (1995).
10. Hess, H.S., Roan, M.A., Bhalla, S., Butnark, S., Zarnescu, V., Boehman, A.L., Tijm, P.J.A. and Waller, F.J., ACS Preprints, Division of Petroleum Chemistry, 43(4):593-596 (1998).
11. Stoner, M. and Litzinger, T., Society of Automotive Engineers Technical Paper No. 1999-01-1475, Society of Automotive Engineers, Warrendale, PA (1999).
12. Litzinger, T., Stoner, M., Hess, H. and Boehman, A., *Int. J. Engine Res.*, accepted for publication (2000).
13. Beatrice, C., Bertoli, C., D’Alessio, J., Del Giacomo, N., Lazzaro, M. and Massoli, P. *Comb. Sci. and Tech.,* 120:335-355 (1996).
14. Bertoli, C., Del Giacomo, N. and Beatrice, C., Society of Automotive Engineers Technical Paper No. 972972, Society of Automotive Engineers, Warrendale, PA (1997).
15. Beatrice, C., Bertoli, C. and Del Giacomo, N. *Comb. Sci. Tech.,* 137:31-50 (1998).
16. Beatrice, C., Bertoli, C., Del Giacomo, N. and Migliaccio, M.na., Society of Automotive Engineers Technical Paper No. 1999-01-3595, Society of Automotive Engineers, Warrendale, PA (1999).
17. Miyamoto, N., Ogawa, H., Nurun, N.M., Obata, K. and Arima, T., Society of Automotive Engineers Technical Paper No. 980506, Society of Automotive Engineers, Warrendale, PA (1998).
18. Nabi, M.N., Minami, M., Ogawa, H. and Miyamoto, N., Society of Automotive Engineers Technical Paper No. 2000-01-0231, Society of Automotive Engineers, Warrendale, PA (2000).
19. Edgar, B.L., Dibble, R.W. and Naegeli, D.W., Society of Automotive Engineers Technical Paper No. 971677, Society of Automotive Engineers, Warrendale, PA (1997).
20. Murayama, T., Zheng, M., Chikahisa, T., Oh, Y.-T., Fujiwara, Y., Tosaka, S., Yamashita, M. and Yoshitake., H., Society of Automotive Engineers Technical Paper No. 952518, Society of Automotive Engineers, Warrendale, PA (1995).
21. Rubino, L. and Thompson, M.J., Society of Automotive Engineers Technical Paper No. 1999-01-3589, Society of Automotive Engineers, Warrendale, PA (1999).
22. Hansen, J., etal. Society of Automotive Engineers Technical Paper No. 950063, Society of Automotive Engineers, Warrendale, PA (1995).
23. Ofner, H., et al., Society of Automotive Engineers Technical Paper No. 981158, Society of Automotive Engineers, Warrrendale, PA (1998).
24. Sivebeck,I, et.al., Society of Automotive Engineers Technical Paper No. 2001-01-2013, Society of Automotive Engineers, Warrendale, PA (2001).
25. Sorenson, S.C., and Mikkelsen, S., Society of Automotive Engineers Technical Paper No. 950064, Society of Automotive Engineers, Wartrendale, PA (1995).
26. Mikkelsen, S.C., et al., *Application of Powertrain and Fuel Technologies to Meet Emissions Standards* , IMechE, p.289, (1996).
27. Christensen, R., et al., Society of Automotive Engineers Technical Paper No. 971665, Society of Automotive Engineers, Warrendale, PA (1997).
28. Kajitani, S., et al., Society of Automotive Engineers Technical Paper No. 972973, Society of Automotive Engineers, Warrendale, PA (1997).
29. Hupperich, P., et al., ASME Technical Paper No. 97-ICE-65, ASME 1997 Fall Technical Conference, ICE-Vol. 29-3, (1997).
30. Ikeda, M., et al., Society of Automotive Engineers Technical Paper No. 2000-01-2006, Society of Automotive Engineers, Warrendale, PA (2000).
31. Hallgren B., and Heywood, J., Society of Automotive Engineers Technical Paper No. 2001-01-0648, Society of Automotive Engineers, Warrendale, PA (2001).
32. Mueller, M., Yetter, R., and Dryer, F., *Twenty-Seventh Symposium (International) on Combustion*, 177-184 (1998).
33. Dagaut, P., Daly, C., Simmie, J., and Cathonnet, M., *Twenty-Seventh Symposium (International) on Combustion*, 361-369 (1998).
34. Amano T., and Dryer, F., *Twenty-Seventh Symposium (International) on Combustion*, 397-404 (1998).
35. Fleisch,T., McCarthy, C., Basu, A., Udovich, C., Charbonneau, P., Slodowske, W., Mikkelsen, S., McCandless, J., Society of Automotive Engineers Technical Paper No. 950061, Society of Automotive Engineers, Warrendale, PA (1995).

36. Hess, H., Boehman, A., Tijm, P., and Waller, F.J., Society of Automotive Engineers Technical Paper No. FL-00-0566, Society of Automotive Engineers, Warrendale, PA. (2000).
37. Chapman, E., Bhide, S., and Boehman, A., Society of Automotive Engineers Technical Paper No. 2000-01-2887, Society of Automotive Engineers, Warrendale, PA (2000).
38. Moffat, R.J., Experimental Thermal and Fluid Science, 1:3-17 (1988).
39. Sidhu, S., et al., *Chemopshere* Vol. 42, pg. 681-690, (2001).
40. Glassman, I. Combustion, 2nd edition, Orlando, FL: Academic Press, 1987.
41. Flynn, P.F.,et al., Society of Automotive Engineers Technical Paper No. 1999-01-0509, Society of Automotive Engineers, Warrendale, PA (1999).
42. Tijm, P.J.A., Waller, F.J., Toseland, B.A. and Peng, X.D., "'Liquid Phase Di-Methyl Ether TM' A promising New Diesel Fuel", Energy Frontiers International Conference, Alaska (1997).
43. Bhide, S. Boehman, A., and Perez, J., "Viscosity of DME-Diesel fuel blends", to be presented at American Chemical Society, National Meeting, Chicago, IL, August 2001.

DEVELOPMENT OF A DIMETHYL ETHER-FUELED SHUTTLE BUS

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Introduction

Dimethyl ether has been considered a potential ultra-clean replacement fuel for diesel engines [1]. Dimethyl ether (DME) burns "smokeless", permits high levels of EGR for in-cylinder NOx control and can be produced from synthesis gas derived from fossil fuel or biomass resources. These potential benefits of DME have motivated studies of the physical properties, the lubricity concerns and the combustion performance of DME [2,3]. In the present work, we seek to operate a laboratory engine and a campus shuttle bus on DME. To overcome the low lubricity and low viscosity of DME so as to be able to operate a conventional, common rail, DI diesel engine on DME, we have chosen to blend DME and diesel fuel. The conversion of the laboratory engine and the shuttle bus required development of a pressurized fuel delivery system to maintain the DME-diesel fuel blend above the vapor pressure of DME. This paper summarizes the outcomes from analyses of fuel properties, the laboratory engine studies and the conversion of the shuttle bus.

Experimental

Viscosity of DME-Diesel Blends. Quantitative measurements of the viscosity of blends of DME in a federal low sulfur fuel were obtained using a high pressure viscometer, using capillary tubes that provided optimal measurement accuracy depending on the viscosity of the fuel mixture [4]. Measurements were obtained over a range of pressures with the viscometer housing immersed in a constant temperature bath at 100°F (38°C). Results obtained at three different levels of chamber pressure are plotted in Figure 1 to show the impact of DME content on viscosity.

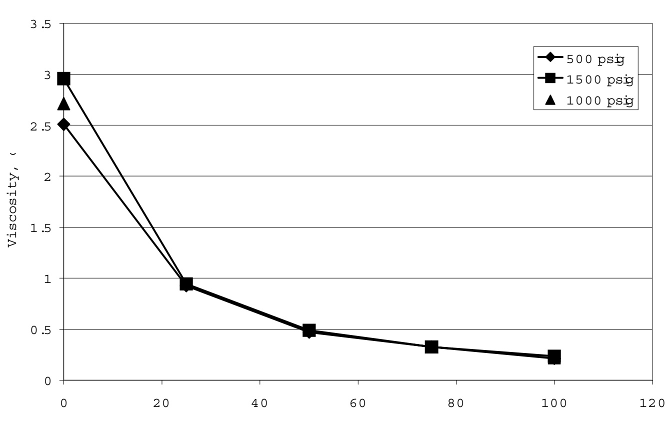

Figure 1. Blend response of viscosity to DME addition at various pressures [4].

Laboratory Engine Studies. The fuel system on the Navistar 7.3L V-8 "T444E" turbodiesel engine had to be modified to permit delivery of the fuel blend at elevated pressure [5]. The fuel rail in the cylinder head of the engine receives fuel at a pressure of about 70 psi. Fuel from this rail is then fed to the injectors.

A study was performed using #2 diesel fuel to measure the temperature rise of the fuel in the fuel rail. This measurement, coupled with the fuel consumption gave an approximate heat transfer rate between the cylinder head and the fuel in the gallery. A maximum target temperature was chosen for the diesel-DME blend based on the vapor pressure curve of DME and the pressure rating of the fuel rail. The required change in fuel recirculation flow rate was then calculated based on the above observations. This recirculated fuel was then cooled down using a water cooled heat exchanger. The fuel delivery pump was sized based on the above calculations.

Selecting a pump for DME was challenging due to the properties of DME. Gasket material for the pump had to be modified, as common materials such as Viton and buna-N have been found to be unsatisfactory. A fuel filter with a high filter surface area and high pressure capacity was needed. A modified propane filter was selected for the application. The fuel tank consisted of a modified 60 lb capacity LPG cylinder which was pressure tested at 120 psi prior to use.

From previous studies on this same engine for 2 wt.% oxygen in the diesel fuel, the cooling capacity of the heat exchanger and fuel circuit was found to be insufficient, based on the fuel temperatures recorded, as well as, observed engine instabilities. Therefore, the system shown in Figure 2 presents the modifications made, which included the addition of a second fuel coil in the cooled bath, and a larger chiller unit for cooling the bath. Additionally, the system was pressurized to 150 psi, which then increases the allowable fuel temperature before the DME becomes vapor.

Operation of the laboratory engine on blends of DME and diesel fuel resulted in reduction of particulate matter emissions. As shown in Figure 3, blending at up to 25 wt.% DME in diesel, corresponding

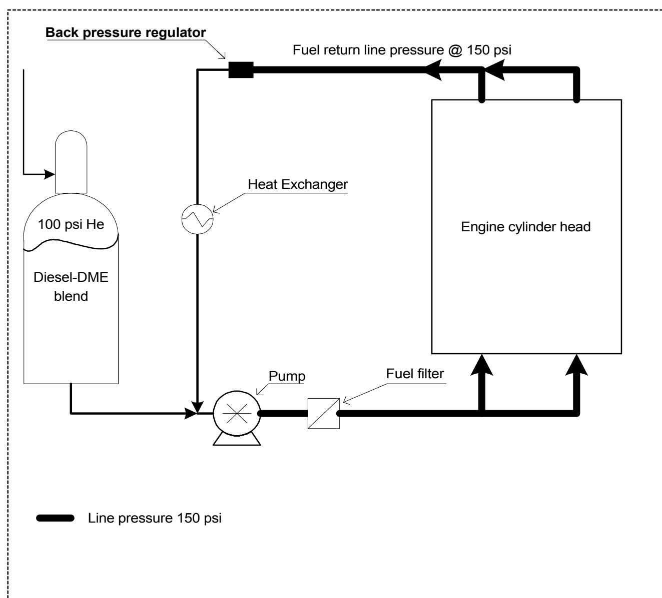

Figure 2. Diagram of the pressurized fuel system [5].

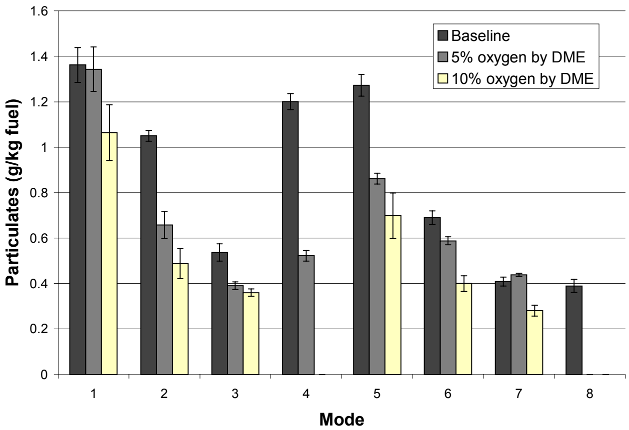

Figure 3. Particulate Matter Results per unit fuel consumed, g/kg fuel [5].

to 10 wt.% oxygen addition resulted in significant reduction in particulate matter emissions.

Shuttle Bus Conversion

The final stage of this project was the conversion of a campus shuttle bus and operation of the bus on the DME-diesel fuel blends. To accomplish this goal, the pressurized fuel system on the laboratory engine was adapted for application to a Champion Motorcoach "Defender" model bus with the same model engine (Navistar T444E) as was used in the laboratory study. To simplify the requirements for the fueling station for the shuttle bus, mixing of the DME and diesel fuel is performed onboard the bus. Figure 4 shows the shuttle bus used in this study. The final design and the operational procedures were reviewed and modified in a detailed "HAZOP" or failure modes effects analysis (FMEA). The outcome of the HAZOP analysis was to increase the number of check valves, manual valves and redundancy in the system.

The system on the bus consists of a transfer pump that delivers diesel fuel from the existing diesel fuel tank to the tank for the blended fuels, a propane tank for a recreational vehicle. This LPG tank was modified only by replacing o-ring materials with Kalrez^{TM} o-rings. The connections on the LPG tank permit diesel fuel to be transferred to the tank, while the tank is vented to the atmosphere. Then, DME is transferred into the LPG tank. During the refueling processes, a handheld controller notifies the operator of the fill level in the LPG tank so that the desired proportions of fuel are transferred. Finally, a compressed cylinder of helium is connected to the LPG tank to provide a blanket of inert gas to maintain a minimum of 120 psig in the LPG tank and keep the DME in the liquid phase. A magnetically coupled gear pump serves to draw fuel from the LPG tank and transfer the fuel blend to the fuel rails in the cylinder heads of the engine. A backpressure regulator maintains the pressure in the fuel rails at a minimum of 150 psig, although during operation the rail pressure is typically near 200 psig. Fuel rejected from the rails passes through a pair of fuel coolers mounted in front of the radiator to keep the fuel temperature from rising above a bulk temperature of 50°C.

Upon completion of the majority of the conversion process, the bus was operated with the pressurized fueling system on diesel fuel but without DME blending. The bus was operated over several days at the Pennsylvania Transportation Institute's test track near the Penn

Figure 4. Particulate Matter Results per unit fuel consumed, g/kg fuel.

State University Park campus. During this shakedown process, emissions measurements were obtained in collaboration with Clean Air Technologies (Buffalo, NY) using their portable diesel emissions analyzer (XXX). Among the chief challenges faced during the conversion and shakedown tasks was the power requirements and stability of operation of the gear pump. However, in-field adjustments and modifications resulted in consistent and stable operation of the components of the pressurized fueling system. The shuttle bus will operate on the DME-diesel fuel blend, at 25 wt.% DME, through Fall 2002 during which time periodic performance, emissions and system integrity tests will be performed.

Conclusions

Operation of a commercial diesel engine on DME-diesel blends has been accomplished with minimal modification to the engine, apart from addition of a pressurized fuel delivery system. This technique permits operation of vehicles, in part, on DME without jeopardizing the long term durability of the engine. Consistent with operation of diesel engines on oxygenated fuels, particulate emissions with the DME-diesel fuel blends are substantially reduced.

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References

(1) Fleisch, T., McCarthy, C., Basu, A., Udovich, C., Charbonneau, P., Slodowske, W., Mikkelson, S.-E., and McCandless, J., **1995**, SAE Paper No. 950061.

(2) Sivebaek, I. M., Sorenson, S. C., and Jakobsen, J., **2001**, SAE Paper No. 2001-01-2013.

(3) Teng, H., McCandless, J.C. and Schneyer, J.B., **2002**, SAE Paper No. 2002-01-0862.

(4) Bhide, S.V., Boehman, A.L. and Perez, J.M., Prepr. – *Am. Chem. Soc., Div. Fuel Chem.*, **2001**, *46*(2), 400.

(5) Chapman, E.M., Boehman, A.L., Tijm, P.J.A. and Waller, F.J., **2001**, SAE Paper No. 2001-01-3683.

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Development of a Dimethyl Ether (DME)-Fueled Shuttle Bus

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ABSTRACT

Dimethyl Ether (DME) is a potential ultra-clean diesel fuel. Its unique characteristics require special handling and accommodation of its low viscosity and low lubricity. In this project, DME was blended with diesel fuel to provide sufficient viscosity and lubricity to permit operation of a 7.3 liter turbodiesel engine in a campus shuttle bus with minimal modification of the fuel injection system. A pressurized fuel delivery system was added to the existing common rail injection system on the engine, allowing the DME-diesel fuel blend to be circulated through the rail at pressures above 200 psig keeping the DME in the liquid state. Fuel exiting the rail is cooled by finned tubed heat exchangers and recirculated to the rail using a gear pump. A modified LPG tank (for use on recreational vehicles) stores the DME- diesel fuel blend onboard the shuttle bus. A small cylinder of helium is used to provide a blanket of inert gas above the fuel mixture to keep the DME in the liquid state and to push the mixture to the fuel rails. A significant challenge is posed by the rapid increase in DME vapor pressure with increasing fuel temperature. As the fuel mixture passes through the rail, it is heated by the surrounding surfaces in the cylinder head. The target for maximum fuel rail temperature was set at 50°C, which corresponds to a DME vapor pressure of 150 psig. Refueling was accomplished by mixing the diesel fuel and DME onboard the bus, with diesel fuel delivered from the existing diesel tank and DME delivered by 1000 lb cylinders at a small refueling station. The shuttle bus operates on the Faculty/Staff loop at the University Park campus of the Pennsylvania State University.

INTRODUCTION

The motivation for researching new fuels stems from several factors. Primarily governments worldwide, including the United States, are setting stricter standards for emissions from new engines and vehicles. This is being done for the benefit of human health and the environment, via the reduction of particulate matter and smog-causing NOx [1]. The final ruling in December 2000 from the U.S. EPA sets the new 2007 standards for heavy duty diesel engines to the following:

- Particulate Matter (PM) emissions to 0.01 grams per brake-horsepower-hour (g/bhp-hr) to take full effect in 2007, and

- NOx and non-methane hydrocarbons (NMHC) to 0.20 g/bhp-hr and 0.14 g/bhp-hr, respectively. These standards will be phased in after 2007 [2].

Table 1 shows the trend in the tightening of emission standards.

Emissions Type	**Current Regulation (g/bhp-hr)**	**2004 (g/bhp-hr)**	**2007 (g/bhp-hr)**
NO_x	4		.2
HC	1.3		.14 (NMHC)
NO_x and HC		2.4	
PM	.1		.01

*Required on-board diagnostics (OBD) systems for vehicles between 8500 and 14000 lbs to be phased-in, beginning in 2005

NO_x- Nitrogen Oxides ; HC- Hydrocarbons; PM- Particulate Matter

Table 1. U.S. Heavy-Duty Diesel Engine Emission Standards [1, 2]

If fuels can be synthesized from domestic resources and engineered to meet the upcoming emissions standards, there will be additional benefits for the energy security of the United States [3]. These new fuels, must then undergo substantial testing to demonstrate their compatibility with engine and vehicle technologies, or to demonstrate the extent to which engine and vehicle technologies need to be altered to make use of the fuel. This means that fuel development projects require both experimental "proof of concept" and field vehicle testing.

Dimethyl ether is a potential ultra clean diesel fuel that could be synthesized from a variety of feedstocks, which can support the use of alternative energy resources [10, 11]. DME is a compound that has been targeted for future use as a fuel in several countries around the world [4-6]. Motivation to use DME exists for several reasons. There has been confirmation that the fuel yields low particulate emissions and possibly lower NOx emissions [7-9].

The following review of the literature will cover a summary of the testing completed to examine the potential use of DME as a fuel. Many technical challenges have been discovered during this testing, shedding light on new approaches for using DME as a fuel. Researchers have started to study the fundamental nature of the combustion process, and to understand the mechanisms of DME combustion [12, 13]. Although use of DME has been demonstrated in compression ignition engines, technical challenges exist in transferring that knowledge to field vehicles.

PROPERTIES OF DIMETHYL ETHER

Compounds in which two hydrocarbon groups are bonded to one oxygen, represented as R-O-R', are called ethers. The organic groups bonded to the ether may be alkyl, aryl, or vinylic, and the molecule can either be an open chain or ring configuration [14]. Ethers commonly observed in long chain structures are referred to as linear ethers. As compared to alkanes of similar structure, where the CH2 group replaced the O atom , the boiling points of ethers are higher [14]. This class of oxygenated compounds have high cetane numbers and excellent cold flow properties [15].

Simply stated, dimethyl ether is an ether with two methyl groups on each side of an oxygen atom. Today, DME is predominantly used as an aerosol propellant because, in contrast to other aerosol propellants used previously, it is not harmful to the ozone layer [10]. Also, it is virtually non-toxic and is easily degraded in the upper atmosphere. It can be represented by the structure: CH3-O-CH3. The physical properties of DME are shown in Table 2 along with diesel fuel and propane for comparison [7, 9, 16, 17].

The properties that are significant for the use of DME as a fuel are cetane number, boiling point, and ignition temperature. However, the properties of concern are viscosity, heating value, and vapor pressure.

The cetane number describes the ignition quality of the fuel. The shorter the ignition delay the better the ignition quality of the fuel, and thus, the higher the cetane number. Since DME has a higher cetane number than conventional diesel fuel, it will ignite readily and burn more completely.

Property	DME	Diesel	Propane
Chemical Formula	C_2H_6O	$C_{10.8}H_{18.7}$	C_3H_8
Mole Weight	46.07	148.6	44.11
Critical Temperature- °C	127	-	95.6
Boiling Point- °C	-24.9	71-193	-42.1
Vapor Pressure at 20 °C-kg/m^2	5.1	<0.01	8.4
Critical Pressure-bar	53.7	-	43
Liquid Viscosity- cP	.15	2-4	.10
Liquid Density at 20 °C-kg/m^3	668	800-840	501
Bulk Modulus (N/m^2)	6.37E+08	1.49E+09	
Specific Density,gas	1.59	-	1.52
Solubility in H2O at 20 °C g/l	70	Negligible	.12
Lower Heating Value-kJ/kg	28430	42500	46360
Heat of vaporization-kJ/kg 20°C	410	233	426
Explosion limit in air-vol%	3.4-17	1.0-6.0	2.1-9.4
Ignition temperature at 1 atm- °C	235	250	470
Cetane Number	55-60	40-55	-

Table 2. Properties of Dimethyl Ether [7, 9, 16, 17]

The viscosity of DME is much lower than that of diesel fuel. This offers an advantage in that the fuel will be easier to deliver into the engine cylinder during cold weather conditions. However, some studies have shown that the DME leaks from the injectors [18, 19]. In addition, using neat DME (100% DME as the fuel) within an engine creates some lubricating problems because of the low viscosity. Researchers are now understanding that the inherent lubricating traits of fuels used in automotive fuel injection systems, are also a very significant factor, especially when additives and alternative fuels are being considered [20-23].

The low boiling point of DME is another important advantage for its use as a fuel. Even in cold starting conditions the DME vaporizes in the cylinder yielding better atomization and hence improving combustion. The vapor pressure of DME is a concern since the fuel is a gas at atmospheric pressureand temperture. A pressurized fuel system is required so that the fuels can be mixed and injected as a liquid. This leads to other complications with fuel delivery, although the technology to do this is similar in nature to LPG (Liquid Propane Gas) because it is also moderately pressurized to keep the fuel in a liquid state [24].

Another important aspect of combustion emissions from a compression ignition engine fueled on DME versus diesel fuel, is the reduction and elimination of particulate emissions. Particulate emissions are also commonly known as “soot” or black smoke. The oxygen content of diesel fuel blended with DME (at roughly 40 to 100 wt.%), allows for the emissions to be smokeless, as shown in the literature [7, 9, 16, 25-28]. Nabi and coworkers have shown “smokeless” engine operation from a diesel fuel mixture with an oxygen content at around 38 wt. % [25]. However, the work by Chen and coworkers confirms that even with 80 wt.% DME addition to diesel fuel, some smoke will be produced at high engine loads, although it is a small amount [28].

The heating value of DME is a concern, because it is just 60% that of diesel. This requires a larger volume of fuel to produce the same output from combustion. By altering injection amounts to the cylinders, the amount can be compensated to counteract the decreased heating value and prevent “de-rating” of engine output.

Other issues will need to be addressed in future work regarding the understanding of DME fuel properties, including, the lubricity of the fuel and the combustion mechanism. Because of the need for the fuel to be tested while in the liquid phase under pressure, further analysis outside of combustion studies may be impractical or require development of highly specialized instrumentation.

RESEARCH WITH DME IN ENGINE APPLICATIONS

Dimethyl ether is a common chemical used as a aerosol propellant [29]. The properties of DME are given in Table 2, and are compared to the diesel fuel used for the baseline testing for this experiment. DME is a liquid when contained under moderate pressure, with a vapor pressure of 5.1 bar at 20°C, and is relatively easy to handle. Over the past ten years, researchers have started to consider the use of DME as a fuel. Because the cetane number and ignition temperature are close to that of diesel fuel, DME was thought to be an excellent substitute for use in compression ignition engines. However, there were some drawbacks to using the fuel, including the reduced viscosity and lubricity of the fuel in neat form, as well as fuel compressiblity effects [10].

To potentially overcome the fuel property effects of DME, as well as, reduce emissions, the experiments for this study focus on mixing dimethyl ether with diesel fuel. The initial goal is to determine the effect of the oxygen concentration on the emissions, with minimal engine modifications. In this part of the work, no changes have been made to the fuel injection timing, fuel injectors, or engine programming. Changes to the fuel system have been made to allow the fuel to be delivered to the common rail as a liquid by maintaining the DME-diesel blend at a pressure greater than 100 psi.

Over the last ten years, many researchers have begun to evaluate the performance and emissions effects of neat dimethyl ether. Sorenson and Mikkelsen [7] found that for a fixed speed and across various loads, the particulate and NOx emissions from a .273 Liter direct injection single cylinder engine fueled with neat dimethyl ether could be significantly reduced as compared to emissions with diesel fuel. In the same study, the HC and CO emissions showed little or no change. Later, Sorenson and Mikkelsen [30] further studied the HC emissions from this same engine, and found that there was an increase in the HC emissions when using neat DME, with more methane found than in a typical diesel engine exhaust, and less light hydrocarbons. With another engine, Christensen and Sorenson [31] looked at various effects on the suite of emissions when using neat DME. Of particular interest, the NOx emissions were significantly reduced when the injection timing was retarded towards Top Dead Center (TDC). However, there was an increase in the CO emissions, and little effect on the HC emissions. Other tests determined that lower injector opening pressure reduces NOx, and nozzle types did not seem to influence NOx emissions. Experiments by Kajitani and coworkers [26] also showed the effects of injection timing on reducing NOx, which had little effect on HC emissions, from a single cylinder Yanmar engine fueled with neat DME.

However, in the work completed by Hupperich and coworkers [32] with a 1.75 liter single cylinder engine for the ECE R49 13-mode test, the cumulative emissions data displayed some differing results. With the use of neat DME, HC emissions are reduced and the trends with the other emissions are similar to what had been determined with previous studies. One difference to note is the change in injection nozzle size, which may have affected the emission results by allowing for more complete combustion of all fuels tested in an effort to maintain consistent test conditions.

Recent experiments by Ikeda and coworkers [27] with a single cylinder engine using a binary fuel injection method showed similar NOx emissions between diesel fuel and 40 volume % DME mixed with diesel fuel, as injection timing was retarded. Also, HC emissions increased and smoke emissions were reduced as injection timing was retarded. In addition, comparisons were made as a function of BMEP Brake Mean Effective Pressure (BMEP). NOx was reduced, HC remained constant and smoke increased with increasing BMEP. The experiments also included % DME fractions mixed with diesel fuel up to 60 volume % addition, with comparisons made to the baseline diesel fuel. The smoke level, indicating presence of soot in the exhaust stream, showed a slight increase between 0 and 20 % DME addition, and then returned to zero for DME addition over 20%. NOx emissions decreased slightly, then increased slightly to the original point for diesel fuel. HC emissions increased slightly up to 45% DME addition, and increased sharply above this point [27].

Many researchers have been evaluating the performance of other oxygenates including blends of glycol ethers with diesel fuel, and have observed decreases in particulate matter emissions with increasing oxygenate concentration. Most recently, Hallgren and Heywood [33] prepared a review of the collection of work which showed that as the oxygen content of the fuel increases, the particulate matter is reduced, suggesting that this occurs regardless of chemical structure or molecular weight. However, their actual testing showed that the oxygenate structure did impact particulate emissions. Studies completed by Hess and coworkers [34] as well as by Litzinger and coworkers [35, 36] have shown that higher molecular weight glycol ethers are also effective in reducing particulate matter emissions, although to a lesser extent than monoglyme or diglyme.

Although it has been shown that glycol ethers effectively reduce particulate emissions, the fundamental mechanisms of the reduction have not been clearly identified. There has been some work in simulating the ignition and rate mechanism behavior of dimethyl ether in comparison to dimethoxymethane [37]. Also, oxidation mechanisms have been proposed for gaseous forms of DME [9, 38, 39]. More recently, the modeling of DME oxidation has proven consistent with experimental results from jet stirred reactor theory and shock-tube conditions, providing confidence in the proposed reaction mechanisms [40].

RESEARCH WITH DME IN VEHICLE APPLICATIONS

Over the years, there have been various attempts to operate vehicles on neat DME. One successful vehicle demonstration involved the Volvo B10BLE bus. Even though there were some technical issues related to the use of DME in the fuel system, the data showed that a DME fueled vehicle with an oxidation catalytic converter could meet the EURO 4 Standards [41]. While the deployment of the Volvo bus was prevented by difficulties with reliability of the fueling system, this project demonstrated chassis dynamometer emissions that were very low. More recently, successful demonstrations of vehicles have occurred in Japan, with DME powering 2 ton trucks [42].

SHUTTLE BUS CONVERSION

The objective of this research project was to demonstrate operation of a campus shuttle bus on dimethyl ether (DME). To accomplish this goal, DME was blended with diesel fuel to provide sufficient viscosity and lubricity to the fuel blend to prevent damage to the fuel injection system of the engine in the shuttle bus. This involved development of a conversion strategy. The ultimate goal of the conversion process was to build a fueling system that allowed for delivery of pressurized fuel with as little modification to the engine as possible, with relatively simple controls and a reasonably convenient re-fueling process. The system layout was based on the design developed by Chapman and Bhide [46, 47] for the same Navistar T444E diesel engine.

In the work by Chapman and Bhide, a T444E engine was converted in a laboratory test cell to operate on blends of DME and diesel fuel. A schematic of the modified fuel system used in the laboratory test cell is shown in Figure 1. The fuel system on the T444E engine had to be modified to account for the need to deliver fuel at an elevated pressure. The fuel rail in the cylinder head of the engine normally receives fuel at a pressure of about 70 psi. Fuel from this rail is then fed to the injectors. To prevent boiling of the DME in the fuel blend, fuel from the rail was kept at a pressure greater than 100 psig and recirculated through a chilled bath to keep the fuel temperature below 50°C before returning to the rail by use of a gear pump. The fuel tank consisted of a modified 60 lb capacity LPG cylinder.

Also in work by Bhide, Perez and Boehman, the viscosity of blends of DME and diesel fuel were measured [48]. The viscosity of a conventional diesel fuel drops below the ASTM specification of 1.3 cSt when the blend ratio approaches 25 wt.% DME. Thus, to protect the fuel injectors from excessive wear due to viscosity-related wear, the target DME concentration for the vehicle tests as set to a maximum of 25 wt.% DME.

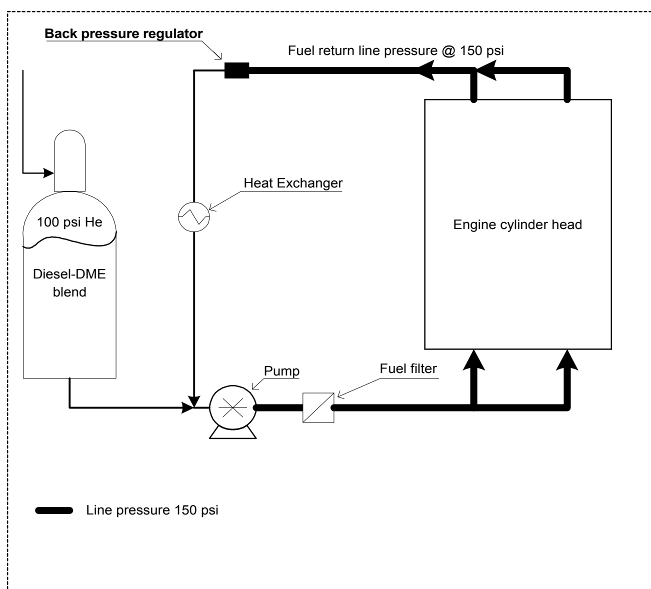

Figure 1. Pressurized Fueling System Developed in Laboratory Studies on DME-diesel Blends [46, 47]

The development of the conversion strategy for the shuttle bus was subjected to a detailed failure mode effects analysis (FMEA), as prescribed by SAE J1739 [49]. A similar procedure, used by Air Products and Chemicals, Inc., is referred to as a Hazardous Operation Process Analysis, or "Hazop". Such an analysis was performed to ensure safe operation of the converted bus. The objective of the Hazop analysis was to review the fuel handling system and fueling procedures in detail and to attempt to foresee any potential problems that could occur. The initial system design was divided arbitrarily into four nodes. This division allowed attention to be focused on a specific subsystem of the design. Each segment of the design was scrutinized for conditions of fluid flow (no flow, high flow, low flow, reverse flow), loss of containment (full and partial), pressure (high pressure and low pressure), temperature (high and low), level (high level, low level, and no level), composition, mixing, reactions, operational procedure, phase, startup, shutdown, erosion, maintenance, and fire. The completion of this analysis increased the complexity of the design considerably but was required to ensure that the vehicle met safety standards of the National Fire Protection Agency (NFPA) and the Pennsylvania Department of Transportation.

COMPONENT SELECTION

Before any hardware could be purchased a significant amount of research needed to be completed. Since DME will attack most polymers, and therefore most o-rings or seals, material compatibility was a top priority. Stainless steel tubing was used for any fuel line that would contain pure DME and was grounded to eliminate hazard from electrostatic discharge. In addition, all of the components had to be durable enough to withstand exposure to road debris and vehicle vibration.

A 33.2 gallon water capacity liquid propane (LP) tank from Manchester Tank (Lynwood, CA) for use on recreational vehicles serves as the primary fuel tank to store and deliver the blend of DME and diesel fuel. The tank size was calculated for the amount of fuel required to run one full day on the Faculty/Staff Shuttle loop at the University Park campus of the Pennsylvania State University. All valves that came installed in the tank were removed and new valves were installed to ensure material compatibility with DME. As many suppliers have various materials to select, Kalrez™, a product of Dupont-Dow Elastomer, was selected when available. To maintain tank certification, an 80% fill valve is required on the LP tank, but a modified fill valve was installed with the desired threaded connection for filling the tank with DME and diesel fuel.

A positive displacement gear pump from Liquiflo Equipment Company (Garwood, NJ) transfers diesel fuel from the existing diesel tank to the liquid propane tank. The pump was ordered to be compatible with diesel only, since under normal operation it would not be exposed to DME.

A magnetically coupled gear pump from Tuthill Pump (Concord, CA) circulates the blended fuel to the cylinder heads and then through two transmission oil coolers. Cooling the fuel is required to maintain the DME in liquid state and hence to avoid two-phase flow in the fueling system.

The fuel was filtered through two types of filters, provided by Parker Racor Filtration. The fuel was passed through a water separator and a high pressure LNG filter. Initially, the high pressure filter which had a 5 micron mesh filter element clogged repeatedly. This fouling of the filter blocked fuel flow and disrupted operation of the engine. The fouling appeared to be due to the solvent action of DME as it cleaned the fuel system and mixture fuel tank, depositing an oily residue on the filter. Eventually, through the technical assistance from Parker Racor, all fuel filtration issues were resolved.

"Fail in position" pneumatically operated ball valves were used throughout the fuel handling system. Solenoid valves delivered compressed air to actuate the ball valves. Since the solenoid valves were not compatible with road elements a cabinet was purchased to house the solenoid valves inside the driver/passenger compartment. To ensure safety and correct flow direction, pressure relief valves and check valves were installed in the fuel handling system to supplement the pneumatic ball valves.

COMPONENT INSTALLATION

The first step of the construction was to drain and modify the existing diesel tank. The tank was removed from the bus and two couplers were welded onto the tank. These couplers serve as the connection points for fuel supply and fuel return from the engine compartment. Two additional vents including vapor traps were also added to the diesel tank to prevent over pressurization of the tank and release of flammable vapors. The existing tank was then remounted on the bus. Next the liquid propane tank, here after referred to as mix tank, was mounted on the bus. This was done using the tank manufacturer's suggested hardware and instructions. Finally, the rest of the fuel handling system hardware (pumps, valves, tubing, fittings, heat exchangers) was installed on the bus. A full diagram of the completed system is shown in Figure 2.

The standard configuration of the T444E engine is for fuel to enter from the backside of the cylinder head (side closest to the firewall) and remain in the fuel rail until needed by the injectors. This configuration, referred to as a "dead heading," causes the fuel to be heated to engine coolant temperatures. When the engine is fueled

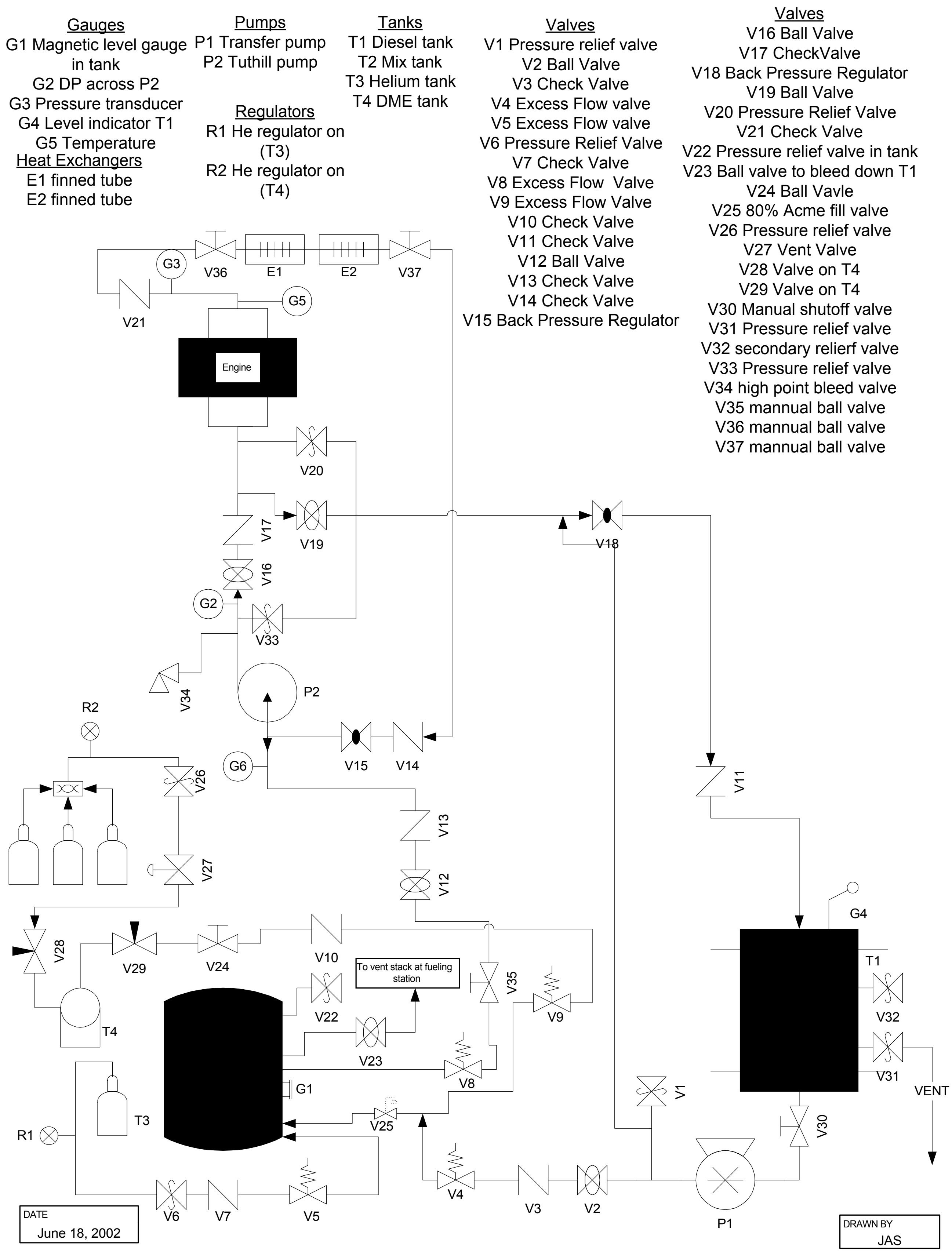

Figure 2. Schematic Diagram of the DME-Diesel Fueling System

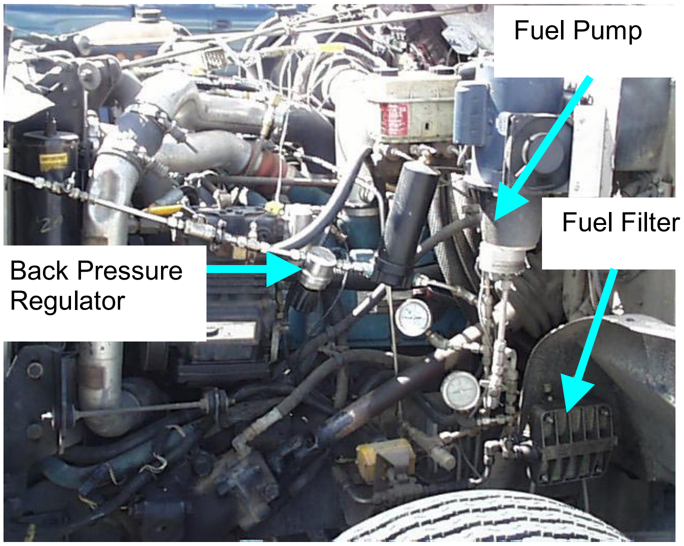

Figure 3. Photograph of the fuel handling system on the converted shuttle bus

on diesel fuel this is not a problem. However, when running on a blend of DME and diesel fuel, this heat soak becomes an issue. To combat the heating of the fuel in the rail, the fuel flow path is changed from a "dead heading" arrangement to a circulation loop. Fuel enters the engine at the same place as in the original configuration and exits at the front of the engine. The fuel from each side of the engine is then combined and routed through four transmission oil coolers (referred to as "fuel coolers") that are mounted just in front of the factory radiator and charge air cooler. This configuration allows the fuel to be cooled and fresh makeup fuel added to the loop before the mixture is re-circulated to the engine. Figure 3 shows a photograph of the fuel handling system installed under the hood of the shuttle bus.

TEST FIRING

Once construction of the fuel handling system was complete, the vehicle was test fired on diesel fuel. This allowed for a full operational check of the new system and a fully pressurized leak check. The vehicle was then operated at the Pennsylvania Transportation Institute Test Track facility to verify vehicle performance, operation of the vehicle with the converted fueling system and refueling procedures. The vehicle was fueled on a conservative mixture of 10 vol.% DME in diesel fuel for initial testing after operation problems had been addressed.

OPERATIONAL ISSUES

With the complexity of the design, several operational issues became evident once construction was completed. These problems involved formation of two-phase flow in the fuel handling system that caused rough engine operation and re-fueling difficulties.

CIRCULATION PUMP

As described above, a magnetically coupled gear pump is used to circulate fuel through the cylinder heads through fuel coolers and back to the engine. Since DME is a vapor at room temperature and pressure, the fuel must be kept pressurized to avoid formation of two-phase flow within the system. When the fuel is exposed to engine temperatures, the amount of pressure needed to keep the DME in the liquid phase increases. The vapor pressure of DME as a function of temperature is shown in Figure 5 for reference, provided by Dupont Technical Bulletin for Dymel A [50]. Since the system pressure is set, the fuel temperature must be lowered via heat exchange through the fuel coolers. Thus, if for some reason the circulation pump does not work, fuel is not moved through the head to provide sufficient cooling and two-phase flow causes rough engine operation

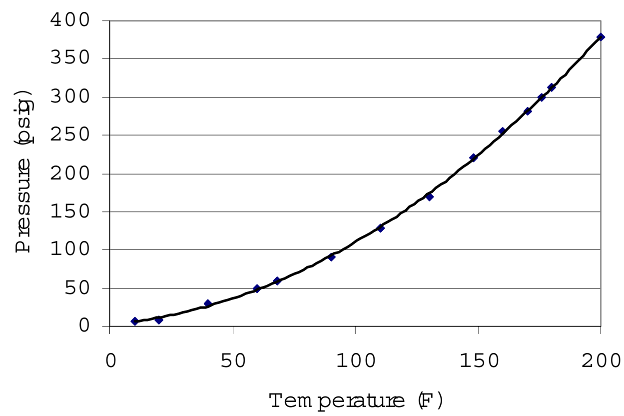

Figure 5. Vapor pressure of DME as a function of temperature [50].

Several scenarios for pump failure were encountered. The pump, which runs off 110 AC power provided by a DC-to-AC converter, was demanding increasing amounts of power due to: inadequate power supply, inadequate flow of fluid through the system due to blockage, jamming of the gears due to debris, thermal shutoff, and swelling of the gears.

Initially, after construction was complete, the bus was fueled on diesel fuel. During this time no problems with the pump were noticed. However, after long periods of operation, the engine ran roughly and the amount of blow-by increased, as observed by an increase in smoke emitted by the crankcase vent and a noticeable increase in odor. When the bus was fueled on DME, the current draw by the electric motor that drives the circulation pump gradually increased over time. The current demand by the pump motor would increase to the maximum rated current for the motor and trip an internal protection circuit in the motor. Hence, the pump would shut off.

The manufacturer was contacted and a larger motor and a motor adapter were purchased and installed. After installation the operation of the pump seemed to become worse and the motor and motor adapter were removed. It was found that the magnetic coupler from the motor shaft to the cap of the pump was destroyed. The pump, motor mate, and coupler were taken to the attention of the regional sales representative who replaced the destroyed coupler and correctly installed a new one. The pump was then reincorporated into the system.

With the motor now working correctly, it became evident that a larger power source was required. Since the pump runs on 110 AC but only 12V DC is available on the vehicle an inverter is used. To obtain the size inverter needed a recreational vehicle dealer was contacted. Once the inverter was in place the pump performed flawlessly on diesel fuel for 8 days. When the vehicle was switched to DME-diesel blends, problems again became evident.

A flow meter was installed to determine if the pump was getting adequate fluid or if it was running dry. The meter was installed in the system with as little changes as necessary to ensure a true reading. The flow was found to be in the acceptable range for the motor rating. This ruled out insufficient flow due to blockage in the system. It was postulated that the flow restriction could be on the outlet side of the pump so the filter element was examined.

The filter was found to have disintegrated at the top and bottom of the element where rubber caps were used in the manufacturing. A new filter element with a completely metal housing and a more resilient rubber was chosen and installed. The pump was then removed and the gears checked for any debris that could be preventing their rotation. Very little material was found in the gears and the pump was reassembled and reinstalled.

By the manufacturer's suggestion, a surface temperature thermocouple was installed on the skin of the pump. It was found that there was inadequate airflow to the motor of the pump so a 12V DC accessory fan was installed to direct air toward the pump. After the installation of the fan, the skin temperature was found to be in the acceptable range, thus ruling out thermal shutoff. With all of these test and modifications, problems were still evident after fueling with DME.

It was thus apparent that gear swell due to prolonged exposure to DME was the source of the problem. The manufacturer was again contacted and a new pump was obtained. Pump shutoff and rough engine operation ceased to be a problem from this point forward.

FUEL LEVEL GAUGE

The level of fuel in the mix tank is monitored by a float gauge inside the tank. The signal is then sent to two individual readouts. One readout is mounted above the driver's seat and the other is attached to a five-pin connector on the side of the bus during fueling.

VEHICLE EMISSIONS TESTING

Emission testing is done by use of on board analysis equipment owned and operated by Clean Air Inc. The equipment consists of two units, which are approx. 24 inches wide by 22 inches deep, and several laptop computers that provide interface and control ability. The equipment measures CO, CO2, NOx, particulate matter, as a function of vehicle speed and load. Fuel consumption is calculated from the CO and CO2 measurements.

DRIVING CYCLES

For the purpose of ensuring and verifying repeatability, a specific testing procedure was adhered to for all testing runs. All testing was performed at The Pennsylvania State Transportation Institute Test Track facility on a one-mile oval track. Four different driving cycles were used for the testing: P20, P40, Orange County, and Manhattan Cycles.

A P20 consists of starting at a specific point on the track and accelerating to 20 mph. The vehicle is held at 20 mph until the first stopping point is reached. The vehicle is then brought to a stop for seven seconds and the driver then accelerates back to 20 mph. There are 8 stops performed in one loop. A complete P20 consists of 2 loops.

A P40 consists of starting again at a specific point on the track and accelerating to 40 mph. The vehicle's speed is then held at 40 mph until the first stopping point is reached. Then vehicle is then brought to a stop for seven seconds and the driver accelerates back to 40 mph. The first stop is at half-track the second is at the original starting point. A complete P40 consists of 2 loops.

An Orange County cycle is a reproduction of a typical bus cycle in Orange County California. The cycle is displayed on a laptop computer running Driver's Aid software® provided by Clean Air Technologies International, Inc. The software also displays the vehicle's speed and the driver matches the speed trace to the prescribed cycle being displayed. The Orange County cycle is broken into two parts to minimize datafile length and can be seen in Figures 6 and 7. A complete Orange County set consists of four complete cycles.

A Manhattan cycle is a reproduction of a typical bus cycle in Manhattan, New York. Again the cycle is displayed by the Driver's Aid ® software and the driver matches the vehicle speed trace to the prescribed cycle. A complete Manhattan set consists of four cycles. The Manhattan cycle is shown in Figure 8.

VEHICLE TESTING PROCEDURES

Since the Driver's Aid® software display is difficult to see during the day the Orange County and Manhattan cycles are run at night and the P20 and P40 cycles are run during the day.

A typical day of testing begins with warming up the equipment. This process takes about one hour to complete during which the vehicle is at idle. At the completion of this time period, several test laps are made to check the equipment status. If redundant instruments indicate conflicting measurements the laps are aborted and the equipment checked. Once consistent results are obtained, actual testing begins.

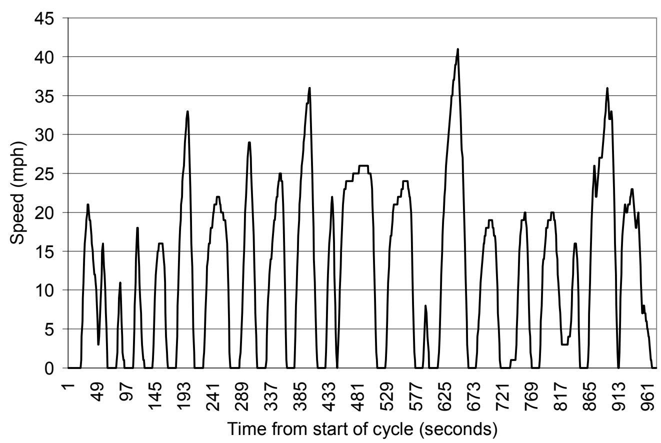

Figure 6. Part One of the Orange County Cycle – Driving Cycle to Represent Transit Bus Operation in Orange County, CA.

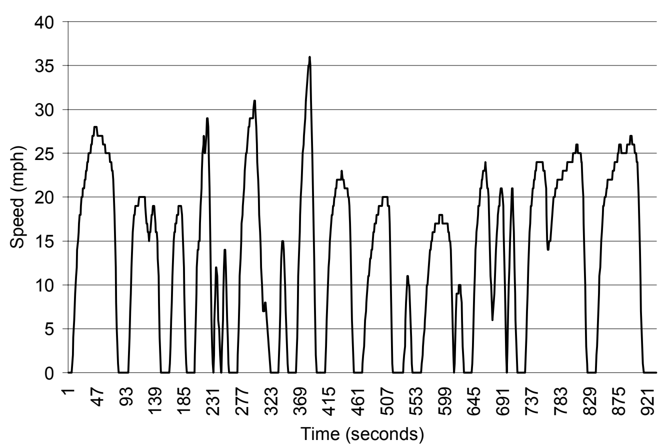

Figure 7. Part Two of the Orange County Cycle.

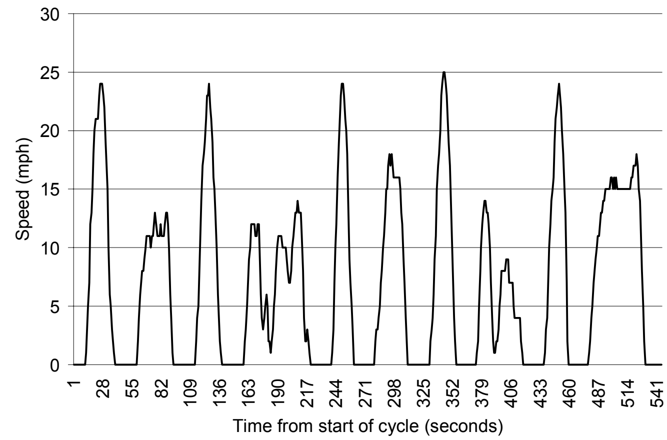

Figure 8. Manhattan Cycle – Driving Cycle to Represent Transit Bus Operation in Manhattan, NY.

Using the onboard equipment as a live monitoring system, three laps at 30 mph are made to burn off particulates that may have accumulated during the warm-up time. If particulate levels continue to trend downward in the last lap, additional laps are done until stable readings are seen.

At the completion of these "burn off" laps, the vehicle is brought to a stop at the P20 starting point. A period of 90 seconds is allowed to transpire allowing for the equipment to be reset. A complete P20 is then run fallowed by a complete P40, this pattern is then continued alternating back and forthwith 90 seconds between each complete set.

An identical pattern is followed for the Orange County and Manhattan cycles. After equipment warm up, "burn off" laps are run, pausing 90 seconds then beginning the desired cycle. The testing pattern consists of running blocks of Manhattan cycles before switching to Orange County cycles.

RESULTS AND DISCUSSION

Testing was performed for 3 different fuel mixtures. The first test served as a baseline run and the vehicle was fueled on pure diesel. The second test was a fuel mixture of 14% by volume DME and diesel; the third test was 25% by volume DME and diesel. While emissions data were monitored for the P20, P40, Orange County and Manhattan test cycles, only data from the Manhattan cycle is presented here.

Total particulate results for all three-fuel compositions for the Manhattan cycle can be seen in Figure 9. As is expected with the addition of an oxygenate as the amount of DME in the fuel mixture increases the measured particulate level drops. For 14 vol.% DME, the PM emissions drop by 60%. For 25 vo.% DME, the PM emissions drop by 80%.

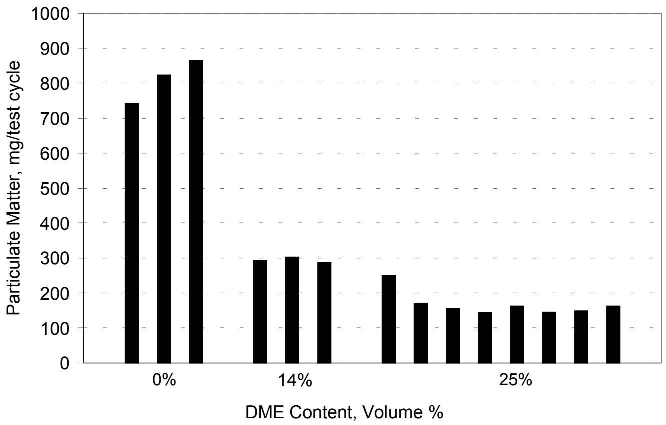

Figure 9. Particulate Matter Emissions During the Manhattan Cycle (cumulative mass emissions per test cycle) for 0, 14 and 25 vol.% DME in Diesel Fuel.

Similar results to those seen by Chapman et al. [47] were seen for hydrocarbons, NOx, and CO in tests with the laboratory engine when operated on DME blends. For a Manhattan cycle, the emissions of hydrocarbons, NOx, and CO are shown in Figures 10,11, and 12, respectively.

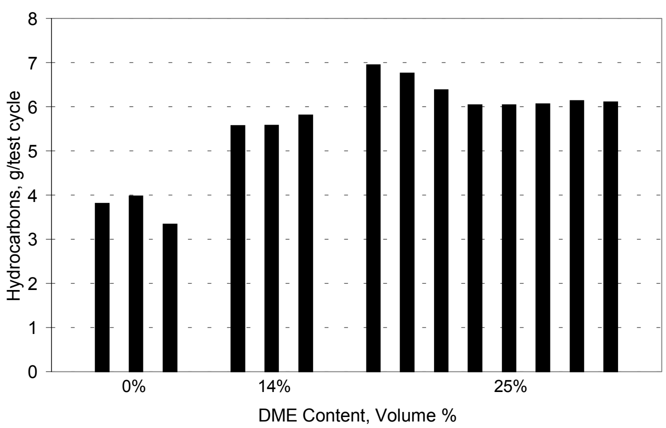

Figure 10. Hydrocarbon Emissions During the Manhattan Cycle (cumulative mass emissions per test cycle) for 0, 14 and 25 vol.% DME in Diesel Fuel.

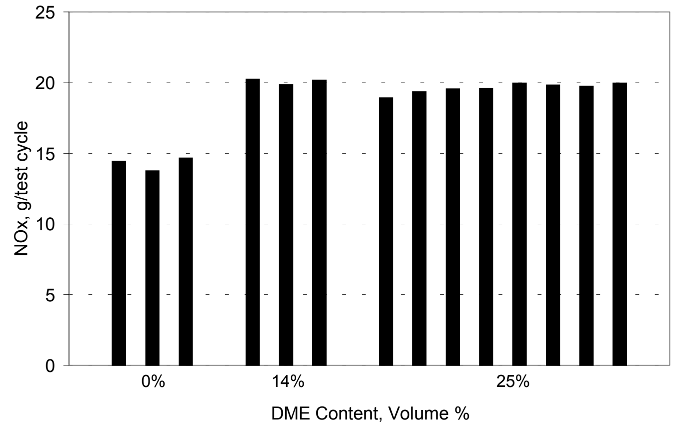

Figure 11. NOx Emissions During the Manhattan Cycle (cumulative mass emissions per test cycle) for 0, 14 and 25 vol.% DME in Diesel Fuel.

While the emissions of particulate were substantially reduced, emissions of hydrocarbons, NOx, and CO were significantly increased with DME addition. While these trends were also observed in the laboratory engine [46,47], they point to a need to optimize the injection characteristics of the fuel blend and to the need to add an oxidation catalyst to a vehicle fueled in this manner. A similar observation was made in the Volvo bus demonstration, that addition of an oxidation catalyst to a DME-fueled vehicle provided very low emissions [41].

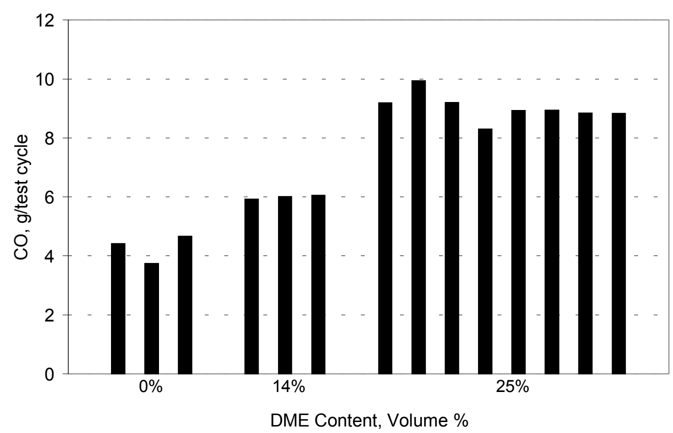

Figure 12. Carbon Monoxide Emissions During the Manhattan Cycle (cumulative mass emissions per test cycle) for 0, 14 and 25 vol.% DME in Diesel Fuel.

TECHNICAL ISSUES WITH THE UTILIZATION OF DME AS A FUEL

Much of the early work with DME utilization has been done at the AVL labs in Graz, Austria. The testing showed that DME reduces particulate emissions to zero, and also showed that the typical diesel fuel injection system does not tolerate DME [18]. The present work shows that with DME-diesel blends, substantial particulate emissions reduction can be obtained while preserving the integrity of the fuel injection system. Figure 13 shows a picture of the DME-Fueled Shuttle bus in operation at Penn State.

Figure 13. DME-Fueled Shuttle Bus Operating on the Faculty/Staff Loop at the University Park campus of the Pennsylvania State University, August, 2002.

Overall, this demonstration project has shown that a vehicle can be successfully operated on DME, but at restricted DME blend levels below 25 wt.% (30 vol.%). The emissions and performance data presented here are restricted to 21 wt.% (25 vol.%) DME addition. There are remaining concerns and challenges, particularly because of the low viscosity of DME. Below is a combined list of concerns not only from the present work, but also from other groups who are now working through the fuel property, design and technology issues for utilization of DME:

- DME was leaking past clearances on the injectors and seals. This caused the need for the camshaft housing and crankcase of the engine to be vented [18].
- At high vapor pressure, the DME was cavitating, which caused difficulties in maintaining stable fuel injection [18].
- While DME is more compressible than diesel fuel, it was found that the compressibility changed with temperature and pressure. Therefore, this made it difficult to inject the maximum fuel quantity at high temperatures and during full load operation using traditional diesel equipment [18].
- DME chemically attacked some seals [18].
- Not much effort has been put towards understanding the environmental impacts of the compound itself or the emissions from the fuel combustion, as compared to other fuels [18].
- A larger fuel tank will be required, as compared to diesel fuel, because of the lower density and heating value of DME [19].
- Since the vapor pressure of DME is low, the fuel vaporizes immediately upon injection into the cylinder. This may or may not be an issue, but further study may confirm how the combustion reaction takes place after the vaporization occurs [19].
- Injection via some fuel pumps causes uncontrollable pressure waves in the entire system [43].
- Predictability of spray behavior and characteristics is important in repeatability of combustion [44].
- Turbulence within the cylinder is important for mixing of the fuel, which in turn reduces emissions [45].

CONCLUSIONS

This work has demonstrated that a conventional diesel vehicle can be converted to operate on blends of DME and diesel fuel. Significant reductions in particulate emissions were observed when the converted shuttle bus was operated on DME – diesel blends, while there were increases in unburned hydrocarbons, NOx and CO. By blending DME with diesel fuel, an acceptable viscosity and lubricity could be obtained in the fuel mixture to provide reliable operation of the fuel injection system. Nonetheless, operation of the vehicle was not without challenges during the conversion and debugging phases, as is documented in this paper. In addition, the vehicle could not meet peak accelerations required during the Manhattan driving cycle, indicating that the engine was de-rated at higher DME concentrations.

DME holds great promise as a fuel for the future. But, many technical challenges remain to be overcome before neat DME-fueled vehicles can be a commercially viable option. Among them are the low viscosity, low lubricity and material incompatibilities.

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REFERENCES

1. EPA, Final Emission Standards for 2004 and Later Model Year Highway Heavy-Duty Vehicles and Engines (EPA 420-F-00-026). 2000, United States Environmental Protection Agency.
2. EPA, Heavy-Duty Engine and Vehicle Standards and Highway Fuel Sulfur Control Requirements (EPA420-F-00-057). 2000, United States Environmental Protection Agency.
3. Cheney, D., Powell, C., O'Neill, P., Norton, G., Veneman, A., Evans, D., Mineta, N., Abraham, S., Allbaugh, J., Whitman, C.T., Bolten, J., Daniels, M., Lindsey, L., Barrales, R., Lundquist, A., "National Energy Policy: Reliable, Affordable, and Environmentally Sound Energy for America's Future". 2001, National Energy Policy Development Group, U.S. Government: Washington, D.C.
4. Phillips, J.G., Reader, G. T., "The Use of DME as a Transportation fuel - A Canadian Perspective." ASME Fall Technical Conference, 1998. 31-3 (98-ICE-152): p. 65-71.
5. Verbeek, R., Van der Weide, J., "Global Assessment of Dimethyl Ether : Comparison with Other Fuels." Society of Automotive Engineers, 1997 (971607).
6. Wakai, K., Nishida, K.,Yoshizaki,T., Hiroyasu, H., "Ignition Delays of DME and Diesel Fuel Sprays Injected by a DI Diesel Injector." Society of Automotive Engineers, 1999 (1999-01-3600).
7. Sorenson, S.C., Mikkelsen S., "Performance and Emissions of a DI Diesel Engine Fuelled with Neat Dimethyl Ether." Society of Automotive Engineers, 1995 (950064).
8. Kapus, P.E., Cartellieri, W.P, "ULEV Potential of a Car Engine Operated on Dimethyl Ether." Society of Automotive Engineers, 1995 (952754).
9. Fleisch, T., McCarthy, C., Basu, A., Udovich, C., Charbonneau, P., Slodowske, W., Mikkelsen, S., McCandless, J., "A New Clean Diesel Technology: Demonstration of ULEV Emissions on a Navistar Diesel Engine Fueled with Dimethyl Ether." Society of Automotive Engineers, 1995 (950061).
10. Hansen, J.B., Voss, B., "Large Scale Manufacture of Dimethyl Ether –a New Alternative Fuel from Natural Gas." Society of Automotive Engineers, 1995 (950063).
11. Tijm, P., Waller, F., Toseland, B., and Peng, X. "'Liquid Phase Di-Methyl Ether TM' A promising New Diesel Fuel". Proceedings in Energy Frontiers International Conference, Alaska, 1997.
12. Maricq, M.M., Szente, J.J., Hybl, J.D., "Kinetic Studies of the Oxidation of Dimethyl Ether and Its Chain Reaction with Cl2." J. Phys. Chem. A, 1997. 101(28): p. 5155-5167.
13. Nash, J.J., Francisco, J.S., "Unimolecular Decomposition Pathways of Dimethyl Ether: An Ab Initio Study." J. Phys. Chem. A, 1998. 102(1): p. 236-241.
14. McMurry, J., Organic Chemistry, 4th ed. 1995, Pacific Grove, CA: Brooks/Cole Publishing Company.
15. Marchionna, M., Patrini, R., Giavazzi, F., Pecci, G. "Linear Ethers as High Quality Components for Reformulated Diesel Fuels". Proceedings in Symposium on Removal of Aromatics, Sulfur and Olefins from Gasoline and Diesel presented at the 212th National Meeting (Aug 25-29), American Chemical Society, 1996. Orlando, FL. 585-589.
16. Kapus, P., Ofner, H., "Development of Fuel Injection Equipment and Combustion Systems for DI Diesels operated on Dimethyl Ether." Society of Automotive Engineers, 1995 (950062).
17. Riesenberg, K.O., Faupel, W., Blaich, B., Stumpp, G., Ungerer, G., Polach, W., Leonard, R., Schneider, V., Ritter, E., Tschoke, H., Dieter, W., Warga, W., Kaczynski, B., Bauer, H., Diesel Fuel Injection. 1st ed. 1994, Stuttgart, Germany: Robert Bosch.
18. Ofner, H., Gill, D.W., Krotscheck, C., "DME as Fuel for CI engines - A New Technology and its Environmental Potential." Society of Automotive Engineers, 1998 (981158).
19. Glensvig, M., Sorenson, S.C., Abata, D. L., "An Investigation of the Injection Characteristics of Dimethyl Ether." ASME Fall Technical Conference, 1997. 29-3 (97-ICE-67): p. 77-84.
20. Johnson, J., Bagley, S., Gratz, L., Leedy, D., "A Review of Diesel Particulate Control Technology and Emissions Effects- 1992 Horning Memorial Award Lecture." Society of Automotive Engineers, 1994 (940233).
21. Schmidt, D., Wong, V., Green, W., Weiss, M., Heywood, J., "Review and Assessment of Fuel Effects and Research Needs in Clean Diesel Technology." ASME Spring Technical Conference, 2001. 36-1: p. 23-37.
22. Nielsen, K., Sorenson, S., "Lubricity Additive and Wear with DME in Diesel Injection Pumps." American Society of Mechanical Engineers, ICE Fall Technical Conference, 1999. 33-1(99-ICE-217): p. 145-153.
23. Nikanjam, N., "Diesel Fuel Lubricity: On the Path to Specifications." Society of Automotive Engineers, 1999(1999-01-1479).
24. Bechtold, R., Alternative Fuels Guidebook: Properties, Storage, Dispensing, and Vehicle Facility Modifications. 1997, Warrendale, PA: Society of Automotive Engineers.
25. Nabi, M.N., Minami, M., Ogawa, H., and Miyamoto, N., "Ultra Low Emission and High Performance Diesel Combustion with Highly Oxygenated Fuel." Society of Automotive Engineers, 2000 (2000-01-0231).
26. Kajitani, S., Chen, Z. L., Konno M., Rhee, K.T., "Engine performance and Exhaust Characterestics of DI Diesel Engine Operated with DME." Society of Automotive Engineers, 1997 (972973).
27. Ikeda, M., Mikami, M., Kojima, N., "Exhaust Emission Characteristics of DME/Diesel Fuel Engine." Society of Automotive Engineers, 2000 (2000-01-2006).
28. Chen, Z., Kajitani, S., Minegisi, K., Oguma, M., "Engine Performance and Exhaust Gas Characteristics of a Compression Ignition Engine Operated with DME blended Gas Oil Fuel." Society of Automotive Engineers, 1998(982538).
29. Rubino, L., Thompson, M.J., "The Effect of Oxygenated Additives on Soot Precursor Formation in a Counterflow Diffusion Flame." Society of Automotive Engineers, 1999 (993589).

30. Mikkelsen, S., Hansen, J., Sorenson, S., Dimethyl Ether as an Alternate Fuel for Diesel Engines, in Application of Powertrain and Fuel Technologies to Meet Emissions Standards, J. Mardell, Parsons, M., Read, J., Lemon, D., Editor. 1996, Professional Engineering Publishing Limites for IMechE: London, UK. p. 289.
31. Christensen, R., Sorenson, S.C., "Engine Operation on DME in a Naturally Aspirated DI Diesel Engine." Society of Automotive Engineers, 1997 (971665).
32. Hupperich, P., Dürnholz, M., Hüchtebrock, B., "Diesel Oil, Water in Carbon Fuel Emulsion, DME or Natural gas? - Comparative tests on a Single Cylinder Engine." ASME Fall Technical Conference, 1997. 29-3 (97-ICE-65): p. 61-67.
33. Hallgren, B., and Heywood, J., "Effects of Oxygenated Fuels on DI Diesel Combustion and Emissions." Society of Automotive Engineers, 2001 (2001-01-0648).
34. Hess, H.S., Roan, M.A., Bhalla, S., Butnark, S., Zarnescu, V., Boehman, A.L., Tijm, P.J.A., and Waller, F.J., Chemistry of Diesel Fuels. "The Use of Oxygenated Diesel Fuels for Reduction of Particulate Emissions from a Single-Cylinder Indirect Injection Engine," Applied Energy Technology Series, ed. C. Song, Hsu, C., Mochida, I. 2000, New York, NY: Taylor & Francis. 255-268.
35. Litzinger, T., Stoner, M., Hess, H., and Boehman,A., "Effects of Oxygenated Blending compounds on Emissions from a Turbo-charged Direct Injection Diesel Engine." Int. J. Engine Research, 2000. 1: p. 57-70.
36. Stoner, M., and Litzinger, T., "Effects of Structure and Boiling Point of Oxygenated Blending Compounds in Reducing Diesel Emissions." Society of Automotive Engineers, 1999 (991475).
37. Murayama, T., Zheng, M., Chikahisa, T., Oh, Y.-T., Fujiwara, Y., Tosaka, S., Yamashita, M., and Yoshitake, H., "Simultaneous Reductions of Smoke and NOx from a DI Diesel Engine Using EGR and Dimethyl Carbonate." Society of Automotive Engineers, 1995 (952518).
38. Hess, H., Szybist, J., Boehman, A., Tijm, P., Waller, F. "The Use of CETANER™ for the Reduction of Particulate Matter Emissions in a Turbocharged Direct Injection Medium-Duty Diesel Engine". Proceedings in Seventeenth Annual International Pittsburgh Coal Conference, September 11-15, 2000. Pittsburgh, PA.
39. Amano, T., Dryer, F. L., "Effect of DME, NOx, And Ethane or CH4 Oxidation : High Pressure, Intermediate - Temperature Experiments And Modelling." Twenty Seventh International Combustion Symposium Proceedings, 1998: p. 397-404.
40. Curran, H., Pitz, W., Westbrook, C., Dagaut, P., Boettner, J-C., Cathonnet, M., "A Wide Range Modeling Study of Dimethyl Ether Oxidation." Inter. Journal of Chemical Kinetics, 1998. 30(3): p. 229-241.
41. Hansen, K., Nielsen, L., Hanses, J., Mikkelsen, S., Landalv, H., Ristola, T., Vielwerth, K., "Demonstration of a DME (Dimethyl Ether) Fuelled City Bus." Society of Automotive Engineers, 2000 (2000-01-2005).
42. Okutsu, S., "NKK Begins DME Vehicle Road Test" Press Release(http://www.nkk.co.jp/en/environment/dme/index.html). 2002, NKK: Tokyo, Japan.
43. Sorenson, S.C., Glensvig M., Abata Duane L, "Dimethyl Ether in Diesel Fuel Injection Systems." Society of Automotive Engineers, 1998 (981159).
44. Wakai, K., Yoshizaki, T., "Numerical and Experimental Analyses of the Injection Characteristics of Dimethyl Ether with a DI Diesel Injection System." Society of Automotive Engineers, 1999 (1999-01-1122).
45. Konno, M., Kajitani, S., Oguma, M., Iwase, T., Shima, K., "NO Emission Characteristics of a CI Engine Fueled with Neat Dimethyl Ether." Society of Automotive Engineers, 1999 (1999-01-1116).
46. Chapman, E., Bhide, S., Boehman, A., Tijm, P.J.A., Waller, F.J., "Emission Characteristics of a Navistar 7.3L Turbodiesel Fueled with Blends of Oxygenates and Diesel." Society of Automotive Engineers, 2000 (2000-01-2887).
47. Chapman, E., Boehman, A. Tijm, P.J.A., Waller, F., "Emissions Characteristics of a Navistar 7.3L Turbodiesel Fueled with Blends of Dimethyl Ether and Diesel Fuel." Society of Automotive Engineers 2001 Transactions-Journal of Fuels & Lubricants, 2001. 110(Section 4) (2001-01-3626): p. 2166-2175.
48. Bhide, S.V., Boehman, A.L. and Perez, J.M., “Viscosity of DME-Diesel Fuel Blends,” in ACS Fuel Chemistry Division Preprints, 46(2), 400-401 (2001).
49. SAE, SAE J1739: "Potential Failure Mode and Effects Analysis (Design FMEA) and Potential Failure Mode and Effects Analysis in Manufacturing and Assembly Processes (Process FMEA Reference Manual)", in 1999 SAE Handbook. 1999.
50. DuPont, Dymel Aerosol Propellants: Dymel A, in Technical Information ATB-25. 1992, Fluorochemicals Laboratory, E.I. duPont de Nemours and Company.