CATALYTICALLY ASSISTED COMBUSTION OF AQUANOL IN DEMONSTRATION VEHICLES

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EXECUTIVE SUMMARY

Aqueous fuels have the potential for lower emissions and higher engine efficiency than can be experienced with gasoline or diesel fuels. Past attempts to burn aqueous fuels in over-the-road vehicles have been unsuccessful due to difficulties in initiating combustion. For this project, we adapted and used SmartPlug™—catalytic igniter technology developed by Automotive Resources, Inc. (Sandpoint, Idaho)—in a transit van supplied by Valley Transit of Lewiston, Idaho. The adaptation entailed retrofitting the cylinders with total seal piston rings, installing corrosion-proof components in the fuel system, and reprogramming the fuel computer. We completed several hundred miles of vehicle testing to demonstrate the robustness of the conversion. Future emission studies are planned to quantify the emission reduction associated with the use of aqueous fuels. The information gained on this project will enable future conversions achieving higher efficiencies and lower emissions than currently possible on existing platforms.

DESCRIPTION OF PROBLEM

Alternative fuels for transportation are likely to be more diverse than those used in current vehicles. As such, assessment of emerging fuels for niche markets requires a comprehensive, albeit efficient, screening process that investigates power output, exhaust emissions, vehicle range, and engine durability in a variety of operating environments. This evaluation should include detailed monitoring under controlled Environmental Protection Agency (EPA) test cycles, as well as long-term, over-the-road testing. It is also desirable that tests with alternative fuels and traditional fuels be done on the same vehicle platform.

The goals of this project were to rapidly assess a new renewable fuel and ignition system and to bring the assessment to the attention of fleet vehicle operators, as well as to individual users who drive vehicles in different applications. An innovative fuel and ignition system is currently being retrofitted to four different engines operated by the National Institute for Advanced Transportation Technology (NIATT) at the University of Idaho. These engines are powered by alcohol-water combustion initiated by a catalytic plasma torch. This project will provide critical data required for documenting and disseminating economic and environmental impacts of this technology. The project will also illustrate a process for supporting acceptance of a promising technology by the public. Engine durability, exhaust emissions benefits, and fueling infrastructure demands will be brought to the attention of niche users such as fleet operators in state agencies, small cities, and pristine rural environments.

The fuel assessed in this project is a high-water content biofuel (70 percent ethyl alcohol and 30 percent water) called Aquanol™. Previous demonstration projects with catalytic igniters completed by a Sandpoint, Idaho, engine research company, Automotive Resources Inc., suggest that Aquanol is a low-emission, low-cost fuel that can be burned in a wide variety of existing internal combustion engines.

Emissions Characteristics of Aqueous Fuels

Studies show that nitrous oxide (NO_x) reductions of up to 40 percent can be obtained by using standard fuels and lean combustion [1]. However, current spark and compression ignition engines still produce as much as 2500 ppm NO_x. In an effort to eliminate the thermal formation of NO_x, water has been used in emulsions with a variety of fossil fuels [2]. Extending the lean burn limit by introducing liquid water as a diluent can reduce NO_x and carbon monoxide (CO) without compromising engine performance. When water is present in the cylinder, its mass absorbs energy. The result is lower peak temperatures as well as reduced CO, because of the water gas shift reaction seen in Eq. (1).

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad (1)$$

Emulsified fossil fuels still burn with flame temperatures high enough to form thermal NO_x (2000 K). Due to the emulsifying agents, they are also more expensive than their anhydrous counterparts. Lean combustion of the emulsified fuels could offset these costs and further lower NO_x emissions, but lean combustion has no effect on sulfur emissions and is generally accompanied by significant power reductions.

The literature suggests that, due to advances in combustion technology, ethanol (E100) could replace gasoline and diesel fuel by the year 2010 [3]. This is not hard to imagine because ethanol is presently being used as both an octane booster for gasoline (E10) and an alternative fuel denatured with gasoline (E95). These fuel mixtures do not significantly reduce NO_x emissions. Theoretically, neat ethanol can afford a slight decrease in NO_x emissions over gasoline and diesel due to its lower adiabatic flame temperature of 2203 K (compared to 2250 K for gasoline and 2327 K for diesel). For significant reduction in NO_x emissions, an inert diluent is needed. Water is a practical choice because of its miscibility, availability and high density at standard temperature and pressure conditions (STP).

Performance Characteristics of Aqueous Fuels

Emission reduction is not the only benefit to be gained from using aqueous fuels. Other performance improvements included increased power output and reduced fuel consumption. Lower combustion temperatures can mean improved thermal efficiency due to decreased heat transfer losses, less dissociation of combustion products, and improved volumetric efficiency. Catalyst ignition can further increase thermal efficiency because of decreased ignition delay. This has the effect of moving toward more constant volume combustion. Figure 1 compares the efficiency and compression ratios for various cycles. It has been proven that catalyst ignition of aqueous fuels is possible using a converted diesel engine with a 17:1 compression ratio changed to a thermodynamic “Otto cycle” to increase thermal efficiency [4].

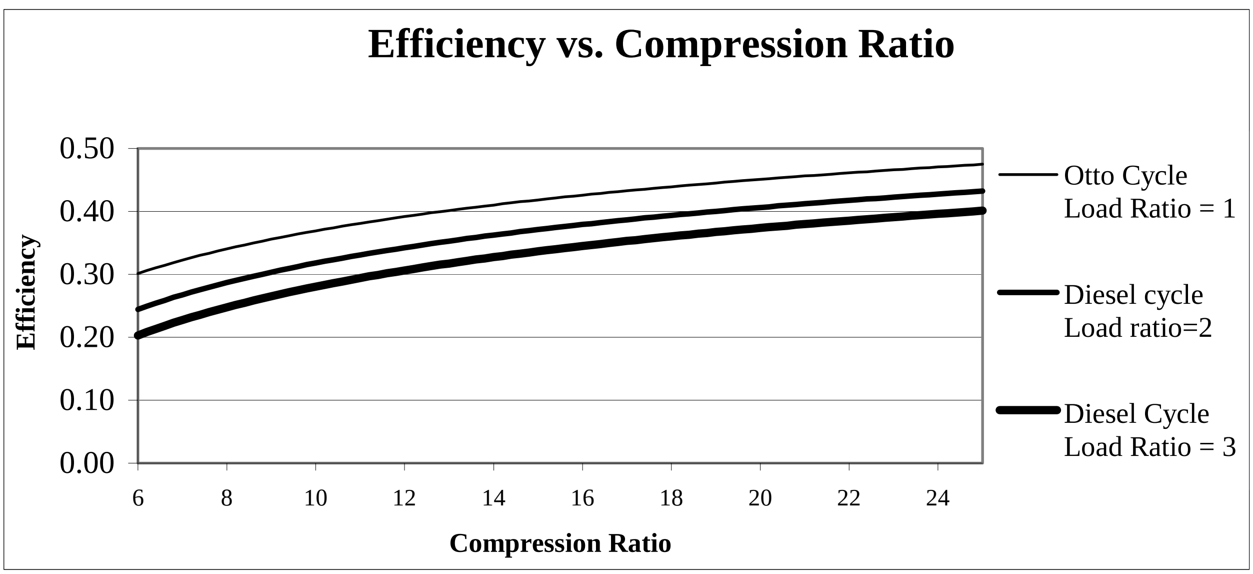

Figure 1. Diesel and Otto cycle efficiencies based on compression ratio [5].

A subtle power-increasing phenomenon associated with ethanol combustion is charge cooling. Ethanol has a high heat of vaporization (886 kJ/kg), which is 2.5 to 3 times that of gasoline or diesel. As ethanol vaporizes, it draws a great deal of energy from the surrounding air. This phenomenon can account for a temperature drop of 77° C for an engine operating with a stoichiometric air/fuel ratio of 9:1 [3]. The temperature drop densifies the charge and allows for additional air and fuel to enter the combustion chamber. This can significantly increase the power output of the engine. Gasoline evaporation under similar conditions only results in a 7° C drop in charge temperature.

Ignition of Aqueous Fuels

Research has been conducted and patents issued on the subject of aqueous fuel combustion with catalytic assistance [1]. Work with water-naphthalene and water-alcohol mixtures pioneered the use of water as a combustion diluent and temperature reducer for NO_x reduction in diesel and spark ignition (SI) engines [2]. These engines were run with as much as 50 percent water, but they only switched to aqueous fuel following warm-up of the engine using the design fuel. If this technology were to be commercialized, gasoline or diesel would have to be delivered to the engine during start-up, necessitating two separate fuel-handling systems. Such technology would not be cost effective and could not be retrofitted to existing engines.

Research has been conducted with 190 proof ethanol and a two-stroke diesel engine to eliminate the last distillation step for ethanol and thus save on its production cost [6]. The research concluded that 190 proof ethanol would make a suitable fuel based on power output as well as oil analysis data. In our research, water is no longer left as a residue in order to save production costs, but instead is a major constituent for the purpose of extended lean-burn operation and NO_x reduction. Cost reduction is only incidental to these other benefits.

Our research was conducted using a mixture of ethanol (C_2H_5OH) and water. The alcohol was dried to 200 proof (100 percent) and then re-diluted with 29.9 percent de-ionized water, yielding a product that is 68.8 percent ethanol by volume. Isopropanol comprises 1.3 percent of the mixture and, along with 6.58 mg/L benzoate, forms the denaturant approved by the Bureau of Alcohol, Tobacco and Firearms (BATF). Our goal was not to investigate fuel properties, such as the optimal amount of water. Table 1, listing properties for gasoline, diesel and pure ethanol, shows the energy content differences as well as the very different flammability limits. Note that ethanol burns over a much wider range of conditions than gasoline or diesel.

Currently, research concerning starting and running engines on as much as 30 percent water is not found in the literature. However, SMARTPLUGs are capable of igniting these high-water mixtures and extending the lean limit of ignition and combustibility.

Table 1. Fuel Properties [7]

Property	#2 Diesel	Gasoline	Ethanol
Boiling Point [K]	461-616	300-498	351
Autoignition Temperature [K]	589	530	696
Stoichiometric Air/Fuel Ratio [Wt./Wt.]	14.6	14.5	9.00
Rich Flammability Limit [vol. percent]	7.60	6.00	19.00
Lean Flammability Limit [vol. percent]	1.40	1.00	4.30
Lower Heating Value [MJ/kg]	43.2	44.0	26.9

APPROACH AND METHODOLOGY

Ignition of aqueous fuels has been a drawback in the development of alternative-fueled vehicles meant for daily use. Typical ignition sources do not deliver the energy necessary to initiate combustion before quenching from the water extinguishes the flame front. As part of the vehicle conversion, it was necessary to study SMARTPLUG technology and learn how to apply it to our problem. With this better understanding, we began converting a larger platform to demonstrate the feasibility of daily use that has been previously unseen in the literature.

Catalytic Igniter

The catalytic igniter explored in this work is known as a SMARTPLUG or Catalytic Plasma Torch (CPT)[1]. The CPT is a self-contained ignition system that can be retrofitted to a variety of spark-ignition and compression-ignition engines (Fig. 2). The igniter consists of a ceramic rod with an embedded heating element and a coating of noble metal catalyst at the end of the rod. The ceramic rod is enclosed in a custom-machined brass shell, which forms a pre-chamber adjacent to the main combustion chamber. The pre-chamber volume is typically 5 to 7 percent of the clearance volume in the main chamber. The CPT assembly is made to fit into existing spark plug or fuel injection ports.

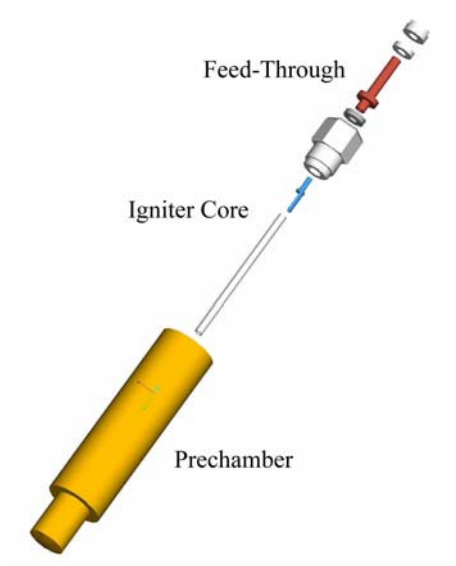

Figure 2. Improved CPT design.

The operating principle of the CPT is auto-ignition of the charge in the presence of a catalyst in the pre-chamber, initiated by carefully timed catalytic surface reaction. This can be adjusted in a manner independent of the homogeneous reaction rate. Several regimes of catalytic activity are possible, each having a different effect on gas phase chemistry.

In order to understand these phenomena, it is valuable to review the physics underlying heterogeneous catalysis. Combustion on catalytic surfaces consists of the following:

(1) Transport of reactants from the bulk phase
(2) Adsorption of reactants onto the surface
(3) Reaction of adsorbed species on the surface
(4) De-sorption of reaction products from the surface
(5) Transport of reaction products to the bulk phase

Since these processes take place sequentially, the slowest step will determine the overall reaction rate. At low temperatures, one of steps 2, 3, or 4 will be kinetically limited and hence rate controlling. In this region, reaction rate is commonly an exponentially increasing function of temperature. As the catalyst temperature is elevated, the reaction rate rapidly becomes limited by the rate at which reactants can be transported to the surface. In this diffusion-controlled regime, the reaction rate is nearly independent across a broad range of temperatures [8]. As the catalyst temperature is elevated further, homogeneous phase reactions in the adjacent gas phase will augment the diffusion-limited reaction rate. This is the phenomenon of heterogeneously catalyzed gas phase combustion described by Pfefferle [9]. This background information helps one understand gas phase ignition as it applies to the CPT.

As the piston moves through the compression stroke, the fresh charge is compressed into the pre-chamber. Products from the last cycle remain and act like a gas spring against the next charge. As the fresh mixture front passes over the heated catalyst, some reactants are adsorbed onto the catalyst surface. Reactions on the surface form radicals and release heat, both of which accumulate at the rear of the pre-chamber (the end opposite the nozzles), along with an ever-increasing amount of unburned mixture. Once the pressure and temperature are high enough, spontaneous gas phase ignition occurs throughout the pre-chamber. The process occurs rapidly and propels active radicals and hot combustion products into the main chamber. The resulting plasma torch initiates multi-point gas phase ignition in the main chamber. The nozzles in the shell of the igniter are machined in such a way that they produce the torch pattern seen in Fig. 3. This high intensity charge is necessary to start the combustion of aqueous fuels. In previous attempts with lesser ignition sources, the water content in the fuel quenched the combustion.

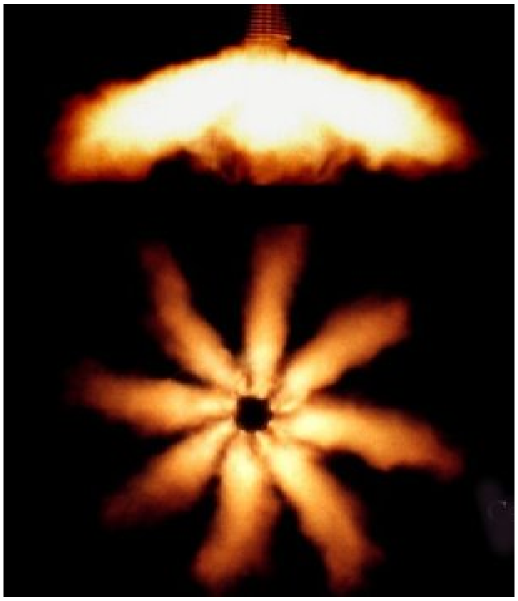

Figure 3. CPT flame pattern.

Vehicle Conversion

Our test vehicle was a Ford Van with a 351W engine provided by Valley Transit (Fig. 4). When we received the van, it had been damaged from an engine fire. The interior and exterior were in fine shape, but the engine compartment was in disarray. What made this work different from our earlier engine conversion work is the size of the motor and its integration in a fleet vehicle platform. We had prior experience converting rotary and four cylinder engines in generator sets and small private automobiles. In this work, we converted a V8 engine in an 8500-pound vehicle. This engine was more than twice the size of the engines we had previously converted.

Figure 4. Conversion van as delivered by Valley Transit.

We began by removing and rebuilding the engine. We used total seal piston rings in the rebuild to help keep water in the fuel from leaking in to the lubrication system. We replaced several components that had been damaged beyond repair by the engine fire. An entirely new cooling system was installed, and all the wiring in the engine bay was redone as well. The only non-stock modification was done while the engine was torn down. A port for a pressure transducer was machined in one of the cylinder heads. We used this port to observe ignition timing, but such a modification would not be necessary in a mass-produced application.

One advantage of using the catalytic igniter is that very little must be added to the vehicle in the conversion process. In fact, on a production level, no new components are necessary to run aqueous fuels—only the substitution of a few select components is needed. Water content in the fuel is the greatest obstacle to conversion. In a traditional gasoline engine, having water in the fuel is a disaster and many precautions are taken to avoid that occurrence. Because of this history, current factory-designed fuel handling systems are not meant to deal with potential corrosion problems associated with water in the fuel. On a production scale, preparing for use of aqueous fuel is simply a matter of substituting water resistant versions of the same components.

Fuel-handling components are the most prone to corrosion from aqueous fuels. This particular van had a steel gas tank that had to be replaced with a plastic one. Many newer vehicles already use plastic fuel tanks, and the general trend indicates even greater use in the future. Fuel lines to engine compartments are usually made of steel, as well, and will corrode if aqueous fuel sits still for extended periods. The alternative is to use stainless steel or aluminum tubing for fuel lines. Neither of these modifications should add much to the production cost of the vehicle.

The high-pressure fuel pump is probably the most affected by aqueous fuels. Standard fuel pumps will corrode if any sort of water is run through them. We use a stainless steel fuel pump, but the cost is significantly greater than that of a typical fuel pump. Also, since more flow is necessary with aqueous fuels, a higher capacity fuel pump is required. Figure 5 shows the different sizes of the stock and modified fuel pumps.

Figure 5. Comparison of stock (bottom) to modified fuel pump (top)

We added other components necessary for the conversion, but factory pieces could be adjusted for the same function on production vehicles. A new fuel control controller (Fig. 6) allowed us to adjust the fuel map, controlling the fuel with a laptop computer. The new fuel map is proportional to the original map, with minimal adjustments where necessary. On a production level, the factory computer could easily be made with the correct fuel map. New fuel injectors were also added to the engine. Because of the lower heating value of aqueous fuels, it was necessary to inject more fuel in the air stream. The stock injectors were not able to flow enough fuel at high loads and were replaced with higher flowing injectors.

Figure 6. Haltech fuel injection controller.

The only new piece of hardware used was the catalyst igniter itself (Fig. 7). The igniter replaces the spark plug in gasoline engines and the glow plug in diesel engines.

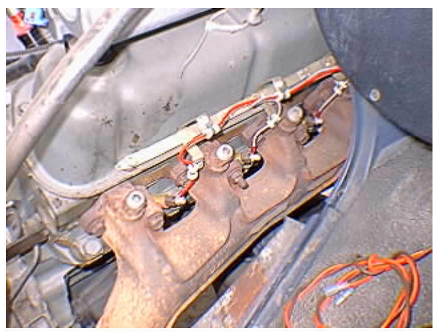

Figure 7. Igniters installed on passenger side of engine.

Table 2 lists the converted components with our conversion cost and the estimated cost in mass production.

Table 2. Comparison of Actual and Production Costs.

	Conversion Cost	**Increased Production Cost**
Rust resistant fuel tank	$150	None
Stainless fuel lines	$40	$40
Water resistant fuel pump	$300	$200
Fuel injection computer	$1200	Not necessary
New fuel injectors	$300	$100
Igniter set	$100 each	$50 each

FINDINGS; CONCLUSIONS; RECOMMENDATIONS

Since this project is still in its early stages, most of what we have learned concerns the conversion of a large platform. We have also gained information about road usability. Logs kept by drivers of the van provide irreplaceable information that characterizes the vehicle in ways that laboratory tests cannot.

After the conversion was completed and the vehicle put in service, our focus has switched to testing and presenting the work. We plan to conduct emissions tests following the EPA Federal Test Protocol.

We also plan to make the van more of a showpiece. We plan to keep the vehicle in the public eye by displaying it at conferences and shows and in daily road use as well as is writing Internet articles and making press releases.

Conversion Findings

We have identified the components and processes necessary to convert a gasoline engine to run on aqueous fuels. Currently, our experimental vehicle has been converted and runs on either gasoline or aqueous fuel with SMARTPLUG ignition. It has been driven several hundred miles, but no fuel consumption or emissions testing have been completed yet. We found that the conversion process used for the larger V8 engine is virtually the same as that for smaller platforms with which we are familiar.

The advantage of an over-the-road test vehicle is the variety of conditions during which it is used. The converted van sees mostly highway use, but is used occasionally on unpaved roads. The vehicle runs in weather conditions that range from subzero conditions in the winter to temperatures around 100° F in the summer, and it starts and runs normally under all conditions. The varying conditions and repetitive use of the van makes it an ideal platform for real world feasibility of aqueous fuels for fleet vehicles.

Cold starting on aqueous fuel is not a serious problem. At low ambient temperatures, the catalyst heaters work best when running at 16 volts. This voltage allows the engine to start normally, but is not a conventional power source for vehicles. Future igniters for this vehicle can be built to add the required level of heat with a 12-volt source.

Engine warm-up time is longer after conversion to aqueous fuels due primarily to the lower combustion temperatures. The temperature enrichment on the fuel controller was modified to facilitate engine warm-up since the van needs to idle for several minutes before being driven. The operating temperature of the engine is lower than before conversion. In cold weather, this could cause heating concerns for the driver and occupants of the van. The engine gets sufficiently warm to heat the cabin area; it just takes longer to do so. This could be corrected with an additional heating source.

As expected with aqueous fuels, the mileage is significantly worse than with gasoline. The original vehicle achieved 6 mpg. Our preliminary fuel monitoring shows that the converted van gets between 3 and 4 mpg. The specific energy of a 30 percent aqueous ethanol mix is just under half of regular gasoline. Based on energy content alone, the mileage should drop in half. However, the charge cooling and slightly higher thermal efficiency leads to only a 33 percent reduction in mileage.

The van has been tested with a new igniter design that is able to control the ignition timing much like the vacuum advance on a spark ignition engine. Previous designs have had closer to constant ignition timing over various loads. The new design couples the mass in the pre-chamber more closely with ignition timing and will retard the timing as load is increased. This allows higher advance in initial timing for steady state loads that produce better fuel economy and emissions characteristics.

Vehicle Testing

To assess the environmental impact of advanced transportation technology, the emissions from vehicles using this technology must be monitored under carefully controlled conditions. The EPA Federal Test Protocol (FTP) (Fig. 8) must be rigorously followed to quantify the reduction in emissions of NO_x, CO, unburned hydrocarbons and particulate matter of the catalytically ignited biofuel in comparison with diesel fuel or gasoline. Additional testing for the production of aldehydes, combustion byproducts characteristic of ethyl alcohol, must be done. These tests require specialized and sophisticated equipment, including a chassis dynomometer integrated with gas analysis and data acquisition systems.

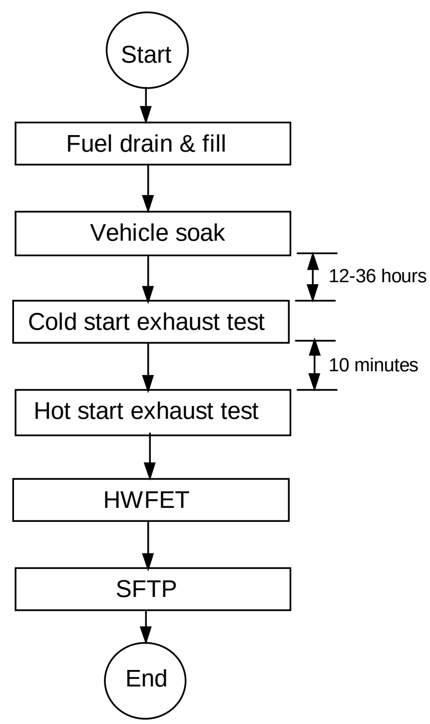

Figure 8. Block diagram of the FTP test cycle

Vehicles are run through EPA-specified driving cycles to compare exhaust emissions under equivalent and repeatable test conditions. Each driving cycle prescribes the vehicle velocity as a function of time. The FTP 72 driving cycle is shown in Fig. 9.

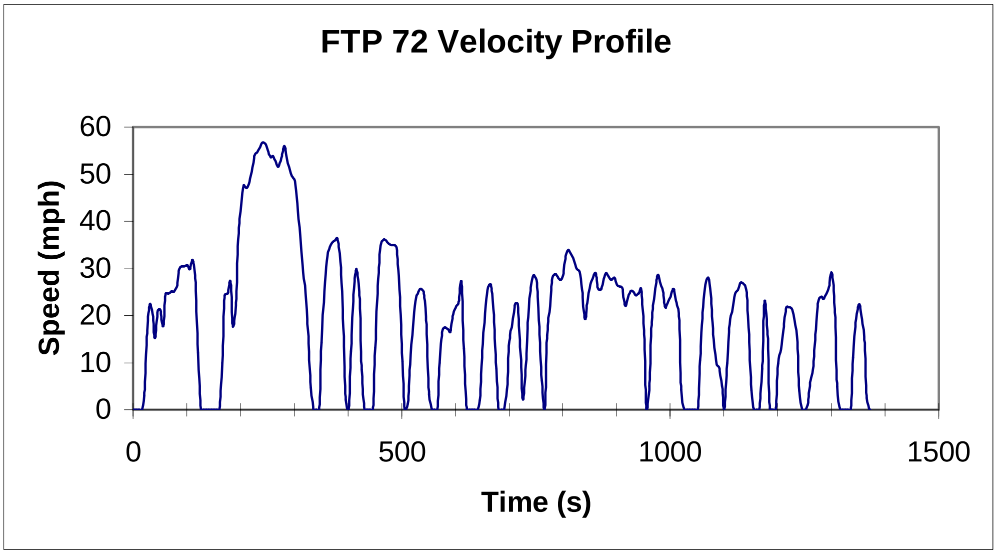

Figure 9. Speed-time trace for the FTP 72.

The FTP 72 cycle, developed in 1972 and the oldest EPA driving cycle, has come to be known as the Urban Dynomometer Driving Schedule (UDDS). The test represents city driving and follows a route that is 7.5 miles long. It takes 1372 seconds (22.87 minutes) to complete with an average velocity from start to finish of 19.6 mph. In 1975, the EPA set a maximum threshold for cold start CO emissions that led to the creation of the FTP 75 driving cycle shown in Fig. 10. The FTP 75 cycle requires that the test vehicle be operated from cold start conditions after an appropriate soak period. By contrast, FTP 72 testing was routinely done with a preconditioned vehicle that had achieved operating temperature. The FTP 75 cycle is the same as the FTP 72 cycle with one exception—the first 505 seconds are repeated at the end under hot start conditions. The cold start phase is defined as the first 505 seconds of FTP 75.

We intend to conduct some tests and measurements on the vehicle and make modifications that will net better emission results before we run the FTP cycles. We will complete the first measurement by creating a local driving cycle, which will be used subsequently to benchmark improvements. We will use a five-gas analyzer to get an approximation of our cycle emissions. Depending on the results of this experiment, we may install a catalytic

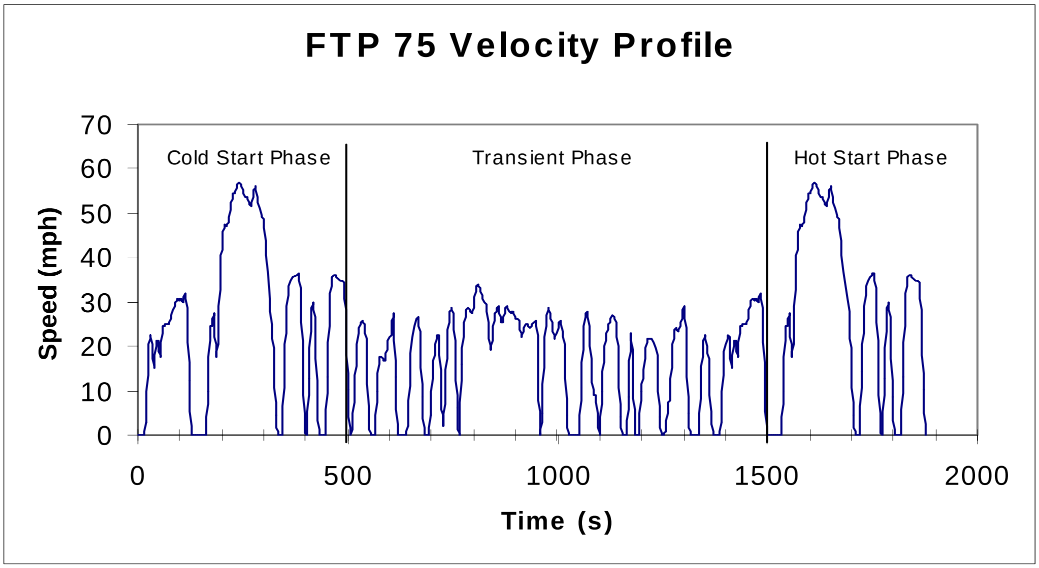

Figure 10. FTP 75.

converter and perform the tests again. We should be able to quantify the emission reduction from the converter and experiment with various types (of converters) to achieve expected emission levels.

After we are comfortable with the emission levels in our driving cycle, we will get some steady state emissions readings. We need to test the vehicle under static operating conditions at various speeds and loads in order to characterize the emissions from the vehicle, using a chassis dynomometer. This will provide valuable data we can compare with stock performance.

Once we are happy with the simulated driving cycle and steady state dynomometer results, we will have the FTP tests performed. We plan to have two sets of data gathered at that time. We will run the vehicle with gasoline using the igniters, and then re-run the tests using aqueous fuel.

The potential for producing vehicles with ultra-low emissions has been established. However, the implementation of the technology on future fleet vehicles will falter unless long-term effects on the engine are also assessed. Engine durability can be established by following the Engine Manufacturer's Association 200-hour screening test protocol for alternative fuels on an engine, performing high-mileage driving tests on vehicles, monitoring engine wear during these tests, and monitoring any deterioration of catalytic elements. Over-the-road high mileage tests using vehicles typically found in fleets are essential for establishing robustness in alternative fueled vehicles and stimulating development of fueling infrastructures.

One area for future work is improved longevity of the catalyst igniter. Overheating or contamination of the fuel can lead to premature failures. Figure 11 shows a Scanning Electron Microscope (SEM) image of an igniter after several hours of clean ignition.

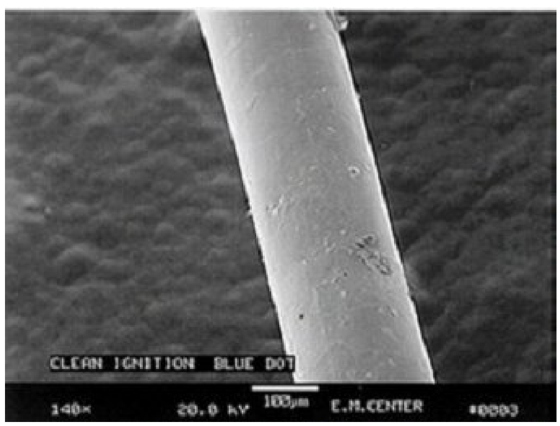

Figure 11. Catalyst after clean ignition.

The catalyst is still smooth and uniform across the whole core. Figure 12 illustrates a failed igniter after several hundred miles of use. The catalyst is beginning to flake from the core and decompose. Research is being done on both the process and composition for the next generation of igniters. Failure analysis is instrumental in providing information on the failure modes and should lead to new, more durable ceramic materials for igniter cores.

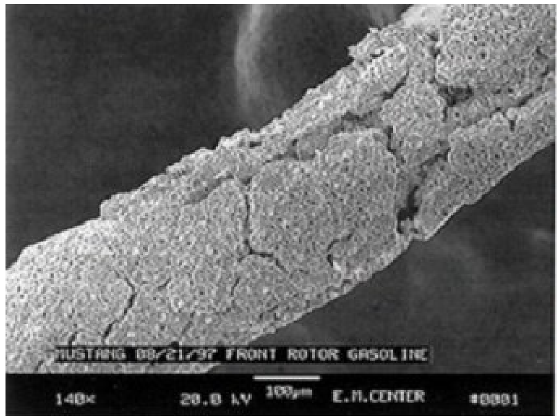

Figure 12. Igniter after catalyst breakdown.

Public Awareness of Alternative Fuels

Another area worth considering is increased public awareness. The van was demonstrated at the Alternative Energy Conference hosted by Idaho Department of Water Resources in Coeur d'Alene, Idaho, on July 7, 2000. The van is also seen frequently driving around Sandpoint, Idaho. However, there is currently nothing that allows this van to be distinguished from those running on normal fuels.

We would like to alter the exterior of the van so that it is more recognizable. At a minimum, we plan to add decals representing the sponsors of the project. We would also like to add some graphics highlighting the fact that aqueous fuels are being used to power the vehicle. We have successfully proved that a vehicle running on aqueous fuels can be put to daily use. We have also made significant advances in the Smart Plug technology. The information gained through our research will help us complete additional conversions that should achieve efficiencies higher than any engines used in transportation today.

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