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Oxygenated Diesel: Emissions and Performance Characteristics of Ethanol-Diesel Blends in CI Engines

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ABSTRACT

Diesel engines are major contributors of various types of air polluting exhaust gasses such as Particulate Matter (PM), Carbon monoxide (CO), Oxides of Nitrogen (NO_x), Sulfur, and other harmful compounds. It has been shown that formation of these air pollutants can be significantly reduced by blending oxygenates into the base diesel. Ethanol blended diesel (e-diesel) is a cleaner burning alternative to regular diesel for both heavy-duty (HD) and light-duty (LD) compression ignition (CI) engines used in buses, trucks, off-road equipment, and passenger cars. Although ethanol has been used as a fuel oxygenate to reduce tail-pipe emissions in gasoline, its use in diesel has not been possible due to technical limitations (i.e., blending). Commercially viable E-Diesel is now possible due to the development of an additive system, *Puranol,* invented by Pure Energy Corporation (PEC). *Puranol* allows the splash blending of ethanol in diesel in a clear solution possible for the first time. Laboratory and field tests have demonstrated over 41% reduction in PM, 27% reduction in CO, and 5% reduction in NOx from a HD diesel engine. Significantly higher emissions reductions are observed from smaller 1.9-L VW TDI engines.

INTRODUCTION

Diesel exhaust is a major contributor to various types of air pollution, including particulate matter (PM), oxides of nitrogen (NO_x), and carbon monoxide (CO). It has been demonstrated that the formation of these air pollutants can be significantly reduced by incorporating or blending oxygenates into the fossil fuels matrix. Over the last two decades in the United States, Brazil, and other parts of the World, oxygenates, such as methyl-tertiary-butyl ether (MTBE) and ethanol, have been recognized as key elements of cleaner burning gasoline.

Over the past decade, researchers have sought for ways to oxygenate diesel. However, it has been found that most conventional fuel oxygenates, such as MTBE, TAME, MEK, etc., were not suitable for diesel fuel use. Ethanol as a diesel oxygenate, while compatible, does not blend effectively with diesel. Ethanol-diesel blends phase separate when exposed to small amounts of water and/or low temperatures. However, it has been proven that ethanol in diesel reduces tailpipe emissions of PM, CO, and NO_x. *Puranol* additive system designed by PEC allows easy blending of ethanol and diesel into a crystal clear and stable fuel for the first time by overcoming the technical limitations.

Pure Energy Corporation has completed extensive fuel testing and demonstration programs in the United States accumulating close to a million miles operating both the heavy-duty bus and truck engines on ethanol-diesel fuel blends with up to 15% ethanol and 1% to 3% *Puranol* in the mix.

The overall results from these test programs have established the ethanol-diesel blends to be compatible with the existing engine technology, fuel distribution, use, and blending infrastructure. Fuel performance, long-term storageability, tail-pipe emissions, durability, materials compatibility, environmental biodegradability, and other engine characteristics have been established to meet the fuel performance specifications.

The United States Clean Air Act Amendments (CAAA) currently mandate lower emissions for certain diesel fleets. Likewise, state and municipal governments (e.g., California Air Resources Board, or “CARB”) are requiring diesel users to adhere to strict emissions levels below that of federal standards. The US EPA has proposed a 0.1 g/bhp-hr rule for particulate matter for year 2002 diesel heavy-duty engines and a further reduction to 0.01 g/bhp-hr by the year 2007. EPA is also developing a health assessment document characterizing diesel fuel exhaust as highly likely to be a human carcinogen at ambient levels.

The objective of this investigation was to first create a stable ethanol-diesel blended fuel with the help of Pure Energy's *Puranol* additive system, and then to generate transient emissions data for an evaluation of different oxygen content based on ethanol content. The fuel blend was also utilized in heavy-duty bus and truck fleets in a comprehensive one million mile demonstration test to determine fuel-engine compatibility, large-scale blending, storage, and distribution logistics. The emission tests were performed based on the EPA HD diesel transient test procedure on a 1991 12.7-L DDC Series 60 engine.

E-DIESEL FORMULATION

In response to regulatory trends and market demand for a better and cleaner diesel fuel, PEC has developed an ethanol-diesel blend as a practical and cost effective solution to the regulatory environmental challenges.

At the heart of E-Diesel invention is a proprietary additive package called *Puranol* that enables ethanol to be splash blended with diesel in a clear and stable solution.

E-Diesel has several performance benefits in addition to superior emission advantages when compared with other regular diesel alternatives such as ultra low sulfur diesel.

- Lower emissions of PM, NOx and CO
- No engine modifications required
- Cost competitive at commercial scale
- Low-cost alternative to modified or new engine equipment
- Low-cost alternative to expensive oil refinery modification to produce ultra low sulfur diesel
- Clear stable liquid with same cloud point as diesel
- Improved lubricity
- Readily biodegradable as per ASTM protocol
- Improved cold-weather performance
- Blendable at terminal

PRODUCT DESCRIPTION

E-Diesel blended fuel formulation contains between 83- to 94-percent No. 2 diesel fuel, 5- to 15-percent ethanol and 1- to 2-percent *Puranol.* The ethanol and *Puranol* impart premium diesel characteristics to the No. 2 diesel fuel such as reduced exhaust emissions, superior cold-performance, improved lubricity (which relates to engine life extension) and long-term storage stability.

Geographical regions that experience moderate or warm climate require less then 1-percent *Puranol* while cold and humid/wet parts of the country would need a higher *Puranol* dosage of the additive of up to 3- to 3.5 percent. Furthermore, given the hydroscopic nature of ethanol, its concentration in finished E-Diesel also plays a role in determining optimum *Puranol* dosage.

Puranol provides the ethanol-diesel blend significant storage stability to very low temperatures. Preliminary emission tests conducted at the Southwest Research Institute (SwRI) on different versions of E-Diesel blends containing 10% and 15% ethanol confirmed a significant reduction in overall emissions from heavy-duty diesel engines. Other environmental benefits associated with E-Diesel include reduced net emissions of greenhouse gases and improved biodegradability.

PEC has focused on creating the most functional and practical E-Diesel fuel by balancing various formulation components and their respective properties. E-Diesel is designed to operate in unmodified diesel engines as an economic alternative to ultra low sulfur diesel (ULSD) for reducing emissions, improving performance parameters and adding domestic renewable content to diesel. PEC's additive package *Puranol* and fuel formulations allow fuel distributors and fleet operators to blend ethanol with any diesel fuel grade that will stay mixed together under extreme conditions. E-Diesel is designed to operate in a full range of climates and customer applications.

E-Diesel is an economically attractive fuel. It does not require dedicated or special-purpose production facilities since it can be blended "in-line" at the terminal or splash blended in the storage tank or tank truck just prior to delivery. Furthermore, *Puranol* is commercially available, and in full-scale use the E-Diesel would be available at a price that is only marginally higher than No. 2 diesel, and yet less than the comparable premium No. 1 diesel.

FUEL PERFORMANCE CHARACTERISTICS

The additive *Puranol* is designed to maintain base diesel fuel properties such as cetane number, improve lubricity, low temperature flow characteristics, storability, and other critical traits of the diesel fuel. *Puranol* is developed based on electrochemistry and fuel chemistry of the two very different fuels – ethanol and diesel. The *Puranol* additive system is designed to stabilize E-Diesel based on low temperature flow test (LTFT) characteristics.

An elemental analysis of *Puranol* additive system shows the four basic environmentally friendly elements: carbon, hydrogen, and oxygen. *Puranol* contains no heavy metal containing compounds or compounds that are harmful to human health or the environment. The resulting E-Diesel fuel conforms to ASTM protocols for diesel fuels.

Ethanol is an excellent oxygenate and has demonstrated the ability to positively impact the tailpipe emissions from diesel engines, however, it does also impact negatively certain key fuel properties of diesel, such as fuel cetane number and lubricity characteristics.

A 23-percent ethanol in diesel would render all cetane property of No. 2 diesel (with a base of 40 cetane) useless. In other words, while a large volume of ethanol in diesel significantly improves emissions, it would impact negatively three of the major properties of the blend—cetane, flash point, and lubricity.

Low lubricity can result in fuel pump failure and injector degradation at an accelerated rate even when ethanol is used in as small a quantity as 5%. *Puranol* is designed to address both lubricity and cetane property limitations.

Fuel Property	E-Diesel
Water & Sediment, % max	N/D
Distillation % vol rec. T-90 (ºC)	311
Kinematic Viscosity, 40ºC (cSt)	2.25
Ash (%) max	0.001
Sulfur (%) max	-20%
Copper Corrosion @ 3 hr max	1a
Cetane Number, min	45
Cetane Index, min	42
Rams. Carbon, 10% res.	0.22
API Gravity, max	38
Lubricity (g) min	5200
Accel. Stability, pass/fail test	Pass
Cloud Point (ºC)	-13
LTFT at -11ºC, pass/fail test	Pass
LTFT at -19ºC, pass/fail test	Pass

Table 1. Critical E-Diesel fuel properties based on a 15-percent ethanol, Puranol and No. 2 diesel formulation.

PEC is working to solve the flash point issue and has made significant progress toward achieving its goals. Results from our flash point research will be introduced as part of our second-generation additive system.

The University of Illinois at Urbana-Champaign, working with Cummins (which donated a new engine), conducted 500-hour durability testing on Pure Energy's E-Diesel. The tests results concluded that E-Diesel does not cause any excessive engine wear on a HD diesel engine over an extended use cycle.

BIODEGRADABILITY PROFILE

According to testing standards of American Society for Testing and Materials (ASTM), E-Diesel, containing a 15% ethanol and up to 3% *Puranol* in a No. 2 diesel is "readily biodegradable." A "readily biodegradable" fuel designation is assigned if a substance under natural aerobic conditions is 60-percent or better degraded in 28 days. The result from an independent study comparing PEC's fuels with conventional and other renewable fuels is available from Pure Energy Corporation.

In comparison to PEC formulated fuels, which included E-Diesel, reformulated gasoline containing MTBE as an oxygenate, regular gasoline and diesel fuels all fail the ASTM test for "readily biodegradable." E-Diesel readily biodegradable designation is significant in light of recent concerns over water contamination from MTBE, which does not biodegrade naturally. Any inadvertent spill of any of the PEC fuels, such as E-Diesel, in contrast with MTBE containing reformulated fuel will have significantly less impact due to *Puranol* additive containing E-Diesel's excellent biodegradation profile.

ENERGY CONTENT OF E-DIESEL

The net energy content of one gallon of undenatured, anhydrous ethanol is 76,000 BTU's compared to 77,900 BTU's per gallon of denatured (including 5% gasoline), anhydrous ethanol, 114,000 BTU's per gallon for regular gasoline and 138,000 BTU's per gallon of #2 diesel fuel.

Assuming that the BTU content of the additive package *Puranol* is similar to that of diesel fuel, the 15% ethanol containing E-Diesel formulation would contain 128,985 BTU's per gallon or 93.5% of the energy content of one gallon of #2 diesel fuel.

(0.15 X 77,900) + (0.85 X 138,000) = 128,985 BTU's/gal.

Theoretically, then, there would be less than a 7% loss of performance and or fuel economy encountered when using E-15 E-Diesel fuel.

EMISSIONS EXPERIMENTS

Emission tests conducted at the Southwest Research Institute (SwRI) on a Series 60 Detroit Diesel heavy-duty engine on different versions of E-Diesel formulations containing 10-percent and 15-percent ethanol confirmed a significant reduction in overall emissions from heavy-duty diesel engines.

The emissions reductions base-lined in the above tests were based upon tests conducted using one of the most popular heavy-duty diesel engine types currently used in the US - a 12.7-L Detroit Diesel DDC Series 60 engine. Both PM and NOx are two of the major tailpipe emissions that have significant impact on human health and the environment.

While most on-road vehicles can be fitted with catalytic converters, the test protocol used by SwRI to evaluate E-Diesel did not use any after treatment devices in order to accurately measure the effect of the fuel alone. However, it is believed that with a catalytic converter the emissions results could be expected to improve considerably. The regulated emissions of particulate matter, hydrocarbons, carbon monoxide, and nitrogen oxides were measured over each transient test.

Two fuel formulations were tested containing variable amount of ethanol. A 10-percent ethanol (corresponding to 3.9-percent oxygen by weight) and 15-percent ethanol (containing 5.7-percent oxygen by weight) containing in No. 2 diesel fuel with Puranol were tested.

Emission Change Compared to Neat No. 2 Diesel		
	15% Ethanol Blend	10% Ethanol Blend
PM	-41%	-27%
NOx	-5%	-4%
CO	-27%	-20%
HC	Neutral	Neutral

Table 2. Average percentage change for the transient emissions between E-Diesel containing 10-percent and 15-percent fuel-grade ethanol, Pure Energy's *Puranol* additive and No. 2 reference diesel fuels.

A 41% reduction in PM and 5% reduction in NOx is significant, considering typically alcohol-containing fuels have been known to actually increase NOx emissions by 20-25%. A net decrease of over 5% in NOx emissions actually represents an overall swing of 25-30% in NOx. This impact on NOx reduction is attributable to ethanol and *Puranol* additive package.

Tests at the AutoResearch Labs and Argonne National Laboratories has shown that significant reductions in PM and NOx emissions are possible when using *Puranol*-based E-Diesel from a 1.9-L TDI Volkswagen industrial diesel engine with direct fuel injection and EGR.

The study created an operational map at different engine speeds and load characteristics for both a 10-percent and 15-percent ethanol containing E-Diesel using Pure Energy's *Puranol* additive. It found that at loads of 105 Nm or above (50-percent or more load) and at engine speeds of 1500 to 1700 rpm, the PM emissions reduced a significant amount between 22- and 75-percent and NOx emissions reduced between 60- and 84-percent.

While Argonne results represent only preliminary data in a narrow operational band and in a single engine type, these still indicate promising results considering that an optimized and integrated fuel-engine configuration can result in significantly large reductions in emissions.

FIELD DEMONSTRATION RESULTS

E-Diesel has been demonstrated in several field test programs, including Archer Daniels Midland Trucking (ADM), the Chicago Transit Authority (CTA) and Waste Management, Inc (WMI). PEC's E-Diesel demonstration programs include numerous participants including fuel suppliers, urban fleets, equipment manufacturers, and other stakeholders.

The objectives of these field demonstration and testing programs include gaining on-road fuel use experience, identifying fuel bottlenecks in fuel distribution logistics, collecting drivability, emissions and other performance data. A results summary from these demonstrations is presented below:

ARCHER DANIELS MIDLAND TRUCKING

Pure Energy and ADM trucking division are conducting a joint demonstration program to evaluate the compatibility of E-Diesel in conventional heavy-duty trucks. The test fleet, which was initiated in November 1998, consisted of six Mack Trucks – four of which operate on E-Diesel (two new trucks and two older trucks, with over 100,000 miles each). The remaining two trucks operated on standard No. 2 diesel to establish baseline data.

The program has completed over 400,000 miles and has been a success in demonstrating operational, excellent cold temperature performance, fuel economy, oil filter conditions and other characteristics.

PEC is continuing this demonstration to achieve 250,000 miles on each of the new engines in order to achieve engine certification on E-Diesel from the MACK engine manufacturer.

CHICAGO TRANSIT AUTHORITY

Chicago Transit Authority operates one of the largest bus fleets in the nation. The State of Illinois Department of Commerce and Community Affairs (IL DCCA), along with Illinois Corn Growers Association (ILCGA), ADM, Detroit Diesel, Growmark (fuel distributor), and several other participants joined forces with PEC and CTA in order to demonstrate E-Diesel in urban buses. A total of 30 buses from the CTA city bus fleet have participated in one-year demonstration project during 1999 and 2000.

The CTA program validated PEC's previous experience with this fuel in truck engines as well as demonstrated the ease of transition from diesel to E-Diesel. The CTA program has also surfaced real-world challenges such as water contamination of the E-Diesel fuel and possible solutions dealing with such issues. The results from the CTA buses operating in this program were in line with the results obtained from ADM trucks. At the end of this program and based on the results, the CTA is evaluating conversion of their entire fleet of over 1,800 buses to E-Diesel.

WASTE MANAGEMENT, INC.

Waste Management, Inc. (WMI) is one of the largest solid waste management companies in the nation. WMI and PEC have tested WMI's off-road waste handling equipment in a fuel evaluation program in Brooklyn, New York beginning in the spring of 2000.

The impact on air quality from the operation of the heavy-duty off-road equipment used at the WMI's waste transfer stations is significant, and this program is expected to assist in the reduction of harmful emissions from Brooklyn waste transfer station. When successfully

demonstrated, WMI would consider converting several of its waste transfer sites to an ethanol-diesel blend.

Getty Petroleum Inc. (Getty) has worked with PEC in the blending and distribution of *Puranol*-based E-Diesel for use at the WMI evaluation program. Getty is a $660 million petroleum marketing and distribution company operating in twelve Northeast and mid-Atlantic states within the United States.

E-DIESEL MARKET OPPORTUNITIES

Compression ignition vehicles are ubiquitous due to their efficiency, reliability, adaptability and cost effectiveness. The US market for diesel is large and more highly fragmented than that of gasoline. However, virtually all heavy trucks and urban buses burn diesel fuel.

Regulatory standards for diesel engines are getting tougher and will push the E-Diesel market as one of the primary drivers. Bus fleet operators have been given the option of complying with these standards by:

1. Rebuilding old engines and retrofitting with approved exhaust treatment kits (costing up to $20,000 each); or
2. Demonstrating that the entire bus/truck fleet meets new emissions standards on an aggregate basis.

A cost-effective way to achieve these new standards is by using cleaner fuels. E-Diesel is an attractive option to fleet operators because it offers an economical solution to bring fleet emissions within mandated levels without expensive hardware retrofits, major modifications to refueling or fuel storage infrastructures or substantial retraining of maintenance staffs.

The initial target market should be the centrally refueled bus and truck fleets in the US whose total diesel fuel use exceeds about 5 billion gallons per year. Because of the superior performance characteristics of E-Diesel, it is believed that it will be an attractive, lower-cost fuel alternative for many users in the two billion gallon No. 1 diesel market and Pure Energy intends to focus its sales efforts on this group accordingly.

E-Diesel is entirely miscible with standard diesel and may be mixed in a consumer's fuel tank without adverse effects. Thus, E-Diesel can be distributed to any diesel consumer through existing commercial infrastructure. Future growth is not limited to centrally refueled fleets and can be expanded into commercial retail distribution and other diesel non-road markets such as, rail, marine, stationary power generation, mining and agriculture.

CONCLUSION

Pure Energy's E-Diesel fuel blend has shown significant improvements over previous attempts by other entities in Europe and Brazil. E-Diesel is a crystal clear, stable fuel that can easily substitute No. 2 diesel on a one-to-one basis with only a slight penalty in fuel economy. The emissions profile for both particulate matter and NOx emissions promises to significantly improve air quality and meet the regulatory requirements for fleets operating on both new and older diesel engines in small-duty, medium-duty, and high-duty configurations.

In full commercial use, E-Diesel promises to bridge the gap between the air quality emission standards and engine technology. E-Diesel will help expand ethanol markets and hence increase the use of corn by over 300 million bushels a year. E-Diesel is a commercially viable alternative to regular diesel and it is currently available for commercial use. *Puranol* has been demonstrated in over one million miles and is available today.

ACKNOWLEDGMENTS

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