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TCEQ Proof of Concept Testing of an SFA International, Inc. Combustion Catalyst

Final Report

Data Produced by Southwest Research Institute
San Antonio, TX
SwRI Project No. 03-11959

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Summary

The Texas Commission on Environmental Quality (TCEQ) awarded a grant to SFA International for "Proof of Concept" testing at Southwest Research Institute in San Antonio in May 2005. This work was carried out in February 2006 and SwRI's Final Report was received in May 2006.[1] TCEQ specified the fuel, engine and operating protocol for the tests.

Comparison of mass emissions and fuel consumption data from these tests demonstrated a significant reduction in fuel consumption even with an ultra clean fuel and 25% engine load over a short 74:40 hour running time. A large decrease in particulate matter was observed when the catalyst oxide contribution was subtracted from the measured values. NOx reductions were observed with the catalyst corresponding to reduced fuel consumption.

	Least Squares	R^2	First/Last
Carbon Balance Fuel Measurement	2.0%	0.47	5.7%
Carbon Dioxide	2.1%	0.49	5.7%
NOx	3.6%	0.82	2.9%
Particulate Matter without Catalyst	5.3%	0.32	11.9%

Test Protocol

The engine was a Detroit Diesel Allison Series 60 in-line six-cylinder 365 HP Diesel engine. The reference fuel was a No. 2 ultra-low sulfur Diesel fuel from Chevron Phillips Chemical Company containing no additives. The candidate fuel was prepared by treating the reference fuel with SFA International's FuelSpec® 116-4509 combustion catalyst at a rate of one part per thousand by volume to achieve 50 ppm Fe and 10 ppm Mg. Each test was run on a predetermined transient cycle. This cycle lasted 20 minutes and demanded about 25% of maximum engine power. The power requested by the transient cycle controlling engine operation was the same for each 20-minute cycle; a letter of confirmation from Robert Fanick of SwRI will be attached.

Six tests were run on reference fuel. The engine was then run for 72 hours on candidate fuel (with catalyst) without stopping. The transient cycle repeated every 20 minutes. At the end of that period, the engine was stopped for 20 minutes and six tests were carried out with candidate fuel. The engine was stopped and cooled overnight before running the final two tests reference fuel.

The TCEQ basic "Proof of Concept" test requires calculation of reference work from an engine torque – rpm map measured at the beginning of the test without any later

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[1] This paper is to be read with the SwRI Final Test Report. Tables and figures in the SwRI Final Report are referred to as "SwRI Figure X". Tables and figures in this paper are referred to without the "SwRI" prefix.

correction for changes in atmospheric conditions during the test period. The computed work for subsequent tests varied randomly.[2] SwRI followed TCEQ protocol in calculating Brake Specific Emissions and Fuel Consumption. As a result, the Brake Specific Emissions and Fuel Consumption were random and no conclusion could be drawn from those data.

About two-thirds of the iron oxide and all the magnesium oxide from the catalyst were recovered from particulate matter in the exhaust. This is well above the 50% threshold value for EPA Registration testing. It is further noted that no harm was done to the engine during this test.

Background

SFA International is a manufacturer of oil-soluble metal compounds used in liquid petroleum fuel additive formulations. In the mid-1990's, SFA supplied a magnesium fuel additive to Westinghouse Electric Corporation for a power plant under construction for Hanwha Energy, Ltd., Pusan, Republic of Korea. The turbines were Model 501 D5 104 MW engines equipped with Heat Recovery Steam Generators for a total of 150 MW each. They were designed to run on Low Sulfur Waxy Residual oil. This aliphatic LSWR fuel had a maximum of 2 ppm vanadium and was water washed to remove water soluble salts of Na, K and Ca. The fuel was treated with 6 ppm magnesium, the normal treating rate to produce magnesium vanadate and raise the melting point of ash to prevent deposit and corrosion problems in the turbine.

The fuel was high pour point indicating a high molecular weight material. It did not complete the combustion process in the turbine combustor resulting in particulate matter in the range of 150 mg./M^3. The Korean Ministry of Environment limit in the Province of Seoul at that time was 60 mg./M^3. Westinghouse asked SFA to develop a fuel additive to meet the Korean MOE requirement.

SFA developed an oil-soluble iron product that reduced the particulate matter below 60 mg./M^3 meeting the requirement. Westinghouse requested that SFA combine the magnesium and iron components so that only one fuel additive was required.[3]

Westinghouse built a similar power plant at the Hyundai Daeson Refinery with four 501 D5 turbines running on the same LSWR fuel. We found that the particulate matter in the turbine exhaust was reduced from 160 to 10 – 20 mg./M^3. This compares with a 50% maximum reduction of particulate matter found in the literature.[4]

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[2] See Table 1, Engine Operating conditions. Statistical t-test evaluation of the work values from the reference work through R6 compared with C7 through R14 demonstrated that the two groups are not within the same population.

[3] "Particulate Emission Reduction Using (Fuel) Additives", B. Rising, Library of Westinghouse Power Generation, Technical Paper TP-98010, January 9, 1998. This paper is available on the SFA International web site Library Page, www.sfainternational.com.

[4] "Boiler Fuel Additives for Pollution Reduction and Energy Saving", Ed. R. C. Eliot, Noyes Data Corp., Park Ridge, NJ, USA, 1978.

While this work was in progress, SFA's catalyst was tested at Korean Institute of Energy Research (KIER) with the LSWR fuel in a test boiler. There we found similar reduction of particulate matter as in the combustion turbines.

This work led to testing in Diesel engines at Automobile Research Association of India in Pune. We found 15% and 18% reduction in fuel consumption in 1,000 km. city and highway driving, respectively.

These results encouraged SFA to apply for a grant from TCEQ to aid in testing the product at a reputable U.S. laboratory. TCEQ awarded the grant to SFA in May, 2005 with the proviso that the work was to be carried out at SwRI with specified fuel, engine and load cycle conforming to TCEQ's basic Proof of Concept protocol.

This work was completed in February 2006 and the report was finished in May 2006. Specific information about the engine, fuel and test data are in the SwRI report attached and will not be repeated except for the purpose of analysis and evaluation.

Engine

TCEQ specified a Detroit Diesel Corporation Series 60 heavy-duty Diesel engine or the equivalent to be used in the tests. SwRI did not want to use a new engine as a metallic fuel additive is in the catalyst. This results in some metal oxide accumulation in the engine. The engine selected was built in 1991 and was in excellent maintenance and repair. Engine specifications and features can be found in SwRI Table 1. Power validation and torque map data are found in Appendix A of the SwRI report.

Transient Torque Maps were measured before test R1, C7 and R13. The parameters for the first map before R1 were used to calculate power output for all subsequent cycles. We plotted reference and candidate (with catalyst) fuel torque maps in Figure 1 for the four sets of data given in the SwRI Table 4. These demonstrate conclusively that the catalyst had no effect on the engine torque map and ability to reproduce power output. These maps are very similar to SwRI Figure 3.

The computer calls on the engine to perform at a certain rpm and torque in each transient cycle. Work is calculated each second from torque, rpm and a constant and these numbers are averaged for each test. The engine throttle is opened or closed until the engine reaches the requirement from the computer. The difference between reference and measured work in each test is the ability of the engine to respond to the computer commands. This varies with atmospheric, fuel and engine conditions. Conditions during the tests are summarized in Table 1.

The parameters for measuring engine work were entered into the computer from the reference map before test R1. Following TCEQ protocol for their basic Proof of Concept test, these parameters were not changed for the remainder of the test although atmospheric conditions did change. As a result, it can be seen in Table 1 that the work measured varied from the reference work by as much as 4% during individual tests. The torque map illustrated in SwRI Figure 3 indicates no effect of the catalyst on engine performance. Therefore, we conclude that these variations were caused by other conditions such as barometric pressure, temperature and relative humidity.

TCEQ requires brake specific emissions and fuel consumption to be calculated by dividing mass emissions for each test by engine power produced. The purpose of this is to compare results between different size engines based on emissions and fuel consumption per horsepower-hour.

Since the power calculated is compared to the reference map, the calculated power for tests C7 through R14 carried out after the 72 hour run period was about 4% lower than during the tests R1 through R6. This leads to higher brake specific emissions and fuel consumption results negating observations on the effect of the catalyst. In more definitive tests, the engine maps are modified daily to reflect the conditions for that day, leading to more accurate power values and brake specific emission and fuel consumption values.

We discussed this situation with Mr. Robert Fanick of Southwest Research Institute, the Group Leader in charge of the tests. He informed us that the mass emissions and fuel consumption could be compared for these tests as the power required by the transient cycle was the same for each test. A letter from Mr. Fanick attesting to this is attached to this report. Trends and differences between data on the reference fuel and fuel with catalyst can be validly compared within the test data. The results are in mass units, not brake specific weight per horsepower hour.

Fuel

The fuel was No. 2 ultra-low sulfur certification Diesel fuel from Chevron Phillips Chemical Company. This fuel did not contain any additives. It was water white in appearance and had a slight hydrocarbon odor. It did not have a characteristic Diesel fuel odor. Fuel analyses results are given in SwRI Table 2.

Test Cycle

The engine was operated on a 20-minute cycles. This is presented in SwRI Figure 2. The cycle consisted of 5 minutes on a New York Non-Freeway cycle, 5 minutes on a Los Angeles Non-Freeway cycle, 5 minutes on a Los Angeles Freeway cycle and the last 5 minutes repeated the New York Non-Freeway cycle. SwRI Figure 2 contains a representation of the torque and speed commands for this transient cycle.

The engine was run through two preparation cycles followed by six cycles on the reference fuel; the fuel without catalyst. The fuel was changed to the candidate fuel: the reference fuel with catalyst. The catalyst was mixed into 50 gallons of fuel in a 55-gallon drum. The catalyst was added at a rate of 1 part to 1,000 parts fuel to yield 50 ppm Fe and 10 ppm Mg. After addition of the catalyst, the fuel was mixed with a drum stirrer for about 30 min. The author of this analysis observed this mixing process and was satisfied with the accuracy. Three hundred gallons of candidate fuel were prepared for the tests.

The first engine map was measured and these data became the reference work for all subsequent tests over the next five days.

Following the six tests on reference fuel (R1 through R6), the engine was operated for 216 20-minute cycles with the candidate fuel. This was the 72-hour run-in period. Six tests were run on the candidate fuel (C7 through C12) finishing the evening of February 19th.

The next morning, February 20th, the fuel was changed to reference fuel and the engine was started cold. It was run through the final R13 and R14 tests.

It is noted that the transient cycles selected for these tests had a large amount of idling and minimal amount of high-speed high-torque running. The Power Validation – Heavy-Duty Diesel Engine tables in SwRI Appendix A show that the fuel consumption at rated power is 114.7 lbs./hr and at peak torque is 102.3 lbs./hr. The actual fuel consumption was approximately 27 lbs./hr. indicating that the engine was operating at about 25% rated power output. A visual inspection of SwRI Figure 2 indicates that 25% is a good estimate of the torque generated vs. the total capability of the engine.

The data for tests R13 and R14, run following cold start on the day after finishing the earlier tests, were run on reference fuel – fuel without catalyst. The catalyst will leave residue in the combustion chambers of the engine continuing to yield catalyst effect for a period of time. Therefore, it is valid to include R13 and R14 in evaluation fuel consumption and mass emissions even though there was no catalyst in the fuel during these final tests.

Data Analysis

As noted above, the brake specific emissions and fuel consumption data did not show any trends with use of the catalyst due to calculation based on work performed during each test. The error introduced by changes in atmospheric conditions using this method is pointed out above.

We evaluated mass emission and fuel consumption data in two ways. The first method was to plot the data over 76:40 hours and calculate the slope, intercept and correlation coefficient. This is illustrated in Figure 2. From this linear regression equation, we calculated change in emissions and fuel consumption from test R1 through R14.

We noted that emissions and fuel consumption were further reduced in tests R13 and R14 even though these tests were run on fuel without catalyst. This was due to "soaking" of the engine overnight. Residual catalyst effects were not removed during two twenty-minute tests. Therefore, we included these data in our calculations. We found that comparing the results from R1 with R14 gave even larger effects on emissions and fuel consumption. These data are presented in Table 3.

Fuel Consumption

Fuel consumption was determined by volumetric and carbon balance fuel measurement. Fuel volumes consumed were reported for Tests R1 – R6, C7 – C12 and R13 – R14. SFA requested these data for the 216 cycles during the 72-hour run-in period. There was an attempt to save these data but they were lost due to a problem in the computer software.

When the tests were set up, we requested a physical volumetric measure of fuel consumed with each test. Volumetric fuel measurements were taken from the computer controlling engine operation. Those measurements were made with a transducer in the fuel line. The volumetric fuel measurements appear random and do not compare with the carbon balance data. No conclusions were drawn from these data.

Fuel measurements from carbon balance were computed by measuring the carbon dioxide in the exhaust. These measurements show a trend in the mass emission and fuel consumption data.

The data for carbon balance measurement of fuel consumption are summarized in Table 3. The linear regression had a correlation coefficient, R, of (0.69) and R^2 of 0.47 indicating good correlation. The fuel consumption decreased 2.06% by the least squares analysis and 3.90% between the first and last numbers measured.

In Table 3 for the volumetric fuel measurements, we found a linear regression analysis with a positive slope yielding 0.35% increase in fuel consumption although a comparison of the first and last values showed a 1.03% reduction. The correlation coefficient, R, is 0.23 and R^2 is 0.055. This indicates that there is little or no correlation between volumetric fuel consumption and time.

SFA has seen an initiation period when catalyst use is started followed by a decay period when use is stopped. This was demonstrated in the ARAI tests in India. This further supports using R13 and R14 in the fuel evaluation.

It was noted above that the transient cycle consumed about 25% of the fuel possible at full engine power. We know that the catalyst works best at high loads as indicated by better performance in highway operation than in city driving. This has been further supported in field tests in Diesel generator sets.

Therefore, we believe that 3.9% difference between beginning and ending numbers with relatively low load operation, ultra clean fuel and a well-maintained engine after a period of 74:40 hours is a significant fuel savings.

Particulate Matter

These data are presented in Table 3. They shows an increase in particulate matter collected on a 2-micron filter by 11.7% according to the regression analysis and 4% by using the first and last values. The correlation coefficient indicates a high level of correlation.

This is a strange phenomenon that does not fit with the combustion turbine data, the boiler data and our mechanism for how the catalyst functions – i.e., more efficient combustion of the fuel.

We know that Diesel trucks and automobiles have passed vehicle inspection to renew registration and we have observed Diesel engine exhausts with visually reduced particulate matter (smoke).

The measured particulate matter emissions were low. This was due to several factors in the test: ultra clean fuel, 25% power demand on the engine and good maintenance engine. The catalyst comprises of 50 ppm Fe and 10 ppm Mg. This contributes 88 ppm of metal oxides to the fuel. Particulate matter analysis showed that 66% of the iron oxide and 100% of the magnesium oxide was collected on the filters. We subtracted this from the particulate matter measurements in Table 3. This yielded a 5.65% reduction in particulate matter by the least squares regression analysis and 14.27% by comparing beginning and ending data. There, we conclude that in this case with very small beginning particulate matter, the oxide from the catalyst contributed to the emissions distorting the observation.

NOx

The NOx revealed a 3.6% reduction with least squares analysis and 2.9% comparing beginning and ending values in Table 3. The correlation of the regression analysis was high at (0.91) with an R^2 of 0.82.

We have predicted from earlier work that the NOx level will reduce by about the same amount at the reduction in fuel consumption. That was confirmed in these measurements.

Unburned Hydrocarbons

Data for unburned hydrocarbons presented in Table 3 indicate a large (32%) increase in unburned hydrocarbons. The probable explanation for this is that the unburned hydrocarbons were extremely low and in the range of the mass of iron and magnesium oxide from the catalyst. The correlation coefficient was 0.21 indicating it was not statistically significant.

This raises the question as to how these were measured. It is not known if the hydrocarbon analyzer is sensitive to these oxides and that question has not been answered.

In any case, the numbers are extremely low due to the very clean fuel and good maintenance engine. As a result, these results have little bearing on these test results.

Carbon Monoxide

The data in Table 3 show a 4.7% increase although the first and last numbers showed 3.9% reduction. The regression coefficient indicated poor correlation. The results were not statistically significant.

Carbon Dioxide

Carbon dioxide measurements in Table 3 show a significant reduction that matched very well the reduction in fuel consumption. The regression coefficient indicated reasonable correlation.

Particulate-Phase Iron and Magnesium Results

SwRI Table 7 gives the results for Fe and Mg collected on the filters. This shows that 97.8% of the magnesium was collected and 66.7% of the Fe was recovered. This indicates that one-third of the iron is retained in the engine as powder on various parts. This can range from the cylinder throughout the exhaust system. This supports using tests R13 and R14 in the fuel consumption calculations as the catalyst is still effective. This is further supported by data from tests on a ferrocene additive in a railway locomotive. In this test, the engine was treated at a lower dosage of iron for four months before continuing their tests.

SwRI measured 51 ppm Fe and 25.5 ppm Mg in the candidate or treated fuel. The magnesium value is in error and should be 10 ppm. The catalyst sample has been tested by SFA's quality control laboratory and manufacturing batch tickets indicate the correct amount of ingredients were added. SwRI used the 25.5 ppm Mg in the fuel to calculate the 97.8% of magnesium collected indicating more than theoretical possible collection. This could be explained by a problem in the analysis that would yield an equal error for Mg in both the fuel and the collection on the filter. SFA and SwRI are investigating this.

Conclusions

Several conclusions can be drawn from the SwRI test data.

Using the TCEQ procedure for calculating brake-specific emissions and fuel consumption, no conclusion could be drawn from these data. This was caused by changes in atmospheric parameters and other conditions that resulted in computed work for each test that varied from the reference work. This resulted in random values for these data.

Using mass emissions and fuel data, a significant change in fuel consumption of up to 3.90% was observed from the carbon balance data. This is a significant result in 74:40 hours of catalyst use with 25% load, an ultra clean fuel and well-maintained engine. We saw a similar reduction in NOx.

The particulate matter, carbon monoxide and unburned hydrocarbons were very low. The particulate matter was in the range of the contribution from the metal oxides from the catalyst. After subtracting out those oxide contributions, a significant reduction in particulate matter was observed.

The mass emission and fuel consumption results, combined with earlier data, indicate the catalyst functioned to an extent expected with 25% engine load and ultra clean fuel.