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Project Title: Biomass-Derived Fuels for Turbo-Generators

Contract Number: RD-29 **Milestone Number:** Final **Report Date:** September 23, 2008

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FINAL REPORT

Executive Summary:

In order to burn new fuels in a gas turbine engine, critical fuel properties need to be determined so that changes in the fuel system can be implemented if needed, and safeguards can be employed to avoid engine damage. Turbine fuels may require extended storage prior to use making it necessary to establish the storage stability of these potential fuels over time, at varying temperatures, and with additives, i.e. antioxidants. Under Task 1, Fuel Selection, a number of Biomass-derived Oils (BDOs) including crude soybean oil, acid oil, recycled oils, yellow grease, black oil and biodiesel were *evaluated* to determine their validity for use as turbine fuels consistent with ASTM specifications. Based on the results of Task 1: Fuel Selection, samples of refined and bleached (RB) soybean oil, refined, bleached and deodorized (RBD) soybean oil, biodiesel and distilled biodiesel were obtained for Task 2: Fuel Storage Assessment. These samples were stored at three different temperatures. Half of the samples were unstabilized and the other half stabilized. The final sample testing has been completed and the results were included in the Milestone 6 report. The RBD soybean oil was selected for testing in the turbine based primarily on the results of the fuel analysis and its availability. The stabilized RBD soybean oil remained very stable throughout the storage and stability testing.

Fundamental atomization and combustion studies are necessary to evaluate whether the BDOs selected for use in turbo-generators can be used reliably (Task 4). While gas turbine combustors are relatively robust and versatile energy conversion units, several important basic questions must be answered before BDOs can be introduced into the SR-30 small-scale gas turbine engine. The initial ignition tests and the comparison of properties of the RBD soy oil to diesel fuel, the typical turbine fuel, indicated a need to modify the properties of the soy oil to allow it to burn in the combustor. Heating alone did not modify the properties enough. Blending a second fuel with the soy oil was attempted as a way to aide ignition and flame sustainability. RBD soy oil blended with biodiesel, petro diesel and butanol has been introduced into the combustor with varying degrees of success. A number of fuel properties have been measured to give some insight as to whether or not a fuel blend will successfully operate in the turbine.

These tests indicated that petro diesel / RBD soy oil blends would be good candidates for use in the turbine.

Combustion studies have been completed in the SR-30 gas turbine engine. Petro diesel was run as the baseline fuel. RBD Soy Oil / Petro Diesel blends were successfully introduced to the turbine engine. The diesel/soy blends tested under Milestone 5 were V25 (25% RBD Soy Oil – 75% Diesel), V50 (50% RBD Soy Oil – 50% Diesel) and V75 (75% RBD Soy Oil – 25% Diesel). The RBD Soy Oil/Diesel blends ran smoothly in the gas turbine engine with little visual or audible difference in engine operation. Additional tests have since been made for all the blends. The initial test run of V75 resulted in a flame-out within the turbine, however subsequent tests were conducted and the engine ran smoothly at 78,000 rpm for this fuel blend. All fuel blend tests were geared to provide accurate thermal analysis. Fuel flow rates were calibrated for each specific diesel/soy blend and thermal data was duplicated for repeatability assurances. Engine efficiency results for the fuel blends tested have been determined. A number of test repeats were conducted to allow for the final set of efficiency calculations to be made. The repeated tests allowed for reasonable error estimates to be made. The engine efficiency calculations are encouraging as they show there was no obvious engine performance degradation with soy oil blends.

Emissions data was also collected while running on the different fuels. The V25 soy oil blend showed a decrease in CO emissions, while the V50 and V75 both caused the CO to increase. NO_x emissions were very low and essentially unchanged. The unburned HC emissions also showed little change. The Particulate Matter (PM) mass concentrations were lower for all the RBD soy oil blends. This would indicate that a slight optimization of either the fuel or the turbine could lead to very good turbine performance RBD soy oil blends up to V75, and perhaps even higher. The next step in the process of demonstrating the use of straight vegetable oils in gas turbines will be running similar blends in a commercial Capstone 30 kW micro-turbine gen-set for a 2000 hour test. After the successful test in the micro-turbine, the next step will be to evaluate these fuels in an industrial turbo-generator of 1-3 MW in size. With the successful completion of that test, the fuels would be ready for testing and demonstration programs in a larger 25-200 MW commercial turbo-generator.

Introduction

The use of biomass for power generation is expected to increase with the impact of renewable portfolio standards and other initiatives being encouraged by the federal government and adopted by many states. The goal of this study is to determine if biomass-derived oils (BDOs) can be effectively used in turbo-generators. A turbo-generator is an electrical generator powered by a gas turbine, and is sometimes referred to as a combustion turbine. For the purposes of this project, BDOs will include crude and refined vegetable oils (such as soybean oil), lower cost products from the vegetable oil industry (such as black oil and acid oil), recycled products from the rendering industry (such as recycled restaurant grease), and biodiesel (if proposed federal subsidies are adopted that make biodiesel cost-competitive with non-esterified oils). This project will also consider blending of BDOs with other fuels to produce lower net cost turbine fuels. The further aim of the project is to determine the technical and market opportunities brought about by generating electricity with turbo-generators fueled with raw or minimally processed vegetable or recycled oils.

The project consisted of five distinct tasks as follows:

1) Assess properties of BDOs as fuels for turbo-generators. Select oils for further analysis and testing.
2) Assess the fuel storage and handling requirements of BDOs.
3) Assess the availability and economic feasibility of candidate BDOs
4) Conduct fundamental oil spray and combustion studies to determine if BDOs can be reliable fuels for turbo-generators.
5) Evaluate the impact of BDOs on performance and exhaust emissions by testing oils in a small-scale turbine engine.

Fuel Selection

ASTM 2880 provides a guide for turbine manufacturers and others to specify fuel for turbine applications. Turbine manufacturers specify that fuels meet ASTM 2880, and typically have additional requirements beyond those contained in ASTM 2880. The requirements vary from manufacturer to manufacturer, and can depend on the type of turbine and if it is liquid or dual-fueled. Dual-fueled turbines can operate on both liquid and gaseous fuels with the typical combination of natural gas and diesel fuel. The manufacturers also recommend that they review fuel specifications before attempting to use fuels that do not meet all of their specifications. Based on this recommendation, and on conversations with turbine manufacturers, they are willing to evaluate any fuel for use in their turbines, even though the fuel may not meet all of the specifications listed in their technical literature. For this reason it is premature to eliminate a fuel based only on the fact that it exceeds one or more specifications.

For the fuel selection portion of this project, turbine fuel specifications were obtained from several turbine manufacturers. Various grades of soybean oil were then analyzed to characterize the properties as candidate turbine fuels. In addition, yellow grease, biodiesel and crude glycerin were analyzed.

Due to the concerns of the results of the original trace metal analysis, done by atomic absorption, of the seven candidate fuels, a second test was conducted. A new set a samples was obtained and analyzed with the results shown in Appendix A Table 1.Based on the results of the candidate fuel analyses, the following recommendations for fuel selection are made:

1) Biodiesel meets most of the recommendations for a turbine fuel, and likely could be used in most turbines without modification. It is also completely miscible in diesel fuels, so it can be blended with distillate fuels if desired.
2) Once refined soy oil, refined bleached, and RBD, with their low metals content and relatively low ash content and carbon residue contest, merit further investigation..
3) Crude soy oil and refined-bleached oil merit further study. They may require a wash process to lower their potassium and calcium contents, but again lead is a concern. These issues need further investigation.
4) Yellow grease, with its extremely high water and sediment, ash content, and trace metals content does not appear to be a viable candidate fuel. However, further review may be worthwhile because of its low cost.
5) Crude glycerin, with its low energy content, high metals content, high levels of ash, water, and carbon residue, is not a viable candidate for further investigation.

Based on the availability of the potential fuels, as well as the desire to choose the “best” available fuel for the initial testing, RBD soy oil was selected for the initial atomization and combustion testing. Further testing on turbine optimized soy oil would be merited. From the results of the analysis, it would appear that refined or RB soy oil would also be acceptable as fuels for a combustion turbine.

Storage and Stability Study

Because Biomass-derived Oils (BDOs) may require up to 1-year storage prior to use, it becomes necessary to establish both oxidative and hydrolytic properties of the feed stocks over time, at varying temperatures, and with additives, i.e. antioxidants. As a result, the Agricultural Utilization Research Institute (AURI) was contacted to conduct a fuel storage and stability study.

The results of these tests determined the stability of the feedstock's by identifying the anticipated time frame that volatile fatty acids begin to appear, ultimately degrading the fuel properties. In addition, fatty acid compositions, iodine values, and moisture contents of the fuel samples will be analyzed pre- and post- stability testing.

Oxidative changes of soybean oil and biodiesel (B100) were monitored during storage at 40°F, 75°F, and 110°F. The observed changes were moderated by the addition of tert-butyl-hydroquinone, TBHQ, as an antioxidant. In general, biodiesel changed more rapidly than refined bleached (RB) soybean oil and was less well protected by the addition of TBHQ. The most sensitive indicator of oxidative change was found to be the Oxidative Stability Index (OSI). The OSI provided a useful tool for tracking changes during storage for "as produced" B100 and distilled samples of biodiesel. Calculated iodine values, free fatty acid values, and acid values indicated that biodiesel samples stored in sealed containers undergo measureable oxidation during six months of storage even in the presence of TBHQ.

Four samples total were obtained for this study. They were as follows:

1) Refined, Bleached (RB) Soybean Oil from Cenex Harvest States, Mankato, Minnesota
2) Refined, Bleached, Deodorized (RBD) Soybean Oil from Cenex Harvest States, Mankato, Minnesota
3) Biodiesel from Farmers Union Marketing & Processing Association, Redwood Falls, Minnesota
4) Distilled Biodiesel from Peter Cremer, Cincinnati, Ohio

Two one-gallon jugs of each sample were obtained. One jug of each sample was stabilized with 500 ppm TBHQ. Each jug was then divided into three portions to be stored at different temperatures. The samples were stored at three temperatures, 40, 75 and 110 °F.

Based on the results of this study, it recommended that an antioxidant be added to the biobased fuel chosen to replace, or partially replace, petroleum-based fuel for turbine generators. As far as the four sample types examined in this study, all four did well in terms of meeting the six-month expiry, but the soybean oils performed better than the biodiesel samples. RB soybean oil stabilized with TBHQ appeared to do the best of the four sample types in this study. OSI, acid value, and calculated free fatty acid analysis provided the most indicative stability data.

Economic Feasibility Study

The Southwest Marketing Advisory Center (SMAC) conducted an economic analysis on the candidate fuels which was originally completed in March of 2007. This original analysis resulted in the following recommendations and conclusions.

RECOMMENDATIONS

- Degummed soy oil has a favorable mix of pricing, availability and energy balance
- Other domestic renewable fuels appear to have unfavorable price increase potential
- Yellow grease should only be selected after careful consideration of future supplies
- Projected demand for biodiesel may adversely affect pricing as supply maximizes

CONCLUSIONS

- Any renewable fuel could prove to be viable for use in powering gas-fired turbines.
- Biodiesel appears to be the current “favorite” of renewable fuels due to its heavy promotion, but its price advantage is questionable and probably will shrink as more demand is created.
- Degummed soy oil appears to have some advantages over crude soy oil based on its byproduct of lecithin and its associated demand as a feed supplement.
- Degummed soy oil also has a more economically favorable energy balance in comparison to crude soy and biodiesel.
- Yellow grease has been touted in the past as a good economical energy source but most data used for this pronouncement is now out-of-date and its historical price advantage seems to be shrinking over time.
- Glycerin, a byproduct of biodiesel production, may hold future promise as a fuel based on its potential cost per BTU of energy available. Performance issues such as consistency of product are questionable and beyond the scope of this study.
- Evaluations of alternatives have been driven by the requirement for domestic production; otherwise, the same potential difficulties could arise that now confront the United States with petroleum products. The constraint of domestic production requirements eliminates other potential choices such as palm oil.

However, with significant changes having occurred in the world markets since March of 2007, an update was provided by Michael k. Rich Ph.D. of the SMAC in July of 2008. The update is as follows:

“The incredible run-up in oil prices in recent months due to increased world demand and speculative pressures in the futures market has drastically changed the conclusions drawn in the previous study. There has been a domino effect on prices for all energy sources as a result. Soy bi-products in the form of biodiesel feed stock oil has doubled in price. The same is true of yellow grease. In the original study, degummed soy oil had a favorable mix of pricing, availability and energy balance. Except for pricing, the availability and energy balances are still favorable. Pricing is not stable enough at the present time to support that previous prediction. Yellow grease would still have a supply issue to consider, especially with the increased intensity to find alternatives to petroleum based products.

The reality of the current situation is that anything related to commodities is suffering from price increases and the relationship between alternative sources is not stable in today’s speculative market. According to some reliable sources, the speculative pressures on petroleum prices will subside somewhat by the end of the year, but the balance between delivered BTUs per dollar expended will not be clear in the foreseeable future. One issue that is becoming more obvious is that with the dramatic increase in petroleum pricing, there will continue to be a cognitive search for alternatives, thus creating increasing upward pressure on these substances."

The markets will have to be continually evaluated to determine if these types of fuels will have a place in the generation of electricity from an economic standpoint, however, current mandates may necessitate the use of these types of fuels to meet national and local renewable energy directives.

Fundamental Spray and Atomization Study

Fundamental studies of fuel properties, atomization and flame testing are necessary to evaluate whether Biomass Derived Oils (BDOs) selected for use in turbo-generators can be used reliably. Selection of RBD soy oil as the primary BDO to be tested was based in part on its low metal, ash and carbon residue content. The initial ignition tests and comparison of properties of RBD soy oil to diesel fuel, and to ASTM specifications, indicated a need to modify the properties of the soy oil to allow it to burn in the gas turbine engine. Heating pure RBD soy oil alone did not modify the properties enough. Blending with a second fuel was the chosen strategy as a way to aide ignition and flame sustainability. Number 2 diesel and butanol were the secondary fuels chosen to be blended with RBD soy oil. Diesel was chosen for its familiarity with gas turbine engine operators and therefore its ease of use. Currently butanol is produced as a petroleum derived fuel, but has the potential to be produced as a second generation renewable fuel. Both of these fuels exhibit properties suitable for gas turbine engines such as appropriate flash point, viscosity and energy content.

These fuels have been introduced into the combustor with a significant degree of success. A number of fuel properties have been measured to give some insight as to the limits on fuel type for operation in a gas turbine engine.

Fuel properties governing the atomization and ignition process were determined and are listed in Table 2. Viscosity and surface tension are critical to atomization. And flash point temperature is an important indicator of ease of ignition. The kinematic viscosity of pure RBD soy oil at 31.28 mm^2/s far exceeds the operating specifications for gas turbine engines. Therefore the soy oil was mixed with diesel or butanol in an effort to lower the viscosity. Heating was also attempted as an alternative method to reduce the viscosity, however, heating adds additional operating costs or complexity if waste exhaust heat is used. Diesel and butanol were measured to have viscosities of 2.4 and 2.28 mm^2/s respectively; a markedly lower viscosity over that of RBD soy oil. Blending the fuels produces an advantageous result as the viscosities do not follow a monotonic trend. The viscosities of the fuel blends are lowered dramatically with small volumes of diesel or butanol. This is an important development as both viscosity and surface tension are important parameters in the atomization process. As viscosity drops for a given nozzle pressure, the jet velocity will also increase and jet breakup will happen more rapidly. A lower fluid surface tension is also expected to aid spray development.

Table 2: Viscosity and Surface Tension measurements of test fuels. (T=40 °C)

Fuel Type	Kinematic Viscosity (mm^2/s)	Surface Tension (dyne/cm)
100% RBD Soy Oil	31.28	34
100% Diesel	2.40	28
100% Butanol	2.28	25
60% Soy Oil – 40% Butanol	8.13	26
75% Soy Oil – 25% Butanol	12.37	
25% Soy Oil – 75% Diesel	5.06	27.6
50% Soy Oil – 50% Diesel	8.71	29.9
75% Soy Oil – 25% Diesel	15.78	

One goal of obtaining the viscosity and surface tension measurements was to use them as a marker to identify preemptively fuel blends which would easily ignite and sustain a flame. However, no clear indicator was found using only the viscosity and surface tension. Therefore, the flash point was also determined for each of the fuels and fuel blends tested. The flashpoint results are given in Table 3. The flash points of the pure fuels were found from reference documents, whereas the fuel blends were determined by AURI. From these results, it is clearly seen that the flash point is not a linear function based on the average of the fuel blends. This is beneficial for introducing RBD Soy Oil to the SR-30 turbojet. For instance, moving from V25 to V50 only raises the flash point 6 degrees, resulting in a flash point of 73 °C. This is far below that of pure RBD Soy Oil—321 °C. The flash point may be important for determining a cut-off point for candidate fuels that will run successfully in the gas turbine engine and is mainly set by the low FP fuel.

Table 3: Flashpoints of RBD Soy Oil, Diesel, Butanol and Soy Oil blends.

Fuel Type	**Flash Point °C**
100% RBD Soy Oil	321*
100% Biodiesel	160*
100% Diesel	38-54
100% Butanol	35
25% Soy Oil – 75% Diesel	67
50% Soy Oil – 50% Diesel	73
75% Soy Oil – 25% Diesel	
60% Soy Oil – 40% Butanol	39
75% Soy Oil – 25% Butanol	39

*Referenced data.

The biofuels combustion study began with an experimental investigation of pure RBD soy oil in the combustor test facility. The goal was to obtain a self-sustaining flame (i.e. a flame with the absence of an ignition source) within the combustor. Two ignition methods were employed for each set of operating conditions. A spark igniter was the prefered method for ignition as it most closely replicates the actual test turbine. A propane torch was used as an additional mode of ignition. Once the flame was ignited the spark igniter or the propane torch was extinguised to determine if the flame would sustain itself. Combustion tests were run for the

RBD soy oil for temperatures up to 250 °F, in order to ease ignition through increased atomization via lower fuel viscosity. For temperatures tested below 150 °F, the soy oil emerged from the fuel nozzle as a single stream, only beginning to breakup by the exit of the combustor, therefore igntion did not occur at those conditions. Beginning at a temperature of 150 °F, the jet began to spread and increasingly broke up into finer droplets. Once this occurred, the spray was able to be ignited with the propane torch. Ignition of the RBD soy oil by the spark igniter did not occur for any of the temperatures tested. The flame was unable to sustain itself at the 200 °F operating point. However, with some extra heating the soy oil did sustain a flame without the presence of an ignition source at a fuel temperature of 250 °F. At this condition the flame is operating near an equivalence ratio of one, therefore would likely blow out if more air was introduced to the facility in an effort to replicate the leaner operating conditions of the lab scale combustion turbine. These tests indicated a second fuel blended with the soy oil may be required to aide ignition and flame sustainability.

Two blends of RBD soy oil and diesel were included in the study. The soy oil/diesel blends were tested with a spark igniter at room temperature. The V25 (75% Diesel – 25% Soy Oil) blend readily lit and a steady flame was maintained after the igniter was turned off. However, the V50 (50% Diesel – 50% Soy Oil) blend was unable to be lit with the spark igniter. It was deemed unnecessary to test the V75 (75% Soy Oil – 25% Diesel) blend due to the inability to spark ignite the V50 blend.

Lab Scale Gas Turbine Engine Testing

Performance and emissions studies in the SR-30 Turbo-Jet burning diesel and RBD soy oil blends have been conducted. The SR-30 Turbo-Jet engine is designed and manufactured by Turbine Technologies, LTD. The compact engine features a centrifugal flow compressor, reverse flow annular combustor and an axial flow turbine stage. The diesel/soy blends tested were V25, V50, and V75. The soy oil/diesel blends did not have the lowest flash point among the biofuel blends tested, however, due to the familiarity and availability of diesel fuel; it provided the easiest transition for introducing biofuels in stand-alone gas turbine generators. The engine was started on diesel fuel and then transitioned to the diesel/soy oil blend. A fuel calibration was conducted for the diesel fuel to determine the fuel flow rate based on specific gravity of the fuel and fuel pressure at the injector. The fuel flow rate of the RBD soy oil blends was determined by weighing the fuel tank during and after the test run. All temperature and pressure measurements were electronically recorded to allow for real time data capture. At each stage of the engine, temperature and pressure were captured at a rate of 2 samples per second. This allowed for monitoring the transient start-up process as well as determining the onset of thermodynamic equilibrium or steady-state, when measurements could begin to be used for the overall engine analysis. The continuous data capture allows for a thermal analysis of engine performance for both the diesel and RBD soy oil blend portions of the test run.

Figure 4 below shows a section of temperature traces from a test running V25 at 68,000, 78,000 and 85,000 RPM, subsequently. It can be seen from the figure that the temperatures, T2-T4 located internal to the engine, ramp up as the RPM is increased. A thermocouple and pitot probe were also positioned to traverse across the exhaust stream thus providing data necessary to determine the exhaust gas mass flow rate, enthalpy flux, thrust, and kinetic power for each test case. The thermocouple shows the exhaust stream increases in temperature as the RPM is increased. From these traces it can be seen that the exhaust gas profile measured with the traverse is not uniform and therefore the increased accuracy of the automated traverse was important to the overall analysis.

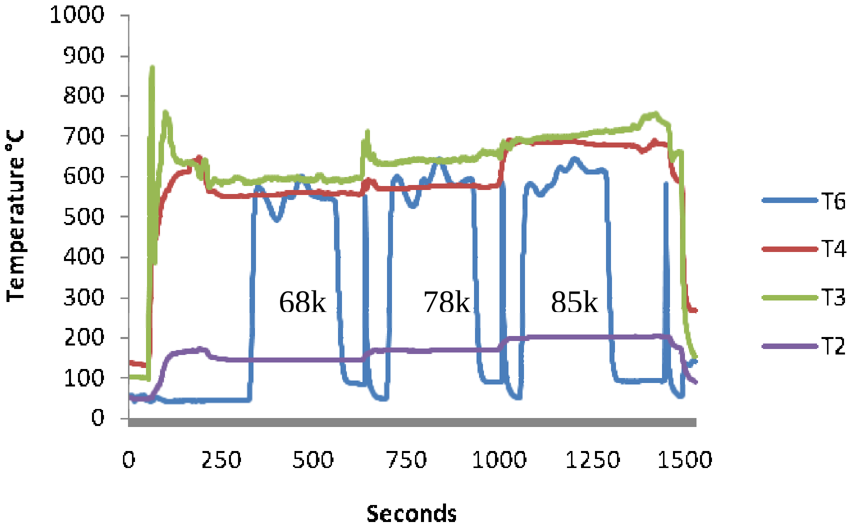

Figure 4: Temperature traces at various engine points, operating on V25 at 68,000, 78,000 and 85,000 RPM respectively.

Blends of RBD soy oil and diesel have made up the primary blends tested in the SR-30 gas turbine engine. The diesel/soy blends tested in the engine were V25, V50 and V75. These fuel blends ran remarkably smoothly in the gas turbine engine with little visual or audible difference in engine operation. The engine experienced only one flame out upon transition to a soy oil blend. This occurred during the first test of V75, however subsequent transitions to V75 occurred smoothly and without incident. Fuel flow rates were calibrated for each specific diesel/soy blend and thermal data was duplicated for repeatability assurances. The engine efficiencies have been determined for each fuel successfully tested and are listed in Table 5. The engine efficiency is the ratio of the chemical-bound energy converted to thermal and kinetic energy at the exhaust to the mass flow of fuel times the LHV of the fuel.

Table 5: Engine efficiencies for varying fuels and engine RPM.

Fuel Type	**Engine Efficiency**		
	68,000 RPM	**78,000 RPM**	**85,000 PRM**
Diesel	55% ± 5%	68% ± 5%	77% ± 5%
V25 (25% RBD Soy Oil – 75% Diesel)	56% ± 5%	68% ± 5%	71% ± 5%
V50 (50% RBD Soy Oil – 50% Diesel)		71% ± 5%	
V75 (75% RBD Soy Oil – 25% Diesel)		70% ± 5%	

The engine's highest efficiency occurs at its maximum acceptable RPM, the highest load point, which is the expected result. A clear trend can be seen for diesel and V25, as the engine RPM is increased the efficiency is also increased. The efficiency of the engine is shown to slightly increase with the soy blends over the baseline diesel. However, based on the error estimates, the increase does not appear to be significant. A repeatability test was also conducted to verify the accuracy of the results listed in Table 6.

A repeatability study was conducted to determine the precision of the turbojet engine and the auxiliary equipment in providing consistent operation. Diesel and V50 were chosen as the test fuels. Diesel was chosen again to provide a baseline for this study. V50 was chosen as it has been shown to run smoothly in the engine and represents a middle point among the blends tested thus far. The engine was run two different days with data collected across the exhaust four times for each fuel and test. Engine testing began with diesel and subsequently switched to V50 after sufficient data was obtained. The exhaust scans occurred once the engine reached steady state at an engine RPM of 78,000 for each fuel tested. Figure 5 below shows a graph of temperatures captured at the combustor exit and spanning the exhaust during one of the tests. The scans of the exhaust can be clearly seen in the graph, where the first four scans are of diesel and the last four are V50.

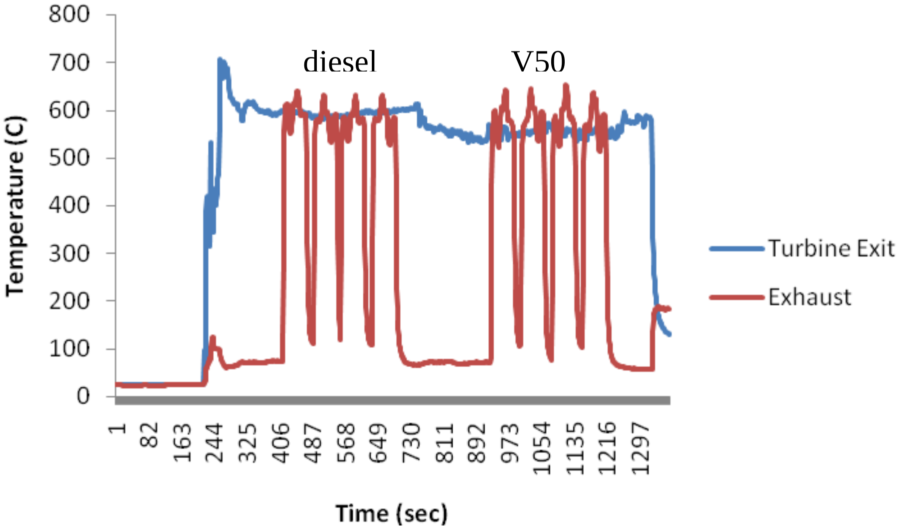

Figure 5: Temperature traces at turbine and exhaust exits.

Engine efficiency was calculated for the diesel and V50 for the four exhaust scans on each day the engine was run. The results are tabulated below in Table 6. An error analysis resulted in an overall error for each calculation of ± 5%. The table shows repeatability is very good from day to day as well as over the engine run time. The largest difference was found to be 6.5%, occurring between consecutive days. The engine efficiencies are also remarkably close between the two fuels with V50 edging out a slightly higher overall efficiency.

Table 6: Summary of Repeatability Tests.

Test Run	**Engine Efficiency**			
	Day 1		**Day 2**	
	Diesel	**V50**	**Diesel**	**V50**
1	68.6% ± 5%	68.5% ± 5%	65.5% ± 5%	66.3% ± 5%
2	67.8% ± 5%	70.9% ± 5%	66.3% ± 5%	68.4% ± 5%
3	68.1% ± 5%	69.5% ± 5%	66.1% ± 5%	66.7% ± 5%
4	NA	69.1% ± 5%	66.1% ± 5%	67.4% ± 5%

Overall, the RBD soy oil/Diesel fuel blends performed well. The ease of transition from running the engine on diesel fuel to the soy oil/diesel blend was remarkable. The engine exhibited no problems with running soy oil blends higher than expected based on the ignition studies. Spark ignition was not successful for diesel/soy blends higher then V25, however when transitioning from diesel, in the environment of a heated engine, blends as high as 75% soy oil ran without difficulty in the turbojet. The engine efficiency calculations are encouraging as they show there was no obvious engine performance degradation with soy oil. The efficiencies suggest that there may even be a slight advantage in engine performance with soy oil. Ignition and atomization challenges are still present with running pure soy oil in the gas turbine engine, however blending the soy oil fuel with diesel has been proven in this study to be a practical solution.

The final phase of the project consisted of collecting emissions data when running on the various fuels. Several techniques we used to collect the emissions data, with varying degrees of success. It has become apparent that a turbine presents unique difficulties with respect to measuring emissions as compared to an internal combustion engine. The turbine's open exhaust is major difference between the two systems. Where a standard sample probe can be used when measuring raw undiluted exhaust emissions from an IC engine, the open turbine exhaust is diluted by the entrainment of the surrounding air immediately as the exhaust leaves the turbine

Emissions data was also collected while running on the different fuels. A Greenline 8000 portable gaseous emissions analyzer was connected to a probe installed on the automated traverse for gaseous emission measurement. A TSI model 3090 Engine Exhaust Particle Sizer (EEPS) was used for particulate matter (PM) number and mass measurements. The V25 soy oil blend showed a decrease in CO emissions, while the V50 and V75 both caused the CO to increase. NO_x emissions were very low and essentially unchanged. The unburned HC emissions also showed little change. The Particulate Matter (PM) mass concentrations were lower for all the RBD soy oil blends. This would indicate that a slight optimization of either the fuel or the turbine could lead to very good turbine performance RBD soy oil blends up to V75, and perhaps even higher.

From Figure 6 we can see the decrease in emissions for the V25 but we also see that the changes are not outside the error estimates. The increase in CO for the V50 and V75 does appear to be a significant change, however.

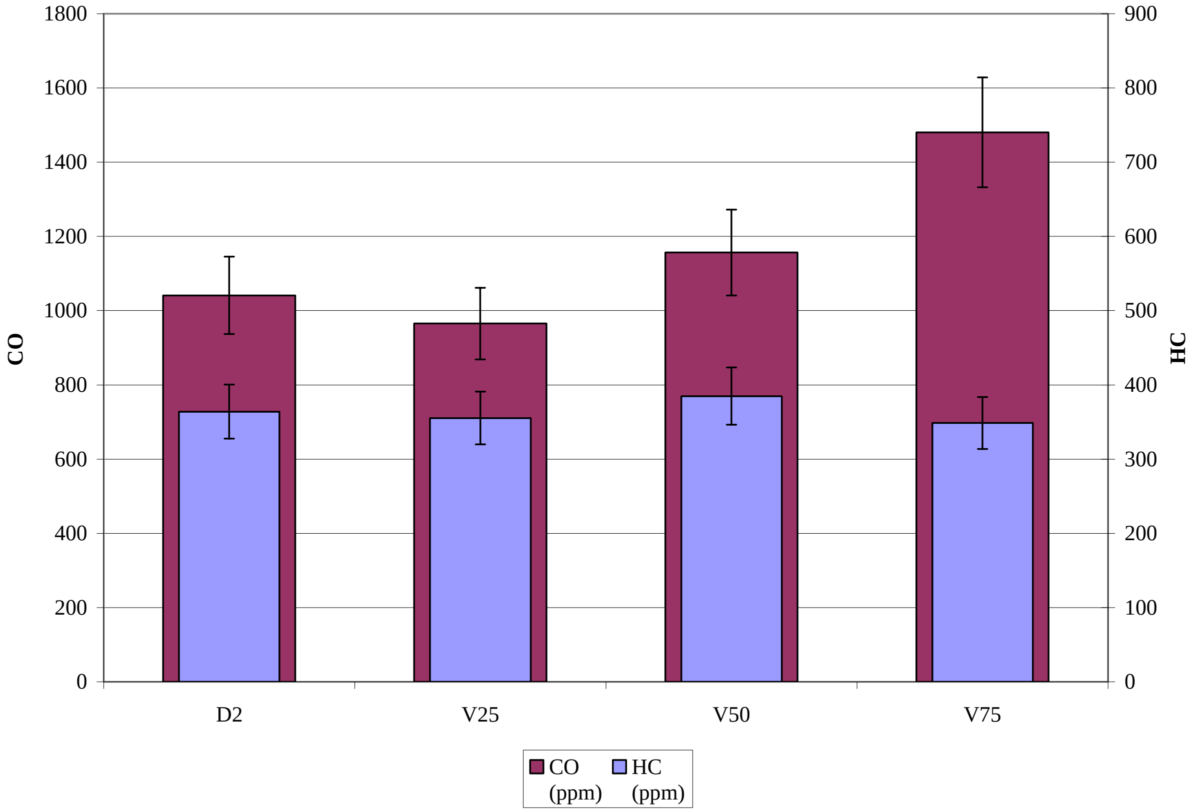

Figure 6. Exhaust CO and HC Concentrations for the 4 fuels.

The EEPS based PM data is presented in Figure 7. The data presented in figure 7 has been normalized to the concentrations for the Diesel fuel test case. This is due to limitations in determining an accurate dilution ratio for the test conditions. These data show a decreased number concentration relative to the Diesel case for all the RBD soy oil blends. The mass concentration for the V25 is less that that of the Diesel case, while the V50 and V75 show higher mass concentrations.

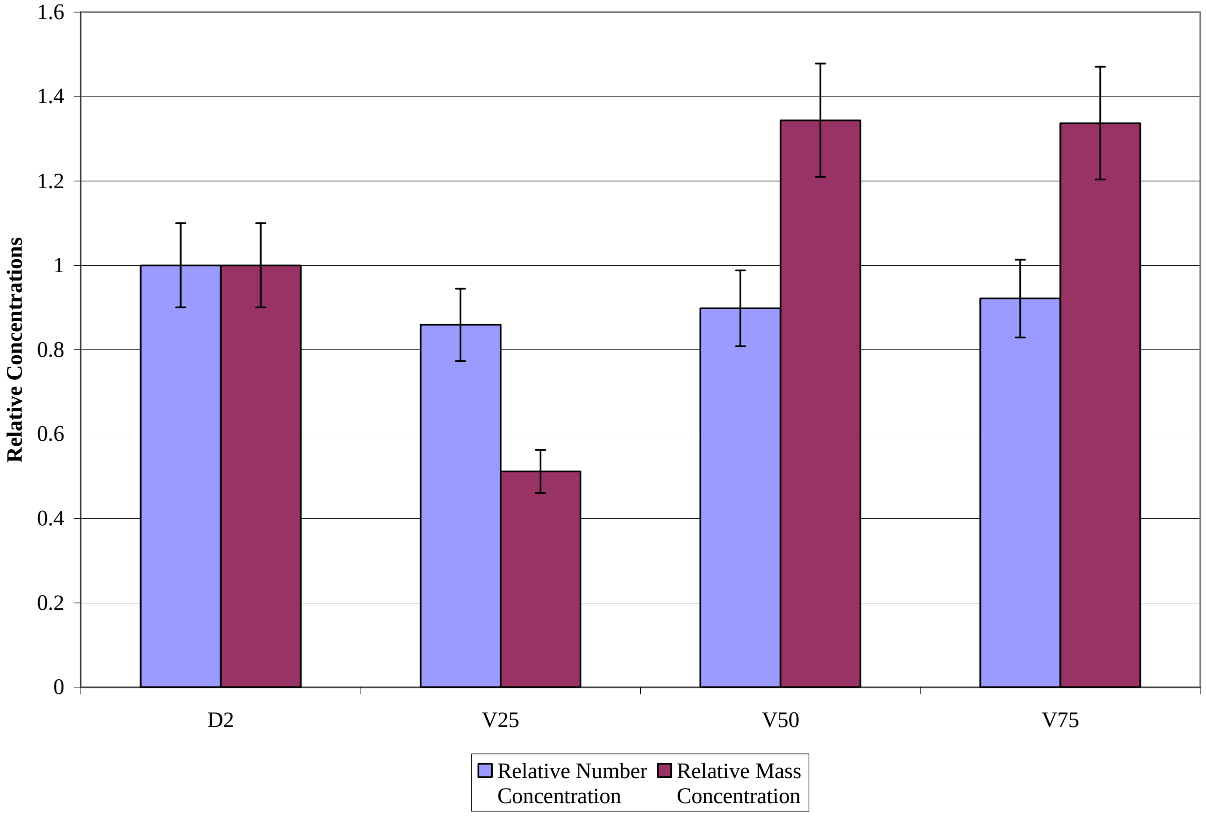

Figure 7. Exhaust Relative Number and Mass Concentrations with Diesel as the Baseline.

Project Benefits

- ***Fuel Selection*** - Soy oils can be used as turbine fuels. RBD was selected for this testing as it is more readily available and was the "best" fuel. Further testing on a turbine optimized soy oil would be merited.
- ***Fuel Storage Assessment*** - The stabilized RD and RBD soy oils performed **better** than biodiesel in the storage assessment.
- ***Economic Feasibility Study*** – The incredible run-up in oil prices in recent months has dramatically affected the conclusions of the economic study. There will continue to be a search for alternative energy sources, thus creating increasing upward pressure on these substances. It is difficult to predict what the foreseeable future holds for pricing of such fuels.
- ***Basic Combustion Studies*** – Blending soy oils with Diesel Fuel or Butanol, a second generation renewable fuel, modifies the properties such that blends of up to 75% soy oil can be atomized effectively.
- ***Small Scale Turbine Engine Studies*** – Soy oils blends of up to 75% can operate effectively in a combustion turbine with no turbine modifications.
    - **A 25% blend operates with equivalent efficiency and improved emissions**.

While ignition and atomization challenges are still present with running pure soy oil in the gas turbine engine, blending the soy oil fuel with diesel has been proven in this study to be a practical solution. The next step in the process of demonstrating the use of straight vegetable oils in gas turbines will be running similar blends in a commercial Capstone 30 kW micro-turbine gen-set for a 2000 hour test. After the successful test in the micro-turbine, the goal will be to evaluate these fuels in an industrial turbo-generator of 1-3 MW in size. With the successful completion of that test, the fuels would be ready for testing and demonstration programs in a larger 25-200 MW commercial turbo-generator.

Appendix A:

Table1: Summary of the repeated trace metal content of candidate fuels.

Test: ASTM D3605	***Candidate Fuel***							
Metal	**Crude Soybean Oil**	**Once Refined Soybean Oil**	**Refined, Bleached Soybean Oil**	**Refined, Bleached Deodorized Soybean Oil**	**Yellow Grease**	**Crude Glycerin**	**Biodiesel**	**ASTM 2880 Spec**
Vanadium, ppm	<0.05	<0.05	<0.05	<0.05	<0.05	3.61	<0.05	0.5
Sodium, ppm	<0.05	<0.05	<0.05	<0.05	39.2	32.22	<0.05	Sodium +Potassium < 0.5
Potassium, ppm	5.85	<0.05	<0.05	<0.05	19.4	2.59	<0.05	
Lithium, ppm	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	
Lead, ppm	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.5
Calcium, ppm	1.85	<0.05	<0.05	<0.05	149.4	2.52	<0.05	0.5

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