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Facility Implementation, Production, and Use of Biodiesel on a University Campus

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by

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This thesis was prepared under the direction of the candidate's thesis committee chairman, Dr. Marc Compere, Department of Mechanical Engineering, and has been approved by the members of her thesis committee. It was submitted to the Mechanical Engineering Department and was accepted in partial fulfillment of the requirements for the degree of Master of Science of Mechanical Engineering.

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Abstract

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During the last two years, Embry-Riddle Aeronautical University has been in the process of having a fully-functional biodiesel processing facility on campus. Within this time, it was shown that biodiesel was a great alternative to diesel fuel based on emissions, performance, and cost, allowing for a grant of $10,000 being awarded to fund the project. Upon properly producing biodiesel, the fuel was tested in a John Deere 2653A tractor to see what differences, if any, existed when using a biodiesel blend over diesel fuel. In doing this, carbon buildup and fuel economy were compared, and a cost analysis conducted. It was concluded that biodiesel can be safely produced on a university campus and can be utilized within diesel engines, while cutting back on costs.

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Chapter I
Introduction

A diesel engine is an internal combustion engine that converts chemical energy from fuel into a mechanical driving force. Mechanical energy is used to move pistons up and down into the engine's cylinders. The piston movement turns the crankshaft creating the rotational motion required to turn the wheels of the vehicle [1]. The fuel is converted into mechanical energy in a basic four stroke cycle consisting of intake, compression, power, and exhaust (see Figure 1).

In the first stroke, the piston moves down drawing air into the cylinder through the intake valve. Then, as the crankshaft rotates, the piston moves upward back into the cylinder compressing the air creating high amounts of heat. Using a fuel injector, the fuel is injected into the cylinder as the piston reaches the top of the compression stroke causing ignition. As the combustion gases expand, the piston moves back down in its third stroke. Finally, the piston moves upward again pushing the fuel back out of the cylinder through the exhaust valve [2].

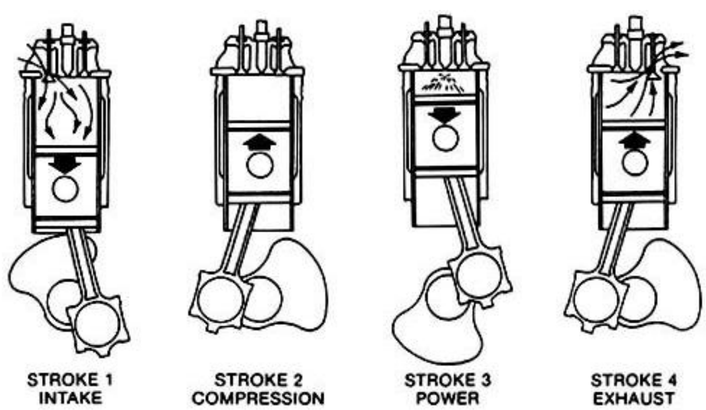

Figure 1. The diesel engine cycle. Diesel engines convert fuel into energy using four separate strokes of a piston. During the strokes, air is drawn into a cylinder and compressed creating a large amount of heat. This heat then combusts the fuel when it is injected into the cylinder. When combusted, the fuel powers the engine and is exhausted during the final stroke [3].

For the fuel to combust, the air must be heated to very high temperatures. Therefore, when the engine is cold, combustion can become very difficult. When this occurs, electrically heated wires known as glow plugs are used in order to heat the combustion chamber up to the required temperature [1]. As diesel fuel contains a lot of carbon molecules, the tips of the glow plugs tend to accumulate small amounts of carbon buildup due to being located within the engine cylinders.

Although this style of internal combustion does not require the need for a spark plug, as gasoline powered engines do, it can be difficult to control the amount of diesel fuel that is injected into the cylinders especially in older vehicles where the injection steps are mechanically controlled. If the mixture is too lean, there is not enough fuel injected required to power the vehicle. If the mixture is too rich, more fuel is injected than is required for combustion significantly increasing the amount of emissions. At lower speeds, incomplete combustion can occur, resulting in wasted fuel and, again, higher emissions [1].

Diesel fuel accounts for just fewer than 6% of the energy consumed in the United States (US) [4] and powers 94% of all freight transportation such as trucks, trains, and boats [1]. Although a very simple process and effective in engines, the exhaust from diesel is very harmful to the environment. Diesel exhaust is a mixture of thousands of gases and fine particles with more than forty toxic air contaminants. Not only harmful to people by containing harmful substances such as arsenic, benzene, formaldehyde, and nickel [5], but the gases are also dangerous to the environment.

In 2010, 3.8 million barrels of diesel fuel were consumed each day in the US alone (~160 million gallons) totaling almost sixty billion gallons of diesel fuel in a single year. In that 3.8 million barrels, 3.211 million barrels came from distillate fuel that had fifteen parts per million (ppm) and under of sulfur, 0.105 million barrels came from distillate fuel that than between fifteen to 500 ppm sulfur, and 0.484 million barrels came from distillate fuel that had greater than 500 ppm sulfur [6]. When these fuels are burned, sulfur dioxide (SO_2), a type of particulate matter (PM), is emitted into the atmosphere. If considering just the 0.484 million barrels of fuel (roughly 20.328 million gallons), that had over 500 ppm of sulfur, there was over 10,000 gallons of SO_2 emitted into the air in a single year.

Besides just SO_2, PM from diesel exhaust contains a lot of other harmful substances such as organic chemicals, metals, soil, and dust particles. If the particles are between ten and two and a half micrometers in diameter, they can easily be inhaled and passed through the throat and nose affecting both the heart and lungs [7]. Being exposed to these particles have been linked to various health problems such as difficulty breathing, a lowered resistance to infection, and increased cardiovascular problems such as heart attacks [8].

Diesel fuel also contains arsenic, benzene, formaldehyde, and nickel, substances which can mutate cells and cause many forms of cancer. The Californian Air Resources Board estimates that about 70% of the cancer risk for the average person living in California can be attributed to various the air pollutants emitted through the burning of diesel fuel [5].

In addition to the major health effects, diesel emissions can also be extremely harmful to the environment. Fine particles such as nitrogen oxides (NO_X) and SO_2 can cause poor visibility and haze around the US. When combined with sunlight and hydrocarbons (HC), NO_X also causes smog. PM is very acidic in nature due to the NO_X and SO_2 and can cause acid rain which not only acidifies lakes, oceans, and soil [9], but also destroys forestry, wildlife, and infrastructure.

Diesel fuel exhaust also emits large amounts of carbon dioxide (CO_2), a type of greenhouse gas (GHG), into the atmosphere and although it is necessary for photosynthesis, the conversion of the gas with water and sunlight into biological compounds, the amounts of CO_2 in the air has exceeded the amount that is reclaimed [10]. With excess CO_2 in the atmosphere, there has been an increase in the temperature on the earth's surface. Excess CO_2 is trapped near the earth's surface and absorbs heat from the sun. As CO_2 emissions have steadily increased since the industrial revolution (280 ppm in 1850 to 364 ppm in the 1990s), there have been increased efforts in finding ways to limit the amount of future emissions [10].

Globally, there are thirty-four billion tons of manmade CO_2 emissions of which diesel fuel is a large contributor. It is used in industrial processes (3% of total emissions), air, road, and other forms of transportation (2%, 13%, and 2% respectively), and also building light and heat (20%) [11]. In the US alone, there was estimated to be five metric tons of carbon emissions, per capita, in 2010 as seen in Figure 2 [12].

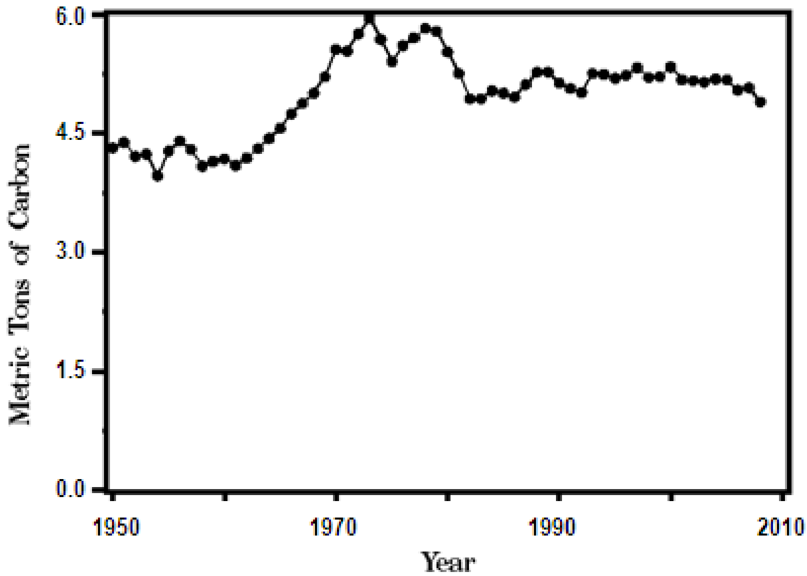

Figure 2. Per capita emission estimates for the US. In 1950, a single person in the US emitted just under four and a half metric tons of carbon into the atmosphere. Since then, the emissions declined slightly, but spiked during the 1970s. However, since 1980, a single person has averaged about five metric tons of carbon emissions each year [12].

To battle the amount of emissions, the Environment Protection Agency (EPA) has set a limit to the amount of carbon content in diesel to 2,778 grams per gallon [13]. By setting this limitation, the US government has started the efforts of decreasing the amount of CO_2 emissions with the intentions of positively helping the environment in the future. The European Union also passed legislation that began requiring airlines to pay for their carbon emissions in 2012 with the purpose of influencing the airlines to find alternative fuels that will reduce the amount of emissions [11].

However, even with these limitations, carbon is still being released into the atmosphere, and with thriving industries and amount of travel in the modern world, fuel is a necessary commodity. But regardless of how necessary it is, it must be rationed out properly as it is not a renewable source of energy.

Crude oil is a fossil fuel that was created over a period of millions of years due to the decomposition of carbon from animals. Out of every barrel of crude oil, roughly 9.2

gallons is refined into diesel fuel [14]. With oil reserves in different countries, the ability to drill greatly depends on political conflicts and agreements within countries. This leads to varying prices in oil. For example, in March 2007 the price was about $70/barrel, in March 2008 it was about $137/barrel, and in March 2012 it cost a little more than $100/barrel (see Figure 3). These high and varying costs of crude oil affect the cost of diesel per gallon which is a major concern for everyday consumers of the fuel.

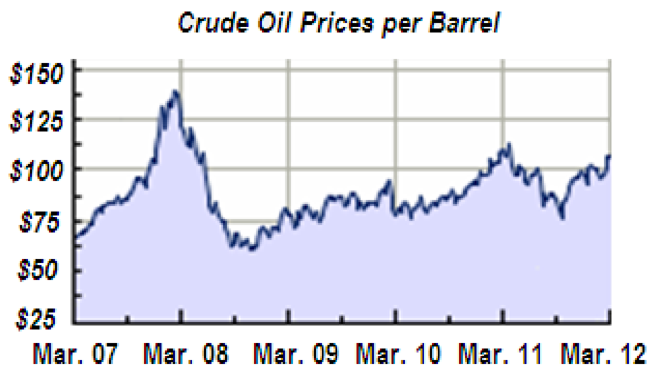

Figure 3. Crude oil prices per barrel over a five year time period. With oil reserves in different countries, the ability to drill greatly depends on political conflicts and agreements within countries leading to varying prices in oil as depicted above [15].

In data collected by the US Energy Information Administration (EIA), on-road highway diesel fuel increased from around $1.00 per gallon in 1994 to about $4.00 per gallon in 2012 as can be seen in Figure 4. These costs, however, do not come just from the cost to purchase crude oil. As of January 2012, 12% of the cost came from taxes, 10% came from distribution and marketing, 11% from refining costs, and 67% from the crude oil itself (see Figure 5). In that month, the retail price of crude oil was $3.83 per gallon. Since then, the cost has risen to $4.05 in late February 2012 and to $4.12 in mid-March 2012 [16]. Given the cost in March 2012 and the percentage of how much came crude oil in January 2012, it can be assumed that in the early part of the 2012, it cost $2.76 per gallon to purchase crude oil.

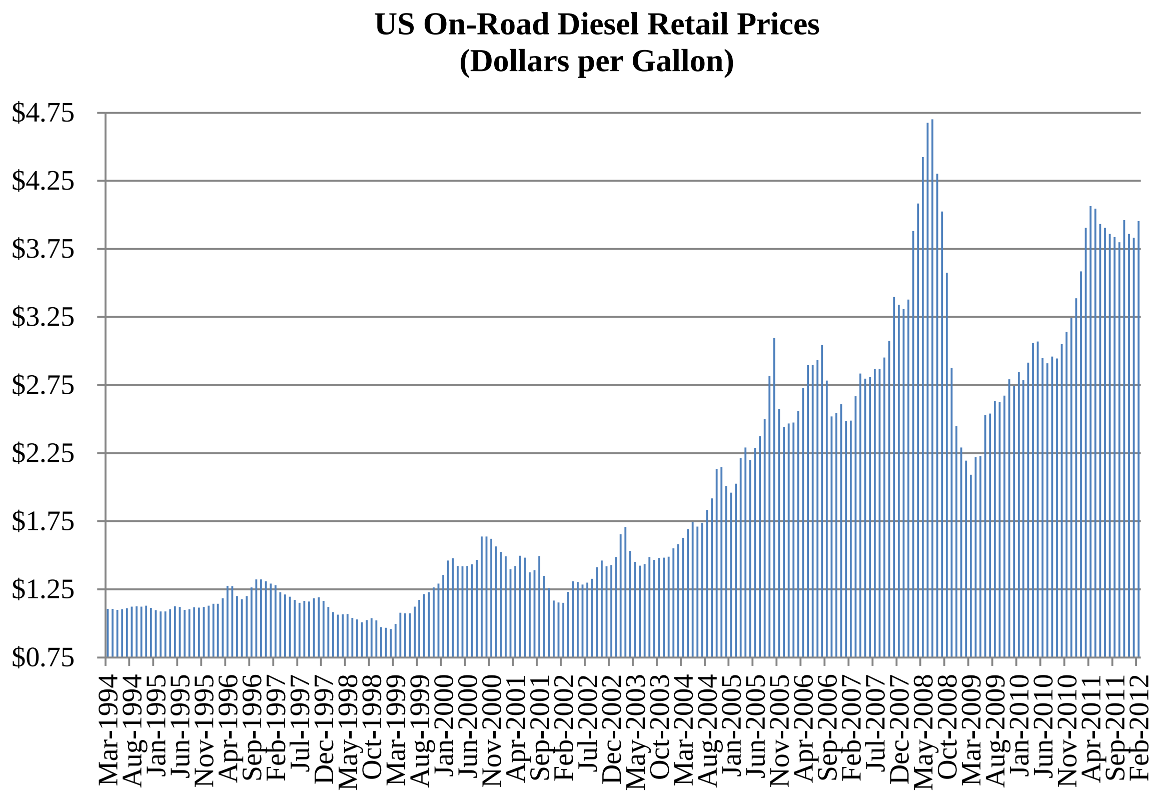

Figure 4. On road diesel fuel costs per gallon. This graph was created using data released by the EIA. It depicts the costs of diesel fuel per gallon during the time frame from March 1994 until February 2012 [16].

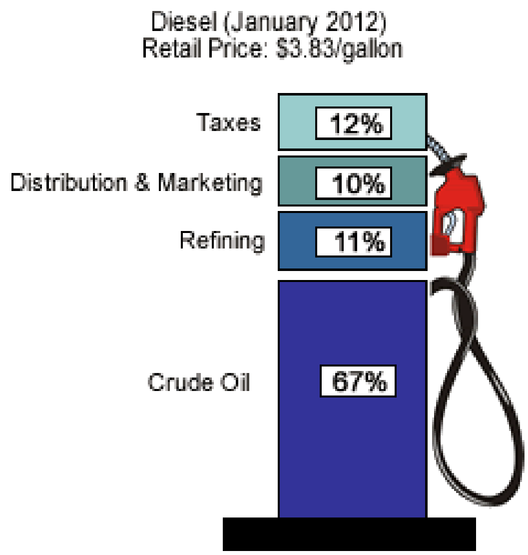

Figure 5. Breakdown of diesel fuel cost. In January 2012, diesel fuel was sold at a retail price of $3.83 per gallon. Of that cost, 12% was attributed to taxes, 10% to distribution and marketing, 11% to refining, and 67% to the purchasing of the crude oil [16].

Significance of the Study

Diesel fuel is a very prominent fuel used every day to power people, communities, and nations; with thriving industries and the amount of travel in the modern world, it has become a very necessary commodity. Unfortunately, although effective in engines, the exhaust created through burning diesel fuel is very harmful to the environment. Not only does it emit pollutants and carcinogens, but it also emits large amounts of CO_2 into the atmosphere. And although CO_2 is recycled back through the environment during photosynthesis, the amount emitted far exceeds the amount reclaimed.

With its harmful effects, there have been increased efforts in the past few years to determine other sources for fuel. Through researching the amount of diesel fuel that is burned each year and the growing amounts harmful emissions in the environment, there is a need for an alternative solution. Biodiesel can be that solution given that it is a clean fuel that is 100% renewable.

Through reducing or even eliminating the usage of diesel fuel by consuming biodiesel, carbon emissions can be lowered because the consumption of biodiesel recycles the existing CO_2 in atmosphere during photosynthesis. Made from biological compounds, biodiesel is fairly simple to produce and can eliminate the dependence on foreign oil, as diesel fuel is refined from fossil fuel deposits. Studies have been conducted that show that biodiesel can combust within a diesel engine without causing irreparable damage, all while being competitive in regards to cost.

Statement of the Problem

Biodiesel will not only help to stabilize GHG emissions, but it is also a very possible and real solution to the ever-growing emission problems. Unfortunately, biodiesel is not readily available for the everyday person to purchase and use in their engines. Therefore, for those wanting to run biodiesel in their diesel engines, they have to not only have the resources to produce biodiesel but also have the knowledge of how to do so. It is more than just purchasing a processor from any of the biodiesel production companies that advertise throughout the world; there are finer details that must be considered such as finding a suitable location for production, maintaining personal safety, and finding a source for the oil used to produce the biodiesel.

In order to begin producing and consuming the fuel, a lot of obstacles must be crossed; however, these obstacles are not necessarily covered by the plethora of biodiesel research studies. It is shown in several studies that biodiesel will lower emissions and is a better fuel for the environment, but knowing that information does not help the everyday consumer. If desiring to produce it on their own, they must fully understand the conversion process and be able to do so safety, effectively, and at a lower cost.

Purpose Statement

The purpose of this study is to show that biodiesel is a valid alternative to diesel and that it can be produced at a university level safely and effectively.

Limitations and Assumptions

As for the biodiesel research conducted for completion of this thesis, the amount of funding was a major limitation. Due to the funding, the amount of available testing techniques for the fuel was also limited. Other limitations included the author's chemical background, biodiesel facility location, and source of oil. Prior to conducting research, it was assumed that biodiesel lowered emissions and could be used within a diesel engine without any engine modifications (as long as the blend was no greater than 20%).

Definitions of Terms

Biodiesel	An alternative fuel to diesel created from biological compounds through the processes of transesterification.
Biofuel	Any type of alternative fuel that is created from biological compounds, e.g. biodiesel, ethanol, etc.
Greenhouse Gas	A gas that traps heat in the atmosphere.
Fine Particles	A type of particulate matter that is less than two and a half micrometers in diameter.
Phenolphthalein	An acid/base indicator solution that is often used in titration experiments; when added to an acidic solution, it appears colorless but when added to a basic solution, it appears to be magenta in color.
Photosynthesis	The conversion of sunlight, carbon dioxide, and water into food and energy for plants (biological compounds) and oxygen.
Transesterification	The chemical reaction in which triglycerides within an oil react with an alcohol to form esters (biodiesel) and glycerin.
Triglyceride	An organic compound formed from glycerol and three fatty acid groups; the main substance found in fats and oils.

List of Acronyms

ASTM	American Society for Testing and Materials
B100	100% biodiesel, 0% diesel blend of fuel
B20	20% biodiesel, 80% diesel blend of fuel

B40	40% biodiesel, 60% diesel blend of fuel
B60	60% biodiesel, 40% diesel blend of fuel
B80	80% biodiesel, 20% diesel blend of fuel
B99	99% biodiesel, 1% diesel blend of fuel
Bio-SPK	Synthetic Paraffinic Kerosene
CO	Carbon Monoxide
CO_2	Carbon Dioxide
EIA	Energy Information Administration
ERAU	Embry-Riddle Aeronautical University
EPA	Environmental Protection Agency
FFA	Free Fatty Acids
GHG	Greenhouse Gas
GPS	Global Positioning System
HC	Hydrocarbons
KOH	Potassium Hydroxide
MSDS	Material Safety Data Sheets
NaOH	Sodium Hydroxide
NO_X	Nitrogen Oxides
NREL	National Renewable Energy Laboratory
OP	Operating Procedures
PM	Particulate Matter
PPE	Personal Protection Equipment
PPM	Parts per Million

ROI	Return on Investment
SO_2	Sulfur Dioxide
SVO	Straight Vegetable Oil
TBHG	Tertiary Butyl Hydroquinone
US	United States
VP	Vice President
WVO	Waste Vegetable Oil

Chapter II
Review of Relevant Literature

Biodiesel as a Viable Alternative to Diesel Fuel

An Introduction to Biodiesel

With the very large amounts of diesel fuel being consumed in the US, the dependence on foreign oil deposits, varying costs, and harmful effects to both people and the environment, it is very important to begin looking at alternative sources for fuel. Registered with the EPA, biofuel, a type of alternative fuel that is created from biological compounds, can be sold legally and distributed commercially [17]. Currently, Asia, Europe, and America are producing biofuels, with the source being from photosynthetic plants [18].

Biodiesel, a type of biofuel, is a clean alternative to diesel fuel and is 100% renewable. From being formed from biological compounds, it is free of harmful chemicals such as sulfur and aromatics which are found in other fuels. Biodiesel, having passed testing requirements to meet the standards of the 1990 Clean Air Act Amendments [17], is the best choice in alternative fuels to replace the use of diesel.

Biodiesel is processed from plants, vegetable oils, and animal fats. These plants, oils, and fats are called triglycerides as they contain glycerin. Glycerin is separated from biodiesel through the process of transesterification (see Figure 6) in which an alcohol turns all of the fats and oils into esters which are types of organic compounds. The alcohol used in this process is methanol. The chemical process is catalyzed using a caustic substance. The caustic substance is typically either sodium hydroxide (NaOH) or potassium hydroxide (KOH) [19]. These animal fats and oils are not only nontoxic, but they are both biodegradable and renewable sources of energy [20].

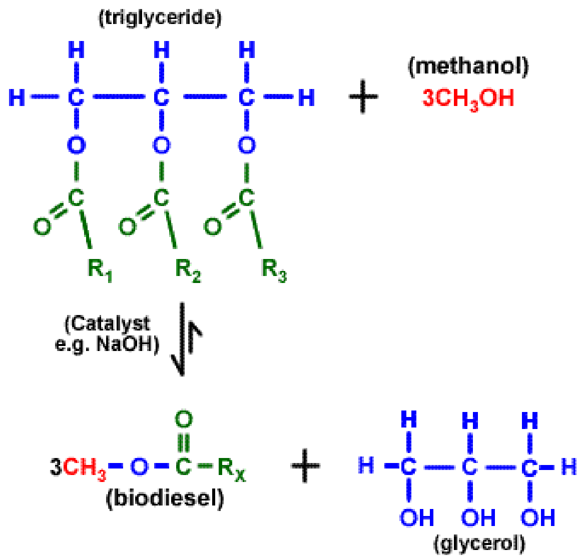

Figure 6. Visual representation of the biodiesel reaction, transesterification. The chemical reaction which produces biodiesel is known as transesterification. With the use of a catalyst, triglycerides from oil react with an alcohol to form biodiesel and glycerol [21].

There is a monumental difference between diesel fuel and biodiesel. Diesel fuel is extracted from fossil fuels and transported to a refinery. From there, it is transported to distribution centers for its different uses whether it be for aviation, road transportation, or industry uses [11]. In each different stage, carbon is emitted into the atmosphere. None of this emitted carbon is ever reclaimed. As biodiesel comes from biological compounds needing carbon to survive, or biomasses, it is not harmful to the environment as is other fuels and helps to recycles the carbon in the air. Unlike diesel, where carbon is only emitted into the air, biodiesel circulates the CO_2.

During photosynthesis, plants absorb CO_2 from the atmosphere. These plants are then either converted into oils which are used to create biodiesel or are eaten by animals whose fat is used to created biodiesel. The biodiesel, when burned, either through transportation, processing, distribution, or use, then emits the CO_2 back into the atmosphere where it is reabsorbed into the plants from which the process started. Even with the production and transportation of biodiesels, it is estimated that there will be an 80% reduction in CO_2 when using biodiesel [11].

Ways to Produce and Consume Biofuel

One way to use biofuel in a diesel engine is by using straight vegetable oil (SVO). However, by using SVO, the engine must be modified with replacement injectors as it is much thicker than regular diesel fuel. Therefore, instead of using pure vegetable oil, it is common to use a blend of SVO and diesel fuel; a typical blend consists of up to 20% SVO. By mixing SVO with the diesel, it makes the mixture thinner which lowers the viscosity allowing for the engine to remain unchanged.

In research conducted by the National Renewable Energy Laboratory (NREL), it was shown that SVO, although capable of combusting in a diesel engine, can lead to problems including injector choking, ring sticking, diluted crankcase oil leading to premature gelling and oxidation, and an increase risk in engine failure. Since there is no chemical conversion required for the fuel when using SVO, it is slightly cheaper than having to produce biodiesel [22] but due to the damages that could occur and possible need to alter an engine for use, it is not a suitable choice for a diesel replacement.

Another way to use biofuel in a diesel engine is to use biodiesel. B100 (100% biodiesel, 0% diesel) can be used in traditional diesel engines without needing modification. The creation of this fuel eliminated the issues that the engines had with using SVO. However, there are small problems with material compatibility with seals, gaskets, and other fuel system components. Fortunately, these can be lessened by adding fuel system heaters [22]. This fuel, like SVO, can also be blended with diesel fuel to create a different biodiesel blend.

Types, Benefits, and Industry Uses of Biofuel

Many companies have begun to notice the benefits to using biofuel. Companies including British Airways, Virgin Blue, Airbus, Boeing, and AirFrance, to name a few, have joined together and formed the Sustainable Aviation Fuel Users Group and set up a commitment to sustainable fuel options. Their commitment states that they "recognize the need for [a] dynamic, new innovation to help reduce aircraft GHG emissions beyond existing advance, while continuing to increase the socioeconomic good that air transport provides to the world." They declared to "advance the development, certification, and commercial use of drop-in sustainable aviation fuels" [23].

As an affiliate of the Sustainable Aviation Fuel Users Group, Boeing has begun their own research into creating sustainable biofuels. The company has started producing biofuels from algae so as to not compete with food crops for land or water. In 2008, Boeing used their first batch of algae-derived biofuels mixed with a kerosene-based fuel in a commercial test flight without needing to make modifications to the aircraft engines. In 2009, they began research and proved that biofuels performed just as well, if not better, than traditional diesel. Their tests showed that "the biofuel blends [met] or [exceeded] all technical parameters for commercial jet aviation fuel, including freezing point, flash point, fuel density, and viscosity" [24].

The algae-derived biofuel, known as Bio-SPK (Synthetic Paraffinic Kerosene) is created not only from algal plants, but also jatropha and camelina plants, and can reduce GHG emissions by 65-80%. Bio-SPK is created in a chemical process that first removes oxygen which reacts with a hydrogen to create paraffin, a mixture of liquid HC used as a fuel. The end result, Bio-SPK, is a biofuel used by Boeing in collaboration with the Sustainable Aviation Fuel Users Group [25].

Bio-SPK was tested using various American Society for Testing and Materials (ASTM) tests and was shown to contain zero impurities. With requirements of a maximum of two ppm of nitrogen, seventy-five ppm of water, and fifteen ppm of sulfur, all of the Bio-SPK fuels produced had significantly lower amounts. These fuels, after having passed initial testing, were flown in various aircraft to ensure that the engines would perform well.

The Boeing 747-400 aircraft was flown with 50% jatropha based Bio-SPK up to 35,000 feet while the fuel flow was monitored; the Boeing 737-800 aircraft was flown with 47.5% jatropha and 2.5% algae based Bio-SPK up to 39,000 feet while the engine operability was monitored; and the Boeing 747-300 aircraft was flown with 42% camelina and 8% jatropha/algae based Bio-SPK up to 39,000 feet while the oil emissions were monitored.

In each of the test flights, the fuels either met or exceeded the expectations as determined by jet-fuel performance. The Bio-SPK biofuels even had a higher density per unit mass as compared to traditional jet fuel allowing for the aircraft to travel to farther distances with less fuel burned. As expected, the aircraft system and engine had no adverse effects from being run with a biofuel instead of traditional jet fuel [25].

Biofuels created from animal fats, used cooking oils, and algal plants have several things in common; they are renewable, sustainable fuels, and better for the environment. Algal based biofuels can be produced domestically reducing the dependence on international fossil fuel deposits and imports, remove large amounts of CO_2 from the atmosphere during photosynthesis, and do not disrupt the food chain [26]. Jatropha can be grown on land surrounding crops acting as a barrier on the edges of fields or on wasteland where no other crops would survive. Algal plants grow in non-potable water and wastewater ponds. Jatropha, algae, and camelina will not disrupt the food chain because jatropha seeds are toxic to humans and animals, algae are produced fifteen times more than oil, and camelina is used as a rotational crop on farms [11].

Biodiesel versus Diesel Fuel

The EIA is projecting that for the conclusion of year 2012, the retail price of on road highway diesel be \$3.92 per gallon and for the year 2013, at \$4.11 per gallon [27]. With these high estimated prices, there is an increased need for finding a way to replace the use of diesel fuel. This replacement should improve upon the environmental and health risks, be similar to diesel fuel in both performance and composition, but also ideally save the consumer cost at the pump.

ASTM Fuel Standards

In comparing diesel fuel to biodiesel based on their ASTM standards (Table 1), it is observed that diesel and biodiesel have similar lower heating values with diesel fuel only exhibiting about 10% more energy per gallon. This indicates that diesel fuel produces just slightly better fuel economy than biodiesel, but depending upon the blend of biodiesel being utilized, the difference could be negligible. It should be noted as well, that biodiesel has a higher viscosity than diesel fuel indicating that biodiesel may not flow as easily as diesel fuel and may clog fuel injectors.

Table 1
ASTM fuel standards.

Fuel property	Diesel	Biodiesel
ASTM fuel standard	D975	D6751
Lower heating value (BTU)	~129,050	~118,170
Kinematic viscosity @ 40° C (BTU/gal)	1.3-4.1	1.9-6.0
Specific gravity @ 60° C (kg/L)	0.85	0.88
Density (lb/gal)	7.079	7.328
Carbon (wt. %)	87	77
Hydrogen (wt. %)	13	12
Oxygen (wt. %)	0	11
Sulfur (wt. %)	0.0015	0-0.0024
Boiling point (° C)	180-340	315-350
Flash point (° C)	60-80	130 -170
Cetane number	40-55	47-65

Note. Adapted from ASTM fuel standards for diesel fuel (B975) and biodiesel fuel (D6751).

Besides these seemingly negative points, biodiesel has less carbon molecules by weight than diesel fuel does. Therefore, not only does biodiesel circulate carbon within the atmosphere due to having been made from photosynthetic organisms, but it also emits less back into the atmosphere than diesel fuel does. In addition to fewer carbon atoms, diesel fuel contains no oxygen, whereas biodiesel contains 11% by weight helping to improve upon combustion of the fuel. The sulfur percentage by weight is variable and at times may be more or less than the diesel fuel depending on the quality of production

The flash point of a fuel indicates the lowest temperature of which the vapors from a fuel will ignite. Biodiesel has a higher flash point and with the addition of oxygen atoms, the fuel is not flammable. Therefore, it is safer to handle and store than diesel fuel [28].

The cetane number of the fuel is a measure of the fuel's ignition quality; the higher the cetane number value, the better performance out of an engine. In comparing the cetane values for diesel and biodiesel, the fuels are both very similar to one another and could arguably have the same performance.

When comparing the fuels based on fuel properties defined in the ASTM standards, there are benefits to both diesel and biodiesel fuel. Therefore, it is important to analyze their differences based on emission studies as the standards alone make it difficult to differentiate between the two.

Comparison Based on Emissions

In findings reported by the US Department of Energy, it was shown that in heavy-duty highway engines, not only does PM emission decrease, but so does carbon monoxide (CO) and HC. However, NO_X emissions do increase from using biodiesel (see Figure 7).

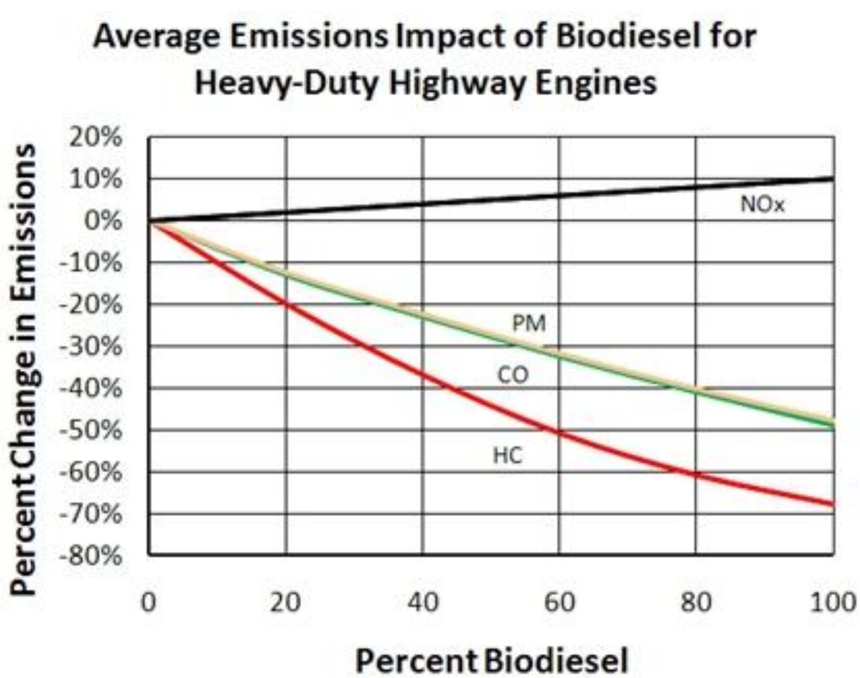

Figure 7. Emissions from biodiesel blends. This figure depicts the average emissions changes between diesel fuel and different biodiesel blends for NO_X, PM, CO, and HC. The blends of biodiesel went from 0% up to 100% [29].

Based on these emission results, it seems as if biodiesel is much better for the environment than diesel fuel because although NO_X increases, it only increases by 10% whereas PM, CO, and HC decrease by up to 50-70%. This reduction makes a far greater positive impact than the negative impact from NO_X.

In another report from North Dakota State University, emissions were observed when comparing diesel fuel to B100 and B20 (20% biodiesel, 80% diesel). For B100, it was shown that CO emissions decreased 43.2%, HC decreased 56.3%, PM decreased 55.4%, air toxins decreased 60-90%, mutagens decreased 80-90%, and CO_2 decreased 78.3%. For B20, it was shown that CO emissions decreased 12.6%, HC decreased 11.0%, PM decreased 18.0%, air toxins 12-20%, mutagens decreased 20%, and CO_2 decreased 15.7%. However, NO_X increased 5.8% for B100 and 1.3% for B20. In the same study, it was shown that B100 had a cetane value of 55, B20 of 50, and diesel of 48 indicating that biodiesel had a better fuel ignition quality than diesel fuel [30]. Therefore, although NO_X emissions increased, this negative to biodiesel is far outweighed by the higher cetane values and far greater reduction in emissions to CO, HC, PM, air toxins, mutagens, and CO_2.

In a renewable and sustainable energy review conducted by authors at the University of Illinois and Nanjing Agriculture University, biodiesel studies from year 2000 and on was discussed in order to help researchers and engine manufacturers optimize the diesel engine as well as for the users of biodiesel to better understand its benefits. It was shown that when using B100, 70.4% of the referenced researchers felt that the power decreased but 87.1% felt that the economy performance increased. 87.7% agreed that PM emissions decreased, 84.4% agreed that CO emissions decreased, 89.5%

agreed that HC emissions decreased, and 84.6% agreed that aromatic compounds decreased when using B100. In regards to NO_X emissions, 65.2% saw an increase, 5.8% saw no difference, and 29% saw a decrease as compared to diesel fuel, and in regards to CO_2 emissions, 46.2% observed an increase, 15.4% observed no difference, and 38.5% observed a decrease in emissions [31].

Overall, it was concluded that biodiesel may lead to a loss of engine power but that the loss may be counteracted by higher fuel consumption. When using biodiesel, carbon deposits were lowered due to the decreased PM emissions. However, due to the presence of oxygen within biodiesel, NO_X emissions increased slightly. CO and HC emissions decreased when using a biodiesel versus a diesel fuel and although the emissions data from CO_2 seemed inconsistent, it can be concluded that when using a biodiesel, the emissions will improve strictly because of the recirculation of carbon during the biodiesel fuel lifecycle [31].

Reviews of Engine Performance

NREL, on behalf of the U.S. Department of Energy Office of Renewable Energy Efficiency and Renewable Energy and Midwest Research Institute, conducted a study to determine the composition of biofuel to show that it is a valid source of alternative fuel. Their research was based around wanting to reduce the dependence on foreign oil by creating a domestic bio-industry. The research stated that "the ease of displacing a petroleum distillate fuel with a biomass oil fuel depends on the application, fuel quality, performance, and price" [22].

It is important to be certain that the use of biodiesel would not negatively affect a diesel engine to the point where damage is irreparable. Different research groups have performed studies comparing the two fuels based upon engine wear and performance. Since lowered emissions is not enough of an incentive to replace diesel fuel with biodiesel, these findings can help to determine if biodiesel can ideally replace the use of diesel fuel because lowered emissions is not enough of a reason to do so.

In a study conducted by the US Postal Service, teardown analysis of engines was performed and fuel systems removed to compare wear characteristics between standard diesel vehicles and biodiesel operated vehicles. Four vans and four tractors were selected for the study, with two control vehicles, all operating in the same climate and drive cycle. For the teardown the fuel injection pumps were tested, internal parts were compared based upon wear and damage, and carbon deposits were analyzed [32].

From the study, it was shown that all of the engines, regardless of the fuel, had normal wear for the amount of mileage accrued. Within the tractors, although the maintenance costs were similar, the cylinder heads contained a large amount of sludge when operating off of B20 and the fuel injector nozzles needed to be replaced. Both of these, however, were attributed to out of specification fuel [32]. The vans, on the other hand, had no filter plugging, no need for injector replacement, and no accumulation of sludge as did the tractors. Like the tractors, the maintenance costs were similar between the vehicles operating on B20 and diesel fuel [32].

POLARIS (Performance Oil Analysis Laboratories and Reliable Information Services) Laboratories claims that biodiesel can increase wear rates on an engine and that it is important to monitor the engine more diligently. Being made from organic materials, biodiesel has a natural polarity that is attracted to zinc dialkyldithiophosphate, a polar additive contained within the diesel engine’s lubrication. This compound attracts to the metal surfaces within the engine creating a protective layer. However, being attracted to the compounds within biodiesel, it disturbs the protective layer leaving the engine susceptible to wear [33].

Based on the current research it is shown that when comparing biodiesel to diesel fuel, it is better for the environment and will decrease the harmful emissions affecting the health of the population. However, although not entirely conclusive, biodiesel can have negative effects on the engine especially if it was out of specification.

When processed using methanol and a caustic catalyst (NaOH or KOH), there may be leftover particles from the chemicals due to improper washing. If this occurs, there could be sodium from the NaOH or potassium from the KOH remaining in the fuel. These particles could cause the fuel to go out of the specifications set by ASTM to ensure that there were no harmful substances left over. However, if produced and tested properly, biodiesel may not negatively affect an engine. But due to the inherent risk, it may be beneficial to use a blend of biodiesel such as B20, versus pure biodiesel, B100, within a diesel engine.

By using a biodiesel blend, no equipment modifications are required, carbon content is reduced, and the better qualities with biodiesel and diesel are combined to create a perfectly running fuel. This fuel is already being used very prominently in on-road transportation, farming equipment, forestry, mining, construction, electricity generation, marine vessels, trains, and in aviation. By combining the best of both fuels, the problems associated with B100 are minimized while offering a better fuel for the environment due to emitting less CO_2 and harmful toxins [22].

Cost Comparison

In 2006, the Virginia State Advisory Board on Air Pollution performed a biodiesel fuel study to evaluate the emission benefits and costs. The board reviewed test data from the Department of Energy and NREL. As with the research already discussed, it was concluded that with the exception of NO_X (having a slight increase), all other emissions decreased (HC, CO, PM, and sulfates).

As for cost of production, the most expensive facet is the purchasing of feedstock. The board claims that it would cost $1.58 per gallon to make biodiesel (with one gallon requiring seven and a half pounds of soybean oil at a cost of $0.21 per pound). When the board conducted their study, it was also stated that the US Department of Energy forecasted that biodiesel cost $1.40 per gallon by 2010 [34]. This forecast was a good estimate as most home-brewers today claim to produce their own biodiesel from anywhere between $1.25 and $1.50 per gallon.

Based on 2012 data (reference Figure 5), before taxes, distribution and marketing, and refining, it costs about $2.76 per gallon for the purchasing of diesel fuel. It can be assumed the biodiesel will have similar increases to its cost, and so, if biodiesel at most the same price as diesel fuel, it is a valid alternative for replacement.

In 2004, legislation was passed for excise tax credits for biodiesel blending. The credit was $1.00 per gallon of biodiesel if created from soybean oil and $0.50 per gallon if created from yellow grease [35]. Unfortunately, this credit expired at the end of 2011. In addition to that legislation, however, the US Department of Agriculture offers grants to those who produce biodiesel through the Commodity Credit Corporation with a rebate of

$0.89 to $0.91 per gallon if producing from yellow grease and $1.45 to $1.47 per gallon if producing from soybean (in 2002 prices) [35].

Currently in the US, there are hundreds of biodiesel stations ready for the average consumer (Figure 8). These stations exist because it has been shown that biodiesel, as long as it is within ASTM test specifications, will not cause any irreparable damage to the engine, will provide for similar engine performance, and with the exception of NO_X, decreases the amount of emissions significantly.

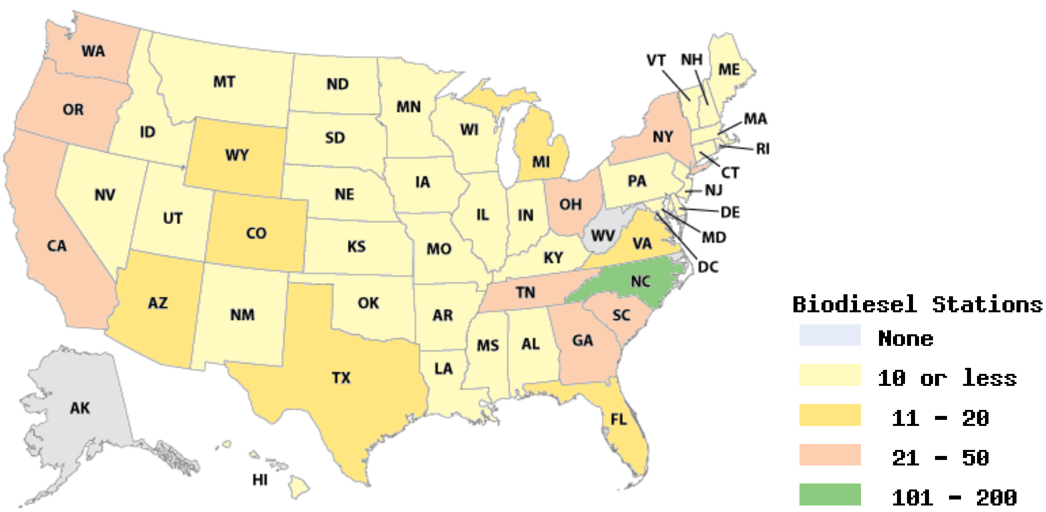

Figure 8. Biodiesel blend stations around the US. This image is a depiction of the US and the amount of biodiesel stations in each of the fifty states [36].

As for costs, *USA Biodiesel Prices* website reported that a station in Florida sold B20 for $3.84 per gallon in December 2011, a station in Texas sold B99 (99% biodiesel, 1% diesel blend) for $3.29 per gallon in January 2012, and a station in Wisconsin sold B20 for $3.79 per gallon in January 2012. These prices are very competitive to the retail price of diesel fuel currently around $4.00 per gallon (Figure 4).

Summary

Biodiesel is a type of biofuel that is produced through the chemical process known as transesterification and that can eliminate the amount of diesel consumption. It can do so because it not only reduces emissions helping the environment but it can be used in a diesel engine without causing irreparable damage.

Diesel fuel and biodiesel were compared based on material properties and cost of production in order to show that biodiesel will not only help to stabilize GHG emissions, but that it is also a very possible and real solution to the ever-growing emission problems. Various studies were also discussed that addressed engine performance with the consumption of different types of biofuels such as Bio-SPK, SVO, and biodiesel processed from WVO. Also, each of the various biofuel recipes were discussed as well as the ways in which each of the fuels are already being utilized in today's transportation industry.

With all of the great qualities of the fuel, it was shown that biodiesel would be a great choice in replacing diesel fuel. It can be produced in several ways without disrupting the environment or food chain and can be produced anywhere. It would decrease America's dependence on foreign oil and lessen the CO_2 concentration in the air while reducing GHG emissions. It is a cleaner, safer, and sustainable fuel and is 100% renewable. Showing that biodiesel is cost efficient in addition to all of the other benefits, makes it a clear alternative to diesel fuel.

Biodiesel, although a great alternative, has one major downfall; it is not readily available to the everyday consumer as there is only one state in the entire US that over 100 stations and over half of the states have less than ten (Figure 8). Therefore, many people have opted to start producing biodiesel for their personal use. But, to fully see the impact that biodiesel can make, it needs to be produced in more places and used in more engines.

Hypothesis

It is proposed that, on a university campus, biodiesel can be produced properly, used effectively through reducing diesel consumption, and managed safely while saving the university money. It is also proposed that B20 can be consumed in a John Deere 2653A diesel tractor without significantly affecting the fuel economy (no more than a 2% reduction in mileage) but while lowering carbon buildup and soot emissions.

Chapter III
Methodology

Developing the Biodiesel Facility

In order to begin producing and consuming biodiesel on a university campus, a lot of considerations need to be accounted for. First and foremost, an interest in the fuel needs to be developed. Once the interest is developed, funding needs to be granted. After obtaining a grant that is able to cover all expenses, different obstacles must be crossed. During the past two years, Embry-Riddle Aeronautical University (ERAU) in Daytona Beach, FL has been doing just that; the university has been planning for and crossing all of the obstacles that came up during the process of going from having nothing to producing and consuming biodiesel on campus.

After performing research and determining that biodiesel was a good alternative fuel to diesel, an interest was developed by presenting the benefits of the fuel to the ERAU Vice President (VP), the Dean of Engineering, and the Mechanical Engineering Department. By presenting the benefits of the fuel and proposing that ERAU begin producing biodiesel and consuming it in the campus vehicles, it was decided that ERAU begin to take the steps towards a cleaner future by producing biodiesel. Between the ERAU VP, Dean of Engineering, and Mechanical Engineering Department, $10,000 was granted and the process began.

It, however, did not start overnight. It required a lot of planning and hard work to prepare the university for the capabilities of production in regards to not only understanding the chemistry behind the process, but also to ensure that the facility was up to safety standards, there was a way to obtain used cooking oil to prepare the batches, and the personnel were properly trained. Once these obstacles were taken care of, it was only a matter of purchasing the chemicals used to process the used cooking oil/WVO before being able to start producing biodiesel.

Selecting a Biodiesel Processer

As the personnel that would be working to produce biodiesel at ERAU had no prior experience in doing so, it was thought best to purchase a processor from a home biodiesel kit company instead of building one from scratch. The processor needed to be able of producing large amounts of biodiesel at a time as well as having storage, cleaning, and filtering capabilities. The selected biodiesel kit was the *Freedom Fueler Biodiesel Processor* built and sold by *Home Biodiesel Kits*.

This processor (Figure 9) was selected as it is capable of processing forty gallons of biodiesel at a single time and had its own oil filtration and pumping system. It included two mixing tanks; the smaller tank was to mix the alcohol and catalyst and the larger tank was to process, clean, and store the biodiesel. With the purchase also came a safety first aid kit with multiple chemical gloves, safety goggles, dust mask, a hands-free explosion-proof methanol pump, and a complete operating manual with step-by-step directions.

Figure 9. The *Freedom Fueler Biodiesel Processer*. This processer was selected to be used at ERAU to produce quality biodiesel [37].

Spill Control and Chemical Storage

The next step was to ensure that the facility was capable of not only holding and storing all of the processing equipment, but also able to handle spills. The facility was designed with the intention of producing forty gallon batches of biodiesel at a single time as it was the maximum allowed by the biodiesel processer. Knowing which chemicals would be used it was important to study their Material Safety Data Sheets (MSDS).

Both KOH and NaOH are used to process biodiesel; they are catalysts and react within the triglycerides in the oil allowing for the separation of glycerin. The major differences between the two chemicals is that when using NaOH, less catalyst is required and the separated glycerin will be much thicker and more likely to solidify. KOH allows for a liquid glycerin, dissolves quicker in the methanol, but is slightly more expensive. Both, however, will provide for high quality biodiesel

NaOH is a corrosive, poisonous liquid that is non-flammable and non-explosive in the presence of open flames, sparks, and shocks. If spilled, it can be diluted with water or absorbed with a dry inert material. With large spills, the chemical can be absorbed with dry earth, sand, or other non-combustible materials. It should not be ingested nor mixed with water, and its fumes are not to be inhaled. It may cause extreme skin irritation and usage of this chemical requires a vapor respirator, gloves, splash goggles and face shield, and covers for both arms and legs.

KOH is similar to NaOH in that it is corrosive, non-flammable, and non-explosive, but as for spills, it can be diluted with acetic acid. It is to never be mixed with water and requires the use of splash goggles, an apron, vapor and dust respirator, boots, and gloves. It also can cause severe skin irritation and burns.

Methanol is also used to produce biodiesel as it bonds with the fatty acids in the oil after having been separated from the triglycerides. Roughly 20% of the total volume of oil is the amount of methanol required for the reaction. It is flammable in both liquid and vapor form and will vaporize at 12° C (53.6° F). Due to its low flash point, it is an explosive chemical and is dangerous within fire situations. It is a toxic liquid and in case of fires, should be extinguished with dry chemical, water spray, or alcohol resistant foams. Methanol requires the use of chemical splash goggles, chemical gloves, and protective clothing.

Because of these chemicals, it was very important to ensure that all safety measures were accounted for. During the processing of biodiesel, a lot of harmful vapors are emitted and so it needs to be processed in a well-ventilated area. Due to spacing availability, the processing plant was designed to be outdoors with an awning cover.

The plant location was decided to be in an allotted space behind the main ERAU Grounds Department building. Upon reading and studying the operating manual provided for the university with the purchase of the processer, it was realized that the facility needed a direct line for both water and air. Therefore, in addition to keeping the processor at a given location, both lines were drilled. To run the processor, a power line was also provided for.

Being that ERAU is located in Florida where the humidity is very high, it was not possible to store the caustic chemicals by the processing facility as the moisture in the air could cause an unwanted reaction. It was decided, instead, to store them at an indoor location, close to the facility, that was not only easily accessible but also capable of storing caustic chemicals. A fire cabinet was obtained and placed in a student organization work garage with access given to those working with the chemicals. Once purchased, it was decided to store the NaOH and/or KOH in that cabinet.

As for the methanol, it was not as important that the chemical be kept from moisture and high humidity and so keeping it outdoors at the processing facility was an acceptable option. However, due to the hazards associated with fire and explosion, it was decided that upon purchasing the methanol, that it was to be constantly grounded.

Appropriate firefighting measures were also taken into consideration. After speaking and meeting with the Environmental Health and Safety Director at ERAU, Justin Grillot, it was decided that a twenty pound fire extinguisher rated for the type of chemicals being used was sufficient for the facility. Prior to the facility being fully functional, the fire extinguisher was purchased and installed at the facility. As for the

NaOH/KOH, being that the facility is outdoors, dirt is readily available if needed to dilute a spill associated with either one of those chemicals.

If any large volume of liquid were to spill, it was agreed with Grillot that the personnel working at the facility would take appropriate measures given by the MSDS and he would be contacted as soon as possible for him to take control of the situation. To ensure that large spills were contained, if for example the entire forty gallon batch were to spill out from the processor, a containment cell with a drainage system was designed and built.

Made out of concrete, the cell is large enough to contain 110% of the maximum possible liquid that could spill out. However, as the cell would contain not only the processor but also a fifty-five gallon methanol drum and an oil storage device, the containment cell was designed with a wall that sat seven inches high from a four foot by eight foot concrete slab. The cell is capable of handling 140 gallons of processing fuel with two fifty gallon drums for storage.

Personnel and Facility Safety Requirements

As multiple persons would be working with the processor, it became important to ensure that they were all trained and had appropriate personal protective equipment (PPE). It was decided, again after meeting with Grillot, that each person working with the chemicals would be required to wear long pants/sleeves, chemical gloves, splash goggles, and an N95 respirator capable of filtering 95% of airborne particles. Prior to using it, however, they were required to be trained on respirator use, storage, and cleaning. In addition to the PPE, each person was required to sit in on a training session that outlined each of the hazards associated with the chemicals and how to be fully prepared for any incident that could occur. If anything were to happen to any of the personnel, the biodiesel facility was built in a location that had close by eyewash and shower stations.

In addition to the training of the personnel, it was necessary to ensure that if needed, the MSDS for each chemical was readily available to everyone. The facility was built behind and in conjunction with the ERAU Grounds Department, and so the MSDS sheets have become available within the garage located adjacent to the biodiesel processing facility. With the MSDS also included a detailed set of Operating Procedures (OP) for the facility.

The OP was written around the step-by-step instructions which were provided for through the purchase of the biodiesel processer, but also defined the potential hazards and precautions to be taken, full instructions as to how to make biodiesel, troubleshoot the equipment, and dispose of waste products. The OP also defined a working zone for the processing facility that would have restricted access while the processor was in use. The working zone defined was a fifteen foot radius with the processer as its center point. In order to be allowed within the working zone, all persons need to be in appropriate PPE. Prior to implementation of the OP, however, it was read and approved by the Grounds Department, Grillot, and members of the ERAU Mechanical Engineering Department.

Locating an Oil Source

One of the required, if not most important of all ingredients needed to process the biodiesel is the oil. When determining how to obtain the oil, several considerations were taken. First, it was necessary to decide whether the oil would come from SVO or WVO. If using SVO, a large cost would be incurred from having to purchase the oil. If using

WVO, little to no cost would be incurred, but a source of oil would need to be identified. With the intentions of producing biodiesel at a lower cost than diesel fuel, it was decided that the oil would come from a WVO stock.

Then, it was necessary to determine where the oil would come from. From meeting with university officials and the general manager of the food services at ERAU, it was agreed that the university cafeterias would save the used cooking oil to be used in the processor. The school uses roughly 1,500 gallons of oil each year which is, coincidentally, the same amount of diesel fuel that is consumed in campus vehicles each year. Theoretically, once ERAU's biodiesel plant is fully functional and the fuel is tested and meets ASTM standards, the use of diesel fuel could be eliminated completely not only saving the university money but also significantly helping to improve the environment.

Waste Handling and Disposal

Once the safety and training obstacles were overcome, as well as the planning of the facility in regards to grounding the methanol tank, storing the NaOH and/or KOH, and preparing for spills, the last step to finalize the design and implementation of the biodiesel facility was to determine how to handle the waste products.

Waste forms at almost every step of biodiesel production. Prior to using the biodiesel processor, small test batches (between one liter and one gallon) must be made. This is done to get practice producing biodiesel as there are many ways that it can go wrong; using too much or too little catalyst or methanol or having a contaminated oil source can significantly alter the outcome. If a bad batch is made, waste is produced either as small emulsions (soap, oil, and water mixture) or thick soap and must be disposed of properly.

When a good batch is produced, a definitive level of glycerin separation will be seen. This layer must be drained and stored. The resulting biodiesel is then washed with water a few times in order to remove any excess contaminants (glycerin or methanol leftover from the reaction). Both the glycerin and wash water are considered waste. When doing test batches, the waste amounts are minimal, but when doing large scale production, there are many gallons of waste materials. Before any biodiesel was made, whether small or large scale, the proper disposal of the waste was discussed with Grillot.

With the small test batches, small storage containers were purchased. Each of the waste products was stored in separate containers for bad batches, glycerin, and wash water. All of the containers were labeled and kept in a fire safe cabinet.

On a larger scale, it was decided that as waste is produced, it is to also be stored in different containers. The selected storage containers, however, were too large to be kept within a fire safe cabinet, and were decided to be stored in a locked area within the ERAU Grounds Department designated for waste. Once the containers are full, Grillot agreed to take appropriate measures to ensure that each of the products is disposed of properly.

Bad Batches of Biodiesel

Upon a batch going bad, i.e. produced improperly, there were many different options discussed with Grillot and the ERAU Grounds Department as to how to dispose of it. If the batch has turned into solid soap, the chunks can be set aside and allow for the excess methanol to evaporate. The chunks can then be used as a soap product. If the emulsions are in a liquid state, the waste can be separated and the left over oil can be reprocessed with a new batch. The emulsions, once stored and set aside, will separate over time into oil and water. This separation can be quickened with the addition of heat. Once separated, the water can be stored in the other containers of wash water, and the oil reprocessed with the next batch.

Wash Water

The waste water cannot just be simply poured down the drain. As it is used to clean the biodiesel and remove methanol and glycerin contaminants, it is a toxic substance. Depending on local governing laws and water treatment plants, the water can be disposed of with them. However, as the head of the Environmental Safety and Health Department at ERAU, Grillot has agreed that his department would handle the disposal of the toxic waste water. All that is required is to collect it all in a container and contact him when full. However, if the water has a pH of seven (indicating that it is neural), it can safely be poured down the drain. The more the biodiesel is washed, the cleaner the water becomes. Therefore, some of water can be disposed of in the drain safely.

Glycerin

The final waste that needed to be considered was glycerin. Unlike bad biodiesel batches and waste water, glycerin can be utilized in different ways. Glycerin is a major ingredient in soaps, and so, the glycerin could be donated to different facilities. However, ERAU found a way in which the university could utilize this waste, transforming the production facility into a 100% recyclable plant (due to recycling WVO from the cafeteria and using the glycerin byproduct). Glycerin acts as an activating agent in a composter. Therefore, at ERAU, the Grounds Department has been collecting dead grass, leaves, mulch, etc. and uses a composter, with the addition of glycerin, to make a potting soil.

How to Properly Make and Test Biodiesel

Upon determining how to handle of the waste products formed from the production of biodiesel, ERAU was ready to begin their production. With the facility set up to the proper safety specifications, all of the personnel trained and ready with appropriate PPE, each of the chemicals ordered and stored safely, the processor and composter purchased and set up, and a valid source for oil determined, all that was left was to begin with small test batches to get the chemistry perfected.

Before making biodiesel, it was important to fully understand what happens chemically. Oil, a substance comprised of triglycerides and free fatty acids (FFA), reacts with sodium or potassium methoxide. This methoxide is formed from the mixing of NaOH or KOH with methanol. The NaOH/KOH acts as a catalyst and attaches to the triglycerides creating glycerin. The methanol then reacts with the FFA creating biodiesel.

It is more than just the reaction that is important however, as there are many steps required to go from having WVO to utilizing biodiesel in a diesel engine. First, the oil must be filtered and all water content removed. Then, the oil is checked for the FFA content through performing a titration of the oil. The titration results give the total amount of catalyst that is required to fully react with the oil. After conducting a titration experiment with oil, it can then be processed. After processing and settling, the glycerin is drained out and the biodiesel washed. Once clean, it is ready for use.

Before using the fuel, however, there are a lot of tests that must be performed which will check for a complete reaction. The detail instructions for these tests were provided in the step-by-step instructions obtained with the purchase of the *Freedom Fueler Biodiesel Processer*. First, there should be a 15-20% separation of glycerin from the total volume which should settle to the bottom. If the percentage is less than 15-20% of the total volume, not enough catalyst was used and the reaction was not complete. Something else to check for is a third layer between the glycerin and the biodiesel. If this layer occurs, then an emulsion was formed indicating that there were half processed oil molecules or water present in the oil. After draining the glycerin, and before washing the fuel, a separation/miscibility test can be performed to check to see if the biodiesel will separate from the oil. In the test, two cups of the biodiesel are added to clear container with a lid. An equal amount of distilled or de-ionized water is added and the two substances are mixed together for a few seconds. If the mixture turns frothy, it indicates that there is contaminants/soap in the biodiesel. If within thirty to sixty seconds the biodiesel and water separate, the biodiesel passed the miscibility test.

While washing the biodiesel, a good indication that it is clean, is that the wash water has a pH of seven. During each of the washes, as well, the water should come out clearer and less milky (the first few washes will be milky in color). If any of the washes come out with foam or soap, more washing needs to occur. Another visual test of the biodiesel is a color test. The biodiesel should never come out darker than the source of the oil and it should range in color from light yellow to dark amber. The final test that should be performed is the 27/3 test. This test is used to determine if there is any un-reacted oil in the biodiesel. To perform this test, twenty-seven milliliters of methanol and three milliliters of unwashed, room temperature biodiesel are added together in a small container and shaken vigorously. After letting settle for thirty to sixty seconds, look to see if any settling occurs. If nothing settles to the bottom of the container, then the biodiesel passes the test. But, if small amounts of oil settle to the bottom, it indicates that the oil did not fully react and must be reprocessed.

Preparing the Small Test Batches

The knowledge of how to process quality biodiesel was not learned over night. It took a lot of test batches, sources of oil, and time to figure out how to properly make biodiesel. To develop the knowledge, production started with small test batches.

Towards the end of September/beginning of October in 2011, vegetable oil was collected from the ERAU kitchens and brought over to the biodiesel production facility. A small sample of the oil was obtained and taken to the university chemistry lab and used in a titration experiment. This experiment determines how much NaOH/KOH was required to catalyze the oil. ERAU began working with NaOH, and so for all titrations, this compound was used.

In a titration, one milliliter of oil is mixed with ten milliliters of isopropyl alcohol. To that mixture, two drops of phenolphthalein, an acid/base indicator solution, was added and mixed in. Then, drop by drop, a measured amount of 0.10% solution of NaOH/water was added. After each drop, the solution was stirred rigorously. As drops are added in, a color change is watched for. Once the solution stays magenta for ten seconds (indicating a basic solution due to the phenolphthalein drops), no more of the 0.10% solution of NaOH/water needs to be added.

At this point, the total amount of solution that was added in can be calculated. To the total amount of milliliters of the solution, a base number of 5.5 grams is added (if using KOH, the base number is roughly 1.4 times higher, or around 7.7). These 'base' numbers are determined based upon the purity of the catalyst. The number that is obtained is the total amount of grams of catalyst that is required to process one liter of oil. To determine the amount of grams required to process one gallon of oil, that value is multiplied by 3.785 (see Equations 1 and 2 below, obtained from the step-by-step instructions provided with the purchase of the *Freedom Fueler Biodiesel Processer*).

$$3.785\frac{\text{gal}}{\text{L}}\left(5.5\frac{\text{g NaOH}}{\text{L}} + \text{milliliters of solution added}\right) = \text{Total}\frac{\text{g}}{\text{gal}}\text{ of NaOH} \tag{1}$$

$$3.785\frac{\text{gal}}{\text{L}}\left(7.7\frac{\text{g KOH}}{\text{L}} + \text{milliliters of solution added}\right) = \text{Total}\frac{\text{g}}{\text{gal}}\text{ of KOH} \tag{2}$$

Conducting the First Titration

On October 3, 2011, the first set of oil was titrated. Six different trials were performed in order to get a better average of results (see Table 2). From averaging each of the trials together, it was determined that to catalyze the sample of oil, 8.28 grams of NaOH would be required for every liter. Using Equation 1, it came out to 31.25 grams of NaOH per every gallon of oil.

Table 2
Titration results from October 3, 2011.

Trial	0.10% NaOH used (mL)	g/L of NaOH (add base number of 5.5)	Difference from average
1	2.4	7.9	4.74%
2	2.1	7.6	8.60%
3	3.2	8.7	4.91%
4	3	8.5	2.58%
5	3.5	9	8.29%
6	2.5	8	3.48%
Average	2.78	8.28	-------

Conducting the First Test Batch

Two days later, on October 5th, the first test batch was made. In this test batch, one gallon of oil was used, 0.2 gallons of methanol (25.6 ounces), and 31.35 grams of NaOH. Typically, 20% of the total amount of oil that is used is the amount of methanol that is needed for the reaction. The NaOH was first added to the methanol and was mixed for ten minutes which was the amount of time required to fully dissolve the NaOH. Then, the methoxide was added to the gallon of oil and shaken vigorously for sixty seconds. The mixture then settled for a few hours. When returning to the mixture, there was a 20% separation of glycerin indicating that the biodiesel passed the first test. When this test was passed, the biodiesel started to get washed.

The first and second washes produced large amounts of emulsions, and by the third wash, the emulsions decreased (Figure 10). The fourth wash had no emulsions, and by the fifth wash, the water came out clear with a neutral pH indicating that the biodiesel was free of all contaminants. Unfortunately, at this point, there was so much emulsions removed that there was only about a 25% return of biodiesel. From further inspection, it was noticed that the stock of oil had separated; although received from the kitchens, the oil was very contaminated. It was filtered prior to processing, but there were large amounts of water in the stock. It was also determined that a lot of moisture was attracted to the NaOH as it was measured outside during high humidity. Needless to say, the first batch was very informative in that it was quickly learned just how precise everything must be during processing.

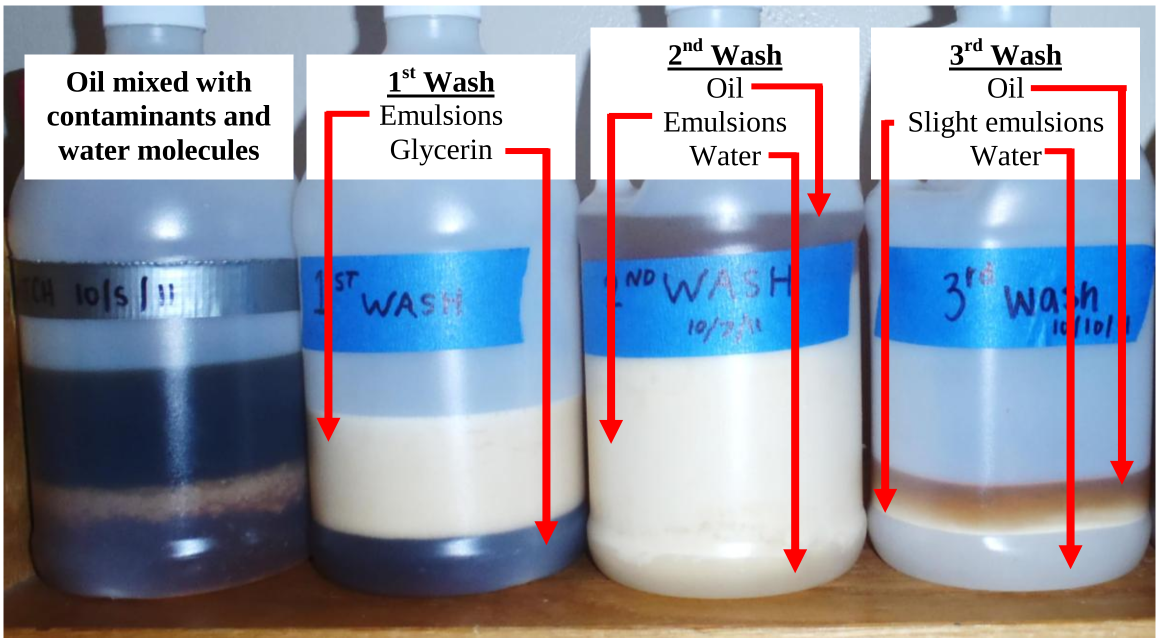

Figure 10. Results from the first test batch. Depicted in this image is the oil source used to process the first test batch as well as the first three test washes. These washes are included to show how emulsions look like when they occur within the biodiesel.

Conducting the Second Test Batch

By the time the second test batch was made on October 14, 2011, there was still a lot of learning that needed to occur. It was decided to not perform a titration on the oil as the FFA content would not change, just the water content. Instead, it was necessary to ensure that the oil, upon leaving the fryer, was poured into an air tight container to prevent any moisture to build-up within the oil (whereas before, no lid was kept on the container, and was stored outside under an awning rooftop leaving the source susceptible to rain). In this batch, like the first, one gallon of oil was used, 0.2 gallons of methanol

(25.6 ounces), and 31.35 grams of NaOH. To prevent any moisture from accumulating in the NaOH, it was measured indoors.

While mixing the NaOH and methanol, the lid of the mixing container came loose and some of the solution spilled out; the amount that spilled was unknown. When mixed with the oil, there was a formation of large clumps within the biodiesel. Although quality biodiesel was not formed, the second test batch did indicate what a bad batch looked like. The large clumps were indicative of too much NaOH within the mixture possibly due to the methanol spilling out and only reacting with a portion of the biodiesel, thus the rest reacted solely with the NaOH. The entire batch was poured into four different glass jars to fully see what occurred; as can be seen in Figure 11, there was some glycerin separation and large amounts of biodiesel created, but large chunks of 'gunk' formed (Figure 12). This 'gunk,' after sitting outdoors in the heat for about a week, eventually had more glycerin settle out leaving what seemed to be large pieces of soap (Figure 13).

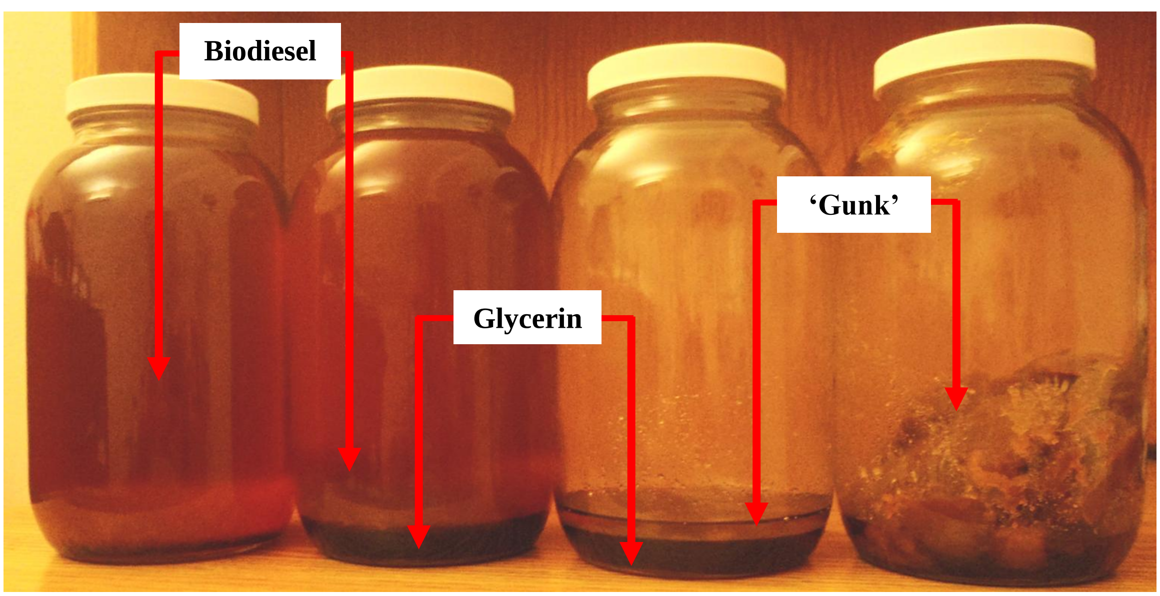

Figure 11. Results from the second test batch. The entire second test batch was poured into four glass jars. Glycerin separated to the bottom of each of the jars but after all of the liquid was poured out (filling the first two jars and part of the third) all that was left was chunks of 'gunk' as seen in the fourth jar on the right.

Figure 12. Chunks of 'gunk' from second test batch. These images are taken of the jar containing all of the chunky material created during the second test batch.

Figure 13. Chunks of 'gunk' after sitting in sun. These images indicate how the chunks of 'gunk' transformed into soap from sitting out in the sun for a week.

Conducting the Second Titration

After the second test batch, it was decided that another titration of the oil must occur. Although methanol did spill out during the procedure, the exact cause of the failed batch was unknown. Therefore, to take out as many errors as possible, it was better to run another titration. On October 19, 2011, six different trials were performed resulting in 9.6 grams of NaOH per liter of oil (see Table 3 for the results and Figure 14 for a depiction of the different trials). Using Equation 1, it came out to 36.34 grams of NaOH per gallon of oil. As compared to the first titration, the amount of catalyst required increased.

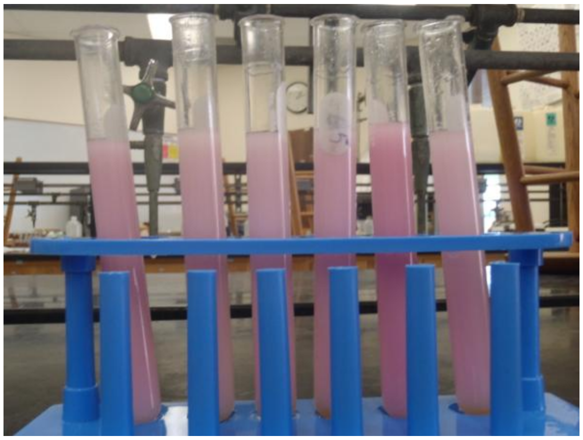

Figure 14. The six trials for the second titration. This image shows each of the six trials performed during the second titration. The magenta color is due to acid/base indicator solution, phenolphthalein, which is used to sense when enough NaOH is added.

Table 3
Titration results from October 19, 2011.

Trial	0.10% NaOH used (mL)	g/L of NaOH (add base number of 5.5)	Difference from average
1	4.5	10	18.78%
2	4.2	9.7	15.76%
3	4.1	9.6	14.73%
4	3.8	9.3	11.56%
5	4.1	9.6	14.73%
6	3.9	9.4	12.63%
Average	4.1	9.6	-------

Conducting the Third Test Batch

After the first and second test batches, a lot of research was conducted and it was found that it was recommended to heat up the oil to 80-130° F. Although the step-by-step instructions provided with the purchase of the processer indicated to heat up the oil for large batches, it did not say to do so for small test batches. However, the more test batches that were done, the more that was learned about how to properly make biodiesel. Hence, from the third test batch and on, the oil was preheated.

The day following the second titration, October 20th, the third test batch was performed. This time, half of a gallon of oil was processed with 0.1 gallons of methanol (12.8 ounces) and 18.2 grams of NaOH. During this trial, the oil was preheated to aid in the reaction. The third test batch was a poor try again; it resulted in a gel-like consistency, similar to the second test batch but more the consistency of jelly.

Figure 15. Results from the third test batch. In the third test batch, the biodiesel did not properly react and formed into a combination of a liquid and a jelly-like substance. The image on the left shows how the mixture looked from the outside of the mixing container. The center image is taken from the top of the mixing container, and the image on the right shows what the mixture looked like when poured into a clear glass jar.

Conducting the Fourth Test Batch

After the third test batch, it was questioned whether the titration results were accurate and if something had gone wrong in the experiment. As the resulting ‘biodiesel’ kept coming out wrong, it was thought that too much catalyst was being used. To test that theory, for the fourth test batch, 90% of the amount of required catalyst per the titration was used which came to 32.71 grams of NaOH per gallon of oil. In this test, conducted on October 31, 2011, one gallon of oil was used, 0.2 gallon of methanol (25.6 ounces), and 32.71 grams of NaOH. Upon pouring in the sodium methoxide with the preheated oil, the mixture gelled up at first. This was later concluded to have happened because the oil was not being mixed at the same time as the sodium methoxide was poured in which, as it was found out, helps.

The batch settled for eight and a half hours and at that time, there was 20% glycerin separation. When performing the miscibility test (Figure 16), the biodiesel was almost perfect; there was a very small layer of what looked to be an emulsion. The biodiesel was also tested with the 27/3 test which had passing results; as can be seen in Figure 17, there was no separation.

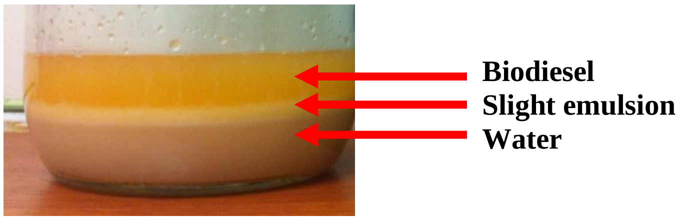

Figure 16. Miscibility test results from the fourth test batch. The miscibility test checks for the presence of soap or other contaminants. As can be seen, there was a small emulsion that formed upon mixing the biodiesel with water.

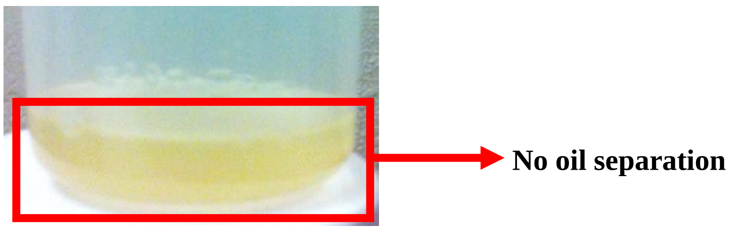

Figure 17. 27/3 Test results from the fourth test batch. The 27/3 test checks for a complete reaction of the oil molecules; if after the test there is any separation, it indicates that there un-reacted oil molecules exist in the biodiesel. This image depicts the results from the fourth test batch, which as it can be seen, indicates no separation.

Then, the washes started (Figure 18). The first wash came out foamy, indicative of too much catalyst. It was not excessively foamy but there were still trace amounts of soap, which was as expected due to the miscibility test results. The second wash came out as a slightly milky color and only with the emulsions that remained from the first wash (as it was difficult to completely drain them out due to the shape of the mixing container). The third wash had no emulsions and came out clearer than the second. By the fifth wash all of the emulsions were removed, the water had a pH of seven, and was perfectly clear. In addition to each of the washes, within a week of starting them, all of the emulsions completely separated with some minor white chunks.

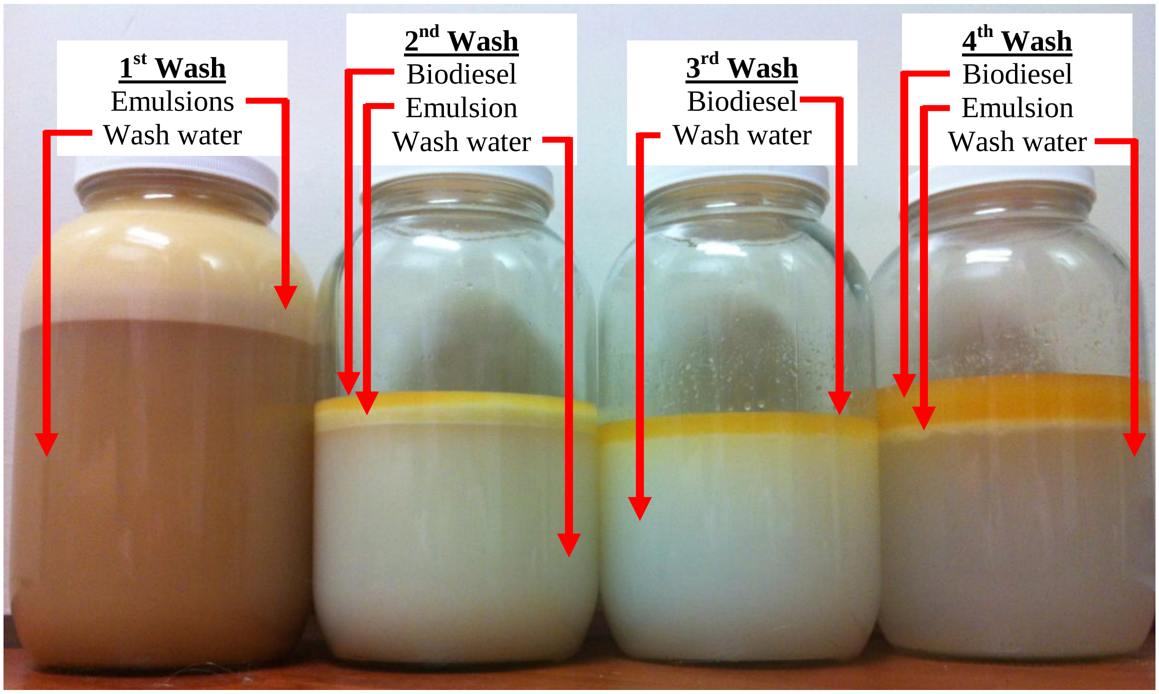

Figure 18. Results from the fourth test batch. In the fourth test batch, emulsions appeared in the first two washes, but by the third and fourth, the emulsions were removed and the wash water came out clearer. By the fifth wash (not pictured), the water was clear and the biodiesel was emulsion free. In the second, third and fourth washes, some biodiesel remained on the top. This is because while draining the wash water from the biodiesel, some of the biodiesel comes out.

Conducting the Fifth Test Batch

As the fourth test batch had better results with using only 90% of the amount of NaOH required per the second titration, it was decided to see if lowering that value even more would eliminate the emulsions that appeared during the fourth test batch. Therefore, for the fifth test batch performed on November 9, 2011, 80% of the required NaOH was used which came to 29.07 grams per gallon of oil. This batch was made from a gallon of oil, and when mixed, it did not gel as did the fourth batch. It passed the glycerin separation test but during the miscibility test, there were more emulsions than in the fourth test batch. Therefore, it was concluded that the NaOH was the not the cause of the emulsions.

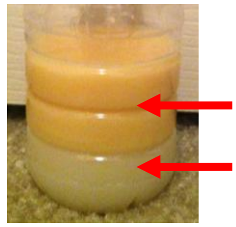

Figure 19. Miscibility test results from the fifth test batch. As indicated in the image above, the fifth test batch failed the miscibility test as the oil did not separate from the water, but instead formed a large emulsion.

Conducting a Ten Sample Test Batch

At this point, how to properly make biodiesel was still unknown; with each batch, more information was learned but the results were undesirable. Therefore, an experiment was performed to see what ‘too much’ and ‘too little catalyst’ did to the oil. On November 21, 2011, a ten sample test batch was performed with varying amounts of NaOH (Table 4). Each of the samples was made with two cups of peanut oil. The results from the last titration, although from a different stock of oil, were used just as a way to vary the amount of NaOH. The amount of NaOH in each sample was varied; in the first sample, 140% of the NaOH titration result was used, and in the last sample, 50% of the NaOH titration result was used.

Table 4

Data from the ten sample experiment with varying amounts of NaOH.

Test Sample	NaOH Amount (Titration %)	Grams of NaOH per gallon	Grams of NaOH per 2 cups	Amount of Oil	Amount of Methanol
1	140%	50.88	6.36	2 cups 473.18 mL	0.4 cups 94.64 mL
2	130%	47.24	5.91		
3	120%	43.61	5.45		
4	110%	39.97	5.00		
5	100%	36.34	4.54		
6	90%	32.71	4.09		
7	80%	29.07	3.63		
8	70%	25.44	3.18		
9	60%	21.80	2.73		
10	50%	18.17	2.27		

When varying the amounts in that manner, and given the small test sizes, it led to NaOH being measured from 6.36 grams down to 2.27 grams. Unfortunately, the available scale did not measure decimal places and so for the in-between values, it was far from exact. It was, however, decided that that was okay because the purpose of the ten samples was to see the differences between 'too much' and 'too little' catalyst. These results would be useful in the future if similar results were seen. From the results (Figure 20), it can be seen that the amount of NaOH was best from between 90% and 60% indicating that the optimum grams of NaOH per gallon fell between thirty and twenty. Also, the more catalyst that was used made the 'biodiesel' turn into a liquid/jelly mixture whereas not using enough catalyst turned the 'biodiesel' solid almost instantly. Knowing what 'too much' and 'too little' look like would help process better biodiesel in the future.

Figure 20. Results from the ten sample experiment. As the amount of catalyst increases, the 'biodiesel' turns into a jelly texture. As the amount of catalyst decreases, the 'biodiesel' turns more solid. The optimum amount of catalyst fell somewhere in between the 90% and 60% of the titration amount.

Troubleshooting the Results

After studying the differences between 'too much' and 'too little' catalyst, it was concluded that even the slightest change in amount could drastically alter the results. Therefore, a more precise scale (measurable up to the hundredth decimal place) was purchased as up until this point, the scale being used came with the purchase of the *Freedom Fueler Biodiesel Processer*. Also, with all of the prior test batches, it was never clear as to what exactly went wrong in each of the batches.

From talking to other home-brewers and biodiesel production companies, different problems that could occur were known but at the time of making the test batch, it was hard to tell what exact problem had occurred. For example, if there was a small amount of water in the oil source, foam would appear on the top surface of the biodiesel, and if there was a large amount of water in the oil source, large chunks of soap would develop. If there was too much methanol, the biodiesel would strongly smell of alcohol, and if there was too little methanol, there would be an incomplete reaction and the biodiesel would fail the 27/3 test. With too much catalyst, foam and soap would form, and with not enough catalyst, there would be an incomplete reaction.

Analyzing the results from the first two test batches, the cause of failure could have been from water in the oil or too must catalyst. Without knowing exactly where the oil came from or if there were any additives used to cook the food, the WVO kept giving poor results. Therefore, it was decided that it was best to start with uncooked vegetable oil, SVO, and make good biodiesel before adding the complications attributed to WVO.

Creamy Liquid Fry Shortening Test Batch

With the overall intention of recycling the WVO from the ERAU kitchens, it was decided that the first SVO test batch should be made using the stock oil that the kitchens used before it was cooked with. Upon meeting the head chef, it was determined that the school uses a brand of creamy liquid fry shortening which is a blend of shortening and soybean oil. It was made from liquid and hydrogenated soybean oil, tertiary butyl hydroquinone (TBHG), and dimethylpolysiloxane. TBHQ is a citric acid and dimethylpolysiloxane a silicone which acts as an anti-foaming agent. From speaking with other home-brewers and biodiesel companies, it was concluded that these additives were of no concern as they had no effect on the conversion process or the fuel quality.

On January 19, 2012, a titration was performed on the creamy liquid fry shortening. In this, seven trials were conducted to get a good average of all of the data. The titration resulted in 5.73 grams of NaOH per liter of oil (21.69 grams of NaOH per gallon). The value obtained was a very good value as each of the trials differed by no more than 1.38% whereas in the other titrations the values differed by up to 8.60% in the first titration (Table 2) and up to 18.78% in the second (Table 3).

Table 5
Titration results using the creamy liquid fry shortening.

Trial	0.10% NaOH used (mL)	g/L of NaOH (add base number of 5.5)	Difference from average
1	0.2	5.7	0.50%
2	0.3	5.8	1.24%
3	0.25	5.75	0.37%
4	0.2	5.7	0.50%
5	0.15	5.65	1.38%
6	0.2	5.7	0.50%
7	0.3	5.8	1.24%
Average	0.23	5.73	-------

Using these results, a test batch was conducted on January 22, 2012 using the creamy liquid fry shortening. The test batch used one liter of oil and so twenty milliliters of methanol and 5.73 grams of NaOH were used; using the new scale, this amount was measured out exactly. The NaOH was mixed with the methanol for about seven minutes until fully dissolved and mixed in with the oil heated up to about 110° F. Because the creamy liquid fry shortening is both shortening and oil, the two substances began to separate upon getting heated up. Once mixed in with the sodium methoxide, however, it was left to settle overnight and was checked on fourteen hours later. When checked on, there was a 20% glycerin separation from the whole volume, but it did not just separate from biodiesel. There was a middle layer in between the two (reference the far left image in Figure 21). Initially, it was thought to be an emulsion, but after the miscibility test, it was realized that no emulsions occurred within the biodiesel nor did they occur when starting to wash the biodiesel (reference the middle and far right images in Figure 21).

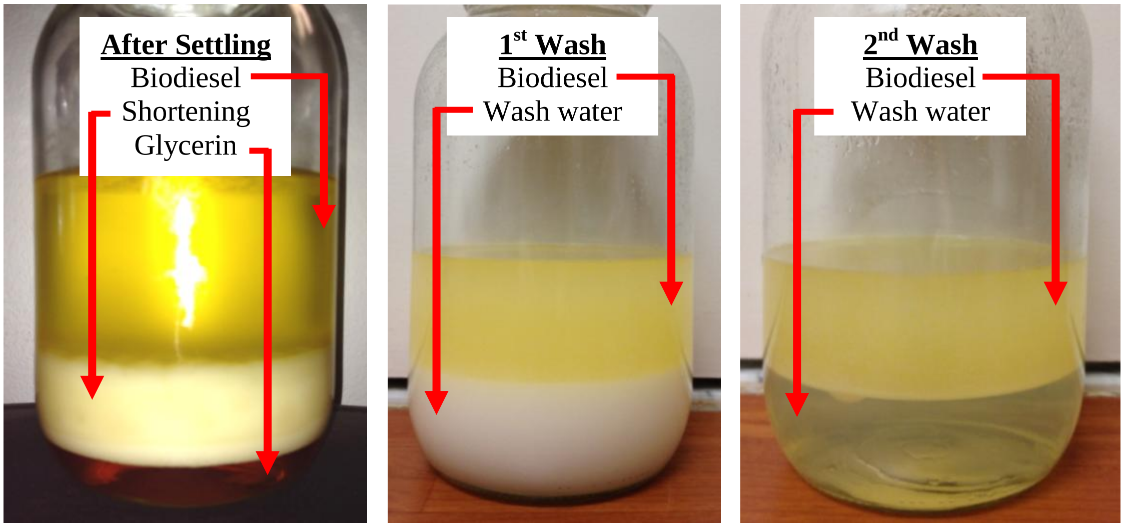

Figure 21. Results from the creamy liquid fry shortening test batch. In the test batch using the creamy liquid fry shortening, a middle layer formed between the biodiesel and glycerin (far left photograph). Upon further inspection, it was realized that the layer, although once thought to be an emulsion, was in fact un-reacted shortening. This was shown when doing the first and second washes as no emulsions were present and the wash water came out exactly as expected.

By the second wash, the water came out clear and with a pH of seven. However, there was still a question as to what the middle layer that occurred in the batch was. Knowing how to try to separate emulsions (heat, time, and even the use of salt), and nothing separating, it verified that the layer was not an emulsion. After conducting more research into biodiesel production and the use of shortening, it became known that shortening cannot and will not process into biodiesel as would liquid oil. Therefore, the middle layer was the unprocessed shortening molecules which made sense because the test batch failed the 27/3 test (not by much, but a few miniscule oil molecules separated).

Processing a Large Batch using Soybean Oil

Knowing that ERAU had intentions of using biodiesel to consume in campus vehicles, it was important to begin making larger batches and utilizing the *Freedom Fueler Biodiesel Processer*. Prior to powering all of the diesel vehicles with the biodiesel, however, it was important to run a test cycle using a single vehicle first to show that it could be consumed without significantly affecting the mileage but while lowering carbon buildup and soot emissions. The test was decided to run using B20 and the vehicle of choice was the John Deere 2653A tractor.

Given that using the SVO provided the best results thus far, it was decided that in conducting the B20 test on tractor that the biodiesel be of high quality. Therefore, for the sake of the test, the first large batch of biodiesel was made using forty gallons of uncooked, SVO, soybean oil. In the meantime of running the test, obtaining better sources of oil and making high quality biodiesel with WVO remained a priority as using WVO would be able to save the university money.

As the kitchen uses a blend of shortening and soybean oil and it created a middle layer in the biodiesel, it was not the best choice of oil stock for the first large batch. But, the soybean oil did provide for good biodiesel and so forty gallons of pure soybean oil was purchased from the local store. This oil was then titrated to check for the FFA content and to ensure that the correct amount of catalyst was used. Between eight trials (see Table 6), it came out to an average of 5.65 grams of NaOH per liter of oil with each of trials differing by less than 1%. When using gallons of oil, it came out to 21.39 grams of NaOH per gallon. Using the titration results, a final test batch was made to double check the amount of NaOH. This test batch proved successful, and ERAU was ready to make the first forty gallons of biodiesel to be consumed on campus.

Table 6
Titration results using the soybean oil.

Trial	0.10% NaOH used (mL)	g/L of NaOH (add base number of 5.5)	Difference from average
1	0.1	5.6	0.89%
2	0.17	5.67	0.35%
3	0.14	5.64	0.18%
4	0.17	5.67	0.35%
5	0.12	5.62	0.53%
6	0.19	5.69	0.71%
7	0.11	5.61	0.71%
8	0.2	5.7	0.88%
Average	0.15	5.65	-------

The first forty gallons were made on February 14, 2012. At 10:30 am, forty gallons of soybean oil were added to the processor and the heating element turned on. By 3:00 pm, the oil was only able to heat up to 90° F. Although it was not quite at the desired temperature, it was decided that the oil was warm enough to process. Then, in the smaller mixing tank, enough NaOH to process forty gallons was added in and eight gallons of methanol was pumped in. The two chemicals were mixed together for about eight minutes which was enough time to dissolve all of the NaOH. This mixture was then pumped into the larger tank full of the oil. This addition caused the oil temperature to drop to 85° F, and so to maintain a warm enough temperature, the heating element remained on until 5:00 pm. The oil and sodium methoxide remained in the mixing state for three hours. After the mixing cycle, a small sample was drained out and used for testing.

In the morning, this sample passed the glycerin separation test as it had roughly 20% separation (Figure 22). Then, the biodiesel was tested using the 27/3 test which it also passed. However, when performing the miscibility test, there was a small amount of emulsions that appeared between the biodiesel and water. But, as the emulsions were very minor, it was decided to move forward with washing the biodiesel as small amounts of emulsions are manageable. Typically, the emulsions are removed and set aside in a settling container. They are left to settle over longer periods of time and should eventually separate, especially with the use of heat.

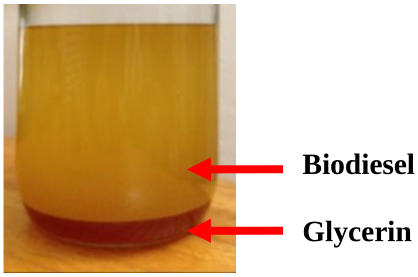

Figure 22. Glycerin separation test for the forty gallon batch. After processing forty gallons of oil, a small sample was drained and used for testing (prior to glycerin separation). This sample was let settle overnight to check for the amount of separation. As can be seen in the image, the biodiesel passed the glycerin separation test (as 15-20% separation is required).

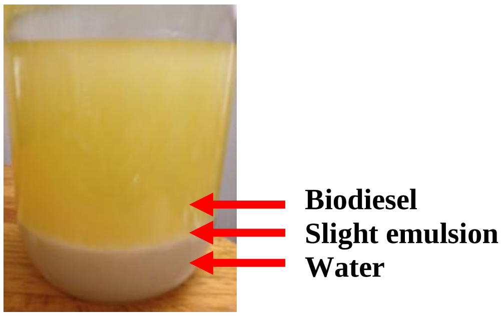

Figure 23. Miscibility test for the forty gallon batch. After processing forty gallons of oil, a small sample was drained and used for testing (prior to glycerin separation). Once settled and the glycerin was removed, the biodiesel underwent the miscibility test in which the biodiesel is mixing in with water and left to separate. In this test, the presence of soap/contaminants is checked for via the appearance of a middle emulsifier layer. As can be seen in the image, the biodiesel produced a slight emulsion. However, it was decided that this small amount was okay because within the larger batch, the emulsions can be removed and more washes completed to remove any excess soap or contaminants.

Once the large batch had settled and the glycerin was removed, the biodiesel was washed twice by adding and mixing eight gallons of water with the biodiesel. Then, after three hours of settling, the water was drained from the bottom. The following day, four more washes were completed. In each wash, minor emulsions were removed, but by the end of the washes, the water had a pH of seven. Once clean, the biodiesel was 'dried.' To dry the fuel, the fuel is ran through a pump and filtered through the processer to rid of any excess water molecules. During the start of the drying cycle, small amounts of foam built up on the top surface of the biodiesel (an expected occurrence as minor water in the biodiesel causes foam). This foam was skimmed off periodically during this cycle to prevent it from becoming mixed back in with the biodiesel. By the end of the drying cycle, roughly four hours, all of the foam had dissipated and the biodiesel, fully reacted, was ready to be used.

Utilizing the Biodiesel in a John Deere 2653A Diesel Tractor

While the purpose of producing biodiesel at ERAU was to eventually power all of the diesel engine vehicles on campus eliminating the use of diesel fuel, a single vehicle was used to test the fuel first. The reasoning behind doing this was to ensure that the vehicle could handle the fuel and perform similarly. The selected vehicle was the John Deere 2653A Tractor. For comparative purposes, the biodiesel blend that was used was B20; given that this blend performed well in the tractor, each of the vehicles would begin using B20. After comparing B20 to diesel fuel, it is expected the future tests be completed using blends of biodiesel (B40, B60, etc.).

Comparison between Diesel Fuel and B20

When comparing diesel fuel to B20, several factors were analyzed. First and foremost was the fuel economy; for biodiesel to be a valid replacement for diesel fuel, it needs to have similar fuel economy. Based on fuel composition, it was known that biodiesel has less energy than diesel fuel, roughly 10%. Therefore, it was expected that the B20 average be about 2% less mile per gallon. Even with this decrease in mileage, the fuel should still be a valid replacement because 2% is small enough of a number.

Another comparative study performed between diesel fuel and B20 is that of engine performance and carbon buildup. To do this, the tractor operators kept notes of how the tractor performed while running on B20; if there were any noticeable differences, it was recorded. As for carbon buildup, the operators also kept note of how much soot was emitted from the tractor while running on B20; if there were any noticeable differences, it was also recorded. In addition to the soot, the carbon buildup on one of the glow plugs within the engine was compared as well as the fuel filter.

To fully compare the two fuels, the engine runtime was closely monitored. Each of the fuels was used within the engine for the same amount of time and when the fuel changed, so did the fuel filter. At the beginning of the diesel cycle, the tractor was at an engine runtime of 4,004 hours. The glow plug of the first cylinder was removed and cleaned. Also, a brand new fuel filter was installed. Then, the tractor was used in regular operations until the end of the cycle at 4,076 hours. At that time, the amount of carbon buildup on the same glow plug was recorded and then cleaned again. The fuel filter was removed and replaced with a new one.

During the total runtime of seventy-two hours, the amount of diesel fuel that was used to power the tractor was recorded. Then, the B20 cycle begin. Again, this cycle ran for the same time as did the diesel cycle and started with a clean glow plug and fuel filter. The results from the glow plug and filter were then compared to results from the diesel cycle to see if there was more, less, or no change in carbon buildup. The total amount of B20 that was used during the cycle was also recorded to as to compare the fuel economy.

Obtaining GPS Data

To determine the mileage obtained using the tractor, more information than just how long the tractor ran and the amount of fuel that was used during that time frame was needed such as a way to model how far, on average, the tractor drove during that time frame. This information was obtained using a global positioning system (GPS) tracker. The data collection device used was an iPhone 4S, with an application called *InstaMapper*. This application transmits the latitude, longitude, speed, altitude, and heading every sixty seconds. The data is sent to an internet browsing website and is available for export to a tab-delimited file.

To ensure that the program worked correctly and would be suitable for the tractor purposes, trail runs were completed. In these runs, a student would walk with the iPhone 4S from their dorm, to class, and back while their progress was monitored online. The program updated the location at regular intervals and had greater than fifty feet of accuracy.

For the tractor purposes, the iPhone 4S was attached to a flat surface on the tractor with clear visibility to the skies. Then, the program was started as the tractor went out for the day to mow at different locations around campus. Data was collected on two separate days to track the tractor at each of the locations that it mows. On the first day (Figure 24), *InstaMapper* showed that the tractor traveled 5.1 miles during a total time of three hours and fifty-two minutes. On the second day (Figure 25), *InstaMapper* showed that the tractor traveled 7.8 miles during a total time of four hours and thirty-seven minutes.

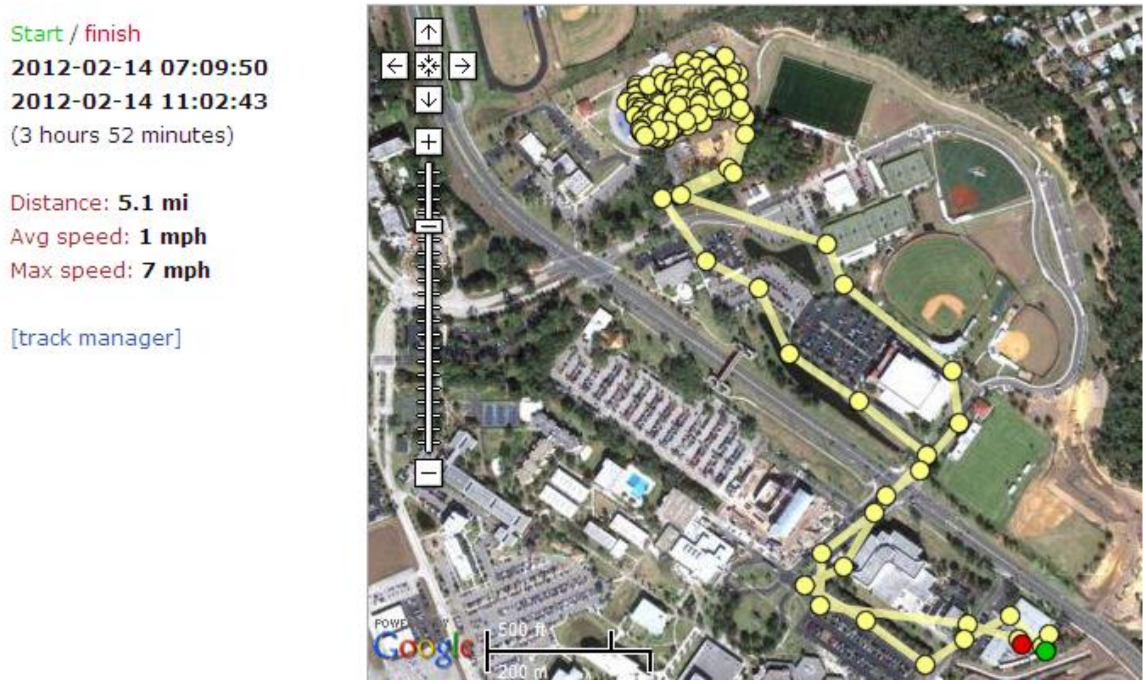

Figure 24. First set of tractor GPS data. To determine the mileage of the tractor, it was necessary to know, on average, how far the tractor drove during a certain amount of time. For this, the GPS was logged.

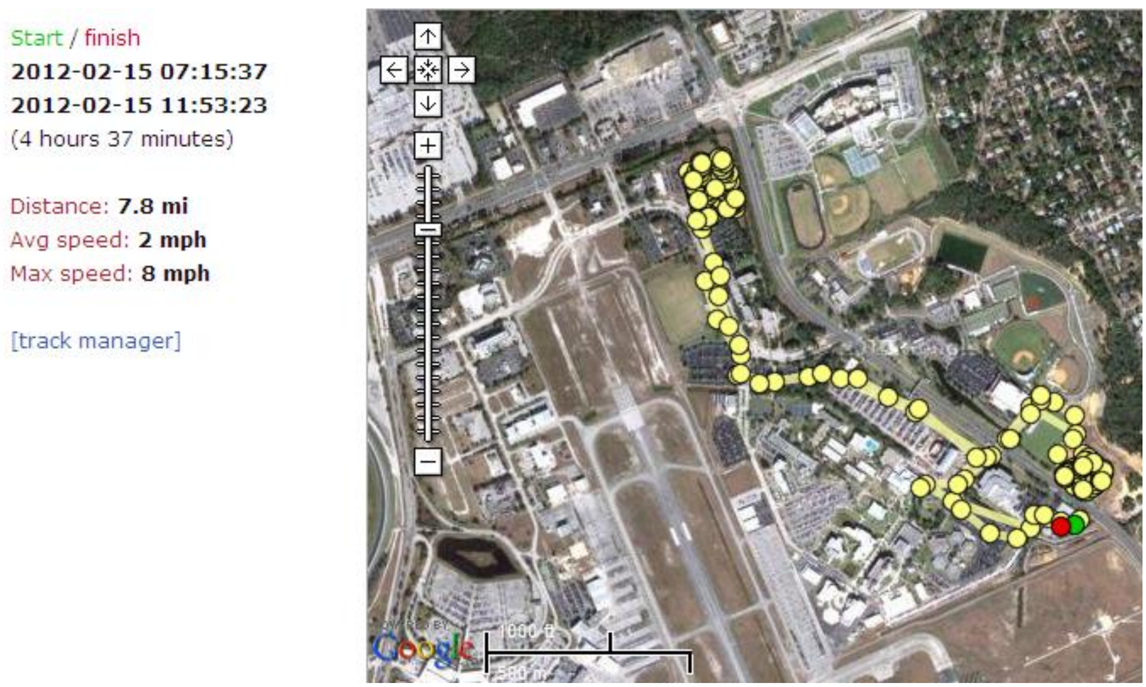

Figure 25. Second set of tractor GPS data. To determine the mileage of the tractor, it was necessary to know, on average, how far the tractor drove during a certain amount of time. For this, the GPS was logged.

Chapter IV
Results

Cost of Production

At ERAU, the cost to produce a single gallon of biodiesel was calculated in order to determine how soon a return on investment (ROI) would be reached from the original grant of $10,000. The goal for the funding was not only to eliminate emissions, but save money for the university by offsetting the cost of diesel fuel. Therefore, biodiesel needed to be cheaper to produce enabling the university to obtain a return.

When making biodiesel, methanol accounts for 20% of the amount of oil that is used. ERAU was able to locate a local company that would sell methanol for $3.50 per gallon with a shipping rate of $30.00. The company would deliver a fifty-five gallon drum and when empty, would pick up the used drum for recycling. With the shipping, the total cost of the methanol comes out to $222.50 (see Table 7). That same company would also sell ERAU fifty pounds of NaOH for $100.00 with a shipping rate of $30.00 coming out to a total of $130.00 (see Table 8).

Table 7
Cost of methanol.

Cost of methanol	$3.50 per gallon
Amount purchased	One drum (fifty-five gallons)
Shipping cost	$30.00
Total cost	$222.50

Table 8
Cost of NaOH.

Cost of NaOH	$100 per container
Amount purchased	One container
Shipping cost	$30.00
Total cost	$130.00

Given that the WVO is to be donated from the ERAU kitchens after having been cooked with, the cost of oil is negligible as it is a recyclable material. However, as the WVO has produced emulsions within the oil, it cannot be assumed that there is a 100% yield of oil used to biodiesel produced (as is the ideal yield). Therefore, for the cost of production calculation, a yielding rate of 75% is assumed.

The *Freedom Fueler Biodiesel Processer* can handle forty gallons of WVO at a single time. When doing so, 20% of that amount (eight gallons) is the amount of methanol that is used. The methanol is purchased in fifty-five gallon quantities and so the purchase of one drum would last for about seven batches (forty gallons) of oil. Based on the results from the first and second titrations, when using WVO, the amount of NaOH needed to react with one gallon of oil was between 31.25 and 36.34 grams. Assuming that, on average, 35 grams of NaOH would be required for each gallon of WVO, it would take about 1,400 grams to react with forty gallons of oil. The NaOH is also purchased in a bulk quantity of 100 pounds (22,679.62 grams) and so the purchase of one container would last for about sixteen forty gallon batches of oil.

To process forty gallons of WVO, eight gallons of methanol and an assumed 1,400 grams of NaOH would be used. The eight gallons of methanol accounts for 14.55% of the total amount purchased, and the 1,400 grams of NaOH accounts for 6.17% of the total amount purchased. Therefore, of the $222.50 spent to purchase the methanol, $32.36 is used, and of the $130.00 spent to purchase the NaOH, $8.02 is used to process forty gallons of oil (see Table 9). Between the methanol and NaOH, the total cost of materials comes out to $40.38. If forty gallons of oil are processed, with an assumed yielding rate of 75%, then thirty gallons of biodiesel would be produced. Based on material cost alone, $40.38 is all that would be spent to produce thirty gallons of biodiesel coming out to roughly $1.35 per gallon (see Table 10).

Table 9

Material cost for a large batch of oil (forty gallons).

Material used	Amount needed to process a large batch	Amount purchased	Cost of purchase	Percentage of the purchased amount used per batch	Cost per batch
WVO	Forty gallons	Not applicable	$0.00	Not applicable	$0.00
Methanol	Eight gallons	Fifty-five gallons	$222.50	14.55%	$32.36
NaOH	1,400 g	100 lb (22,679.62 g)	$130.00	6.17%	$8.02

Note. The amount of NaOH used is an assumed value determined based upon the first and second titration results. It was assumed that 35 grams of NaOH would be used per gallon of oil processed. Also, given that the WVO is to be donated from the ERAU kitchens after having been cooked with, the cost of oil is negligible as it is a recyclable material.

Table 10

Material cost per gallon of biodiesel produced

Oil amount processed for a large batch	Forty gallons
Yielding rate	75%
Amount of biodiesel yielded	Thirty gallons
Material cost for a large batch	$40.48 ($32.36/methanol, $8.02/NaOH)
Cost per gallon of biodiesel	$1.35

Note. The yielding rate of 75% was assumed based upon results obtained using WVO.

John Deere 2653A Tractor Findings

Although *InstaMapper* gave the speed, altitude, and heading of the tractor, this data was not used. The data for total time and distance was also not used. The only values used by the program were latitude, longitude, and the timestamp. This was because using the latitude and longitude only, the distance was able to be calculated using the spherical law of cosines (Equation 3). This provided for a more accurate distance calculation. Also, by using the time stamp, the exact time for the cycle was determined and not a rounded number.

$$d = \cos^{-1}[\sin(A_1)\sin(A_2) + \cos(A_1)\cos(A_2)\cos(B_2 - B_1)] \cdot R \quad (3)$$

Where:

d = Calculated Distance.
A_1 = Initial Latitude Point.
A_2 = Final Latitude Point.
B_1 = Initial Longitude Point.
B_2 = Final Longitude Point.
R = Radius of the Earth (units of the radius will be the same units for distance).

The latitudinal and longitudinal points as well as the timestamps for each day was removed from the provided tab-delimited file and saved into a single Microsoft Excel spreadsheet so as to combine the data from both days into one. Then, using MatLAB, the data points were read in and using the spherical law of cosines, the distance traveled was calculated. Then, using the time stamps, the total time was calculated allowing for the calculation of average speed measure in mph.

For the total amount of time collected, the tractor ran for 8.51083 hours, and traveled 12.9202 miles. During that time, it averaged 1.51808 mph. These values were deemed acceptable as they were very similar to the data give by *InstaMapper*, only slightly more accurate. Between the two days of data logging, the tractor ran for a total of 12.9 miles over a time of 8 hours and 29 minutes (8.48 hours). The total drive cycle for the tractor between both of the days of data logging can be seen in Figure 26. In the figure, there is a changing speed for each time stamp representing the instantaneous speed. There is also a horizontal line running through the entire figure. This line represents the average speed.

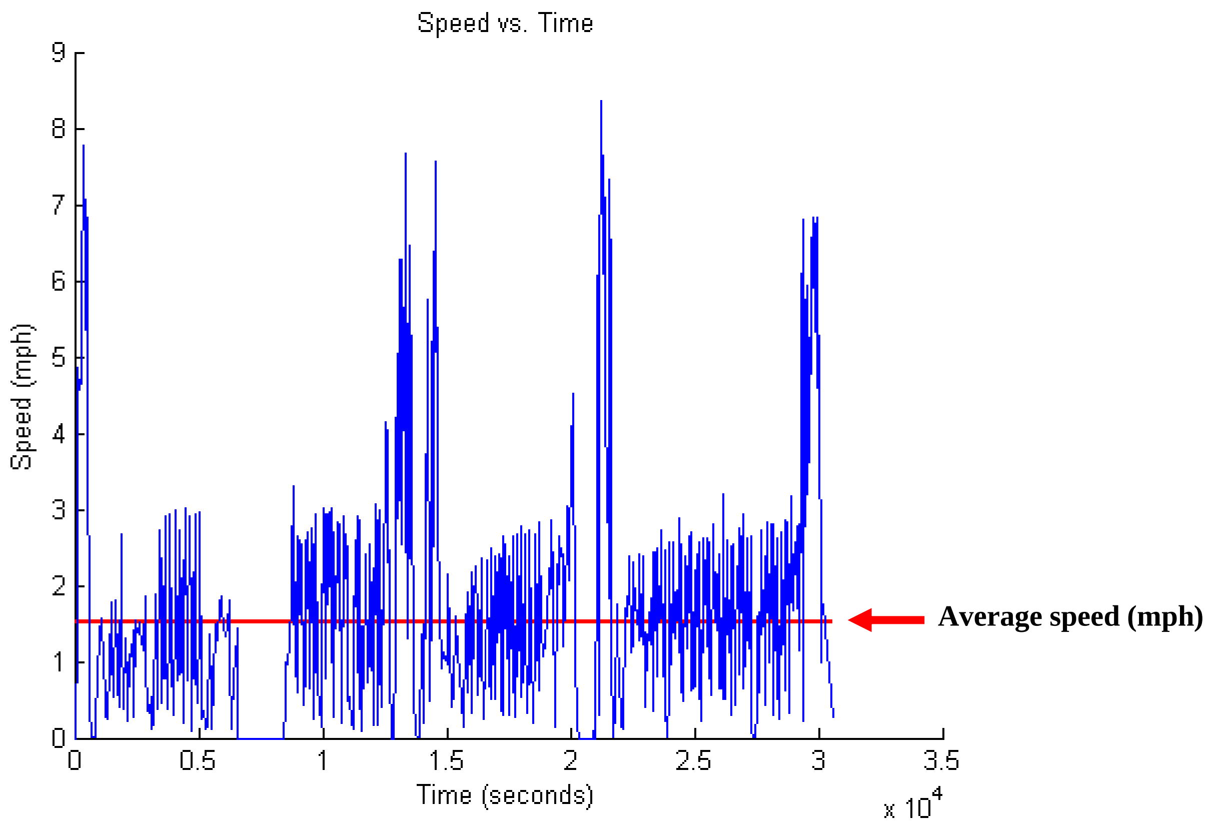

Figure 26. Drive cycle for the John Deere 2653A tractor. This graph depicts the speed of the tractor in mph versus the time in seconds. The horizontal line through the graph represents the average speed which was roughly 1.5 mph.

Diesel Cycle

At the start of the diesel cycle, a brand new fuel filter was inserted in the tractor and the glow plug on the first cylinder was removed and cleaned before being reinstalled. At the end of the cycle, both the glow plug and fuel filter were removed and inspected. This was done to create a baseline to compare the B20 results to.

Fuel Economy

The diesel cycle began on December 9, 2011 and ended on February 21, 2012. During this time, seventy-two hours of runtime were accumulated on the tractor (the engine hours began at 4,004 hours and ended at 4,076 hours). The tractor did not run every day but on the days that it did run, the amount of diesel added to the tractor was recorded (Table 11). Overall, fifty-two gallons of diesel fuel was used. Using the GPS data of the tractor averaging 12.9202 miles over 8.51083 hours, the mileage the tractor achieved using diesel fuel was 2.10196 mpg (see Equation 4).

$$\text{Diesel, fuel economy (mpg)} = \frac{12.9202 \text{ miles}}{8.51083 \text{ hours}} \cdot \frac{72 \text{ hours}}{52 \text{ gallons}} \tag{4}$$

Table 11
Diesel cycle fuel usage data.

Date	Diesel Fuel Use (gallons)	Date	Diesel Fuel Use (gallons)
9-Dec	3	17-Jan	2
13-Dec	2	20-Jan	3
16-Dec	3.5	23-Jan	2.5
19-Dec	2.5	2-Feb	2.5
20-Dec	1.5	6-Feb	3.5
5-Jan	4.5	7-Feb	2.5
6-Jan	4	14-Feb	2.5
11-Jan	2.5	15-Feb	4.5
13-Jan	2.5	21-Feb	3

Carbon Buildup

To compare carbon buildup, the fuel filter and glow plug of the first cylinder were used. At the start of the diesel cycle, a brand new fuel filter was inserted and at the end, it was removed and saved to compare to the removed fuel filter from the B20 cycle. Also at the end of the cycle, the glow plug (which was clean at the start) was removed and cleaned off to observe the amount of carbon residue that accumulated during the test. The results were saved and used as a comparison to the B20 cycle (see Figure 27 for the glow plug comparison).

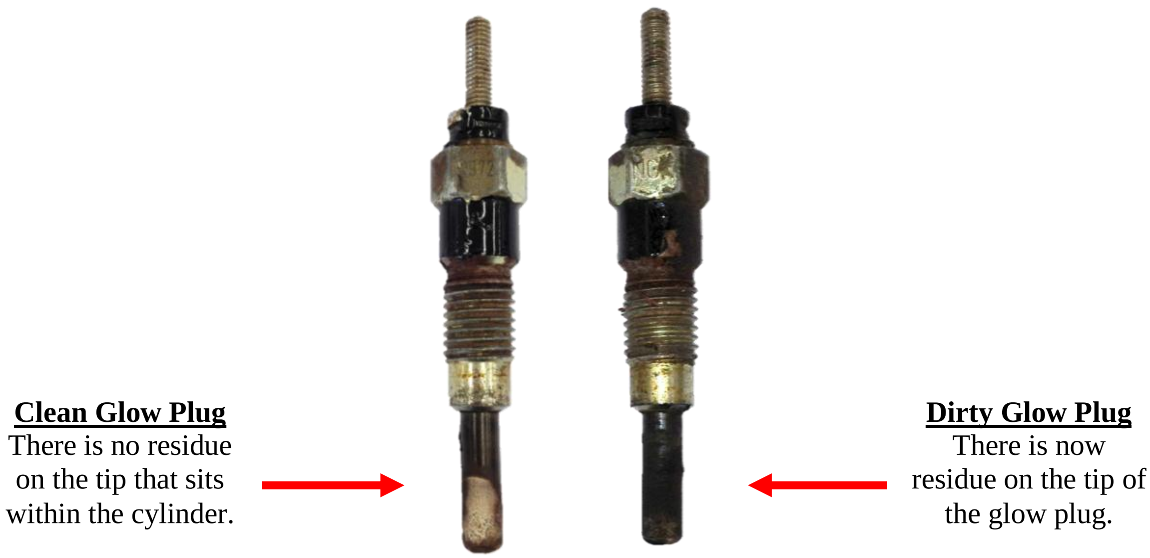

Figure 27. Clean vs. dirty glow plug for the diesel cycle. Depicted above is the glow plug from the first cylinder cleaned off at the start of the diesel cycle (left) and dirty again at the end of it (right).

B20 Cycle

At the start of the B20 cycle, another brand new fuel filter was inserted in the tractor and the glow plug, recently cleaned from the end of the diesel cycle was reinstalled. At the end of the cycle, both the glow plug and fuel filter were removed and inspected. The results were compared to those obtained during the diesel cycle.

Fuel Economy

The B20 cycle began on February 22, 2012 and ended on April 10, 2012. During this time, seventy-three hours of runtime were accumulated on the tractor (the engine hours began at 4,076 hours and ended at 4,149 hours). At the start of this cycle, all of the diesel fuel was emptied from the fuel tank and replaced with a B20 blend of fuel. As the fuel was consumed, B20 was made and stored in a fire safe cabinet until ready for use in the engine. The days in which B20 was made can be seen in Table 12.

Table 12

B20 cycle fuel usage data.

Date	Amount of B20 Made (gallons)
21-Feb	7.5
22-Feb	5
27-Feb	7.5
1-Mar	5
8-Mar	10
15-Mar	7.5
2-Apr	13

Note. The fuel that was made on February 21st was the amount of fuel that initially used to fill the engine. This same amount was remaining at the end of the cycle.

At the end of the cycle, a total of fifty-five and a half gallons of B20 was made. However, not all of this fuel was consumed; there was still a remaining nine gallons of B20 stored in the fire safe cabinet as well as a full tank of fuel (seven and a half gallons). By subtracting the unused fuel from the amount that was made resulted in determining the total amount of fuel that was consumed during the cycle. Overall, thirty-nine gallons of diesel fuel was used. Using the GPS data of the tractor averaging 12.9202 miles over 8.51083 hours, the mileage the tractor achieved using diesel fuel was 2.84155[1] mpg (see Equation 5).

$$\text{B20, fuel economy (mpg)} = \frac{12.9202\text{ miles}}{8.51083\text{ hours}} \cdot \frac{73\text{ hours}}{39\text{ gallons}} \qquad (5)$$

Engine Performance

While the tractor was being powered with B20, the operators kept note of any noticeable differences between how the tractor normally runs to how it was running off of the different fuel. Immediately, the operators began noticing that less soot was being

[1] The fuel economy for the diesel cycle was calculated to be 2.10196 mpg. With the biodiesel having less energy than diesel fuel, it was expected that the fuel economy worsen in the B20 cycle. However, the fuel economy improved by 35% to 2.84155 mpg. Therefore, an error occurred.

emitted from the tractor. However, on March 27, 2012, when the tractor was at 4,128 hours (fifty-two hours into the B20 cycle), the operators noticed that when the tractor ran at full load (mower reels down), the engine began to stall. But, when the load was decreased (mower reels up), the engine would run fine. Upon inspection, it was realized that the pickup screen, a filter that prevents large pieces of dirt from being drawn into the fuel line, had become clogged. Once the screen was cleaned and the source of the clog was removed, the engine performed properly once more.

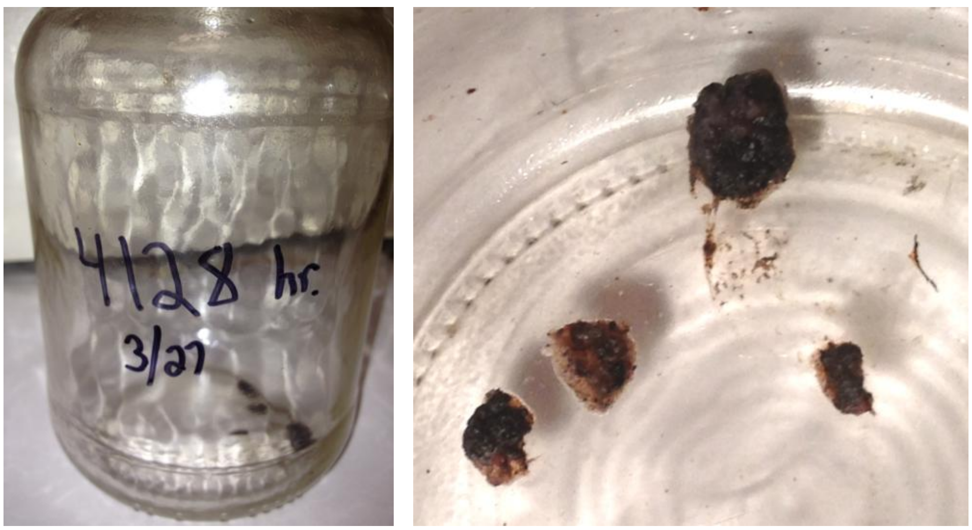

Figure 28. Clogged substance found on the pickup screen. Depicted in the image above is the substance found on the pickup screen which caused a blockage in the engine.

Carbon Buildup

At the end of the B20 cycle, the fuel filter was removed and compared to the removed fuel filter from the diesel fuel cycle (see Figure 29). Also at the completion of the cycle, the glow plug was removed and cleaned off again so as to compare the amount of carbon residue that accumulated to the amount that accumulated during the diesel cycle (see Figure 30 for the glow plug comparison).

Diesel Cycle
Depicted is the fuel filter from the diesel cycle.

B20 Cycle
Depicted is the fuel filter from the B20 cycle.

Figure 29. Fuel filter comparison of the diesel and B20 cycle. Depicted above is the fuel filter from the diesel cycle (left of image) and from the B20 cycle (right of image).

Diesel Cycle
Depicted is the glow plug from the diesel cycle.

B20 Cycle
Depicted is the glow plug from the B20 cycle.

Figure 30. Glow plug comparison of the diesel and B20 cycle. Depicted above is the glow plug from the first cylinder with the amount of carbon residue from the diesel cycle (left) and with the amount of carbon residue from the B20 cycle (right).

It appeared that the B20 cycle had a cleaner/lighter in color fuel filter than the one removed from the diesel cycle. Also, from comparing the amount of residue that accumulated on the glow plugs, it seemed as if less carbon residue had accumulated during the B20 cycle.

Chapter V
Discussion, Conclusions, and Recommendations

Discussions

Facility Implementation Steps

In order to get a properly running biodiesel facility at ERAU, different implementation steps were completed. First, an invested interest was developed around campus which allowed for a grant of $10,000. Then, knowing that there would be money to fund the facility, a suitable location was determined. With that location, different safety protocols were followed. Based on the chemicals that were to be used, methanol and NaOH, the facility had to be prepared for fire and explosion hazards as well as spills. For fires, a suitable fire extinguisher was purchased, and the methanol grounded. As for spills, an appropriately sized containment cell was built (based around the maximum amount of fluid that could spill which was determined from the selected biodiesel processer).

Given that the chemicals would need to be stored, appropriate storage facilities were determined for both the methanol and the NaOH. Also, as both of these chemicals are toxic, each of the personnel who would be working to process the biodiesel was trained on their hazards and on the required PPE.

A source of oil was also found as oil is a necessary ingredient in processing biodiesel. In addition to the source of biodiesel, ways to dispose of produced waste (glycerin, waste water, bad biodiesel batches) was also determined. Then, once the safety (both facility and personal) was taken care of, there was a suitable way to store the chemicals, a source of the oil was found, and a way to dispose of waste was determined, the facility only needed to be prepared for the selected biodiesel processer. For this, a water line, air line, and grounding system was installed, as well as an written set of operation instructions including the MSDS for each of the chemicals, was developed and approved by the ERAU Environmental Health and Safety Director.

Good Practices when Producing Quality Biodiesel

After making a lot of test batches and seeing what both good and bad looks like, it was easier to determine how to make quality biodiesel. In order to do so, several different factors must be taken into consideration such as the oil quality, amount of catalyst required, and the mixing times and temperatures during production.

First and foremost, the oil must be free of water molecules and other substances that could affect the production results. To do this, the oil must first be filtered to remove any large food chunks (if using SVO, these steps are unnecessary as the oil will have no contaminants in it). Once filtered, the oil must be checked for water content; if there is anything more than 5,000 ppm (0.05%), it must be removed. If there is water in the oil source, it will mix with the catalyst and cause soap. The higher the water content, the more soap that is formed. This soap will either turn to large chunks or create emulsions within the batch. Not only does this create unwanted waste, but will require reprocessing of the leftover oil.

To test for water in the oil, a small sample can be collected and heated up. If at around the boiling point, small bubbles appear, there is water in the oil. To get rid of this water, there are three different things that can be done. First, the oil can be heated up for about an hour. Then, once the heat is turned off, the oil will begin to settle out with the water falling to the bottom. Once settled, the water can be removed. With this method, the higher temperature that the oil is heated up, the less time it will take for the water to separate. Another method to remove water would be to heat the oil up to the boiling point of water and allow it to remain heated until all of the bubbling has stopped indicating that the water has evaporated out. When doing this, however, it is best to keep mixing the oil as it will not only help the water evaporate out, but it will also prevent any sources of steam developing within the oil and exploding out causing hot oil to splash out. The final method that can be done is to circulate the oil through a bubble system in which air is circulated through the oil causing the oil to dry.

To ensure that the right amount of catalyst is used, it is important to run several trials during the titration. As the slightest change in catalyst can significantly change the results, it is imperative that the titration be as close to perfect as possible. When doing the titration, care must be taken to make sure to use the same NaOH or KOH that will be used when processing the oil and make sure to follow the directions precisely. Once determining the amount of catalyst required, make sure that the scale used to measure the substance is as precise as possible. For example, if 5.25 grams of NaOH is needed, a scale that only measures to the nearest whole number would not be a suitable scale. Also, when measuring the NaOH, the importance of keeping the substance away from all sources of humidity was learned. NaOH attracts moisture in the air and if it is exposed to humidity, large amounts of moisture will be soaked into the substance. This will not only introduce water into the biodiesel process, but also will affect the amount of NaOH that is measured because the moisture will add to the weight.

For best results, it was found that the oil should be heated to at least 100° F. By heating the oil, it helps with the reaction process and allows for a better mix of the oil with the methoxide; colder oil will not allow for proper mixing. As for the methoxide, ensure that all of the catalyst, whether sodium or potassium hydroxide, is fully dissolved within the methanol prior to mixing with the oil. If there is excess catalyst that is not dissolved, the biodiesel will not be processed properly.

Cost Analysis of Diesel Fuel vs. B20

For biodiesel to be a valid replacement for diesel fuel, it not only needs to lower emissions and perform well in an engine, but it also needs to be cost effective. It is already known that biodiesel lowers harmful emissions such as CO_2, and based on relevant studies, that it is projected to have similar performance characteristics. However, cost of production is a big facet in determining its likelihood of replacing diesel fuel.

As already discussed, in January 2012, diesel fuel cost $3.83 per gallon at the pump and had risen to $4.12 in March (Figure 4 and Figure 5). Of that price, around 67% of the cost came from the purchasing of crude oil. Therefore, it can be assumed that in the early part of the 2012, it cost $2.76 per gallon to purchase crude oil. For ERAU's biodiesel production to be financially advantageous, it would need to cost less than $2.76 per gallon to produce based on material price alone. As long as ERAU uses recycled oil (WVO) from the kitchens and achieves a yielding rate of at least 75%, the material cost per gallon is $1.35 (Table 10). Therefore, at ERAU, it costs less per gallon of biodiesel for material cost than the average cost of crude oil used for each gallon of diesel fuel as of March 2012.

Knowing that ERAU will save money by producing biodiesel versus purchasing diesel fuel, it was important to determine the ROI. The cost of diesel fuel is very variable but based on past data (see Figure 4), the ROI is determined based on an average cost of $4.00 per gallon. To determine the ROI, it was necessary to determine, on average, how much fuel was currently being consumed on a daily basis at ERAU. From September 14 until December 6, 2011, the amount of diesel fuel used by the John Deere 2653A tractor was recorded (Table 13). From tracking the amount of fuel, it was shown that, on average, 2.90 gallons of diesel fuel were consumed on each day that the tractor was in operation.

Table 13
Diesel fuel usage each day for the John Deere 2653A tractor.

Date	Diesel fuel use (gallon)	Date	Diesel fuel use (gallon)
14-Sep	2.75	20-Oct	3.5
15-Sep	4	21-Oct	2
16-Sep	4	24-Oct	4
19-Sep	2.5	25-Oct	3.5
23-Sep	6.5	27-Oct	3
26-Sep	3	1-Nov	2.5
27-Sep	3	2-Nov	3
29-Sep	1	7-Nov	2.5
30-Sep	3	8-Nov	3
3-Oct	2	10-Nov	4
4-Oct	2.75	15-Nov	1
6-Oct	2.5	16-Nov	3.5
11-Oct	4.5	18-Nov	2.5
12-Oct	3.5	21-Nov	2.5
13-Oct	3	28-Nov	2
15-Oct	3	28-Nov	1.5
17-Oct	2	2-Dec	3.5
18-Oct	2.5	5-Dec	3
19-Oct	2.25	6-Dec	2

However, the tractor was not in operation every day. During the time in which data was collected, there was only sixty working days for the university. Therefore, out of the 110.25 total gallons that was consumed, about 1.84 gallons of diesel fuel were consumed on each working day.

As B100 contains about 10% less energy than diesel fuel, there is an expected loss of fuel economy when it is consumed. It can be assumed that if B20 is used there is a 2% loss of fuel economy, if B40 (40% biodiesel, 60% diesel) is used there is a 4% loss of fuel economy, if B60 (60% biodiesel, 40% diesel) is used there is a 6% loss of fuel economy, and if B80 (80% biodiesel, 20% diesel) is used there is an 8% loss of fuel economy. Therefore, if any of these biodiesel blends were to replace diesel fuel, more fuel would be required to power the tractor each day; 1.87 gallons of B20, 1.91 gallons of B40, 1.95 gallons of B60, 1.98 gallons of B80, and 2.02 gallons of B100.

If using B20 to power the tractor, of the 1.87 gallons used each day, 20% would come from biodiesel and 80% from diesel. Therefore, 0.37 gallons of biodiesel would be used and 1.50 gallons of diesel fuel. Since 1.84 gallons of diesel fuel are currently being used each day, there would be an offset of 0.34 gallons of diesel fuel from what would have been used if B20 was not powering the tractor. Using an average of $4.00 per gallon for diesel fuel, this offset accounts for a savings of $1.35 each day. However, the cost of biodiesel needs to be accounted for as it is being consumed in place of diesel fuel. Since 0.37 gallons of biodiesel fuel would be used each day if consuming B20, there would be an incurred cost of $0.50 decreasing the overall savings to $0.85. With wanting to payback the original grant of $10,000, it would take roughly 11,796 days of running a single tractor to reach a return. Assuming a five day work week, it would take 2,360 weeks, or about 45.4 years (see Table 14).

Table 14

ROI based on running a single tractor on B20.

Initial grant	$10,000
Estimated cost/gallon of diesel fuel	$4.00
Calculated cost/gallon of biodiesel	$1.35
Original use of diesel/day (gallons)	1.84
Fuel economy change (loss)	2%
Use of biodiesel blend/day (gallons)	1.87
Use of biodiesel/day (gallons)	0.37
Use of diesel/day (gallons)	1.50
Offset use of diesel/day (gallons)	0.34
Amount saved/day from diesel fuel	$1.35
Amount spent/day from biodiesel	$0.50
Total saved/day	$0.85
Days until a return is reached	11,796
Weeks until a return is reached	2,360
Years until a return is reached	45.4

Note. The estimated cost of diesel fuel was determined based on past data shown in Figure 4. Also, as the work week is five days long, the weeks until a return is reach was based on a five day work week.

Organic substances like biodiesel can eat away at rubber materials. Unfortunately, many of the fuel lines in older engines are made of rubber and so when biodiesel is used to power the vehicle, damage may occur. When using biodiesel at a maximum B20 blend, the fuel lines are not affected. However, in blends of fuel with more than 20% biodiesel, the biodiesel will begin to eat away at the rubber allowing for fuel to leak. In these cases, all of the natural rubber lines should be replaced with synthetic rubber lines to prevent any damage from occurring. Due to this, when using blends higher than B20, there is a cost associated with engine maintenance.

The synthetic rubber material used in the fuel lines is known as viton. This material sells for a little less than $4.50 per foot on average. Given the current sales tax in FL of 6%, the cost of these lines is estimated to be $4.75 per foot. If replacing all of the lines with the John Deere 2653A tractor, roughly twelve feet would need to be purchased giving a total material cost of $57.00. From speaking with the mechanics at the ERAU Grounds Department, it is estimated to take a full work day to replace all of the lines in a single tractor. Estimating the hourly rate at $15.00 per hour with a factor of two built in to account for the employee burden rate, the labor would cost about $240.00. Given the material and labor cost, it is estimated that to replace the rubber lines in the engine with synthetic lines, there will be an incurred cost of $300.00 per tractor.

Following the same steps as with the B20 analysis, only with including the cost to replace all of the rubber lines with synthetic lines, the ROI was determined for higher blends of biodiesel. If using B40, there would be a savings of $1.73 per day allowing ERAU to reach a return within 22.8 years. If using B60, there would be a savings of $2.66 per day allowing ERAU to reach a return within 14.9 years. If using B80, there would be a savings of $3.62 per day allowing ERAU to reach a return within 10.9 years, and if using B100, there would be a savings of $4.63 per day allowing ERAU to reach a return within 8.6 years (see Table 15).

Table 15

ROI based on running a single tractor on different biodiesel blends.

Biodiesel blend	B20	B40	B60	B80	B100
Initial grant	$10,000	$10,000	$10,000	$10,000	$10,000
Incurred cost from line replacement	$0	$300	$300	$300	$300
Estimated cost/gallon of diesel fuel	$4.00	$4.00	$4.00	$4.00	$4.00
Calculated cost/gallon of biodiesel	$1.35	$1.35	$1.35	$1.35	$1.35
Original use of diesel/day (gallons)	1.84	1.84	1.84	1.84	1.84
Fuel economy change (loss)	2%	4%	6%	8%	10%
Use of biodiesel blend/day (gallons)	1.88	1.91	1.95	1.99	2.02
Use of biodiesel/day (gallons)	0.38	0.77	1.17	1.59	2.02
Use of diesel/day (gallons)	1.50	1.15	0.78	0.40	0.00
Offset use of diesel/day (gallons)	0.34	0.69	1.06	1.44	1.84
Amount saved/day from diesel fuel	$1.35	$2.77	$4.24	$5.77	$7.36
Amount spent/day from biodiesel	$0.51	$1.03	$1.58	$2.15	$2.73
Total saved/day	$0.85	$1.73	$2.66	$3.62	$4.63
Days until a return is reached	11,799	5,940	3,873	2,842	2,226
Weeks until a return is reached	2,360	1,188	775	568	445
Years until a return is reached	45.4	22.8	14.9	10.9	8.6

Note. The estimated cost of diesel fuel was determined based on past data shown in Figure 4. Also, as the work week is five days long, the weeks until a return is reach was based on a five day work week.

These returns, although seeming high, are based on the assumption that only one tractor would be running off of biodiesel, the John Deere 2653A tractor. But, if each of the tractors operated by the ERAU Grounds Department were to run off of biodiesel, the savings would multiply significantly lowering the time it would require to reach a return.

The ERAU Grounds Department has a total of six tractors that are powered by a diesel engine. Each of them accumulate similar engine runtimes every day; the operators all leave at the same time in the morning and get back around the same time in the afternoon while rotating the fields which are mowed. Given that, it can be assumed that each of the tractors consume roughly the same amount of diesel fuel every day. With that assumption, all of the tractors together consume an average of 11.04 gallons of diesel fuel on a daily basis.

If using B20 to power the entire fleet of tractors, there is an assumed fuel economy loss of 2%. With that loss, the amount of B20 that is used per day increases to 11.26 gallons. Of the 11.26 gallons of diesel fuel used each day, 20% would come from biodiesel and 80% from diesel. Therefore, 2.25 gallons of biodiesel would be used and 9.01 gallons of diesel fuel. Since 11.04 gallons of diesel fuel are currently being used each day, there would be an offset of 2.03 gallons of diesel fuel from what would have been used if B20 was not powering the tractor. Using an average of $4.00 per gallon for diesel fuel, this offset accounts for a savings of $8.13 each day. However, the cost of biodiesel needs to be accounted for as it is being consumed in place of diesel fuel. Since 2.25 gallons of biodiesel fuel would be used each day if consuming B20, there would be an incurred cost of $3.04 decreasing the overall savings to $5.09. With wanting to payback the original grant of $10,000, it would take roughly 1,967 days of running all of the tractors to reach a return. Assuming a five day work week, it would take 393 weeks, or about 7.6 years (see Table 16).

Table 16

ROI based on running every single tractor on B20.

Initial grant	$10,000
Estimated cost/gallon of diesel fuel	$4.00
Calculated cost/gallon of biodiesel	$1.35
Original use of diesel/day (gallons)	11.04
Fuel economy change (loss)	2%
Use of biodiesel blend/day (gallons)	11.26
Use of biodiesel/day (gallons)	2.25
Use of diesel/day (gallons)	9.01
Offset use of diesel/day (gallons)	2.03
Amount saved/day from diesel fuel	$8.13
Amount spent/day from biodiesel	$3.04
Total saved/day	$5.09
Days until a return is reached	1,967
Weeks until a return is reached	393
Years until a return is reached	7.6

Note. The estimated cost of diesel fuel was determined based on past data shown in Figure 4. Also, as the work week is five days long, the weeks until a return is reach was based on a five day work week.

Following the same steps as with the B20 analysis, only with including the cost to replace all of the rubber lines with synthetic lines in the entire fleet of tractors, the ROI was determined for higher blends of biodiesel. If using B40, there would be a savings of $10.40 per day allowing ERAU to reach a return within 4.4 years. If using B60, there would be a savings of $15.96 per day allowing ERAU to reach a return within 2.8 years. If using B80, there would be a savings of $21.74 per day allowing ERAU to reach a return within 2.1 years, and if using B100, there would be a savings of $27.77 per day allowing ERAU to reach a return within 1.6 years (see Table 17).

Table 17

ROI based on running every single tractor on different biodiesel blends.

Biodiesel blend	B20	B40	B60	B80	B100
Initial grant	$10,000	$10,000	$10,000	$10,000	$10,000
Incurred cost from line replacement	$0	$1,800	$1,800	$1,800	$1,800
Estimated cost/gallon of diesel fuel	$4.00	$4.00	$4.00	$4.00	$4.00
Calculated cost/gallon of biodiesel	$1.35	$1.35	$1.35	$1.35	$1.35
Original use of diesel/day (gallons)	11.04	11.04	11.04	11.04	11.04
Fuel economy change (loss)	2%	4%	6%	8%	10%
Use of biodiesel blend/day (gallons)	11.26	11.48	11.70	11.92	12.14
Use of biodiesel/day (gallons)	2.25	4.59	7.02	9.54	12.14
Use of diesel/day (gallons)	9.01	6.89	4.68	2.38	0.00
Offset use of diesel/day (gallons)	2.03	4.15	6.36	8.66	11.04
Amount saved/day from diesel fuel	$8.13	$16.60	$25.44	$34.62	$44.16
Amount spent/day from biodiesel	$3.04	$6.20	$9.48	$12.88	$16.39
Total saved/day	$5.09	$10.40	$15.96	$21.74	$27.77
Days until a return is reached	1,967	1,134	739	543	425
Weeks until a return is reached	393	227	148	109	85
Years until a return is reached	7.6	4.4	2.8	2.1	1.6

Note. The estimated cost of diesel fuel was determined based on past data shown in Figure 4. Also, as the work week is five days long, the weeks until a return is reach was based on a five day work week.

Engine Analysis of Diesel Fuel vs. B20

To compare the diesel fuel to the B20, both of the fuels were consumed in the same tractor for the same amount of time. At the start of each cycle, a new fuel filter was installed and the glow plug was cleaned. By doing this, the carbon deposits at the end of each cycle were able to be compared. Also, the amount of fuel used during the time frame was monitored to compare the fuel economy.

The diesel cycle began on December 9, 2011 and ended on February 21, 2012. During this time, seventy-two hours of runtime were accumulated on the tractor (the engine hours began at 4,004 hours and ended at 4,076 hours). Overall, fifty-two gallons of diesel fuel was used. Using the GPS data of the tractor averaging 12.9202 miles over

8.51083 hours, the mileage the tractor achieved using diesel fuel was 2.10196 mpg. The B20 cycle began on February 22, 2012 and ended on April 10, 2012. During this time, seventy-three hours of runtime were accumulated on the tractor (the engine hours began at 4,076 hours and ended at 4,149 hours). Overall, thirty-nine gallons of diesel fuel was used. Using the GPS data of the tractor averaging 12.9202 miles over 8.51083 hours, the mileage the tractor achieved using diesel fuel was 2.84155 mpg.

As biodiesel has about 10% less energy than diesel fuel, the mileage was expected to decrease by about 2% during the consumption of B20. However, instead of having a decreased fuel economy, the tractor had an increase of about 35% when running off of B20. These results were not only unexpected but invalid as well.

This invalidity can be attributed to many different factors. For one, the diesel and biodiesel fuel logs were maintained by two different entities. At the conclusion of each day, the operator using the tractor filled up the tank and recorded the total on a log sheet. However, the biodiesel records were maintained by the author and were carefully measured so as to ensure that the blend was correct. Although the operator recorded the total that was added to the tank at the end of the day, the dial on the diesel fuel storage tank could have been misleading and if not set to zero before pumping could have provided invalid measurements. Therefore, if the operator read the dial wrong or the calibration was off, the amount of fuel logged would have been incorrect causing the total amount of fuel for the diesel cycle to be wrong. Other possible causes could have been the off-chance that the operator recorded the fuel on the wrong sheet (as there was a designated sheet for the 2653A model) or that the operator filled up more than one tractor and logged the total used on a single sheet.

In regards to the carbon buildup and engine performance, at the start of the B20 cycle, the operators immediately began to notice that less soot was being emitted from the engine. However, fifty-two hours into the cycle, the pickup screen in the fuel tank had become clogged with a coagulated substance. As for the carbon buildup, by inspection, it was shown that the diesel cycle created more carbon deposits on the tip of the glow plug. The fuel filters for the diesel cycle also appeared dirtier.

These results were expected as biodiesel is a cleaner fuel than diesel. Given that a 20% blend of fuel was used, the carbon buildup was also expected to decrease by at least that amount. As for the clogging on the pickup screen filter, those findings were typical of other research studies as biodiesel is more viscous than diesel fuel and tends to coagulate.

Prior to conducting research, it was assumed that biodiesel lowered emissions. To verify this assumption, the total GHG emissions were calculated. It is estimated that for every gallon of diesel that is burned, 22.4 pounds of carbon is emitted [38]. As seen in Table 1, diesel has about 87% by weight of carbon and biodiesel has about 77% by weight of carbon. Using a ratio of carbon in diesel to carbon in biodiesel, it is estimated that for every gallon of biodiesel that is burned, 19.8 pound of carbon is emitted (see Equation 6).

$$\text{Biodiesel, carbon emission (lb/gal)} = \frac{22.4\ \text{lb}}{\text{gal, diesel}} \cdot \frac{77\%\ \text{in biodiesel}}{87\%\ \text{in diesel}} \tag{6}$$

During the diesel cycle, fifty-two gallons of diesel fuel was consumed. From that amount, it was calculated that 1,164.80 pounds of carbon (0.528 metric tons) were emitted (see Equation 7). During the B20 cycle, thirty-nine gallons of fuel was consumed. Of those thirty-nine gallons, 80% came from diesel and 20% came from biodiesel; a total of 31.2 gallons of diesel was consumed and 7.8 gallons of biodiesel was consumed. From those amounts, it was calculated that 853.52[2] pounds of carbon (0.387 metric tons) were emitted (see Equation 8).

$$\text{Diesel emissions (lb)} = 52 \text{ gal, diesel} \cdot \frac{22.4 \text{ lb}}{\text{gal, diesel}} \tag{7}$$

$$\text{B20 emissions (lb)} = \left[31.2 \text{ gal, diesel} \cdot \frac{22.4 \text{ lb}}{\text{gal, diesel}}\right] + \left[7.8 \text{ gal, biodiesel} \cdot \frac{19.8 \text{ lb}}{\text{gal, biodiesel}}\right] \tag{8}$$

Conclusions

The purpose of this study was to show that biodiesel is a valid alternative to diesel and that it can be produced at a university level safely and effectively.

Proper Production of Biodiesel

It was proposed that biodiesel could be produced properly on a university campus. This was proven true based on the fact that in February 2012, forty gallons of biodiesel were produced, passed the necessary tests, and were consumed in a diesel engine the following week without causing any harmful effects or irreparable damage to the engine. This was after a little less than a year of learning how to make quality biodiesel through determining what went wrong and working through the failed batches.

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[2] Given that it was concluded that the diesel cycle results were invalid, it can be assumed that the carbon emission calculations were invalid as well.

Effective Use of Biodiesel

It was also proposed that biodiesel could be used effectively on a university campus. This was proven true because as of late February 2012, a tractor at ERAU has been powered solely by B20. This tractor, the John Deere 2653A, began running of B20 once a successful forty gallons of biodiesel were produced, and although there was a slight hiccup when the pickup screen was clogged, there have been no other issues. The tractor has been emitting less soot, exhibiting no difference in performance, and as for requiring more maintenance in regards to cleaning filters, there have been no other downfalls as to the use of biodiesel. Although the filters must be cleaned more often, the use of biodiesel has not only helped to lower emissions but also reduced the amount of diesel fuel consumption at ERAU which is why the proposal of being able to effectively produce biodiesel has been proven true.

Safety Management

The proposal that biodiesel could be managed safely at a university level was also proven true. Upon having the biodiesel facility fully functional, it was necessary to ensure that all facets of safety were considered both facility and personnel wise. As for the facility, each of the chemicals has been safety stored and used. Also, in preparation for an accident, there is a fire extinguisher handy, closely located eyewash and body stations, and a way to handle large spills. Each of the personnel who would be using the biodiesel were informed of the potential hazards associated with the chemicals and were trained with what PPE they were required to wear and how to wear it properly.

Cost Savings

In addition to proposing that biodiesel could be produced properly, used effectively, and managed safely (all of which were proven true), it was also proposed that it would all be done while saving the university money. Based on the calculations showing that, in regards to material cost only, biodiesel costs less ($1.35) than diesel fuel ($2.67), it is shown that the university can save money. The amount saved, however, depends on the blend of biodiesel that is used, and how many tractors are using the fuel. It was determined that if a single tractor uses the B20, there would be a ROI within forty-five years, but if using B100, there would be a ROI within nine years. It was determined that if all of the tractors use B20, there would be a ROI within 7.6 years, but if using B100, there would be a ROI within 1.6 years. No matter the ROI, though, because regardless, the university is capable of saving money by producing biodiesel as it only needs to purchase two chemicals whose materials cost less than the cost of crude oil from which diesel fuel is refined.

B20 Consumption

It was also proposed that B20 can be consumed in a John Deere 2653A diesel tractor without significantly affecting the fuel economy (no more than a 2% reduction in mileage) but while lowering carbon buildup and soot emissions.

Fuel Economy

As for the fuel economy not significantly changing (no more than a 2% reduction in mileage), the proposal was proven inconclusive because the findings showed that B20 exhibited an increased fuel economy of about 35%. This was concluded to be the result of the improper logging and measurement of the amount of diesel fuel that was consumed during the diesel cycle. Due to those issues, the total diesel fuel value obtained was wrong causing the mileage calculated to be incorrect.

Carbon Buildup

As for having a lower amount of carbon buildup, the proposal was proven true. This was because during the B20 cycle, less soot was observed being emitted from the engine, the fuel filter was cleaner, and glow plug had less of an accumulation of carbon as compared to the diesel cycle.

Recommendations

Based upon the steps that ERAU took to get a properly running biodiesel facility in place, there are different approaches that would have been useful in making the process more efficient. First and foremost, more research could have been done prior to purchasing a biodiesel processer in regards to keeping the facility outdoors. As the location was not really negotiable, it would have been a better idea to purchase a processor that had less metal parts and/or parts that were capable of rust. Being outdoors for over a year, the current processer has accumulated large amounts of rust on the metal components and it requires a lot of regular maintenance to keep the processer clean and free of contaminants. It would also have been useful to wait to purchase the processer until it was ready for use. As it took a lot of time to learn how to properly make biodiesel, the processer was sitting unused for over a year.

To produce quality biodiesel, it is recommended to be patient with the process. It takes time guaranteeing that the titration is acceptable and for each of the mixing cycles to process. Time is never wasted when producing biodiesel but if done too hastily, a lot of chemicals can be wasted due to a failed batch. As long as proper notes are taken and each of the steps recorded, if anything were to have gone wrong, it will be easier to troubleshoot the results. Also, more test batches should be produced using WVO.

As NaOH tends to produce solid glycerin and KOH liquid glycerin, it is recommended that ERAU begin using KOH. Although it is a little pricier, it will help when it comes to using glycerin for a composting agent. As more research was conducted based on methods of different home-brewers and biodiesel production companies, it was found that KOH is an easier substance to work with and tends to produce higher quality biodiesel. Also currently, more glycerin is being produced than is being recycled in the composter. Therefore, it is recommended to find alternative uses for this waste product.

As for future testing, it is recommended that higher blends of biodiesel are compared to diesel fuel as was B20 in this experiment. It is important to see the differences between each of the blends of fuel before powering all of the ERAU diesel vehicles with the biodiesel. By doing this, an optimum blend can be determined based on fuel economy and performance. Before doing this, however, it is recommended to redo the diesel cycle test; in doing so, the amount of fuel should be just as carefully monitored as was the amount of B20 produced. In addition to this, more research should be conducted on the effects of using an organic based fuel such as biodiesel in vehicles that have rubber lines as it has been shown in other studies that blends of biodiesel higher than 20% can begin to eat away at the rubber causing leaks. If this is proven to be true, it is also recommended that all of the rubber lines be replaced with a synthetic material.

Future Work

Since the creamy liquid fry shortening did not produce the desired results, it is necessary to begin finding other sources of oil. To do this, one can either try to convince the ERAU kitchen staff to purchase other blends of oil or must begin to look off-campus for a different oil stock. Before defining what exactly should be done though, it was necessary to first find out why the creamy liquid fry shortening is used in the first place.

After speaking with the ERAU kitchen staff, it was determined why they use the creamy liquid fry shortening blend of oil. The hydrogenated oil within this blend helps to increase the product shelf life. When cooking with this oil, it does not burn as fast as other types of vegetable oils and less is soaked into the food. By not burning as fast or soaking into the food as easily, not only is a lesser amount used allowing for a savings of money, but the food is slightly healthier. The kitchens also have a contract with a food distributing company in which they are required to use that specific product. For all of these reasons, this oil is used all but one of the dining establishments on campus.

In that one other dining establishment, ERAU uses peanut oil. Given that there is no shortening in peanut oil, it can be processed with no issues as long as no water exists in the oil and the correct amount of catalyst is used; for example, this type of oil was used during the ten sample test batch. The issue with peanut oil, however, is that it is a "summer fuel"; once processed into biodiesel, it solidifies at much higher temperatures than biodiesel processed from most other oils. Therefore, when it gets cold outside, this fuel would need to be preheated prior to use.

Although it may seem to be difficult or near impossible to convince the ERAU kitchen staff to change from using the creamy liquid fry shortening to a different oil, it should still be attempted. Before doing so, however, one should perform an analysis of all different kinds of oil and determine if any can compare to the benefits associated with the shortening blend (increased shelf life, healthier, less consumption, etc.) If one does, this option should be presented to the kitchen staff; by doing this, they could hopefully adjust their current contract with their food distributor and start using oil that could easily be processed into biodiesel. If this proves unsuccessful, it will become necessary to look off-campus for other oil products or to determine a way in which biodiesel could be preheated prior to being used in an engine. By determining a method of pre-heating the biodiesel, the peanut oil on campus could be used.

In addition to finding other sources of oil, one must also begin running more test batches off of a WVO. Although a successful batch of biodiesel was made during the research conducted, it was processed with oil that had not yet been cooked with. Therefore, work must resume with where the test batches had been left off using only WVO. Once a valid source of oil is determined, small test batches must continually be made until they are proven successful. Although many processing techniques and applications were learned, there is a lot more than can be found out to help improve upon the production process.

As it is recommended to redo the diesel cycle test to reanalyze the differences between diesel fuel and biodiesel, it is important to ensure that no error occurs. The original diesel cycle test occurred during the winter months in FL and the B20 cycle test occurred during the spring months in FL. Not only did the climate change drastically, but it can also be assumed that the grass grew at different rates; both of these differences could have affected the results of the two tests. When re-conducting the diesel cycle test, the time of year should be considered. By conducting the test during a time in which the climate is similar to the B20 test, many of the unknown variables affecting the results can be removed such as temperature and grass growing rates. Before conducting the test, however, all possible sources of error should be determined and analyzed. The experiment should be designed around preventing any of those errors from occurring. For example, to ensure that the fuel consumption rate is correctly determined, the amount used each day must be measured to a more exact number than was done originally.

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