Experiment Design for an Undergraduate Energy Laboratory Course

A Major Qualifying Project
Submitted to the Faculty
Of the
WORCESTER POLYTECHNIC INSTITUTE
In partial fulfillment of the requirements for the
Degree of Bachelor of Science
by

Steven Cortesa
Adam Morin
Jack Tyson

Date: April 29th, 2014

Approved:

____
Prof. Isa Bar-On, Major Advisor

Contents

Table of Figures

Abstract

Worcester Polytechnic Institute currently lacks an undergraduate course on energy conversion methods and technologies. A hands-on laboratory course focusing on energy conversion technologies would fill this gap while also fulfilling many key components of the WPI undergraduate experience. This Major Qualifying Project proposes laboratory experiments on the topics of anaerobic digestion, photovoltaic energy, bioethanol production, and fuel evaluation. As part of an undergraduate course, these experiments will give WPI students a broad understanding of energy conversion, energy density, and alternative energy resources.

Introduction

As commonly used fossil fuels are rapidly depleted, alternative energy has become an important political topic. Concurrently, leading technical universities have begun implementing courses on this subject, with support from the Department of Energy's effort; *Energy 101*. In order to remain at the forefront of technical universities and provide appropriate educational opportunities to its students, Worcester Polytechnic Institute must develop a hands-on course on alternative energy technologies. This laboratory course would benefit both WPI and its students by fulfilling the educational needs of undergraduates to have a practical component in their curriculum.

This Major Qualifying Project will develop experiments to be performed in an upperclassmen laboratory-based class for Worcester Polytechnic Institute. The experiments will teach engineering principles that pertain to energy conversion. Specifically, photovoltaic energy, anaerobic digestion, bioethanol production, and fuel evaluation were selected as laboratory topics, based on criteria necessary for a successful college laboratory.

Background

Energy Laboratory Course Structure

The laboratory experiments described in this Major Qualifying Project are intended to be included as part of a course curriculum for a 3000- or 4000- level Engineering Science course at Worcester Polytechnic Institute. The topics of energy conversion covered in these experiments are multidisciplinary and may be of interest to a students in any program offered at WPI.

The structure for this course would imitate the structure of other WPI laboratory-based courses with accompanying lecture periods. Lecture periods would cover the background of one or more energy technology topics, and students would apply the knowledge gained during subsequent laboratory periods in order to understand the experiments being performed and expand their familiarity with the topic further.

There are additional project groups working on the development of this laboratory course this year. Brandon Shaw and Austin Waid-Jones completed their Interactive Qualifying Project on the pedagogy of the course, and Marshall Bernklow and Ian Corcoran contributed additional laboratory experiment procedures in their MQPs. These projects are intended to coordinate toward the development of a proposal for a complete laboratory course curriculum.

Laboratory courses are integral to the undergraduate engineering education at WPI. Group work in a laboratory setting prepares students for a professional work environment through problem-based learning (Carnegie Mellon). The laboratory experiments described in this report incorporate open-ended problems to allow students to employ their own engineering skills and draw conclusions.

Engineering Principles

There are many criteria that affect the experiment design for engineering education. ABET upholds 11 general criteria for engineering programs (Felder, Brent). Laboratory classes fulfill these criteria, which include; knowledge of math and science, designing and conducting experiments, designing systems to meet desired needs, functioning on multidisciplinary teams, problem solving, practice in technical work, ethical responsibility, communication, global impact of engineering decisions, knowledge of contemporary issues, and lifelong learning.

The topic of renewable energy is of particular interest in the world today and has many qualities that make it more pertinent to these criteria. The laboratory experiments cover a range of engineering disciplines including electrical engineering, biology/chemical engineering, and mechanical design. The experiments are designed to have open-ended problems that require more involved problem solving and student-driven design of the experiment itself. Analysis of the results will require understanding of the engineering equations and principles that govern the processes occurring in the experiments.

Perhaps most importantly the experiments will all yield results of energy density or energy potential that are comparable to each other. These results will reflect real world engineering decisions made in the field of energy generation. Policies are being made in the

United States and across the globe to support renewable energy; because we as a society have a responsibility to reduce our environmental impact.

Laboratory Safety

Safety is paramount in university laboratory experiments. These experiments use a number of hazardous materials and processes, including but not limited to combustion, gas emissions, and pathogens. Students should be aware of all of WPIs safety policies, which can be accessed on the Office of Environmental and Occupational Safety website. The policies include use of materials safety data sheets (MSDS), proper use of lab equipment, exposure risks, waste disposal guidelines, and emergency response procedures. Safety guidelines specific to each experiment are included in this paper's methodology section.

Fuel Evaluation

The goals of the fuel evaluation laboratory are:

1) To determine the energy density and emissions of traditional fuels such as gasoline, diesel, coal, and wood, as well as alternative fuels such as methane, natural gas, bioethanol, and biodiesel
2) To gain experience with the use of a cone calorimeter for the measurement of energy density and a number of emissions characteristics
3) To evaluate tested fuels based on the data produced by the cone calorimeter

The premise behind the fuel evaluation experiment is to give students first-hand knowledge of the relative value of fossil fuels versus alternative fuel sources. The term "clean energy" has been thrown around so often that it is now difficult for laymen to determine what exactly "clean" means. Is clean energy "zero-emissions" or is clean energy "cleaner than coal" energy? By performing a hands-on experiment involving several distinctively different commonly used fuels and a cone calorimeter, students will be able to draw their own conclusions about which fuel technologies can be considered most "clean."

Cone calorimeters are commonly used for evaluating the incineration of materials. The material being tested could range from a sample of fuel, the focus of this experiment, to a fully furnished mockup room used to evaluate furniture materials for fire resistance. Cone calorimeter operation is a straightforward process. Before each test session, the calorimeter must be calibrated by running it for 1-2 minutes without a test material in order to establish temperature, pressure, and air quality of the laboratory space. Next, a material sample is weighed and loaded into the calorimeter, and the operator begins data collection. The sample is then ignited by an external flame, typically a blow torch, and the operator indicates the time of ignition on the data collection program. Once the material is completely incinerated and the flame is extinguished, the program is stopped by the operator, and an excel data sheet is produced automatically. Information including mass loss rate, heat release rate, CO and CO_2 emissions, and duration of burn are automatically recorded and shown in graphical form.

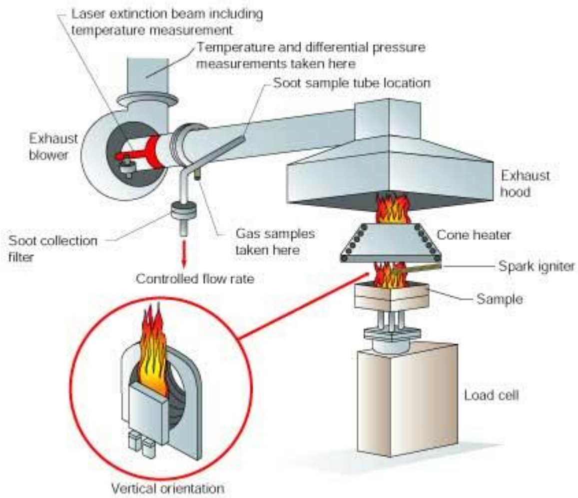

Figure 1 - Cone Calorimeter

Anaerobic Digestion

Anaerobic digestion is a way to produce natural gas (Methane) from organic matter. Anaerobic digesters can use a variety of matter; but which is best? This is the question that students would try to answer in the anaerobic digestion lab experiment. The goal of the experiment is to determine and compare the efficiencies of different organic materials as food for an anaerobic digester. Student groups would each choose a different form of organic waste or food, and then use a miniature anaerobic digester to produce methane, which would be collected and measured.

Anaerobic digestion is a bacterial process that produces methane, a.k.a. natural gas, which can be used to produce heat, or used by a natural gas power plant. The process occurs in two stages, acidogenic and methanogenic (Dublein, Steinhauser). Acidogenic bacteria consume sugars and amino acids and convert them into a number of organic acids, which ends with acetic acid. The acetic acid and other present byproducts (ammonia, CO_2, etc.) are consumed by the methanogenic bacteria and they produce methane and carbon dioxide. Before the experiment a pre-lab teaches students this process. Other topics for the pre-lab will include existing commercial-grade anaerobic digesters i.e. “cow power”.

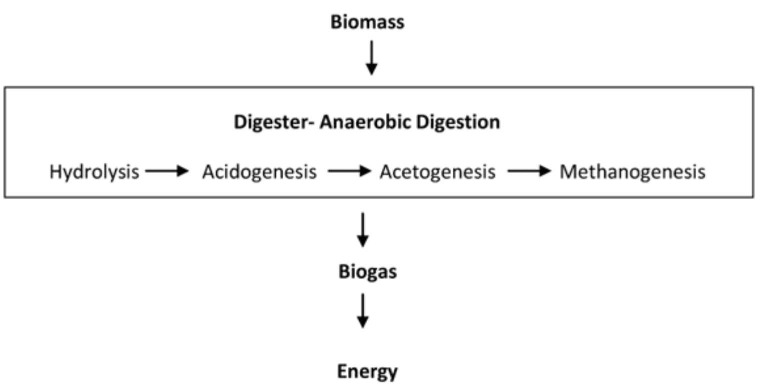

Figure 2 - Anaerobic Digestion Flow Diagram

The anaerobic digester experiment takes 4-6 weeks, to allow the bacteria to consume as much of the food as possible, and produce the most methane. It requires use of a fume hood during set up and again when the methane is released. It also requires continuous proximity to a sink or drain for the duration of the experiment. The equipment consists of one ~5gal container, one ~2gal container, two hoses/tubes, a sampling septum, and two sealed stoppers for the containers. The first container contains the food and digester seed, which needs to be provided by a nearby, running anaerobic digester. That container is sealed except for the hose/tube that is connected to the second sealed container, which is initially filled with a measured amount of water. The second hose is sealed from the gas chamber by water displacement. As the second chamber fills with gas, water is displaced from the container into the sink/drain.

The volume of gas produced is determined by the volume of water displaced during production, by measuring the volume of water before and after. The concentration of methane is measured by a gas sampling kit through the septum. These are used to calculate the amount of methane produced. The energy in the methane produced is compared to the energy cost of the production of the food to learn the efficiency, and compared to the mass of fuel to learn the energy density.

Bioethanol Production

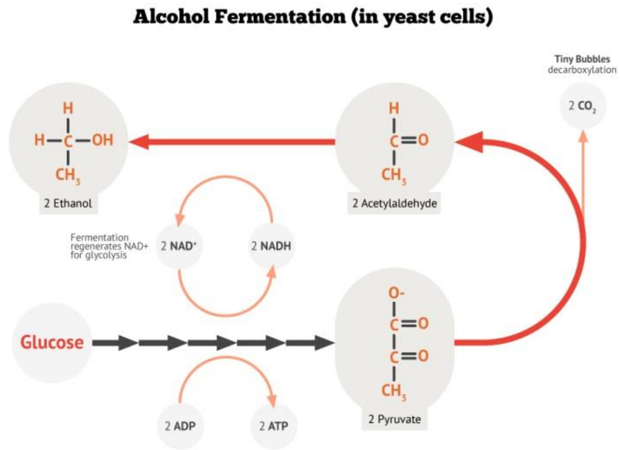

Figure 3 - Alcohol Fermentation

The Bioethanol Production Lab was designed as a small-scale representation of the bioethanol production process. Biothanol can be produced from different natural feedstocks, such as corn or sugarcane. Today ethanol is mixed with gasoline to create E85, a mix of 85% ethanol and 15% gasoline. The ethanol used in this mixture is produced in three steps: fermentation, distillation, and dehydration. For experimental purposes however, we will only be focusing on the first two steps. During fermentation yeast reacts with the sugars present in the particular feedstock (corn, sweet potato, and straw). This reaction leads to the generation of carbon dioxide gas in the form of small bubbles in the reactor vessel. The reaction between the yeast and sugar can be seen in Figure 3 (above). In this lab students will be testing various feedstocks for fermentation as well as changing the acidity of the fermentation solution. Students will measure the amount of CO_2 produced during fermentation to see if acidity and feedstock selection has any effect on CO_2 production. In order to measure the amount of carbon dioxide produced during fermentation students will assemble and use the water displacement method (Figure 4).

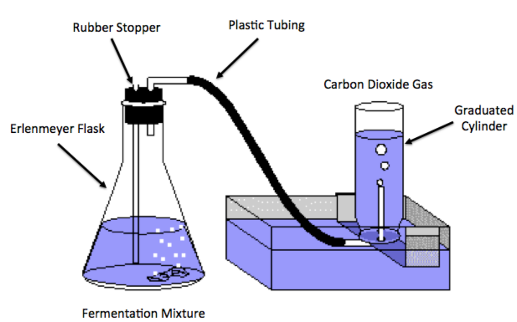

Figure 4 - Alcohol Fermentation

After fermentation has taken place the students must distill the fermented mixture using the distillation equipment provided in the lab. Students will be measuring the temperature at which ethanol vaporizes as well as the amount and concentration of the ethanol produced. Before any distillation can take place the equipment must first be assembled to resemble Figure 5. When distilling the ethanol students must place extreme caution in the handling of the ethanol. As the distillation process progresses students will observe that the temperature of the vaporized ethanol is lower than 100 degrees centigrade. The students should observe the temperature at which vapor begins to appear in the distiller to be about 78 degrees centigrade. Students should recognize the low vaporization temperature and draw some conclusions as to why it is lower than 100 degrees and why it is important to measure this value.

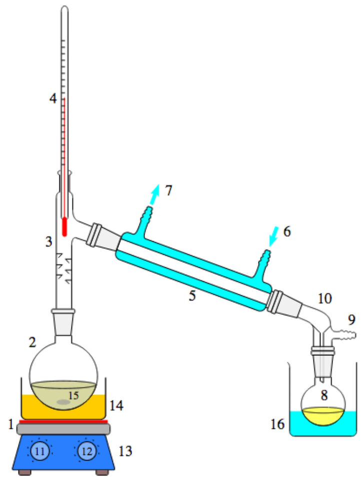

Figure 5 - Distillation

When the distillation process is complete the students will compare the concentration and energy density of the bioethanol they produced to lab grade ethanol. To do this, students will be using the cone calorimeter they used in the introductory Fossil Fuels Lab.

This lab was created to teach students not only about other sources of energy besides conventional oil and gasoline but the processes necessary for bioethanol production. Although this lab represents these processes on a small scale it still teaches the concepts behind fermentation, distillation, and energy density. The lab will also teach students about the importance of following lab procedures and general lab safety.

Solar Cell Effectiveness

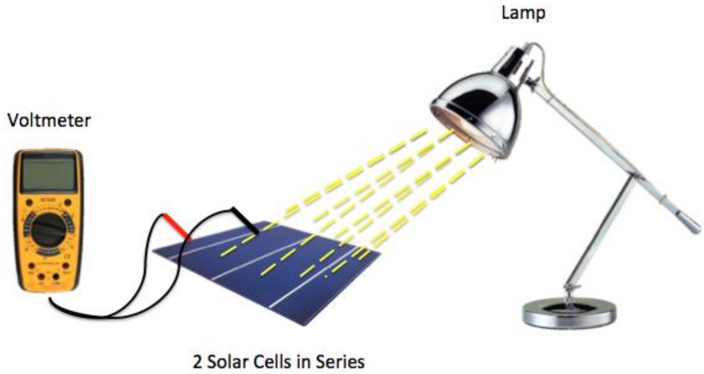

Figure 6 - Solar Cell Effectiveness Lab Setup

The Solar Cell Effectiveness Lab is designed to explore variables that affect the conversion of light into electricity in a photovoltaic cell. Before conducting the experiment some prior knowledge about photovoltaic cells and how they operate must be known. For this students will be required to read two short articles on photovoltaic cells and answer several pre lab questions based on the reading. An example of a pre lab question topic would be which material gives off electrons when exposed to ultraviolet radiation. These questions will ensure that the student has an understanding of the basic principles behind this lab and ensure that they completed the reading.

In order to teach students about what environmental factors affect the power output of a solar cell the students will be conducting various small-scale experiments. These small-scale experiments will involve shading, angle of incidence, light wavelength, and light intensity. In order to measure the effectiveness or efficiency of the solar cells students will be required to measure both the current and voltage of the cells after each variable is changed using a voltmeter. With both the voltage and amperage readings students can generate a power curve for the solar cell. In order to conduct the experiments students will have to construct the basic lab setup pictured in Figure 6. The experimental procedure for the first part of this lab can be found in the methodology section and is fairly simple, but requires attention to detail. In order to observe the effects the change in environmental condition has on the solar cell students are required to calculate the efficiency at which the cell converts light into electrical power. In order to calculate the efficiency of a solar cell the power across the LED light source must be found.

$$\eta = \frac{Energy\ Produced\ by\ Cell}{Energy\ Felt\ on\ Surface\ of\ Cell} * 100$$

To find the power drop across the LED students will use the voltmeter and obtain a voltage and current value. These two measurements can be multiplied together to obtain the power produced by the LED. Next the distance at which the solar cell is mounted from the LED's is measured and entered into the equation for pointance.

$$Pointance = \frac{S}{4\pi r^2}$$

Where S is the power drop across the LED and r is the distance from the solar cell to the LED's. Pointance is the amount of energy felt on a surface a certain distance away from a point source of light. In order to calculate the efficiency of the cell the energy "felt" on the entire surface of the solar cell must be found. This can simply be done by multiplying the pointance by the area of the cell. Students will find that a simple hobby solar cell is not extremely efficient. Observing first-hand the efficiency of a solar cell generates interest in this renewable energy and may lead to further research in the photovoltaic field.

From the first part of the solar cell effectiveness lab students will gain further knowledge as to what environmental factors play a key role in the overall energy production of a solar cell. Although hands-on experience is the main purpose of this lab, the knowledge gained may be lost if it cannot be applied to a real world situation. To do this the second part of the lab requires students to design and optimize a solar field. Seeing first-hand how their knowledge can be applied in the real world will ensure that the knowledge gained has meaning.

Methodology

The methodology section outlines the laboratory procedures for the proposed lab experiments to be used in an undergraduate energy laboratory course at Worcester Polytechnic Institute. This section contains the preparation, materials needed, experimental set-up, lab procedures, and instructions for calculation for each of the experiments discussed in the background section.

Fuel Test Lab

The goal of the Fuel Test Lab is to evaluate energy density and relative cleanliness of several commonly used fuels. Energy density is the term used to describe how much energy is in a given amount of a material, typically defined as MJ/kg. Students will use a cone calorimeter to determine the energy density of several fuels and will be able to contrast the CO and CO_2 emissions produced by the different fuels. This laboratory will emphasize proper laboratory safety procedures, the use of advanced equipment, data analysis, and analysis of tradeoffs between different fuel sources.

Safety

Since the basis for the laboratory is the ignition of high energy fuels, the most significant danger comes from fire. Precautions like proper attire, footwear, and safety equipment like fire retardant gloves should be observed.

Preparation

Preparation for the Fuel Test Lab primarily involves learning about the function and operation of a cone calorimeter.

Figure 7 - WPI's ASTM E1354 Cone Calorimeter

WPI has a single cone calorimeter, located in Gateway Park. Instructions for safe use of a standard ASTM E1354 can be found on ASTM International's website. However, because WPI's calorimeter has been modified extensively, students should follow instructions provided by the lab monitor.

Students could be asked to complete additional research on commonly used fuel sources as a supplement to this procedure. Students should familiarize themselves with the laboratory topic prior to arrival by completing the following tasks:

1. Identify several safety concerns affiliated with use of a cone calorimeter
2. Provide instructions for safe use of a cone calorimeter
3. Describe physical and chemical properties of a variety of commonly used fuels:
    a. Color, state of matter at standard temperature and pressure, density, etc.
    b. Heat of combustion, chemical structure, etc.
4. Define energy density, emissions, life cycle assessment, etc.
5. Describe the relative benefits of using renewable fuels versus fossil fuels

Materials Needed

- Cone calorimeter: ASTM E1354
- Fuels in containers labeled with a number but no name
    - 25g gasoline per group
    - 25g diesel per group
    - ~2g or 1L STP bioethanol gas per group
    - ~2g or 1L STP biodiesel gas per group
    - ~1g or 1 L STP methane gas per group
    - Additional fuels as needed (wood, coal, etc.)
- Fuel test plates
- Ignition source (blow torch)
- Data collection program and computer (lab provided)
- Oven mitts
- Water source
- Fire Extinguisher

Experimental Set-Up

Students will measure a sample of test fuel and combust it in the cone calorimeter apparatus.

Laboratory Procedures

1. Obtain samples of each gas and store at a safe distance from the calorimeter
2. Run air at STP through the calorimeter to calibrate the equipment
3. Pour sample 1 into a test plate, place cover over sample
4. Measure weight of sample 1 inside test plate
5. Start cone calorimeter test

6. Place sample 1 into holder on cone calorimeter, remove cover
7. Ignite fuel source 1
    a. Immediately after ignition, indicate ignition start time on data collection apparatus
8. Observe appearance of flame as the fuel sample is incinerated
9. Immediately after fuel is consumed, indicate flame completion time on data collection apparatus
10. Make sure data collection was completed
11. Using oven mitts, remove the sample plate from apparatus
12. Clean sample plate under cold water until it returns to room temperature
13. Repeat steps 3-12 for remaining samples

Post-Lab

1. Attempt to identify test fuels as known fuels based on measured vs. known factors. A sheet defining these values for each fuel used in the laboratory should be provided by the laboratory instructor:
    a. Energy density (see equation below)
    b. Density of fuel
    c. State of matter
    d. Flame appearance
    e. Duration of burn
    f. Emissions
2. Evaluate gasses based on energy density versus CO and CO_2 emissions
    a. CO and CO_2 emissions are automatically recorded by calorimeter through the use of filtration systems
    b. Students must calculate the energy density of a fuel base on Equation 1 below
    c. Students will be able to draw conclusions about the fuel samples based on energy density versus CO and CO_2 emissions, as well as heavy metal emissions estimated by the cone calorimeter.
3. On the topic of life cycle assessments
    a. Though an accurate life cycle assessment of each fuel would take students beyond the intended scope of this laboratory experiment, the experiment instructions should include an excerpt on life cycle assessments and how they can be applied to a material or product. The Environmental Protection Agency provides a standardized process for completing a life cycle assessment on their Sustainable Technology resource center (Environmental Protection Agency).

Instructions for Calculations

Calculations for this lab will primarily consist of the Density-Mass-Volume relation (Equation 1) and Energy Density (u) equations (Equations 2 or 3, depending on the context).

$$\rho = \frac{m}{v} \quad (1)$$

$$u = \frac{E}{V} \quad (2)$$

$$u = \frac{E}{m} \quad (3)$$

Additionally, students may be asked to compare the graphical results produced by the cone calorimeter's data program between two or more fuels. Students could visually or mathematically compare characteristics such as duration of burn, heat released, emission release rates, etc.

Anaerobic Digestion Feedstock Lab

The anaerobic digestion lab is designed to allow students to compare the effective energy density of different types of organic feedstock for biogas production. Anaerobic digestion is a bacterial process that produces biogas from organic waste, and almost any organic waste can be used. The first phase of the lab will use a small-scale anaerobic digester, with a chosen feedstock added, and a gas trap to collect gases produced. The second phase of the lab will use a cone calorimeter to measure the energy in the gas when it is burned (see fuel efficiency lab). The students will then rank their feedstock based on the ratio of total energy produced to mass of feedstock used.

Safety

This lab requires samples from a live anaerobic digester to be brought into the lab, and pathogens are a major concern. Proper lab attire will be required, i.e. goggles, rubber gloves, coat, & mask. As most labs will not allow fecal waste on the premises, the Wastewater Treatment Lab would need to be used. This lab is equipped to easily decontaminate experiment materials afterwards, and to disposal of organic waste. The second phase also has safety concerns. The fire protection lab requires goggles to be worn, and a short training must be completed to use the cone calorimeter.

Preparation

Students working with the anaerobic digester will need background research in order to fully comprehend and perform the lab. The book "Biogas from Waste and Renewable Resources: an Introduction" by Deublein, Steinhauser is a textbook available at the WPI library that lays out the fundamentals for anaerobic digestion. Students should be knowledgeable in the various stages of anaerobic digestion (acidogenic, methanogenic), this knowledge can be used to perhaps choose the best feedstock available.

In addition to student preparation, the lab preparation is very involved. The seed digester mass must be attained from a live anaerobic digester, so that it contains living cultures of the bacteria. This seed could be obtained from a number of farms & wastewater treatment plants in the Worcester area. The seed must also be kept warm (never below room temp) throughout the experiment, as the bacteria cultures will die otherwise.

Materials

The following is a bill of materials necessary to carry out the lab:

1. Anaerobic bacteria seed cultures
2. Organic waste samples to be tested

   A few examples:

   a. Food waste from a nearby restaurant or campus cafeteria
   b. Yard waste from facilities dept. (leaves)
   c. Organic waste from other processes (beer malt/coffee grounds are used widely in industrial digesters)

3. Containers to keep feedstock fresh until use (smaller Nalgene, Tupperware, etc.)
4. Rubber gloves
5. Face masks
6. Lab coats
7. Fume Hood (available in the Waste Water Treatment Lab)
8. 2 ~10L Nalgene containers (airtight, with outlets)
    a. Nalgene containers are chosen in order to be easily decontaminated in "E-Z Clean" machine post-lab.
9. 2 lab hoses
10. A sink for water/drainage
11. Hand air pump
    used to make sure all gas is burned in test
12. Cone Calorimeter (Fire Protection Lab)

As a note, other materials may be necessary to elevate the temperature of the lab, such as a space heater/water bath, if the lab temperature cannot be maintained at temperatures necessary for anaerobic digestion to occur.

Experimental Set-up

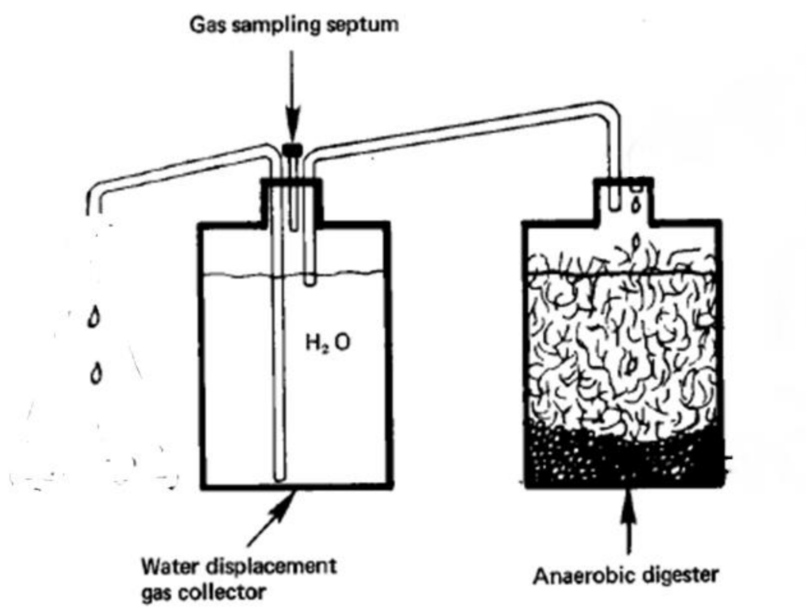

Figure 8 - Anaerobic Digester

The feedstock and seed are put in the right Nalgene, which is sealed with a hose coming out. That hose is inserted into the top of the left Nalgene, the gas trap, which is filled with water. The gas hose will be near the top of the Nalgene, and the outlet tube will sit at the bottom. As gas is produced it will accumulate in the gas trap and the pressure will push the water through the outlet hose into a sink.

Procedure

This lab will be completed over the entire course, as the time between set-up (step 2) and testing (step 3), will be roughly 1 month.

Students will follow these steps:

1) Choose a feedstock
    a. Acquire feedstock from source
    b. Weigh/measure feedstock mass, volume, cost, etc.
2) Set up digester (done under hood to prevent smell/contamination)
    a. Add feedstock and seed together in Nalgene 1
    b. Fill Nalgene 2 with water
    c. Connect hoses/seal containers
    d. Place outlet hose drainage sink
3) Detach gas trap
    a. Seal outlet hose
    b. Detach/seal inlet hose
4) Transport Gas trap to FPE Lab
5) Test Gas
    a. Align outlet hose with cone calorimeter
    b. Attach hand pump to inlet hose
    c. Open outlet hose
    d. Pump gas into cone calorimeter
    e. Record total energy produced during combustion

Instructions for calculations

Students will use their measurements from the burn test and feedstock to calculate various modes of efficiency of their feedstock. In this context ε_1, ε_2, and ε_3 are the mass, volume, and cost efficiencies, respectively. Q is the energy produced by burning the gas. *m* is the mass of the feedstock used, V is the volume, and EC is the energy cost of the feedstock. Mass and volume would be measured by the students upon starting the experiment, and energy cost will be roughly estimated based on student research.

$$\varepsilon_1 = \frac{Q}{m}$$

$$\varepsilon_2 = \frac{Q}{V}$$

$$\varepsilon_3 = \frac{Q}{EC}$$

The class-wide data will be used to compare the feedstock. Statistical analyses of the efficiencies will be used to calculate the mean efficiencies and standard deviation.

Bioethanol Production Lab

The goal of the Bioethanol Production Lab is to learn about how different sources or feedstocks affect the concentration of the ethanol produced within a laboratory setting. Students will be measuring the amount of carbon dioxide produced during the fermentation process as well as the energy density of the final product after simple distillation. Students will learn about not only how ethanol is produced, but will learn about various factors that may affect the final concentration of the distilled ethanol. In the first part of the lab students will measure the amount of CO_2 produced during the fermentation of their selected feedstock using a simple water displacement method. The second part of the lab students will be distilling the fermented mash to obtain their bioethanol and compare the energy density by using a bomb calorimeter.

Safety

The ethanol production lab has various safety concerns that should be taken seriously because they can cause serious harm if not treated immediately.

- Ethanol is flammable. Be sure to use caution when moving solution. Do not expose to open flame unless underneath a fume hood.
- A Bunsen burner has an open flame. Do not expose skin or other flammable materials to open flame.
- Follow all laboratory procedures, consult lab instructor if instructions are unclear.
- Do not ingest Ethanol. This is not ingestible alcohol, if ingested the solution could cause serious harm.

Preparation

Preparation for the bioethanol production lab includes reading an article on the use of ethanol as a transportation fuel written by the California Energy Commission. The link below will direct the students to the website where they can read more about how ethanol is being produced and some socioeconomic factors that play a role in the acceptance of bioethanol use.

http://www.consumerenergycenter.org/transportation/afvs/ethanol.html

After reading the article students should be able to answer the following questions:

1. If you use different sources or feedstocks to produce bioethanol what are some characteristics that you would look for in the feedstock?
2. What are some of the factors that affect the industrial production of ethanol?
3. Can you think of any different feedstocks that could be used to produce more ethanol?
4. Do you see bioethanol as being a viable source of renewable energy for the future?
5. Do some research of your own. Are there any new technologies that will play a role in the future development of bioethanol production?

For the overall preparation of the laboratory experiment be sure that all equipment is clean and dry before starting the lab. The thorough cleaning of your equipment will ensure that your results are valid.

Materials Needed

The following materials and equipment will be needed for the completion of the bioethanol production lab.

- Fermenter: 1L Erlenmeyer Flask
- Yeast: *saccharomyces cerevisiae* ~ ½ cup
- Feedstocks:
    - Corn Seeds – ½ lb.
    - Sweet Potatoes – 1 lb.
    - Hay or Straw – small bundle (about ½ inch in diameter)
- Hot Plate
- 3 Test tubes
- 3 Test Tube Clamps
- Thermometer in degrees Centigrade ranging from 0-100 degrees
- 10 pH test strips (may not all need to be used)
- Stirring Rod
- Sulfuric Acid – 10 ml
- Graduated Cylinder
- Deionized Water
- Plastic Tubing ~2.5 feet
- Small Plastic tub
- Coffee Grinder or Grinding Apparatus
- Scale or Balance
- Cloth for filtering mash
- Plastic stoppers
- Lighter
- Lab grade Ethanol fo/r comparison
- Extra Beakers
- Bomb Calorimeter
- Grease for lubrication of glass on glass joints in the distillation set-up.

Experimental Set-Up

The bioethanol production lab consists of two stages therefore; there are two different experimental set-ups. The first part, fermentation, the Figure 9 below should be assembled. To assemble water displacement apparatus fill small plastic tub halfway with tap water. Next fill graduated cylinder with water and carefully invert in plastic tub. If some water is lost in the transition do not worry. Use one of the test tube clamps to hold graduated cylinder in place. Take an initial reading of water level in graduated cylinder for reference.

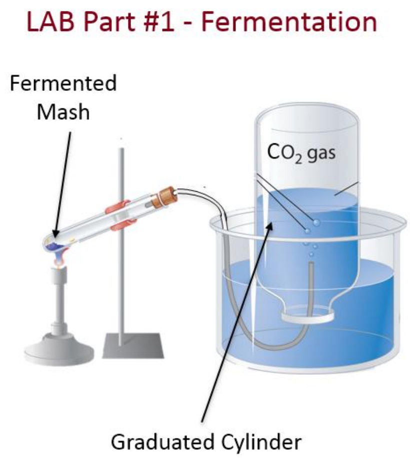

Figure 9 - Fermentation

In order to perform the second portion of the lab, distillation, the apparatus depicted in Figure 10 below should be assembled. The equipment needed for the distillation set-up will be able to be obtained from the lab instructor before continuing the lab. Be sure when assembling to lightly grease all glass on glass joints. Use hotplate or Bunsen burner with a beaker of water to heat filtered mash. Use caution when inserting thermometer into rubber stopper at the top of the vapor tube. After connecting the hoses to the distillation tube turn on water and be sure there are no leaks in system. Before proceeding with the experiment get the instructors permission to ensure your experimental set-up is correct.

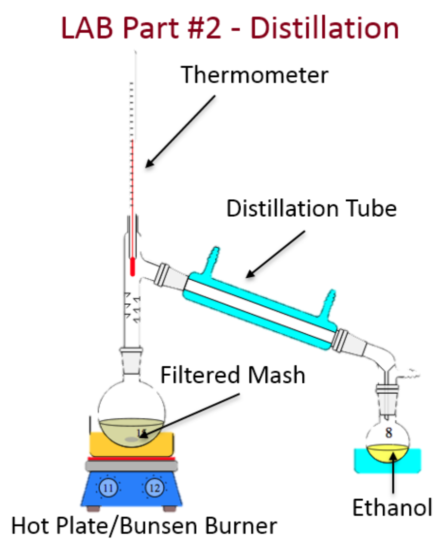

Figure 10 - Distillation

Laboratory Procedures

For the fermentation part of the lab the following laboratory procedures should be followed. Before proceeding with the experiment read the laboratory procedures thoroughly to ensure your understanding of the lab.

1. Obtain all the necessary equipment needed from the instructor including a randomly assigned feedstock.
2. Prepare the mash.
    a. In a beaker, mix 50 g of the assigned feedstock with 300 ml of preheated distilled water (~30º C). In order to get a larger surface area for fermentation it may be necessary to grind up your feedstock in the grinder.
    b. Add 1 or 2 drops of sulfuric acid to adjust pH to 5. Test the pH with the provided pH strips. This step may be repeated with various levels of acidic and basic properties.
    c. Bring mixture to a boil while stirring constantly. Boil for 15 minutes.
    d. Set aside and allow to cool while stirring constantly for 5 minutes.
3. Prepare the yeast.
    a. In a test tube, mix 0.5 g of yeast with 20 ml of warm (29°C or 85°F) water.
    b. Add a pinch of sugar and watch for bubbling to show yeast is active. Set aside for later use.
4. Carefully cool mash (from step 2b) to 28°C (83°F) while stirring occasionally. (It may be necessary to place beaker in warm, cool, then ice water.)
5. Add yeast solution to cooled mash solution.
6. Carefully cover beaker with a glass or plastic top with attached tubing.
7. Place tubing into opening of graduated cylinder in the water displacement setup and acquire the first water height measurement on the graduated cylinder.
8. Record the amount of CO_2 produced for remainder of lab (increments of 10 minutes)

For the distillation part of the lab the following laboratory procedures should be followed. Before proceeding with the experiment read the laboratory procedures thoroughly to ensure your understanding of the lab.

1. Set up distillation apparatus (obtain Teacher's approval before continuing).
2. Carefully squeeze fermented mash through a cloth into a beaker OR while being very careful not to disturb the mash, use a pipette to draw off the top clear layer of liquid and place in beaker. State which method used in lab report.
3. Carefully transfer 200ml of the obtained liquid into the Erlenmeyer flask.
4. Start the hotplate and place the flask into the distillation apparatus.

5. Distill the first 10% (approximate) of the liquid. **DO NOT DISTILL TO DRYNESS.** Record the temperature of the vapor when you

6. first see drops coming out the end of the distillation tube. Try to keep the mash at this temperature. This temperature is the evaporation temperature of the ethanol. (Ethanol evaporates first, so you should get mostly ethanol with the first 5ml that are distilled.)

7. Carefully smell the fuel by using your hand to slowly fan the vapors toward your nose. Compare the smell to lab grade ethanol.

8. Pour half of the ethanol fuel into a Petri dish and light it with a match underneath a fume hood. Compare it to the burning of lab grade ethanol. Does it burn longer? Does it take longer to light?

9. Use the rest of the ethanol in the bomb calorimeter and calculate the energy density of the bioethanol and compare this value to the known value of lab grade ethanol.

Instructions for Calculations

In this lab students will be measuring both the amount of CO_2 released during fermentation and the overall concentration of the produced ethanol. After obtaining several measurements of CO_2 students should plot the amount of CO_2 released versus time. During the fermentation process carbon dioxide is released. The amount of CO_2 released is related to the amount of sugars that are being converted into ethanol. Students should use stoichiometry to estimate the amount and concentration of ethanol that they are expected to produce.

Photovoltaic Energy Lab

The solar cell efficiency lab is aimed to introduce students to the varying efficiency of a single solar cell under various environmental conditions. The students will then apply this information to a real world application in the design of a solar field. The assessment of students' ability to follow laboratory procedures, collect and analyze data, and apply knowledge gained will be evaluated by the completion of two different laboratory experiments and a formal written lab report.

Part 1: Assessing the Effects of Light Intensity, Wavelength, Shading, and Angle of Incidence on the Efficiency of a Solar Cell

Using a solar cell with a maximum output of 1.5V at 500mA, students will measure the power output (voltage and current) of the cell under different conditions. The environmental conditions evaluated will include: varying intensity of light, wavelengths of light, angles of incidence, and percentages of shading. Modifying all of these conditions the students should be able to generate a power curve of the solar cell and assess the effects of these different environments.

Preparation

In order to prepare for this laboratory the following articles should be read:

http://chemistry.about.com/od/electronicstructure/a/photoelectric-effect.htm
http://www.britannica.com/EBchecked/topic/552905/solar-energy

The first article explains the photoelectric effect and also Einstein's equations for the photoelectric effect. The second article is the Britannica online encyclopedia entry for solar energy, it gives an overall picture of what solar cells and panels are being used for and provides links to other sources for more exploration.

The second portion of the preparation phase is to get the solar cell ready for use in the lab. For this students will need to assemble the Tamiya Solar Panel with stand. Although the instructions for constructing the cell and stand are not in English, however drawings and diagrams presented in the instructions are straightforward and simple to follow. It is important to construct the cell and stand because they provide stability to the cell and allow for consistent results to be obtained.

Materials Needed

This lab as mentioned before is split into two separate labs, for the first lab (efficiency testing) the following materials are needed:

- Tamiya Solar Panel - Single Solar Cell with stand
- Small Screw Driver
- 2 Alligator Clips
- Large Protractor
- Colored Filters – Red, Blue, Green, and Yellow
- Voltmeter
- 100 LED light string

- Ruler
- Cardboard
- LED Apparatus

Experimental Set-Up

For the experimental set-up of the solar cell efficiency lab the students will have to assemble the single solar cell with stand and affix it the LED apparatus. The final set-up can be seen in Figure 11 below.

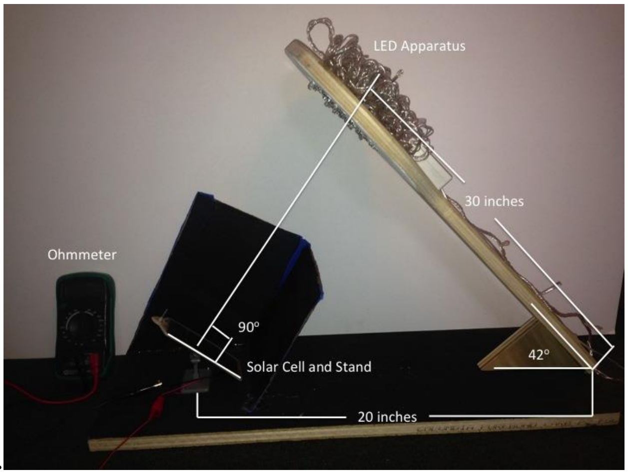

Figure 11 - Photovoltaic Laboratory Set-up

Lab Procedures

Below are the steps necessary for the successful completion of the solar cell efficiency lab.

1. Assemble provided single solar cell with stand.
2. Fix base of solar cell stand a distance of 20 inches from the base of the LED apparatus.
3. Adjust the angle of the solar cell so that the cell face is perpendicular to the LED apparatus.
4. For each of the following steps take readings using the voltmeter for both Voltage and overall Current. (Use the single digit volt scale and mA scale).
   a. In part a you will be measuring the effects of light intensity on the overall power output of the solar cell. To do this place one LED light bulb in the center hole of the LED apparatus and take a voltage and amperage reading.
      i. Repeat step a until all LED lights have been used. Record your results for current and voltage in an appropriately named Excel file (e.g. Light Intensity) and produce a power vs. number of LED's curve.
   b. In part b you will be measuring the effect of incidence angle on the output of the single solar cell. To do this keep the solar cell at maximum power (i.e. keep all 100 LED's in the apparatus) and vary the angle at which the light is striking the solar cell.

i. Record your results for at least 5 different angles, and discuss your findings. A suggestion for discussion may be to plot another power curve of the results to observe the effect of incidence angle.

c. In part c you will be testing the effects of various wavelengths of light on the power output of the solar cell. To do this find the angle for maximum power production (part b) and place one of the colored filters over the LED apparatus and repeat the same steps taken in part a of the lab.

   i. Repeat for all four colors (Red, Green, Blue, and Yellow), record your results, and discuss your findings.

d. In part d of the experiment you will be testing the effects of shadowing or shading on a single solar cell. In order to conduct this portion you will need to measure the area of the solar cell. Then take a piece of cardboard and carefully place a section of the cardboard over varying percentages of the cell (start with the lower corner and work your way up). First shade 10% and increase this percentage by 10 until 90% of the cell is shaded. Record your results of current and voltage in an appropriately named Excel file and discuss your findings. For discussion a suggestion may be to produce a graph of percent shading vs. power.

Instructions for Calculations

In order to measure the effectiveness or efficiency of the solar cells students will be required to measure both the current and voltage of the cells after each variable is changed using a voltmeter. With both the voltage and amperage readings students can generate a power curve (power vs. number of LED's) for the solar cell. In order to calculate the efficiency of a solar cell the power across the LED light source must be found. To find the power drop across the LED students will use the voltmeter and obtain a voltage and current value from the two wires leading to the LED. These two measurements can be multiplied together to obtain the overall power produced by the LED. Next the radial distance at which the solar cell is mounted from the LED's is measured and entered into the equation for pointance.

$$Pointance = \frac{S}{4\pi r^2}$$

Where S is the power drop across the LED and r is the distance from the solar cell to the LED's. Pointance is the amount of energy felt on a surface a certain distance away from a point source of light. In order to calculate the efficiency of the solar cell the energy "felt" on the entire surface of the cell must be found. This can simply be done by multiplying the pointance by the area of the cell. The value obtained from this calculation is the amount of energy that is "felt" on the surface of the solar cell from a single LED. From this calculation students can evaluate the efficiency of the cell under all of the environmental conditions evaluated by using the equation below.

$$\eta = \frac{Energy\ Produced\ by\ Cell}{Energy\ Felt\ on\ Surface\ of\ Cell} * 100$$

Part 2: Designing a Solar Field

In the second part of the solar cell lab the students will apply their knowledge obtained from part 1 of the experiment into the design of a solar field. They will use a design software offered by the company ETAP. This software optimizes and creates a visual representation of a solar panel array in a desired area of land. The students will have to calculate the number of solar panels that can feasibly fit onto their field and find the maximum power output their field can generate using this software.

Preparation

For the second experiment the students will be required to read an article that can be found on online through the WPI library titled, *Optimal Design of Solar Fields*. This article will be useful because it outlines many of the parameters that students should take into account when designing the solar field. The link below can be followed to display the PDF of the article.

http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1178380

Materials Needed

The materials needed for the second portion of the solar cell lab are as follows:

- ETAP Solar Field Design Software
- Field Evaluation Sheet - Sample plot of land that includes the following:
    - GPS coordinates indicating the location of the field
    - A scale to measure the area of the field
    - Size of solar panels to be used and their optimum power production
    - Slope of land

Experimental Set-Up

This experiment requires the use of a computer with the appropriate software correctly installed and the use of the field evaluation sheet. No set-up of equipment is necessary for this portion of the lab.

Lab Procedures

The following steps should be taken when completing the design of a solar field lab.

1. Obtain the field evaluation sheet from the lab instructor.
2. Observe the information provided on the sheet. Why are these parameters given to you?
3. Calculate the number of solar panels that can fit on the plot of land taking into account the knowledge gained from part 1 of the photovoltaic energy lab.
4. Calculate the maximum power that can be produced by the solar field.
5. Go to a computer and open the Solar Field software from ETAP and enter in the necessary information in order to obtain a total power produced value.
6. Compare the value obtained from the software to your calculated value. Are they close? If so what conditions did you take into account? If not what environmental conditions do you think the software used that you did not?

Instructions for Calculations

After reading the appropriate article students should have an understanding of the different aspects and conditions that need to be met in order to optimize the production of a solar field. Using the provided field evaluation sheet the students will calculate the overall function of the field on an optimum day and generate a value for the amount of power that their field can produce. For simplification purposes this value can be calculated by simply multiplying the number of solar panels by their optimum power production value. This number will then be compared to the amount of power produced using the provided software. Comparing these two values students should be able to assess the effects of the different conditions that the software takes into account. They should find that the software evaluates the field production using GPS coordinates and slope of the land. With these conditions taken into account the software changes the overall irradiance on the field based on conditions such as where the sun is positioned in the sky. Students should be able to discuss this information in their formal lab report.

Results

Fuel Evaluation Lab

A trial of the fuel evaluation experiment was completed by the project team. In this trial run, gasoline and diesel were used as sample comparison fuels because of their relative availability and familiarity. The full data results of this trial run are included in Appendix A. The experiment ran smoothly, and the expected data outputs were observed, proving that the experimental procedure outlined in the methodology section of this report is practical.

As part of the proposed laboratory course, students would use the results from this experiment to compare and contrast fuel samples based on the information provided by the cone calorimeter's data collection program. This process will give students firsthand knowledge of the relative energy density and cleanliness of commonly used fuels.

Anaerobic Digestion Lab

The anaerobic digestion lab has not been tested completely. The investigations completed by this MQP team determined that the only laboratory with all the necessary equipment and facilities for the experiment is the Wastewater Treatment Lab, and the lab could not be reserved during the timeframe of the experiment. This MQP provides all of the procedures and information necessary to obtain approval for the experiment. To obtain said approval Jeannine Plummer is the supervisor of the Wastewater Treatment Lab.

Bioethanol Production Lab

The Bioethanol Production lab was not completed because of the inability to gain access to available lab space. We were unable to gain access because of limits on WPI laboratory space and availability. Although the lab was not completed by the MQP team we were able to calculate results that students can expect to see when completing the lab. In the first portion of the Bioethanol Production lab students are asked to measure and record the amount of CO_2 that is released during the fermentation process. The overall chemical equation for fermentation is as follows; $C_6H_{12}O_6$ + zymase → 2 C_2H_5OH + 2 CO_2. Where the glucose molecules react with an enzyme called zymase, which is found within the yeast. To calculate the amount of CO_2 that was released during fermentation for a sample feedstock of corn we used simple stoichiometry. The calculation for the amount of CO_2 released for corn can be seen below.

$$CO_2\ released\ (g) = \left(\frac{50g\ Corn}{1}\right)\left(\frac{3.22g\ Sugar}{100g\ Corn}\right)\left(\frac{1mol\ Sugar}{180.15g\ Sugar}\right)\left(\frac{2mol\ CO_2}{1mol\ Sugar}\right)\left(\frac{44.01g\ CO_2}{1mol\ CO_2}\right)$$

$$CO_2\ released\ (g) = 0.786g$$

$$CO_2\ released\ (ml) = 7.86x10^{-4}kg\left(\frac{1m^3}{1.98kg}\right)\left(\frac{1ml}{1x10^{-6}m^3}\right)$$

$$CO_2\ released\ (ml) = 397ml$$

From this students should expect to see about 400ml of CO_2 being released after fermentation is complete. Due to limitations in the lab students will not be able to record the amount of CO_2 over the entire fermentation process because fermentation can take in upwards of one week. Instead students are required to measure for the remainder of time they are in the lab. The recording of these values is to ensure that the fermentation process is happening and to observe the rate at which fermentation occurs.

The outcome of the lab is to produce ethanol from an assigned feedstock. Although the lab was not completed by the MQP team we were able to calculate results that students can expect to see when distilling the ethanol. Similar to the amount of CO_2 released the amount of ethanol produced can be calculated using stoichiometry. The results of these calculations can be seen below.

$$Ethanol\ Produced\ (g) = \left(\frac{50g\ Corn}{1}\right)\left(\frac{3.22g\ Sugar}{100g\ Corn}\right)\left(\frac{1mol\ Sugar}{180.15g\ Sugar}\right)\left(\frac{2mol\ Ethanol}{1mol\ Sugar}\right)\left(\frac{46.06g\ Ethanol}{1mol\ Ethanol}\right)$$

$$Ethanol\ Produced\ (g) = 0.823g$$

$$Ethanol\ Produced\ (ml) = 8.23x10^{-4}kg\left(\frac{1m^3}{789kg}\right)\left(\frac{1ml}{1x10^{-6}m^3}\right)$$

$$Ethanol\ Produced\ (ml) = 1.04ml$$

This is a very small amount of ethanol and is the value for the amount of pure ethanol that is produced. In this experiment students will be comparing the ethanol they produced to lab grade (essentially pure) ethanol. Students should be able to observe a difference between the two when conducting the burn test in lab and under the cone calorimeter.

Photovoltaic Energy Lab

The results for the Photovoltaic Energy lab are divided into separate sections and are presented in this portion of the report. For raw data samples of the Cell Efficiency lab please refer to Appendix B.

Cell Efficiency Lab

In the cell efficiency lab students are required to calculate and compare the efficiency of a solar cell under different environmental conditions. Figure 12 below shows effects on the efficiency of the solar cell while increasing the intensity of light exposed to the cell. In order to test efficiency an operator must connect a load to the cell. The load in the case of this experiment is the ohmmeter that is measuring the current and voltage. An ohmmeter has several settings that the user can adjust in order to obtain the correct current value. Each of these settings has a different resistance value associated with them. For the results of this experiment to be obtained the mA setting was used. This setting has a resistance value of 104.4Ω, which is the load that is being applied to the solar cell.

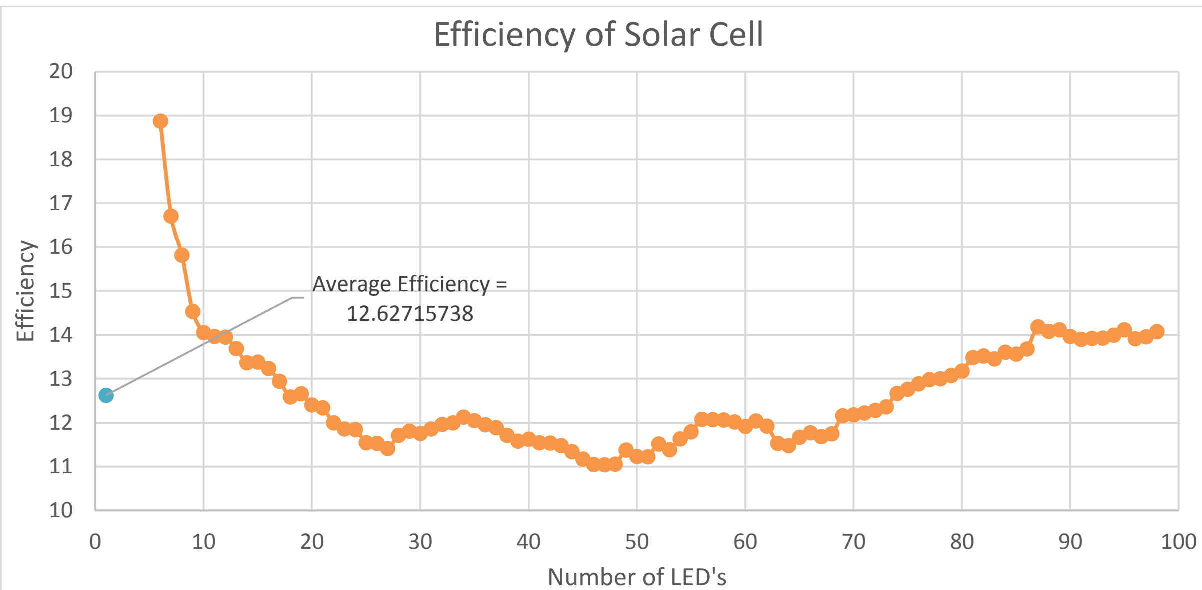

Figure 12 - Efficiency of a Solar Cell

The plot above shows the average measured efficiency is 12.62%. Although this value is fairly low it does prove to be compatible with efficiency values found in literature. One reason that the overall efficiency may be low is because the solar cell used in the lab is intended for hobby use and is not made from the most precise or high quality materials. Another observation regarding the chart above asks the question as to why the efficiency is so high at a low intensity of light. The reason for this is because during the experiment the team was unable to eliminate all of the external light from the room. When conducting this experiment in a laboratory setting students should expect this result. A way to eliminate this error would be to enclose the cell and light source together.

When following the experimental procedures the next step is to change the angle at which light is hitting the cell, or angle of incidence. In Figure 13 below the effects of five different angles on the power production of the solar cell can be seen.

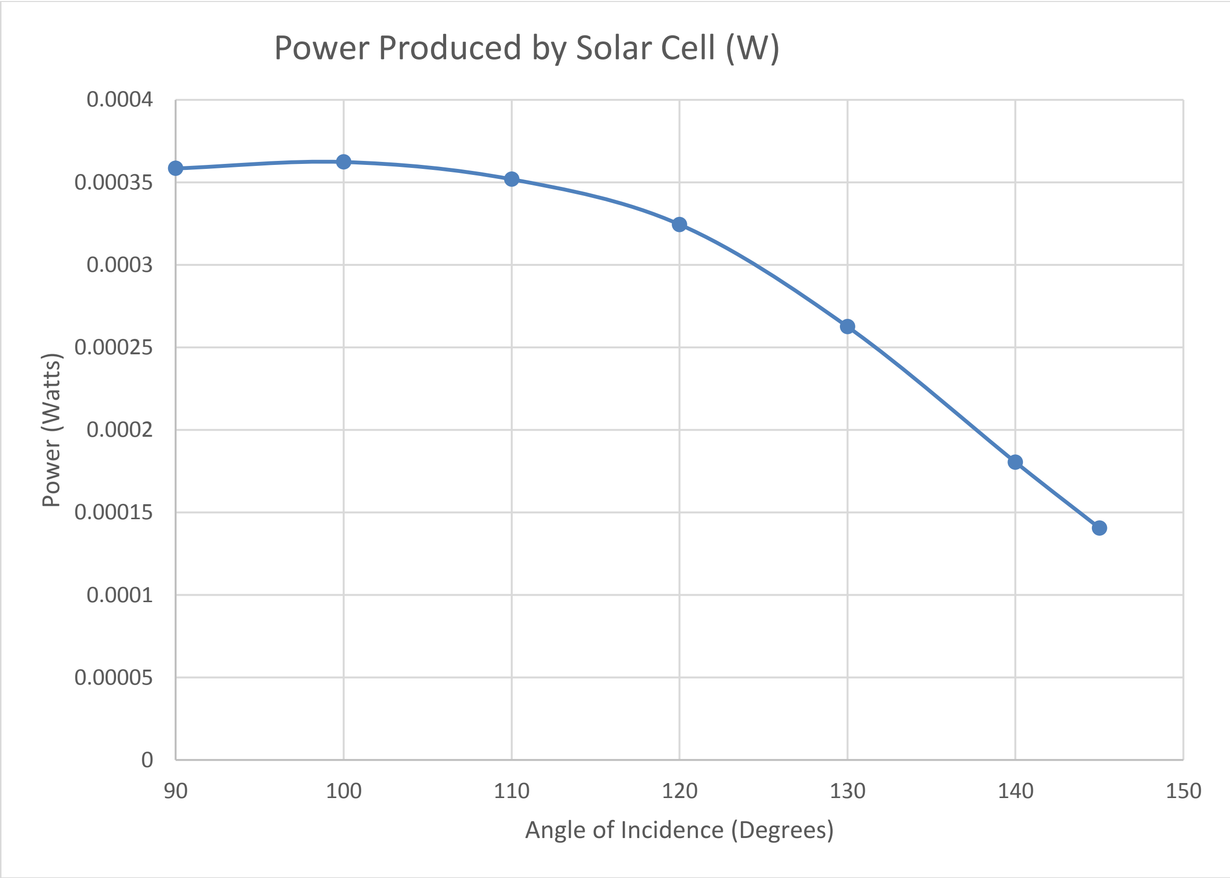

Figure 13 - Power Curve

The plot above presents the angle at which light comes to contact with the solar cell affects the amount of power that is produced. In most cases, except for one, the greater the angle became the lower the power production was. For the case at which the angle was measured to be 100 degrees the power output increased slightly. This increase in power is somewhat puzzling and would require more testing and improved accuracy to draw any further conclusions.

The third portion of this lab requires students to change the wavelength of light that is being exposed to the solar cell. To accomplish this a colored filter was placed over the light source to affectively change the wavelength. Four colors were used, red, green, blue, and yellow. In Figure 14 below the efficiency of the cell is represented for all colored filters as well as a comparison to having no filter. As described in the article read before conducting the experiment, some materials release electrons at different wavelengths of light. The theory that a photovoltaic cell could release more electrons, producing more power, is the basis behind this experiment.

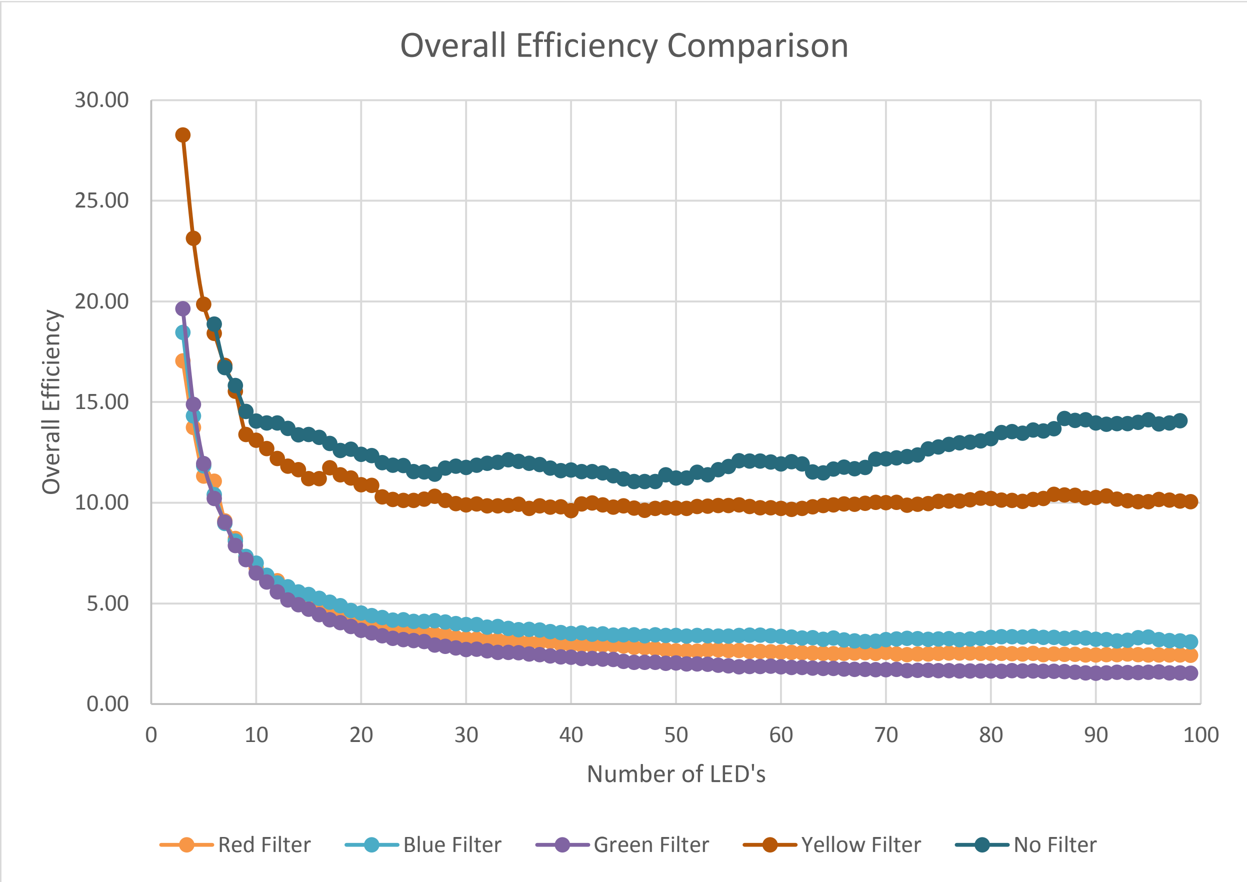

Figure 14 - Efficiency Comparison

When comparing the efficiency of the different wavelengths of light we see that the overall efficiency drops significantly for the red, blue, and green filters. Although the yellow filters efficiency does not drop as rapidly the overall efficiency is around 10%, which is 2% lower than when the light source has no filter. The reason that the power produced is less when the source has a colored filter is because the intensity of the light goes down. In order to calculate this new intensity it would require further knowledge about the material and opacity of the colored filters. For this experiment it may not be necessary to analyze the effects of the wavelength of light on solar cell efficiency. As a suggestion removing this section of the lab may be considered.

The final step in completing this part of the Photovoltaic Energy lab is to test the effects of shading on the power production of the solar cell. It should be intuitive that the smaller the area that is available to convert light into energy the lower the power output will be. The purpose here is not to simply understand this, but how much of the energy is unable to be converted because of this shading. This part of the experiment becomes important when designing the solar field. The results of this test are depicted in Figure 15 below.

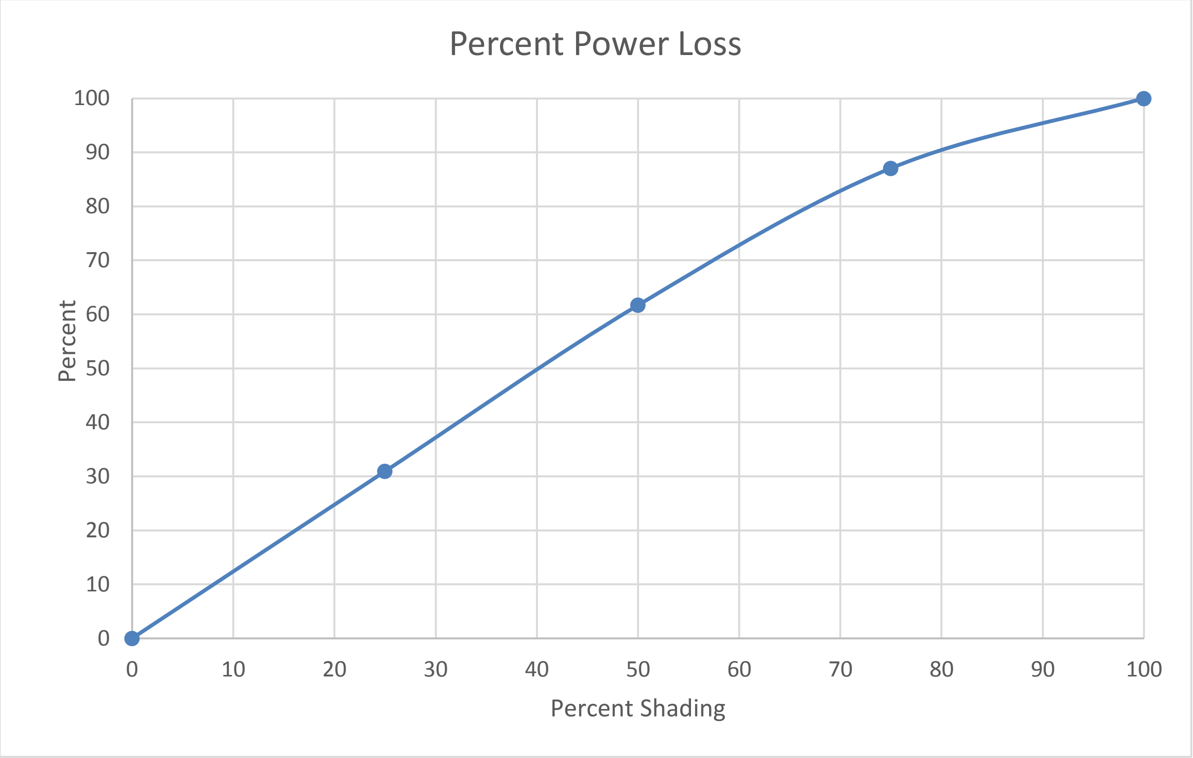

Figure 15 - Percent Power Loss

As mentioned before it is intuitive that the cell will produce less power as it becomes increasingly shaded. The plot above helps put a value on the actual percent of power that is lost due to a portion of the cell being shaded. When analyzing the graph we see that every 10% the cell is shaded roughly 12% of the power is not being produced. Simply not allowing a small portion of a solar cell or solar panel to be exposed to the light can significantly change the overall power produced by the system. Avoiding any type of shading is imperative when designing a solar system that is to be installed on a house or in an open field. In this laboratory experiment students learn about the photoelectric affect and the factors that play into the conversion of light into energy. This knowledge will be applied in the next lab where students will design a solar field.

Solar Field Design Lab

A trial run of the Solar Field Design portion of the Photovoltaic Energy lab was unable to be conducted because of administrative privileges and technical issues with computers and laptops. Although a trial run was not conducted the software is designed to have a user input necessary information and output expected power production. The results of the computer program can then be compared to the power production value that students evaluate. When comparing these two values students can draw conclusions on why these two values are not the same. One of these reasons may be that the computer program takes solar irradiance and GPS location into account. The amount of light energy available to be converted into electrical energy changes with location. Students may not realize as this being a factor when designing their solar field and will realize this when observing the results of the software.

Conclusions and Recommendations

The experiments detailed in this report are intended to be used as part of an undergraduate laboratory course on energy conversion technology. Through the establishment of this course, Worcester Polytechnic Institute will give its students an opportunity to learn about a topic of global importance and expand the practical component of their undergraduate experience. We hope that this project, in coordination with the other energy laboratory projects completed this year, will be used to establish a proposal for such a course.

Works Cited

Ashok, S. "Solar Energy." *Encyclopedia Britannica Online*. Encyclopedia Britannica, n.d. Web. 29 Apr. 2014.

Deublein, Dieter, and Angelika Steinhauser. *Biogas from Waste and Renewable Resources: An Introduction*. Weinheim: Wiley-VCH Verlag, 2012. Print.

"Ethanol as a Transportation Fuel." *Ethanol as a Transportation Fuel*. Consumer Energy Center, n.d. Web. 29 Apr. 2014.

Felder, Richard M., and Rebecca Brent. "Designing and Teaching Courses to Satisfy the ABET Engineering Criteria." *Journal of Engineering Education*(2003): 7-25. Web. 29 Apr. 2014.

"Labs / Studios - Teaching Excellence & Educational Innovation - Carnegie Mellon University." *Labs / Studios - Teaching Excellence & Educational Innovation - Carnegie Mellon University*. Carnegie Mellon University, n.d. Web. 29 Apr. 2014.

"Life Cycle Assessment (LCA)." *EPA*. Environmental Protection Agency, n.d. Web. 29 Apr. 2014.

"Optimal Design of Solar Fields." *IEEE Xplore*. Institute of Electrical and Electronics Engineers, n.d. Web. 29 Apr. 2014.

"Photoelectric Effect - Explanation of the Photoelectric Effect." *About.com Chemistry*. N.p., n.d. Web. 28 Apr. 2014.

Appendix A

Fuel Evaluation Laboratory Data Samples

Gasoline, Raw Data:

Time	Mass Loss Calculations		Air Flow Calculations		
	Mass Loss Rate	Mass Lost	Exhaust Mass Flow Rate	Air Density	Volumetric Flow Rate
[s]	[g/s]	[g]	[kg/s]	[kg/m^3]	[m^3/s]
128	0.03	0.04	0.027108	1.21017	0.0224
129	0.04	0.04	0.028778	1.205604	0.02387
130	0.03	0.03	0.025212	1.191104	0.021167
131	0.03	0.04	0.027524	1.179154	0.023342
132	0.04	0.04	0.025456	1.169591	0.021765

Smoke Calculations				
Extinction Coefficient	SPR	Smoke Release	SEA (S)	Smoke Yield
[m^{-1}]	[m^2/s]	[m^2]	[m^2/g]	[g/g]
-10.979461	-0.245938	-0.253733	-8.19793	-0.964462
-10.956243	-0.261527	-0.246297	-6.538187	-0.769198
-10.91653	-0.231067	-0.242427	-7.70222	-0.906144
-10.872646	-0.253788	-0.244858	-8.459596	-0.995247
-10.839846	-0.235928	-0.227152	-5.898205	-0.693906

Heat Release Calculations					
Heat Release Rate	Heat Released	Heat Released (Summed)	HHR/m2	Heat Released	Heat of Combustion
[kW]	[kJ]	[kJ]	[kW/m^2]	[kJ/m^2]	[kJ/g]
2.789992	2.911331	31.204691	315.75288	329.485189	92.999748
3.03267	2.881932	34.0859	343.217498	326.157956	75.816745
2.731194	2.881209	37.030352	309.098415	326.076117	91.039786
3.031224	2.944452	39.797485	343.053819	333.233622	101.040785
2.857681	2.767133	42.646968	323.413426	313.16579	71.442026

CO/CO2 Calculations					
CO Production Rate	CO Produced	CO Yield	CO2 Production Rate	CO2 Produced	CO2 Yield
[g/s]	[g]	[g/g]	[g/s]	[g]	[g/g]
0.000055	0.00006	0.001832	0.012168	0.012453	0.405587
0.000065	0.000059	0.001629	0.012739	0.011949	0.318464
0.000053	0.000053	0.00177	0.01116	0.012014	0.371999
0.000054	0.000053	0.001788	0.012867	0.012305	0.428915
0.000052	0.000057	0.00129	0.011743	0.012888	0.293566

Diesel, Final Results:

Test Parameters		
Ambient Temperature:	70	F
Relative Humidity:	10	%
Heat Flux:		kW/m^2
Exhaust Duct Flow Rate:		30 g/s
Orientation:		Horizontal
Specimen Holder:		TRUE
Specimen Preparation:		none
Notes:		1" Separation
Specimen Information		
Specimen Color:	[]	
Specimen Thickness:	[mm]	10.0
Specimen Test Area:	[m^2]	0.0088
Specimen Initial Mass:	[g]	
Specimen Final Mass:	[g]	22.4
Specimen Density:	[g/cm^3]	0.0
Mass Lost:	[g]	22.4
Total Heat Evolved:	[kJ]	966
Test Times [s]		
Shutter Open:		108
Time to Ignition:		212
Flameout:		604
Clean Air/End of Test:		0

Parameter	Unit	Value
Heat Release		
Peak Heat Release Rate	[kW/m^2]	397
Average Heat Release Rate	[kW/m^2]	279
Total Heat Release	[MJ/m^2]	109
Average HRR for the first 60s	[kW/m^2]	235
Average HRR for the first 180s	[kW/m^2]	292
Average HRR for the first 300s	[kW/m^2]	302
Peak Heat of Combustion	[kJ/g]	151
Average Heat of Combustion	[kJ/g]	46
Gas Production Rates		
Peak Carbon Monoxide	[g/s]	0.003
Average Carbon Monoxide	[g/s]	0.002
Peak Carbon Dioxide	[g/s]	0.893
Average Carbon Dioxide	[g/s]	0.618
Mass Loss		
Peak Mass Loss Rate	[g/s]	0.110
Average Mass Lass Rate	[g/s]	
Initial Mass	[g]	0.0
Final Mass	[g]	22.4
Mass Loss Fraction	[]	#DIV/0!
Burn Time		
Time to Ignition	[s]	104
Duration of Flaming	[s]	392
Duration of Test	[s]	-108

Appendix B

Solar Cell Efficiency Laboratory Data Samples

Intensity Raw Data:

	A	B	C	D	E	F	G
1	# of LED Bulbs	Voltage (V)	Current (mA)	Power Produced By Solar Cell	Power Produced By LED's (W)	Power Felt on Surface of Cell	Efficiency = (Power Produced / Power Felt)*100
2	6	0.369	0.081	0.000029889	0.032035712	0.000158385	18.87115758
3	7	0.372	0.083	0.000030876	0.037374997	0.000184782	16.7094209
4	8	0.384	0.087	0.000033408	0.042714283	0.000211179	15.81972379
5	9	0.388	0.089	0.000034532	0.048053568	0.000237577	14.53508679
6	10	0.399	0.093	0.000037107	0.053392853	0.000263974	14.05705198
7	11	0.418	0.097	0.000040546	0.058732139	0.000290372	13.96348226
8	12	0.425	0.104	0.0000442	0.064071424	0.000316769	13.95338026
9	13	0.435	0.108	0.00004698	0.069410709	0.000343167	13.69014559
10	14	0.441	0.112	0.000049392	0.074749995	0.000369564	13.36493907
11	15	0.453	0.117	0.000053001	0.08008928	0.000395961	13.38539561
12	16	0.462	0.121	0.000055902	0.085428566	0.000422359	13.2356651
13	17	0.461	0.126	0.000058086	0.090767851	0.000448756	12.94377502
14	18	0.471	0.127	0.000059817	0.096107136	0.000475154	12.58897959
15	19	0.481	0.132	0.000063492	0.101446422	0.000501551	12.65912864
16	20	0.485	0.135	0.000065475	0.106785707	0.000527949	12.401777
17	21	0.492	0.139	0.000068388	0.112124992	0.000554346	12.33670031
18	22	0.494	0.141	0.000069654	0.117464278	0.000580743	11.99393766
19	23	0.5	0.144	0.000072	0.122803563	0.000607141	11.85886341
20	24	0.507	0.148	0.000075036	0.128142848	0.000633538	11.84395748
21	25	0.508	0.15	0.0000762	0.133482134	0.000659936	11.54658001
22	26	0.514	0.154	0.000079156	0.138821419	0.000686333	11.53317544
23	27	0.518	0.157	0.000081326	0.144160704	0.000712731	11.41048369
24	28	0.528	0.164	0.000086592	0.14949999	0.000739128	11.71542764
25	29	0.535	0.169	0.000090415	0.154839275	0.000765525	11.81084297
26	30	0.538	0.173	0.000093074	0.16017856	0.000791923	11.75291325

Wavelength Raw Data:

	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1		RED (665 nm)				BLUE (470 nm)				GREEN (550 nm)				YELLOW (600 nm)			
2	Power Felt By Cell	Voltage (V)	Current (mA)	Power (W)	Efficeincy	Voltage (V)	Current (mA)	Power (W)	Efficeincy	Voltage (V)	Current (mA)	Power (W)	Efficeincy	Voltage (V)	Current (mA)	Power (W)	Efficeincy
3	7.91922E-05	0.27	0.05	0.0000135	17.05	0.281	0.052	0.000014612	18.45131212	0.288	0.054	0.000015552	19.63829771	0.334	0.067	0.000022378	28.25783347
4	0.00010559	0.279	0.052	1.451E-05	13.74	0.285	0.053	0.000015105	14.30538614	0.291	0.054	0.000015714	14.88214748	0.344	0.071	0.000024424	23.13106594
5	0.000131987	0.282	0.053	1.495E-05	11.32	0.289	0.054	0.000015606	11.82389175	0.292	0.054	0.000015768	11.94663111	0.354	0.074	0.000026196	19.84740921
6	0.000158384	0.302	0.058	1.752E-05	11.06	0.294	0.056	0.000016464	10.39496314	0.294	0.055	0.00001617	10.2093388	0.369	0.079	0.000029151	18.40522173
7	0.000184782	0.295	0.057	1.682E-05	9.10	0.296	0.056	0.000016576	8.970580436	0.298	0.056	0.000016688	9.031192466	0.379	0.082	0.000031078	16.81875596
8	0.000211179	0.299	0.058	1.734E-05	8.21	0.3	0.057	0.0000171	8.097388379	0.297	0.056	0.000016632	7.875775645	0.386	0.085	0.00003281	15.536568
9	0.000237577	0.299	0.058	1.734E-05	7.30	0.3	0.058	0.0000174	7.323953622	0.299	0.057	0.000017043	7.173686297	0.383	0.083	0.000031789	13.38052653
10	0.000263974	0.302	0.059	1.782E-05	6.75	0.308	0.06	0.00001848	7.000689462	0.301	0.057	0.000017157	6.499503739	0.393	0.088	0.000034584	13.10129028
11	0.000290371	0.304	0.059	1.794E-05	6.18	0.309	0.06	0.00001854	6.384926339	0.303	0.058	0.000017574	6.052248947	0.405	0.091	0.000036855	12.69236571
12	0.000316769	0.313	0.062	1.941E-05	6.13	0.312	0.061	0.000019032	6.008167471	0.304	0.058	0.000017632	5.566204752	0.411	0.094	0.000038634	12.19627691
13	0.000343166	0.311	0.061	1.897E-05	5.53	0.317	0.063	0.000019971	5.819629089	0.306	0.058	0.000017748	5.171838019	0.418	0.097	0.000040546	11.81526619
14	0.000369564	0.315	0.062	1.953E-05	5.28	0.321	0.064	0.000020544	5.558989035	0.309	0.059	0.000018231	4.933115707	0.426	0.101	0.000043026	11.64238036
15	0.000395961	0.315	0.063	1.985E-05	5.01	0.326	0.066	0.000021516	5.433868487	0.311	0.06	0.00001866	4.71258533	0.43	0.103	0.00004429	11.18544503
16	0.000422358	0.318	0.064	2.035E-05	4.82	0.331	0.067	0.000022177	5.250753862	0.312	0.06	0.00001872	4.432254692	0.442	0.107	0.000047294	11.19759901
17	0.000448756	0.321	0.065	2.087E-05	4.65	0.334	0.068	0.000022712	5.061104503	0.313	0.06	0.00001878	4.184904128	0.458	0.115	0.00005267	11.73689566
18	0.000475153	0.323	0.065	2.1E-05	4.42	0.336	0.069	0.000023184	4.879268413	0.314	0.061	0.000019154	4.03112091	0.462	0.117	0.000054054	11.37612038
19	0.000501551	0.325	0.066	2.145E-05	4.28	0.337	0.069	0.000023253	4.636222148	0.316	0.061	0.000019276	3.843281216	0.469	0.12	0.00005628	11.22120081
20	0.000527948	0.326	0.066	2.152E-05	4.08	0.34	0.07	0.0000238	4.508019729	0.316	0.061	0.000019276	3.651117155	0.471	0.122	0.000057462	10.88402646
21	0.000554345	0.328	0.067	2.198E-05	3.96	0.343	0.071	0.000024353	4.393109422	0.316	0.062	0.000019592	3.534258605	0.478	0.126	0.000060228	10.86470637
22	0.000580743	0.331	0.068	2.251E-05	3.88	0.346	0.072	0.000024912	4.289678667	0.318	0.062	0.000019716	3.394962452	0.478	0.125	0.00005975	10.2885477
23	0.00060714	0.332	0.068	2.258E-05	3.72	0.346	0.073	0.000025258	4.160159383	0.319	0.062	0.000019778	3.257567198	0.482	0.128	0.000061696	10.16173859
24	0.000633538	0.336	0.069	2.318E-05	3.66	0.353	0.075	0.000026475	4.178915348	0.322	0.063	0.000020286	3.202019896	0.489	0.131	0.000064059	10.11131778
25	0.000659935	0.338	0.07	2.366E-05	3.59	0.356	0.076	0.000027056	4.099797707	0.324	0.064	0.000020736	3.142127634	0.494	0.135	0.00006669	10.1055407
26	0.000686332	0.341	0.071	2.421E-05	3.53	0.361	0.078	0.000028158	4.102676779	0.327	0.065	0.000021255	3.096895906	0.502	0.139	0.000069778	10.16679382
27	0.00071273	0.343	0.072	2.47E-05	3.46	0.368	0.08	0.00002944	4.130597598	0.326	0.064	0.000020864	2.927336559	0.511	0.144	0.000073584	10.32424911
28	0.000739127	0.347	0.073	2.533E-05	3.43	0.371	0.081	0.000030051	4.065741323	0.326	0.065	0.00002119	2.8668949	0.508	0.147	0.000074676	10.10326775
29	0.000765525	0.346	0.073	2.526E-05	3.30	0.372	0.082	0.000030504	3.984718453	0.327	0.065	0.000021255	2.776527364	0.511	0.149	0.000076139	9.945989979
30	0.000791922	0.348	0.074	2.575E-05	3.25	0.376	0.083	0.000031208	3.940792149	0.329	0.065	0.000021385	2.70039221	0.515	0.152	0.00007828	9.884811888
31	0.000818319	0.352	0.075	0.0000264	3.23	0.38	0.085	0.0000323	3.947114049	0.332	0.067	0.000022244	2.718254022	0.521	0.156	0.000081276	9.932063202
32	0.000844717	0.355	0.076	2.698E-05	3.19	0.38	0.085	0.0000323	3.823766735	0.333	0.067	0.000022311	2.641240236	0.523	0.159	0.000083157	9.844364407
33	0.000871114	0.358	0.077	2.757E-05	3.16	0.385	0.087	0.000033495	3.845075651	0.333	0.067	0.000022311	2.561202653	0.529	0.162	0.000085698	9.837745728

Angle of Incidence Raw Data:

F17

	A	B	C	D	E	F
1	Angle From Reference	Volts (V)	Amps (mA)	Incedence Angle	Power (W)	Efficiency
2	0	0.727	0.493	90	0.00035841	13.8596674
3	10	0.729	0.497	100	0.00036231	14.0105568
4	20	0.721	0.488	110	0.00035185	13.6058778
5	30	0.71	0.457	120	0.00032447	12.5471771
6	40	0.675	0.389	130	0.00026258	10.1537123
7	50	0.616	0.293	140	0.00018049	6.97942769
8	55	0.574	0.245	145	0.00014063	5.43812838

Percent Shading Raw Data:

I11

	A	B	C	D	E	F
1	% Shading	Voltage (V)	Current (mA)	Power (W)		Percent Power Loss
2	0	0.761	0.606	0.00046117		0
3	25	0.7	0.455	0.0003185		30.935932
4	50	0.605	0.292	0.00017666		61.6927527
5	75	0.442	0.135	0.00005967		87.0610583
6	100	0.002	0	0		100