Solar Aqua Sterilization System

With Micro-plasma Ozone Reactor

ECE 445 – Final Report

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Abstract

The Solar Aqua Sterilization System (S.A.S.S.) is a water sterilization system designed to incorporate the ozone reactor. The reactor utilized was researched and developed by Professor Gary Eden and Professor Sung-Jin Park. Their research paper titled "Linear Arrays of Micro-channel Plasmas in Monolithic Al/Al_2O_3 Sheets" goes into detail of the process in making the actual reactor where channels in Al/Al_2O_3 are created. Professor Gary Eden and Professor Sung-Jin Park came to us and asked us to design a solar power system to power the reactor. Due to the high AC voltage required to run the reactor, our design challenge was to take the output from the solar panel and battery and convert it to AC with a high peak-to-peak voltage. The outcome of our build resulted in its ability to power the reactor and produce a reasonable amount of ozone for use to purify water.

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1. Introduction

Professor Gary Eden and Professor Sung-Jin Park brought us their desire to explore and develop a humanitarian application for their new technology, a compact ozone reactor. The motivation to develop a new application arose from the technology's ability to produce clean water by breaking down harmful bacteria and chemicals with high efficiency at a low cost. Implementing the compact ozone reactor along with solar technology to create a water filtration system allows for an environmentally friendly implementation.

This final report will focus on the different subsystems required for the filtration system. The first half of this report explains the subsystems in detail needed for the system to operate. The latter half will cover the testing and verifications of the subsystems, costs, and a conclusion to this project.

1.1 Purpose

The purpose of this senior design project is to create a water sterilization system that incorporates the compact ozone reactor developed by Professor Gary Eden and Professor Sung-Jin Park. Currently, water purification systems are expensive and utilize environmentally harmful chemicals to purify water. In comparison, our system:

1) Utilizes low cost, environmentally friendly materials;
2) Provides sustainable energy to produce clean water;
3) Cleans an adequate amount of water in reasonable amount of time;
4) Helps resist breakdown and limit the maintenance costs with our non-convoluted design.

The effectiveness and simplicity of our design can greatly increase the chance to deploy the system in developing countries, where the lack of clean water is a growing issue.

1.2 System Overview

The Solar Powered Water Sterilization System with Micro-plasma Ozone Reactor consists of several components, which deal with energy transfer as well as airflow through the reactor. The main components between the solar panel and the reactor include a solar charge controller, a battery, a DC-to-Dc converter, and DC-to-AC inverters. The solar panel keeps the system running by charging the battery through the solar charge controller, which prevents the battery from over-draining or overcharging. The battery provides a stable DC power supply to the system. The DC-to-DC converter, flyback converter, steps up the battery voltage before it enters two DC-to-AC inverters, the half-bridge circuit and the reactor circuit. At the half bridge circuit, the inverter converters the DC supply to AC and steps up the voltage before going to the oxygen pump, which will feed oxygen to the reactor to produce ozone. Similarly, the reactor circuit converts the DC supply to AC and steps up the voltage to the desired value to provide power to the reactor. See Figure 1.1 below for a diagram of the system overview described above.

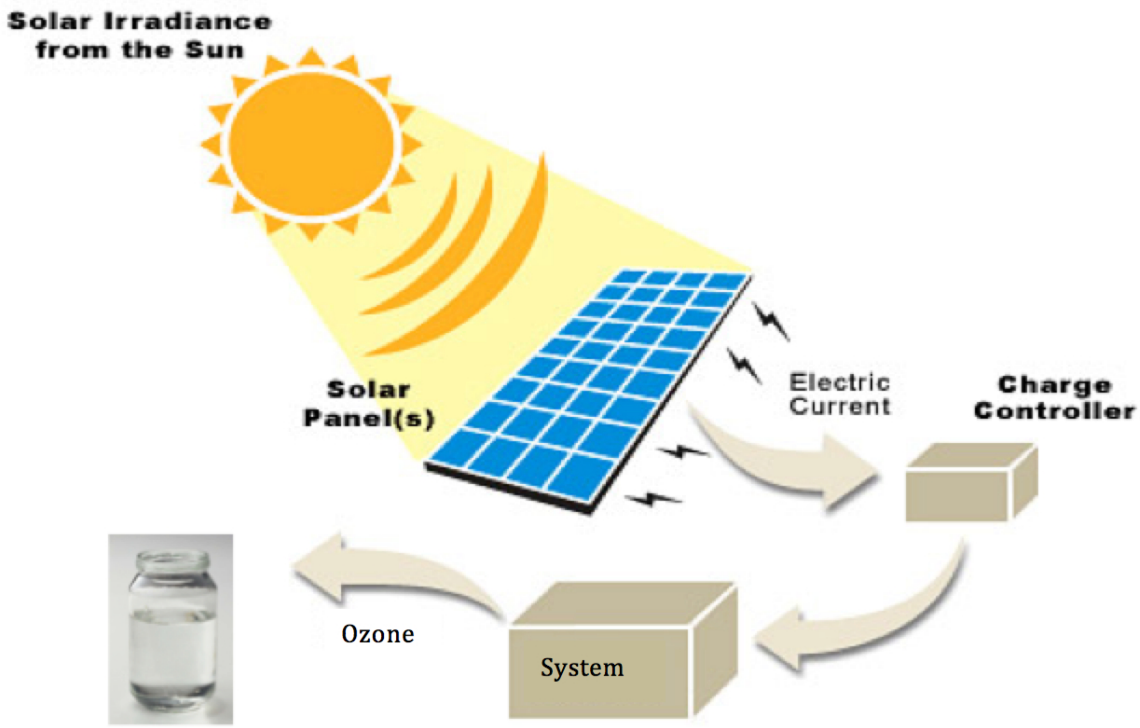

Figure 1.1 System Overview Diagram

1.3 Subsystems

The Solar Powered Water Sterilization System with Micro-plasma Ozone Reactor comprises of eight subsystems as shown in Figure 1.2. Each subsystem is in charge of specific tasks and can be tested individually.

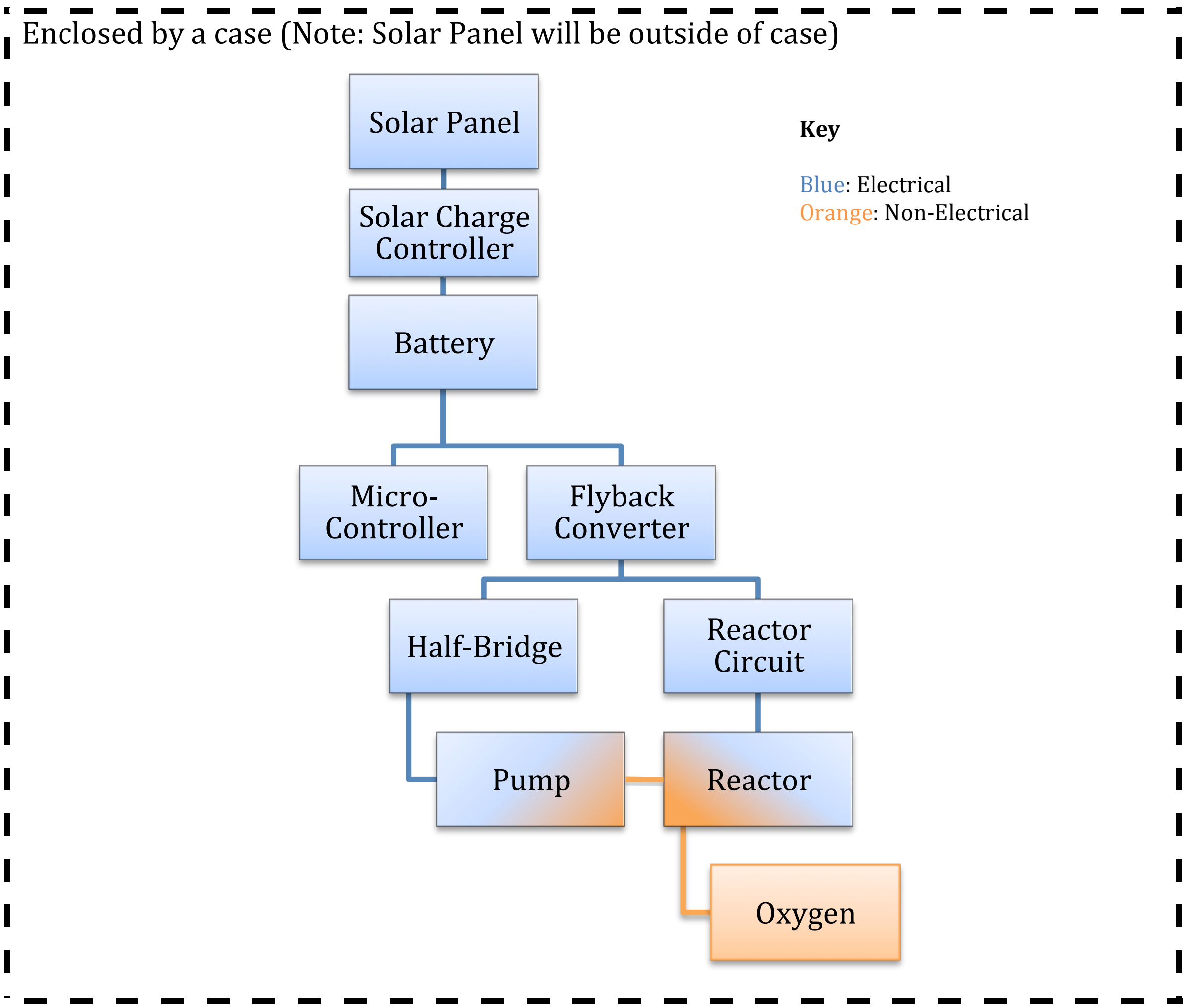

Figure 1.2 Block Diagram of Solar Powered Water Filtration System

1.3.1 Solar Panel

The solar panel is the main source of power for the entire system. It will be used to charge the battery when the battery is undercharged.

1.3.2 Solar Charge Controller

The solar charge controller is installed between the solar panel and the battery. Its role is to determine the charge status of the battery. When the battery is over-draining, it will allow the solar panel to charge the battery. Once the battery is over-charging, the controller will cut off power received from the solar panel.

1.3.3 Battery

The battery is 12 V sealed lead- acid battery. The battery will provide power to run the power converters, fan, microcontroller, and reactor.

1.3.4 Flyback Converter

The DC-to-DC converter, flyback converter, will step up the voltage from the battery of 12 V to ~180 V. This helps the DC-to-AC inverter to further step up to the desired voltage of 2-3 kV in order run the reactor

1.3.5 Reactor Circuit

The reactor circuit, DC-to-AC inverter, is the component that will step up the required voltage needed for the reactor to operate. It will receive a voltage of ~180 V from the DC-to-DC converter and further step it up to 2-3 kV.

1.3.6 Half-Bridge

This DC-to-AC Inverter is used for powering the fish pump, which will be used to provide oxygen into the reactor.

1.3.7 Pump

The pump is the component that will provide airflow to the reactor giving it the necessary oxygen it needs to produce ozone.

1.3.8 Reactor

The reactor is the main component in the entire system. It is in charge of converting oxygen into ozone, which will ultimately clean contaminated water.

1.3.9 Microcontroller

The microcontroller provides the necessary information for the user. It will display and monitor information such as power, current, and voltage on a LCD display. It will further calculate the amount of ozone being produced based on the amount of voltage input.

1.3.10 Enclosure/Case

The case will enclose all the circuits and components to prevent any damages from the outside environment. It also provides safety for the user during operation.

2. Design

The design of the Solar Powered Water Filtration System contains eight components as listed in section 1.3. Each component has been chosen to accommodate for optimization, efficiency, and pricing.

2.1 Solar Panel

The water filtration system is a self-sustaining system. This is made possible with the usage of a solar panel. The solar panel will recharge the battery once it has reached its discharged state as determined by the solar charge controller and stops charging once the battery has been fully charged. The solar panel will be the upper level schematic as seen in Figure 2.1.

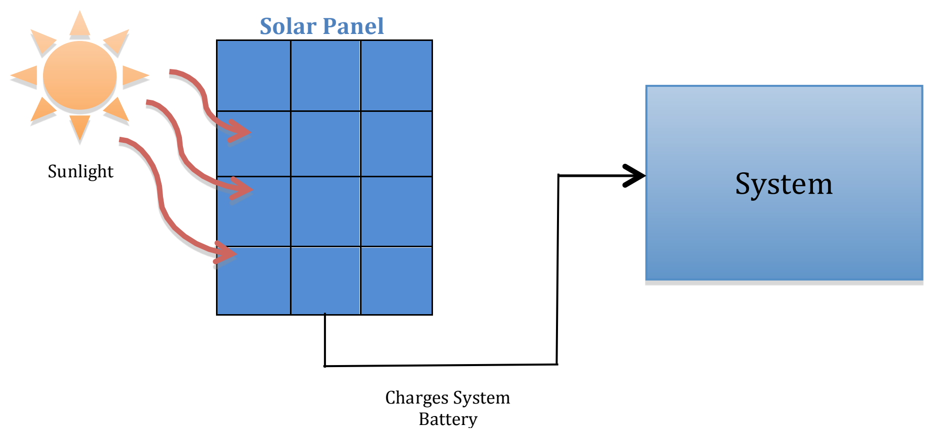

Figure 2.1 Solar Panel Schematic

The reactor requires 10 watts of power to operate. The fish pump we are using to deliver oxygen to the reactor requires another 2 watts to operate. Thus, the solar panel has to be able to deliver 12 watts. Due to low efficiencies with solar panels, we had to decide on a panel that has a higher power rating than what our system requires. Also, the power ratings for solar panels are rated during perfect weather conditions. We had taken into account for this matter, which resulted in our decision to go with a solar panel with a much higher power rating.

Based on the requirements, the solar panel we decided is rated at a maximum power of 50 watts. With this amount of power, it would make up for the low efficiency and power loss during poor weather conditions. The specification for the solar panel we purchased is shown on the following page in Table 2.1.

Specification	Value
Max Rated Power	50 Watts
Rated Voltage	17.6 Volts
Rated Current	2.85 Amps
Open-Circuit Voltage	21.6 Volts
Short-Circuit Current	2.98 Amps

Table 2.1 Solar Panel Specifications

The solar panel decided was based on the cost per power ($/Watt). This particular solar panel had the best cost per power offer. See Appendix A for price comparison.

2.2 Solar Charge Controller

The solar charge controller is installed between the solar panel, battery, and the system circuit. The controller regulates the power flow between the solar panel, battery, and the system circuit. It monitors the current and power flow to prevent any electrical harm to the battery and system circuit. The solar charge controller schematic is shown below in Figure 2.2.

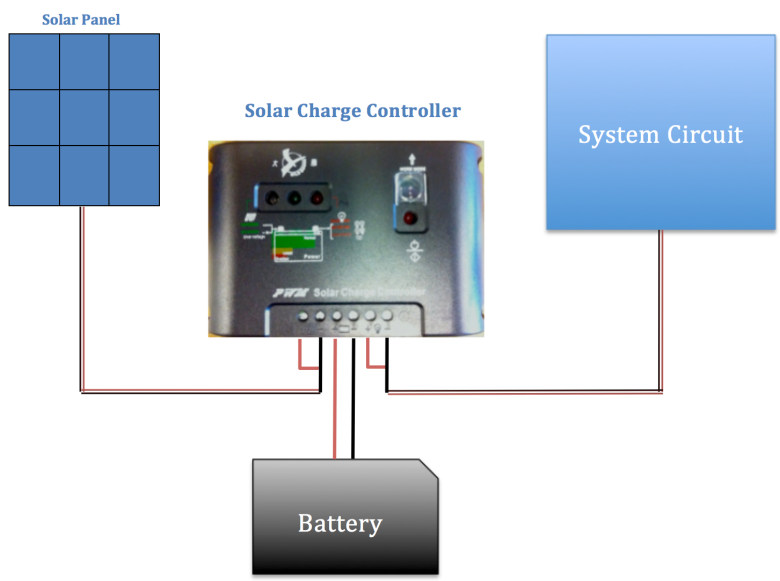

Figure 2.2 Solar Charge Controller Schematic

The solar charge controller has 3 functioning LED lights. The left LED shines white when good source of power is being inputted from the solar panel, thus charging the battery when necessary. The middle LED shines green when the battery has been discharged. The right LED shines red when the battery has been fully charged, thus cutting power transfer from solar panel to battery. See Appendix B, Figure B.1 for solar charge controller map out.

The solar charge is also capable of performing several functions. The functions are the following:

- Charging off voltage (HVD) setting
- Automatic recognition of input voltage
- Micro processing controller PWM charge
- Temperature sensor for charging battery in compensation
- Overload protection
- Overcharge protection
- Temperature compensate
- Short circuit protection
- Thunder protection
- Reverse discharge protection
- Converse polarity connection protection
- Low voltage protection

2.3 Battery

The battery utilized in this project is a rechargeable 12 V sealed lead-acid battery. This component is the main power source for the system. This particular battery was chosen due to its ability to recharge and discharge for many cycles. See Figure 2.2 above for the battery schematic.

2.4 Flyback Converter

The flyback converter steps up 12 V to 180 V to help achieve a maximum output of 2-3 kV. Our original design implemented a buck-boost converter. However, this design was not able to provide us with the sufficient gain. Thus, we went with the fly-back, because it was proven to be more feasible and can easily step up 12 V to 180 V [3]. A schematic of the flyback converter is shown below in Figure 2.3.

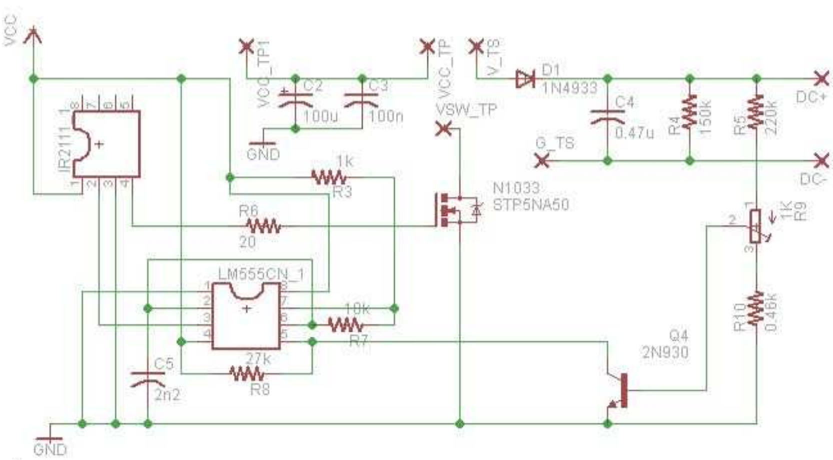

Figure 2.3 Flyback Converter Schematic

The flyback converter uses a 1:10 turn ratio transformer to step up 12 V from battery to 180 V. The expected turn ratio is 1:15; however, it was found that in practice a smaller ratio would suffice. The simulation seen above actually confirms that a 1:10 ratio produces an output much above the necessary 180 V. The vertical axis has units of Volts and the horizontal units of time. One should note that the red trace is the output voltage, which rises well above 180 V. Another observation can be made in the continuously increasing output, which will be corrected with a feedback loop. A 555 timer [1] produces a switching signal at a frequency of 30 kHz. The gate signal passes through a gate driver [2] first and then to the NMOS gate, because the gate driver is capable of sourcing much more current than the 555 timer, providing more efficient switching. The switch allows for charging and discharging of the transformer, a characteristic of the indirect power conversion of a fly-back circuit. Initially, a ferrite pot core was used for our transformer. However, it was suspected that saturation occurred at a low input voltage ~6 V. Therefore, we resorted to using a toroid powdered iron core. The difference between the cores arises in their magnetic properties. The saturation level for powdered iron cores, ~3 [Tesla], is much larger than ferrite cores, ~300 [mTesla]. This is reflected in the inductance index and core area for the ferrite pot core and toroid powdered iron core, which are shown in Figures 2.4 and 2.5, respectively. Equations (2.1) and (2.2) show the inductance calculation [2].

Figure 2.4 Ferrite Pot Core

- A_L = 400 [nH/N^2]
- A_c = 172 [mm^2]

Figure 2.5 Toroid Powdered Iron Core

- A_L = 69 [nH/N^2]
- A_c = 3.38 [cm^2]

The equations for the maximum current and inductance are

$$L * I_{max} = N * B_{sat} * A_c \tag{2.1}$$

$$L = A_L * N^2 \tag{2.2}$$

where A_L is the inductance index, A_C is the core area, N is the number of turns, B_{sat} is the saturation, I_{max} is the maximum current, and L is the inductance. Two transformers are utilized in this circuit. One transformer dedicated to the reactor circuit, while the other transformer is dedicated to the half-bridge circuit.

2.5 Reactor Circuit

The reactor circuit regulates the entire circuit for operation. It receives 180 V from the flyback converter and further steps the voltage to 2-3 kV with a transformer. It uses a microcontroller, Atmel Atmega 88, and monitors the H-Bridge in the circuit to produce a pulse wave needed to drive the reactor. See Appendix B, Figure B.2 and Figure B.3 for the schematic of the circuit and an image of the actual circuit, respectively.

2.6 Half-Bridge

The half-bridge is used to convert the DC output from the flyback converter to AC in order to power the pump. It converts the flyback output of 180 V to 180 V RMS.

$$V_{RMS} = \frac{V_p}{\sqrt{2}} \tag{2.3}$$

Using Equation (2.3), about 180 V_{RMS} goes into powering the pump. Much like the flyback converter, it uses a 555 timer [1] for a square wave along with a half-bridge gate driver [2] to drive the MOSFETs. The schematic and simulation for the half-bridge circuit are shown below in Figures 2.6 and 2.7, respectively. The simulation shows the MOSFET HI and LO switching signals, which the gate driver would output, in the bottom two plots. The output appears in the topmost plot and demonstrates a square wave shape. However, the peaks are not what would be expected, which may have something to do with how the circuit was set up for simulation. In practice, as will be seen later on, the circuit performed as expected.

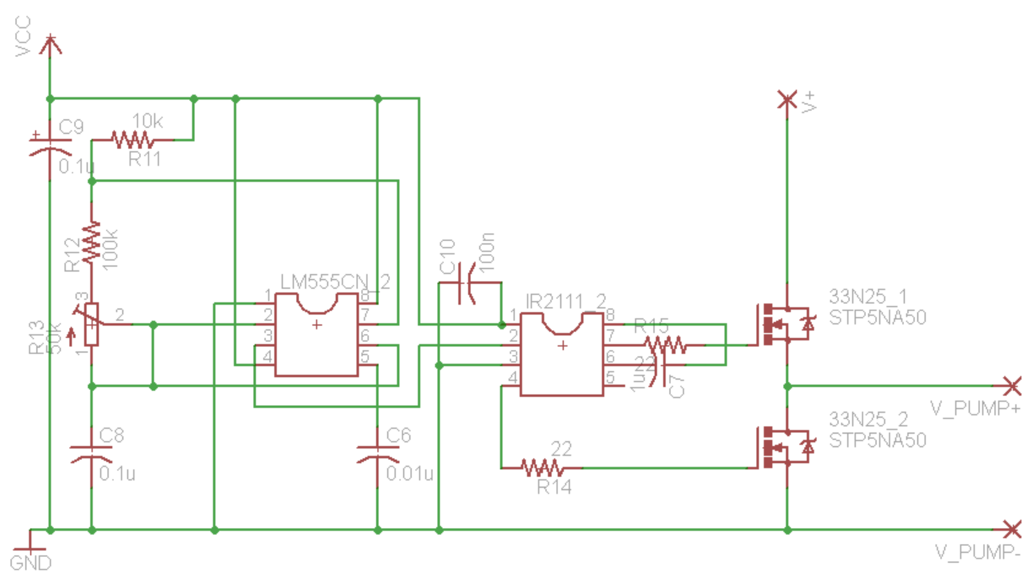

Figure 2.6 Half-Bridge Schematic

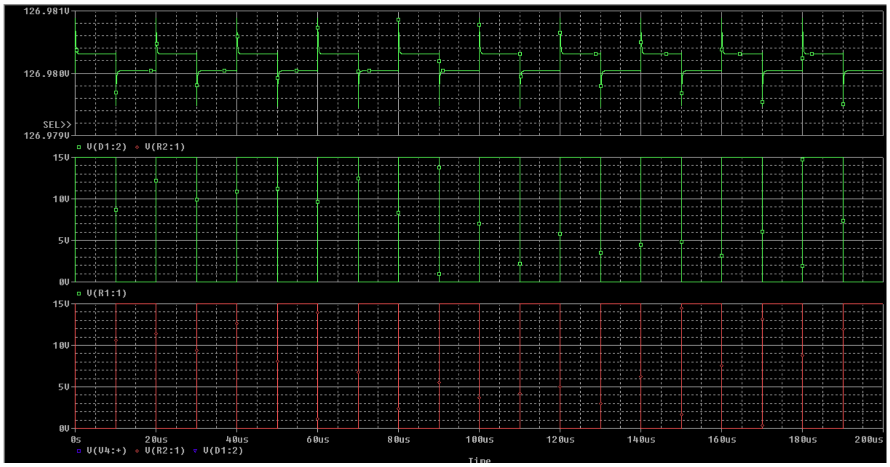

Figure 2.7 Half-Bridge Simulations

2.7 Pump

The purpose for the pump is to provide oxygen to the reactor for ozone production. It receives power of about 120 V from the half-bridge circuit to operate. See Appendix B, Figure B.4, for the pump used in the system.

2.8 Reactor

The reactor is the main component in the system. It receives oxygen from the pump and produce ozone to sanitize contaminated water. The operational voltage for the reactor is in the range of 2-3 kV. See Appendix B, Figure B.5, for the physical reactor used in the system. The reactors ability to produce ozone depends on two main factors. The peak-to-peak voltage that the reactor receives plays a main role. There are several types of reactors currently in development. Our system was designed to operate a reactor in the 2-3 kV range. However, the voltage input is not the only important factor. Because air does not consist solely of oxygen, the amount of airflow through the reactor plays an important role. In order to produce ozone efficiently, the reactor needs a voltage input inversely proportional to air flow. So with a weaker flow of air, the peak-to-peak voltage input must increase to produce reasonable results. In contrast, with an adequate flow of pure oxygen the reactor can operate near the lower end of its input voltage range.

2.9 Micro-Controller

The micro-controller provides the user with information such as voltage, current, and power output onto the LCD display. The micro-controller is a Texas Instruments Launch Pad MSP430. Furthermore, the INA219 chip is used to read in values. The TI Launch Pad with INA219 schematic is shown in Appendix B, Figure B.6, and the device itself is shown on the following page in Figure B.7. There was a problem with the language that was used with the micro-controller. The language used is an older version of C that did not have Boolean and strings. So when INA219 sends information to the TI Launchpad, it sends the number as a float. However, the TI

Launchpad cannot display the float so it is translated into an integer variable and then display each unit place by itself of the decimal number [6]-[8].

2.10 System Enclosure

The casing needed for this system requires it to be weather proof because it will be used outdoors. The dimension of the enclosure is 18" x 18" x 18". There is a removable lid that allows the circuitry to be moved in and out. It also provides a waterproof seal to prevent water from getting into the container and damage the circuitry. Furthermore, two holes have been punched out to allow wires connecting to the solar panel, solar charge controller, switch, and output of ozone to connect to the circuitry inside the enclosure. Refer to Appendix B, Figure B.8, to see enclosure explained above.

2.11 Overall Design

The overall design incorporates all the components explained in this section. A rechargeable 12 V battery powers the system. In addition, the solar panel charges the battery when discharged to provide a sustainable power source. The flyback converter then receives 12 V from the battery and steps up the voltage to 180 V, which output to both the half-bridge circuit and reactor circuit. At the half-bridge circuit, 180 V DC is inverted to 180 V RMS AC to power the pump in order to provide airflow to the reactor. On the other hand, the reactor circuit takes in 180 V DC and further steps up to 2-3 kV AC to power the ozone reactor. The overall circuit schematic is shown in Appendix B, Figure B.9.

3. Design Verifications

The design verifications tested and verified each component individually to show they were functioning correctly as explained in Section 2. The requirement and verification procedure created during the design process shown in Appendix C, Table C.1 were used to ensure each component satisfy their required specification.

3.1 Solar Panel

Based on the requirements shown in Table C.1, the solar panel satisfies Requirement 1. The solar panel was tested during sunny conditions and poor weather conditions. Table 3.1 below shows the testing results obtained.

	Weather Condition	Open-Circuit Voltage (V)	Short-Circuit Current (A)	Power (W)
Specification	N/A	Rated: 21.6	Rated: 2.98	Rated: 50
Test 1	Sunny	~21.8	~1.3	28.34
Test 2	Poor Sunlight	~6.68	~0.94	6.27

Table 3.1 Solar Panel Testing

As seen from the results shown in Table 3.1, during sunny conditions, we were able to obtain a power of 28.34 W. This is more then enough power for the system function properly as our system uses about 12 W. Lower values are to be expected due to the low efficiencies with solar panel as explained in section 2.1.

3.2 Solar Charge Controller & Battery

According to the requirements listed in Table C.1, the solar charge controller & battery satisfies Requirement 2. The solar charge controller proved to be functioning correctly together with the battery. The white LED light indicates battery is charging, green LED light indicates battery is discharged, and red LED light indicates battery is fully charged. Table 3.2 shows the results found during different testing. For further verifications see Figure C.1, Figure C.2, and Figure C.3 in Appendix C.

Type of Testing	LED Indicator	Battery Voltage (V)	Solar Panel Input Voltage (V)
Charging	White LED On	12.65	13.50
Discharged	Green LED On	6.689	N/A
Fully Charged	Red LED On	14.70	13.50

Table 3.2 Solar Charge Controller Testing

3.3 Flyback Converter

The flyback converter satisfies Requirement 3 listed on Table C.1. The 555 timer runs at a frequency of 30 kHz with an output of 180 V. According to the output generated on the flyback converter circuit shown below in Figure 3.1, the 555 produced a frequency of 29.89 kHz and an output of 177 V, which is approximately within the required specification.

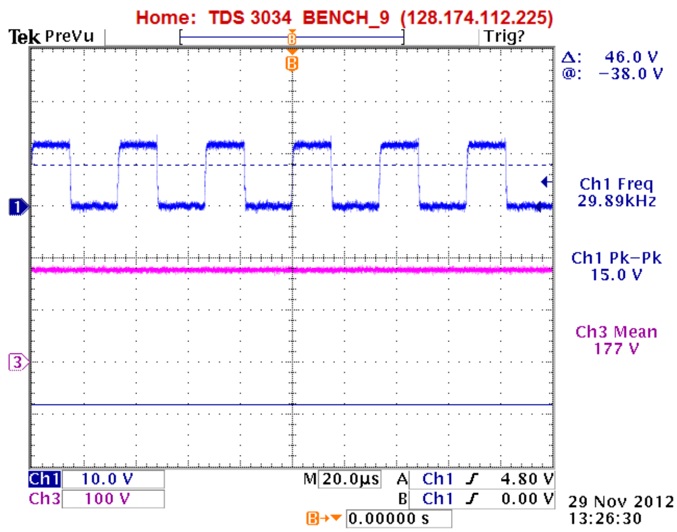

Figure 3.1 Flyback Converter Output

Using a multimeter to read the output of the fly-back converter, 179.01 V was measured without the reactor circuit connected. However, once the reactor circuit was connected to the fly-back converter, the output dropped to 137.41 V. Although the output voltage did not reach 180 V once connected to the reactor circuit, the output to the reactor still falls in the range of 2-3 kV, which means all reactor circuit requirements are met and therefore so are the fly-back requirements. See Figure C.4 and Figure C.5 for the output displayed on the multimeter without reactor circuit connected and with reactor circuit connected, respectively.

3.4 Reactor Circuit & Reactor

The reactor circuit and reactor satisfy Requirement 4 listed in Table C.1. The reactor circuit outputs a pulse wave with a voltage of 2.44 kV peak-to-peak, which lies in the range of 2-3 kV. This pulse wave was able to run the ozone reactor. The waveform generated on the oscilloscope is shown on the following page in Figure 3.2.

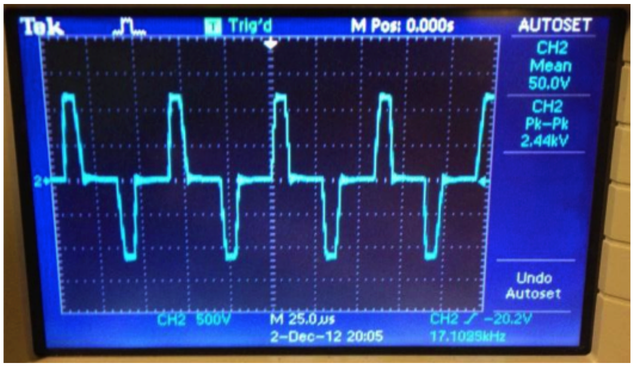

Figure 3.2 Reactor Circuit Pulse Wave Output

3.6 Half-Bridge Circuit

The half-bridge circuit satisfies Requirement 5 listed in Table C.1, without the pump attached. An output of 180 V RMS is required to run the pump. The circuit was able to output 197 V RMS. However, once the pump was connected to the half-bridge circuit, the output lowered to 89.6 V RMS. Thus, failing to meet the requirement. This decreased the airflow produced by the pump. To find a solution to this issue, an increase in supply voltage can compensate for the decrease in voltage. In Figure 3.3 and Figure 3.4, channel 2 shows the output generated on the oscilloscope without and with the pump attached, respectively.

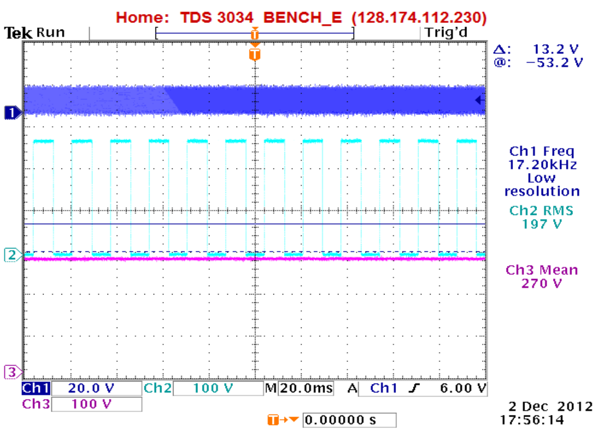

Figure 3.3 Half-Bridge without Pump Output

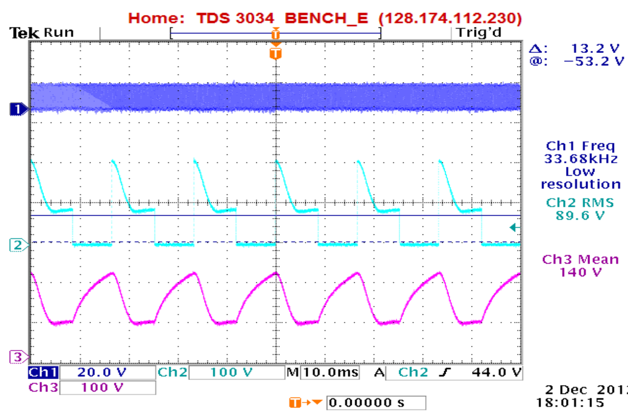

Figure 3.4 Half-Bridge with Pump Output

3.8 Microcontroller

When looking at the display of the microcontroller, it is clear that the display is functioning and displaying properly from both a USB source and battery source. In the microcontroller picture shown in Appendix B, B.7, two displays are shown that a decimal number can be displayed along with text. Furthermore, the display matching the code meets the requirement in which the code compiles and displays properly. However, since INA219 circuit was never built because of a miss-made

PCB, it fails to meet the requirement of reading and displaying the input voltage and current.

4. Costs

4.1 Components

Component	Total Price ($)
Solar Panel	159.99
Solar Charge Controller	15.00
Battery	25.00
Flyback Converter	7.44
Reactor Circuit	11.00
Half-Bridge Circuit	6.95
TI Launchpad	4.99
LCD Display	12.00
Fish Pump	10.00
Reactor	5.00
Total Parts Cost	257.37

Table 4.1 Costs of Components

Break down of individual component parts are listed in Table D.1 and D.2 in Appendix D.

4.2 Labor

Name	Hourly Rate (HR)	Total Hours Invested (THI)	Total Cost = HR x THI x 2.5
Matt Dubois	$30	160 Hours	$12,000
Albert Lo	$30	160 Hours	$12,000
Eric Liu	$30	160 Hours	$12,000
Total Labor Cost			$36,000

Table 4.2 Costs of Labor

4.3 Total Costs

Grand Total = Total Parts Cost + Total Labor Cost
= $257.37 + $36,000.00
= **$36,257.37**

5. Conclusions

The design of the Solar Aqua Sterilization System with Micro-plasma Ozone Reactor has been completed and is operational. However, there are still work that needs to be performed with future work that need to be considered.

5.1 Accomplishments

The S.A.S.S. successfully produced ozone using a rechargeable battery as the power source. Furthermore, attaching a solar panel allows the system to be self-sustaining and eco-friendly.

5.2 Future Work

The testing of the reactor itself is still in development. It is still uncertain when the development of the ozone reactor will be completed for consumer usage. Also, the system has not been tested on the actual site where it will be used. Depending on where the system will be located, the solar panel will need to be adjusted to obtain the optimized angle for receiving sufficient amount of sunlight in order to charge the battery.

5.3 Ethical Considerations

In doing this project, our goal was to create a system purely for humanitarian purposes. In no way will the abilities of this project be exploited. It will be used for only one purpose, to give the people in third world countries access to clean, affordable water. According to IEEE Code of Ethics and ACM Code of Ethics, the ethical guidelines will be met.

No profit will be made of this project since other people designed most of the main components. We were the ones that brought it all together. On that note, throughout the entirety of this project there have been many circuits and components that were not designed by us. The circuit design for the pulse generator as well as the reactor were designed and built by Professor Gary Eden, Professor Sung-Jin Park, and the graduate students at the optical lab. Thus, based on ACM Code of Ethics, code 1.5 states "*give proper credit for intellectual property*". In no way will credit be taken for coming up with the design for any of these components and they will be properly credited for their design.

Furthermore, the system will operate at high voltage and frequency. According to the first code of IEEE ethics, "to accept responsibility in making decisions consistent with the safety, health and welfare of the public, and to disclose promptly factors that might endanger the public or the environment", the system will make sure to satisfy the public safety standards.

References

[1] LM555 Timer, datasheet, Texas Instruments, Inc., 2006. Available at: http://www.ti.com/lit/ds/symlink/lm555.pdf. Accessed September 2012.

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[3] R. Dekker. Flyback Converters for Dummies. [Online]. Available at: http://www.dos4ever.com/flyback/flyback.html. Accessed September 2012.

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[7]Lars Kristian Roland. LCD-Button-BP v2. [Online]. Available at: http://lars.roland.bz/lcd/lcd-button-bp-v2/. Accessed October 2012.

[8]Texas Instruments. MSP430 LaunchPad (MSP-EXP430G2). [Online]. Available at: http://processors.wiki.ti.com/index.php/MSP430_LaunchPad_(MSP-EXP430G2). Accessed October 2012.

Appendix A

50-Watt Solar Panel Comparison

Sunforce 50-Watt Amorphous Solar Panel:

Available at: http://www.homedepot.com/buy/electrical/solar-power/sunforce-50-watt-amorphous-solar-panel-50042.html#.UMaLRqX3C8U

Price: $299.66
Price/Watt: $299.66/50 Watt = **$5.99/Watt**

Sunforce 50-Watt Solar Panel:

Available at: http://www.lowes.com/pd_322515-11338-50042_0__?productId=3197263

Price: $385.00
Price/Watt: $385.00/50 Watt = **$7.70/Watt**

Sunforce 50-Watt Pro-Series Amorphous Solar Panel:

Available at: http://www.radioshack.com/product/index.jsp?productId=12964239

Price: $249.99
Price/Watt: $249.99/50 Watt = **$4.99/Watt**

Purchased 50-Watt Solar Panel:

Available at: http://www.ebay.com/itm/New-50-Watt-W-50W-Solar-Panel-Cell-Charger-Charge-Controller-Regulator-Mono-12V-/221093765885?pt=US_Lighting_Parts_and_Accessories&var=&hash=item791895b69a

Price: $159.99
Price/Watt: $159.99/50 Watt = **$3.19/Watt**

Appendix B

Schematics & Devices

B.1 Solar Charge Controller Map Out:

Figure B.1 Solar Charge Controller Map Out

B.2 Reactor Circuit Schematic

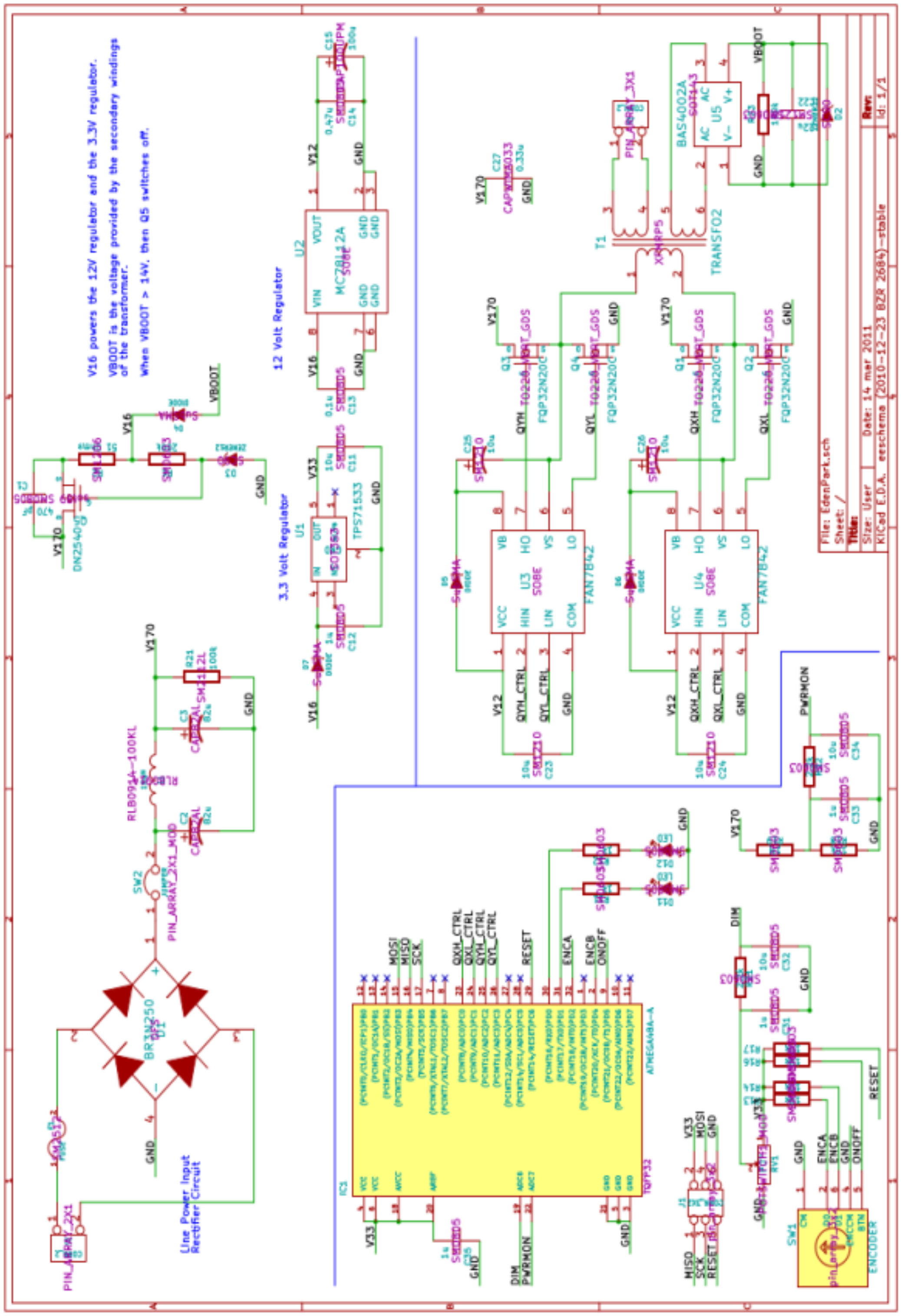

Figure B.2 Reactor Circuit Schematic

B.3 Reactor Circuit Device

Figure B.3.1 Reactor Circuit Device

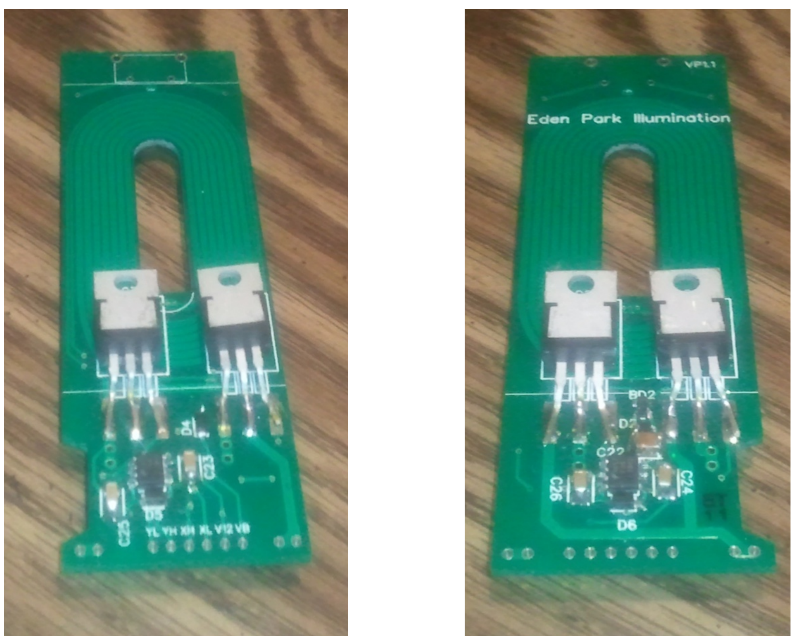

Figure B.3.2 Reactor Circuit Device (Half-Bridge)

B.4 Pump Device

Figure B.4 Pump

B.5 Ozone Reactor

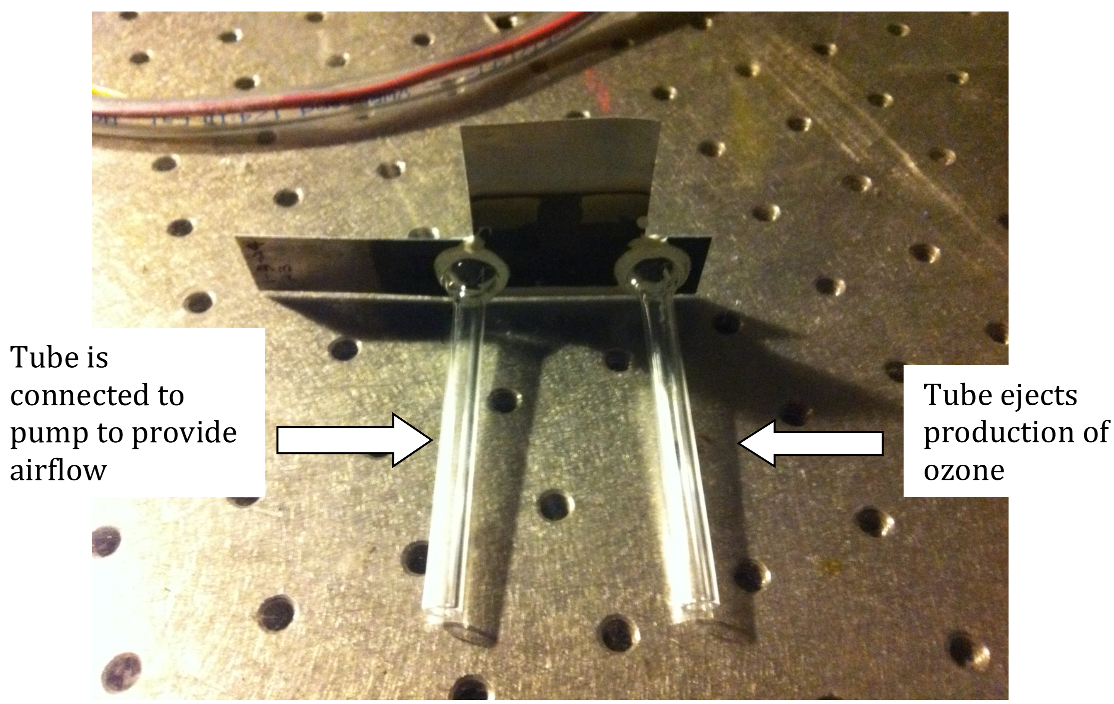

Figure B.5 Ozone Reactor

B.6 TI Launch Pad with INA219 Schematic

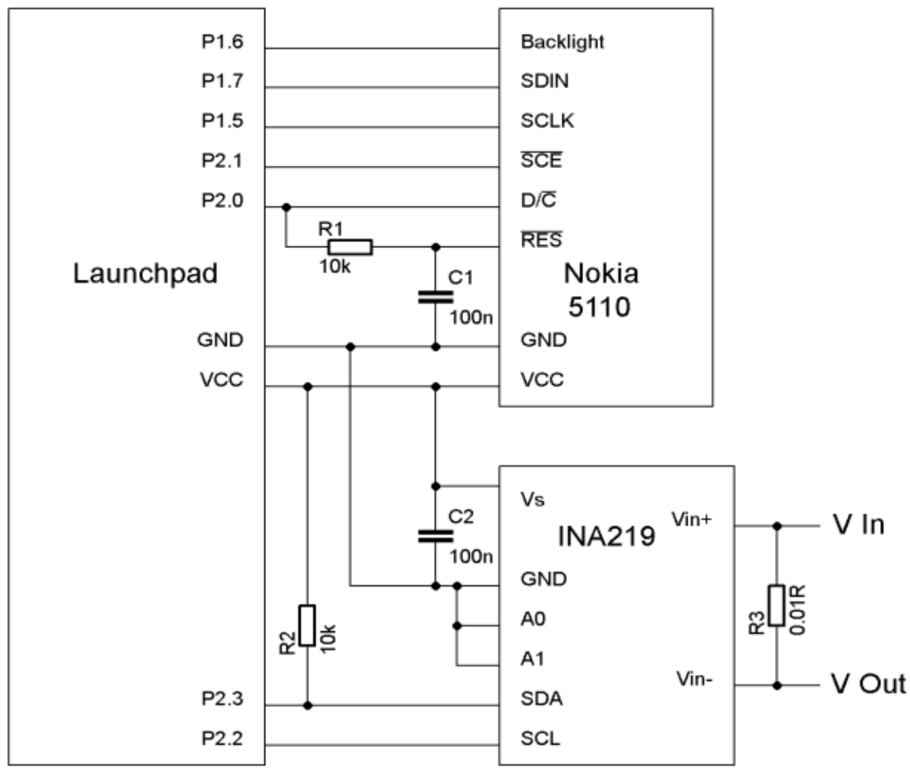

Figure B.6 TI Launch Pad with INA219 Schematic

B.7 TI Launch Pad with INA219 Device

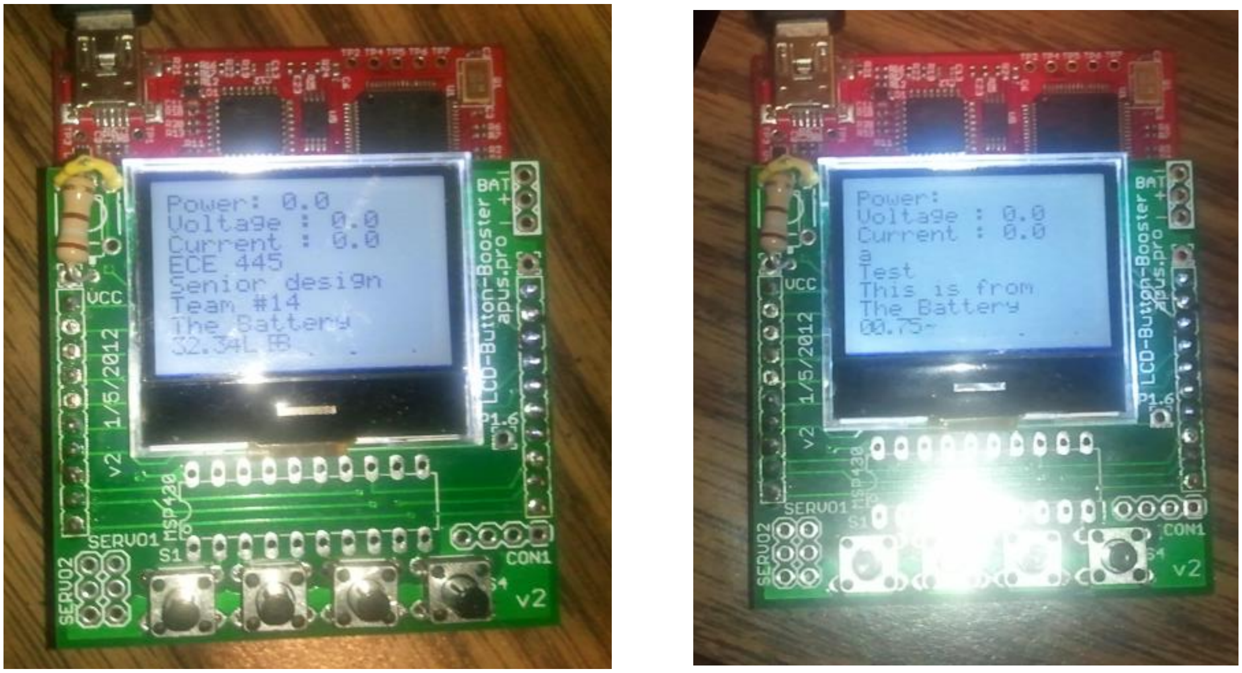

Figure B.7 TI Launch Pad with INA219 Device

B.8 Enclosure

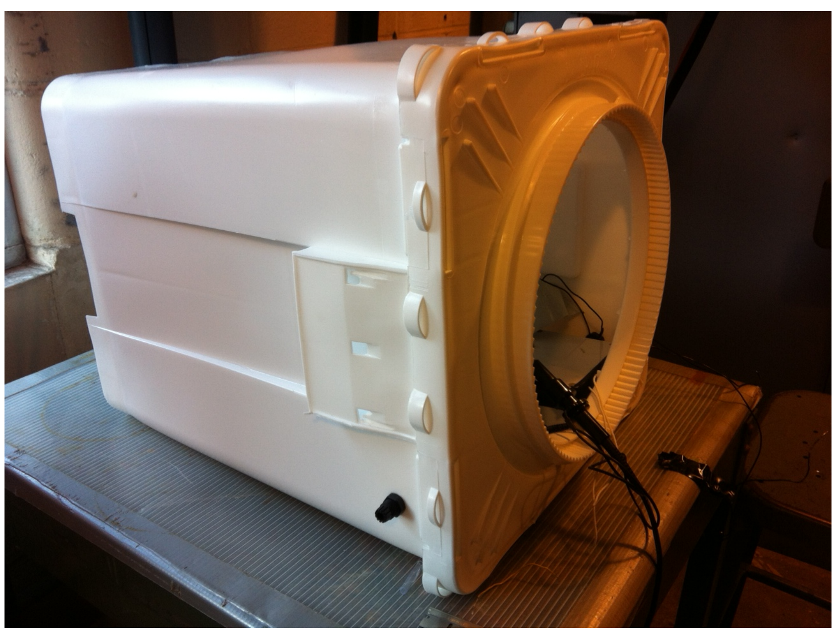

Figure B.8.1 Enclosure for system

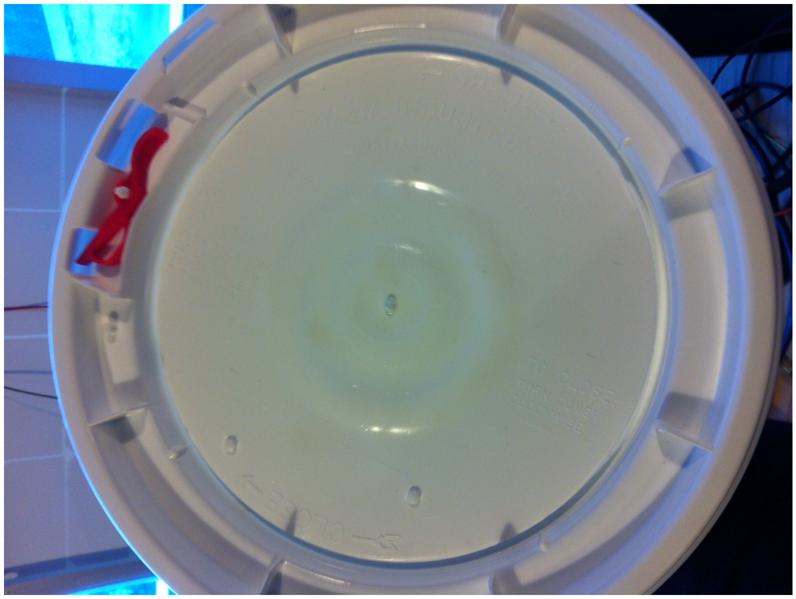

Figure B.8.2 Enclosure Lid

B.9 Overall Circuit Schematic

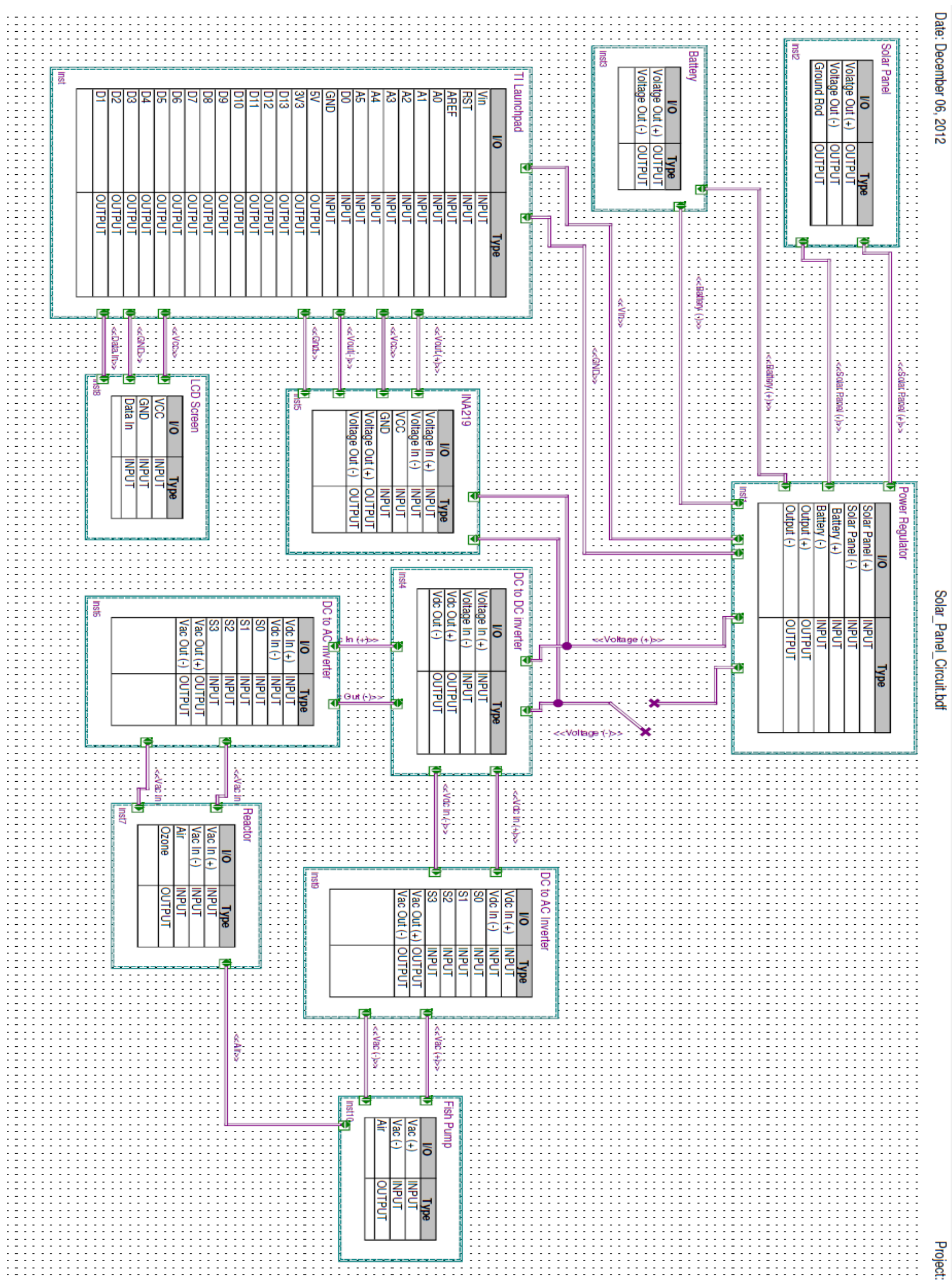

Figure B.9 Overall Circuit Schematic

Appendix C

Requirement and Verification Table C.1

Requirement	Verification
1. Solar Panel outputs sufficient power a. Opened-Circuit voltage is 21.60 V. Rated Voltage is 17.60 V. b. Maximum Short-Circuit current is 2.98 A. Rated current is 2.85 A. c. The Rated Maximum Power for the panel is 50W. d. Voltage greater than 12 V and current should charge battery in reasonable amount of time.	1. Place solar panel in proper lighting. a. Connect panel to the multimeter using voltage probes to the connections rated for proper voltage. b. Connect panel to multimeter probing for current. c. Multiply the measured voltage and current. d. The battery is a 12 V 12 A-h battery, so with the measured voltage and amps one can calculate the charge time. With voltage above 12 V, dividing 12 A-h by current output in Amps will give how long charging will take.
2. Solar Charge Controller functions properly with battery charged to ≥ 12 V a. If battery voltage < 12 V the green LED should be on b. If battery voltage ≥ 12 V the red LED should be on	2. Connect the solar panel and battery to the solar charger. a. The green LED should be lit if the battery needs charging. b. Check the charge controller. The red LED should be lit for full charge.
3. The input of the Reactor Circuit is ~180 V. a. The output should read 180 V. i. Voltage at high side of primary winding should be 12 V. ii. Gate signal of MOSFET should be a square wave with ~12 V pk-pk and	3. Use a multimeter with proper voltage ratings. These can be checked in the manual. a. Probe the output terminals with a voltage probe and multimeter. i. Probe voltage at primary winding with voltage probe and multimeter with reference to

	~30 kHz frequency. iii. Source of MOSFET should be connected to ground. iv. Drain of MOSFET should be connected to the negative wire of the transformer. v. Output of gate driver, pin 4, should be a square wave with ~12 V pk-pk and ~30 kHz frequency. vi. Input to pin 1 of gate driver should be ~12 V. vii. Pin 3 of gate driver should be ground. viii. Input of gate driver, pin 2, or output of LM555CN_1 should, pin 3, should be a square wave of ~12 V pk-pk and 30 kHz. ix. Resistance of R3 is 1 kΩ. Resistance of R6 is 20 Ω. Resistance of R7 is 10 kΩ. Resistance of R8 is 27 kΩ. Resistance of R5 is 84 kΩ. Resistance of R4 is 150 kΩ. x. Pin 8 of LM555CN_1 is 12 V. xi. Pin 6 is connect to pin 2 on LM555CN_1. xii. Pin 4 is connected to 12 V on LM555CN_1.	ground. ii. Use oscilloscope and voltage probe to view waveform. iii. Use multimeter and visual inspection. iv. Visual inspection. v. Use oscilloscope and voltage probe to view waveform. vi. Probe pin 1 with multimeter. vii. Probe pin 1 with multimeter. viii. Use oscilloscope and voltage probe to view waveform at both pins. ix. Use multimeter to probe across resistors. x. Use multimeter. xi. Visual inspection. xii. Use multimeter. xiii. Use multimeter.

xiii. Pin 1 of LM555CN_1 is connected to ground.	
4. Reactor input is in the 2-3 kV pk-pk range. a. A pulse wave with a 2-3 kV pk-pk should appear. i. A square wave of ~20 V pk-pk and frequency 17 kHz should be present at each test point at the gates of MOSFETS Q1, Q2, Q3 and Q4 of the Reactor Circuit. ii. Check the voltages at the output of the microchip ATMEGA4BA-A for pins 23, 24, 25 and 26. The outputs should also be square waves with ~20V pk-pk and frequency 17 kHz. iii. 12V should appear at the input of the voltage regulators. iv. Voltage regulator MC78L12A should output almost exactly 12 V. v. Voltage regulator SDT353 should output almost exactly 3.3 V.	4. Use an oscilloscope with proper voltage ratings and display capabilities. These can be checked in the manual. a. Connect a voltage probe across pins 3 and 4 of the output of the Reactor Circuit. i. Using a voltage probe connected to an oscilloscope, probe the voltage points V1, V2, V3, and V4 on the Reactor circuit. ii. Using a voltage probe connected to an oscilloscope, probe the voltage points V5, V6, V7, and V8 on the Reactor circuit. iii. Using a voltage probe connected to an oscilloscope, probe the voltage points V5, V6, V7, and V8 on the Reactor circuit. iv. Connect a voltage probe to a multimeter and pin V12. Almost exactly 12 V should appear. v. Connect a voltage prove to a multimeter and pin V33. Almost exactly

	3.3 V should appear.
5. Input of the pump is ~180 V (RMS). a. Square wave with ~180 V pk-pk at connection between 33N25_1 Source and 33N25_2 Drain. i. Gate signal of 33N25_1 should be a square wave with ~12 V pk-pk and ~60 Hz frequency. ii. Gate signal of 33N25_2 should be a square wave with ~12 V pk-pk and ~60 Hz frequency. iii. Output of gate driver HI and LO, pin 7 and pin 4 respectively are ~12 V pk-pk and ~60 Hz. iv. Pin 3 of gate driver should be ground. v. Pin 1 of gate driver should be ~12 V. vi. Input of gate driver, pin 2, and output of LM555CN_2, pin 3, match a signal of ~12 V pk-pk and frequency of ~60 Hz. vii. Pin 1 of LM555CN_2 should be ground. viii. Pin 4 and pin 8 of LM555CN_2 should be ~12 V.	5. Use an oscilloscope or multimeter. a. Use voltage probe and oscilloscope to display wave at the test point. i. Use voltage probe and oscilloscope to display wave at the test point. ii. Use voltage probe and oscilloscope to display wave at the test point. iii. Probe pins with oscilloscope. iv. Use multimeter. v. Use multimeter. vi. Probe pins with oscilloscope. vii. Use multimeter. viii. Use multimeter.

6. Micro-Controller a. The Microcontroller displays the proper voltage, power, and current i. The display should properly have Power, Voltage, and Current Displayed on the screen. ii. 3.5 V maximum input to the microcontroller iii. Code has to compile with no warnings. iv. Correct reading from the INA219	6. Use a voltmeter and ammeter a. Use voltmeter and ammeter as a comparison to see if the reading is correct within a 3% difference. i. At different points of the circuit, measure voltage, current, and power and compare the value gotten ii. Use voltmeter to make sure proper voltage is provided iii. Check compiler iv. Use voltmeter and ammeter as a comparison to INA219 to see if the value is correct.

Appendix D

Component's Parts Cost

Flyback Converter

Part Number/Description	Quantity	Per Price ($)
IR111 (Gate Driver)	x1	3.36
LM555 (555 Timer)	x1	1.11
Capacitor (2n2)	x1	0.10
Capacitor (100 u)	x1	0.10
Capacitor (100 n)	x1	0.10
Capacitor (0.47 u)	x1	0.10
Resistor (27 k)	x1	0.09
Resistor (10 k)	x1	0.15
Resistor (20)	x1	0.15
Resistor (1 k)	x1	0.15
Resistor (150 k)	x1	0.15
Resistor (84 k)	x1	0.15
Resistor (1 k Pot)	x1	0.10
Resistor (0.46 k)	x1	0.15
IPP47N10S-33 (N-MOS)	x1	1.48

Table D.1 Flyback Converter Parts Cost

D.2 Half-Bridge Circuit

Part Number/Description	Quantity	Per Price ($)
IR111 (Gate Driver)	x1	3.36
LM555 (555 Timer)	x1	1.11
Capacitor (0.1 u)	x2	0.10
Capacitor (0.01 u)	x1	0.1
Capacitor (100 n)	x1	0.1
Capacitor (1 u)	x1	0.1
Resistor (10 k)	x1	0.15
Resistor (100 k)	x1	0.15
Resistor (50 k Pot)	x1	0.10
33N25 (MOSFETs)	x2	1.68

Table D.2 Half-Bridge Circuit Parts Cost