# Fluid Analysis in Solar Heat Pipes

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# INTRODUCTION

This senior project is centered on evacuated tube solar collector technology. The sponsor of this project, Professor Mason Medizade, owns a system like this sold by Duda Energy that he offered to let the team use to experiment with and potentially discover some optimizations that could be made with this technology. Specifically, this investigation is focused on the working fluid in the heat pipe within the evacuated tube. The goal of this project is to find the most effective configuration for this working fluid by changing the type of fluid and changing the volume of fluid inside the heat pipe. Effectiveness will be measured by the average temperature rise seen at the condenser over the total length of the test.

Evacuated tube solar collectors are most often used to heat water. They do so by having a highly absorptive interior film, inside of two layers of glass with a partial vacuum inside. The glass allows lots of radiant heat energy in from the sun, but the vacuum prevents that heat from escaping back out the walls of the tubes. Inside a cavity in these glass tubes there is normally a fin that touches the walls of the glass, and a heat pipe which is held by the fin. The heat from the sun is conducted into the heat pipe. Inside the heat pipe, a working fluid in liquid form sits at the base (either because of the angle of the tubes, or a wick inside). The heat vaporizes the working fluid and it rises to the top of the heat pipe, where a bulb sticks out of the glass cavity and into the water being heated. The heat is transferred to the water and the vaporized working fluid condenses, falls to the bottom, and the cycle repeats. A graphic representation of this is shown below.

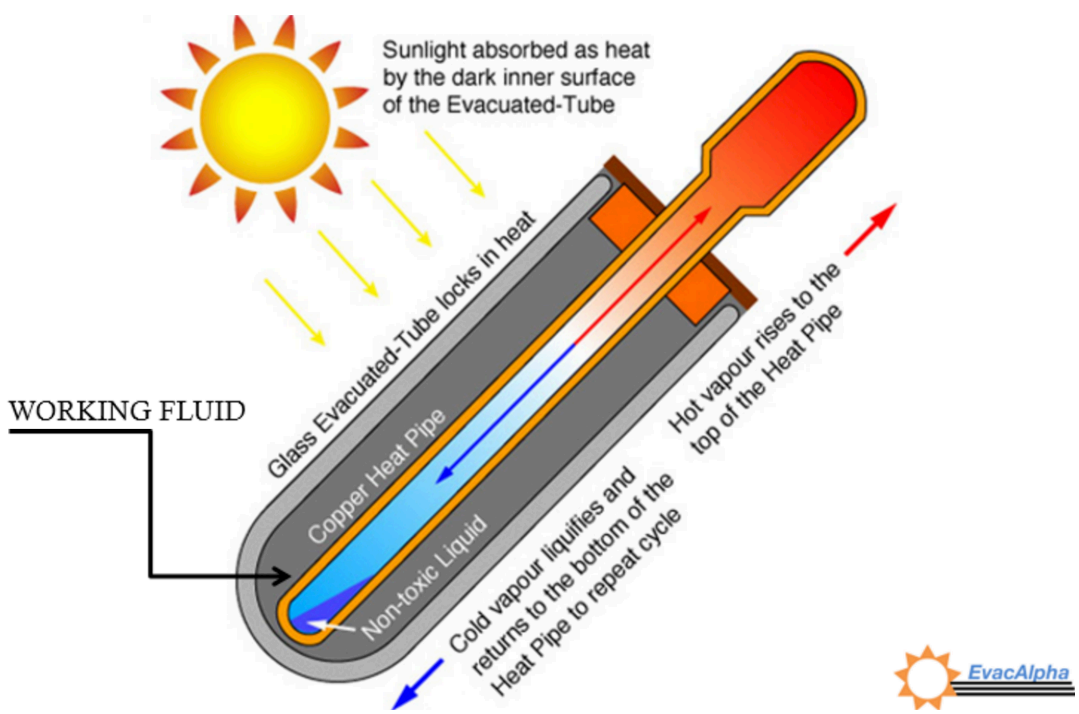



Figure 1. Explanation of the function of a heat pipe within a solar collector

The focus of the project is on the effect of the working fluid during a transient period. Evacuated Tube collectors have been studied immensely in terms of collecting more radiation from the sun. Heat pipes have been studied in a variety of functions (from spacecraft to electronics) but there has not been much research done on heat pipes in a situation where the heat entering the system can fade in and out of intensity, like it can with a solar source and unpredictable weather conditions. This is the niche where this project will contribute to furthering the knowledge of these systems.

## PREVIOUS CONCEPTS

In previous concepts the testing rig was similar to the final design. Even thought the testing rig is not the main part of this project, it is essential to build one that would allow the team to successfully test different parameters. In early concepts, a complete Solar Water Heater system design was taken into consideration for its functionality. A Solar Water Heater system is comprised of four main components: evacuated tubes, heat pipes, manifold, and mounting frame. Each of these parts serves a specific role in the system. A simplification of these is shown in Figure 2.


Figure 2. Evacuated Tube Solar water heater

After having a good understanding of the system and the goal of the project, the next step was to come up with a design what would allow the team to gather high quality data. Since the main goal of the project was to find the most effective configuration of the fluid inside the heat pipe, the only thing that needed to be designed was some kind of reservoir or storage for the water to be heated with the heat pipes, similar to the manifold. Unlike standard systems of this type, where the water coming in contact with the bulb is a relatively constant temperature and moves past it, to simplify the design for these tests the test rig will heat an insulated container of stationary water. The insulated box will protect the containers from the sun, wind, rain and other unwanted factors that would interfere with the experiments. These series of containers would replace the function of the manifold. It was decided that the material used to build the box and the mounting frame to be plywood and 2X4 wood studs. Sketches of the preliminary design details are shown in the figures below.

The figures below show the insulated box made out of wood and the main support made out of 2X4 wood studs and inside the box there are four containers. As mentioned above, these containers would be filled up with about one gallon of water. These containers are available to buy online and are 2 gallon Styrofoam buckets which would be adequate for the purpose of the project. Dimensions for the box would be determined based on the size of the container. For convenience, the box was designed so that it also has a hinged cover that would allow the operator to easily open and close the container and work with the components inside the box.

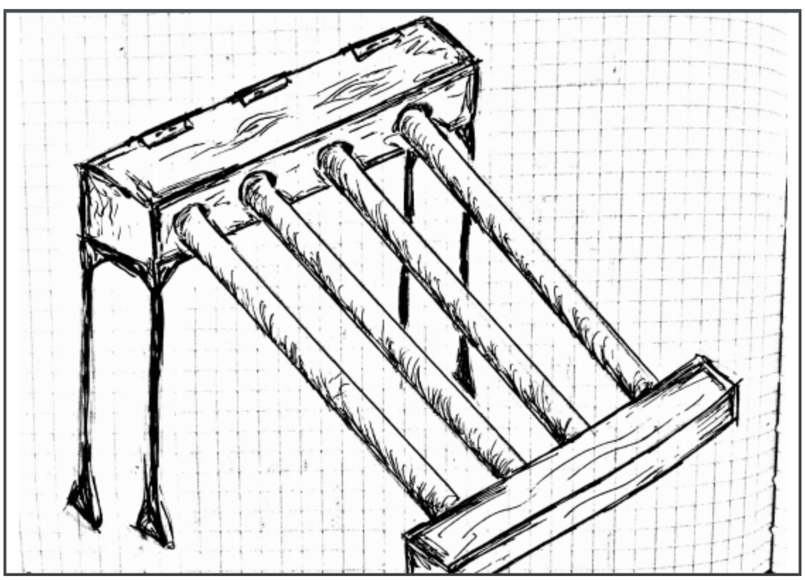


Figure 3. Complete preliminary design of test rig

When analyzing the different components of the test rig, the team concluded that manufacturing these components would not be very complicated since most of the material is wood. Also, all of the cuts in the wood would be made in-house using the equipment in the Hangar and Mustang 60 machine shops. The only main issue would be making special cuts in the wood, which could add some complexity and time going into manufacturing these parts. This is not the emphasis of this project; the emphasis is on testing. By eliminating manufacturing time the team can spend more time experimenting with fluids inside the heat pipe.

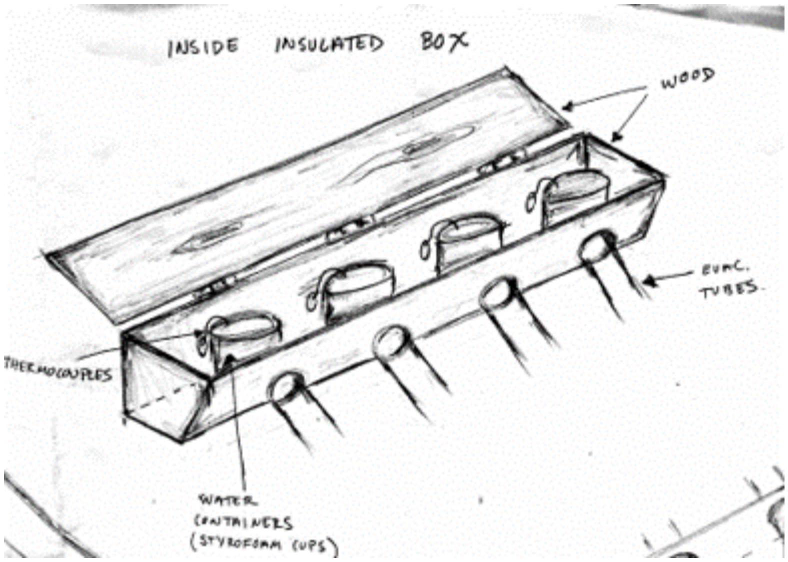



Figure 4. Opened insulated box with buckets

Figure 5 shows a more detailed design of the preliminary testing rig. It shows the heat pipe bulb completely submerged in water inside the container. There are also various thermocouples placed in specific spots inside the buckets. These thermocouples will then be connected to a DAQ (Data Acquisition) system that would be recording temperature changes in the water.

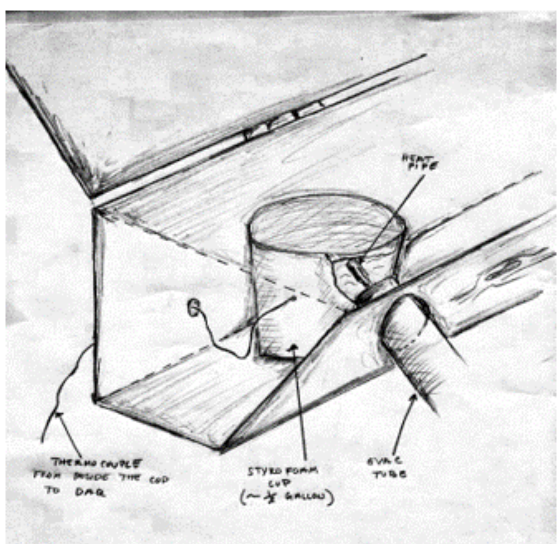



Figure 5. Detailed design inside the insulated box

# TEST RIG

After recognizing the added complexity of manufacturing a test stand, it was chosen to use a sawhorse that is screwed into a manufactured table holder. This final test rig design is shown below. The blue base is a sawhorse that is bought from Amazon. The wooden table will be manufactured. This design saved about 15 hours of shop work and is a lower risk design that has a higher chance of success. The saved time will be better spent on running tests.

Figure 6. Overall Test Rig

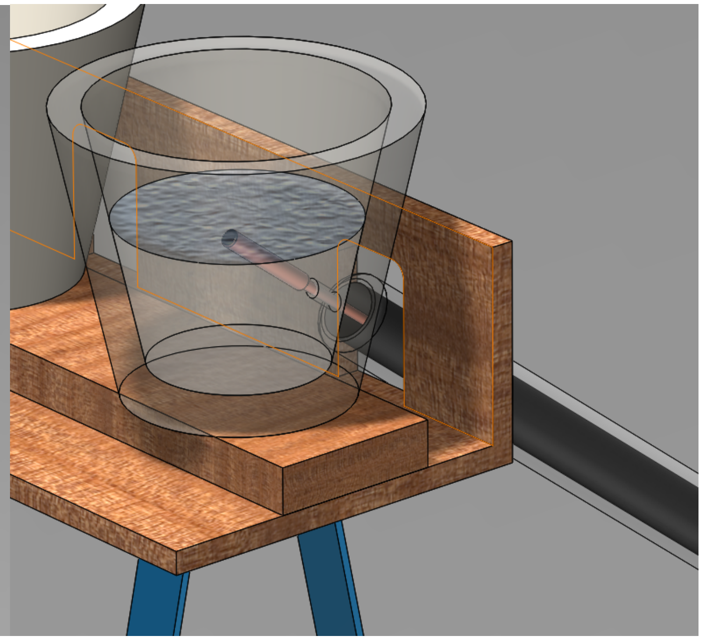


Figure 7. Test Rig-Tube Interface

The overall test rig design includes four testing stations. The heat pipes will be primarily supported by the wooden slot and will be prevented from sliding away with blocks placed at the base of the tube as shown in the figure. Setting the distance between these blocks and the table will establish the constant angle the tubes will be held at. The buckets are held up by a riser board, which is needed to allow the volume of water to be reduced while keeping the condenser of the heat pipe submerged. The four buckets are made out of Styrofoam and will have a hole cut into them at an angle. This hole will allow the heat pipe to be inserted into the bucket. Its size will be just larger than the condenser diameter. The hole will be sealed during testing with reusable putty. The buckets will be covered with a lid that was manufactured to fit. There will be one thermocouple that is in the water and another that sits on the surface of the condenser. The L shape configuration was chosen because it provides simple manufacturing, less material and with the amount of water in the buckets there was no need for wind shielding to prevent spilling. A full box was considered but was not needed because the thick Styrofoam buckets provide adequate sun and wind shielding.

## MANUFACTURING

The manufacturing of the test table took place first. The cutting of the Styrofoam cups followed because the holes in the cups needed to be located by using the heat pipes and test rig. This procedure helped to compensate for any tolerance stack up during the test rig manufacturing. A process sheet is shown below.

Table 1. Manufacturing Processes

| Op. # | Procedure | Tool |
|---|---|---|
| 1 | Cut Wood to Size | Table Saw |
| 2 | Cut Slots for Heat Pipes | Router |
| 3 | Screwing Table Wall to Base Plate | Drill |
| 4 | Riser Pilot Holes | Drill |
| 5 | Riser Screws | Drill |
| 6 | Screw table assembly to Saw Horse | Drill |
| 7 | Mark Hole Locations on Cups | Test Rig and Sharpie |
| 8 | Cut Holes in Styrofoam | Drill |

The wood was cut to size at Miner's hardware when it was purchased. The table wall that has slots to hold the heat pipe was cut to size with the table saw and then the slots cut using a jig saw. Because the faceplate is the only non rectangular part, a drawing was made. This drawing can be seen in Appendix G. A skill saw was used to cut the straight lines and a drill used to get in to the internal right angles. The table wall was fastened to the base plate with 90° angle brackets that use two screws on each face. All screw holes have pilot holes to prevent cracking of the wood. When cutting the holes in the Styrofoam there was a risk for the foam to disintegrate and tear. The problem was mitigated by drilling a small hole first and then gradually stepping up the hole size. The hole size will be equal to the condenser diameter in order to keep it as small as possible. This reduced the amount of putty required and lowered the risk of leaking.

## TEST PROCEDURE

The very first step in this project's testing phase was be to preform a series of preliminary tests to assure the accuracy of future tests and to gain a better understanding of the fundamental aspects of the evacuated tube system. Once the test rig was built, the preliminary tests began. Below is a table of the questions about the system that are to be answered by these preliminary tests.

Table 2. Preliminary Tests Verifying Test Procedure Design

| Question | Test |
|---|---|
| Does the rotational orientation of the evacuated tube matter? | Have four identical tubes tested at the same time, each with a 90˚ different rotation for the tube. |
| Does the method of sealing the heat pipes after changing the fluid affect its performance significantly? | Compare an unmodified stock evacuated tube from Duda Energy to one where the fluid has been removed, put back in, and sealed with the plugs and or aluminum tape. |
| Does the normalization of temperature measurements with solar intensity work as an accurate standardization between different days of testing? | Using identical configurations, measure temperature at the output of the heat pipe bulb and normalize it using the solar intensity recorded at the same time on two days with different sky conditions and check to make sure the scaled values of $\Delta T/(W/m^2)$, which is the temperature measurement normalized by intensity, is roughly the same for the two days. |
| Is it critical to evacuate the heat pipe of air before resealing with a new fluid inside it? | If the resealing method does not significantly impact the results, then test a configurations where the heat pipe is unmodified (partially evacuated) to one that has been opened and resealed (contains air in the heat pipe). |

These preliminary tests were done during winter and spring quarter to show that the variables in question do not have a significant impact on the system. If, however, one of these variables was significant in its impact on system performance, then it would have needed to be monitored and maintained constant for all subsequent tests. The tube rotational position proved significantly different for different angles, one of these angles will be selected (the highest performing one) and would be maintained constant for all subsequent experimental tests. The resealing method did not work in terms of keeping the tests at an equivalent performance as the unmodified tubes because the resealing did not involve pulling the air out of the tubes, but the performance was adequate to compare our tests to other tests. Tests would often have leaking issues once the heat pipes got to much higher temperatures but, at this point any trends from the tests would have already been shown and the leaking did not often ruin any test's data. The normalization of measurements with the solar intensity proved to be mathematically unnecessary, and was also complicated by a malfunctioning DAQ that did not allow intensity measurements to be taken at the same frequency as the temperature measurements so a proper normalization could not be achieved. However the pyranometer data is relatively unchanging from test to test because all test days were clear, in the same location, at roughly the same time so the temperature data from test to test can be considered comparable. Resealing without evacuating the air was not done because of the complications it would create for the testing process. It would significantly reduce the amount of data that could be taken.

In order to keep the tests consistent and the data reliable, the team established a procedure as if this experiment were to be preformed in a class for a lab activity. The test was broken into Setup, Testing, and Clean Up but the setup became the largest portion since the test rig, evacuated tubes, and data collection system all needed some preparation before data could be collected. Below, see the procedure written up in the style of a lab handbook.

# EXPERIMENT PROCEDURE

## SETUP

### *PREPARING THE TUBES*

Before any testing can begin the heat pipes within the evacuated tubes must be set up with the working fluid of interest. First, remove the heat pipe from the evacuated tube and clamp in on to a flat surface. Use a 1/8" drill bit to make a hole at the bottom of the evaporator end of the heat pipe. Be careful to not drill through the far end of the pipe. Drain the fluid inside the heat pipe and rinse the heat pipe using distilled water and drain again. Use a syringe to measure and insert the test fluid into the heat pipe. The test fluid schedule was performed follows. Repeat all these steps until every test has been preformed.

| Fluid | Volume | | | |
|---|---|---|---|---|
| [none/dry] | 0mL | | | |
| Distilled Water | 1mL | 3mL | 6mL | 9mL |
| Ethanol (95% soln) | 1mL | 3mL | 6mL | 9mL |
| Acetone | 1mL | 3mL | 6mL | 9mL |

Each of these tests will be performed twice.

Once the test fluid at the volume of interest is filled into the heat pipe, insert a heat resistant plug into the heat pipe and secure the plug using a 7/32 - 5/8" hose clamp. Then, insert the heat pipe back into the evacuated tube. Secure the thermocouple tip at the heat pipe bulb by using another hose clamp.

### *PREPARING THE RIG*

Bring the 3-foot-tall sawhorse-plywood rig into the balcony in a sun-lit region for the test. Face the rig towards the south and place the cinderblocks roughly 4' in front of the rig. Lean four evacuated tubes through the slits in the rig onto the table, and anchor them at the cinderblocks (the cinderblocks may need adjusting) depending on what angle you are testing. Put a towel in between the tubes and the cinderblocks to protect them. Check that the angle of the tubes is roughly 35° with a digital level then cover the evacuated tubes with a black towel.

### *PREPARING THE TEST*

Bring over a cart with a laptop, DAQ, and thermocouple wire to the test rig. Set up the DAQ software on the computer to measure temperature from each of the four thermocouples. Use tape to attach one more thermocouple on each of the heat pipe bulbs to record the exact temperature. Set up the global pyranometer on the cart at an angle equal to the angle of the tubes, next to the test rig and plug it in to the DAQ. Set up the voltmeter to measure voltage from the global pyranometer and record it. Set the DAQ to record a data point every 10 seconds.

***Note***: When performing test using the buckets, bring the four insulated buckets to the test rig, and push the condenser end of the heat pipes into the buckets. Use the BluTack putty to seal the holes in the buckets round the heat pipes. Fill each bucket with 1 gallon of room temperature water recheck that the thermocouples are properly secured, and then close the lid on the bucket.

Figure 8. Page 1 of the Testing Procedure

## TESTING

### DATA COLLECTION

Once setup is complete, remove the towel covering the evacuated tubes and begin collecting data on the DAQ. Ideally, test between 10AM and 3PM to maximize solar intensity. Leave the system to collect data for the desired time. The data should be four plots of temperature (˚C) versus time of day or time in seconds, and one plot of voltage (V) versus time of day for the pyranometer data. Use the calibration constant on the pyranometer to convert the voltage output to a solar intensity (W/m^2).

### CLEAN UP

After the time is up or steady state data has been reached, stop the DAQ and save all data. Disconnect the thermocouples from the DAQ but leave the ones on the condenser side of the pipe. Keep in mind that pipes are extremely hot and avoid touching the pipe or fin right after the DAQ has been stopped. Bring the test rig and cinderblocks out of the way, and store the evacuated tubes in a safe place before preparing them for the next round of tests. When performing the test with buckets, wait for the condenser to reach a safe level before removing the BluTack, removing the heat pipe from the bucket, and draining the water.

***Note***: If time allows, after placing the heat pipes in a safe place, remove the heat pipe and fin from the tube and let me cool off to room temperature. Take off the hose clamp and plug and drain the fluid inside the pipe and rinse with distilled water. Place the heat pipe and fin back inside the tube.

Figure 9. Page 2 of the Testing Procedure

Adherence to a common testing procedure, and following the testing outlined in the Design Verification Plan (Appendix C) should keep the collected data valid and useful for analysis. Testing all the measurement equipment beforehand (checking that the thermocouples accurately measure temperature, and that the syringes are accurate and consistent for measuring out working fluid) is an important step outlined in the DVP but not stated as a part of this procedure. This is because, continuing with the analogy of this being a classroom experiment, those checks would be the responsibility of the lab instructor to test before the experimenters begin their testing. The team, however preformed these checks themselves before any setup or testing is done.

This testing procedure presented above was slightly modified during actual the testing phase. The use of buckets to hold water for a temperature measurement was not feasible given the limited functionality of the Data Acquisition System we received for our project. Since there were only four functional inputs to the DAQ we could only measure one temperature for each tube configuration during a test. Since the heat pipe bulb temperature is a more significant representation of the functionality of the system and doesn't complicate the measurement with the mixing and diffusion of temperature in the water reservoir, the heat bulb was the only measurement taken during the majority of the tests. This simplified the procedure and reduced the necessary testing time from 3 hours to roughly 1.5 hours.

Some important details illustrated below include plugging the heat pipes, measuring solar intensity, and thermocouple placement in the reservoirs. The heat pipes will be opened up with a drilled hole, and that will be used to drain, flush out, and refill the tube with the appropriate type and volume of fluid. The hole is very small (pictured below) so precision was needed in this step.

Figure 10. Close up of the hole used to drain, flush, and refill the heat pipe

After the heat pipes have been refilled, multiple processes can accomplish sealing them. The first option was to use Aluminum Tape. This is commonly used in the HVAC industry and is chemically and thermally resistant. Since we are working with chemicals and high temperatures, it is appropriate to use this. However, since the working fluid will be vaporizing, the pressure inside the heat pipe will be increasing. The tape was not strong enough to hold in this pressure. Instead, heat resistant plugs like the one shown below were used and those were held on with hose clamps around the base of the heat pipe. This proved to not be as effective as we hoped, but still usually held the heat pipe sealed for long enough to get a significant amount of data. Several tests were considered over once it was clear there had been a leak in the resealing method. We could see these leaks in the form of vapor and rapid temperature drop measured on the heat pipe bulb.

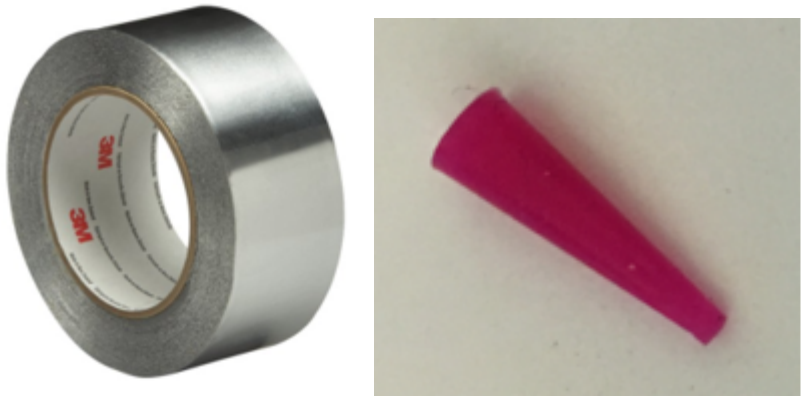


Figure 11. Aluminum tape and silicone plugs to be used to seal the hole in the heat pipe.

Measuring solar intensity is fairly simple and requires only a pyranometer, which outputs a voltage that can be converted into Watts per square meter with the calibration constant listed on the device. Further information about the pyranometer can be found in the next section, *Equipment*. Throughout the course of the day the intensity will peak at solar noon (some time between 11:00 and 13:00 depending on the time of year). The measurements made during the experiment of solar intensity can be compared to the weather station on campus that uploads their measurements online to check their accuracy. An example plot of solar intensity from this weather station on Building 52 on Cal Poly campus is shown below. The temperatures measured on the heat pipes and in the water will be normalized by this measurement because solar performance depends on the time and the day but this measurement of incoming power is an accurate way of comparing data taken on different days at different times.

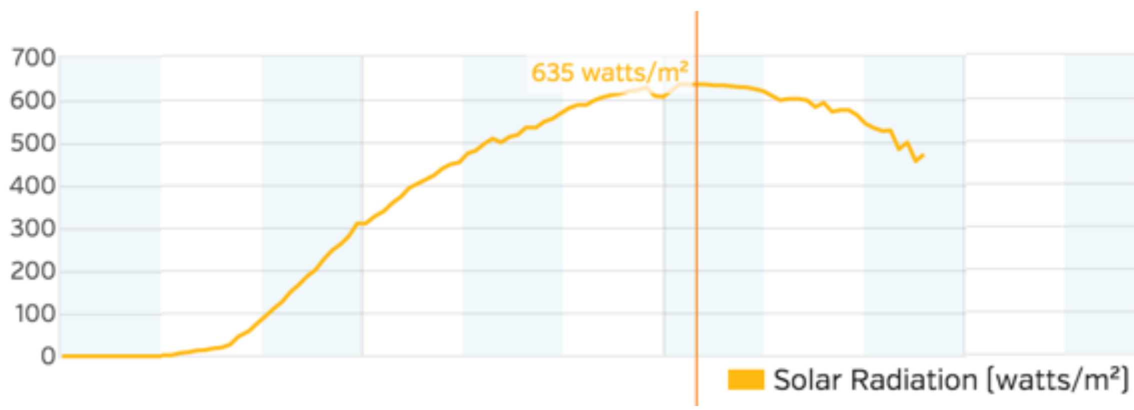



Figure 12. This is a sample of the solar intensity data plotted by a weather station on Cal Poly campus taken on January 26th, 2016

The two temperature measurements taken in each reservoir during the tests would have been difficult to keep exactly constant from test to test but the intention is to measure the temperature of the bulb of the heat pipe, and to measure an average temperature of the water in the reservoir. Since the bucket measurement was not taken due to the DAQ not having enough inputs, this was not an issue. The thermocouple was secured to the heat pipe bulb with a hose clamp to ensure it was reading accurately. This design should be taken as a future recommendation.

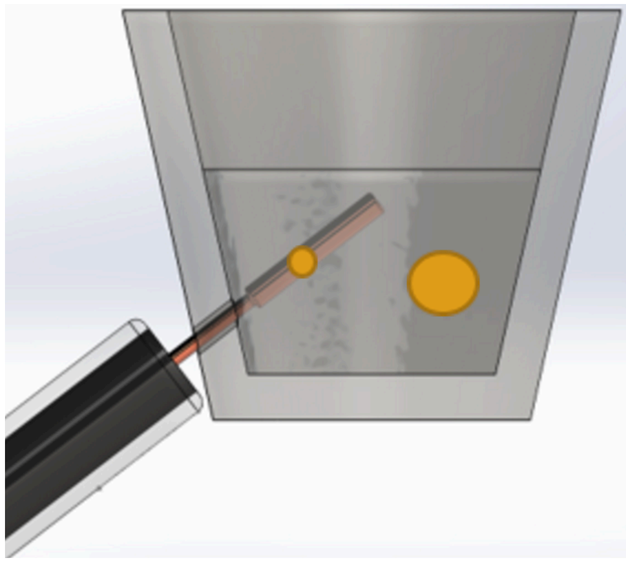


Figure 13. Thermocouple placement inside the reservoir

## EQUIPMENT

An Omega DAQ was used to collect temperature data as well as insolation data from the pyranometer. Normally, the DAQ system has eight inputs for thermocouples or 16 inputs if a common ground is used. The DAQ would have first been run using four inputs from the condenser thermocouples, which need to be more responsive than the water temperature thermocouples. There would be a total of nine inputs: four condenser thermocouples, four water thermocouples and one pyranometer.

However, after trying to use the DAQ in this configuration, it was discovered that 4 of the channels we had were defective, and buying a new one was outside the budget of this project. We could only record four inputs and chose to record the heat pipe bulb temperature with those inputs so we could have a data point taken every 10 seconds for those temperatures. The pyranometer data was taken by hand at a much slower rate, which is not a problem because the solar intensity in San Luis Obispo on the testing days was steady and slowly changing. An image of the Omega DAQ used for the entire project is shown below.


Figure 14. Omega Data Acquisition System

The condenser thermocouples were used in channels one through four and were plugged into the H and L Analog inputs. The single ended inputs would have been connected with the ground input inserted into the COM ports had we choose to use them.

Eppley manufactured the Pyranometer the team used. It was used with the clear filter shown which allows all wavelengths of light to be absorbed. The pyranometer was kept at the same angle as the tubes during testing in order to ensure accuracy in the results. Its voltage output was unfortunately unable to be fed into the Omega DAQ. This voltage was converted into insolation by the calibration constant: $10.2x10^{-6}$ [$V/Wm^{-2}$].

Figure 15. Eppley Pyranometer used for measuring solar intensity

# Cost Analysis

Part of the material needed to build the test rig was available in local stores like Ace Hardware and some was available online. The bill of materials is attached in Appendix A. The most expensive item is the blue saw horse that is replacing the wood base of the rig. It is worth the cost, however, because using it significantly reduced the amount of time the team spent in the machine shop.

The other relatively expensive item are the buckets. Eric Pulse, who runs the Mustang '60 Machine shop has used similar insulated buckets in the past and confirmed that the price the team found for them is albeit an unreasonable one, but the only price available for such an item. Other items such as tape, syringes, plugs etc. are relatively inexpensive and ship in multi-packs.

The final cost for the project was roughly $250, including the working fluids purchased to be tested. This is well under budget and we were glad to be able to save our sponsor, Professor Medizade, the extra money.

Figure 16. Adjustable Height Sawhorse

Figure 17. Frabill Insulated Bucket Reservoir

# Modeling

Simple modeling techniques knowing the specific heat of water and the average intensity incident on the evacuated tube system can be used to find a high-end estimation for the temperature change in the water that could be expected for one hour. The other assumption necessary for this first calculation is the estimated area that the solar radiation is incident upon. For a flat plate collector, the area is an easy width by length; for an evacuated tube, the assumption used for this model was that half of the tube (a hemisphere of the glass) had equal solar irradiation incident upon it.

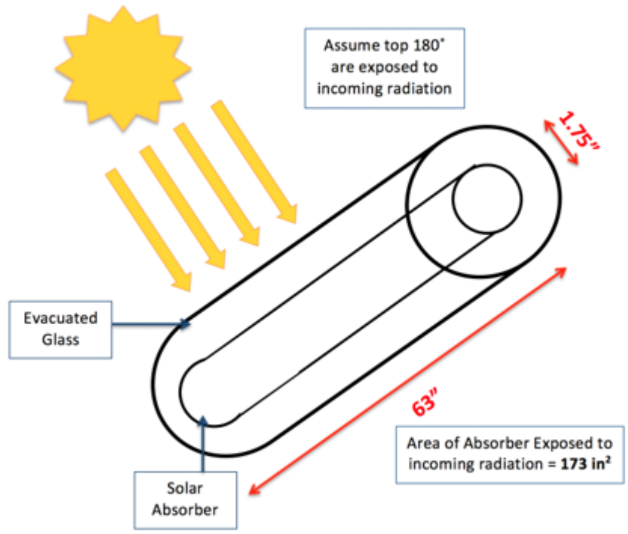



Figure 18. Area assumption for initial temperature output modeling.

Using these assumptions the following spreadsheet theoretical model was created where the input is the solar intensity and the output is the estimated temperature change of a gallon of water in one hour.

| PARAMETER | VALUE | UNITS |
|---|---|---|
| Diameter Absorbing Surface | 1.75 | [in] |
| Angle Exposed to Radiation | 180 | [˚] |
| Length of Exposed Section | 63 | [in] |
| Area Exposed to Radiation | 173 | [in^2] |
| | | |
| Incoming Solar Intensity* | 500 | [W/m^2] |
| | | |
| Specific Heat of Water | 4.184 | [J/g˚C] |
| Volume of Water | 1 | [gal] |
| Mass of Water | 3.78 | [kg] |
| | | |
| Water Temp Change in 1 hr | 13 | [Δ˚C] |
| | 23 | [Δ˚F] |

Figure 19. Preliminary Spreadsheet model for lossless heat transfer from solar radiation to water.

This model does not account for losses in the evacuated tube system that would stop the water from heating up this much in the allotted time. During winter quarter, this senior project group was enrolled in ME 450, *Solar Thermal Power Systems*, which taught the specifics of how to thoroughly analyze a solar collecting system for water heating and account for the losses inherent to it. After taking the class however, the methods used in typical analysis did not apply to the set testing methods the team used. Had the team been aware of and taken the class previous to the design of the experiments, a more useful model could have been made.

However using the textbook for this class, and the Engineering Equation Solver program's extended library associated with it, a plot of the solar irradiation as a function of the day was made.

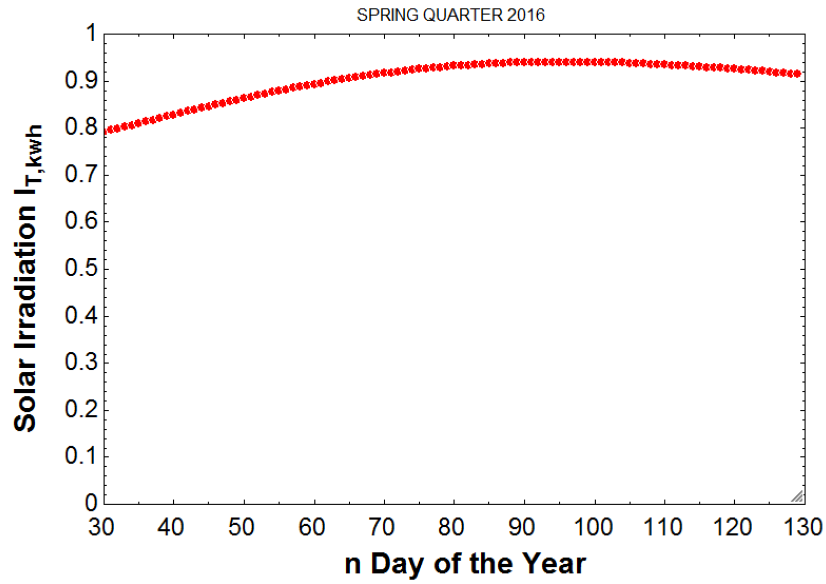



Figure 20. Plot of Irradiation on a tilted surface as a function of day of the year.

This figure shows the irradiation that was to be expected to be incident on a tilted surface at the 36.8˚ angle, the angle the test rig will have the evacuated tubes tilted at, for the noon hour, at the location of testing (the balcony of building 13), as a function of day of the year. The plot begins on day 30 (January 30th) and spans the length of time the team intends to fit testing into (day 130 is May 10th). Notice that there is a peak in irradiation near day 90. This is because solar collectors tilted at the angle of their latitude have a maximum at the spring and fall equinox. This test rig will have a tilt of roughly 37˚ and the latitude in San Luis Obispo is roughly 35˚ so the maximum irradiation is expected to be near the equinox (March 21st, day 81). Please see Appendix E for the EES code to create this graph.

## PREVIOUS RESULTS

There have been numerous papers published on the performance of heat pipes. These studies have focused mostly on heat pipe behavior under steady state conditions. Some tested at different powers and in applications ranging from laptops to solar water heating. In the paper titled *Experimental analysis of a heat pipe operated solar collector using water–ethanol solution as the working fluid,* It was found that the best performance characteristics were found with a tilt angle of 35°. The 35° optimum angle was at the top of a very broad peak, meaning that the angle had little influence on performance and angles between 20° and 50° showed similar performance. It was also found that ethanol in the working fluid improves the heat pipe performance at low heat flux and that concentrations of between 50% and 75% show the best performance (Jahanbakhsh et al. 2015).

Other papers have found that with too little fluid in the boiler section of the heat pipe, a phenomenon described as "starving" or "burnout" would occur. This is a process where the entirety of the liquid has been vaporized and the heat pipe can no longer effectively transport heat. The evaporator section overheats and the condenser section drops in temperature. This starvation state will continue until the power applied to the heat pipe is dropped below the critical value. (Mozumder et al. 2010)

Again, these studies are related to this project, however, the team intends to contribute more to this field of study. In particular the focus was on the transient state of the system as the system ramps up in heat as a function of the fluid within the heat pipes.

## RESPONSIBILITIES

Each member of the team has contributed to most every aspect of the project. However, certain duties in terms of leadership have fallen on individual members of the team. The breakdown of these responsibilities is shown in the table below.

Table 3. Breakdown of specific responsibilities.

| Michael Agavo | Will Dundon | Ben Krumholz |
|---|---|---|
| Materials & Costs<br>• Maintained and updated Bill of Materials as designs changed | Testing Procedure<br>• Explicitly defined the requirements order of operations for each test | CAD Model and Rig Design<br>• Created a CAD Model of the Test Rig and defined specifics of the design |
| Organizational Lead<br>• Kept track of official documents and receipts | Data Lead<br>• Created post-analysis sheet for every test documenting all results | Manufacturing Lead<br>• Lead the team in building and assembling the test rig |

Every member of the team contributed to the testing phase. This included working together to set up the tubes, set up the test rig, and set up the data measuring system. After running through the full test procedure a few times, the team became much more comfortable with the process of setting up the heat pipes, setting up the heat rig and DAQ, documenting the results, and cleaning up safely. Almost every test was performed with the entire team present. Each member was able to take on different roles because we all knew the process as a whole very well.

## RESULTS AND CONCLUSIONS

There were a total of 13 tests performed over the course of 2 months using the evacuated tubes and test rig. Each test's results are presented below, but see Appendix H for a summary of the dates of each particular test. Since there were some slight differences between the evacuated tubes, they were kept track of over the course of the tests to make sure no bias was being slipped through into the data from one tube being more effective than another. For example, tube B had a considerably more damaged aluminum fin than the other tubes, but by tracking it's performance across all test, we were able to conclude that this had no significant effect because Tube B did not perform considerably worse across all tests.

The first tests done were preliminary tests. If a comparison between rotation angles is to be made, first the tubes must be measured all at the same rotation as a control test. The figure below shows this test, where all the tubes were at 0 degrees. The legend is in reference to the subsequent test where the tubes were rotated to different orientations.

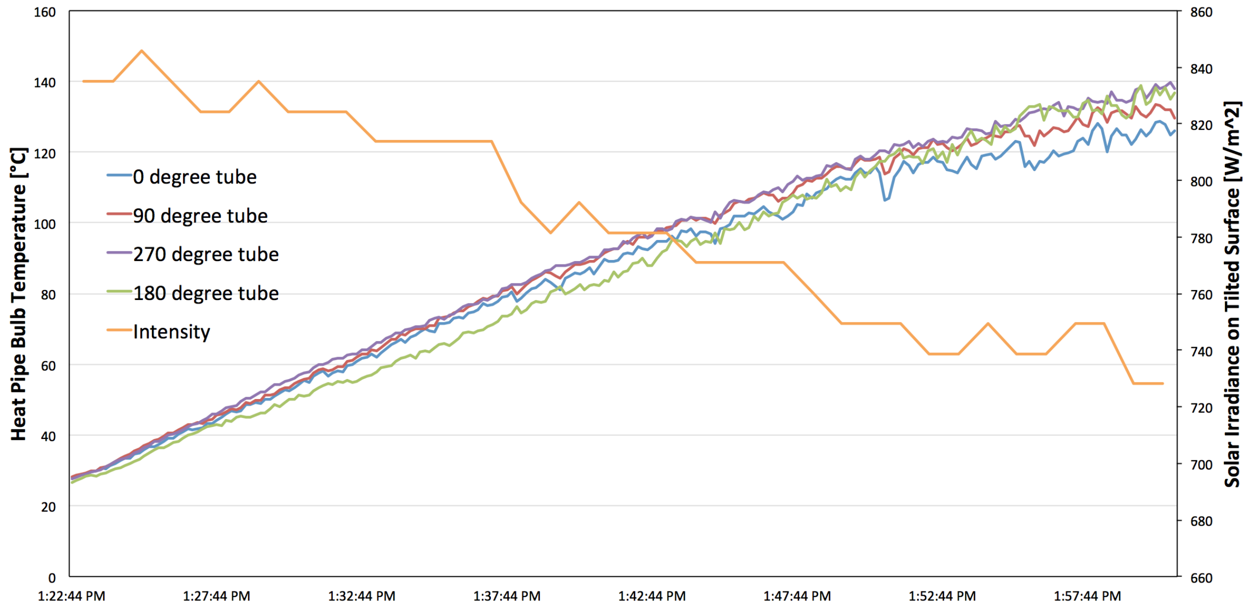



Figure 21. This is a plot of the heat pipe bulb temperature as a function of time for the test where all four tubes were rotated to the same angle. The labels on this plot indicate the rotated test that that particular tube was used later for. The pyranometer measurements are also shown here.

Based off of the control test data in**,** it is clear that the tubes preformed approximately identically when rotated at the same angle. This is seen in how closely the four tube's temperature vs. time lines overlap. This helps validate our results from the rotation tests because it shows there was no tube that was inherently better performing than another. It should be noted that the separation towards the end of the test is likely due to technical difficulties that were noticed near the end of the test. Namely, the thermocouples that were attached to the heat pipes began to separate from them and the tension from the wires and heat loosened the connection made by aluminum tape between the two.

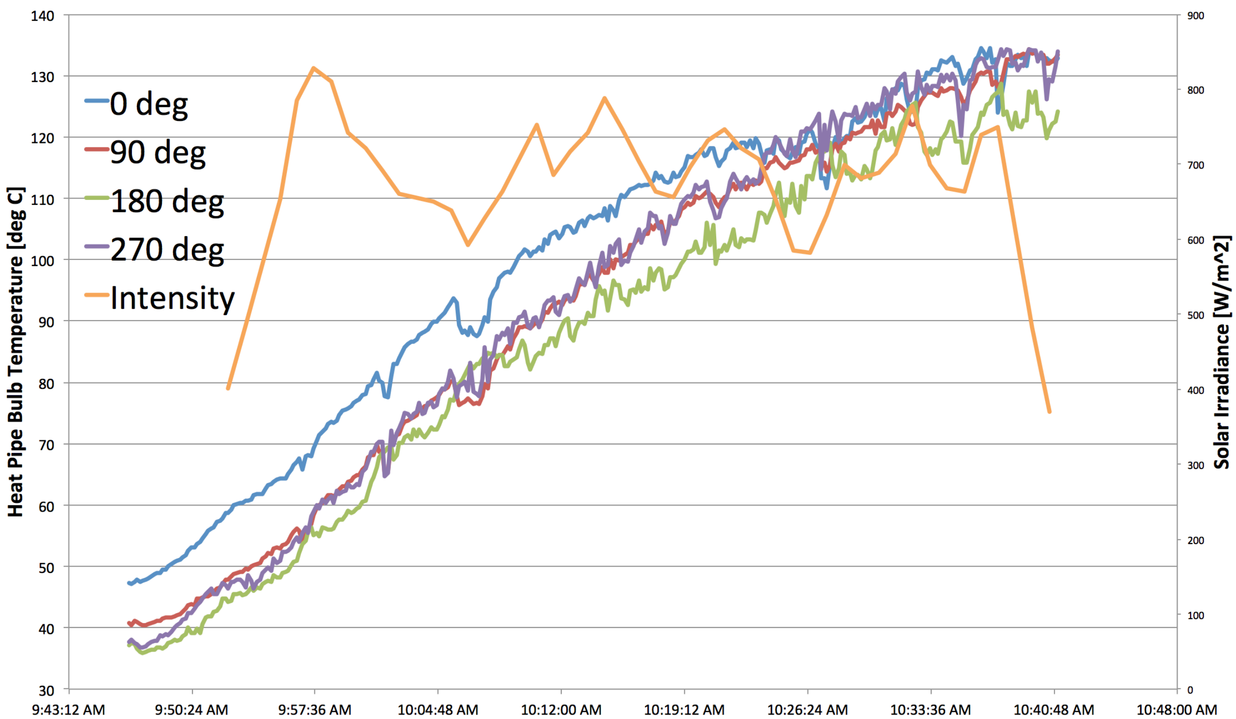



Figure 22 Temperature outputs at four different rotation angles.

The plot above shows each orientation relative to the other rotation angles. The 0 degree tube was brought out into the sun the earliest which explains the vertical offset in the collected data. It seems that the 180 degree orientation is significantly less effective because it does not reach the same temperature as the other angles after the hour of testing while the final temperature of the 0, 90 and 270 degree orientations are all roughly the same. This is important because the focus of the senior project is the transient state of operation.

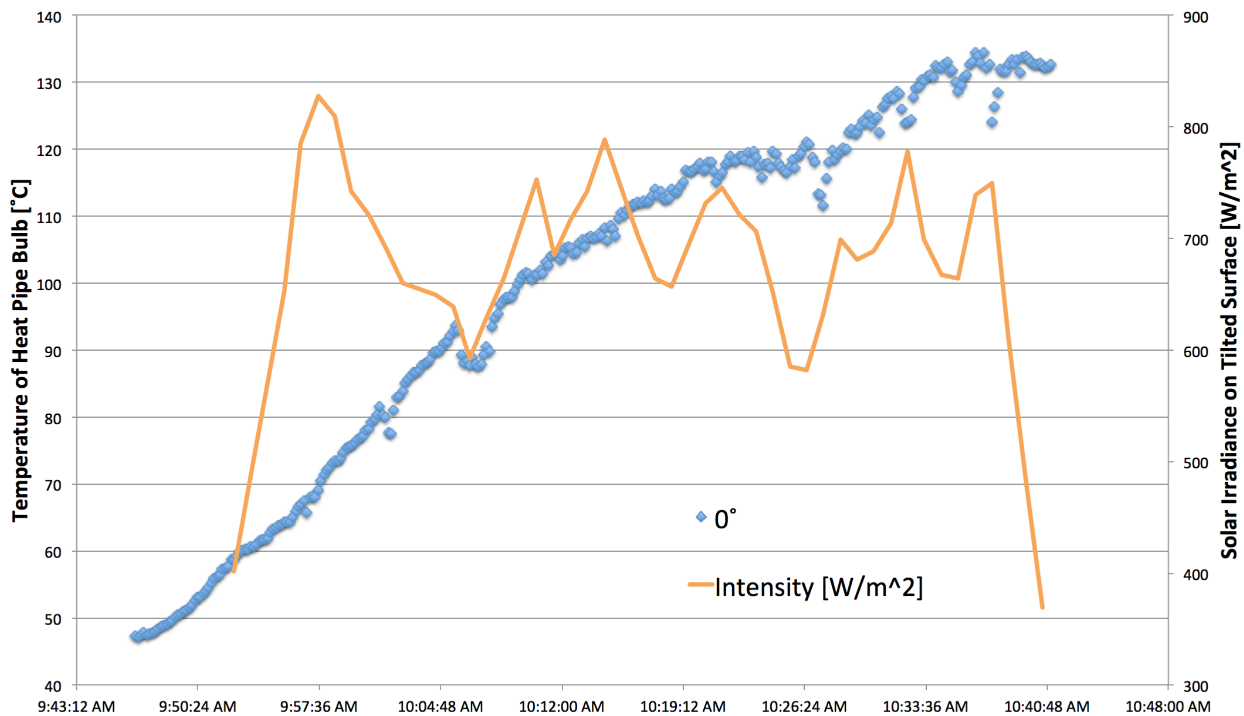



Figure 23. Temp. Output of the 0 degree tube with incoming solar irradiance for comparison.

The plot above compares the 0 degree orientated tube with the solar irradiance $G_T$ measured at the same angle as the tubes (roughly 35 degrees). The clouds on the morning of testing were very intermittent, so the irradiance data is very scattered. The plotted data for irradiance is plotted as a running average where each point is an average of it and the two points on either side of it. This was done as an effort to smooth the scatter of data points taken. Fortunately, this smoothing leaves the valleys intact. Most notably, the large drop in irradiance from 9:57:36 AM to 10:04:48 AM is mirrored in the temperature plot in a slight drop at the bottom of the irradiance plot's valley. This happens again around 10:26:24 AM. This orientation shows the most sensitive response to changes in incoming irradiance. This makes it a better candidate for a transient response analysis as proposed by the senior project, however in a real world application it would be most desirable for the heat pipe to resist cooling during a cloud transient.

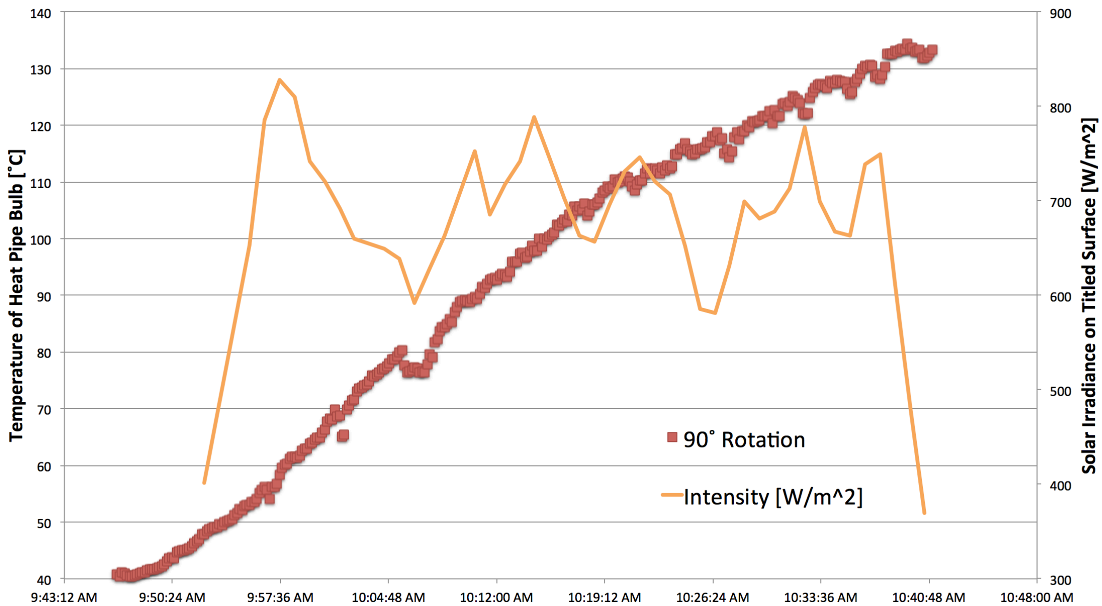



Figure 24 Temp. output of the 90 degree tube with incoming solar irradiance for comparison

This comparison seen in shows that the 90 degree orientation also responds slightly to the larger drops in incoming solar irradiance, but is clearly not as sensitive to it as the 0 degree orientation.

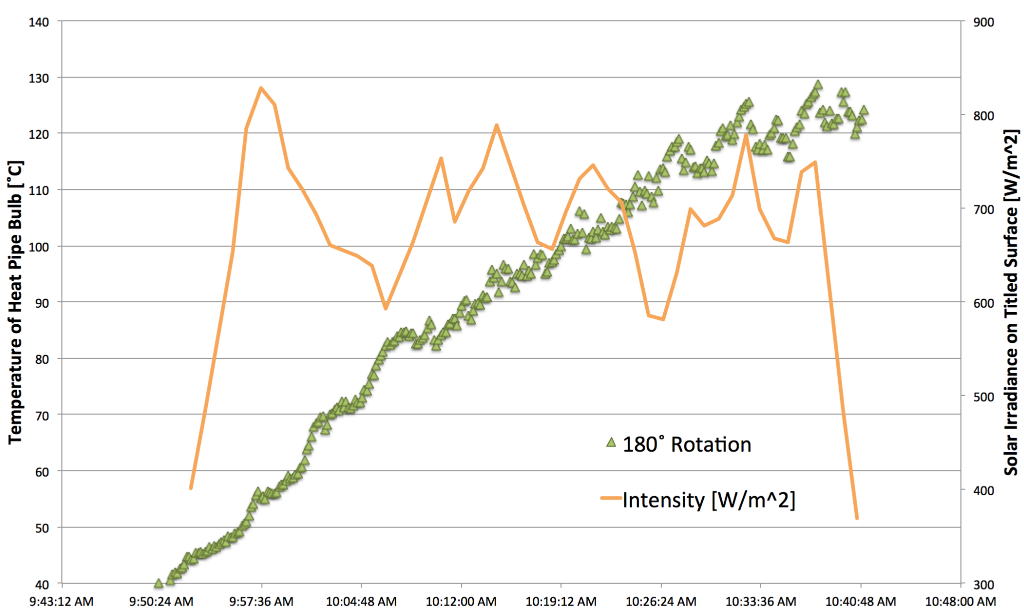



Figure 25. Temp. output of the 180 degree tube with incoming solar irradiance for comparison.

The 180 degree orientation data, seen in above has lowest offset and heats up to the lowest value likely because the fin is faced away from the sun. As can be seen in Figure 1, the heat path of the 180 degree orientation is by far the longest which results in a larger temperature gradient and an overall less effective fin. Another interesting piece to this plot is the dispersion of values as the tube heats up. This is either due to the thermocouple or that the heat pipe bulb is more sensitive to ambient changes at hotter temperatures.

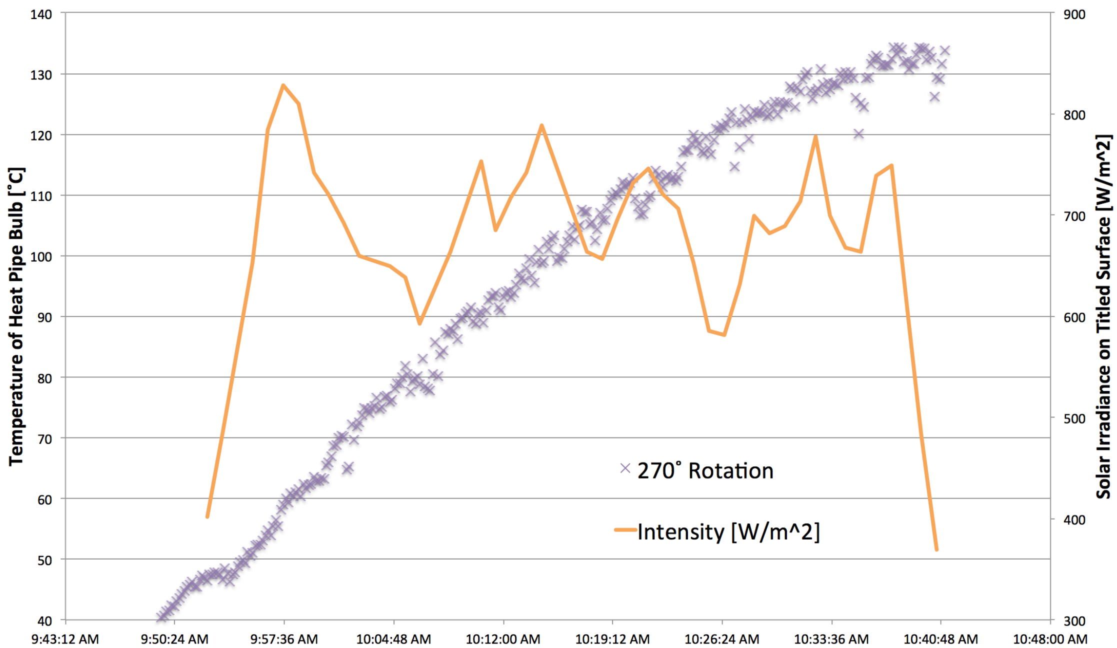



Figure 26 Temp. output of the 270 degree tube with incoming solar irradiance for comparison.

The plot of the 270 degree oriented tube response is very similar to the response from the 90 degree tube. This make sense because there is geometric symmetry between these two orientations. The test performed for this was done close to the middle of the day. It would be interesting to see if the 90 degree and 270 degree performed inversely better and worse in the morning versus the afternoon. From this experiment, it can be concluded that having the heat pipe face the sun increases the temperature at the heat pipe bulb, so likely the differences between the 90 and 270 degree orientations would be accentuated by comparing their performance when the sun has a more considerable azimuthal angle.

Based off of the data collected with regards to fin orientation it is clear that, although it does not knock out the hypothesis that it can change the max temperature achieved by the copper tubing, it does in fact play a role in the time it takes to reach the heat pipe's working temperature. The 0 degree orientation of the fin, which if you refer back to Figure 1 is the open end facing towards the sky, surpassed the rate of change of temperature of the other orientations. As stated earlier, this is important because the focus of the senior project is the transient state of operation. No matter the orientation the temperature of the fluid in the copper tube will eventually reach its max value, however, it is desirable for the water being heated by the system to heat up and recover from lower solar irradiances faster.

After the rotation tests, a control test using the unmodified evacuated tube, a tube with the stock fluid resealed using the plugs and hose clamps that would be used for all future tests, and two dry heat pipes.

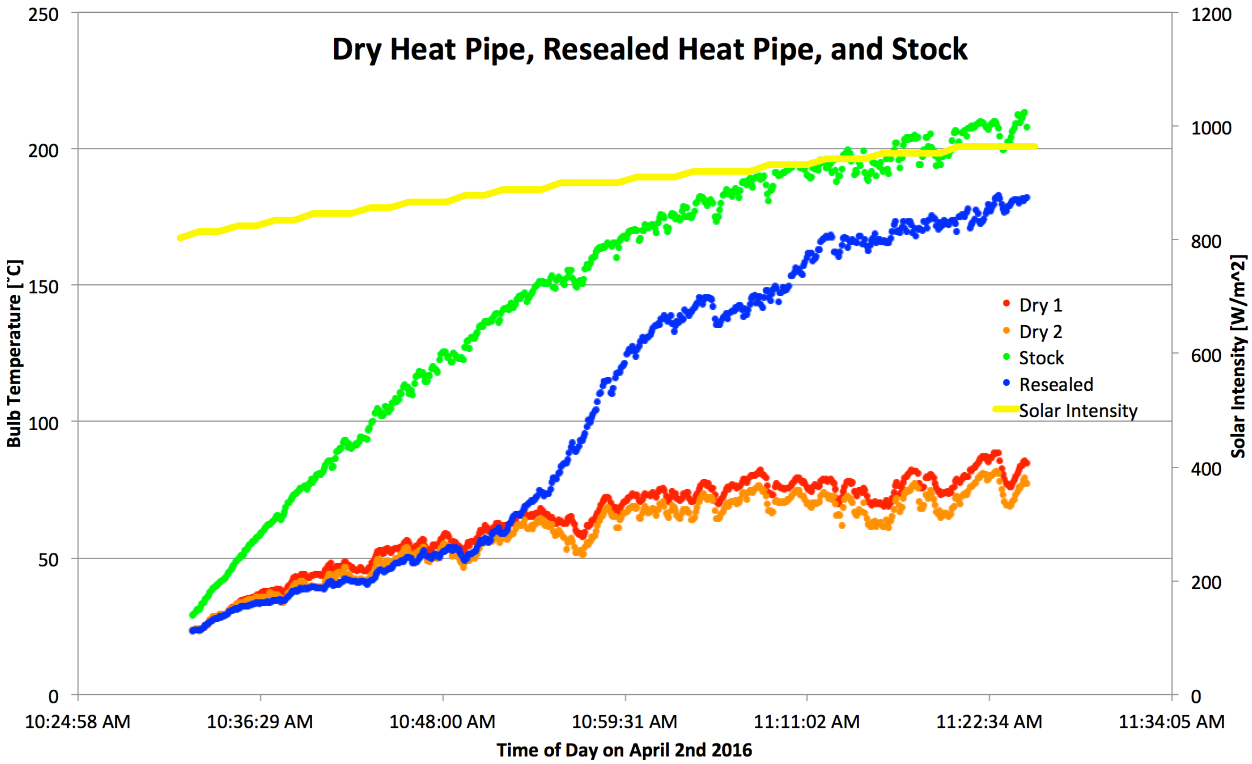



Figure 27. Control test with stock fluid and dry heat pipes.

From this control test, a start contrast is seen between the resealed and unmodified heat pipe. Through research the team learned that some heat pipes are sealed with the air having been evacuated from them. The resealing method used for these tests did not pull the air out of the heat pipes. The lack of air would allow the working fluid to vaporize more quickly. The unmodified tube shows that the heat pipe "takes off" instantly; whereas the resealed heat pipe only takes off once it reaches a certain temperature (roughly 55˚C). Before it takes off the resealed performs equivalent to the dry heat pipes. This indicates that the fluid's evaporation-condensation cycle is not happening initially: the heat pipe is only heating up due to conduction, like the dry heat pipes are. Seeing this trend showed that it was unlikely any combination of fluid/volume would ever rival the unmodified heat pipe because of inefficient resealing. But it showed another interesting point to monitor for future tests: the take off point. This is the temperature at which the system's vapor cycle begins and could be different for different fluid/volume combinations.

The main tests performed after the control tests were finished were done according to the following schedule.

Table 4. Schedule of main tests and setup used for each tube

| | Distilled Water | | | 5mL | Acetone | | Ethanol | | Bucket |
|---|---|---|---|---|---|---|---|---|---|
| Tube | 4/6/16 | 4/13/16 | 4/20/16 | 4/27/16 | 5/1/16 | 5/8/16 | 5/11/16 | 5/14/16 | 5/18/16 |
| A | 5 mL | 15 mL | 5 mL | Acetone | 3.6 mL | 7 mL | 9 mL | 10 mL | 6 mL acetone |
| B | 1 mL | 10 mL | 2.3 mL | Water | 1 mL | 11 mL | 3 mL | 4 mL | 5 mL water |
| C | 10 mL | 5 mL | 4.6 mL | Acetone | 5 mL | 5 mL | 7 mL | 8 mL | 7 mL water |
| D | 15 mL | 1 mL | 1 mL | Ethanol | 2.3 mL | 9 mL | 5 mL | 6 mL | 7 mL ethanol |

The first main test performed was using distilled water as a working fluid. The first two tests (shown below) helped the team establish their bearings with how each future test would be performed, so the exact same configuration was used both times because by the second test the team was much more prepared for how to conduct the experiment.

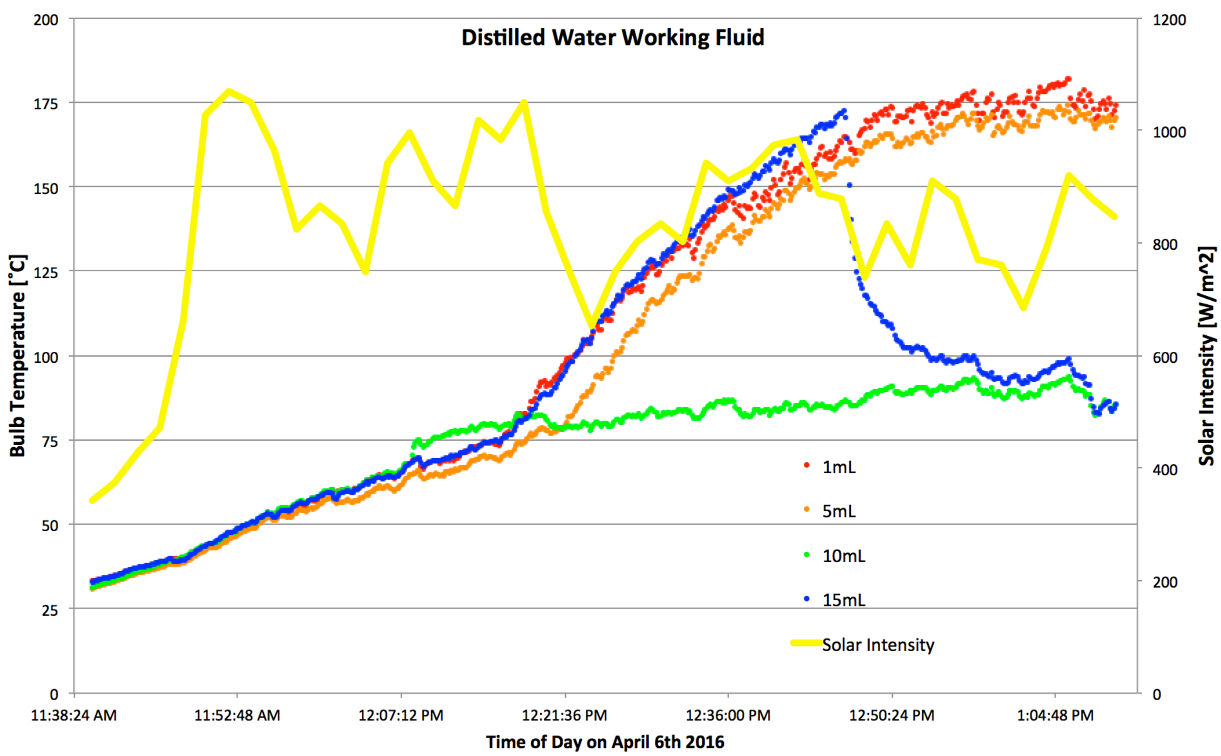



Figure 28. First distilled water test; performed on April 6$^{th}$, 2016

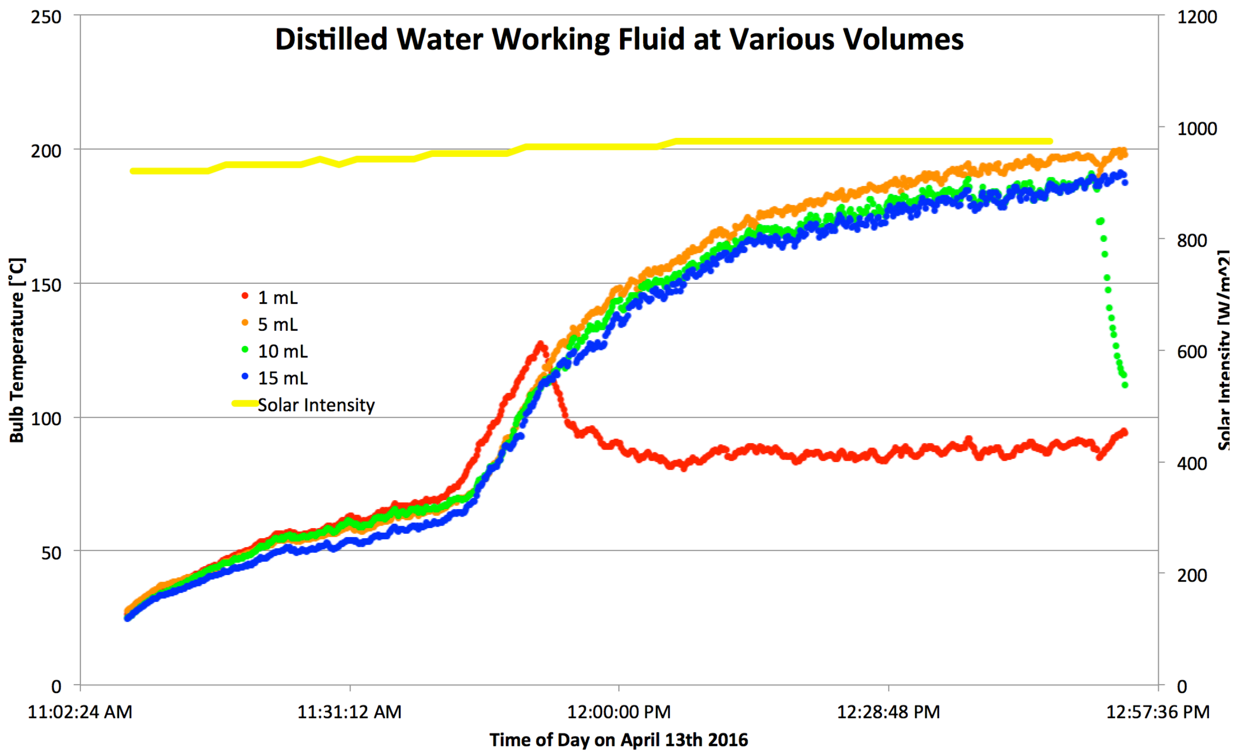



Figure 29. Second distilled water test; performed on April 13th, 2016

The April 6th test had very unstable solar irradiation and the 10 mL tube had significant sealing issues (noted in the post test analysis in Appendix I). The April 13th test was much more successful. It appears that the lower volumes of water performed better, however the 1 mL configuration may have burned out. Burnout is a situation in a heat pipe where all the fluid has vaporized and the cycle slows down as it waits for fluid to condense. The post test analysis showed no fluid remaining in the 1 mL heat pipe. This could have meant that there was a leak, but there was no evidence of one during testing. Also, withdrawing only 1 mL from the heat pipes is often difficult because of the tubes' natural capillary action. The last few drops of fluid were often removed by evaporation. For the notes taken during the post analysis of these tests see Appendix I.

In an attempt to find a maximum performance volume for water, the next test was between 1mL and 5mL of working fluid. We hoped to see where burnout started to become a problem.

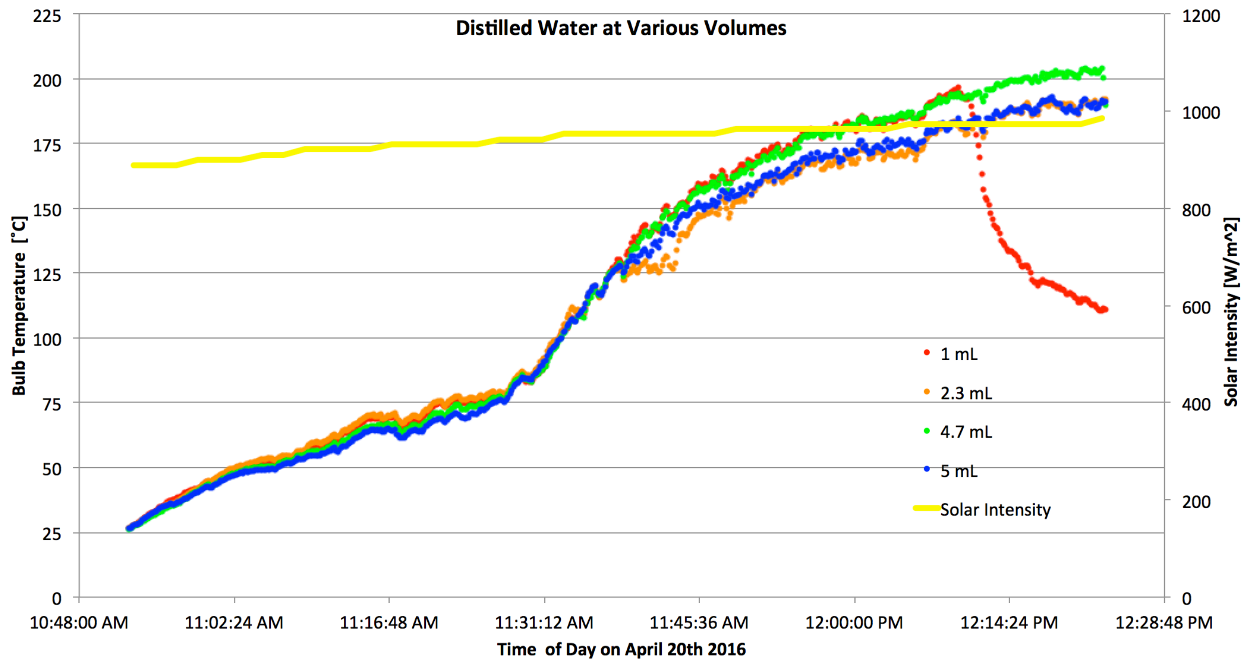



Figure 30. Distilled Water Working Fluid Test on April 20th

From this data, the take off point is the same for all four volumes. This is to be expected because they are all relatively similar volumes and the exact same fluid. The general trend is that lower volumes perform slightly higher, but not significantly higher. Overall, this data for water is not very significant for representing any sort of trend. If more time were available, more tests could be conducted on low volumes of water to better pick out a maximum performance value. For the notes taken during the post analysis of this test see Appendix I.

However, in order to do a multiple-fluid study, the team moved on to studying other fluids. The next test was designed to be a baseline to see how ethanol and acetone performed compared the distilled water. Each fluid was tested with 5mL in the heat pipe. This volume was used as a baseline because it is the volume of fluid used in the unmodified Duda Solar heat pipes.

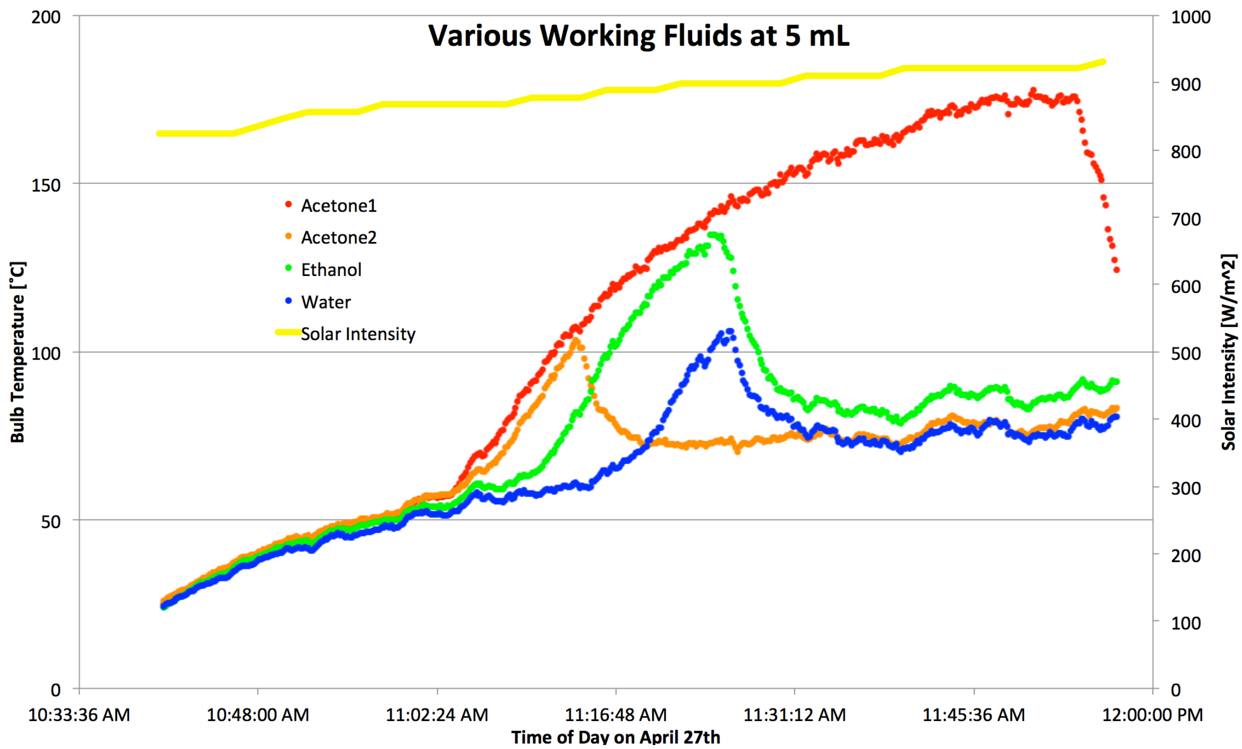



Figure 31. 5mL test of all fluids on April 27$^{th}$

The test on April 27$^{th}$ was unfortunately fraught with sealing issues. See Appendix I for the notes taken detailing the lack of fluid in the pipes found during the post test analysis. However, before any sealing issues affected the data and caused those large drops in bulb temperature seen above, it is clear that acetone "takes off" before ethanol, which in turn takes off before water. It is likely that this is because of the differences in boiling points. Since the heat pipe has some air in it, it takes the working fluid to get to a certain temperature and pressure before the vapor cycle in the heat pipe begins. Acetone has the lowest boiling point of the three fluids, then ethanol, then water. So it makes sense that the order of temperatures rapidly increasing would follow the same pattern. Also note that when the heat pipes leak they return to nearly the same curve they would have been if they were dry: the conduction only heating curve.

The first working fluid studied in more detail was acetone. The team's goal was again to find a volume that provided maximum performance. Acetone was first tested a lower volumes because of the trend seen in water where lower volumes showed higher performance.

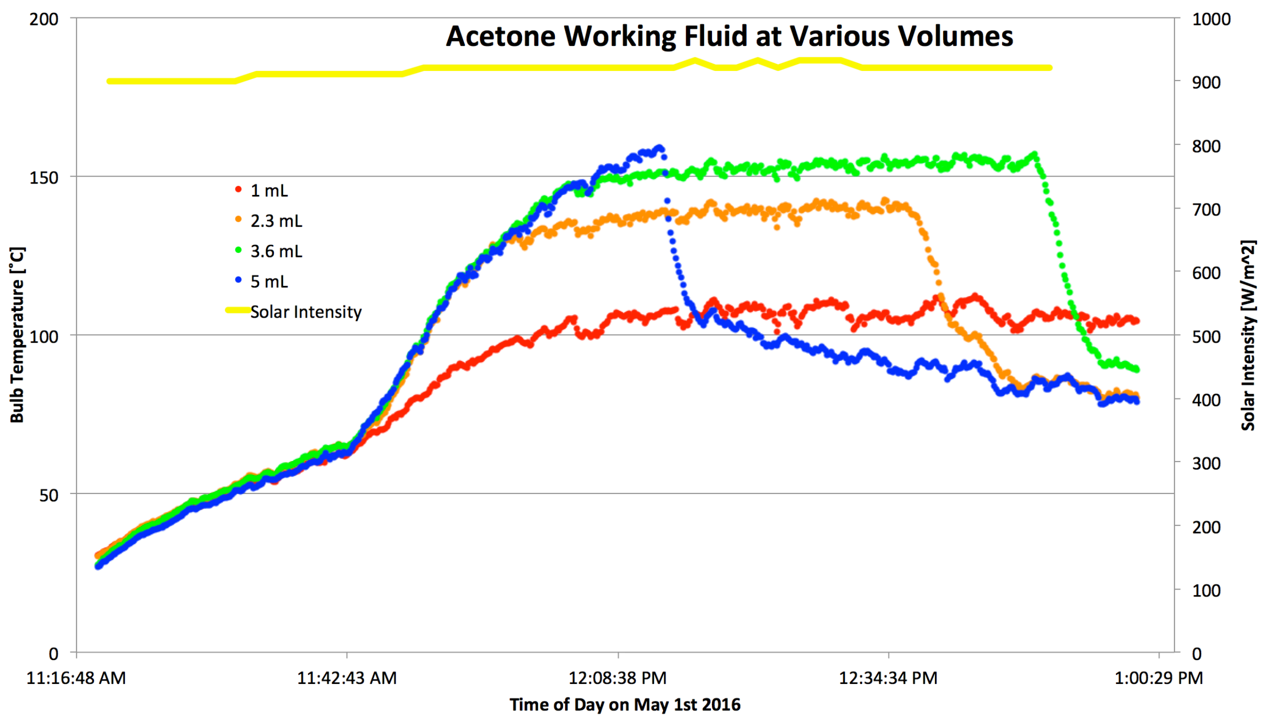



Figure 32. Acetone at Low Volumes test on May 1st, 2016

Acetone has a lower boiling point that water, and reduced fluid can cause burnout easily. These results of leveling off temperatures are a pretty clear indication that burnout was slowing temperature rise in the lowest volumes. The 5mL did not burn out but did leak (see Appendix I for full post test analysis notes). From this test it became apparent that a larger volume would provide the maximum performance because burnout is a larger issue for Acetone than it is for water.

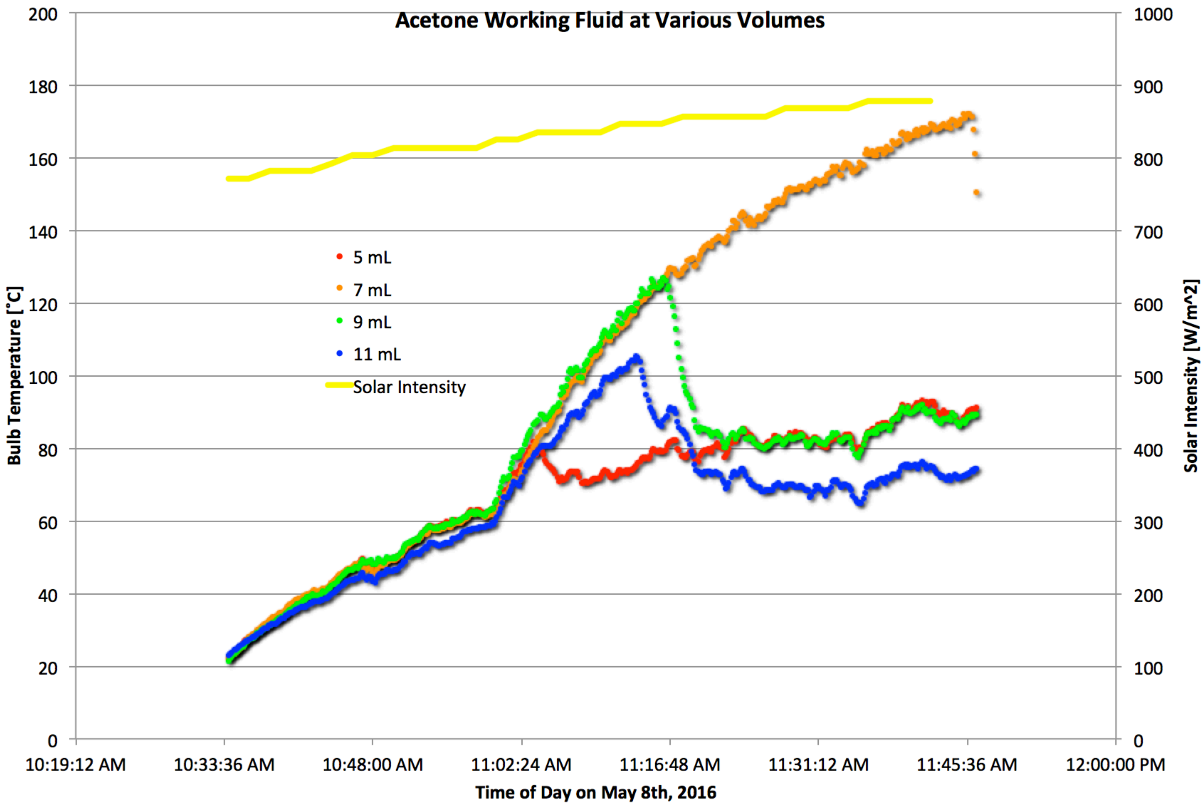



Figure 33. Acetone Test with Larger Volumes on May 8th, 2016

These results unfortunately had resealing issues (see Appendix I for full post test analysis notes) but show that Acetone has a lower "take off" temperature than water (60˚F as opposed to ~75˚F). It also appears that the 11mL was leveling off before it leaked, and the 7mL and 9mL configurations were accelerating more. It seemed the maximum performance for acetone would occur above 5mL, but not too far above.

Ethanol was the next working fluid to be tested. From seeing that Acetone performed better at higher volumes, since ethanol also has a lower boiling point that water the team started with testing above 5mL fill.

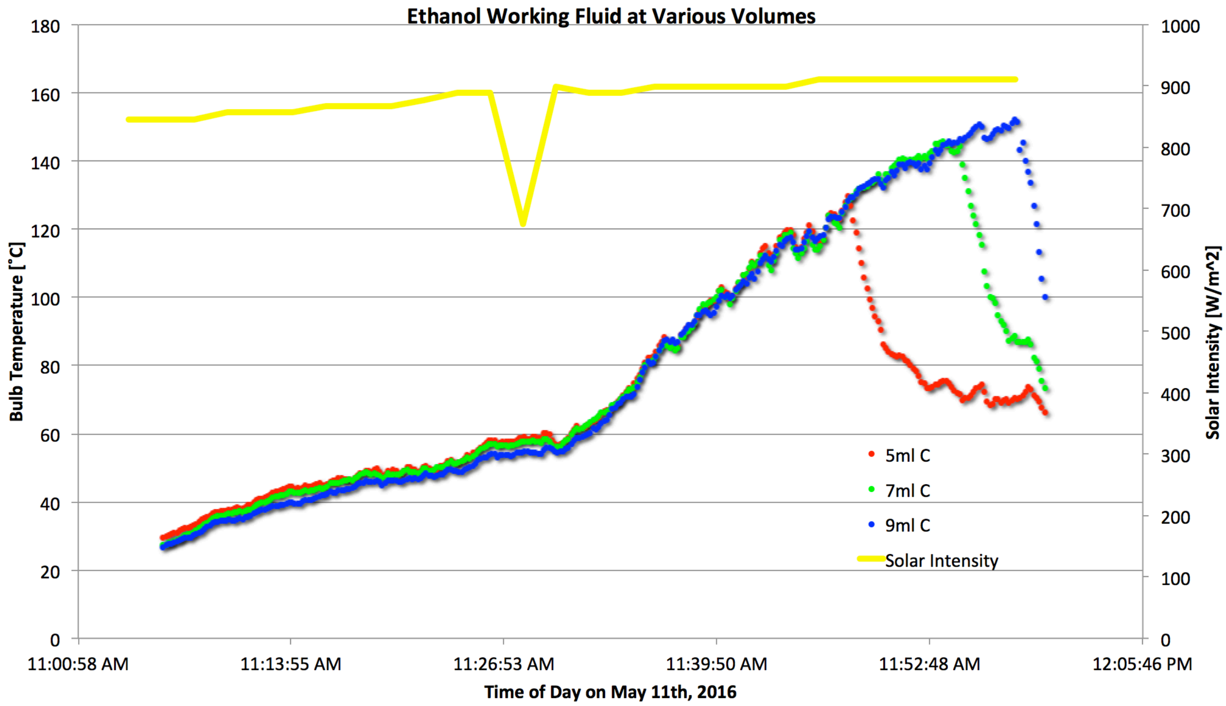



Figure 34. Ethanol Working Fluid test performed on May 11th, 2016

This test unfortunately lost one configuration due to a broken thermocouple that broke just as the test began. Every configuration performed very similarly, and they all eventually leaked. The 5mL was likely the first to leak because it pressurized the ethanol the fastest because it was the smallest fill volume. This test also was the first where the plugs becoming stuck in the heat pipes became a problem. The plugs were not as chemically resistant as had been hoped, and pieces of them fell into the heat pipes and sometimes were not recovered. The details of this are in the post test analysis and are included in Appendix I.

The next test was at similar volumes of ethanol, this time all four thermocouples were working.

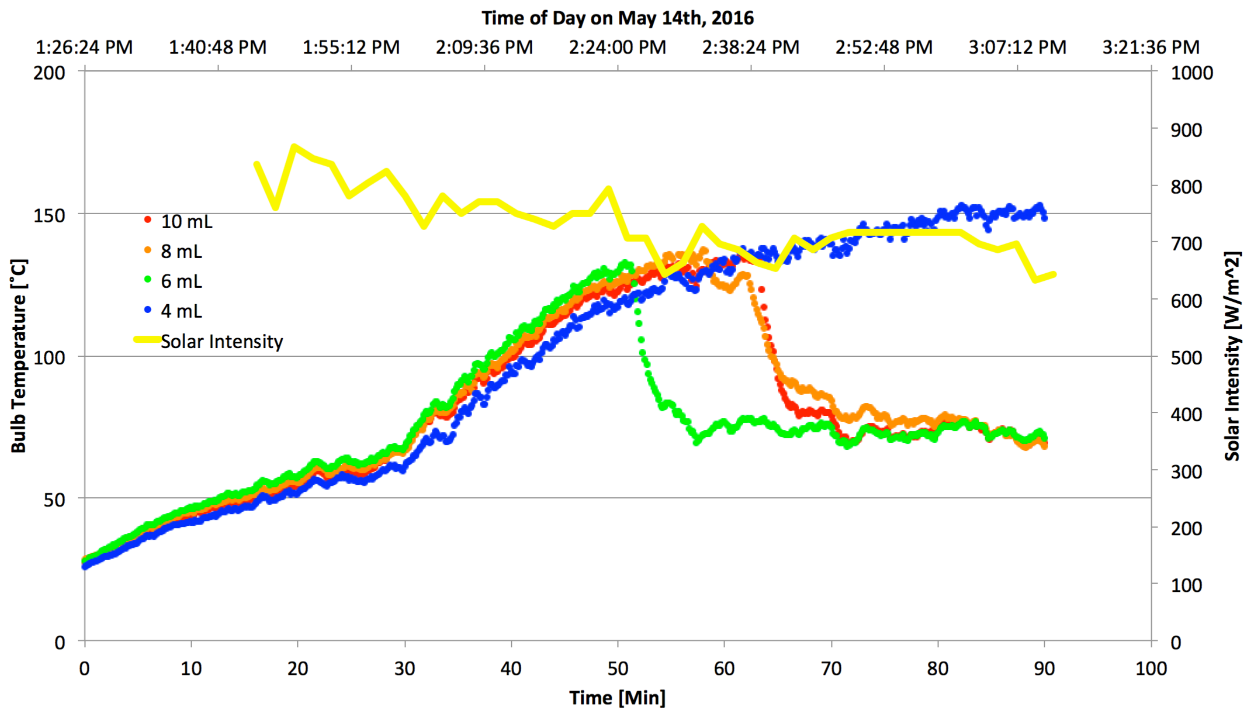



Figure 35. Ethanol Working Fluid test on May 14th, 206

These results had no particular trend, though it is clear that the take off point is again at a lower temperature than distilled water. The pyranometer data is more erratic than usual, but still fairly consistent over the 90 minute period. It is likely that the maximum performance for ethanol is also slightly above 5mL of fill.

These results for distilled water, acetone, and ethanol were all analyzed assuming equivalent incoming solar irradiation (a reasonable assumption since all tests were performed at roughly the same time in the same location in a consistently clear geographical area). Their performance at every volume tested was numerically integrated, and normalized to not include data after the heat pipe leaked/failed. This data was plotted as an Average Bulb Temperature rise versus the fill volume to find the peak performances for each fluid.

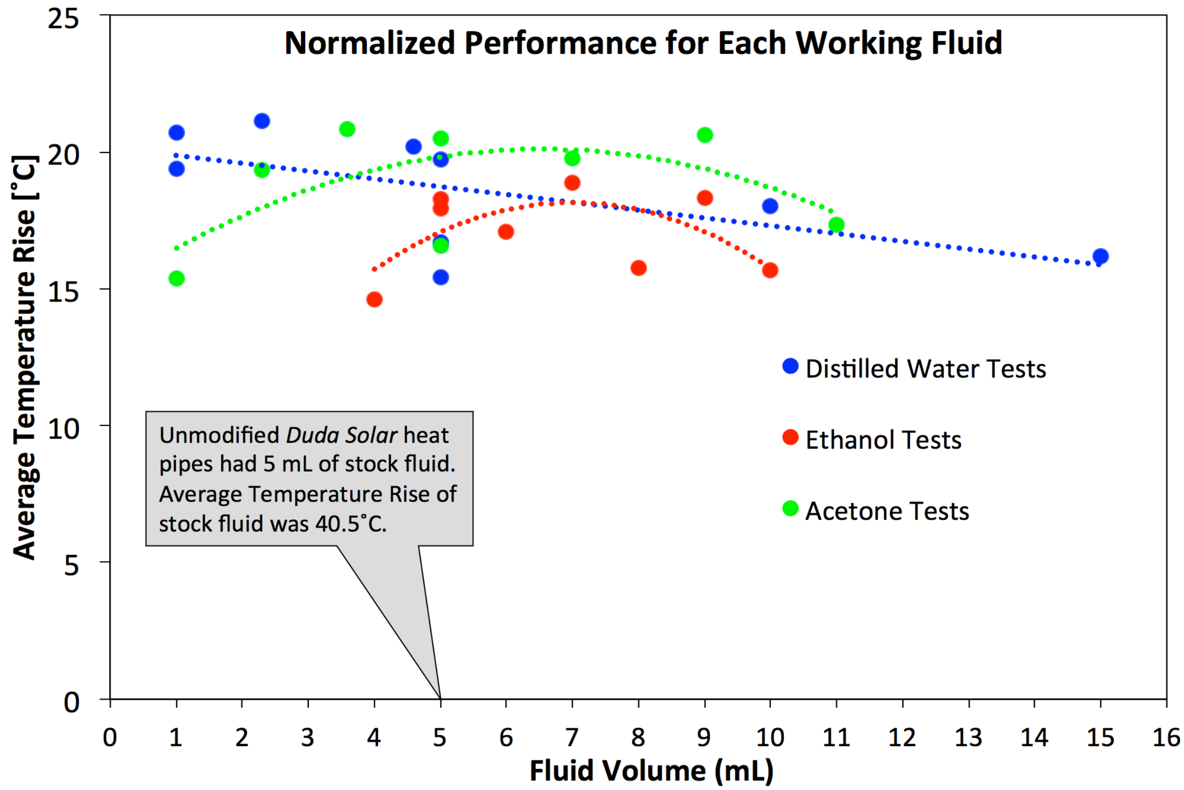



Figure 36. Average Temperature Rise vs. Fluid Volume for all tests

Analysis of the three fluids showed a not particularly helpful trend in the distilled water data, just that lower volumes seemed to increase the temperature more. However, with a 2$^{nd}$ order polynomial fit to the data, Acetone was shown to have a maximum performance around 6mL of fill, and Ethanol a maximum performance around 7mL of fill. This supports our hypothesis that there must exist some maximum performance where the volume of fluid being higher would be too slow a system and the volume being any lower would cause burnout or not provide enough heat transfer. It should also be noted that these maximums are all lower than the Duda Solar stock fluid, even when accounting for the loss of performance through our resealing method. The Duda Solar fluid was kept secret by the company, and not investigated at other volumes, but likely has a maximum performance of 5mL because that is the volume used in the stock tubes.

The last test was done where water reservoirs were actually being heated, not just the bulbs open to the air. This test compared the different fluids at each of their respective maximum performance volumes.

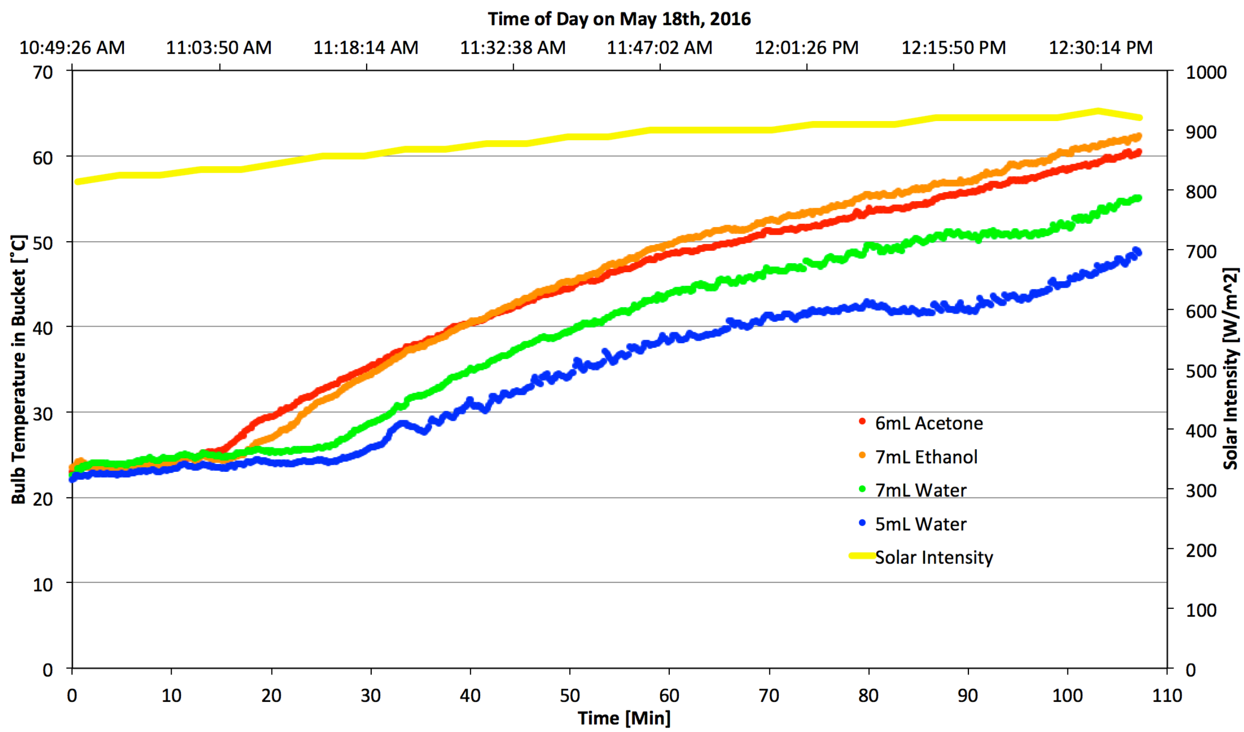



Figure 37. Water Reservoir Test at Each Fluid's Max Performance Volume

These are all much lower temperatures because the heat pipe bulbs are each resting in 2 liters of water in an insulated reservoir. The order of temperatures beginning to "take off" is consistent with the relative boiling points, which is to be expected. Ethanol and Acetone perform very similarly, but ethanol eventually does surpass acetone just barely making it the top performing fluid. Both perform better than water at the two different volumes tested (since a clear maximum for water was not clearly seen). Strangely, water performed better at lower volumes before but in this test the larger volume (7mL) performed better. If more time were available perhaps more of these reservoir type tests could have been performed and more clearly illustrated the performance of distilled water as a working fluid.

## SUGGESTIONS FOR FURTHER RESEARCH

Much research already been done and many papers have been published in the area of Solar Water Heaters, the majority of these studies are on ways to improve performance. This project contributes more in this area of study by focusing in the transient state of the system and the fluid within the heat pipes. Throughout the testing phase of the project, the team had a few issues about the overall quality of the testing, mainly resealing the heat pipes in a way to avoid any kind of spillage and high-pressure resistance burst. For this, the team tried Aluminum tape which was not successful. The last option was to use a heat resistant plug but it proved not be as effective. There were other options for this application like the Swagelok or something similar from McMaster Carr. Due to the lack of time and the cost of this device, we were not able to try it but it would be recommended to try something else besides the plugs. Having a better way to reseal the heat pipes will yield better more detailed results. Another recommendation is to do more tests using the buckets with water and place one more thermocouple inside the bucket to record the temperature change of the water. For this, a DAQ system with all eight channels functioning will be required (our team was only provided with a 4 channel DAQ system). For the purpose of our project only the four working channels were required.

Another issue we encounter when testing is that we noticed the aluminum fins were getting wrinkled; this lowers the heat transfer distribution from the fin to the heat pipe inside the tube. Having a few of these fins ready to replace would increase the quality of the tests. Lastly, having other types of liquids that can be adequate to use and be tested besides Ethanol and Acetone would be interesting and perhaps yield similar results.

During the first phase of the project and when looking for different variables to analyze, Professor Mason Medizade suggested to study the heat distribution inside the evacuated tube itself and eliminate the testing of the fluids. This test would involve placing a series of thermocouples along the inside of the glass evacuated tube and watch for the temperature distributions. There are software available that allow for a 3D visual representation of the heat distribution such as fluent. Due to time constrains and the vast research we had already done for the test of liquids, we were not able to consider what he proposed but it is a test to consider.

## SUMMARY

The main conclusions to be taken away from this senor project are that acetone showed the most desirable results with earlier take off and larger temperature rise. This is most likely due to the lower boiling temperature of the fluid. Ethanol showed the second most desirable results with a peak in average temperature rise only 2°C lower than the peak for acetone. The results for water can be assumed to be inconclusive. This is because the water tests were the first tests performed and they were subject to numerous technical difficulties. The acetone showed a trend in a maximum performance at 6 mL of fill, and ethanol at 7 mL. These values are for a system that does not evacuate the air from the heat pipe. The stock pipes, however, it is believed did evacuate the air and showed much higher performance than any other combination done during the teams testing. This is likely due to the lack of air in the pipe allowing the working fluid to vaporize and begin the cycle of heating and cooling immediately.

The largest technical challenge of this project was the effective resealing of the heat pipes. It can be seen in numerous figures such as Figure 35, that when the heat pipes depressurized the test results were no longer useful past that point. The team compensated for this in their analysis by only using the data up to the time of failure. If future tests are to be performed then a more in depth design of a sealing system needs to be conducted. The sealing system must allow for easy addition and removal of working fluid and an option for pulling a vacuum. It was recommended during the safety review to look into the use of Swageloks to solve this sealing problem. Part of this problem was also due in part to not having the condenser ends of the heat pipes in cold enough reservoir. The heat pipe bulbs were just exposed to the open air, which allowed them to get to temperatures, and therefore pressures, that might not be experienced during normal usage.

Over the past eight months, the team has learned a great deal about solar collector systems, heat pipes, and the manufacturing of evacuated tube systems. While the results of the test may not improve the state of the art in these technologies, they have certainly provided an enormously useful learning experience and stepping stone towards the larger world of solar applications of heat pipes and solar water heating in general. It is a technology that is unfortunately overlooked by the majority of the United States due to the low cost of natural gas for water heating, but it is a very efficient and effective way to reduce the use of fossil fuels and decrease humanity's footprint on the earth.

# REFERENCES

[1] Bergman, T. L. *Introduction to Heat Transfer*. Hoboken, NJ: Wiley, 2011. Print.

[2] Duffie, John A., and William A. Beckman. *Solar Engineering of Thermal Processes*. New York: Wiley, 1980. Print.

[3] Jahanbakhsh, A., H.r. Haghgou, and S. Alizadeh. "Experimental Analysis of a Heat Pipe Operated Solar Collector Using Water–ethanol Solution as the Working Fluid." *Solar Energy* 118 (2015): 267-75. Web.

[4] Mozumder, A. K., A. F. Akon, M. S. H. Chowdhury, and S. C. Banik. "Performance Of Heat Pipe For Different Working Fluids And Fill Ratios." *Journal of Mechanical Engineering J. Mech. Eng.* 41.2 (2011). Web.

# APPENDIX A: BILL OF MATERIALS

**Team 14**

**Team Members:**

| |
|---|
| Michael Agavo |
| Ben Krumholz |
| Will Dundon |

**Senior Project**

Sponsor: Prof. Medizade

## MATERIALS LIST

| Qty | Item Name | Description | Unit Cost | Supplier Link | Total |
|---|---|---|---|---|---|
| 1 | Plywood Sheet | Table and Wall Structures | $29.89 | http://www.homedepot.com/plywood | $32.38 |
| 4 | 2 Gal. Styrofoam Container | Water Reservoirs | $11.71 | http://www.amazon.com/Frabill-Foam-Bucket | $46.84 |
| 1 | Metal Folding Sawhorse | Main Support for Rig | $41.99 | http://www.amazon.com/sawhorse | $61.12 |
| 4 | Cinderblocks | Bottom Support | $1.05 | http://www.homedepot.com/cinderblocks | $4.54 |
| 1 | Plugs (Pkg 50) | Seal Holes in Heat Pipe | $7.50 | http://www.mcmaster.com/pinkplugs | $13.72 |
| 1 | Pack of syringes (Pkg 10) | Heat Pipe Fluid Insertion | $7.99 | http://www.amazon.com/Industrial-Syringes | $13.17 |
| 2 | Blue-Tack® Reusable Adhesive | Seal Reservoir Holes | $5.83 | http://www.amazon.com/Blu-Tack | $18.97 |
| 1 | Angle brackets (Pkg 4) | Table and Wall Structure | $4.68 | http://www.homedepot.com/brackets | $5.05 |
| 1 | 2 X 6 wood stud | Riser for Reservoirs | $4.56 | http://www.homedepot.com/2x6 | $4.92 |
| 1 | Aluminum Tape | Seal Reservoir Holes | $10.08 | http://www.amazon.com/AlTape | $15.08 |
| 1 | 1/2" Wood Screws | Fasten Table and Wall | $3.82 | http://www.homedepot.com/HalfInchScrew | $3.82 |
| 1 | 1.5" Wood Screws | Fasten Riser | $7.25 | http://www.homedepot.com/LongScrew | $7.25 |
| | | | | **Materials Total** | **$211.78** |

**Note: Total prices include tax plus shipping and handling**

# APPENDIX B: FAILURE MODE AND EFFECT ANALYSIS

## Failure Mode & Effect Analysis (FMEA)

Team 14: EvacAlpha (Michael Agavo, Will Dundon, Ben Krumh

Solar Heat Pipes

Sponsor: Prof. Medizade

| Component | Potential Failure Mode | Potential Cause(s) | Local Effects of Failure | Next Higher Level Effect | System Level Effect | Prob. | Sevr. | Detc. | RPN | Recommended Action(s) |
|---|---|---|---|---|---|---|---|---|---|---|
| Cinderblock | Slides on ground | Slick surface | Evacuated Tubes unsteady | Evacuated tube slides pulling bucket/spilling water | Evacuated tube crashes and shatters | 2 | 6 | 2 | 24 | Check cinderblock is static before leaning evacuated tubes on it |
| Test Rig Sawhorse | Leans or falls over | Unbalanced weight on table, extreme wind, | Table and buckets unsteady | Buckets spill/fall, | Test rig falls over and evacuated tubes shatter | 4 | 9 | 4 | 144 | Anchor sawhorse on ground with balanced weights/supports if necessary, keep weight on table in center |
| Putty Sealant | hole in putty seal | improperly applied, failture by manufacturer | Water leaks out of side of bucket | All water drains out of buckets, test is useless | Water leak widens and heat pipe slips out of bucket | 2 | 6 | 3 | 36 | Follow instructions for putty application, use putty specifically for foam and sealing water |
| Thermocouples | Wire separates/solder breaks | Poor soldering, reckless handling | Stop collecteing data | That evacuated tube stops contributing data | Need to remake thermocouple wires and redo test | 3 | 2 | 5 | 30 | Check thermocouple wire before using for test, handle with care |
| DAQ | Thermocouple pulled out of connection point | Loose wires in the way, poorly connected | Stop collecting data on that wire | DAQ pulled off table | DAQ breaks | 2 | 2 | 3 | 12 | Be aware of thermocouple wires and hold them in place with tape if necessary |
| Styrofoam bucket | Cracks in wall | Hole made for heat pipe | Water leaks out of side of bucket | All water drains out of buckets, test is useless | Water leak widens and heat pipe slips out of bucket, need to buy new bucket | 4 | 2 | 2 | 16 | Carefully handle bucket, especially when drilling hole and applying/removing putty |
| Heat Pipe Plug | Leaks | Pressure in heat pipe | Leaks working fluid | Heat Pipe does not perform as planned | Experiment must be thrown out and redone | 4 | 2 | 5 | 40 | Cover plug with thermal tape to ensure it stays put |

# APPENDIX C: DESIGN VERIFICATION PLAN

| Solar Heat Pipes | | Design Verification Plan |
|---|---|---|
| Senior Project Team 14: | Michael Agavo, Will Dundon, Ben Krumholz | |
| **No.** | **Procedure Description** | **Acceptance Criteria** |
| 1 | Measurement of Temperature in the Water Reservoir | Verify thermocouples are functional by placing in ice bath at 0˚C |
| 2 | Measurement of Diffuse Solar Radiation | Compare measurement to Solar Intensity measured at Building 52 Weather Station |
| 3 | Measurment of Water in Reservoir | Use consistant measuring/pouring device for each bucket |
| 4 | Measurment of Fluid | Verify syringe's accuracy and consistancy before using for experiment by comparing to graduated cylinder. |
| 5 | Rotation of Evacuated Tubes | Have four identical tubes tested at the same time, each with a 90˚ different rotation for the tube. If there is variation show, all further tests will be with every evacuated tube at 0˚. |
| 6 | Resealing Heat Pipes | Compare an unmodified stock evacuated tube from Duda Energy to one where the fluid has been removed, put back in, and sealed with the plugs and or aluminum tape. |
| 7 | Normalization of Temperature Measurements using Solar Intensity from Pyranometer | Using identical configurations, measure temperature at the output of the heat pipe bulb and normalize it using the solar intensity recorded at the same time on two days with different sky conditions and check to make sure the scaled values of $\Delta T/(W/m2)$, which is the temperature measurement normalized by intensity, is roughly the same for the two different days. |
| 8 | Evacuating Air from Heat Pipe before Resealing | If the resealing method does not significantly impact the results, then test a configurations where the heat pipe is unmodified (partially evacuated) to one that has been opened and resealed (contains air in the heat pipe). |

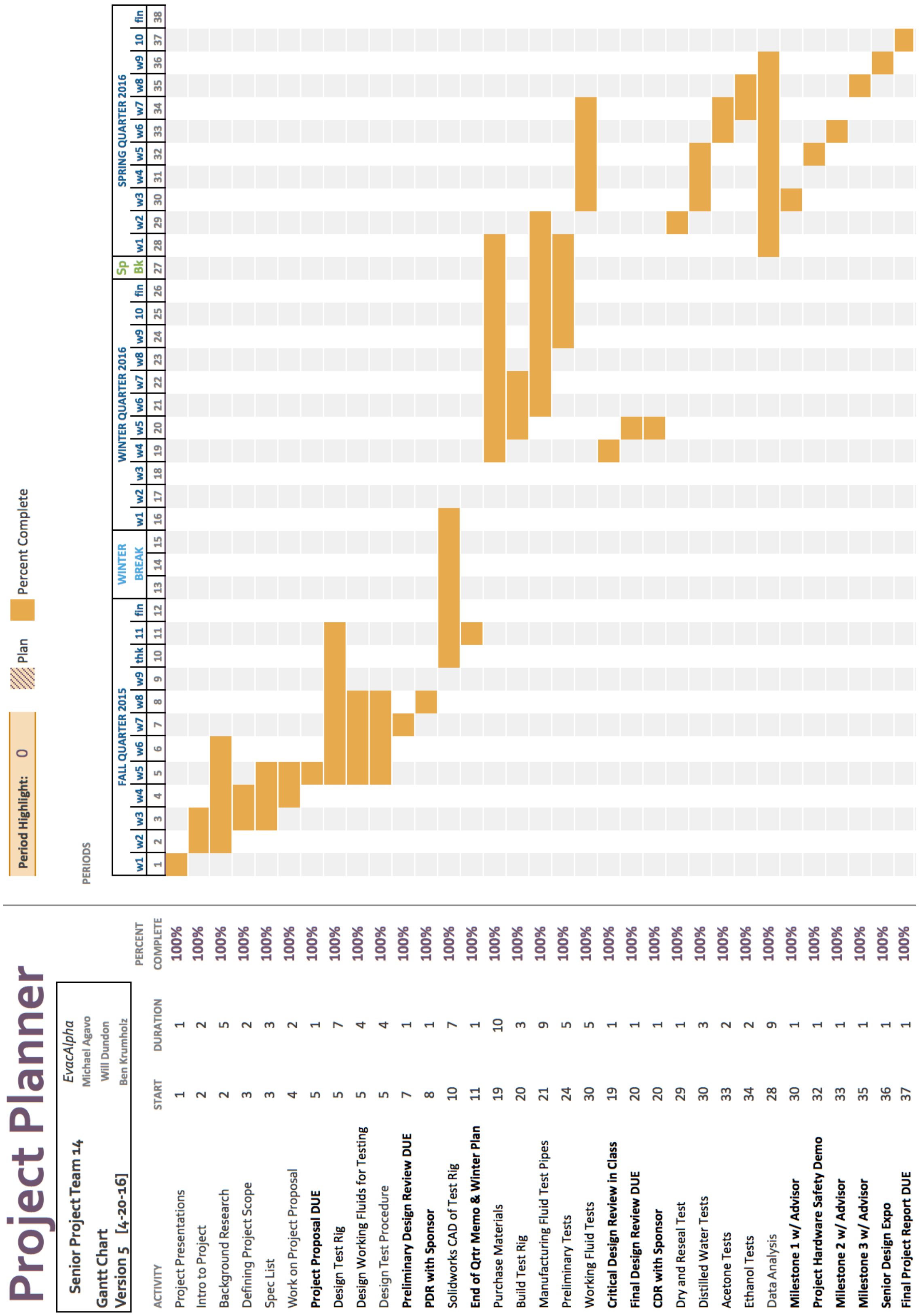
# APPENDIX D: MULTI-LEVEL BILL OF MATERIALS

**MULTI-LEVEL BILL OF MATERIALS**

| Level 0 | Level 1 | Level 2 | Level 3 | Level 4 | Part # | Quantity | Name | Function | Supplier |
|---|---|---|---|---|---|---|---|---|---|
| X | | | | | 0 | 1 | Test Rig | Hold Evacuated Tubes for Testing | n.a. |
| | X | | | | 10 | 1 | CinderBlock Base | Prevent Evacuated Tubes from Sliding while leaning on the Test Rig Body | n.a. |
| | | X | | | 100 | 4 | Cinderblock | Resist Sliding | Home Depot |
| | | X | | | 101 | 2 | Towel | Prevent Scratching of glass tubes by cinderblock | Personal |
| | X | | | | 11 | 1 | Test Rig Body | Provide space for Evacuated Tubes to lean against and for reservoirs to be placed on top of to hold the system at an angle and facilitate the water heating | n.a. |
| | | X | | | 102 | 1 | Sawhorse | Give the Test Rig Body its stability, height, and structural basis for the Table Top | n.a. |
| | | X | | | 104 | 3 | 1/2 " Screw | Secure the Table Top to the Sawhorse through the premade holes on the top of the Sawhorse | Home Depot |
| | | X | | | 103 | 1 | Table Top | Surface that Reservoirs will sit on and Evacuated Tubes will lean against | n.a. |
| | | | X | | 1000 | 1 | 2x6 Riser Board | 2x6 wood board to lift the surface that the Reservoirs sit on by 1.5" so that the bulb of the Evacuated Tube sits lower in the bucket | Home Depot |
| | | | X | | 1001 | 4 | 1.5" Screw | Connect the Riser Board to the ELL | Home Depot |
| | | | X | | 1002 | 1 | ELL | Basis of surface for the Reservoirs and the Wall that the Evacuated Tube will rest on/in | n.a. |
| | | | | X | 10000 | 1 | ELL Base | 48"x12"x3/4" Plywood to rest Evacuated Tubes on and serve as base for Reservoirs and the Riser to sit on top of | Home Depot |
| | | | | X | 10001 | 1 | ELL Wall | 48"x7"x3/4" Plywood Wall with Four 3" wide x 4.5" tall slots cut for the Evacuated Tubes to rest inside | Home Depot* |
| | | | | X | 10002 | 5 | Angle Bracket | Provide a connection point for screws to hold ELL Wall to ELL Base | Home Depot |
| | | | | X | 10003 | 10 | 1/2" Screw | Secure, through the Angle Bracket, the ELL Wall to the ELL Base | Home Depot |

* This part will start with plywood purchased at Home Depot, but will require manufacturing of the slots by the team personally.

# APPENDIX E: GANTT CHART




| ACTIVITY | START | DURATION | PERCENT COMPLETE |
|---|---|---|---|
| Project Presentations | 1 | 1 | 100% |
| Intro to Project | 2 | 2 | 100% |
| Background Research | 2 | 5 | 100% |
| Defining Project Scope | 3 | 2 | 100% |
| Spec List | 3 | 3 | 100% |
| Work on Project Proposal | 4 | 2 | 100% |
| **Project Proposal DUE** | 5 | 1 | 100% |
| Design Test Rig | 5 | 7 | 100% |
| Design Working Fluids for Testing | 5 | 4 | 100% |
| Design Test Procedure | 5 | 4 | 100% |
| **Preliminary Design Review DUE** | 7 | 1 | 100% |
| **PDR with Sponsor** | 8 | 1 | 100% |
| Solidworks CAD of Test Rig | 10 | 7 | 100% |
| **End of Qrtr Memo & Winter Plan** | 11 | 1 | 100% |
| Purchase Materials | 19 | 10 | 100% |
| Build Test Rig | 20 | 3 | 100% |
| Manufacturing Fluid Test Pipes | 21 | 9 | 100% |
| Preliminary Tests | 24 | 5 | 100% |
| Working Fluid Tests | 30 | 5 | 100% |
| **Critical Design Review in Class** | 19 | 1 | 100% |
| **Final Design Review DUE** | 20 | 1 | 100% |
| **CDR with Sponsor** | 20 | 1 | 100% |
| Dry and Reseal Test | 29 | 1 | 100% |
| Distilled Water Tests | 30 | 3 | 100% |
| Acetone Tests | 33 | 2 | 100% |
| Ethanol Tests | 34 | 2 | 100% |
| Data Analysis | 28 | 9 | 100% |
| **Milestone 1 w/ Advisor** | 30 | 1 | 100% |
| **Project Hardware Safety Demo** | 32 | 1 | 100% |
| **Milestone 2 w/ Advisor** | 33 | 1 | 100% |
| **Milestone 3 w/ Advisor** | 35 | 1 | 100% |
| **Senior Design Expo** | 36 | 1 | 100% |
| **Final Project Report DUE** | 37 | 1 | 100% |

# APPENDIX F: EES CALCULATIONS

EES Ver. 9.925: #0552: for use only by students and faculty, Mechanical Engineering, Dept. Cal Poly State University

```
HrAng = 0 [deg]      "centered over the hour of solar noon"
rho_g = .23          "Oke 1987, Clarke, J.A. 2001 reference"
Lat = 35.301278      "Building 13 Balcony, found using Google Maps"
Beta = 36.8 [deg]    "3 foot tall table, base of triangle 4 feet"
SurfAzAng = 0 [deg]  "Collector faces directly south"
I_o = I_zero_(n, Lat, HrAng-7.5, HrAng+7.5)

"assume clear sky midlatitude summer"
A = .071 [km]
r_0 = .97
r_1 = .99
r_k = 1.02
a_0star = .4237 - .00821*(6 - A)^2
a_1star = .5055 + .00595*(6.5 - A)^2
k_star = .2711 + .01858*(2.5 - A)^2
costheta_z = CosZenAng_(Lat, n, HrAng)
m = 1/costheta_z
Tau_b = r_0*a_0star + r_1*a_1star*exp(-r_k*k_star*m)     "Calc beam thru atmo"
Tau_d = .271- .294*Tau_b                                  "Calc diffuse thru atmo"

I_b = I_o*Tau_b
I_d = I_o*Tau_d
I = I_b + I_d        "Total Horizontal Irradiation"

I_T = I_T_('HDKR', 1, I, 1, Lat, n, Beta, SurfAzAng, rho_g, HrAng)
I_T_kwh = I_T*Convert(MJ/m^2,kW*hr/m^2)

```

Parametric Table: Table 1

| | n | $I_T$ | $I_{T,kwh}$ |
|---|---|---|---|
| Run 1 | 30 | 2.857 | 0.7935 |
| Run 2 | 31 | 2.87 | 0.7971 |
| Run 3 | 32 | 2.883 | 0.8008 |
| Run 4 | 33 | 2.896 | 0.8045 |
| Run 5 | 34 | 2.91 | 0.8082 |
| Run 6 | 35 | 2.923 | 0.8119 |
| Run 7 | 36 | 2.936 | 0.8156 |
| Run 8 | 37 | 2.949 | 0.8193 |
| Run 9 | 38 | 2.963 | 0.823 |
| Run 10 | 39 | 2.976 | 0.8266 |
| Run 11 | 40 | 2.989 | 0.8303 |
| Run 12 | 41 | 3.002 | 0.8339 |
| Run 13 | 42 | 3.015 | 0.8375 |
| Run 14 | 43 | 3.028 | 0.8411 |
| Run 15 | 44 | 3.041 | 0.8447 |
| Run 16 | 45 | 3.054 | 0.8482 |
| Run 17 | 46 | 3.066 | 0.8517 |
| Run 18 | 47 | 3.079 | 0.8552 |
| Run 19 | 48 | 3.091 | 0.8586 |
| Run 20 | 49 | 3.103 | 0.8619 |
| Run 21 | 50 | 3.115 | 0.8652 |
| Run 22 | 51 | 3.127 | 0.8685 |
| Run 23 | 52 | 3.138 | 0.8717 |
| Run 24 | 53 | 3.15 | 0.8749 |

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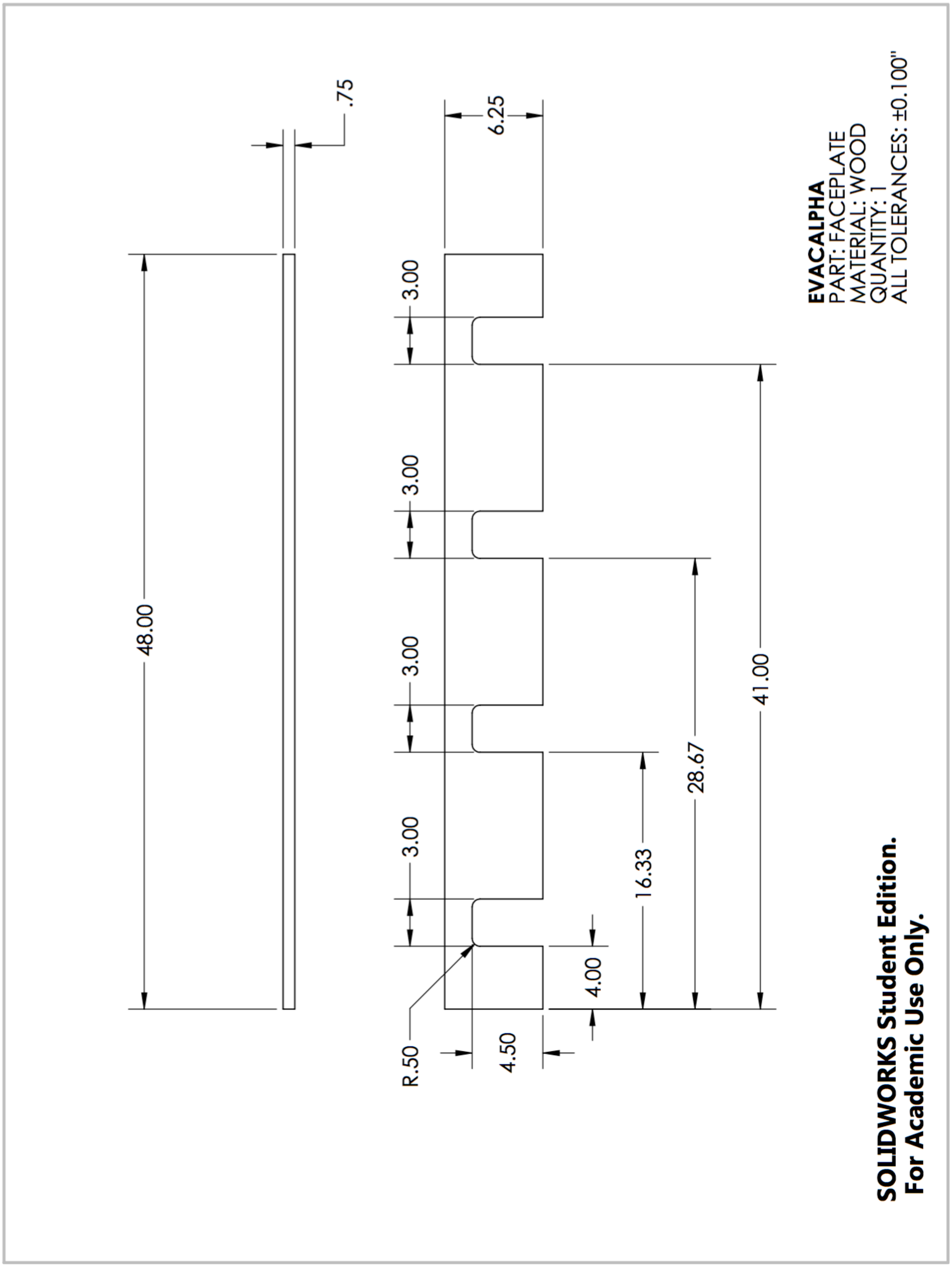
Parametric Table: Table 1

| | n | $I_T$ | $I_{T,kwh}$ |
|---|---|---|---|
| Run 25 | 54 | 3.161 | 0.878 |
| Run 26 | 55 | 3.172 | 0.881 |
| Run 27 | 56 | 3.182 | 0.884 |
| Run 28 | 57 | 3.193 | 0.8869 |
| Run 29 | 58 | 3.203 | 0.8898 |
| Run 30 | 59 | 3.213 | 0.8925 |
| Run 31 | 60 | 3.223 | 0.8953 |
| Run 32 | 61 | 3.232 | 0.8979 |
| Run 33 | 62 | 3.242 | 0.9005 |
| Run 34 | 63 | 3.251 | 0.903 |
| Run 35 | 64 | 3.26 | 0.9054 |
| Run 36 | 65 | 3.268 | 0.9078 |
| Run 37 | 66 | 3.276 | 0.9101 |
| Run 38 | 67 | 3.284 | 0.9123 |
| Run 39 | 68 | 3.292 | 0.9144 |
| Run 40 | 69 | 3.299 | 0.9165 |
| Run 41 | 70 | 3.306 | 0.9184 |
| Run 42 | 71 | 3.313 | 0.9203 |
| Run 43 | 72 | 3.32 | 0.9222 |
| Run 44 | 73 | 3.326 | 0.9239 |
| Run 45 | 74 | 3.332 | 0.9256 |
| Run 46 | 75 | 3.338 | 0.9271 |
| Run 47 | 76 | 3.343 | 0.9286 |
| Run 48 | 77 | 3.348 | 0.9301 |
| Run 49 | 78 | 3.353 | 0.9314 |
| Run 50 | 79 | 3.358 | 0.9327 |
| Run 51 | 80 | 3.362 | 0.9339 |
| Run 52 | 81 | 3.366 | 0.935 |
| Run 53 | 82 | 3.37 | 0.936 |
| Run 54 | 83 | 3.373 | 0.937 |
| Run 55 | 84 | 3.376 | 0.9378 |
| Run 56 | 85 | 3.379 | 0.9386 |
| Run 57 | 86 | 3.382 | 0.9394 |
| Run 58 | 87 | 3.384 | 0.94 |
| Run 59 | 88 | 3.386 | 0.9406 |
| Run 60 | 89 | 3.388 | 0.9411 |
| Run 61 | 90 | 3.389 | 0.9415 |
| Run 62 | 91 | 3.391 | 0.9419 |
| Run 63 | 92 | 3.392 | 0.9422 |
| Run 64 | 93 | 3.393 | 0.9424 |
| Run 65 | 94 | 3.393 | 0.9425 |
| Run 66 | 95 | 3.393 | 0.9426 |
| Run 67 | 96 | 3.394 | 0.9426 |
| Run 68 | 97 | 3.393 | 0.9426 |
| Run 69 | 98 | 3.393 | 0.9425 |
| Run 70 | 99 | 3.392 | 0.9423 |
| Run 71 | 100 | 3.392 | 0.9421 |
| Run 72 | 101 | 3.39 | 0.9418 |
| Run 73 | 102 | 3.389 | 0.9414 |
| Run 74 | 103 | 3.388 | 0.941 |
| Run 75 | 104 | 3.386 | 0.9406 |
| Run 76 | 105 | 3.384 | 0.9401 |

Parametric Table: Table 1

| | n | $I_T$ | $I_{T,kwh}$ |
|---|---|---|---|
| Run 77 | 106 | 3.382 | 0.9395 |
| Run 78 | 107 | 3.38 | 0.9389 |
| Run 79 | 108 | 3.378 | 0.9382 |
| Run 80 | 109 | 3.375 | 0.9375 |
| Run 81 | 110 | 3.372 | 0.9368 |
| Run 82 | 111 | 3.37 | 0.936 |
| Run 83 | 112 | 3.367 | 0.9352 |
| Run 84 | 113 | 3.363 | 0.9343 |
| Run 85 | 114 | 3.36 | 0.9334 |
| Run 86 | 115 | 3.357 | 0.9324 |
| Run 87 | 116 | 3.353 | 0.9315 |
| Run 88 | 117 | 3.35 | 0.9305 |
| Run 89 | 118 | 3.346 | 0.9294 |
| Run 90 | 119 | 3.342 | 0.9283 |
| Run 91 | 120 | 3.338 | 0.9272 |
| Run 92 | 121 | 3.334 | 0.9261 |
| Run 93 | 122 | 3.33 | 0.925 |
| Run 94 | 123 | 3.326 | 0.9238 |
| Run 95 | 124 | 3.322 | 0.9226 |
| Run 96 | 125 | 3.317 | 0.9215 |
| Run 97 | 126 | 3.313 | 0.9202 |
| Run 98 | 127 | 3.308 | 0.919 |
| Run 99 | 128 | 3.304 | 0.9178 |
| Run 100 | 129 | 3.3 | 0.9165 |

# APPENDIX G: DESIGN DRAWINGS



# APPENDIX H: TRACKING OF EACH TUBE

| | Rotation Angle Tests | | | ReSeal Test | Distilled Water | | | 5mL | Acetone | | Ethanol | | Bucket |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tube | 3/3/16 | 3/8/16 | 3/10/16 | 4/2/16 | 4/6/16 | 4/13/16 | 4/20/16 | 4/27/16 | 5/1/16 | 5/8/16 | 5/11/16 | 5/14/16 | 5/18/16 |
| A | 180˚ | 180˚ | 180˚ | Dry 1 | 5 mL | 15 mL | 5 mL | Acetone | 3.6 mL | 7 mL | 9 mL | 10 mL | 6 mL acetone |
| B | 0˚ | 0˚ | 0˚ | Resealed | 1 mL | 10 mL | 2.3 mL | Water | 1 mL | 11 mL | 3 mL | 4 mL | 5 mL water |
| C | 270˚ | 270˚ | 270˚ | Dry 2 | 10 mL | 5 mL | 4.6 mL | Acetone | 5 mL | 5 mL | 7 mL | 8 mL | 7 mL water |
| D | 90˚ | 90˚ | 90˚ | Stock | 15 mL | 1 mL | 1 mL | Ethanol | 2.3 mL | 9 mL | 5 mL | 6 mL | 7 mL ethanol |

# APPENDIX I: POST TEST ANALYSES

Post Test Analysis for test done 4/6/16 with water at 15, 10, 5, 1 mL
Done on 4/13/16

15mL tube
Leaked all of the water out.
This is the one that had the wave shaped temp v time curve that saw a decrease in performance as we saw it start to steam out the end of the tube.
It was also sputtering and steaming as it was put away after the test.
Plug possibly ripped due to overtightening the hose clamp.
DISCOVERED DIFFICULTY DRAINING IT WHEN IT WAS FULL. "FULL" CAPACITY DISCOVERED TO BE 65 mL

10 mL tube
Plug looked ripped and lost some material.
This one had a very low performing curve.
No fluid inside the pipe leads us to believe it all leaked out (causing poor performance)
NEW RESEALING STRATEGY WILL BE TO NOT DO IT SO TIGHT

1 mL tube
Plug was flush with the pipe, seemed to still be sealed.
Verified it was sealed when we measured 1mL still inside the tube
*SUCCESSFUL SEALING!*

5 mL tube
Plug sealed properly, verified with 5 mL still inside the tube
Fluid left yellow (which was not the case for the 1mL)
*SUCCESFUL SEALING!*

April 13th Post Test Analysis

1 mL
no fluid remaining inside, but there wasn't evidence of leaking during the test.
Plug looks chewed up and is squishier than the unused one, but no holes in it.

10 mL
No fluid remaining in heat pipe, there were signs at the end of the test that it had leaked (steamed)
plug looks very similar to 15 mL: chewed up at squishy

5 mL
No fluid remaining in heat pipe, but there was not sign of leaking during the test.
Similar looking plot.

15 mL
fluid inside the heat pipe, plug looked relatively intact compared to the others

We suspect that the reason so many of these were dry is that we did not measure the fluid remaining in them until a week after the test, so any leakage in the sealing could have allowed them to evaporate off in that time.

April 20th Post Test Analysis

5mL
plug was split at top, did not seem to fill hole entirely when the hose clamp was removed
at least 3 mL were remaining in the tube. Some spilled so can't be exact but it was likely the full 5mL remaining in the tube so we had a successful sealing

4.6 mL
very chewed up plug, top was split.
No fluid remaining the heat pipe.
When it was flushed out 6mL were put in to flush it out but only a little over 5 could be removed.

1 mL
top of the plug was stuck in the hose clamp turning mechanism and was ripped off of the plut when the hose clamp came off. The plug was still partially in the hole though.
No water could be extracted from the heat pipe.
7 mL used to flush but only a little over 6 mL could be removed

2.3 mL
this plug was stuck in the hose clamp too but came out of the hole in the heat pipe in one piece attached to the hose clamp. The plug looked relatively unscarred, but still some splitting at the top.
2ish mL were recovered from the heat pipe so it appears this was another successful sealing.
All fluid used in flushing it out was recovered.

April 27th Post Test Analysis
All heat pipes were at 5mL full
This analysis was done immediately after testing. Using water to cool off the heat pipes so they could be handled.

Acetone 1
performed the best and had pressure remaining inside it

Acetone 2
leaked during the test but still had some pressure remaining inside it

Ethanol
appeared to have burnout (did not see evidence of leaking during test, but declined after a certain time), also had some pressure remaining. While removing this one, part of a plug fell into the heat pipe and could not be removed. (this was tube D)

Water
leaked during test but still had some pressure inside when removed

May 1st Acetone Test
Post Test Analysis – 4 Acetone volumes

5mL
this tube leaked during the test. When it was opened shortly after the test, there was still some remaining pressure inside. The plug seemed like it fell apart as the hose clamp was removed and a small piece fell into the heat pipe

3.6 mL
no pressure felt when removing the plug. Plug came out in one piece, attached to the hose clamp

2.3 mL
no pressure felt when removing plug. Plug came out in one piece with thee hose clamp.
Very very small amount of fluid pulled out before flushing the tube (a single drop really).

1 mL
no pressure when removing plug, plug came out in one piece. Not really (very teeny tiny) amount of fluid remaining in heat pipe before flushing it out.

Noticed glass tubes got hotter when fins were removed to flush out the heat pipes. Once the fin+heat pipe were put back in the surface temp of the glass decreased and condensation formed at the top as the remaining water from flushing the pipes evaporated out of the hole in the pipe

May 8th - Acetone 2
Post Test Analysis

5mL
No pressure, plug split in half inside of heat pipe. This was the first heat pipe to leak during the test.

7mL
No pressure, plug split in half in heat pipe. This heat pipe did not leak for the vast majority of the test.

9mL
no pressure remaining, plug split. Leaked during test

11mL
no pressure remaining, plug split, leaked during test and was the slowest to get going

May 11th - Ethanol at different volumes
Post Test Analysis

3mL
This tube's thermocouple broke at the beginning of the test so no data was taken for it.

5mL
leaked first during test. Plug got stuck inside.

7mL
leaked second during test. Plug also got stuck inside

9mL
also leaked during test but plug was recovered