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Solar Thermal Collector

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Solar Collector for Water Heating

By

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Project Partner
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1. INTRODUCTION

1a. Motivation:

This project was motivated by a need for a device that will heat water, using solar energy as the only input, for use in Central Washington University's MET 411 course. The solar water heater is necessary for lab research, and the current solar water heater is poorly constructed and inefficient.

The project was motivated by an interest in alternative energy, especially solar energy. Upon talking to the professor of the MET 411 course, Professor Beardsley, it was discovered that numerous pieces of lab equipment were in need of repair or replacement. One such piece of equipment was the solar water heater. The combined interest in solar energy and the need for a solar water heater gave rise to this project.

1b. Function Statement:

A device is needed that will heat water using only solar energy in compliance with the needs of MET 411 student outcomes.

1c. Design Requirements:

Thus, a device is required that would:

- Increase the temperature of water by 25 degrees Celsius between the inlet and outlet pipes
- Be powered solely from solar energy
- Weigh no more than 25lbs
- Be no larger than 2.5 ft wide by 3ft long by 6in deep, to fit through a standard doorway
- Take no more than 20 hours to manufacture
- Cost no more than $100 to manufacture
- Be able to absorb and utilize at least 50% of the incoming solar radiation on a day where irradiance is equal to 800 W/m^2
- Be in compliance with MET 411 student outcomes
- Fit on the accompanying stand

1d. Engineering Merit:

Engineering is required for this project. For example, the equation $Qdot = IA\eta = mdotCp\Delta T$, will be used to find the required mass flow rate to achieve the desired efficiency. In this equation, Qdot is the rate of heat transfer. Once all of the other components have been calculated, or assumed, Qdot can be determined. In the equation, I is equal to solar flux, which will be assumed, based on online data, and measured during testing. A is the surface area of the solar collector, which will be set at 28.5in by 34.5in. η is the collector efficiency, which, for this project, is required to be 50%, or 0.5. In the last part of the equation, mdot is equal to the mass flow rate of the water traveling through the solar collector. This will be the value that is calculated as a result of using this equation. Cp is the specific heat of the water traveling through the collector. In this case, 4.18 KJ/kg-K will be used as the Cp of water, as found in Fundamentals of Thermal-Fluid Sciences, by Çengel and Cimbala. ΔT is the temperature change of the water between the inlet and outlet pipes of the solar collector. For this project, the required temperature change is 25 degrees Celsius, and will be measured during testing. Once all of the components have been determined, mdot and Qdot can be calculated. Once the mass flow rate of water is determined, the volume flow rate of the water can be calculated, using the equation mdot=ρvdot. The mass flow rate of the water is equal to the density of water multiplied by the volume flow rate of the water. The density of the water can be looked up, based on temperature, and the mass flow rate that was already calculated will give the volume flow rate of the water. From there, a Reynolds number can be calculated, using the equations $Re = \rho vD/\mu$ and mdot=ρvA, where v is equal to the water velocity, D is equal to pipe diameter, A is equal to the cross sectional area of the pipe, and μ is equal to the viscosity of the water. The pipe diameter (and therefore, cross sectional area) will be assigned, and the viscosity of the water can be looked up in tables. Solving for ρ yields the following two equations: $\rho = Re\mu/vD$ and ρ = mdot/vA. Setting the equations equal allows the velocity of water to be cancelled. From there, Re can be solved for, since all other variables will be known by this point. The Reynolds number will indicate the type of flow. In this case, the flow will probably be laminar, and some kind of static mixer will likely be used to mix the water and prevent and cool patches in the center of the pipe. Once the Reynolds number is calculated, the velocity of the water can be determined, using the equation $v = Re\mu/\rho D$. Once the water velocity is calculated, a back pressure can be calculated, and an appropriate pump assigned. To calculate the back pressure, the following equation will be used: $\Delta P = f(L/D)(v^2/2) + \rho gh$. ΔP is equal to back pressure, f is equal to Re/64 for laminar flow, L is equal to pipe length, g is equal to the acceleration of gravity ($9.81 m/s^2$), and h is equal to the height that the water will travel (which can be measured). All else will be known by this point.

1e. Scope of Effort:

The scope of this project will be the solar collector. The water container, piping, and stand are already in the lab storage cupboard. A replacement stand is currently being constructed by Tyson Nakamura as part of another project. The new stand will be usable before the solar collector is needed for lab

1f. Success Criteria:

The success of the project will be measured in a three part phase: part one being set up of the lab, part two being the lab itself, and part three being tear down of the lab setup. See appendix for the lab sheet, equipment, and instructions. The solar collector and equipment will be set up by the lab technician in the ten minutes before lab starts. The solar collector will then be placed in direct sunlight, and used to gather data by students within the two hour lab time. Finally, the solar collector will be dismantled and put away by the lab technician and Professor Beardsley, in the ten minutes between lab and the next class. Other success criteria include: the solar collector set up being transportable and able to fit within the designated storage location. The solar collector and setup equipment have to be able to be used, and maneuvered, by a group of 2-3 students, and be stored by Professor Beardsley in the store cupboard.

1g. Success Scenario:

The success of the project depends on whether or not Professor Beardsley is able to use the solar collector for MET 411 labs.

2. DESIGN AND ANALYSIS

2a. Approach: Proposed Solution:

A device is needed that will heat water using only solar energy. Therefore, a solar collector will be manufactured. A solar collector is a device that, when placed in direct sunlight, will absorb a portion of the input radiation and convert it to heat energy. Pipes will be run over the top of the collector, and water will be pumped through. As the water travels over the collector, it will absorb some of the heat energy, and rise in temperature. To determine how to design the solar collector to generate the desired output, a few factors have to be determined or assumed. The equation, Qdot = IAη = mdotCpΔT, will be used to find the desired mass flow rate of the water, necessary to achieve the desired output. For this project, the desired outputs are a temperature increase of 25 degrees Celsius (ΔT), and an efficiency of 50% (η). A temperature increase of 25 degrees Celsius was chosen, because a 25 degree temperature increase is reasonable to achieve during a 2 hour lab period, and is a large enough temperature increase to be able to observe and record data for. An efficiency of 50% was chosen, because according to www.builditsolar.com, a single-glazed copper collector placed in typical Ellensburg April conditions, would have an estimated efficiency of around 55%. An efficiency of 50% was selected to allow for design errors and variations in incoming solar irradiance. The solar flux (I) will be estimated using an online database, and the collector surface area (A) will be set at 2 feet and 4.5 inches, by 2 feet and 10.5 in, so that with the frame added, the solar collector does not exceed the maximum 2.5 feet by 3 feet. Note: the frame will have a width of 0.75 inches on all sides of the collector, and will therefore add 1.5 inches from top to bottom and left to right, as shown in Appendix A, Figure A1. A width of 2.5 feet overall was selected, because the narrowest doorway that the solar collector will have to pass through is approximately 32in wide. Therefore, a width of 2.5 feet, or 30in, was selected to allow for some wiggle room. If the collector is a couple of inches narrower than the doorway, then the collector will be easier to transport by Professor Beardsley and the lab tech. A collector height of 3 feet was selected to be in compliance with the collector stand. The stand has to fit through the narrowest doorway with the collector mounted. The stand will also be carrying the water tank underneath the collector. For the collector to be at a reasonable height (to allow for ease of access when removing the plastic cover and for adjusting pipes if necessary), while being mounted above the water tank, a collector height of 3 feet was chosen. The plastic cover can be taken in and out at the top of the collector, therefore, the top of the collector should not exceed a height of 5.5 feet above the ground, so professor Beardsley and the lab tech can adequately reach the top of the collector. Since the water tank is approximately 2 feet tall, and will be a few inches off the ground, the collector could not exceed 3 feet in height. The collector can absorb more incoming solar irradiation the larger its surface area, therefore the width and height were maximized at 2.5 feet by 3 feet, given the constraints. Cp will be assumed based on tabulated data, so the mass flow rate of the water (mdot) can be calculated. From there, the volume flow rate (vdot) will be calculated, using the equation, mdot=ρvdot, with the density of water (ρ) assumed based on tabulated data. Once the flow rates are determined, a Reynolds number, water velocity, and back pressure can be calculated, and the required pump can be determined.

2b. Design Description:

A couple of collector designs will be analyzed. These designs include a curved zig zag pipe path (Figure 1a), and a manifold design in which the water splits off down several pipes between the inlet and outlet of the solar collector (Figure 1b).

Figure 1a:

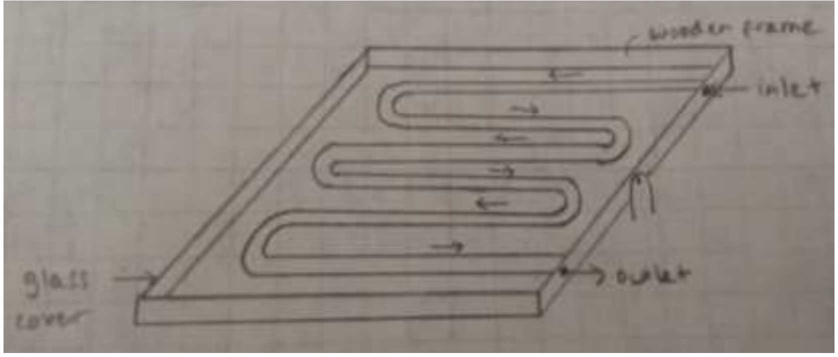
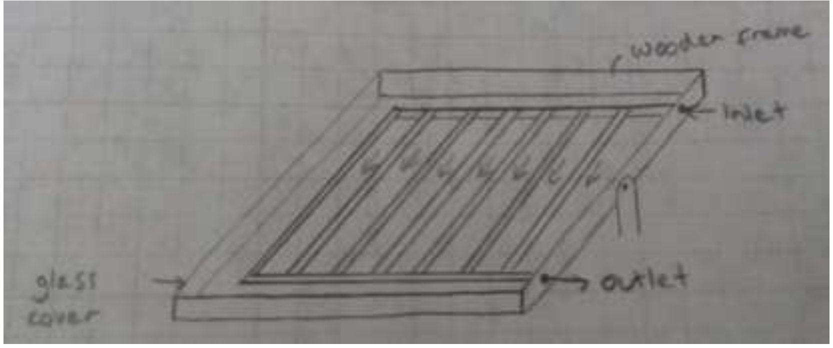


Figure 1b:



The curved, zig-zag pattern provides for a uniform path of water travel, and a longer travel time for the water through the solar collector. This allows for more opportunity for the water to be heated by the solar collector. However, the manifold pipe design allows for narrower pipes and more surface area exposure to the solar radiation. This design allows for a greater concentration of solar radiation to heat the water up.

Both designs will be constructed during the manufacturing phase, and both will be tested during the testing phase. Professor Beardsley would like both designs available for testing and analyzing during MET 411 labs.

2c. Benchmark:

The benchmark for the solar water heater is other MET 411 lab equipment. For example, for the photovoltaic solar module lab, solar panels and the necessary wires, multimeters, and resistors needed to be able to be set up, used, and put away within the two hour lab time. The photovoltaic modules and their required set up equipment needed to be transportable by students, and able to fit into the designated storage cupboard. The same criteria apply to the solar collector. The solar water heater system has to be simple enough for the lab technician to set up and tear down within the ten minutes between classes. The solar collector also has to be used to gather usable data within the two hour lab time. Finally, the solar collector system has to be able to fit within the designated storage closet, and be transportable by students.

2d. Performance Predictions:

The solar collector is predicted to have a solar collection efficiency of 50%. This means, that of all of the potential solar flux that reaches the solar collector, 50% will be absorbed and used to heat up the water traveling through the solar collector. 50% may not sound like a difficult efficiency to attain, however, 50% is a reasonable solar heater efficiency. The solar collector is expected to cost $100 to manufacture. This includes the frame, black paint, plastic cover, pipes, and fittings. The solar collector is predicted to take 20 hours to manufacture. This includes constructing the frame, manufacturing the collector pipes, attaching the pipes and fittings, and installing the plastic cover. Furthermore, the solar collector is expected to weigh no more than 25lbs. Finally, the solar collector is expected to gather conclusive data within a two hour lab period.

2e. Description of Analyses:

First, as shown in Appendix A, Figure A2, the heat transfer coefficient has to be determined, from the equation $Qdot = IA\eta = mdotCp\Delta T$. Second, the mass flow rate (mdot) will be calculated from the same equation, as shown in Figure A3. Third, the volume flow rate will be calculated from the equation $mdot=\rho vdot$, as shown in Figure A4. Fourth, the Reynolds number will be calculated, from the equations $Re = \rho vD/\mu$ and $mdot=\rho vA$, as shown in Figure A5. Solving for ρ yields the following two equations: $\rho = Re\mu/vD$ and $\rho = mdot/vA$. Setting the equations equal allows the velocity of water to be cancelled. From there, Re can be solved for, since all other variables will be known by this point. The Reynolds number will indicate the type of flow. Once the Reynolds number is calculated, the velocity of the water can be determined fifth, using the equation $v = Re\mu/\rho D$, as shown in Figure A6. Sixth, once the water velocity is calculated, a back pressure can be calculated, and an appropriate pump assigned. To calculate the back pressure, the following equation will be used: $\Delta P = f(L/D)(v^2/2) + \rho gh$, as shown in Figure A8 for the curved path. Figure A7 shown the calculation for determining the curved path length for use in the back pressure equation. For the manifold pipe path, the back pressure was calculated in a different manner. First, the change in pressure across the 36 in pipes was calculated, as shown in Figure A9. Next the change in pressure of the larger pipes between each segment of small pipe was determined. Three pipe diameters were analyzed, to determine which would be the most efficient. As shown in Figure A10, the back pressure for the first segment of pipe was calculated for a diameter of 0.375in, and the rest of the segments were calculated in Excel and the results are shown in Figure A13. Figure A11 shows the back pressure for the first segment of pipe was calculated for a diameter of 0.5in, and the rest of the segments were calculated in Excel and the results are shown in Figure A14. Figure A12 shows the back pressure for the first segment of pipe was calculated for a diameter of 0.75in, and the rest of the segments were calculated in Excel and the results are shown in Figure A15. Figure A16 shows the calculations that took place to decide on the final pipe diameter. The total back pressure across all 36 segments of large pipe were compared to the change in pressure across the thin pipes. As shown, the 0.75in diameter pipe created the smallest pressure difference, which means that the 0.75in diameter pipe more evenly distributes the water flow between the 36 thin pipes.

2f. Scope of Testing and Evaluation:

A few resources are available to test the needed parameters. The website www.wunderground.com will be used to measure and record the solar flux. If the actual solar flux is much lower, (if there are more clouds than expected), then the efficiency of the solar collector will appear to be less efficient. If the actual solar flux can be measured, a more accurate collector efficiency can be determined. Furthermore, a flow meter will be used to make sure that the assumed water volume flow rate is being met. If the flow rate is too high or too low, power supplied to the pump tuned to accordingly to return the water to the desired flow rate. A device will also be installed on the solar collector to ensure that the surface of the collector is angled to the optimal position. A small rod will be placed in the top right corner of the collector. When the collector is optimally facing the sun (with the collector surface perpendicular to the sun's rays), the rod will not cast a shadow. All of these devices will be used to ensure that the solar collector is placed in conditions that are optimal and close to the assumed conditions used in calculations.

2g. Analyses:

Before calculations can take place, a few factors have to be determined or assumed. The heat transfer equation Qdot = $IA\eta$ = mdotCpΔT, will be used to find the heat transfer coefficient (Figure A2, Appendix A) and the desired mass flow rate (Figure A3, Appendix A) of the water, necessary to achieve the desired output. For this project, the desired outputs are a temperature increase of 25 degrees Celsius (ΔT), and an efficiency of 50% (η). The solar flux (I) will be estimated using an online database. The collector frame thickness will be optimized, and the collector surface area (A) will be optimized, so that with the frame added, the solar collector does not exceed the maximum 2.5 feet by 3 feet to fit on the frame. As shown in Appendix A, Figure A1, the surface area of the solar collector is maximized by determining the narrowest thickness for the frame that can still support the collector. This area is found to be 28.5in by 34.5in. The equation Qdot = $IA\eta$ = mdotCpΔT will be used, as shown in Appendix A, Figure A2. Cp is assumed to be 4.18kJ/kgK as found in Fundamentals of Thermal-Fluid Sciences, by Çengel and Cimbala, so the mass flow rate of the water (mdot) can be calculated, as shown in Appendix A, Figure A3. The mass flow rate is the calculated parameter in this case. The mass flow rate leads down the path towards finding the necessary pipe diameters.

Next, the volume flow rate (vdot) will be calculated, as shown in Appendix A, Figure A4, using the equation, mdot=ρvdot, with the density of water (ρ) assumed based on tabulated data. The calculated parameter in this case will be the volume flow rate. The volume flow rate is another step towards determining the necessary pipe diameter for the solar collector.

Third, a Reynolds number can be calculated, using the equations $Re = \rho vD/\mu$ and mdot=ρvA. Solving for ρ yields the following two equations: $\rho = Re\mu/vD$ and ρ = mdot/vA. The v (water velocity) cancels in both equations, leaving only the Reynolds number to be solved for. The Reynolds number will help determine the type of flow of the water traveling through the solar collector. The type of flow will help to determine the pipe diameter necessary to achieve the desired efficiency of 50%, and temperature increase of 25 degrees Celsius, as shown in Appendix A, Figure A5. Fourth, the water velocity can be determined from the equation $v = Re\mu/\rho D$, as shown in Appendix A, Figure A6. Fifth, the required pump can be determined, based on the back pressure of the water, using the equation $\Delta P = \rho gh + f(L/D)(V^2/2)$, as shown in Appendix A, Figure A8. The length of the pipe can be calculated, as shown in Appendix A, Figure A7, and f can be calculated from the equation $f = Re/64$. The calculated parameter in this case, will be the pump required to drive the system. A possible issue that could arise is that the necessary pump may not be available. If this is the case, a pump will have to be ordered, impacting the budget for this project.

As shown in Figure A4 in Appendix A, the volume flow rate is very small (147.46 mL/min). This equates to a very small Reynolds number, as shown in Figure A5 in Appendix A. The

Reynolds number is 890, which means that the flow of water will be laminar. Turbulent flow would be better in the case of the solar collector, because turbulent flow means that the water is mixing well. In laminar flow, the water flows smoothly, and does not mix well. In the case of the solar collector, if the water does not mix well, then the heat absorbed by the water will not be evenly distributed, and the heat could get trapped in the pipes. To account for this issue, static mixers and/or static mixer putty can be placed in the pipes. Static mixers provide obstacles for water to pass through, thereby mixing the water and the collected heat.

For the manifold pipe path, the back pressure was calculated in a different manner. First, the change in pressure across the 36 in pipes was calculated, as shown in Figure A9. Next the change in pressure of the larger pipes between each segment of small pipe was determined. Three pipe diameters were analyzed, to determine which would be the most efficient. As shown in Figure A10, the back pressure for the first segment of pipe was calculated for a diameter of 0.375in, and the rest of the segments were calculated in Excel and the results are shown in Figure A13. Figure A11 shows the back pressure for the first segment of pipe was calculated for a diameter of 0.5in, and the rest of the segments were calculated in Excel and the results are shown in Figure A14. Figure A12 shows the back pressure for the first segment of pipe was calculated for a diameter of 0.75in, and the rest of the segments were calculated in Excel and the results are shown in Figure A15. Figure A14 shows the calculations that took place to decide on the final pipe diameter. The total back pressure across all 36 segments of large pipe were compared to the change in pressure across the thin pipes. As shown, the 0.75in diameter pipe created the smallest pressure difference, which means that the 0.75in diameter pipe more evenly distributes the water flow between the 36 thin pipes.

2h. Device: Parts, Shapes, and Conformation

The solar collector will have a slot in the top of the frame for the plastic cover to slide in and out. The purpose of this is for teaching. Professor Beardsley will be able to slide the plastic cover in and out to allow for student analyses to take place on the effects of the plastic cover on the collector efficiency.

2i. Device Assembly, Attachments

The solar collector will comprise of several parts. These parts include: the frame, plastic cover, plywood backing, insulation, copper sheet, aluminum sidings, pipes, power supply, fittings, flow meter, and pump. For a full assembly drawings, refer to Figure B1 in Appendix B. Figure B1 shows all parts of solar collector and how they fit together. Figure B2 in Appendix B shows the curved path collector assembly. This includes the plastic cover, frame components, backing, copper sheet, insulation, aluminum sidings, and curved path collector piping. Figure B3 in Appendix B details the manifold path collector assembly. This includes all the same components as Figure B2, but with the manifold piping instead of the curved path. Figure B4 in Appendix B shows the curved path pipes in more detail. Figure B5 in Appendix B depicts the manifold collector pipes in more detail. Figure B6 shows the header pipes for the manifold. Figure B7 shows the aluminum sidings, which will be mounted on the frame, to support the plastic cover. Figure B11, located in Appendix B shows the backing, which will be placed on the back of the frame for support, and Figure B12 shows the plastic cover. Figure B8 shows the copper sheet, which the pipes will be mounted on. Figure B9 shows the manifold backing, which will work in much the same way as the copper sheet, but for the manifold collector tubing. Figure B10 shows the insulation, which will reside between the copper sheet and the plywood backing. Figures B13-15 in Appendix B show the frame with slots and holes to accommodate the plastic cover and the pipes.

2j. Tolerances/Ergonomics

The overall efficiency of the solar collector depends on more than pipe diameter, volume flow rate, and the surface area of the collector. The solar flux input and the angle of the collector also play a role in the efficiency of the solar collector. If not placed at the optimal angle, or if the collector is placed in a shaded area, then the solar input will be dampened. A lower solar input will lead to a lower temperature increase output. For the best results, the solar collector should be placed in direct sunlight at an angle that is perpendicular to the sun. Furthermore, the volume flow rate of the water will have some human influence. If the volume flow rate of the water is not at the optimal rate, as measured by a flow meter, then the desired flow rate will have to be attained by tuning the power to the pump accordingly. While the majority of the components that affect the overall efficiency of the solar collector will be incorporated into the design, the positioning of the solar collector, and the flow rate of the water will be dependent on the user.

2k. Technical Risk Analysis, Failure Mode Analyses, Safety Factors, Operation Limits

There are many types of possible risks. For example, there is a financial risk of going over budget. The budget for this project is $100. One way to save money is to use existing equipment. For example, there are several pumps available in the MET 411 lab equipment. The pumps are currently not being used, so they are available for use with the solar collector. The same applies to flow meters, and connecting nozzles. Using items that are available, but not currently in use, will help to mitigate costs. There is also the possibility of a scheduling risk. The solar collector is required to take no more than 20 hours to manufacture. However, if any issues with parts arise, then this time limit may need to be extended. One way to reduce the risk of this occurring would be to plan out exactly how to construct the solar collector ahead of time, and to check the parts for compatibility before construction occurs. Finally, ordering the necessary parts with plenty of time for shipping, would allow time for any errors with part compatibility to be noticed and resolved.

There are also several possible modes of failure that could occur. For example, a leak could occur. If a connection is not fitted correctly, water could escape. This could lead to a safety hazard if someone slips in the spilled water. Furthermore, the water in the pipes will be under pressure, due to the pump. If a leak does occur, the operator must shut off the pump immediately. Another possible mode of failure would be the pump not performing sufficiently. If the pump does not generate a high enough volume flow rate, then the heat transfer coefficient will drop, due to the equation $Qdot = IA\eta = mdotCp\Delta T$, where mdot is equal to the flow rate of the water. If the heat transfer coefficient (Qdot) drops, then the efficiency (η) will also decrease, because the area of the collector (A) and the incoming solar flux (I) will not change. Finally, a possible safety issue could be excessive heat. If the solar collector is left in direct sunlight for the two hour lab course, it will heat up. If the collector gets hot enough, it could burn the operator. A warning sticker will be placed on the collector to warn users of this risk. To help mitigate the risk of the solar collector getting too hot, the collector should be put away promptly at the end of the lab period.

3. METHODS AND CONSTRUCTION

3a. Construction

The solar collector will be constructed out of a wooden frame, plastic cover, insulation, copper sheet, plywood backing, aluminum sidings, and piping (copper and rubber). The wood frame will be made out of two by fours cut to size. The sides of the frame will have slots sawed out of them to accommodate for the connecting joints between them. The four sides of the solar collector will be glued together and a thin plywood backing will be attached, with glue and nails. The entire frame and backing will be painted black, to increase solar absorptivity. The insulation will be placed in the solar collector frame. Then, the copper piping will be bent into shape and soldered to a copper sheet for the curved path design. For the manifold design, two header pipes will have holes drilled, and small sections of copper pipe will be welded into the holes. The sections of copper pipe will connect the header pipes to the black collector tubing in a manifold fashion. Next, the copper sheet (or manifold, depending on the design) will be placed on top of the insulation layer. Two slots will be cut in the right-hand side of the solar collector frame to accommodate the inlet and outlet pipes. Next, the aluminum sidings will be attached to accommodate the plastic cover. The collector will then be repainted, and mounted on the stand for the final phase of construction. Finally, the rest of the piping system will be connected to the collector pipes, making sure that the pump, fittings, and flow meter are incorporated effectively, and the plastic cover will be installed.

3ai. Description

The solar collector will comprise of a wooden frame, a plywood backing, insulation, copper sheet, copper and/or rubber pipes, aluminum sidings, fittings, a pump, a plastic cover, and a volumetric flow meter. The wooden frame and plywood backing will house part of the piping system, and the plastic cover. These components comprise the collector assembly, which will be labeled Assembly A. The collector piping system, plastic cover, and black paint will serve the purpose of heating water. As sunlight hits the solar collector, the plastic cover and black paint will absorb and collect the solar radiation in the form of heat. This heat will be concentrated on the pipes, through which, water will be flowing. As a result, the water will heat up between the inlet and outlet holes in the collector. The rest of the piping system, the fittings, pump, and flow meter comprise the piping assembly, which will be labeled Assembly B. For Assembly B, the pipes will connect the pump and the flow meter to the collector piping system. The pump will drive the water through the system, and the volumetric flow meter will display this flow of water. The power supply to the pump in the piping system will help to control the flow rate of the water, so that it remains within optimal conditions. The pump, flow meter, and solar collector will be attached to the stand, which is currently being designed and constructed by Tyson Nakamura as part of another project.

3aii. Drawing Tree

To complete the project, a drawing tree will be made and followed, as shown in Figures 2a and 2b. The roots of the tree will be the frame of the collector, as shown in Figures 13, 14, and 15 in Appendix B. The frame of the collector will be constructed first, and will be a large contributor to the structure of the solar collector. The wooden frame attaches the collector to the stand, supports the piping system, and holds the plastic cover. From there, the backing of the frame will be constructed and attached to the solar collector next, as shown in Figure 11 in

Appendix B. The backing and the plastic cover form the trunk of the solar collector, because they are also some of the first components to be constructed. The plastic cover can be seen in Figure 12 in Appendix B. The plastic cover will be attached to the collector frame with the aluminum siding, as shown in Figure 7 in Appendix B. Next, the collector piping will be assembled, as shown in Figures 4, 5, and 6 in Appendix B. The piping can be seen as the final component of the roots of Assembly A, as shown in Figure 1. Next, the power supply, fittings, volume flow meter, and pump will be connected to the solar collector. The wooden frame, backing, plastic cover, and some of the pipes comprise the collector assembly (Figures 2 and 3 in Appendix B), or the roots of Assembly A. They provide the structure and support of the solar collector. The rest of the pipes, fittings, pump, and volume flow meter comprise the piping assembly, or the roots of Assembly B. Finally, Figure 1 in Appendix B shows the full assembly in its entirety, with all components labeled. Assembly C (the stand) will be constructed by Tyson Nakamura as a separate project. Figure 1 shows that Assemblies A, B, and C combined complete the solar collector assembly.

Figure 2a: Curved Path

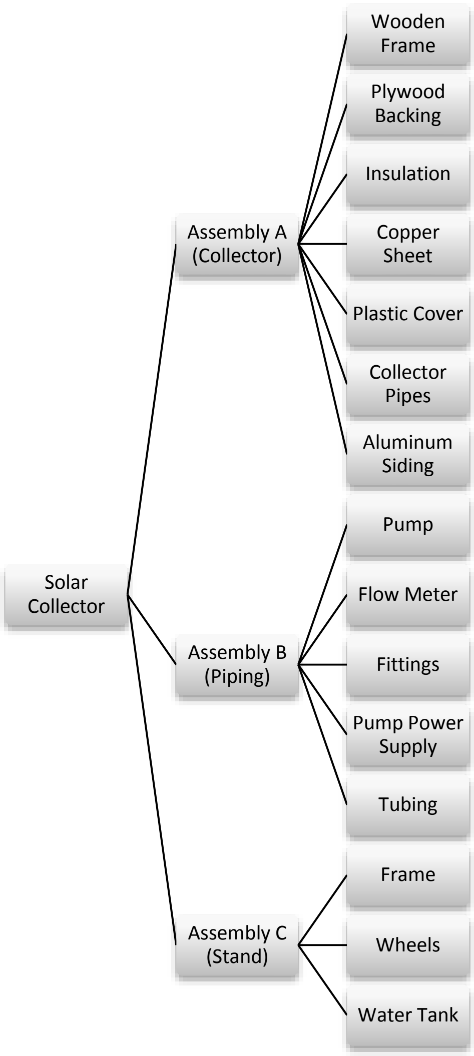


Figure 2b: Manifold Path

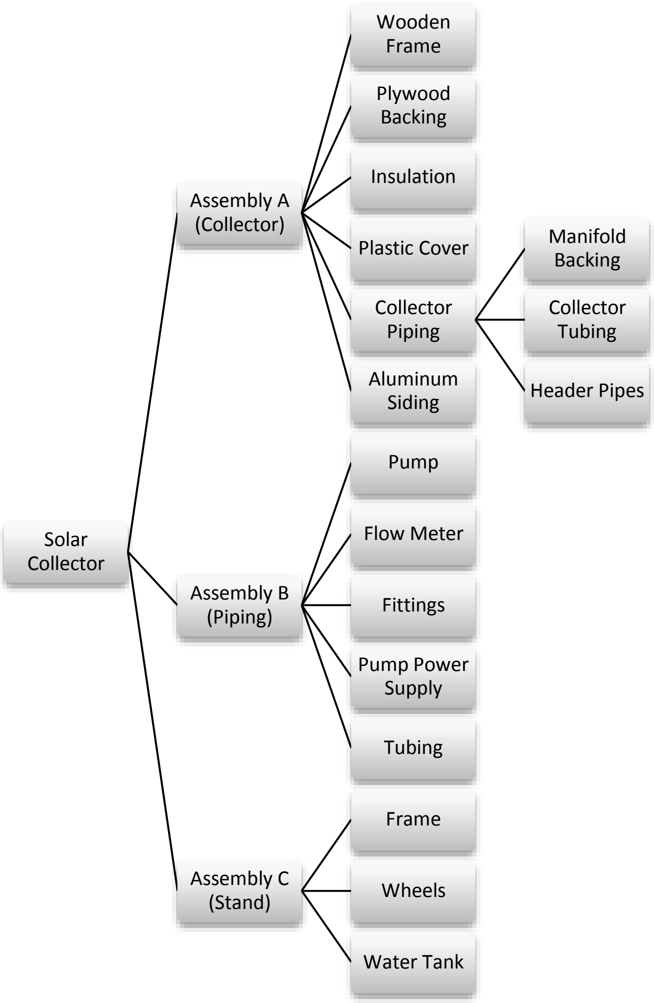


Figure 2a shows the drawing tree for the curved path collector, with the first group of roots (wooden frame, plywood backing, copper sheet, insulation, plastic cover, aluminum sidings, and collector pipes) comprising Assembly A, and the second group of roots (pump, flow meter, fittings, and power supply) comprising Assembly B. The third group of roots (frame, wheels, water tank, etc.) comprise Assembly C, which is part of Tyson Nakamura's project. Assemblies A, B, and C comprise the entire solar collector. Figure 2b shows a similar drawing tree for the manifold pipe path. The first group of roots (wooden frame, plywood backing, insulation, plastic cover, aluminum sidings, and collector piping, which include the manifold backing, header pipes, and collector tubing) comprising Assembly A. Assemblies B and C are the same for both collector paths.

3aiii. Part List and Labels

For a full parts list, please refer to Appendix C. A simple parts list includes:

- Wooden frame boards –Ai
    - Cost: $10.35 for 4 from Lowes
- Plywood backing –Aii
    - Cost: $15.09 from Lowes
- Copper Pipes -Aiii
    - Cost: $19.12 for 20 feet from Lowes
- Plastic Cover –Aiv
    - Cost: $23.74 from Lowes
- Insulation –Av
    - Cost: $0 from MET 411 Store Cupboard
- Copper Sheet –Avi
    - Cost: $0 from MET 411 Store Cupboard
- Aluminum Siding –Avii
    - Cost: $0 from MET 411 Store Cupboard
- Manifold Collector Tubing –Aviii
    - $0 from MET 411 Store Cupboard
- Header Pipes –Aix
    - $0 from MET 411 Store Cupboard
- Manifold Backing –Ax
    - $0 from MET 411 Store Cupboard
- End Caps –Axi
    - $0 from MET 411 Store Cupboard
- Black paint (and paintbrush) –Axii
    - Cost: $5 from Ace Hardware
- Pump Power Supply - Bi
    - Cost: $0 from MET 411 Store Cupboard
- Fittings –Bii
    - Cost: $0 from MET 411 Store Cupboard
- Volumetric flow meter -Biii
    - Cost: $0 from MET 411 Store Cupboard
- Pump -Biv
    - Cost: $0 from: MET 411 Store Cupboard

- Tubing – Bv
    - Cost: $0 from: MET 411 Store Cupboard

Identification labels were determined primarily by the assembly in which the component plays a significant role (A or B), and then by order of assembly, with the components that will be necessary for manufacturing earliest listed first. See Appendix C for a full parts list.

3aiv. Manufacturing Issues

During the manufacturing phase, several issues have occurred. For example, there was only enough copper to make one copper sheet. Originally, both the curved collector path and the manifold path were going to be mounted on copper sheets. However, due to the lack of copper sheeting, the manifold path was redesigned to be manufactured out of rubber collector tubing. The rubber collector tubing is made in rolls of 6 tubes mounted on a rubber backing. This backing eliminated the need for another copper sheet. The manifold pipe path will now be glued onto a plywood board for support, instead of the original design of copper pipes soldered to a copper sheet. Another manufacturing issue which has occurred is that the copper sheets which were available were not large enough. Therefore, 4 sections of copper sheet had to be cut and soldered together. This made manufacturing the curved pipe path slightly more difficult. However, soldering was successful. An additional manufacturing issue which has occurred involved cutting the dovetail joints on the collector frame components. Each male and female pair had to match up, or the frame components would not fit together. Although this was challenging, the frame components were successfully cut. Another manufacturing issue involved soldering the copper pipes to the copper sheet. Mr. Burvee originally tried soldering at 150°F, however, the copper pipe and sheet came apart. Mr. Burvee eventually had to solder the copper pipes to the copper sheet in the 500-550°F range. This was successfully done, but required extra time and special solder. Finally, joining the manifold header pipes to the rubber collector tubing was quite challenging. The 3/4in header pipes had 1/4in holes drilled into it. Next, small sections of 1/4in copper pipe were soldered into the header pipes. Finally, the rubber collector tubing was slid on top of the 1/4in pipe sections. However, this was a tight fit, and the collector tubing was reluctant to surround the copper pipe sections. To remedy this issue, hand soap was used as a lubricant. This method worked well, and the collector tubing was able to be joined with the header pipes. Another issues which occurred was fitting all of the collector components together once everything was painted. Before painting, the manifold pipe path fit snuggly in the collector. However, after painting the frame and the manifold backing, the pipe path no longer fit in the collector. To resolve this issue, the manifold backing was filed to decrease its size. Now, the manifold backing fits in the collector again. The final manufacturing issue which occurred involved connecting up the full piping path. Finding a pump and flow meter small enough to accommodate the needs of the collector was a challenge. Luckily, Professor Beardsley had one of each in the MET store cupboard. Next, finding fittings that allowed the collector pipes to go to hose fittings was also a challenge. However, Professor Beardsley was able to find the correct fittings and hose pipes. Finally, when attaching and detaching the hose fittings to the curved path collector, the collector piping would twist. To remedy this issue, more permanent fittings and a 3/8” hose was attached to each end of the curved pipe path. These fittings and the hose were set aside to be permanently attached to the curve pipe path. This way, any connecting between the curved pipe path and the rest of the system will occur at the other end of the 3/8” hoses, and not damage the curve pipe path.

3av. Discussion of Assembly

First, the wooden frame was constructed. The four sides were cut individually, and they were glued together. Once the frame was finished, the plywood backing was then nailed to the back of the frame, to make the housing of the collector. The collector was painted black as an initial coating. While waiting for the stand to be constructed, the collector piping systems were manufactured. The curved path pipes were bent into shape and then the manifold piping system was cut and assembled (by drilling holes in the piping, attaching the sub pipes, soldering, and joining the collector tubing to the sub pipes). The curved path copper pipes were soldered onto a copper sheet. The manifold pipes were glued to a plywood board for stability. Next, the insulation was placed in the collector frame, followed by the copper sheet or manifold backing and piping. Next, the inlet and outlet slots were mapped on the frame. These were then cut, and the piping system attached to the collector housing. The aluminum sidings were attached to the wooden frame to ensure secure support for the plastic cover. The collector (Assembly A) was painted black, to ensure universal coloring for practicality and aesthetics. Once the paint dried, the collector was fixed to the stand, and the piping assembly (Assembly B) was attached. The volumetric flow meter was mounted onto one of the legs of the stand so that it could be more easily read. This also provided some support for the connecting pipes. The pump was also attached to the stand for support and stability. Once the volume flow meter and pump were in place, connecting pipes were attached, with the help of some fittings, to connect the water tank, pump, flow meter, and collector, in a loop.

4. TESTING METHOD

4a. Introduction

To test the performance of the solar collector, a couple of methods will be used. First, the incoming solar irradiance will be measured and recorded, using www.wunderground.com and the weather data on top of the Hogue Technology building. The difference between the input and output temperatures of the water in the collector will also be measured. The goal is to achieve a temperature difference of at least 25 degrees Celsius. The flow rate of the water will also be measured with a flow meter. The flow rate will be measured for calculation purposes. The solar irradiance, flow rate, and temperature difference will be measured every 10 minutes throughout the two hour lab period. Students will be given the collector dimensions, C_p, and density of water, so that they can calculate the efficiency of the collector, and the heat transfer coefficient, Qdot. Students will graph any changes that occur over the two hour lab period, and answer discussion questions related to the collector.

The other way that the performance of the collector will be measured is through actually carrying out a lab. Professor Beardsley will be given ten minutes to bring the collector setup and additional equipment out of the MET 411 storage cupboard to the Hogue patio, and set it up. Next, the principal engineer will be given two hours to use the collector to gather data. Finally, Professor Beardsley will be given ten minutes to dismantle and put away the solar collector setup. Carrying out the three phase process in full within the time limits would be considered a success.

4b. Method/Approach

To test the performance predictions outlined in section 2d, a number of items need to be carried out. These items include:

- Measuring the time it takes for the lab tech to setup the collector and associated equipment
    - The goal is no more than ten minutes
- The time it takes for Professor Beardsley to take the collector assembly from the MET 411 store cupboard to the Hogue patio will be measured and recorded to determine ease of transportation
- During a two hour lab period, the principal will use the solar collector to gather data and complete the lab analysis
- The time it takes Professor Beardsley to dismantle and put away the lab setup will be measured and recorded
    - The goal is no more an ten minutes
- Measuring the temperature change between the inlet and outlet pipes
- Determining the collector efficiency
    - Qdot = IAη = mdotCpΔT will be used
    - The solar irradiance (I) will be measured
    - The collector area (A) will be given, but can be double checked by students
    - The flow rate (mdot) will be measured and calculated
    - The water property, C_p will be given
    - The temperature change (ΔT) will be measured
- Manufacturing time will be measured and recorded
    - The goal was no more than 20 hours to manufacture
- Cost of manufacturing will be measured and recorded
    - The goal is no more than $100 to manufacture

The measurement tools that will be needed are the following:

- www.wunderground.com – to measure solar irradiance
- Thermometers – to measure inlet and outlet water temperatures
- Flow Meter – to measure the volumetric flow rate of the water
- Tape Measure – to double check the surface area of the collector
- Stop Watch – to measure the time it takes to setup, use, and dismantle the collector set up, as well as for measuring the time it takes to manufacture the collector

The test sites will include:

- The MET 411 store cupboard – to make sure that the solar collector assembly can be stored within the designated area
- Hogue Technology Building – the collector assembly will be transported through the building to test for ease of transportation
- The Hogue patio – this is where the solar collector will be placed in direct sunlight for data to be recorded

4c. Test Procedure

Data acquisition will take place in accordance with Figures G1, G2, and G3 in the appendix. These forms lay out the data that will be recorded to test the performance of the solar collector. Figure G1 outlines the testing data that will be recorded with regards to the usability of the collector. Figure G2 lays out the data sheet that will be used during lab to gather data for determining the collector efficiency and the temperature change between the inlet and outlet pipes. Figure G3 is a log of manufacturing time. A goal of 20 hours was set for the completion of manufacturing the solar collector. Figure G3 will help to determine if this goal was met. A running expenditure list will also be kept to keep track of the budget and spending. A budget of $100 was set to complete the solar collector. The expenditure list will help to determine if this goal was met.

4d. Deliverables

To complete the testing procedure, a few reservations will have to be made ahead of time. For example, six ten minute blocks of time will have to be reserved with Professor Beardsley and the lab tech to complete Figure G1. Three trials will take place to determine if the solar collector can be set up within a ten minute block between classes. The same applies for three trials of clean up within a similar ten minute block between classes. Furthermore, the lab tech will need to be reserved to test the transportability of the solar collector for the three trials. Finally, a group of 2-3 students will need to be reserved to carry out a trial lab, and complete Figure G2. The deliverables of the testing data will be completed Figures G1, G2, G3, and the expenditure list/budget. The results of the testing will be summed up in the evaluation sheet, which can be found in Appendix H. The final testing report can be found in Appendix I. All of these items will be completed after testing has taken place.

5. BUDGET/SCHEDULE/PROJECT MANAGEMENT

5a. Proposed Budget

There is still a potential risk of going over budget to complete the project. For example, if any errors are made while finishing up the manufacturing process, then parts will need to be repurchased. This will also call for return trips to hardware stores, costing extra time and money. Furthermore, if manufacturing takes longer than planned, labor costs could increase. CWU is paying the labor costs. Each incidence would require more money than was initial planned and budgeted. The parts list can be found in Appendix C, and the full budget in Appendix D. The full budget includes parts, labor, and transportation. The parts list includes an estimated vs. actual cost of each item, including taxes, the place of purchase, and a description of each item. The full budget includes estimated and actual costs for each component, with categories broken down and summed for the grand total. The following sections break the budget down further.

5ai. Part suppliers, substantive costs, and sequence or buying issues

Appendix C shows a full parts list. A large portion of the parts are currently available in the MET 411 store cupboard. These parts include: the copper sheets, collector tubing, fittings, insulation, flow meter, hose tubing, pump, and pump power supply. Since these components are readily available, there should not be any costs or buying issues associated with any of them. Several parts were purchased from Lowe’s in Yakima. These parts include: the wooden frame components, the plastic cover, copper pipes, and the plywood backing. The black paint will be purchased from Ace Hardware in town. The transportation budget accounts for a couple of extra trips into town, just in case any return trips need to be made.

5aii. Determine labor or outsourcing rates & estimate costs

To complete the project, Mr. Burvee was necessary for soldering the copper pipes to the copper sheet. Mr. Burvee's salary is paid by Central Washington University, so he is essentially a free resource. An estimated metal worker's salary for the project can be found in Appendix D. In addition, the lab teach, two MET 411 students, and Professor Beardsley will also be necessary during the testing phase of the project, to determine whether or not the solar collector is in compliance with the requirements. These requirements include: the solar collector must be in compliance with MET 411 labs, the solar collector must be able to be set up and dismantled by the lab tech and Professor Beardsley within ten minutes each, and the solar collector must be able to obtain usable data by two MET 411 lab students within a two hour lab period. The MET 411 students will be volunteers, and Professor Beardsley and the lab tech are paid by Central Washington University. An estimated lab tech salary can be found in Appendix D. All human resources are either volunteers, or are paid by another source, so there are no labor costs for this project.

5aiii. Labor

Construction of the solar collector is mainly being carried out by the principal engineer, who is volunteering her time. As mentioned in section 5aii, Mr. Burvee helped to solder the collector pipes to the copper sheet, Professor Beardsley has been providing guidance, and the student machinist has been helping to manufacture the pipe paths. The lab tech, Professor Beardsley, and the two MET 411 students will be assisting in the testing phase. All laborers are either volunteering their time, or are being paid by Central Washington University. The stand for the collector is being assembled by Tyson Nakamura. The collector and the stand will come together by week 22 of the project (week 10 of winter quarter). Tyson is also volunteering his time to assemble his portion of the project.

5aiv. Estimate total project cost

Ad shown in Appendix D, the estimated total cost for this project is $91.04. With designations as follows: $79.84 for parts, $11.20 for transportation, and $0 for labor costs.

5av. Funding sources

The project is being paid for by a combination of the CWU engineering department and contributions from the principle engineer. Some items have been donated from the MET 411 store cupboard, such as: the insulation, copper sheet, volumetric flow meter, pump, and pipe fittings. Labor costs are being covered by Central Washington University.

5b. Proposed schedule

See Appendix E, for full Gantt schedule. As shown in Figure E1, the project will be spread across three quarters (fall, winter, and spring), spanning a total of 34 weeks. Fall quarter was the proposal stage, which as shown, includes writing up all proposal components and analyses in preparation of manufacturing. Winter quarter is the manufacturing stage, during which parts will be purchased, cut to size, and assembled. This state also includes soldering pipes, and mounting the solar collector on the stand. Finally, spring quarter will be the testing stage, which will include 3 tests of the solar collector efficiency, and 4 tests of the usability of the solar collector for MET 411 labs. See Gantt chart for detailed estimates and actual timings. The total time required to complete the project is 141.25 hours as of May 27th, 2016.

5c. Project Management

There are several potential sources of risk still involved with this project. For example, the project could go over budget, errors in manufacturing or purchasing parts could lead to delays, or resources may fall through. To help reduce the risk of one of these issues from occurring, a project management plan is being followed. This plan includes several components. As previously mentioned, a full budget and schedule have been drawn up. This forward planning helps to encourage forward thinking, and generate detailed plans, so that the risk of falling behind is reduced. By planning ahead, potential risks can be identified and combative methods can be put in place. Having a detailed plan with overestimated times of completion for each task reduces the risk of procrastination or surprises in the schedule. Another way to reduce the risk of unforeseen errors would be to ensure that all resources are in place as needed. For example, human resources, such as Mr. Burvee, Professor Beardsley, and the lab tech have been met with well in advance to ensure that appointments are set up, and tasks are completed on time. Furthermore, use of facilities, such as the CWU wood shop, have been organized beforehand to ensure that the space is available. Finally, the MET 411 store cupboard, which is providing several parts for the solar collector, has already been searched and parts have been set aside for use in the solar collector project.

5ci. Human Resources

This project will succeed due to the availability of appropriate technical expertise and resources. The principle engineer will provide expertise in heat transfer as shown in Appendix G. Additional human resources for this project include, Professor Beardsley, the MET 411 lab tech, two MET 411 students, and Mr. Burvee. Professor Beardsley will act as the project sponsor and guide. The solar collector is being manufactured for use in his MET 411 lab class. Professor Beardsley's constraints and guidance are being followed throughout the project. The lab tech and two MET 411 students will be necessary during the testing phase of the project, to assure that the solar collector meets the needs of the MET 411 lab. MET professors may be used as guides throughout the project to provide a deeper level of expertise where necessary. Mr. Burvee has been necessary during the manufacturing stage of the project for assistance with soldering the collector pipes to the copper sheet.

5cii. Physical Resources

To complete this project, a wood shop was necessary. The solar collector frame components were cut to size. In addition, access to a soldering iron was essential for soldering the collector pipes to the copper sheet. Basic cutting tools have been used to cut the copper pipes, plastic cover, and insulation. These tools were available in the MET 411 storage cupboard.

5ciii. Soft Resources

As shown in Appendix B, SolidWorks software was used to complete part drawings and assembly drawings for this project. In addition, websites, such as lowes.com, acehardware.com, homedepot.com, and knudsonlumber.com were used to research available item options and prices for each item that was purchased for the assembly of the solar collector.

5civ. Financial Resources

The main financial resource for this project has been the MET 411 store cupboard. A number of items were available for use during the project, such as insulation, copper sheets, pipes, a pump, pipe fittings, collector tubing, and a volumetric flow meter. Furthermore, tools for cutting the insulation, and copper pipes were also available in the MET 411 store cupboard. Finally, Central Washington University is paying for the lab tech and metal worker salaries, along with operational costs of the soldering iron and machine shop. All of these donations, and/or access to tools have been successful in keeping costs down.

6. DISCUSSION

6a. Design Evolution

Initially, two piping designs were drawn, as shown in section 2b. These designs included a zig zag path and a manifold path for the water to travel down. Originally, one design was to be chosen. However, both of these piping paths will be constructed and tested during the manufacturing and testing phases. These two path types can also be tested as part of the MET 411 lab. Other adaptations have been made throughout the designing phase. For example, the cover for the collector was originally going to be made out of glass, however, plastic is much cheaper, easier to cut to size, and has less of a risk of breaking. The collector will have to be used by students, and Professor Beardsley. If the cover were to fall during transportation, or when changing out the collector piping, then glass has a much higher chance of shattering. Therefore, plastic is the more logical choice. The cover will have to be removed a couple of times during each lab that the collector is in use, so the risk of dropping the cover is somewhat high. Another adaptation that was made to the solar collector was the sizing of the wooden frame. Originally two by four’s were going to be used, so the width of each of the frame components were approximately 1.5in. However, after several calculations, it was determined that the beams could be a little at 0.75in thick, to optimize the collector surface area. Finally, the mounting design for the plastic cover was recently altered. Originally, slots were going to be cut in the sides of the wooden frame for the plastic to slide into. However, once the thickness of the frame components were reduced, cutting slots into the wood would seriously compromise the structural integrity of the frame. Therefore, aluminum sidings will be added to the wooden frame components, for the plastic cover to slide into. This method will reduce weight and maximize the surface area of the solar collector, compared to using the original 1.5 in thick beams for the frame.

Other design changes have occurred throughout the manufacturing phase. For example, the manifold piping assembly was originally going to be made out of copper, much like the curved pipe path. However, there was only enough copper to make one copper sheet, and 1/8in copper pipes were not readily available. Therefore, black collector tubing is being used instead. Professor Beardsley had two rolls readily available, which provided more than enough collector tubing to make the manifold assembly. To accommodate for the change in manifold tubing, the header pipes for the manifold design increased from 0.5in to 0.75in. See Appendix A for calculations. Furthermore, the copper sheet which was used for the curved pipe path had to be cut into four sections due to a lack of size in the provided copper sheets. Having four copper sheet components did require extra soldering, however the finished pipe path was successfully constructed. Finally, instead of using standard hose pipes to connect up the curved pipe path with the rest of the system, a 3/8” hose and smaller fittings will be permanently attached to the curved pipe path. This reduces the risk of twisting and breaking the ends of the ¼” copper pipes. When standard hose pipes were used, attaching and detaching the hose fittings was causing too heavy of a torsional force on the copper pipes, and the pipes were starting to incur damage. By adding permanent fittings and a set aside hose pipe, the need for attaching and detaching fittings to the curved pipe path was eliminated, and therefore the risk of damage reduced.

6b. Project Risk Analysis

Several risk factors were at work during the project. These include: time, budget, and unforeseen errors. To reduce the risk of going over budget, many items were salvaged from the MET 411 store cupboard. Items, such as the pump, volume flow meter, and the copper sheets would have been expensive to purchase otherwise. To reduce the risk of running out of time to complete the project, many plans have been established ahead of time. These include, talking to human resources, such as Mr. Burvee and the lab tech, to ensure that appointment times were met as scheduled. Furthermore, frequent checking of the machine shop and wood shop hours of operation has been carried out to ensure that no unforeseen errors of scheduling hinder the estimated rate of production. Finally, ordering parts well in advance was crucial in starting the project off ahead of schedule, and ensured that no time was wasted waiting around for parts to arrive. Weekly meetings with Professor Beardsley have taken place all of fall and winter to confirm the progress and validity of the project. Professor Beardsley has been checking calculations, making suggestions, and answering questions to guarantee the quality of the project.

6c. Success

Thus far, a vast amount of engineering and project management knowledge has already been learned, which would make this project a success. From a deeper understanding of Gantt charts, and heat transfer, to further practice with SolidWorks and project planning, this project has been a challenge with many lessons learned and solidified. The project has not only taught engineering lessons, but also a deeper understanding of personal abilities have been learned, including the achievable pace of work, and skill boundaries. Furthermore, the project has also taught the value of staying ahead of schedule, as changes in the design set back manufacturing by one week, due to recalculations. However, due to being two weeks ahead of schedule prior to this incident, the project did not fall behind schedule. As a whole, the success of this project is primarily based on learning. Thus far, the project has been a success.

6d. Project Documentation

The results of the testing phase will be documented in Appendix G, in the form of results tables. One table will include assembly and disassembly times, for the purpose of testing the compliance of the solar collector with MET 411 labs. The other table will test the efficiency of the solar collector. Both of these tables will be filled out 4 times throughout spring quarter. Theoretically, the assembly and disassembly times should lessen with practice, and the solar collector should increase in efficiency as the quarter progresses towards summer, when the incoming solar flux will be greater. Furthermore, the estimated scheduling times to complete each task will be tested through documentation. As shown in figure G3 in Appendix G, the time taken to complete each task during the construction phase will be recorded and then compared to the estimated times. This allows for learning as far as a reasonable pace of work goes. Often individuals tend to underestimate how long it takes to complete a task. Learning physical capabilities is a valuable life lesson that can be applied to all future work endeavors. Finally, any future adaptations made to the proposal or the solar collector itself will be documented and discussed through winter and spring quarters. This proposal is a living document and adaptations will happen.

7. CONCLUSION

7a. Design Title and Readiness

A device has been conceived, designed, and analyzed that meets the function requirements discussed in section 1. The device also meets the requirements for a successful senior project. For example, the project includes engineering merit, such as the analyses shown in appendix A. The project also requires acquiring the necessary resources required to complete the construction of the solar collector. These resources include parts, labor, and tools. All parts have been specified, sourced, ordered and/or obtained, and budgeted for. Labor includes Mr. Burvee, and the lab tech, both of whom have been helping with construction. Tools include the machine shop and woodshop, both of which have their schedules checked weekly and have already been utilized. With the information presented, and drawings shown, the device is currently being constructed.

7b. Important Analyses

To complete the project, a series of calculations had to be performed. These analyses include, using beam deflection to find the narrowest frame dimensions possible for optimizing the surface area of the collector. The heat transfer coefficient, mass and volume flow rates, Reynolds number, water velocity, and back pressure were also calculated. Each of these parameters led to choosing an appropriate pipe diameter, and pump.

7c. Design Predicted Performance

The solar collector is designed to heat water by approximately 25 degrees Celsius between the inlet and outlet pipes, at an efficiency of at least 50%. The solar collector is also designed to be assembled and disassembled within ten minutes by the lab tech and Professor Beardsley, in compliance with MET 411 labs. The testing phase will determine if the solar collector met these performance predictions.

8. AKNOWLEDGEMENTS

This project was made possible with help from Professor Beardsley, Mr. Burvee, Tyson Nakamura, and the MET department at Central Washington University. Professor Beardsley acted as a guide throughout the entire project. Mr. Burvee made possible the soldering of the collector pipes to the copper sheets, without which, the collector would not have been able to conduct heat from the copper sheet to the pipes for heating up the water. Tyson Nakamura is constructing the stand for the solar collector to be mounted on. Without a stand, the solar collector would not be transportable, or user friendly for gathering data. Finally, the MET department supplied several of the collector materials, paid the wages of the lab tech and Mr. Burvee, and allowed access to the wood shop and metal shop during the manufacturing phase of the project.

9. REFERENCES

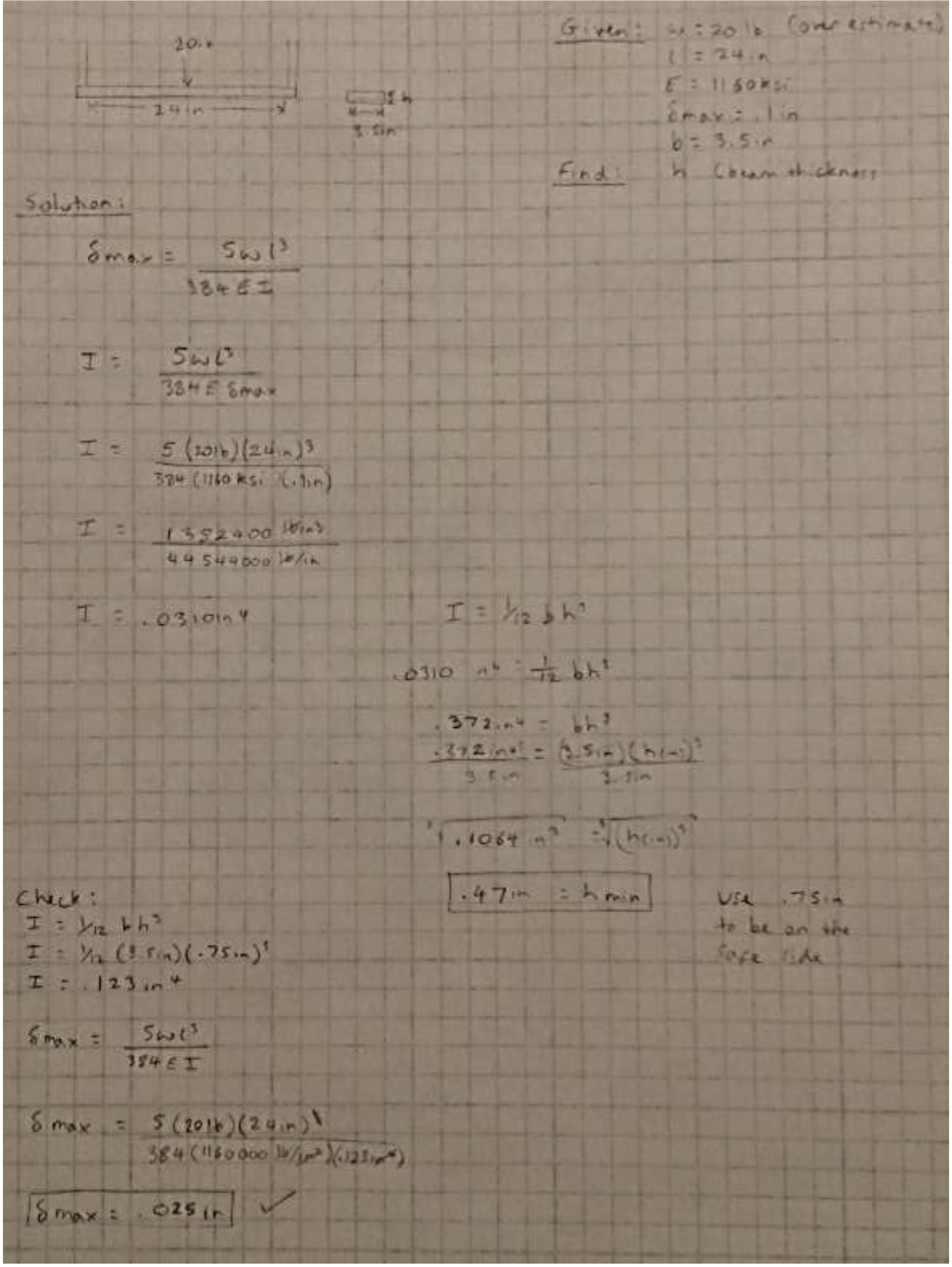
References for this project include:

- Beardsley, Roger. *MET 411 Syllabus*. N.p.: n.p., 15 Sept. 2015. PDF.
    - The MET 411 course syllabus was used to find the MET 411 student outcomes
- Beardsley, Roger. *MET 411 Lab 2*. N.p.: n.p., 15 Sept. 2015. PDF.
    - MET 411 Lab 2 was used to create the lab sheet for the solar collector lab
- "BuildItSolar: Solar Energy Projects for Do It Yourselfers to save Money and Reduce Pollution." *BuildItSolar: Solar Energy Projects for Do It Yourselfers to save Money and Reduce Pollution*. N.p., n.d. Web. 3 Oct. 2015.
    - This reference was used to determine an achievable collector efficiency
- Çengel, Yunus A., and Cimbala, John M. *Fundamentals of Thermal-Fluid Sciences*. 4th ed. New York: McGraw-Hill Higher Education, 2012. Print.
    - This reference provided many of the heat transfer and fluid dynamics equations used in the analysis
- http://www.engineeringtoolbox.com/young-modulus-d_417.html
    - This reference provided Young's Modulus for pine, for use in the calculations when determining the minimum beam thickness for components of the wooden frame.
- Mott, Robert L. *Machine Elements in Mechanical Design*. 5th ed. N.p.:, n.d. Print.
    - This book was used for providing the beam deflection formula, used when calculating the minimum beam thickness for components of the wooden frame
- http://solarenergylocal.com/states/washington/ellensburg/
    - This website was used to approximate the incoming solar flux of the solar collector for use in the coefficient of heat transfer equation
- http://wunderground.com
    - This website was used to find the solar irradiance throughout the testing phase

APPENDIX A

Calculations:

Figure A1: Frame Thickness Calculations



Given: $w = 20\,lb$ (over estimate)
$l = 24\,in$
$E = 1160\,ksi$
$\delta_{max} = .1\,in$
$b = 3.5\,in$

Find: h (beam thickness)

Solution:

$$\delta_{max} = \frac{5wl^3}{384EI}$$

$$I = \frac{5wl^3}{384E\delta_{max}}$$

$$I = \frac{5(20lb)(24in)^3}{384(1160\,ksi)(.1in)}$$

$$I = \frac{1382400\ lb\,in^3}{44544000\ lb/in}$$

$$I = .0310\,in^4$$

$$I = \tfrac{1}{12}bh^3$$

$$.0310\,in^4 = \frac{1}{12}bh^3$$

$$.372\,in^4 = bh^3$$

$$\frac{.372\,in^4}{3.5\,in} = \frac{(3.5in)(h(in))^3}{3.5in}$$

$$\sqrt[3]{.1064\,in^3} = \sqrt[3]{(h(in))^3}$$

$$\boxed{.47in = h_{min}}$$

Use .75in to be on the safe side

Check:

$$I = \tfrac{1}{12}bh^3$$

$$I = \tfrac{1}{12}(3.5in)(.75in)^3$$

$$I = .123\,in^4$$

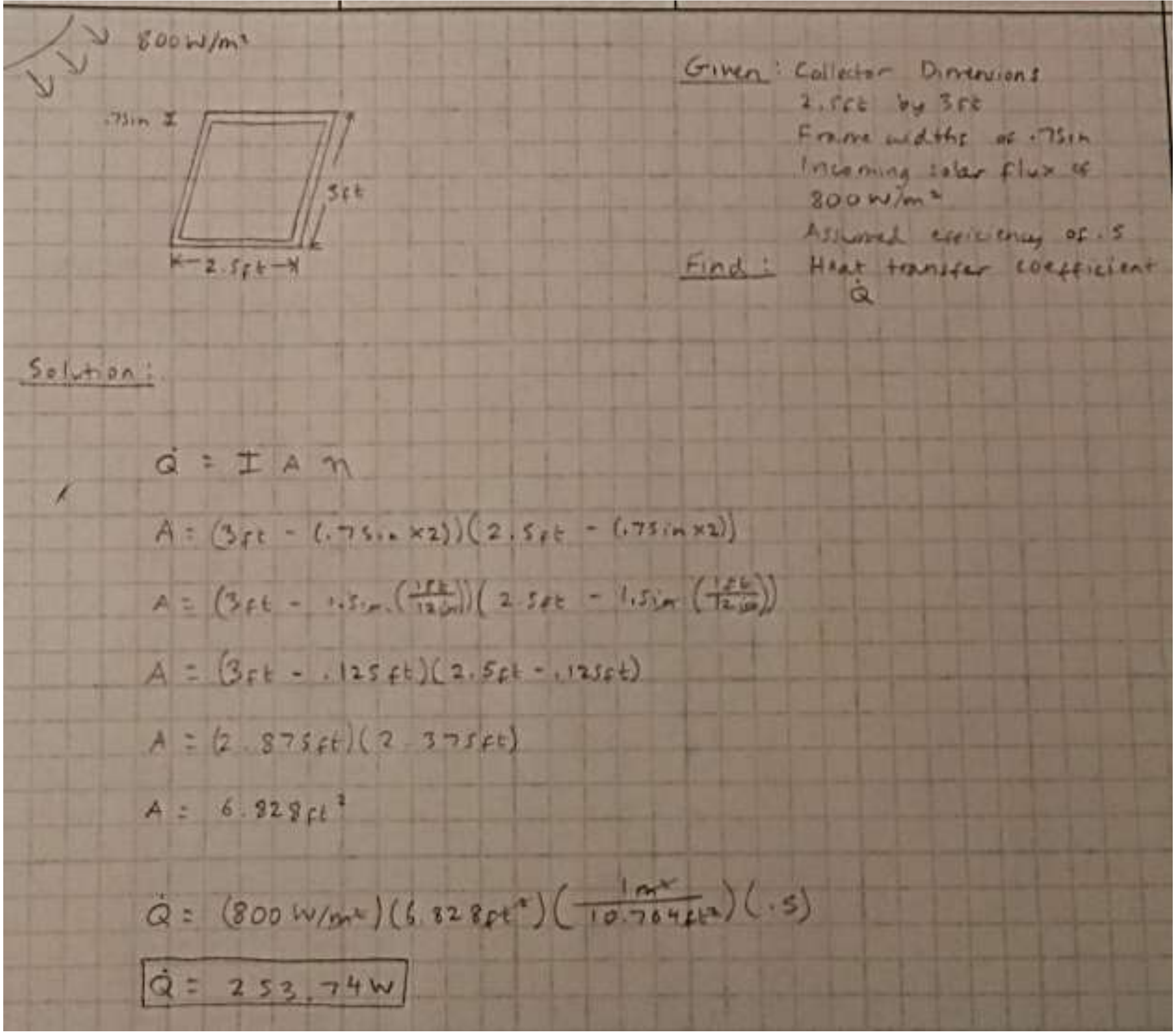
$$\delta_{max} = \frac{5wl^3}{384EI}$$

$$\delta_{max} = \frac{5(20lb)(24in)^3}{384(1160000\,lb/in^2)(.123in^4)}$$

$$\boxed{\delta_{max} = .025\,in}$$ ✓

Figure A1 shows the calculations for determining the beam thickness of the frame components. The minimum thickness required was calculated to be 0.47in. Therefore, 0.75in will be used, since it is a standard size and guarantees a safety factor of 1.5.

Figure A2: Heat Transfer Coefficient Calculations



Given: Collector Dimensions
2.5ft by 3ft
Frame widths of .75in
Incoming solar flux of
800 W/m²
Assumed efficiency of .5

Find: Heat transfer coefficient
$\dot{Q}$

Solution:

$$\dot{Q} = I A \eta$$

$$A = (3ft - (.75in \times 2))(2.5ft - (.75in \times 2))$$

$$A = \left(3ft - 1.5in\left(\frac{1ft}{12in}\right)\right)\left(2.5ft - 1.5in\left(\frac{1ft}{12in}\right)\right)$$

$$A = (3ft - .125ft)(2.5ft - .125ft)$$

$$A = (2.875ft)(2.375ft)$$

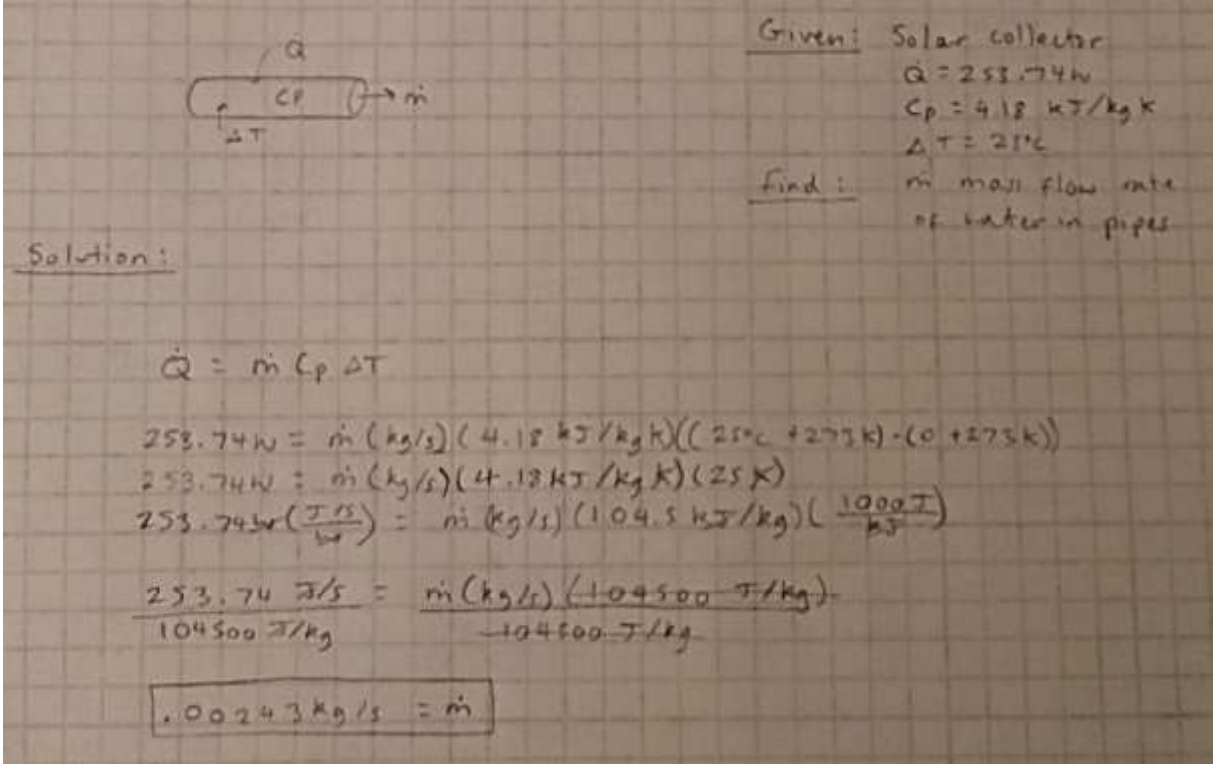
$$A = 6.828ft^2$$

$$\dot{Q} = (800\,W/m^2)(6.828ft^2)\left(\frac{1m^2}{10.764ft^2}\right)(.5)$$

$$\boxed{\dot{Q} = 253.74W}$$

Figure A2 shows the calculations performed to determine the heat transfer coefficient of the solar collector. This value is based on an incoming solar flux of 800 W/m^2, a surface area of 2.875ft by 2.375ft, and an assumed efficiency of 50%.

Figure A3: Mass Flow Rate Calculations



Given: Solar collector
$\dot{Q} = 253.74\,W$
$C_p = 4.18\ kJ/kg\,K$
$\Delta T = 25°C$

Find: $\dot{m}$ mass flow rate of water in pipes

Solution:

$$\dot{Q} = \dot{m}\, C_p\, \Delta T$$

$$253.74\,W = \dot{m}\,(kg/s)(4.18\ kJ/kg\,K)((25°C + 273\,K) - (0 + 273\,K))$$

$$253.74\,W = \dot{m}\,(kg/s)(4.18\ kJ/kg\,\cancel{K})(25\,\cancel{K})$$

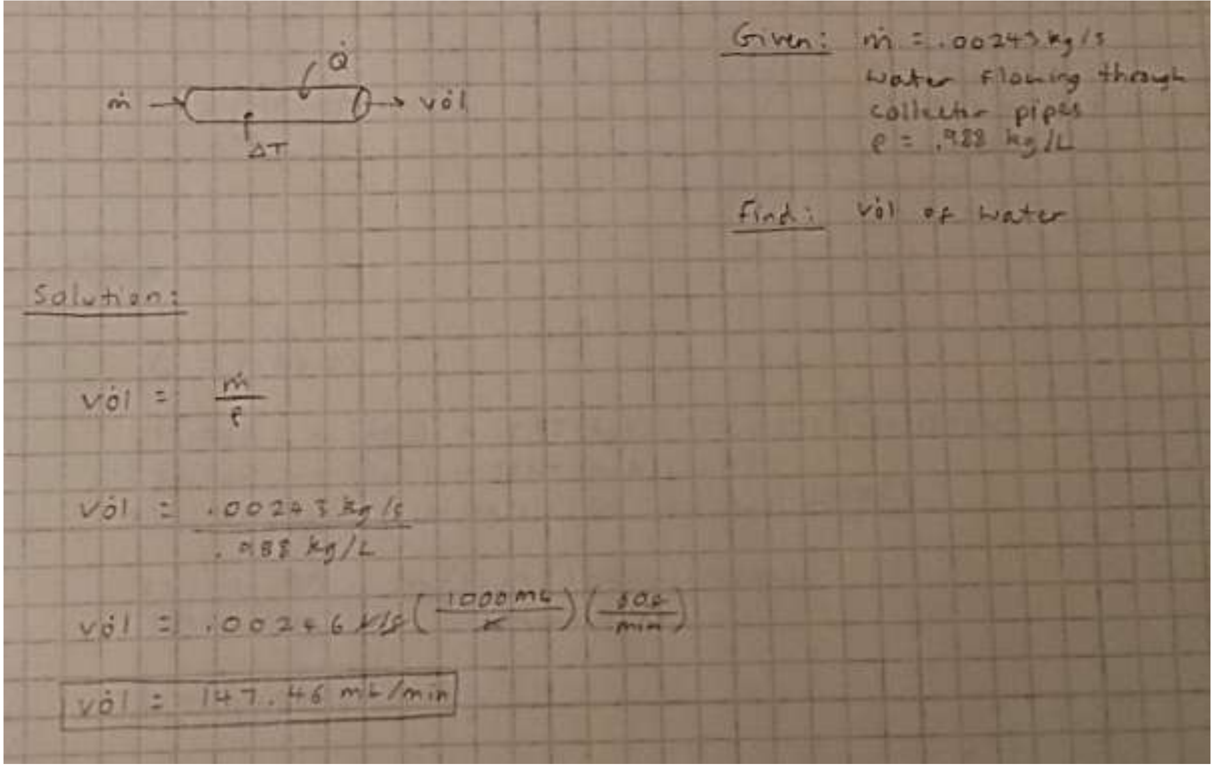
$$253.74\,W\left(\frac{J/s}{W}\right) = \dot{m}\,(kg/s)(104.5\ kJ/kg)\left(\frac{1000\,J}{kJ}\right)$$

$$\frac{253.74\ J/s}{104500\ J/kg} = \frac{\dot{m}\,(kg/s)\,\cancel{(104500\ J/kg)}}{\cancel{104500\ J/kg}}$$

$$\boxed{.00243\ kg/s = \dot{m}}$$

Figure A3 shows the calculations carried out to determine the mass flow rate of the water flowing through the pipes.

Figure A4: Volume Flow Rate Calculations



Given: $\dot{m} = .00243\ kg/s$
water flowing through collector pipes
$\rho = .988\ kg/L$

Find: $v\dot{o}l$ of water

Solution:

$$v\dot{o}l = \frac{\dot{m}}{\rho}$$

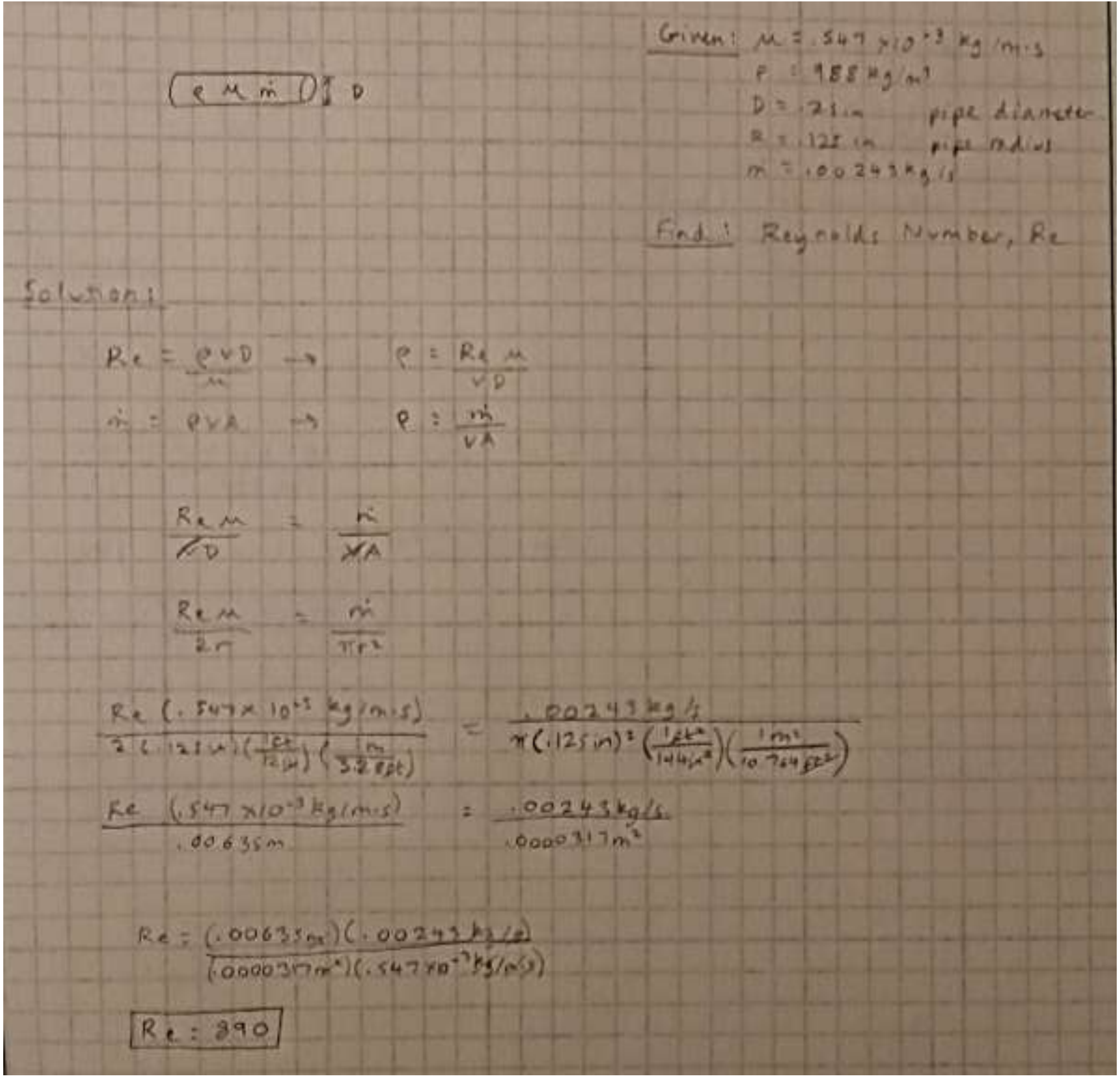
$$v\dot{o}l = \frac{.00243\ kg/s}{.988\ kg/L}$$

$$v\dot{o}l = .00246\ \cancel{L}/\cancel{s}\left(\frac{1000\,mL}{\cancel{L}}\right)\left(\frac{60\,s}{min}\right)$$

$$\boxed{v\dot{o}l = 147.46\ mL/min}$$

Figure A4 shows the calculations carried out to determine the volume flow rate of the water traveling through the collector pipes, based on the mass flow rate and water density of .988kg/L.

Figure A5: Reynolds Number Calculations – Curved Path



Given: $\mu = .547 \times 10^{-3}$ kg/m·s
$\rho = 988$ kg/m^3
$D = .25$ in pipe diameter
$R = .125$ in pipe radius
$\dot{m} = .00243$ kg/s

Find: Reynolds Number, Re

Solution:

$$Re = \frac{\rho V D}{\mu} \rightarrow \rho = \frac{Re\,\mu}{VD}$$

$$\dot{m} = \rho V A \rightarrow \rho = \frac{\dot{m}}{VA}$$

$$\frac{Re\,\mu}{\cancel{V}D} = \frac{\dot{m}}{\cancel{V}A}$$

$$\frac{Re\,\mu}{2r} = \frac{\dot{m}}{\pi r^2}$$

$$\frac{Re\,(.547 \times 10^{-3}\ \text{kg/m·s})}{2(.125\ \text{in})\left(\frac{1\ \text{ft}}{12\ \text{in}}\right)\left(\frac{1\ \text{m}}{3.28\ \text{ft}}\right)} = \frac{.00243\ \text{kg/s}}{\pi(.125\ \text{in})^2\left(\frac{1\ \text{ft}^2}{144\ \text{in}^2}\right)\left(\frac{1\ \text{m}^2}{10.764\ \text{ft}^2}\right)}$$

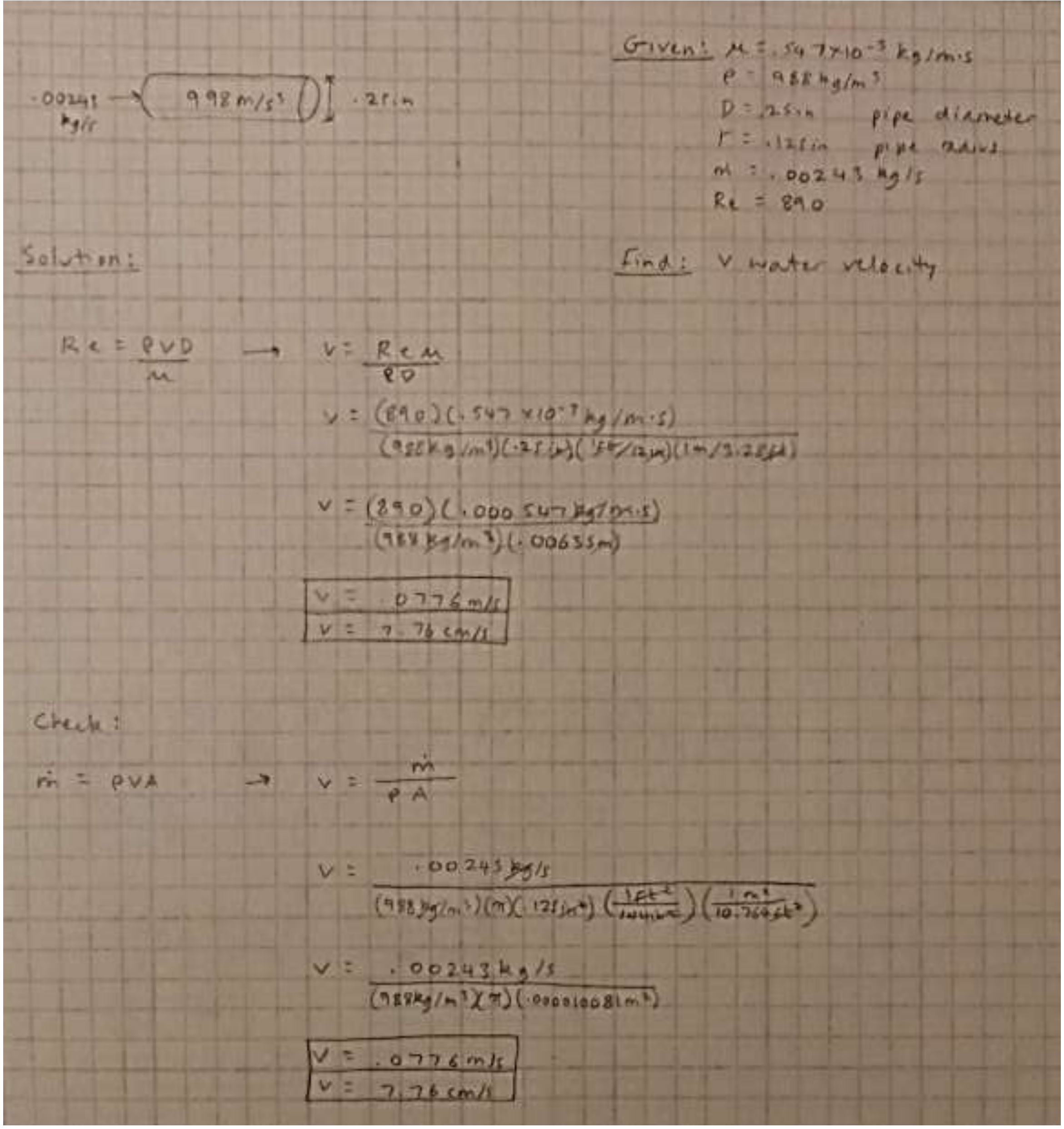
$$\frac{Re\,(.547 \times 10^{-3}\ \text{kg/m·s})}{.00635\ \text{m}} = \frac{.00243\ \text{kg/s}}{.0000317\ \text{m}^2}$$

$$Re = \frac{(.00635\ \text{m})(.00243\ \text{kg/s})}{(.0000317\ \text{m}^2)(.547 \times 10^{-3}\ \text{kg/m·s})}$$

$$\boxed{Re = 890}$$

Figure A5 shows the calculations for generating the Reynolds number of the water in the collector pipes. The Reynolds number of 890 signifies laminar flow. Therefore, some form of static mixer will be used to blend the water.

Figure A6: Water Velocity Calculations – Curved Path



.00243 kg/s → 998 m/s³ .25 in

Given: $\mu = .547 \times 10^{-3}$ kg/m·s

$\rho = 988$ kg/m³

$D = .25$ in pipe diameter

$r = .125$ in pipe radius

$\dot{m} = .00243$ kg/s

$Re = 890$

Solution:

Find: V water velocity

$Re = \frac{\rho V D}{\mu} \longrightarrow V = \frac{Re\,\mu}{\rho D}$

$$V = \frac{(890)(.547 \times 10^{-3}\ \text{kg/m·s})}{(988\ \text{kg/m}^3)(.25\ \text{in})(1\ \text{ft}/12\ \text{in})(1\ \text{m}/3.28\ \text{ft})}$$

$$V = \frac{(890)(.000547\ \text{kg/m·s})}{(988\ \text{kg/m}^3)(.00635\ \text{m})}$$

$$\boxed{\begin{array}{l} V = .0776\ \text{m/s} \\ V = 7.76\ \text{cm/s} \end{array}}$$

Check:

$\dot{m} = \rho V A \rightarrow V = \frac{\dot{m}}{\rho A}$

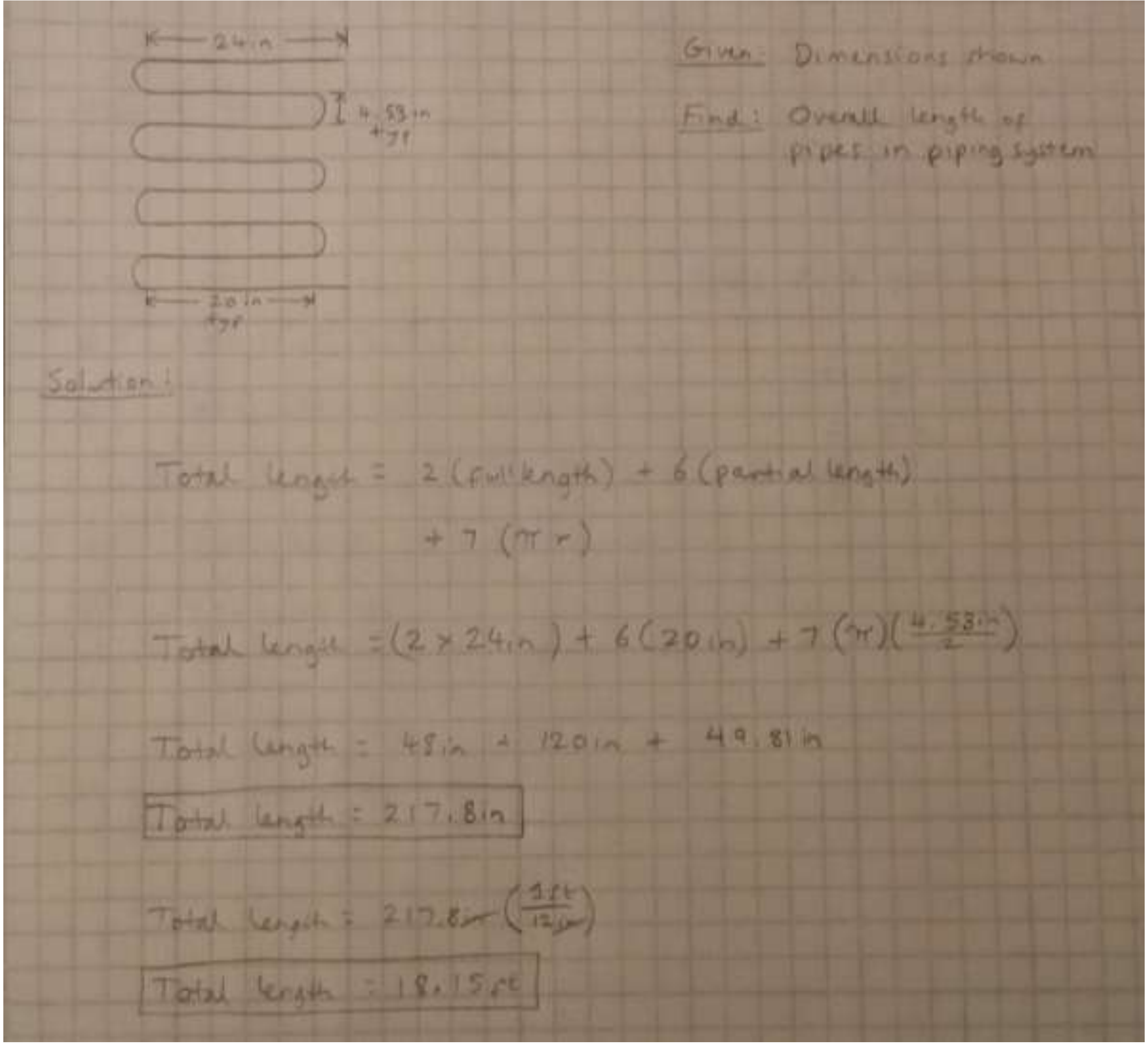
$$V = \frac{.00243\ \text{kg/s}}{(988\ \text{kg/m}^3)(\pi)(.125\ \text{in}^2)\left(\frac{1\ \text{ft}^2}{144\ \text{in}^2}\right)\left(\frac{1\ \text{m}^2}{10.764\ \text{ft}^2}\right)}$$

$$V = \frac{.00243\ \text{kg/s}}{(988\ \text{kg/m}^3)(\pi)(.00001008\ \text{m}^2)}$$

$$\boxed{\begin{array}{l} V = .0776\ \text{m/s} \\ V = 7.76\ \text{cm/s} \end{array}}$$

Figure A6 shows two methods for calculating the velocity of the water in the solar collector. Two methods were used to double check that the calculated number was correct. As shown, the water velocity was determined to be 7.76cm/s, which is reasonable for such thin pipes.

Figure A7: Curved Path Pipe Length Calculations



Given: Dimensions shown

Find: Overall length of pipes in piping system

Solution:

$$\text{Total length} = 2(\text{full length}) + 6(\text{partial length}) + 7(\pi r)$$

$$\text{Total length} = (2 \times 24\text{in}) + 6(20\text{in}) + 7(\pi)\left(\frac{4.53\text{in}}{2}\right)$$

$$\text{Total length} = 48\text{in} + 120\text{in} + 49.81\text{in}$$

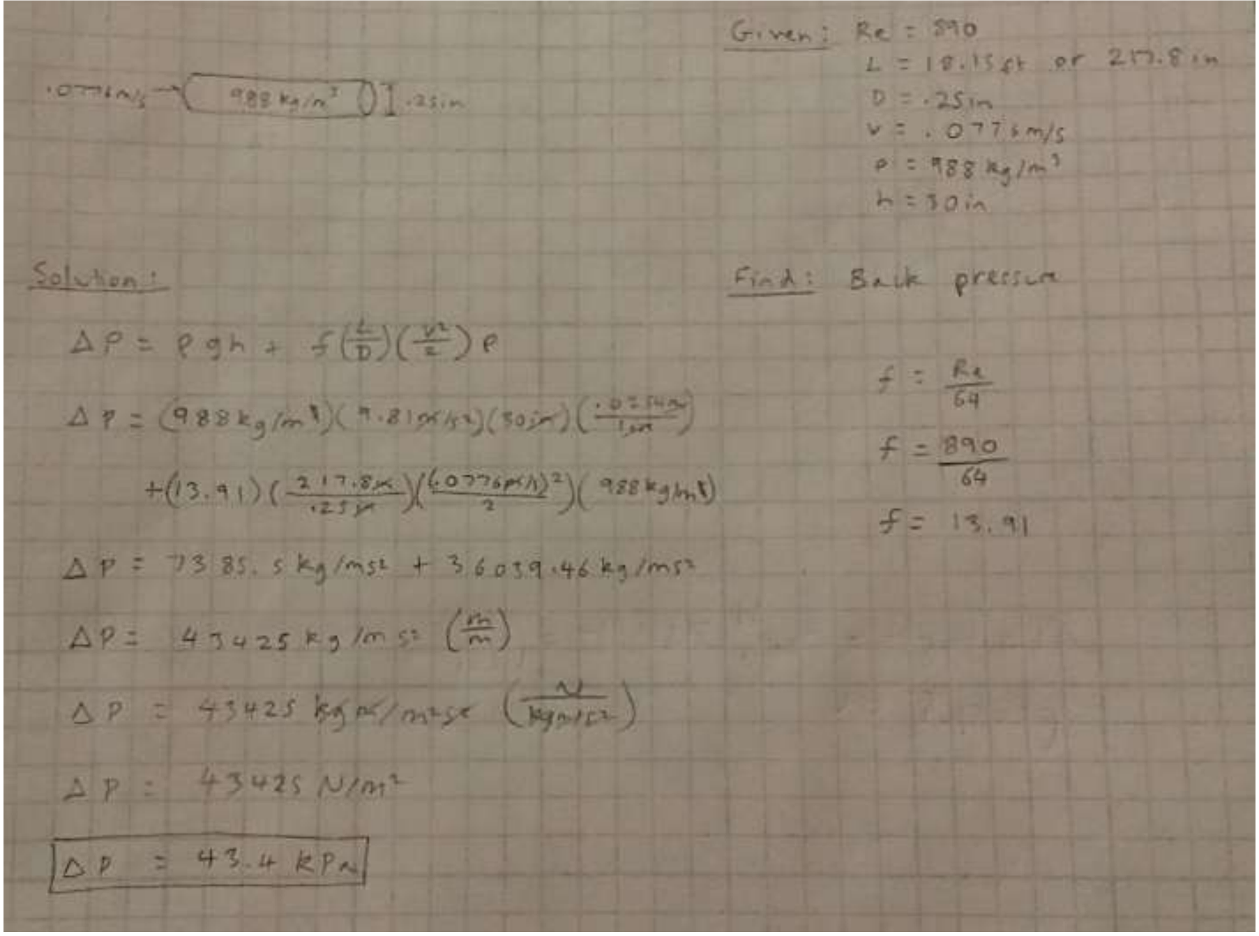
$$\boxed{\text{Total length} = 217.8\text{in}}$$

$$\text{Total length} = 217.8\cancel{\text{in}}\left(\frac{1\text{ft}}{12\cancel{\text{in}}}\right)$$

$$\boxed{\text{Total length} = 18.15\text{ft}}$$

Figure A7 shows how the length of the zig zag pipe path was calculated. As shown, the total length of the zig zag pipe path was 217.8in or 18.15ft.

Figure A8: Back Pressure Calculations – Curved Path



.0776m/s → 988 kg/m³ .25in

Given: Re = 890
L = 18.15ft or 217.8in
D = .25in
v = .0776m/s
ρ = 988 kg/m³
h = 30in

Find: Back pressure

Solution:

$$\Delta P = \rho g h + f\left(\frac{L}{D}\right)\left(\frac{V^2}{2}\right)\rho$$

$$\Delta P = (988\,kg/m^3)(9.81\,m/s^2)(30\cancel{in})\left(\frac{.0254m}{1\cancel{in}}\right)$$

$$+(13.91)\left(\frac{217.8\cancel{in}}{.25\cancel{in}}\right)\left(\frac{(.0776m/s)^2}{2}\right)(988\,kg/m^3)$$

$$\Delta P = 7385.5\,kg/ms^2 + 36039.46\,kg/ms^2$$

$$\Delta P = 43425\,kg/ms^2\left(\frac{m}{m}\right)$$

$$\Delta P = 43425\,\cancel{kg\,m}/m^2s^2\left(\frac{N}{\cancel{kg\,m/s^2}}\right)$$

$$\Delta P = 43425\,N/m^2$$

$$\boxed{\Delta P = 43.4\,kPa}$$

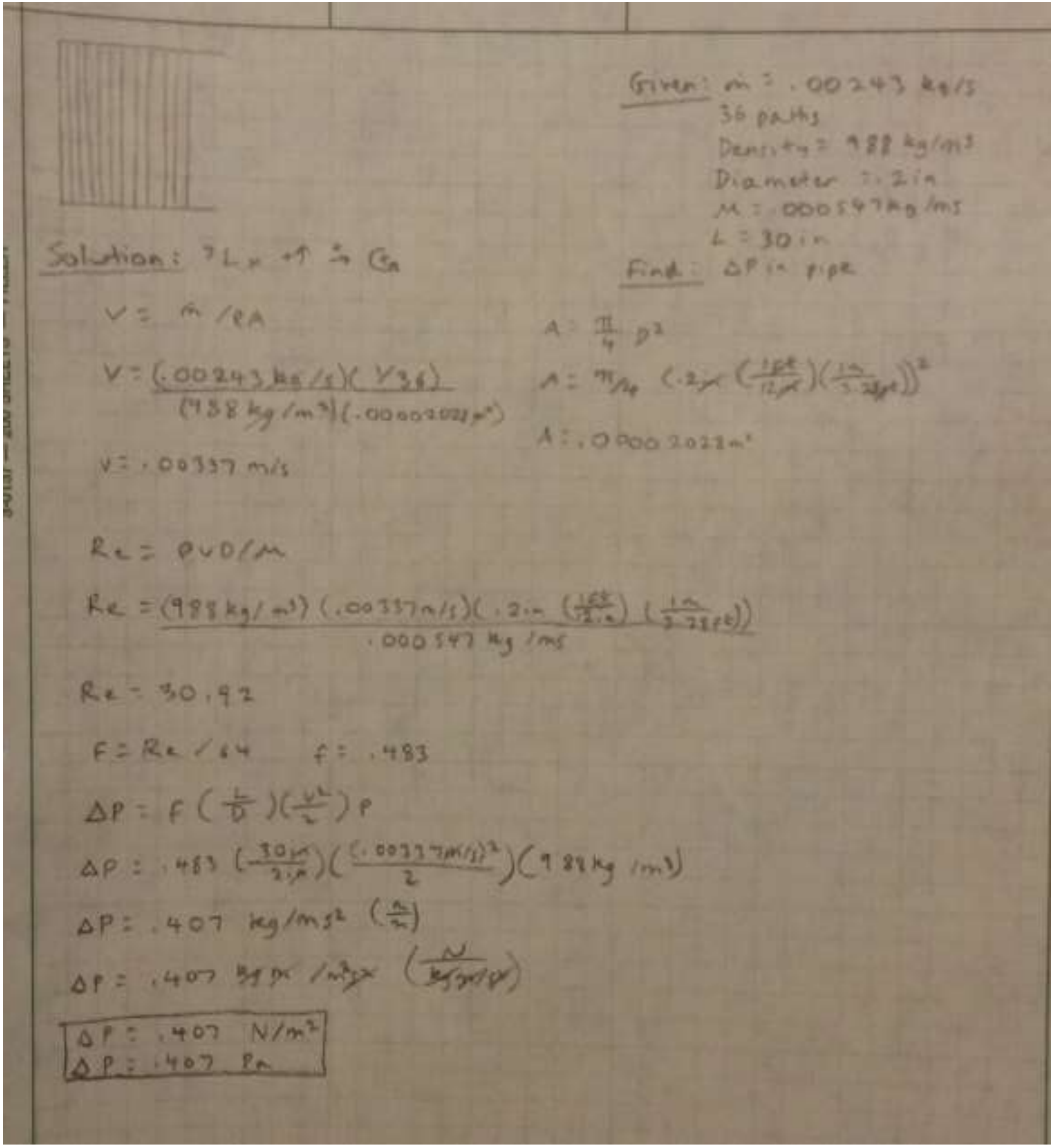
$$f = \frac{Re}{64}$$

$$f = \frac{890}{64}$$

$$f = 13.91$$

Figure A8 shows the back pressure calculations for the zig zag pipe.

Figure A9: Calculating Change in Pressure across the 36 Thin Manifold Pipes



Given: $\dot{m} = .00243\ kg/s$
36 paths
Density $= 988\ kg/m^3$
Diameter $= .2\ in$
$\mu = .000547\ kg/ms$
$L = 30\ in$

Find: ΔP in pipe

Solution: [illegible]

$V = \dot{m}/\rho A$

$V = \frac{(.00243\ kg/s)(1/36)}{(988\ kg/m^3)(.00002022\ m^2)}$

$V = .00337\ m/s$

$A = \frac{\pi}{4} D^2$

$A = \pi/4\ \left(.2\ in \left(\frac{1\ ft}{12\ in}\right)\left(\frac{1\ m}{3.28\ ft}\right)\right)^2$

$A = .00002022\ m^2$

$Re = \rho V D/\mu$

$Re = \frac{(988\ kg/m^3)(.00337\ m/s)\left(.2\ in \left(\frac{1\ ft}{12\ in}\right)\left(\frac{1\ m}{3.28\ ft}\right)\right)}{.000547\ kg/ms}$

$Re = 30.92$

$F = Re/64$ $\quad f = .483$

$\Delta P = f\left(\frac{L}{D}\right)\left(\frac{v^2}{2}\right)\rho$

$\Delta P = .483\left(\frac{30\ in}{.2\ in}\right)\left(\frac{(.00337\ m/s)^2}{2}\right)(988\ kg/m^3)$

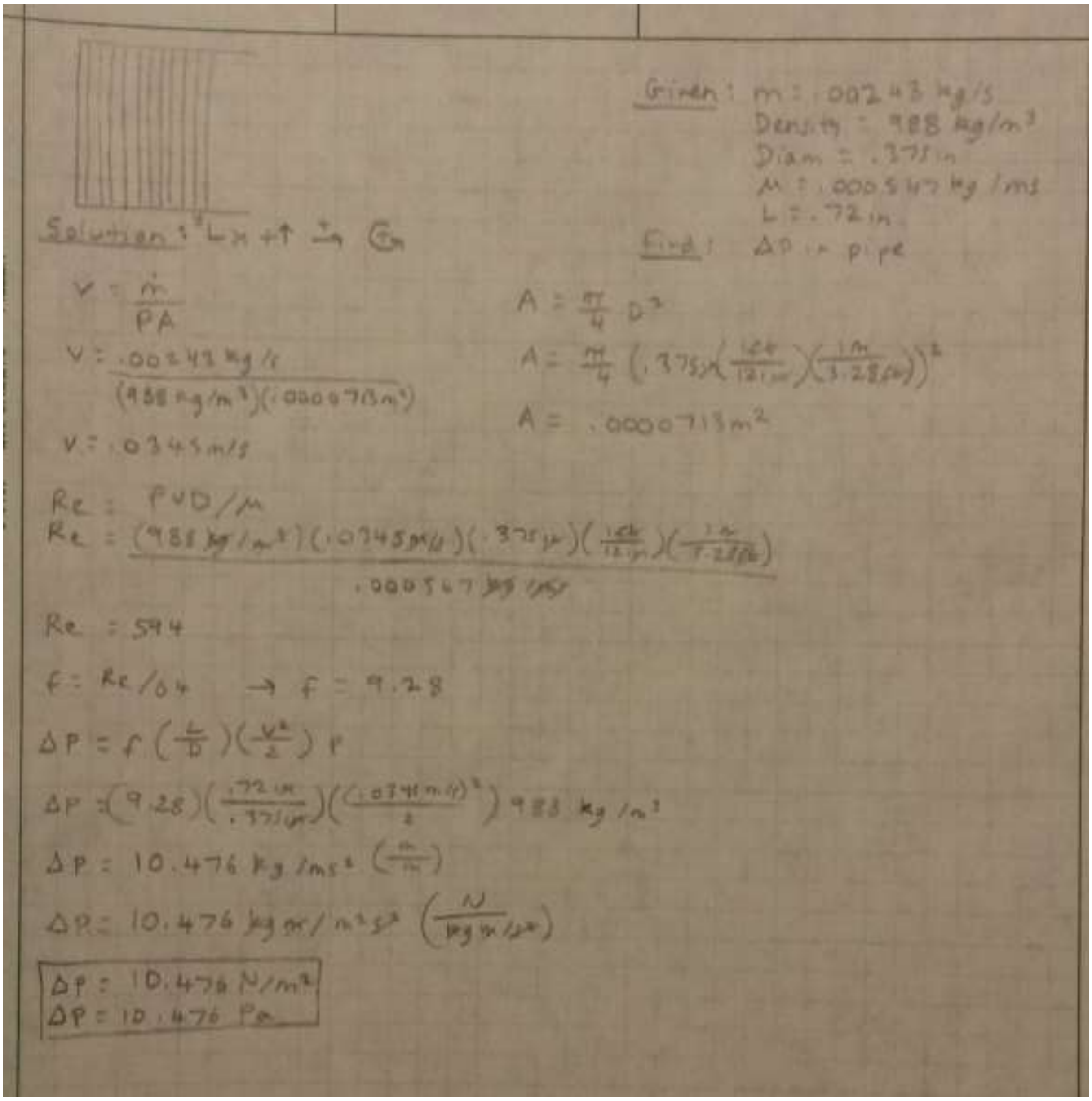
$\Delta P = .407\ kg/ms^2 \left(\frac{m}{m}\right)$

$\Delta P = .407\ \cancel{kg}\,\cancel{m}/m^2\cancel{s^2} \left(\frac{N}{\cancel{kg}\,\cancel{m}/\cancel{s^2}}\right)$

$$\boxed{\begin{array}{l} \Delta P = .407\ N/m^2 \\ \Delta P = .407\ Pa \end{array}}$$

Figure A9 shows the calculations carried out for determining the change in pressure across the 36 thin manifold pipes.

Figure A10: Calculating Change in Pressure in the First Section of Manifold Piping – 0.375in Diameter



Given: $\dot{m}$ = .00243 kg/s
Density = 988 kg/m³
Diam = .375 in
μ = .000547 kg/ms
L = .72 in

Find: ΔP in pipe

Solution: [illegible]

$$V = \frac{\dot{m}}{\rho A}$$

$$V = \frac{.00243\ \text{kg/s}}{(988\ \text{kg/m}^3)(.0000713\ \text{m}^2)}$$

$$V = .0345\ \text{m/s}$$

$$A = \frac{\pi}{4} D^2$$

$$A = \frac{\pi}{4}\left(.375\ \text{in}\left(\frac{1\ \text{ft}}{12\ \text{in}}\right)\left(\frac{1\ \text{m}}{3.28\ \text{ft}}\right)\right)^2$$

$$A = .0000713\ \text{m}^2$$

$$Re = \rho V D / \mu$$

$$Re = \frac{(988\ \text{kg/m}^3)(.0345\ \text{m/s})(.375\ \text{in})\left(\frac{1\ \text{ft}}{12\ \text{in}}\right)\left(\frac{1\ \text{m}}{3.28\ \text{ft}}\right)}{.000547\ \text{kg/ms}}$$

$$Re = 594$$

$$f = Re/64 \rightarrow f = 9.28$$

$$\Delta P = f\left(\frac{L}{D}\right)\left(\frac{V^2}{2}\right)\rho$$

$$\Delta P = (9.28)\left(\frac{.72\ \text{in}}{.375\ \text{in}}\right)\left(\frac{(.0345\ \text{m/s})^2}{2}\right) 988\ \text{kg/m}^3$$

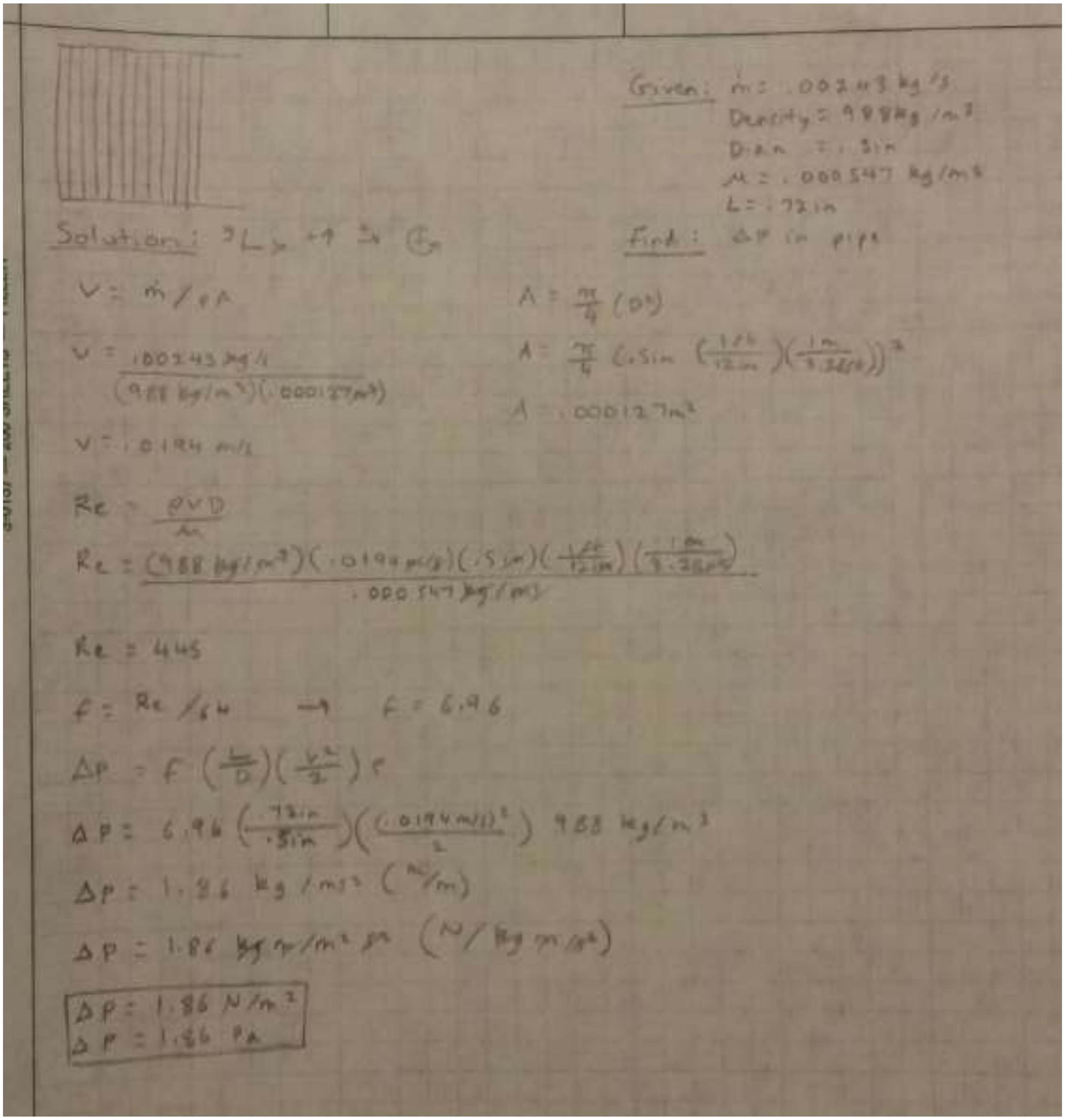
$$\Delta P = 10.476\ \text{kg/ms}^2 \left(\frac{m}{m}\right)$$

$$\Delta P = 10.476\ \text{kg m/m}^2\text{s}^2 \left(\frac{N}{\text{kg m/s}^2}\right)$$

$$\boxed{\begin{aligned}\Delta P &= 10.476\ \text{N/m}^2 \\ \Delta P &= 10.476\ \text{Pa}\end{aligned}}$$

Figure A10 shows the calculations carried out to determine the change in pressure in the first section of manifold piping (0.375in diameter)

Figure A11: Calculating Change in Pressure in the First Section of Manifold Piping – 0.5in Diameter



Given: $\dot{m} = .00243\ kg/s$
Density $= 988\ kg/m^3$
Diam $= .5in$
$\mu = .000547\ kg/m\,s$
$L = 72in$

Find: ΔP in pipe

Solution: [illegible]

$V = \dot{m}/\rho A$

$V = \frac{.00243\ kg/s}{(988\ kg/m^3)(.000127\ m^2)}$

$V = .0194\ m/s$

$A = \frac{\pi}{4}(D^2)$

$A = \frac{\pi}{4}\left(0.5in\left(\frac{1ft}{12in}\right)\left(\frac{1m}{3.28ft}\right)\right)^2$

$A = .000127\ m^2$

$Re = \frac{\rho V D}{\mu}$

$Re = \frac{(988\ kg/m^3)(.0194\ m/s)(.5in)\left(\frac{1ft}{12in}\right)\left(\frac{1m}{3.28ft}\right)}{.000547\ kg/(m\,s)}$

$Re = 445$

$f = Re/64 \rightarrow f = 6.96$

$\Delta P = f\left(\frac{L}{D}\right)\left(\frac{V^2}{2}\right)\rho$

$\Delta P = 6.96\left(\frac{72in}{.5in}\right)\left(\frac{(.0194\ m/s)^2}{2}\right)988\ kg/m^3$

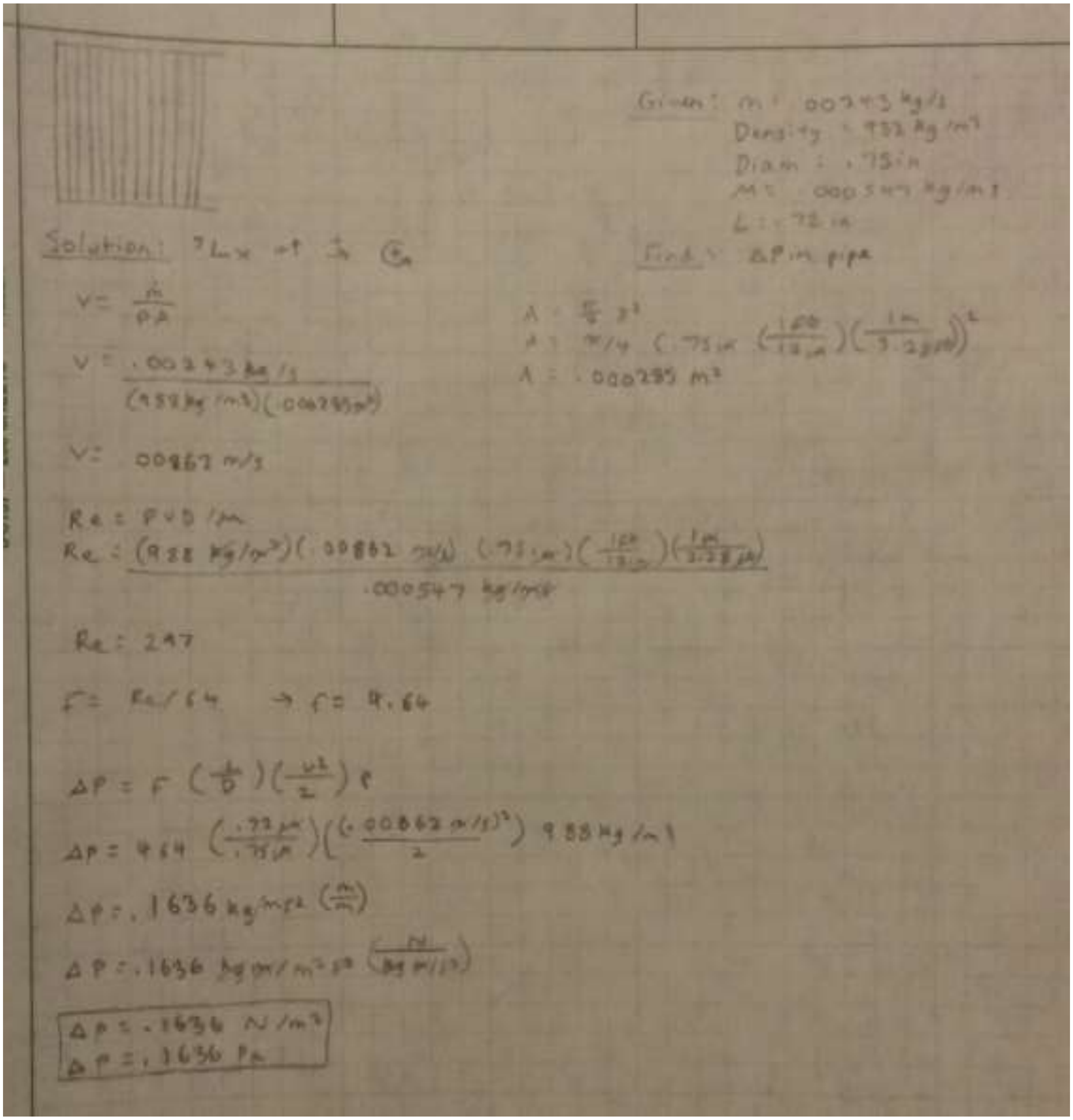
$\Delta P = 1.86\ kg/ms^2\ (m/m)$

$\Delta P = 1.86\ kg\,m/m^2 s^2\ (N/kg\,m/s^2)$

$\boxed{\begin{array}{l}\Delta P = 1.86\ N/m^2 \\ \Delta P = 1.86\ Pa\end{array}}$

Figure A11 shows the calculations carried out to determine the change in pressure in the first section of manifold piping (0.5in diameter)

Figure A12: Calculating Change in Pressure in the First Section of Manifold Piping – 0.75in Diameter



Given: $\dot{m}$ = .00243 kg/s

Density = 988 kg/m³

Diam = .75in

μ = .000547 kg/m s

L = 72 in

Find: ΔP in pipe

Solution: [illegible]

$V = \frac{\dot{m}}{\rho A}$

$A = \frac{\pi}{4} d^2$

$A = \pi/4 \left(.75\,in \left(\frac{1\,ft}{12\,in}\right)\left(\frac{1\,m}{3.28\,ft}\right)\right)^2$

$A = .000285\ m^2$

$V = \frac{.00243\ kg/s}{(988\ kg/m^3)(.000285\ m^2)}$

$V = .00862\ m/s$

$Re = \rho V D / \mu$

$Re = \frac{(988\ kg/m^3)(.00862\ m/s)(.75\,in)\left(\frac{1\,ft}{12\,in}\right)\left(\frac{1\,m}{3.28\,ft}\right)}{.000547\ kg/m\,s}$

$Re = 247$

$f = Re/64 \rightarrow f = 4.64$

$\Delta P = f \left(\frac{L}{D}\right)\left(\frac{V^2}{2}\right)\rho$

$\Delta P = 4.64 \left(\frac{72\,in}{.75\,in}\right)\left(\frac{(.00862\ m/s)^2}{2}\right) 988\ kg/m^3$

$\Delta P = .1636\ kg/m\,s^2 \left(\frac{m}{m}\right)$

$\Delta P = .1636\ kg\,m/m^2 s^2 \left(\frac{N}{kg\,m/s^2}\right)$

$\boxed{\Delta P = .1636\ N/m^2}$

$\boxed{\Delta P = .1636\ Pa}$

Figure A12 shows the calculations carried out to determine the change in pressure in the first section of manifold piping (0.75in diameter)

Figure A13: Pressure Values for all 36 Sections of Pipe – 0.375in Diameter

mdot (kg/s)	Density (kg/m^3)	Area (m^2)	Velocity (m/s)	Diameter (in)	Viscosity (kg/m*s)	Reynolds	f	Length (in)	Pressure (kg/ms^2)
0.00243	988	0.000071	0.034517	0.375	0.000547	593.98	9.28	0.72	10.4876
0.00236	988	0.000071	0.033558	0.375	0.000547	577.48	9.02	0.72	9.6377
0.00230	988	0.000071	0.032599	0.375	0.000547	560.98	8.77	0.72	8.8350
0.00223	988	0.000071	0.031640	0.375	0.000547	544.48	8.51	0.72	8.0781
0.00216	988	0.000071	0.030681	0.375	0.000547	527.98	8.25	0.72	7.3658
0.00209	988	0.000071	0.029723	0.375	0.000547	511.48	7.99	0.72	6.6966
0.00203	988	0.000071	0.028764	0.375	0.000547	494.98	7.73	0.72	6.0692
0.00196	988	0.000071	0.027805	0.375	0.000547	478.49	7.48	0.72	5.4823
0.00189	988	0.000071	0.026846	0.375	0.000547	461.99	7.22	0.72	4.9345
0.00182	988	0.000071	0.025887	0.375	0.000547	445.49	6.96	0.72	4.4245
0.00176	988	0.000071	0.024929	0.375	0.000547	428.99	6.70	0.72	3.9508
0.00169	988	0.000071	0.023970	0.375	0.000547	412.49	6.45	0.72	3.5123
0.00162	988	0.000071	0.023011	0.375	0.000547	395.99	6.19	0.72	3.1074
0.00155	988	0.000071	0.022052	0.375	0.000547	379.49	5.93	0.72	2.7350
0.00149	988	0.000071	0.021093	0.375	0.000547	362.99	5.67	0.72	2.3935
0.00142	988	0.000071	0.020135	0.375	0.000547	346.49	5.41	0.72	2.0817
0.00135	988	0.000071	0.019176	0.375	0.000547	329.99	5.16	0.72	1.7983
0.00128	988	0.000071	0.018217	0.375	0.000547	313.49	4.90	0.72	1.5418
0.00122	988	0.000071	0.017258	0.375	0.000547	296.99	4.64	0.72	1.3109
0.00115	988	0.000071	0.016299	0.375	0.000547	280.49	4.38	0.72	1.1044
0.00108	988	0.000071	0.015341	0.375	0.000547	263.99	4.12	0.72	0.9207
0.00101	988	0.000071	0.014382	0.375	0.000547	247.49	3.87	0.72	0.7587
0.00095	988	0.000071	0.013423	0.375	0.000547	230.99	3.61	0.72	0.6168
0.00088	988	0.000071	0.012464	0.375	0.000547	214.49	3.35	0.72	0.4939
0.00081	988	0.000071	0.011506	0.375	0.000547	197.99	3.09	0.72	0.3884
0.00074	988	0.000071	0.010547	0.375	0.000547	181.49	2.84	0.72	0.2992
0.00068	988	0.000071	0.009588	0.375	0.000547	164.99	2.58	0.72	0.2248
0.00061	988	0.000071	0.008629	0.375	0.000547	148.50	2.32	0.72	0.1639
0.00054	988	0.000071	0.007670	0.375	0.000547	132.00	2.06	0.72	0.1151
0.00047	988	0.000071	0.006712	0.375	0.000547	115.50	1.80	0.72	0.0771
0.00041	988	0.000071	0.005753	0.375	0.000547	99.00	1.55	0.72	0.0486
0.00034	988	0.000071	0.004794	0.375	0.000547	82.50	1.29	0.72	0.0281
0.00027	988	0.000071	0.003835	0.375	0.000547	66.00	1.03	0.72	0.0144
0.00020	988	0.000071	0.002876	0.375	0.000547	49.50	0.77	0.72	0.0061
0.00014	988	0.000071	0.001918	0.375	0.000547	33.00	0.52	0.72	0.0018
0.00007	988	0.000071	0.000959	0.375	0.000547	16.50	0.26	0.72	0.0002
									99.7050

Figure A13 shows the pressure calculations for all 36 components of the manifold pipe (0.375in diameter) as following Figure A10.

Figure A14: Pressure Values for all 36 Sections of Pipe – 0.5in Diameter

mdot (kg/s)	Density (kg/m^3)	Area (m^2)	Velocity (m/s)	Diameter (in)	Viscosity (kg/m*s)	Reynolds	f	Length (in)	Pressure (kg/ms^2)
0.00243	988	0.000127	0.019416	0.5	0.000547	445.49	6.96	0.72	1.8666
0.00236	988	0.000127	0.018876	0.5	0.000547	433.11	6.77	0.72	1.7153
0.00230	988	0.000127	0.018337	0.5	0.000547	420.74	6.57	0.72	1.5724
0.00223	988	0.000127	0.017798	0.5	0.000547	408.36	6.38	0.72	1.4377
0.00216	988	0.000127	0.017258	0.5	0.000547	395.99	6.19	0.72	1.3109
0.00209	988	0.000127	0.016719	0.5	0.000547	383.61	5.99	0.72	1.1918
0.00203	988	0.000127	0.016180	0.5	0.000547	371.24	5.80	0.72	1.0802
0.00196	988	0.000127	0.015640	0.5	0.000547	358.86	5.61	0.72	0.9757
0.00189	988	0.000127	0.015101	0.5	0.000547	346.49	5.41	0.72	0.8782
0.00182	988	0.000127	0.014562	0.5	0.000547	334.11	5.22	0.72	0.7875
0.00176	988	0.000127	0.014022	0.5	0.000547	321.74	5.03	0.72	0.7032
0.00169	988	0.000127	0.013483	0.5	0.000547	309.37	4.83	0.72	0.6251
0.00162	988	0.000127	0.012944	0.5	0.000547	296.99	4.64	0.72	0.5531
0.00155	988	0.000127	0.012404	0.5	0.000547	284.62	4.45	0.72	0.4868
0.00149	988	0.000127	0.011865	0.5	0.000547	272.24	4.25	0.72	0.4260
0.00142	988	0.000127	0.011326	0.5	0.000547	259.87	4.06	0.72	0.3705
0.00135	988	0.000127	0.010786	0.5	0.000547	247.49	3.87	0.72	0.3201
0.00128	988	0.000127	0.010247	0.5	0.000547	235.12	3.67	0.72	0.2744
0.00122	988	0.000127	0.009708	0.5	0.000547	222.74	3.48	0.72	0.2333
0.00115	988	0.000127	0.009168	0.5	0.000547	210.37	3.29	0.72	0.1966
0.00108	988	0.000127	0.008629	0.5	0.000547	197.99	3.09	0.72	0.1639
0.00101	988	0.000127	0.008090	0.5	0.000547	185.62	2.90	0.72	0.1350
0.00095	988	0.000127	0.007550	0.5	0.000547	173.24	2.71	0.72	0.1098
0.00088	988	0.000127	0.007011	0.5	0.000547	160.87	2.51	0.72	0.0879
0.00081	988	0.000127	0.006472	0.5	0.000547	148.50	2.32	0.72	0.0691
0.00074	988	0.000127	0.005933	0.5	0.000547	136.12	2.13	0.72	0.0532
0.00068	988	0.000127	0.005393	0.5	0.000547	123.75	1.93	0.72	0.0400
0.00061	988	0.000127	0.004854	0.5	0.000547	111.37	1.74	0.72	0.0292
0.00054	988	0.000127	0.004315	0.5	0.000547	99.00	1.55	0.72	0.0205
0.00047	988	0.000127	0.003775	0.5	0.000547	86.62	1.35	0.72	0.0137
0.00041	988	0.000127	0.003236	0.5	0.000547	74.25	1.16	0.72	0.0086
0.00034	988	0.000127	0.002697	0.5	0.000547	61.87	0.97	0.72	0.0050
0.00027	988	0.000127	0.002157	0.5	0.000547	49.50	0.77	0.72	0.0026
0.00020	988	0.000127	0.001618	0.5	0.000547	37.12	0.58	0.72	0.0011
0.00014	988	0.000127	0.001079	0.5	0.000547	24.75	0.39	0.72	0.0003
0.00007	988	0.000127	0.000539	0.5	0.000547	12.37	0.19	0.72	0.0000

17.7453

Figure A14 shows the pressure calculations for all 36 components of the manifold pipe (0.5in diameter) as following Figure A11.

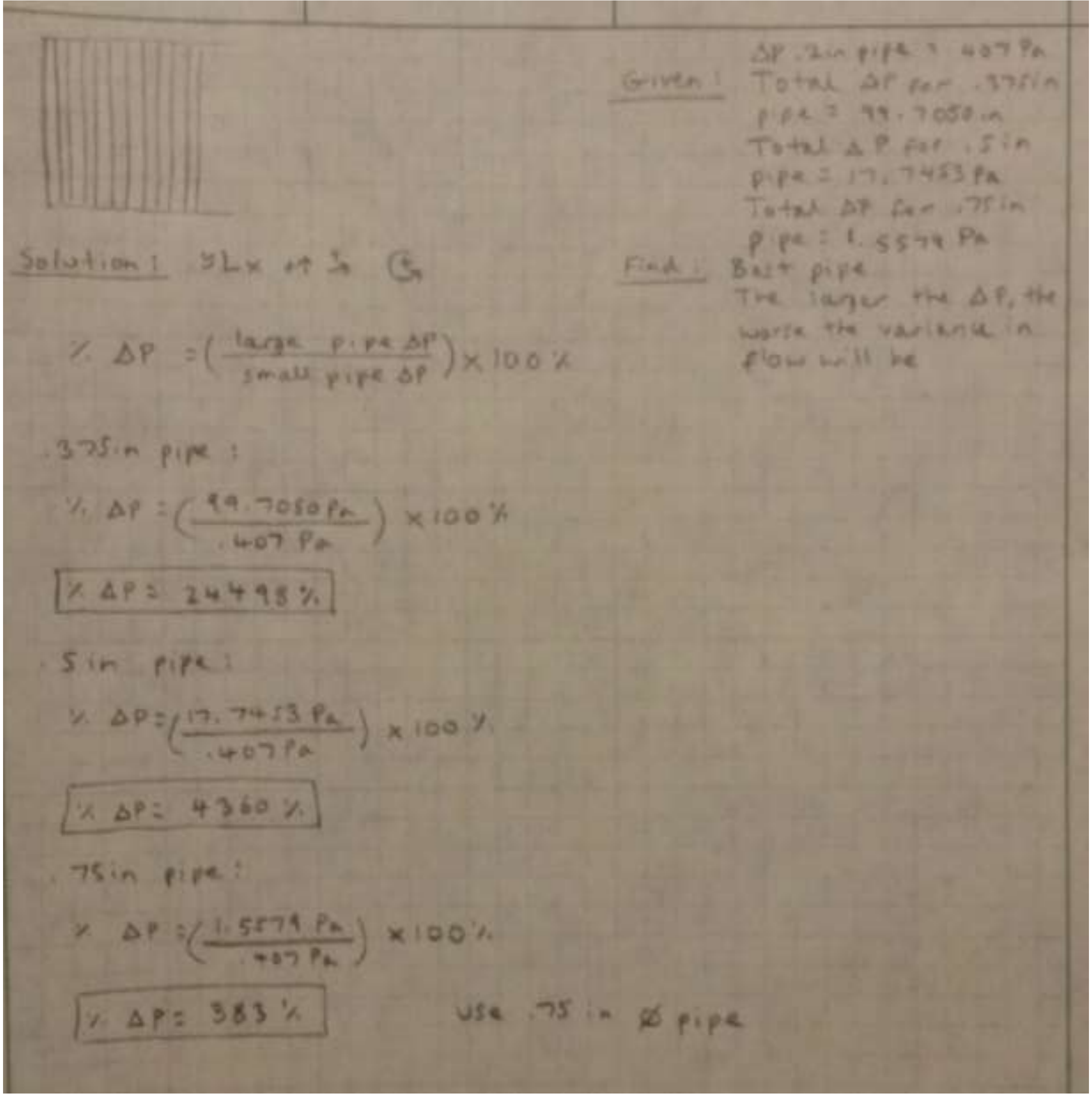
Figure A15: Pressure Values for all 36 Sections of Pipe – 0.75in Diameter

mdot (kg/s)	Density (kg/m^3)	Area (m^2)	Velocity (m/s)	Diameter (in)	Viscosity (kg/m*s)	Reynolds	f	Length (in)	Pressure (kg/ms^2)
0.00243	988	0.000285	0.008629	0.75	0.000547	296.99	4.64	0.72	0.1639
0.00236	988	0.000285	0.008389	0.75	0.000547	288.74	4.51	0.72	0.1506
0.00230	988	0.000285	0.008150	0.75	0.000547	280.49	4.38	0.72	0.1380
0.00223	988	0.000285	0.007910	0.75	0.000547	272.24	4.25	0.72	0.1262
0.00216	988	0.000285	0.007670	0.75	0.000547	263.99	4.12	0.72	0.1151
0.00209	988	0.000285	0.007431	0.75	0.000547	255.74	4.00	0.72	0.1046
0.00203	988	0.000285	0.007191	0.75	0.000547	247.49	3.87	0.72	0.0948
0.00196	988	0.000285	0.006951	0.75	0.000547	239.24	3.74	0.72	0.0857
0.00189	988	0.000285	0.006712	0.75	0.000547	230.99	3.61	0.72	0.0771
0.00182	988	0.000285	0.006472	0.75	0.000547	222.74	3.48	0.72	0.0691
0.00176	988	0.000285	0.006232	0.75	0.000547	214.49	3.35	0.72	0.0617
0.00169	988	0.000285	0.005992	0.75	0.000547	206.24	3.22	0.72	0.0549
0.00162	988	0.000285	0.005753	0.75	0.000547	197.99	3.09	0.72	0.0486
0.00155	988	0.000285	0.005513	0.75	0.000547	189.74	2.96	0.72	0.0427
0.00149	988	0.000285	0.005273	0.75	0.000547	181.49	2.84	0.72	0.0374
0.00142	988	0.000285	0.005034	0.75	0.000547	173.24	2.71	0.72	0.0325
0.00135	988	0.000285	0.004794	0.75	0.000547	164.99	2.58	0.72	0.0281
0.00128	988	0.000285	0.004554	0.75	0.000547	156.75	2.45	0.72	0.0241
0.00122	988	0.000285	0.004315	0.75	0.000547	148.50	2.32	0.72	0.0205
0.00115	988	0.000285	0.004075	0.75	0.000547	140.25	2.19	0.72	0.0173
0.00108	988	0.000285	0.003835	0.75	0.000547	132.00	2.06	0.72	0.0144
0.00101	988	0.000285	0.003595	0.75	0.000547	123.75	1.93	0.72	0.0119
0.00095	988	0.000285	0.003356	0.75	0.000547	115.50	1.80	0.72	0.0096
0.00088	988	0.000285	0.003116	0.75	0.000547	107.25	1.68	0.72	0.0077
0.00081	988	0.000285	0.002876	0.75	0.000547	99.00	1.55	0.72	0.0061
0.00074	988	0.000285	0.002637	0.75	0.000547	90.75	1.42	0.72	0.0047
0.00068	988	0.000285	0.002397	0.75	0.000547	82.50	1.29	0.72	0.0035
0.00061	988	0.000285	0.002157	0.75	0.000547	74.25	1.16	0.72	0.0026
0.00054	988	0.000285	0.001918	0.75	0.000547	66.00	1.03	0.72	0.0018
0.00047	988	0.000285	0.001678	0.75	0.000547	57.75	0.90	0.72	0.0012
0.00041	988	0.000285	0.001438	0.75	0.000547	49.50	0.77	0.72	0.0008
0.00034	988	0.000285	0.001198	0.75	0.000547	41.25	0.64	0.72	0.0004
0.00027	988	0.000285	0.000959	0.75	0.000547	33.00	0.52	0.72	0.0002
0.00020	988	0.000285	0.000719	0.75	0.000547	24.75	0.39	0.72	0.0001

0.00014	988	0.000285	0.000479	0.75	0.000547	16.50	0.26	0.72	0.0000
0.00007	988	0.000285	0.000240	0.75	0.000547	8.25	0.13	0.72	0.0000
									1.5579

Figure A15 shows the pressure calculations for all 36 components of the manifold pipe (0.75in diameter) as following Figure A11.

Figure A16: Determining the Manifold Pipe Diameter



Given: ΔP .2in pipe = .407 Pa
Total ΔP for .375in pipe = 99.7050 Pa
Total ΔP for .5in pipe = 17.7453 Pa
Total ΔP for .75in pipe = 1.5579 Pa

Find: Best pipe
The larger the ΔP, the worse the variance in flow will be

Solution: [illegible]

$$\% \Delta P = \left(\frac{\text{large pipe } \Delta P}{\text{small pipe } \Delta P}\right) \times 100\%$$

.375in pipe:

$$\% \Delta P = \left(\frac{99.7050 \text{ Pa}}{.407 \text{ Pa}}\right) \times 100\%$$

$$\boxed{\% \Delta P = 24498\%}$$

.5in pipe:

$$\% \Delta P = \left(\frac{17.7453 \text{ Pa}}{.407 \text{ Pa}}\right) \times 100\%$$

$$\boxed{\% \Delta P = 4360\%}$$

.75in pipe:

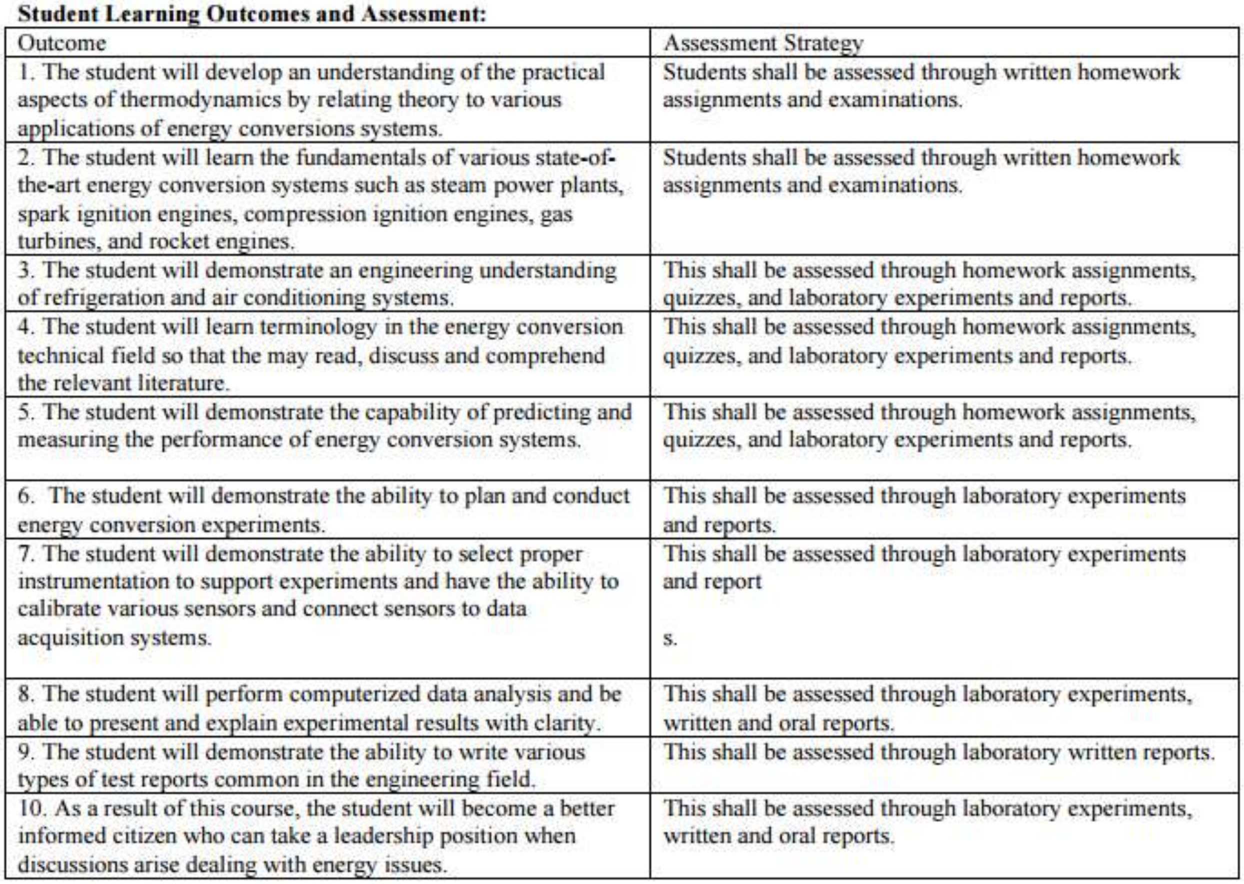
$$\% \Delta P = \left(\frac{1.5579 \text{ Pa}}{.407 \text{ Pa}}\right) \times 100\%$$

$$\boxed{\% \Delta P = 383\%}$$

Use .75 in ⌀ pipe

Figure A16 shows the calculations used when determining which pipe provided the least change in back pressure between the two ends of the pipe. The total changes in pressure can be found in Figures A13, A14, and A15.

Figure A17: MET 411 Student Outcomes



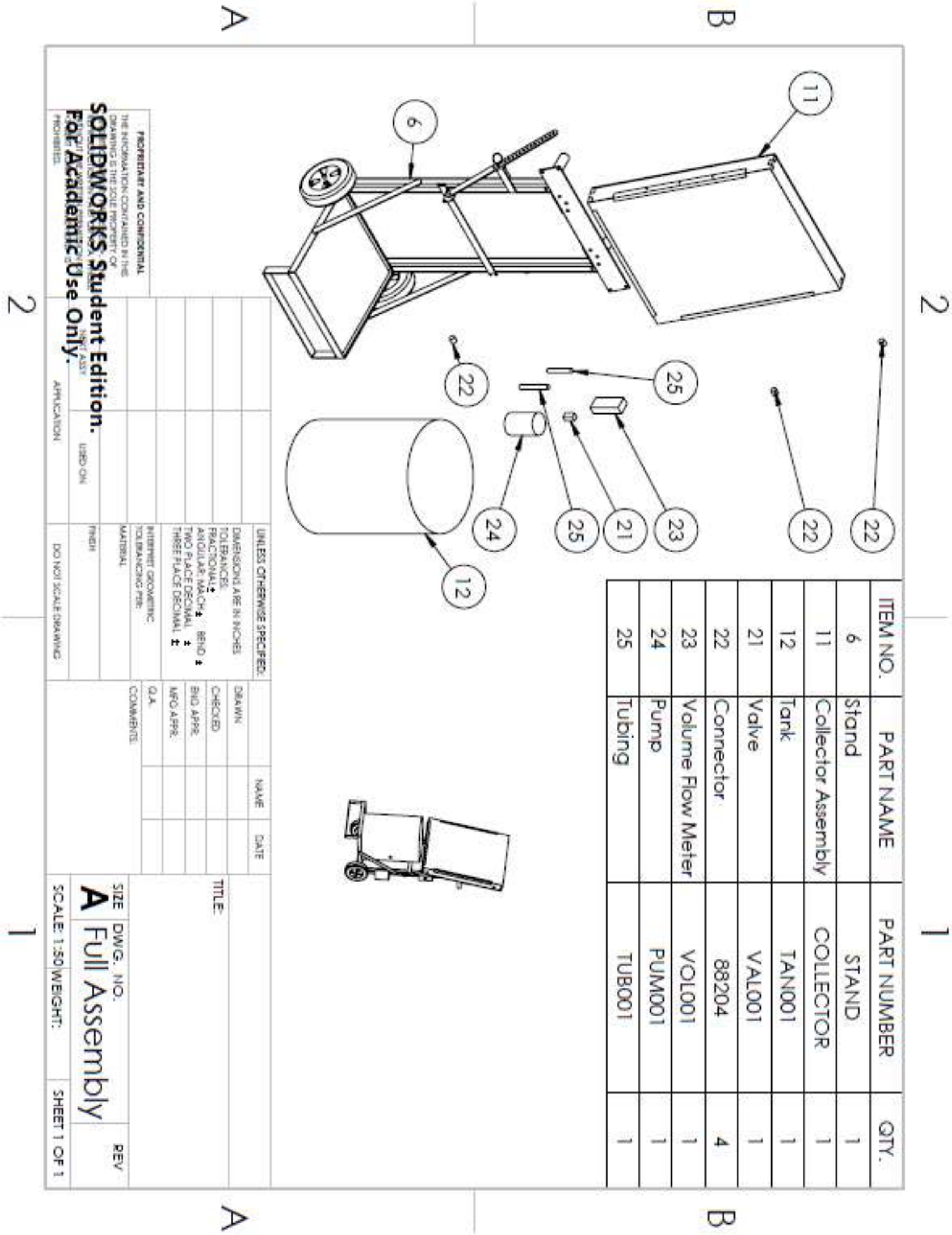
Student Learning Outcomes and Assessment:

Outcome	Assessment Strategy
1. The student will develop an understanding of the practical aspects of thermodynamics by relating theory to various applications of energy conversions systems.	Students shall be assessed through written homework assignments and examinations.
2. The student will learn the fundamentals of various state-of-the-art energy conversion systems such as steam power plants, spark ignition engines, compression ignition engines, gas turbines, and rocket engines.	Students shall be assessed through written homework assignments and examinations.
3. The student will demonstrate an engineering understanding of refrigeration and air conditioning systems.	This shall be assessed through homework assignments, quizzes, and laboratory experiments and reports.
4. The student will learn terminology in the energy conversion technical field so that the may read, discuss and comprehend the relevant literature.	This shall be assessed through homework assignments, quizzes, and laboratory experiments and reports.
5. The student will demonstrate the capability of predicting and measuring the performance of energy conversion systems.	This shall be assessed through homework assignments, quizzes, and laboratory experiments and reports.
6. The student will demonstrate the ability to plan and conduct energy conversion experiments.	This shall be assessed through laboratory experiments and reports.
7. The student will demonstrate the ability to select proper instrumentation to support experiments and have the ability to calibrate various sensors and connect sensors to data acquisition systems.	This shall be assessed through laboratory experiments and report s.
8. The student will perform computerized data analysis and be able to present and explain experimental results with clarity.	This shall be assessed through laboratory experiments, written and oral reports.
9. The student will demonstrate the ability to write various types of test reports common in the engineering field.	This shall be assessed through laboratory written reports.
10. As a result of this course, the student will become a better informed citizen who can take a leadership position when discussions arise dealing with energy issues.	This shall be assessed through laboratory experiments, written and oral reports.

Figure A17 shows the student outcomes for MET 411

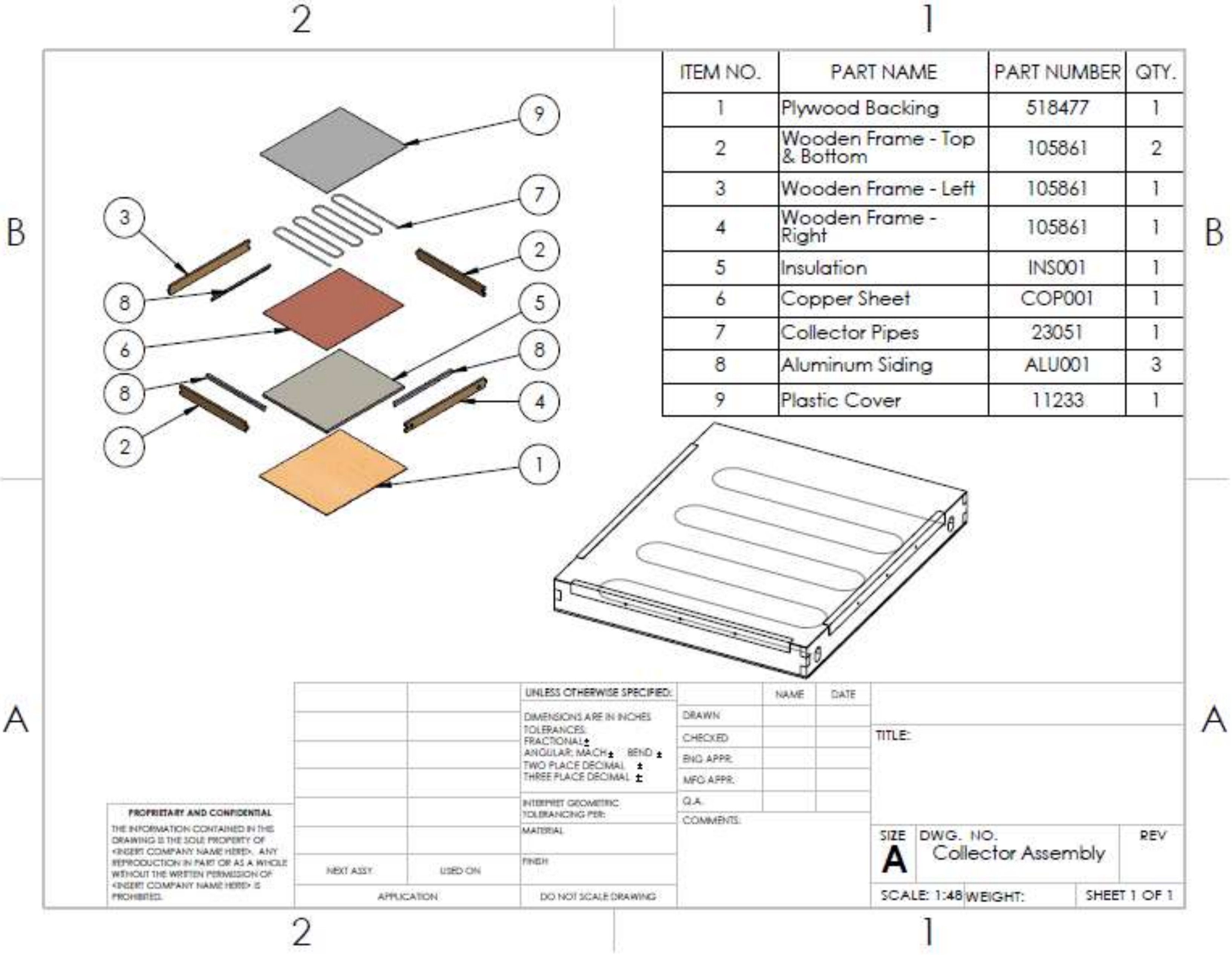
APPENDIX B

- Drawings
  - Figure B1: Full Assembly



ITEM NO.	PART NAME	PART NUMBER	QTY.
6	Stand	STAND	1
11	Collector Assembly	COLLECTOR	1
12	Tank	TAN001	1
21	Valve	VAL001	1
22	Connector	88204	4
23	Volume Flow Meter	VOL001	1
24	Pump	PUM001	1
25	Tubing	TUB001	1

- Figure B2: Collector Assembly (A)



ITEM NO.	PART NAME	PART NUMBER	QTY.
1	Plywood Backing	518477	1
2	Wooden Frame - Top & Bottom	105861	2
3	Wooden Frame - Left	105861	1
4	Wooden Frame - Right	105861	1
5	Insulation	INS001	1
6	Copper Sheet	COP001	1
7	Collector Pipes	23051	1
8	Aluminum Siding	ALU001	3
9	Plastic Cover	11233	1

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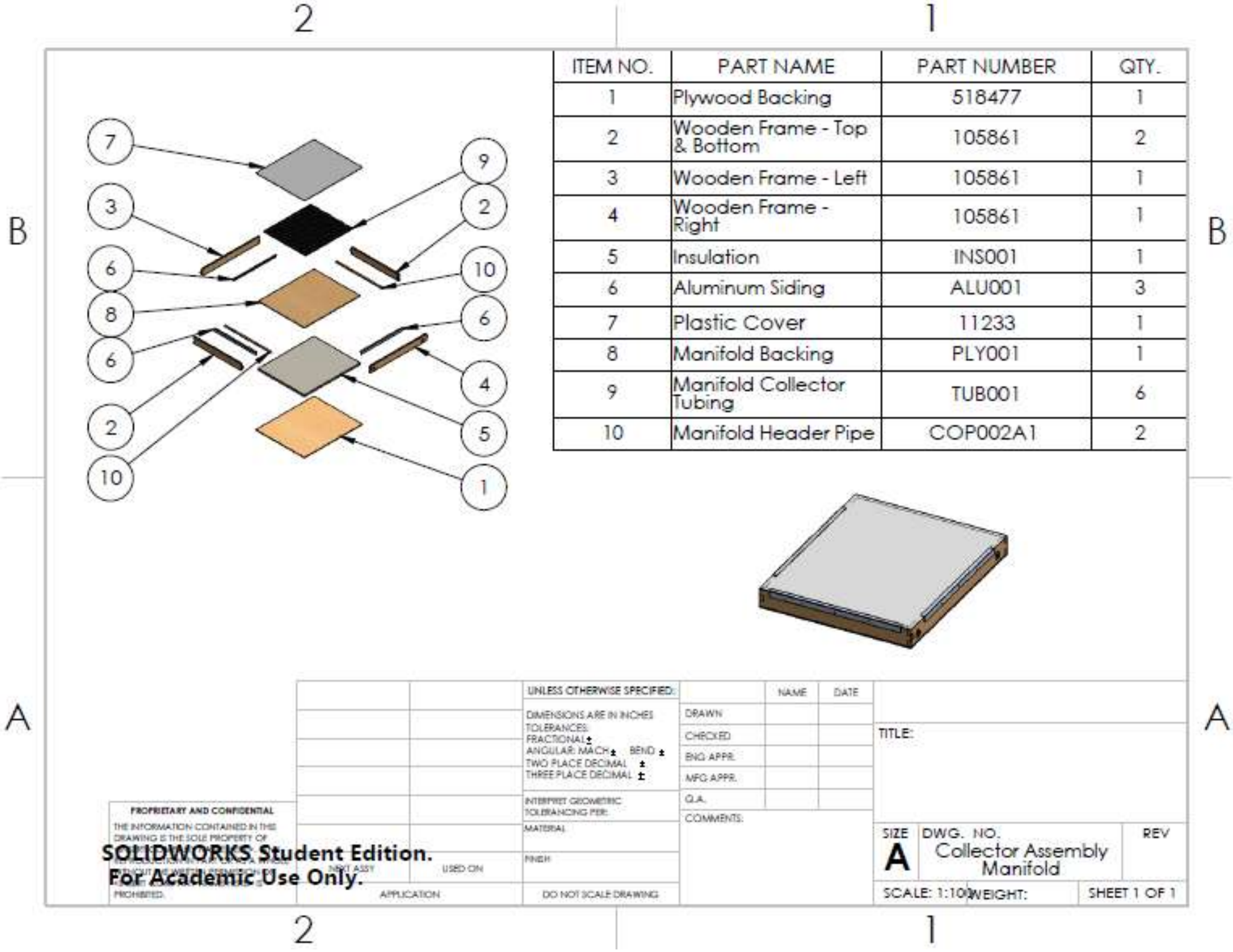
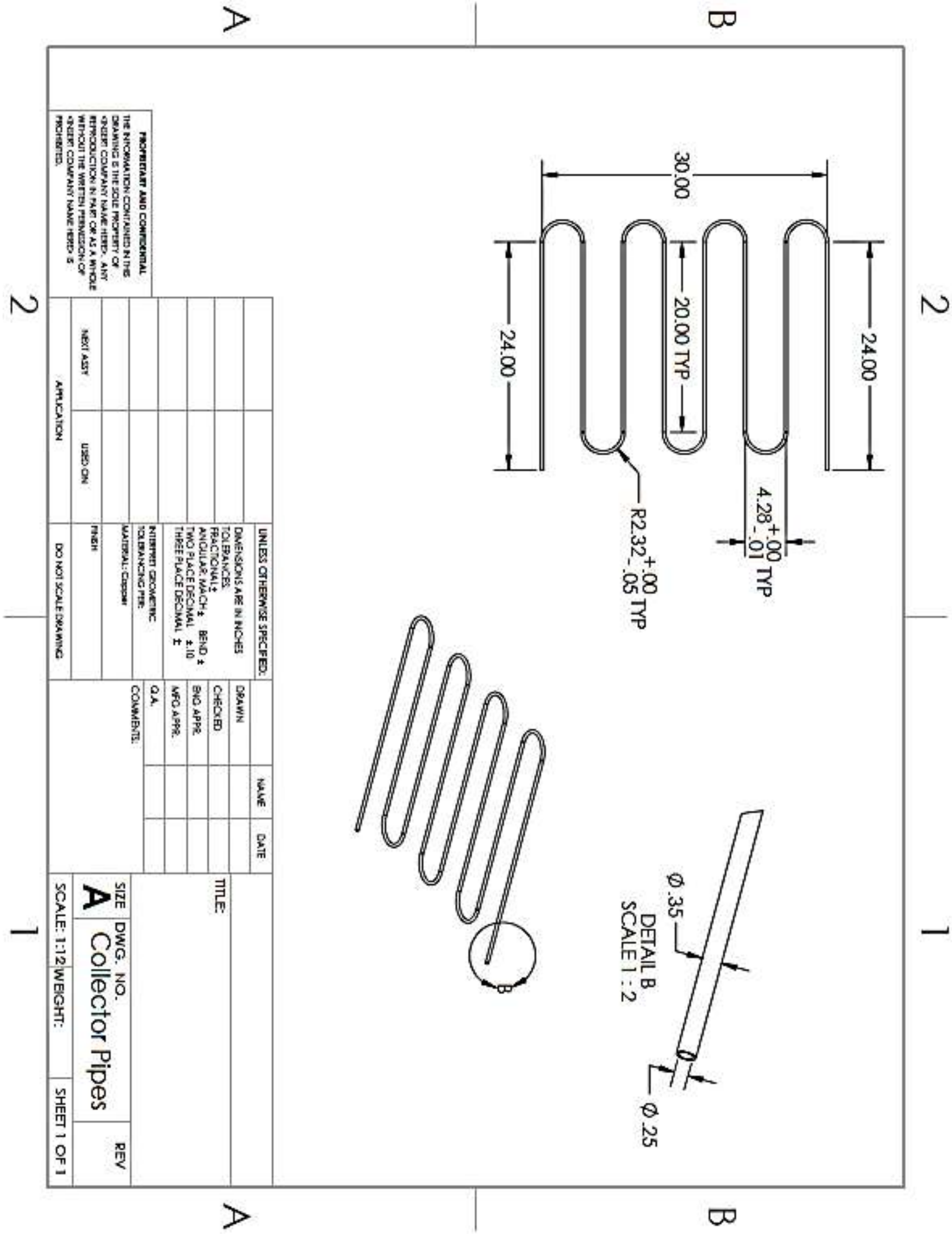
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

- Figure B3: Manifold Assembly (B)

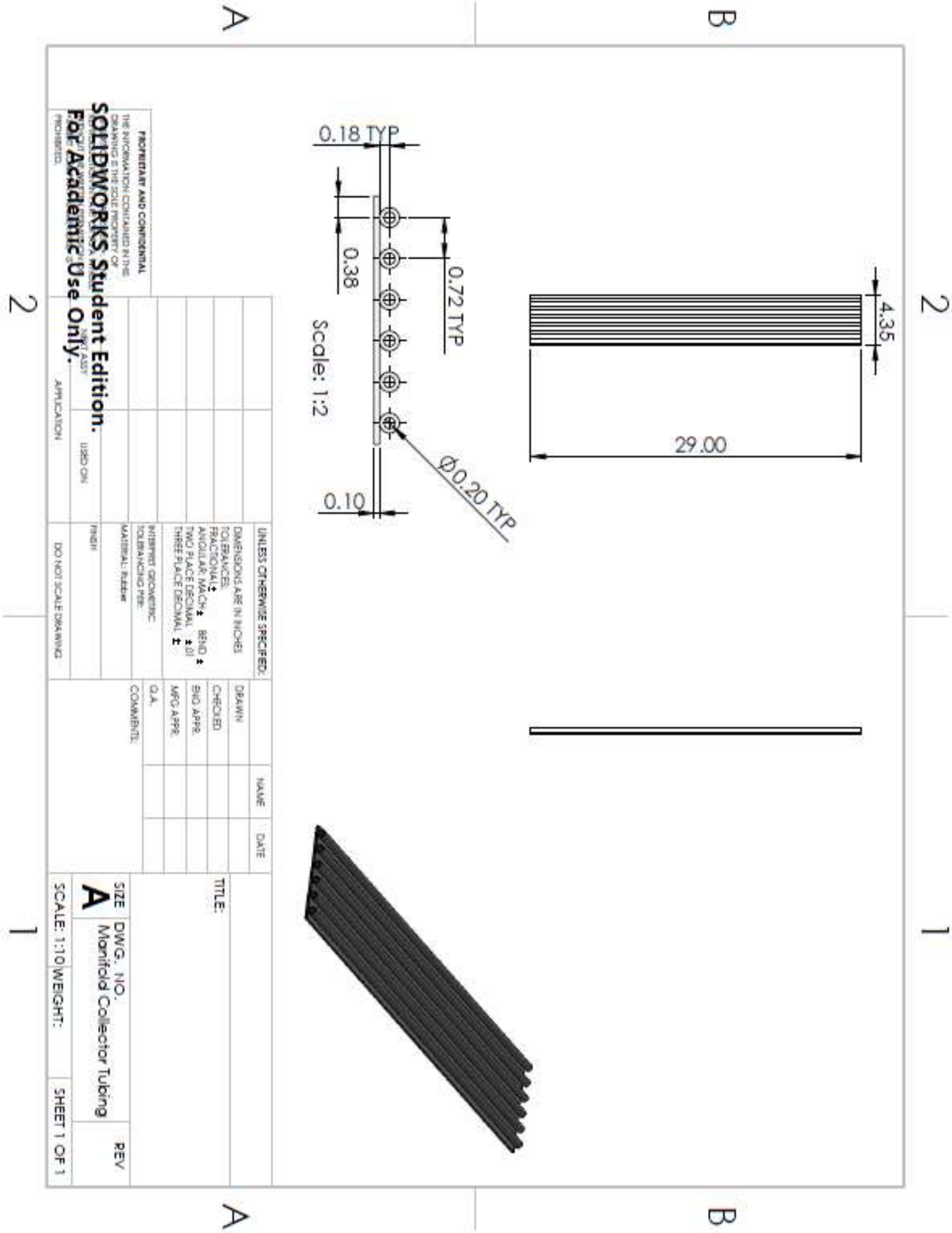


ITEM NO.	PART NAME	PART NUMBER	QTY.
1	Plywood Backing	518477	1
2	Wooden Frame - Top & Bottom	105861	2
3	Wooden Frame - Left	105861	1
4	Wooden Frame - Right	105861	1
5	Insulation	INS001	1
6	Aluminum Siding	ALU001	3
7	Plastic Cover	11233	1
8	Manifold Backing	PLY001	1
9	Manifold Collector Tubing	TUB001	6
10	Manifold Header Pipe	COP002A1	2

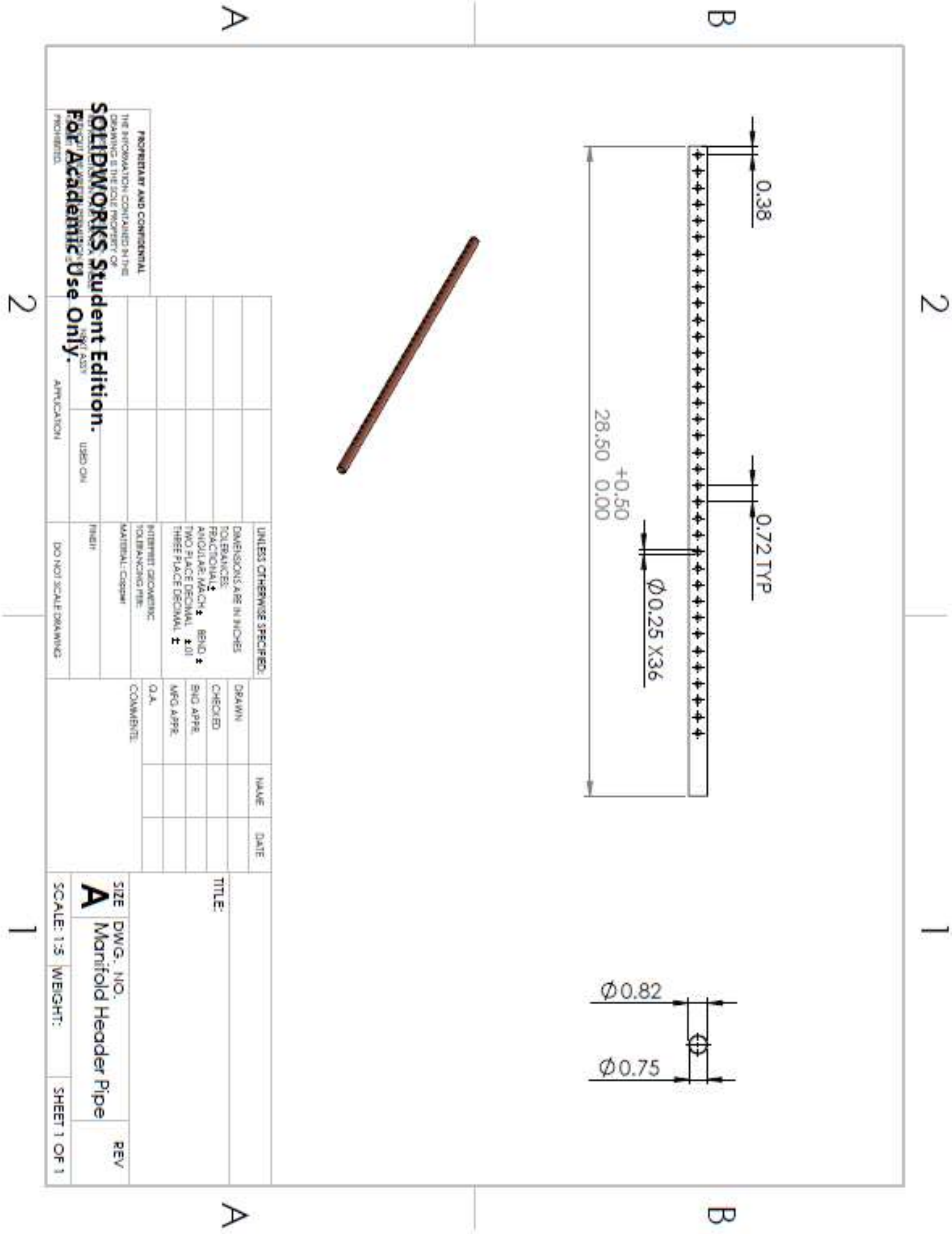
- Figure B4: Collector Pipes



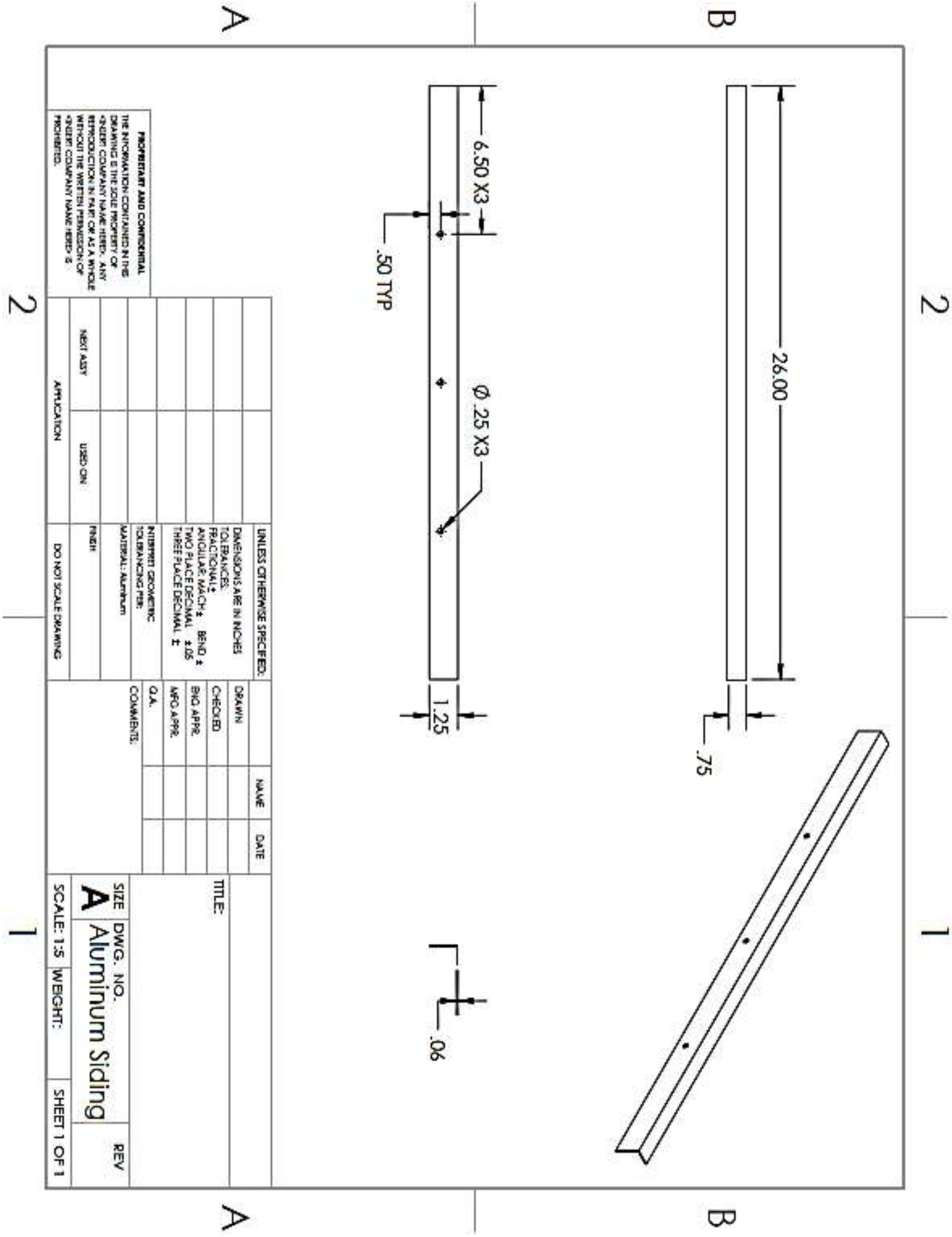
- Figure B5: Manifold Collector Tubing



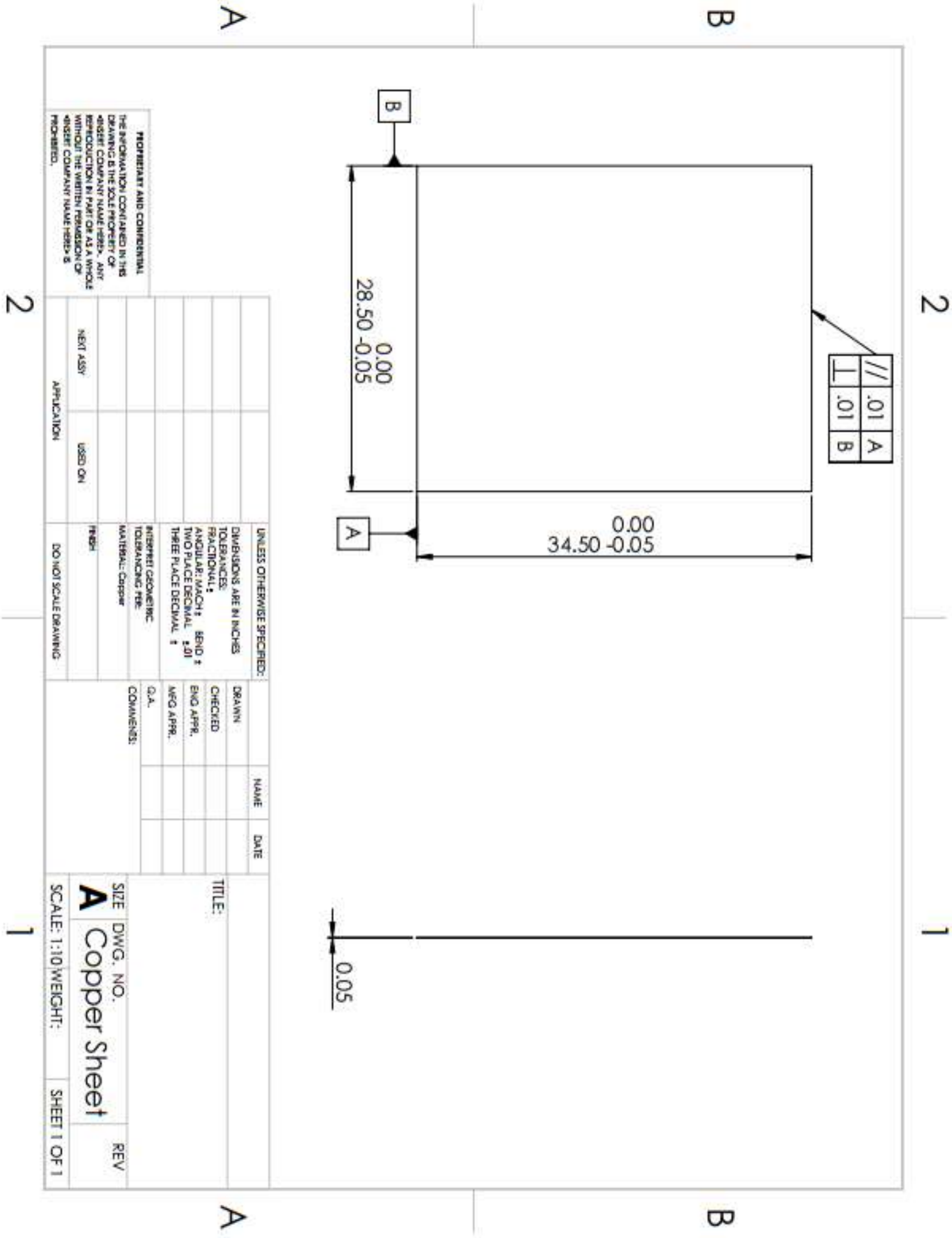
- Figure B6: Manifold Header Pipe



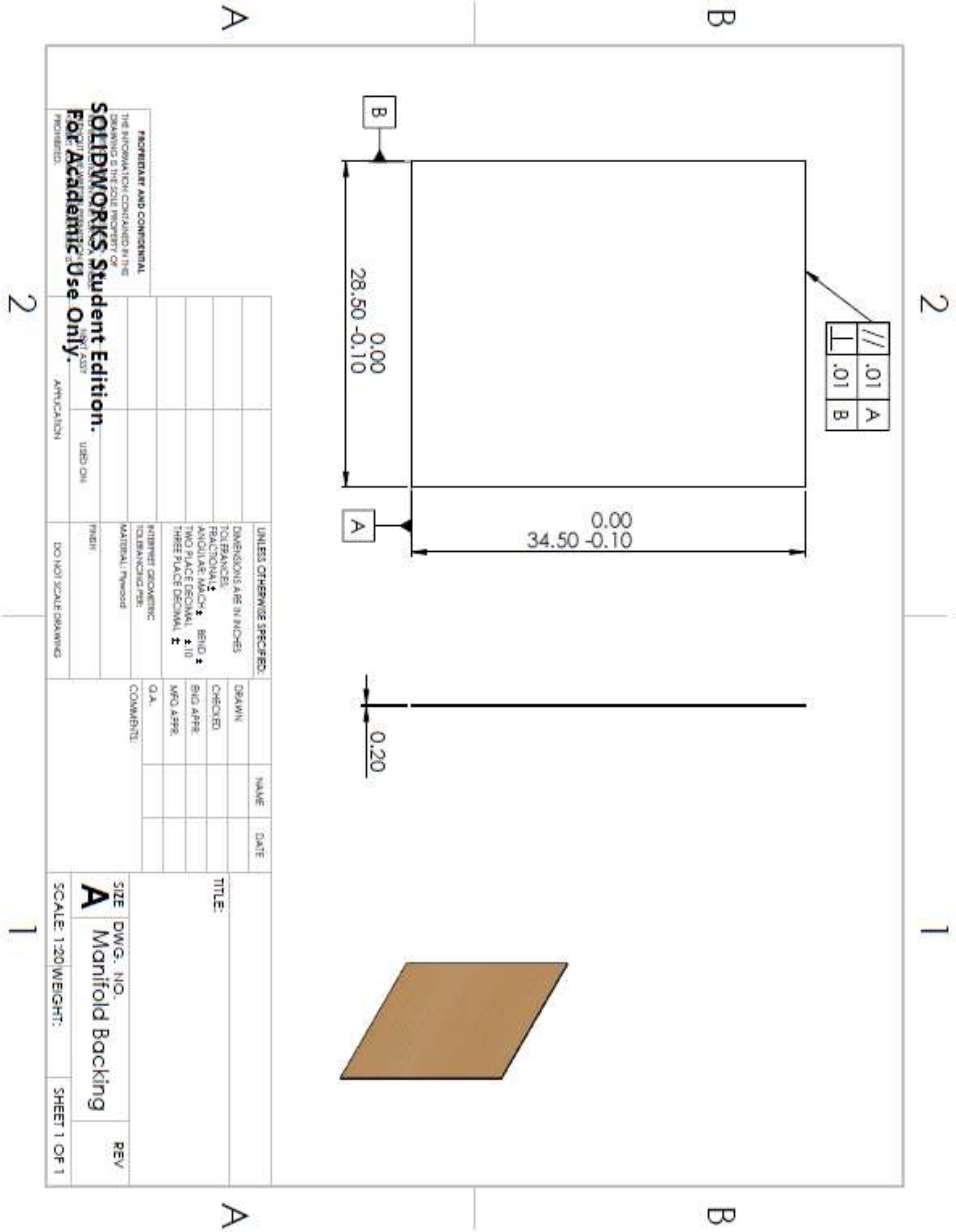
- Figure B7: Aluminum Siding



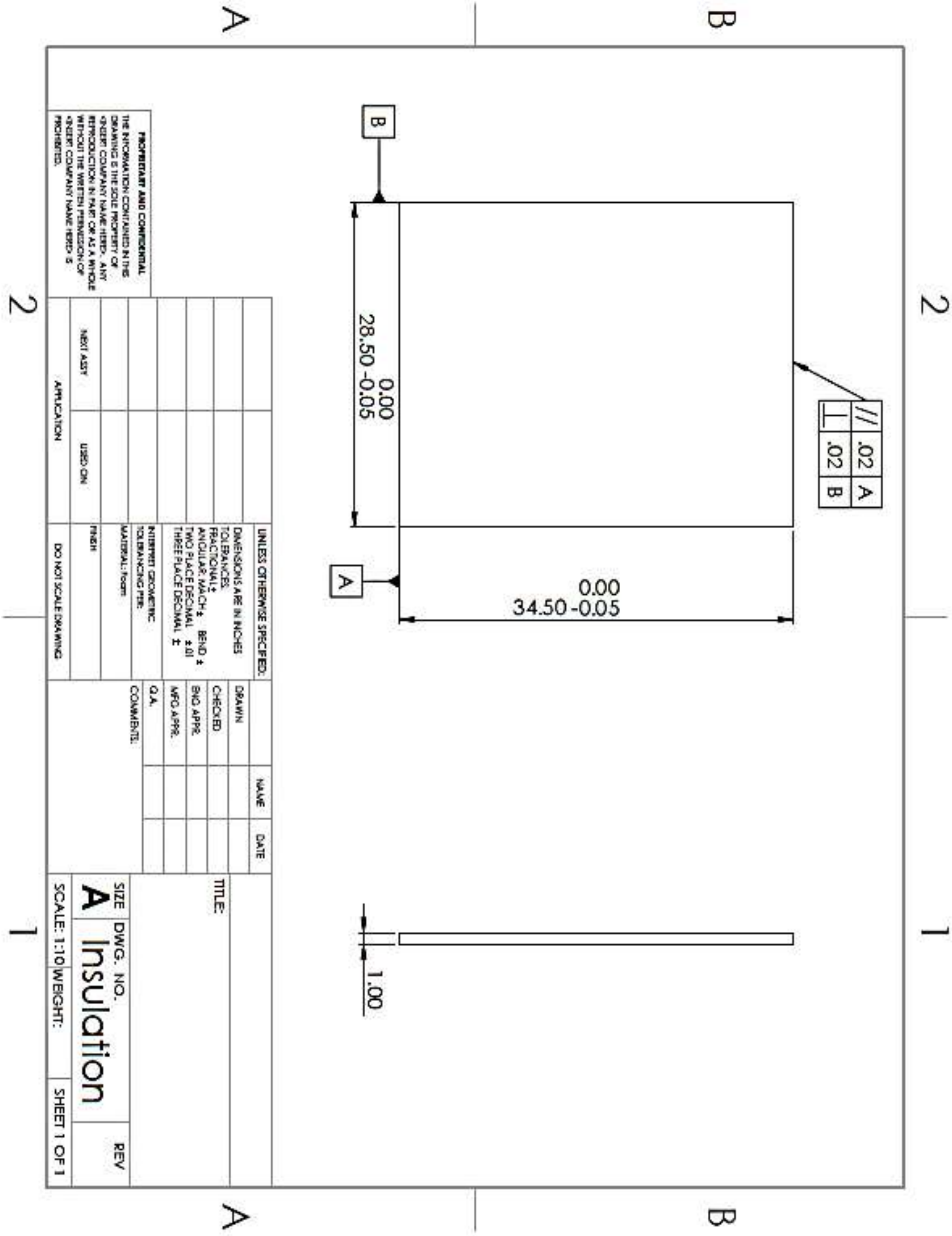
- Figure B8: Copper Sheet



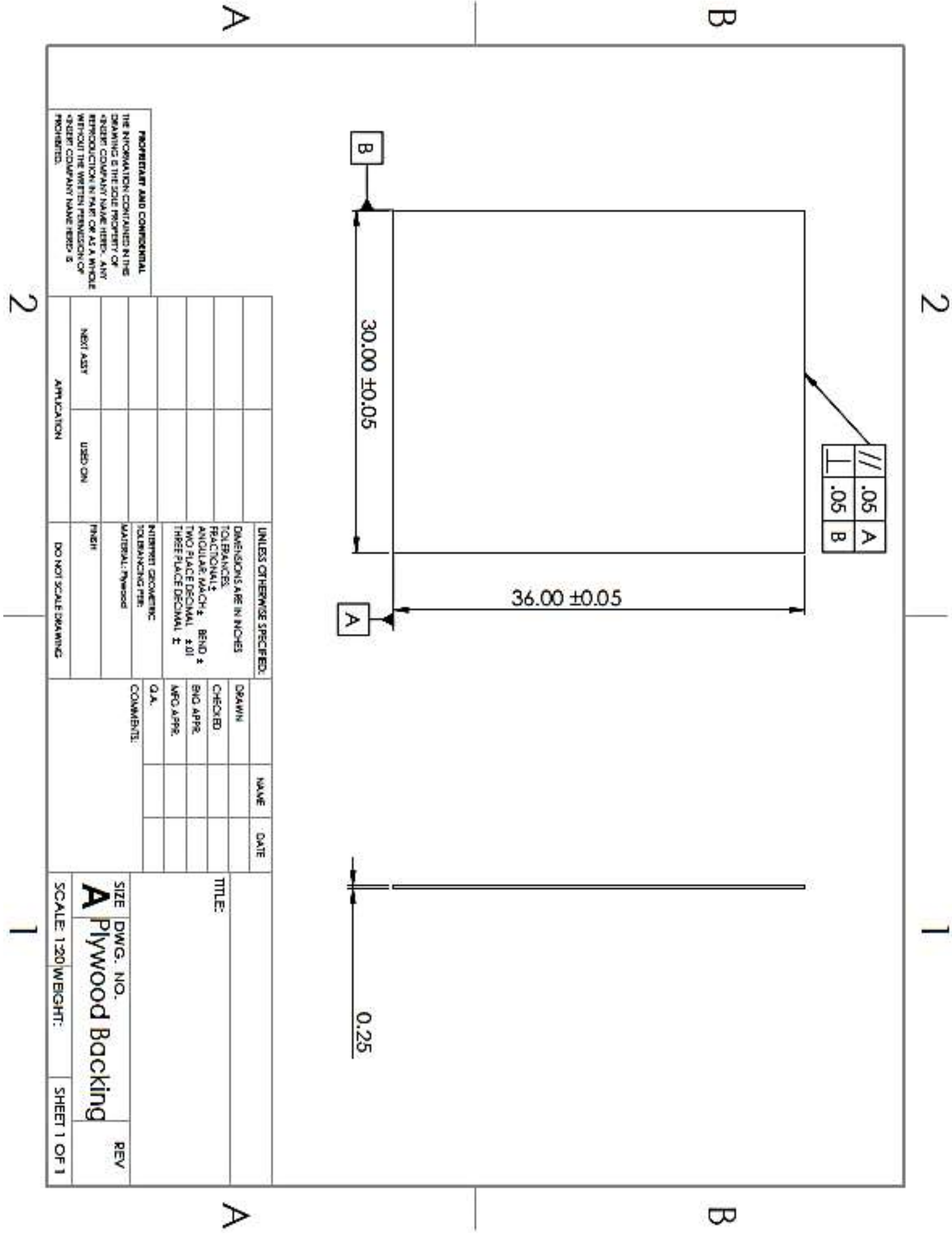
- Figure B9: Manifold Backing



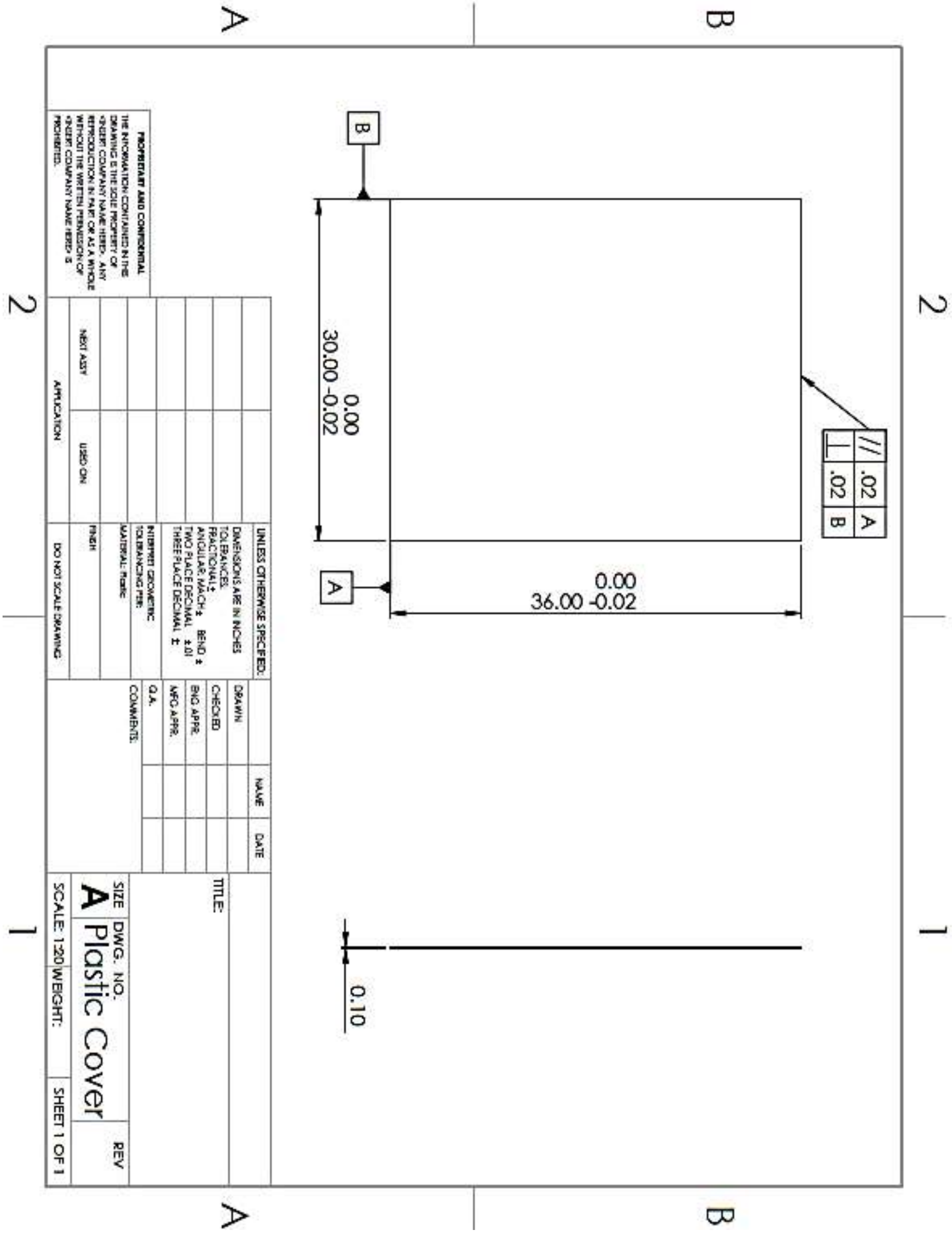
- Figure B10: Insulation



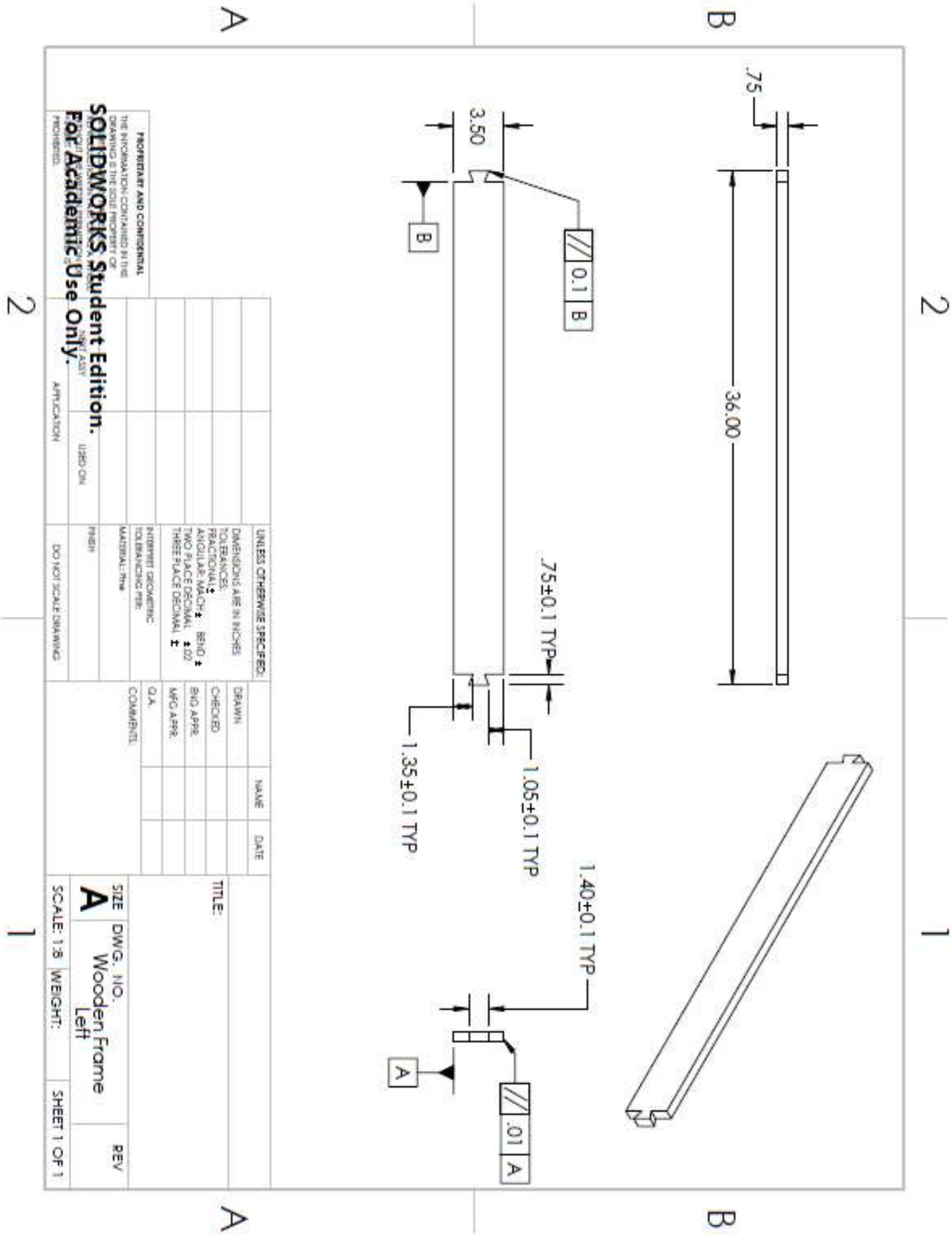
- Figure B11: Plywood Backing



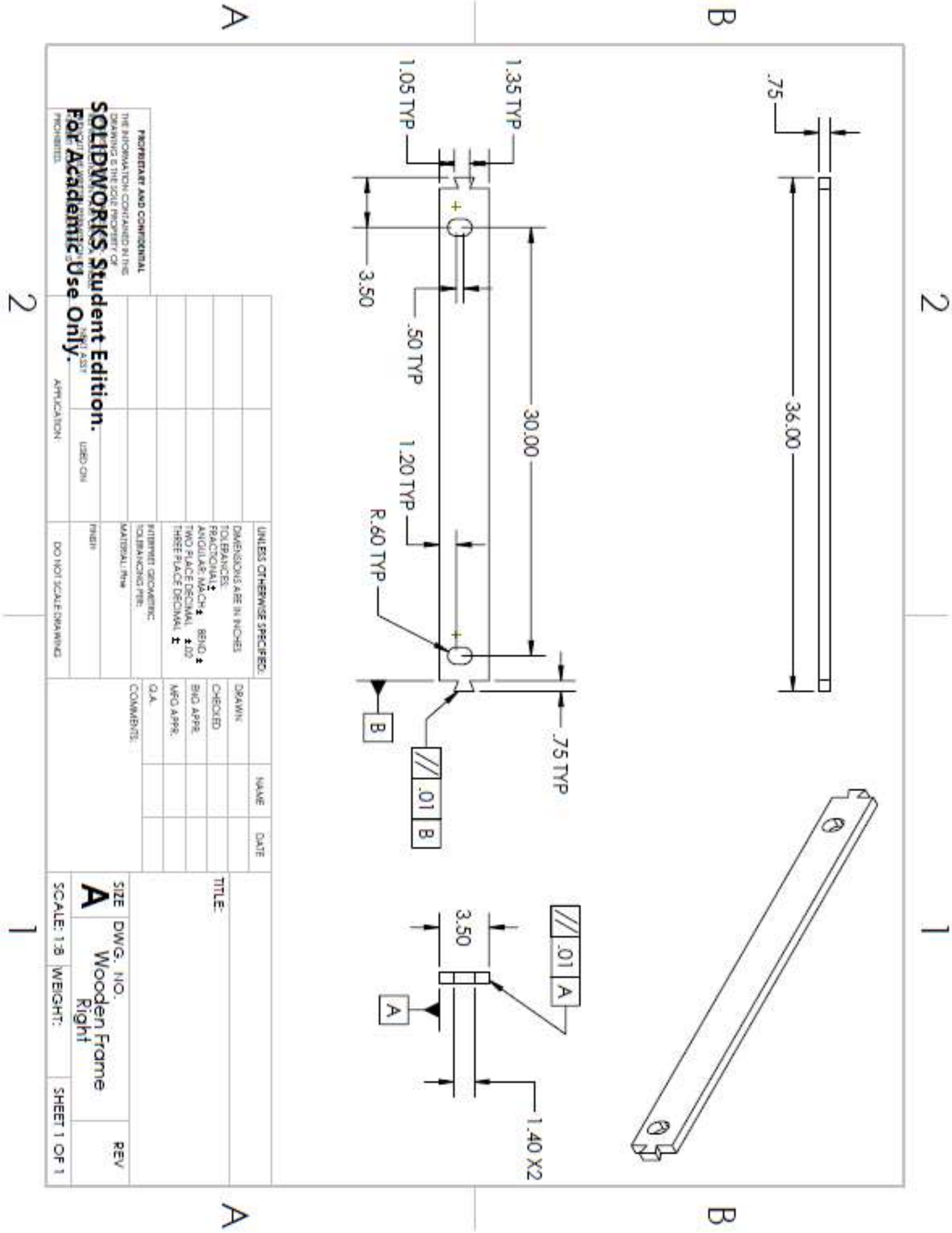
- Figure B12: Plastic Cover



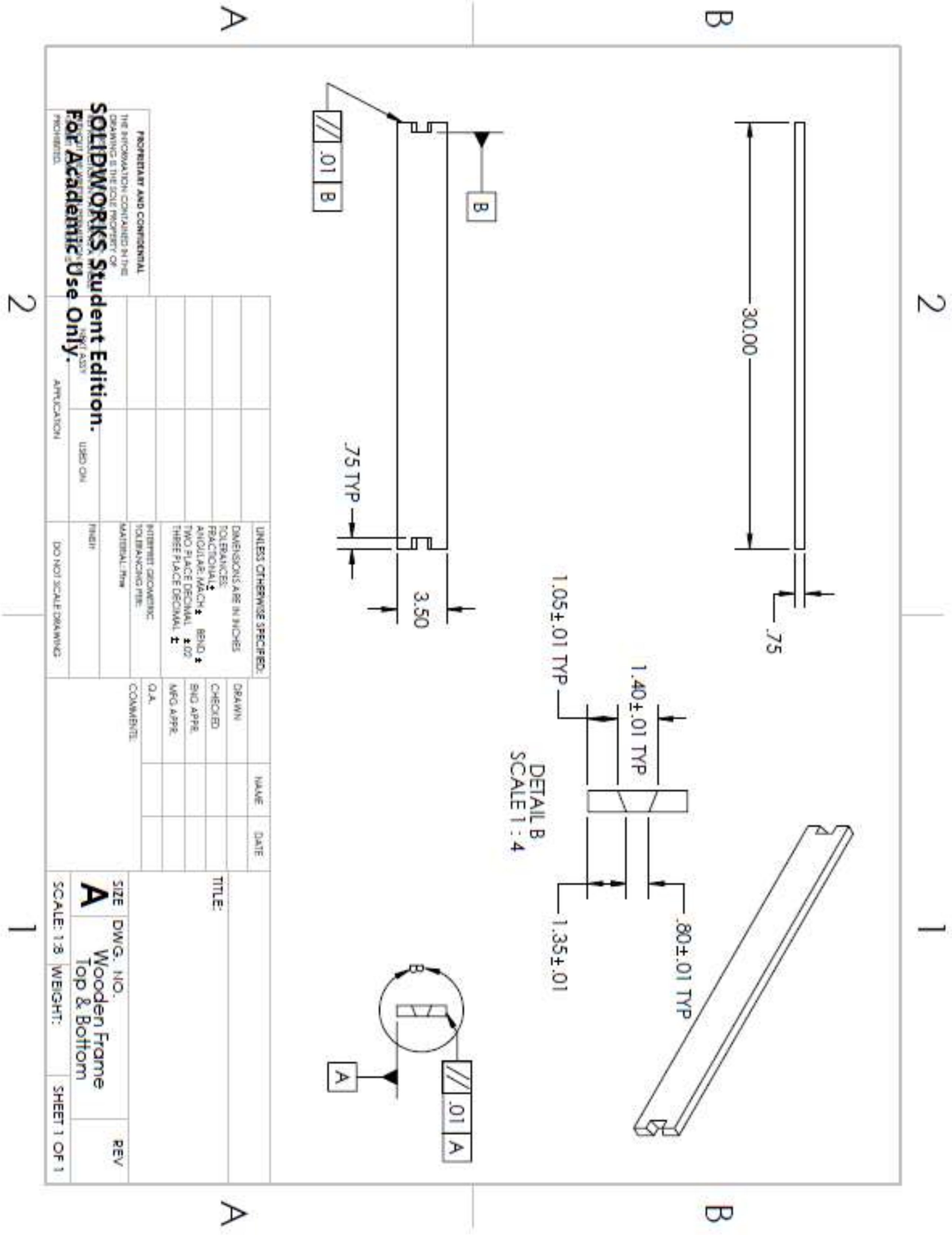
- Figure B13: Frame Left



- Figure B14: Frame Right



- Figure B15: Frame Top & Bottom



APPENDIX C

Figure C1: Parts List

Part	Description	Source	Estimated Cost	Actual Cost	Disposition
Wooden Frame	Four 2 by 4's	Knudson Lumber Item #105861	$9	$10.35	Purchased 12/18
Plywood Backing	¼ in x 3ft x 2.5ft	Lowes Item #518477	$15	$15.09	Purchased 11/24
Copper Pipes	¼ in pipes x 20ft	Lowes Item #23051	$10	$19.12	Purchased 11/24
Plastic Cover	OPTIX Clear Acrylic Sheet	Lowes Item # 11233	$30	$23.74	Purchased 11/24
Insulation	1 in thick	MET 411 Store Cupboard Item # INS001	$0	$0	Obtained 11/24
Copper Sheet	28.5in x 34.5in	MET 411 Store Cupboard Item # COP001	$0	$0	Obtained 11/24
Collector Tubing	0.2in tubing, 6 tubes per roll	MET 411 Store Cupboard Item # TUB001	$0	$0	Obtained 1/26
Manifold Backing	¼ in plywood x 28.5in x 34.5in	MET Machine Shop Item # PLY001	$0	$0	Obtained 2/3
Manifold Header Pipes	.75in copper pipe, 5ft long	MET Machine Shop Item # COP002	$0	$0	Obtained 2/3
.75 in End Caps x 2	Copper end caps for header pipes	MET Machine Shop Item # CAP001	$0	$0	Obtained 2/3
Aluminum Sheets	Scrap Metal	MET Machine Shop Item # ALU001	$0	$0	Available for use
Black Paint	For wood and metal	Ace Hardware Item #1534288	$5	$4.85	Order 1/5
Pump Power Supply	For Pump	MET 411 Store Cupboard Item # PWR001	$0	$0	Available for use
Tubing	To connect piping components	MET 411 Store Cupboard Item # TUB002	$0	$0	Available for use
Fittings	For ¼ in pipe and ¾ in pipe	MET 411 Store Cupboard Item # FIT001	$0	$0	Available for use
Volume Flow Meter	Liter/min flow rate	MET 411 Store Cupboard Item # VOL001	$0	$0	Available for use
Pump		MET 411 Store Cupboard Item # PUM001	$0	$0	Available for use
Nails	7/8 x 17	Ace Hardware	$1.29	$1.29	Purchased 1/31
Gorilla Glue	236mL	Ace Hardware	$5.39	$5.39	Purchased 1/31

Figure C1 shows the parts list, with estimated vs. actual costs of each item, along with how each item will be obtained.

APPENDIX D

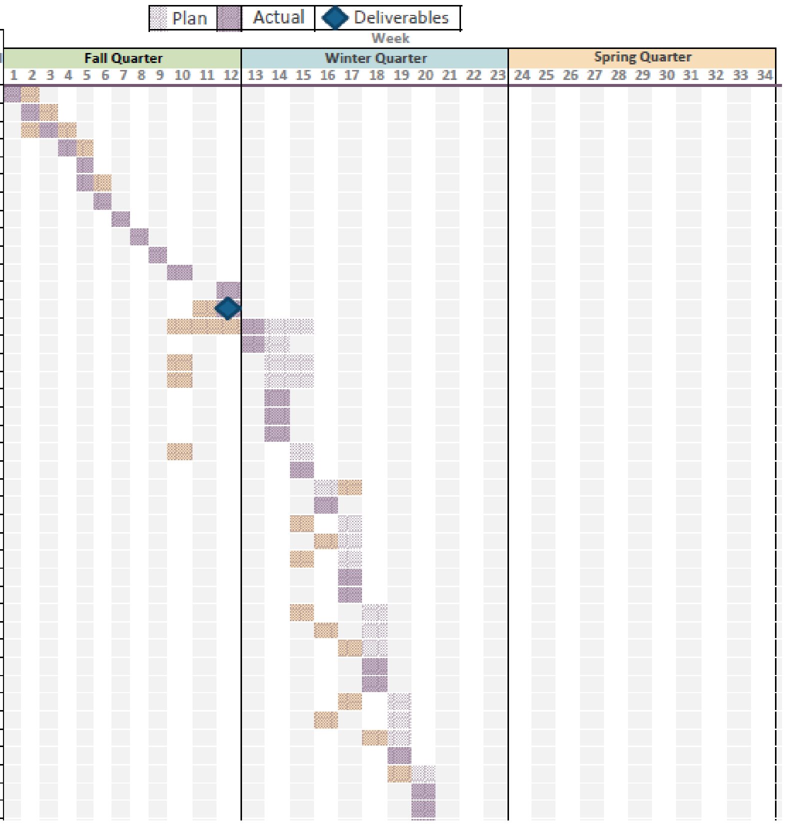
Figure D1: Budget

Item	Description	Estimated Cost	Actual Cost
Wooden Frame	Four 2 by 4's	$9	$10.35
Plywood Backing	¼ in x 3ft x 2.5ft	$15	$15.09
Copper Pipes	¼ in pipes x 20ft	$10	$19.12
Plastic Cover	OPTIX Clear Acrylic Sheet	$30	$23.74
Insulation	1 in thick	$0	$0
Copper Sheet	28.5in x 34.5in	$0	$0
Collector Tubing	0.2in tubing, 6 tubes per roll	$0	$0
Manifold Backing	¼ in plywood x 28.5in x 34.5in	$0	$0 (paid by CWU)
Manifold Header Pipes	.75in copper pipe, 5ft long	$0	$0 (paid by CWU)
.75 in End Caps x 2	Copper end caps for header pipes	$0	$0 (paid by CWU)
Aluminum Sheets	Scraps	$0	$0
Black Paint	For wood and metal	$5	$4.85
Pump Power Supply	For Pump	$0	$0
Hose Tubing	To connect piping components	$0	$0
Fittings	For ¼ and ¾ in pipe	$0	$0
Volume Flow Meter	Liter/min flow rate	$0	$0
Pump		$0	$0
Nails	7/8 x 17	$1.29	$1.29
Gorilla Glue	236mL	$5.39	$5.39
Total Parts		**$75.68**	**$79.84**
Transportation	To hardware stores: 120 miles, 28 mpg, $2.45/gal	$11.20	$11.20
Total Transportation		**$11.20**	**$11.20**
Lab Tech Salary	8 hours for testing phase at $9.47 per hour	$75.76	$0 (paid by CWU)
Student Machinist Salary	$5 hours for assistance during assembly at $9.47 per hour	$47.35	$0 (paid by CWU)
Metal Worker Salary	4 hours for soldering pipes at $40 per hour	$160	$0 (paid by CWU)
Student Salary	2 MET 411 student volunteers	$0	$0
Total Salary		**$283.11**	**$0**
Total Costs		**$369.99**	**$91.04**

APPENDIX E

Figure E1: Schedule

Task	ACTIVITY	PLAN START Week	PLAN DURATION (Weeks)	ACTUAL START Week	ACTUAL DURATION (Weeks)	PLAN DURATION (Hours)	ACTUAL DURATION (Hours)
1	State Problem - Proposal Introduction	1	1	1	2	1	1
2	Functions/Requirements - Proposal Introduction	2	1	2	2	1	1
3	Introduction - Finish Proposal Part 1	3	1	2	3	3	4
4	Design and Analysis - Proposal Part 2	4	1	4	2	4	6
5	Methods/Construction/Part Drawings - Proposal Part 3	5	1	5	1	4	5
6	Integrate 3D Models with Tyson	5	1	5	2	1	2
7	Testing Method - Proposal Part 4	6	1	6	1	4	4
8	Budget/Schedule - Proposal Part 5	7	1	7	1	3	5
9	Discussion - Proposal Part 6	8	1	8	1	2	2
10	Conclusion - Proposal Part 7	9	1	9	1	3	2
11	Finalize Appendices/Acknowledgements/References	10	1	10	1	3	3
12	Interview with Professors Pringle and Johnson	12	1	12	1	1	1
13	Finalize Proposal (finish editing)	12	1	11	2	2	4
14	Purchase materials that are not in MET 411 cupboard	13	3	10	4	3	2
15	Size and Cut the 4 Frame Sides	13	2	13	1	2	2
16	Size and Cut Insulation	14	2	10	1	1	0.25
17	Size and Cut Plywood Backing	14	2	10	1	2	0.25
18	Plan manufacturing methods with Professor Beardsley	14	1	14	1	0.25	0.5
19	Plan manufacturing methods with Mr. Burvee	14	1	14	1	0.25	0.5
20	Memo 1	14	1	14	1	1	1
21	Cut and Size Plastic Cover	15	1	10	1	0.25	0.25
22	Memo 2	15	1	15	1	1	1
23	Assemble backing, and four frame sides - glue and nail together	16	1	17	1	1	2
24	Memo 3	16	1	16	1	1	1
25	Cut and Size 4 Copper Sheet Components	17	1	15	1	2	1
26	Calculations	17	1	16	1	2	2
27	Bend Copper Piping for Curved Path	17	1	15	1	1	1
28	Memo 4	17	1	17	1	1	1
29	Update Proposal - Mid Report	17	1	17	1	4	4
30	Size and Cut Large Manifold Pipes (Headers)	18	1	15	1	1	0.25
31	Size and Cut Small Manifold Pipes	18	1	16	1	1	2
32	Assemble Manifold Pipes - Drill into the Header Pipes	18	1	17	1	2	1.5
33	Solder Manifold Pipes into Header Pipe	18	1	18	1	2	1.5
34	Memo 5	18	1	18	1	1	1
35	Cut and Size Collector Tubing	19	1	17	1	1	0.5
36	Solder Pipes to Copper Sheet	19	1	16	1	2	3
37	Cut and size manifold backing	19	1	18	1	0.25	0.25
38	Memo 6	19	1	19	1	1	1
39	Update calculations and proposal	20	1	19	1	2	2
40	Assemble Manifold Piping Assembly	20	1	20	1	0.5	1
41	Cut slots in frame - right side, to accommodate pipes	20	1	20	1	0.25	0.5



42	Memo 7	20	1	20	1	1	1
43	Cut and bend aluminum sidings to size	21	1	21	1	0.25	0.25
44	Paint the collector black	21	1	21	1	1	1.5
45	Attach connecting bar	21	1	21	1	0.25	0.25
46	Solder/attach fittings to the inlet and outlet collector pipes	21	1	21	1	0.25	0.25
47	Memo 8	21	1	21	1	1	1
48	Attach the aluminum sidings to the collector	22	1	22	1	1	0.25
49	Connect piping path - tank, pump, valve, flow meter, collector	22	1	21	1	1	1.5
50	Functional Collector	22	1	21	1	1	1
51	Memo 9	22	1	22	1	1	1
52	Update Website	23	2	16	1	1	2
53	Update Proposal	23	1	22	1	2	2
54	Abstract	24	1	24	1	2	2
55	Memo 1	24	1	24	1	1	1
56	Update Website	25	1	25	1	1	1
57	Test Plan	25	1	25	1	3	3
58	Career Account	25	1	25	1	2	2.5
59	SOURCE Plan	25	1	25	1	3	2
60	Test 1 April 8th 2016 1-3pm	25	1	25	1	2	2
61	Memo 2	25	1	25	1	1	1
62	Test Demo 1	26	1	26	1	2	1
63	Memo 3	26	1	26	1	1	1
64	Test 2 April 18th 2016 1-3pm	27	1	27	1	2	2
65	Memo 4	27	1	27	1	1	1
66	Test 3 April 24th 2016 1-3pm	28	1	28	1	2	2
67	Test 4 April 25th 2016 1-3pm	28	1	28	1	2	2
68	Test Demo 2	28	1	28	1	2	1
69	Memo 5	28	1	28	1	1	1
70	Test 5 May 1st 2016 1-3pm	29	1	29	1	2	2
71	Test Report	29	1	29	1	3	5
72	FE Response	29	1	29	1	2	1
73	Update Website	29	1	29	1	2	2
74	Memo 6	29	1	29	1	1	1
75	SOURCE Poster	30	1	30	1	3	4
76	Memo 7	30	1	30	1	1	1
77	SOURCE	31	1	31	1	4	2
78	Memo 8	31	1	31	1	1	1
79	Final Presentations	32	1	31	1	3	3
80	Memo 9	32	1	32	1	1	1
81	Final Report	33	1	32	1	3	3
82	Memo 10	33	1	33	1	1	1
83	Jump Drive	34	1	33	1	2	2.5
				Total Time:		136.5	141.25

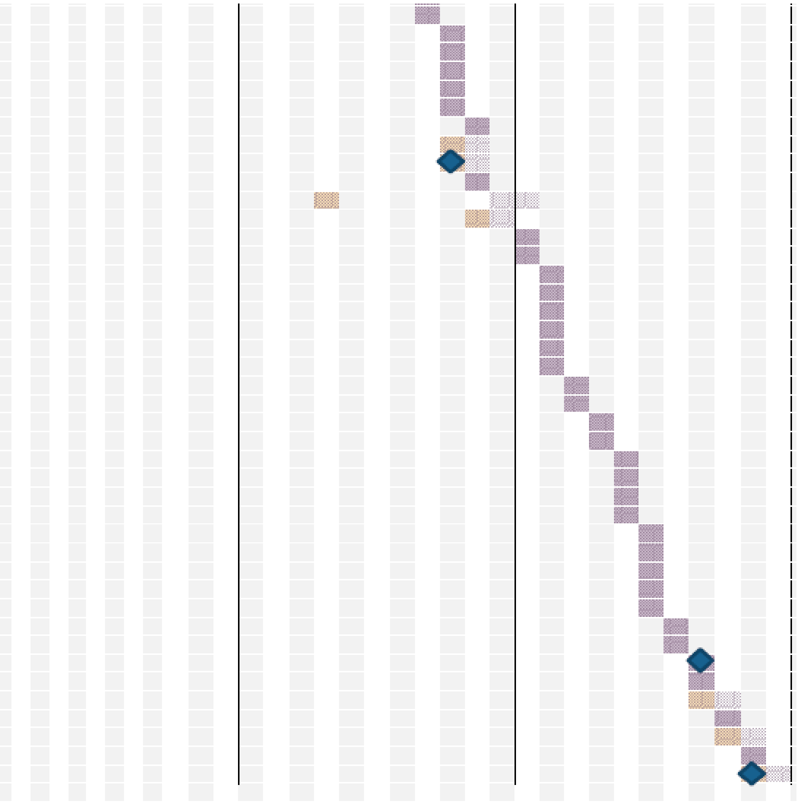


Figure E1 shows the Gantt chart schedule for the entire project. The actual and estimate start weeks and weeks of duration are shown for each task. The project was divided up into 3 quarters, fall, winter, and spring, with three phases of the project, design, manufacture, and test, respectively.

APPENDIX F

Expertise and Resources

Designing:
Professor Beardsley
Hogue Technology Building
CWU

Soldering:
Matt Burvee
Hogue Technology Building
CWU

APPENDIX G

Testing Data

Figure G1: Lab Testing

Trial	Time to Assemble	Time to Transport	Time to Clean Up
1			
2			
3			

Figure G1 shows the form that will be used to record the test data with regards to the usability of the solar collector. The sheet will be used to record the assembly time taken by the lab tech to set up the lab, the time taken by the lab tech to transport the assembly outside, and the time taken by the lab tech and professor Beardsley to dismantle and put away the collector assembly. For assembly and clean up, only ten minutes are available. This is because, if the collector is to be used for MET 411 labs, there will only be ten minutes between classes for the lab to be set up and put away, before the next class is scheduled to start. For the collector to be successful, the lab tech and professor Beardsley should be able to use the allocated time to adequately prepare the collector for lab, and put it away again before the following class is scheduled to begin. The time to transport the assembly will also be recorded as a guide to the transportability of the collector. If the collector can be transported from the MET 411 classroom to the Hogue patio in a matter of minutes, then the solar collector can be considered easily transportable. If the collector takes more than a few minutes to be transported to the Hogue patio, then it could be designed to be more efficient, transportation wise.

Figure G2: Collector Efficiency Testing

Time	Solar Irradiance (W/m^2)	Collector Area (m^2)	Volume Flow Rate (mL/min)	Inlet Temperature (°K)	Outlet Temperature (°K)
Noon					
12:10pm					
12:20pm					
12:30pm					
12:40pm					
12:50pm					
1:00pm					
1:10 pm					
1:20pm					
1:30pm					
1:40pm					
1:50pm					

Figure G2 shows the test data form that will be used during the lab to analyze the output efficiency of the solar collector. The solar irradiance, collector area, volume flow rate, and temperature change will all be measured. The area of the collector, the density of water, and Cp water will all be given. From there, the collector output efficiency, mass flow rate, and heat transfer coefficient can all be calculated.

Figure G3: Schedule Testing

Description of Activity	Time Taken to Complete

Figure FG shows the table that will be used to record all activities associated with manufacturing the solar collector, to ensure that the project stays on track and doesn't go over the time limit.

APPENDIX H

Evaluation Sheet

Figure H1: Results Summary

Time	Solar Irradiance (W/m^2) (I)	Collector Area (m^2) (A)	Calculated Efficiency (η)	Volume Flow Rate (vdot)	Water Density (kg/m^3) (ρ)	Mass Flow Rate (mdot)	Cp Water (Cp)	Change in Temp (°K) (ΔT)	Heat Transfer Coefficient (Qdot)
Obtained	Measured with pyrano-meter	Measured with ruler	Calculated: η = Qdot/(IA)	Measured with flow meter	Given	Calculated: mdot = (vdot)(ρ)	Given	Measured between inlet and outlet	Calculated: Qdot = (mdot)(Cp) (ΔT)
Noon					.988kg/ m^3		4.18 kJ/kgK		
12:10pm					.988kg/ m^3		4.18 kJ/kgK		
12:20pm					.988kg/ m^3		4.18 kJ/kgK		
12:30pm					.988kg/ m^3		4.18 kJ/kgK		
12:40pm					.988kg/ m^3		4.18 kJ/kgK		
12:50pm					.988kg/ m^3		4.18 kJ/kgK		
1:00pm					.988kg/ m^3		4.18 kJ/kgK		
1:10 pm					.988kg/ m^3		4.18 kJ/kgK		
1:20pm					.988kg/ m^3		4.18 kJ/kgK		
1:30pm					.988kg/ m^3		4.18 kJ/kgK		
1:40pm					.988kg/ m^3		4.18 kJ/kgK		
1:50pm					.988kg/ m^3		4.18 kJ/kgK		

Figure H1 shows the results summary for determining the efficiency, mass flow rate, and heat transfer coefficient of the solar collector. The equations for calculating these values are shown. The values calculated will determine whether or not the solar collector met the performance predictions.

APPENDIX I

Testing Report

Introduction:

To test the performance of the solar collector, a couple of methods will be used. First, the incoming solar irradiance will be measured and recorded, using www.wunderground.com data from the Hogue roof. The solar input will be the largest factor in determining the performance of the solar collector. The solar collector was designed for an input of $800W/m^2$, and if the solar irradiance is vastly different from this estimate, then the performance will not be as expected. The difference between the input and output temperatures of the water in the collector will also be measured. The goal is to achieve a temperature difference of at least 25°K, at 50% efficiency, when the solar input is 800W/m^2. The flow rate of the water will also be measured with a flow meter. The flow rate will be measured for calculation purposes. The solar irradiance, flow rate, and temperature difference will be measured every 10 minutes throughout the two hour lab period, or in this case, a two hour block of testing time. Students will be given the collector dimensions, C_p, and density of water, so that they can calculate the efficiency of the collector, and the heat transfer coefficient, Qdot. Students will graph any changes that occur over the two hour lab period, and answer discussion questions related to the collector.

Another way that the performance of the collector will be measured is through actually carrying out a lab. The principal engineer or Professor Beardsley will be given ten minutes to bring the collector setup and additional equipment out of the MET 411 storage cupboard to the Hogue patio, and set it up. Next, the principal engineer will be given two hours to use the collector to gather data. Finally, the principal engineer and Professor Beardsley will be given ten minutes to dismantle and put away the solar collector setup. Carrying out the three phase process in full within the time limits would be considered a success.

Data will be acquired in the data tables following. See Report Appendix for the data tables. Table 1 shows the lab testing data collection, which involves recording the test setup and dismantle times, to ensure that the collector is compliant with MET 411 lab schedules. Tables 2, 4, 6, 8, and 10 show the data acquisition that took place during testing. From there, the data tables in Tables 3, 5, 7, 9, and 11 were used to keep a record of the measured and calculated values, to test the efficiency of the collector. The solar irradiance, flow rate, and temperature difference were measured every 10 minutes throughout the two hour block of testing time.

Other factors that will need to be tested to assure that the solar collector meets all of the design requirements are as follows: the collector needs to be able to heat the water using only solar energy, the collector should weigh no more than 25lbs, the collector should be no more than 2.5ft wide by 3ft long by 6in deep, the collector should take no more than 20 hours to manufacture, it should cost no more than $100 to manufacture, and the collector should be able to fit on the accompanying stand.

Method/Approach:

To test the performance predictions set for the solar thermal collector, a number of items need to be carried out. These items include:

- Measuring the time it takes for the principal engineer and/or Professor Beardsley to take the collector assembly from the MET 411 store cupboard to the Hogue patio will be measured and recorded to determine ease of transportation, along with the time to setup the collector and associated equipment
    - The goal is no more than ten minutes
- During a two hour lab period, the principal engineer will use the solar collector to gather data and complete the lab analysis
- The time it takes the principal engineer and/or Professor Beardsley to dismantle and put away the lab setup will be measured and recorded
    - The goal is no more an ten minutes
- Measuring the temperature change between the inlet and outlet pipes
    - The goal is to achieve a 25°K difference
- Determining the collector efficiency
    - $Qdot = IA\eta = mdotCp\Delta T$ will be used
    - The solar irradiance (I) will be measured

    - The collector area (A) will be given, but can be double checked by students
    - The flow rate (mdot) will be measured and calculated
    - The water property, C_p will be given
    - The temperature change (ΔT) will be measured
- The collector will need to be weighed
- The collector's outside dimensions will need to be measured and recorded
- The manufacturing time will need to be measured and recorded
- The actual costs of each component of the collector will need to be recorded

The measurement tools that will be needed are the following:

- www.wunderground.com – to measure solar irradiance
- Thermocouples and an accompanying FLUKE meter – to measure inlet and outlet water temperatures
- Flow Meter – to measure the volumetric flow rate of the water
- Tape Measure – to double check the surface area of the collector
- Stop Watch – to measure the time it takes to setup, use, and dismantle the collector set up, as well as for measuring the time it takes to manufacture the collector
- Scales – to weigh the collector
- http://aa.usno.navy.mil/data/docs/AltAz.php can be used to determine the altitude of the sun at ten minute intervals.

In addition to the measuring tools, the collector assembly, a power source, and some volunteers will be necessary for completing testing. The collector and the power source are necessary to run the tests, and volunteers may be needed to help move the collector setup.

The operational limitations lie with the testing equipment. For example, the flow meter is not particularly precise, and therefore allows for some error in the flow rate measurement. Furthermore, attaching the thermocouples to the inlet and outlet pipes will allow for an influence in temperature by the pipes. The water and pipes will not be exactly the same temperature, so there will be some room for slight errors there too. Finally, clouds will affect the incoming solar radiation. If clouds pass over the collector in between when measurements are taken, then the collector, and therefore water, temperature will be affected.

Once the data is collected, the results of the temperature change in the water, the solar irradiance, and the collector efficiency will be graphed as a function of time. Patterns and/or trends will be observed and conclusions may be drawn. All three testing trials will be compared once all data has been collected.

Test Procedure:

The time and duration of the testing phase are as follows:

- Most of the data collection will take place between 1-3pm.
    - Due to class schedules and that being the optimal time of day for sunlight.
    - There was some variation due to access of equipment around classes, and random cloud coverage.
- The entire set up, lab, and clean up should take approximately 2 hours per trial.
    - Lab time is approximately 2 hours, and so the testing has to be completed within that time frame.

The test sites will include:

- The MET 411 store cupboard – to make sure that the solar collector assembly can be stored within the designated area.
- Hogue Technology Building – the collector assembly will be transported through the building to test for ease of transportation.
- The Hogue patio – this is where the solar collector will be placed in direct sunlight for data to be recorded.
- The Hogue foundry – this is where the collector will be weighed.

Potential risks for the testing phase of the project are:

- Heat – the collector is designed to heat water when placed in sunlight. It will be hot to the touch, and students should be careful not to burn themselves.
- Heavy stand – the collector stand is heavy, especially with the water tank. Students, the principal engineer, and Professor Beardsley should be careful not to hurt themselves during transportation and adjustments.

The lab set up is as follows:

1. Gather all equipment (collector mounted on stand, pump, volume flow meter, thermometers, tubing, and fittings).
2. Make sure that the tank is at least half full.
   a. If not, use a hose pipe connected between a faucet and highest tank fitting.
   b. The tank should already be at least half full, but it is still wise to check.
3. Connect the tank to the pump, using the tubing and fittings provided.
4. Connect the pump to the flow meter, using the tubing and fittings provided.
   a. This should be thin, clear tubing.
5. Connect the flow meter to the bottom collector inlet, using the tubing and fittings provided.
6. Connect the collector outlet back to the tank, using the tubing and fittings provided.

*Note: steps 3-6 are likely to have already been completed, but it is wise to double check all of the pipe connections to be sure. These steps are listed in case any connections come loose, so the lab tech knows the order of components in the circuit.

7. Transport the assembly down to the Hogue Patio, and place in direct sunlight.
8. Take one of the thermocouples, and place the sensor on the inlet copper pipe at the edge of the collector.
9. Wrap a film of Styrofoam around the thermocouple and the pipe a few times, and tape down.
10. Take the other thermocouple, and place the sensor on the outlet copper pipe at the edge of the collector.
11. Wrap a film of Styrofoam around the thermocouple and the pipe a few times, and tape down.

*Note: The thermocouples should be pressed tightly against the inlet and outlet pipes, and tied down with the Styrofoam. This could be carried out before taking the collector outside, however, transportation is likely to move the thermocouples around and may dislodge them from their proper placement.

12. Connect the pump to a power source. An extension cable may be necessary.

13. Start the pump, and adjust the flow rate, until it is close to 150ml/min or 9L/hour.
14. Adjust the collector face as necessary, so that it is directly facing the sun.
    a. http://aa.usno.navy.mil/data/docs/AltAz.php gives the sun's altitude in 10 minute intervals.

The second part of the testing procedure includes following the lab sheet:

MET 411 Energy Systems
Lab #1: Efficiency of a Solar Collector

Objectives: To plot the solar irradiance vs. efficiency and temperature change vs. efficiency of a 2.5ft by 3ft solar collector throughout a two hour lab period. Determine the maximum solar collector efficiency for irradiance and temperature, and calculate the heat transfer coefficient at each point.

Equipment:
Solar collector assembly and stand
Two thermometers
Direct sunlight
Volume flow meter
www.wunderground.com – to measure solar irradiance

Tasks:
1. Place solar collector setup in full direct sunlight.
2. Connect the two thermometers to the inlet and outlet solar collector.
3. Every ten minutes throughout the 2 hour lab period, measure and record the solar irradiance, volume flow rate, and inlet and outlet temperatures for the zig zag collector path.
4. Go to www.wunderground.com to find the solar irradiance data for the Hogue roof.
5. Calculate the efficiency, mass flow rate, change in temperature between the inlet and outlet pipes, and the heat transfer coefficient for each set of data.
6. Plot the irradiance vs. efficiency, and temperature change vs. efficiency graphs for each condition. Record observations.

Formulas:
Mass Flow Rate (mdot) = Volume Flow Rate x Water Density
Change in Temperature (ΔT) = (Outlet Temp – Inlet Temp) + 273K
Heat Transfer Coefficient (Qdot) = mdot x Cp x ΔT
Calculated Efficiency = Qdot / (Solar Irradiance x Collector Area)

Lab Report: Due in one week. Produce an individual report in lab report format (including an introduction, materials list, procedure, results, discussion, conclusion, and appendix with raw data). Include the four graphs, with efficiency on the y axis for both. In the discussion, address the following questions:

1. Describe the two graphs for each collector path type. Are they linear? Another pattern?
2. What is the maximum efficiency under each condition?
3. How do the heat transfer coefficient and efficiency change over the two hour period? Why do these changes occur?
4. How do the calculated efficiencies compare for the two collector path types? Why?

Lab Grading:	20	Format
	20	Grammar
	40	Technical Content
	20	Effectiveness
	100	Total

The other design requirements were tested as follows:

- The collector should be able to heat water only using solar energy – no other heat source was used. Any increase in temperature was therefore entirely due to the sun.
- The collector should weigh no more than 25lbs – the collector was weighed.
- The collector should be no more than 2.5ft wide by 3ft long by 6in deep – the dimensions of the collector were measured.
- The collector should take no more than 20 hours to manufacture - See Table 13.
- The collector should cost no more than $100 to manufacture – See Appendix D (budget).
- The collector should be able to fit on the accompanying stand – the collector was transported to make sure that is securely fit to the stand.

Deliverables:

The deliverables for the testing phase of the project will take the form of data tables. As shown in the Report Appendix, Table 1 contains the timings for assembly and transportation, and clean up in regards to the collector setup. The measured variables are the timings, and these timings determine the success of the collector. Since the collector can be transported and set up/cleaned away within ten minute increments, as shown in Table 1, then the collector set up is considered to be a success.

Tables 2, 4, 6, 8, and 10 in the Report Appendix show the data tables of recorded values, which were used during testing. Note: during the MET 411 labs, both pipe paths will be tested on the same day. The principal engineer tested each pipe path for 2 hours to gather more data for testing and analysis. The measured/observed values are: solar irradiance, collector area, inlet temperature, outlet temperature, and volume flow rate. From there, the remaining values can be calculated, and all values have been recorded in the summary table, as shown in Tables 3, 5, 7, 9, and 11. In addition to the observed values, the given values are: water density, and Cp water. Finally, the calculated values are: the collector efficiency, water mass flow rate, change in temperature, and the heat transfer coefficient. These values determine if the solar thermal collector is a success. To be successful, the change in temperature has to be at least 25°K, and the calculated efficiency has to be at least 50%.

As shown in Table 3, during the testing of the curved path collector on April 8th, the calculated efficiency was above 50% at all points. Furthermore, the change in temperature was above 25°K at all points, except for the 2:10pm data point, which was at 23.7°K. This is due to the increase in flow rate. As shown, the flow rate was at 233.3mL/min, when is should have been at 150mL/min. This is due to the pump being temperamental.

As shown in Table 5, during the testing of the curved path collector on April 18th, the calculated efficiency was above 50% at all points but the first. This was likely do to the fact that the solar collector was still heating up. In addition, temperature increase between the inlet and outlet pipes was not always above 25°K. This was in part due to the solar input dropping below 800W/m^2, and also due to the pump only being stable at a higher flow rate. The pump became temperamental at the lower flow rates, and so the flow rate had to be increased for the duration of that test, reducing the time the water had to heat up while traveling through the collector. If the flow rate is too high, then the water flows through the pipes too quickly, and does not have a chance to absorb all of the heat energy that it would be able to at lower flow rates.

As shown in Table 7, during the testing of the curved path collector on April 24th, the calculated efficiency was above 50% at all points but the last two. This was likely do to the drop in irradiance. At this point, the irradiance dropped below 200W/m^2. Furthermore, the change in temperature between the inlet and outlet pipes was not always above 25°K. This is due to the drop in solar input. The pump was designed for 800W/m^2, but the data shows that on the 24th, the input never reached 800W/m^2.

As shown in Table 9, during the testing of the manifold collector on April 25th, the calculated efficiency was above 50% at all points. During this test, the solar collector was only able to achieve a temperature increase of 25°K for a couple of the data points shown. This is due to the pump. The pump was not able to maintain the low flow rates necessary for the collector to achieve its maximum capacity. As shown, the flow rates were around 300mL/min, when they should have been at 150mL/min for maximum capacity.

As shown in Table 11, during the testing of the manifold collector on May 1st, the calculated efficiency was above 50% at all points. Furthermore, the collector was able to maintain a temperature increase of 25°K for almost all of the data points. The last two were under, due to the solar input dropping below 800W/m^2 and the flow rate increasing above 150mL/min.

As shown, the collector was able to maintain an efficiency of 50% and maintain a temperature increase of 25°K for a majority of the testing points. All of the data points which fell short can be explained by either a drop in the solar irradiance below 800W/m^2 or in increase in the flow rate greatly above 150mL/min. If the incoming solar irradiance is below 800W/m^2, then the collector does not have in input that is needs to maximize its output, and it will likely fall short, as proved. Furthermore, the collector needs a flow rate of 150mL/min, because that is what is was designed for. Given its size and pipe diameters, the collector needs a flow rate of 150mL/min. Anything greater that this will move the water too quickly and reduce the capabilities of the collector. When the environmental requirements were met, the collector performed at or above spec. Therefore, the collector is a success for these two design requirements.

Figures 1-4 in the Report Appendix also demonstrate that the collector reasonably maintained an efficiency of 50%. There are a couple of points in Figures 1 and 2 which are below this benchmark. However, they can be explained by a drop in insolation, and an increase in flow rate. Figure 3 shows that there is somewhat of an upward trend between insolation and collector efficiency. However, the data does not show as much of a trend as was expected. There are likely other factors at work, such as flow rate. Figures 2 and 4 show somewhat clear trends between the change in temperature and the output efficiency. Figure 4 more so than Figure 2.

This is likely due to the equation $Qdot = IA\eta = mdotCp\Delta T$, which was used, first to find the heat transfer coefficient (Qdot) and then backtrack to find efficiency (η). The higher the change in temperature, the higher the heat transfer coefficient. Mass flow rate also plays a part in this equation, which is important to note. The higher the heat transfer coefficient, the higher the efficiency, because the surface area stayed the same. The insolation played a role too, but it changed by smaller percentages of the whole than did the temperature change. For example, a change of 20 – 30°K is a 50% increase, but a change in insolation between 820 – 830W/m^2 is only a 1.22% increase.

Now to address the other design requirements. The solar collector was not given any aid in heating the water, therefore it was powered entirely by the sun. There was a small power pack for running the pump, by the pump was only involved in the movement of the water, not in heating it up. The collector also was able to be mounted on the stand and moved around. It was therefore successful with its requirement of being compatible with the stand. The collector failed the weight test. As shown in Table 12, the collector was supposed to weigh 25lbs or less. However, the collector weighed 31.7lbs, which is 6.7lbs over spec. Weight was attempted to be reduced as much as possible, but the collector was still over spec. No more weight-cutting measures can be taken without compromising the structure or capacity of the collector. The collector was in spec for size though. As shown in Table 12, the collector measured 30.0in by 35.9in by 4.3in, which is within the limits of 30in by 36in by 6in. As shown in Appendix D in the full report, the collector was within its budget limits. The goal was for the cost to be no more than $100, and the final cost was calculated to be $84.35. However, the collector was slightly over spec for the time it took to manufacture. As shown in Table 13, the collector took 21.25 hours to manufacture, when the requirement was no more than 20 hours. Now that the prototype has been built, the principal engineer is confident that another collector could be built in 20 hours or less.

In conclusion, the collector passed a majority of the success criteria. It was able to heat water by 25°K, and do so at an efficiency of 50%, when environmental conditions were in compliance with the collector's needs. The collector was also within budget, within size limits, was compliant with the stand, could be set up and put away in less than 10 minutes, in compliance with MET 411 labs, and was powered only by the sun (for heating). However, the collector did fail two of the design requirement tests. It weighed more than the 25lbs limit, and it took more than 20 hours to manufacture. Without a full redesign, there is little that can be done for the weight issue, since weight-cutting measured were utilized. However, with more practice, future collectors could be built in less than 20 hours. Overall, the project was a success.

Report Appendix:

Table 1: Lab Time Testing

Trial	Time to Transport and Assemble	Time to Clean Up and Transport
1	6 min 35 sec	3 min 57 sec
2	5 min 21 sec	4 min 36 sec
3	5 min 1 sec	4 min 5 sec
4	5 min 47 sec	4 min 28 sec
5	6 min 3 sec	4 min 52 sec
Average	5 min 33 sec	4 min 24 sec

Table 1 shows the form that was used to record the assembly time taken by the principal to set up the lab and transport the assembly outside, and the time taken by the principal engineer to dismantle and put away the collector assembly. For assembly and clean up, only ten minutes are available. This is because, if the collector is to be used for MET 411 labs, there will only be ten minutes between classes for the lab to be set up and put away, before the next class is scheduled to start. For the collector to be successful, the principal engineer should be able to use the allocated time to adequately prepare the collector for lab, and put it away again before the following class is scheduled to begin. If the collector can be transported from the MET 411 classroom to the Hogue patio in a matter of minutes, then the solar collector can be considered easily transportable. As shown, the average set up time was 5 minutes and 33 seconds, and the average clean up time was 4 minutes and 24 seconds. Therefore, the collector is a success with regards to compliance with MET 411 labs and set up.

Table 2: Collector Efficiency Testing – Curved Path 4/8

Time	Solar Irradiance (W/m^2)	Collector Area (m^2)	Volume Flow Rate (mL/min)	Inlet Temperature (°K)	Outlet Temperature (°K)
1:30pm	803	0.643	150.0	303.6	346.3
1:40pm	798	0.643	133.3	303.1	356.3
1:50pm	793	0.643	150.0	303.5	342.6
2:00pm	780	0.643	116.7	303.8	337.8
2:10pm	765	0.643	233.3	302.5	326.2
2:20pm	745	0.643	150.0	304.1	340.0
2:30pm	722	0.643	183.3	301.7	335.9

Table 2 shows the lab data form that will be used during the lab to analyze the output efficiency of the solar collector. The solar irradiance, collector area, volume flow rate, and temperature change will all be measured during labs, and were all measured during testing. The area of the collector, the density of water, and Cp water will all be given. From there, the collector output efficiency, mass flow rate, and heat transfer coefficient can all be calculated.

Table 3: Collector Efficiency Results Summary – Curved Path 4/8

Time	Solar Irradiance (W/m^2) (I)	Collector Area (m^2) (A)	Calculated Efficiency (η)	Volume Flow Rate (mL/min) (vdot)	Water Density (kg/m^3) (ρ)	Mass Flow Rate (kg/s) (mdot)	Cp Water (kJ/kg K) (Cp)	Change in Temp (°K) (ΔT)	Heat Transfer Coefficient (W) (Qdot)
Obtained	Measured with www.wunderground.com	Measured with ruler	Calculated: η = Qdot/(IA)	Measured with flow meter	Given	Calculated: mdot = (vdot)(ρ)/ 60000	Given	Measured between inlet and outlet	Calculated: Qdot = (mdot)(Cp)(ΔT)
1:30pm	803	0.643	0.854	150.0	0.988	0.0025	4.18	42.7	440.86
1:40pm	798	0.643	0.952	133.3	0.988	0.0022	4.18	53.2	488.24
1:50pm	793	0.643	0.792	150.0	0.988	0.0025	4.18	39.1	403.69
2:00pm	780	0.643	0.544	116.7	0.988	0.0019	4.18	34.0	273.03
2:10pm	765	0.643	0.774	233.3	0.988	0.0038	4.18	23.7	380.63
2:20pm	745	0.643	0.774	150.0	0.988	0.0025	4.18	35.9	370.65
2:30pm	722	0.643	0.930	183.3	0.988	0.0030	4.18	34.2	431.57

Table 3 shows the results summary for determining the efficiency, mass flow rate, and heat transfer coefficient of the solar collector. The equations for calculating these values are shown. The values calculated will determine whether or not the solar collector met the performance predictions. These results show the data that was collected for the curved pipe path on April 8th 2016. There is only one hour's worth of data, because the pump gave out. A filter was later installed and the pump now works properly. As shown, the calculated efficiency was above 50% at all points. Furthermore, the change in temperature was above 25°K at all points, except for the 2:10pm data point. This is due to the flow rate increase.

Table 4: Collector Efficiency Testing – Curved Path 4/18

Time	Solar Irradiance (W/m^2)	Collector Area (m^2)	Volume Flow Rate (mL/min)	Inlet Temperature (°K)	Outlet Temperature (°K)
1:00pm	840	0.643	158.3	303.8	326.85
1:10pm	842	0.643	141.7	305.3	341.45
1:20pm	842	0.643	166.7	304.9	340.45
1:30pm	842	0.643	166.7	301.8	337.55
1:40pm	844	0.643	150.0	300.4	333.95
1:50pm	838	0.643	200.0	300.2	325.15
2:00pm	830	0.643	333.3	301.8	314.95
2:10pm	824	0.643	366.7	301.6	314.85
2:20pm	811	0.643	333.3	301.2	314.65
2:30pm	800	0.643	533.3	301.7	310.25
2:40pm	784	0.643	533.3	302.7	311.75
2:50pm	774	0.643	533.3	302.5	311.45

Table 4 shows the lab data form that will be used during the lab to analyze the output efficiency of the solar collector. The solar irradiance, collector area, volume flow rate, and temperature change will all be measured during labs, and were all measured during testing. The area of the collector, the density of water, and Cp water will all be given. From there, the collector output efficiency, mass flow rate, and heat transfer coefficient can all be calculated.

Table 5: Collector Efficiency Results Summary – Curved Path 4/18

Time	Solar Irradiance (W/m^2) (I)	Collector Area (m^2) (A)	Calculated Efficiency (η)	Volume Flow Rate (mL/min) (vdot)	Water Density (kg/m^3) (ρ)	Mass Flow Rate (kg/s) (mdot)	Cp Water (kJ/kg K) (Cp)	Change in Temp (°K) (ΔT)	Heat Transfer Coefficient (W) (Qdot)
Obtained	Measured with www.wunderground.com	Measured with ruler	Calculated: η = Qdot/(IA)	Measured with flow meter	Given	Calculated: mdot = (vdot)(ρ)/ 60000	Given	Measured between inlet and outlet	Calculated: Qdot = (mdot)(Cp)(ΔT)
1:00pm	840	0.643	0.466	158.3	.988	0.0026	4.18	23.1	251.75
1:10pm	842	0.643	0.652	141.7	.988	0.0023	4.18	36.2	352.99
1:20pm	842	0.643	0.754	166.7	.988	0.0027	4.18	35.6	408.40
1:30pm	842	0.643	0.759	166.7	.988	0.0027	4.18	35.8	410.69
1:40pm	844	0.643	0.639	150.0	.988	0.0025	4.18	33.6	346.91
1:50pm	838	0.643	0.639	200.0	.988	0.0033	4.18	25.0	344.15
2:00pm	830	0.643	0.567	333.3	.988	0.0055	4.18	13.2	302.85
2:10pm	824	0.643	0.634	366.7	.988	0.0060	4.18	13.3	335.66
2:20pm	811	0.643	0.594	333.3	.988	0.0055	4.18	13.5	309.74
2:30pm	800	0.643	0.614	533.3	.988	0.0088	4.18	8.6	315.70
2:40pm	784	0.643	0.663	533.3	.988	0.0088	4.18	9.1	334.06
2:50pm	774	0.643	0.664	533.3	.988	0.0088	4.18	9.0	330.39

Table 5 shows the results summary for determining the efficiency, mass flow rate, and heat transfer coefficient of the solar collector. The equations for calculating these values are shown. The values calculated will determine whether or not the solar collector met the performance predictions. These results show the data that was collected for the curved pipe path on April 18th 2016. There is only one hour's worth of data, because the pump gave out. A filter was later installed and the pump now works properly. As shown, the calculated efficiency was above 50% at all points but the first. This was likely do to the fact that the solar collector was still heating up. Furthermore, the temperature change between the inlet and outlet pipes was not always above 25°K. This was in part due to the solar input dropping below 800W/m^2, and also due to the pump only being stable at a higher flow rate. The pump became temperamental at the lower flow rates, and therefore the flow rate had to be increased, reducing the time the water had to heat up while traveling through the collector.

Table 6: Collector Efficiency Testing – Curved Path 4/24

Time	Solar Irradiance (W/m^2)	Collector Area (m^2)	Volume Flow Rate (mL/min)	Inlet Temperature (°K)	Outlet Temperature (°K)
1:50pm	705	0.643	150.0	301.9	339.9
2:00pm	612	0.643	200.0	296.9	322.2
2:10pm	519	0.643	300.0	299.3	310.7
2:20pm	443	0.643	300.0	296.5	304.7
2:30pm	356	0.643	350.0	297.3	305.9
2:40pm	176	0.643	333.3	294.2	296.2
2:50pm	137	0.643	333.3	293.2	295.2

Table 6 shows the lab data form that will be used during the lab to analyze the output efficiency of the solar collector. The solar irradiance, collector area, volume flow rate, and temperature change will all be measured during labs, and were all measured during testing. The area of the collector, the density of water, and Cp water will all be given. From there, the collector output efficiency, mass flow rate, and heat transfer coefficient can all be calculated.

Table 7: Collector Efficiency Results Summary – Curved Path 4/24

Time	Solar Irradiance (W/m^2) (I)	Collector Area (m^2) (A)	Calculated Efficiency (η)	Volume Flow Rate (mL/min) (vdot)	Water Density (kg/m^3) (ρ)	Mass Flow Rate (kg/s) (mdot)	Cp Water (kJ/kg K) (Cp)	Change in Temp (°K) (ΔT)	Heat Transfer Coefficient (W) (Qdot)
Obtained	Measured with www.wunderground.com	Measured with ruler	Calculated: η = Qdot/(IA)	Measured with flow meter	Given	Calculated: mdot = (vdot)(ρ)/ 60000	Given	Measured between inlet and outlet	Calculated: Qdot = (mdot)(Cp)(ΔT)
1:50pm	705	0.643	0.865	150.0	0.988	0.002470	4.18	38.0	392.33
2:00pm	612	0.643	0.885	200.0	0.988	0.003293	4.18	25.3	348.28
2:10pm	519	0.643	0.705	300.0	0.988	0.004940	4.18	11.4	235.40
2:20pm	443	0.643	0.594	300.0	0.988	0.004940	4.18	8.2	169.32
2:30pm	356	0.643	0.905	350.0	0.988	0.005763	4.18	8.6	207.18
2:40pm	176	0.643	0.405	333.3	0.988	0.005489	4.18	2.0	45.89
2:50pm	137	0.643	0.521	333.3	0.988	0.005489	4.18	2.0	45.89

Table 7 shows the results summary for determining the efficiency, mass flow rate, and heat transfer coefficient of the solar collector. The equations for calculating these values are shown. The values calculated will determine whether or not the solar collector met the performance predictions. These results show the data that was collected for the curved pipe path on April 24th 2016. There is only one hour's worth of data, because it got too cloudy. The experiment also started late due to a scheduling conflict. As shown, the calculated efficiency was above 50% at all points but the last two. This was likely do to the drop in irradiance. Furthermore, the change in temperature between the inlet and outlet pipes was not always above 25°K. This is due to the drop in solar input. The pump was designed for 800W/m^2, but the data shows that on the 24th, the input never reached 800W/m^2.

Table 8: Collector Efficiency Testing – Manifold Path 4/25

Time	Solar Irradiance (W/m^2)	Collector Area (m^2)	Volume Flow Rate (mL/min)	Inlet Temperature (°K)	Outlet Temperature (°K)
1:00pm	875	0.643	300.0	299.3	321.0
1:10pm	868	0.643	300.0	299.3	322.2
1:20pm	862	0.643	300.0	298.5	324.6
1:30pm	872	0.643	300.0	298.2	314.2
1:40pm	863	0.643	283.3	297.5	320.6
1:50pm	860	0.643	283.3	299.2	317.5
2:00pm	856	0.643	233.3	298.3	321.2
2:10pm	844	0.643	150.0	296.8	324.5
2:20pm	840	0.643	166.7	297.9	326.4
2:30pm	830	0.643	333.3	296.9	311.2
2:40pm	789	0.643	300.0	297.7	310.7
2:50pm	785	0.643	333.3	297.6	310.5

Table 8 shows the lab data form that will be used during the lab to analyze the output efficiency of the solar collector. The solar irradiance, collector area, volume flow rate, and temperature change will all be measured during labs, and were all measured during testing. The area of the collector, the density of water, and Cp water will all be given. From there, the collector output efficiency, mass flow rate, and heat transfer coefficient can all be calculated.

Table 9: Collector Efficiency Results Summary – Manifold Path 4/25

Time	Solar Irradiance (W/m^2) (I)	Collector Area (m^2) (A)	Calculated Efficiency (η)	Volume Flow Rate (mL/min) (vdot)	Water Density (kg/m^3) (ρ)	Mass Flow Rate (kg/s) (mdot)	Cp Water (kJ/kg K) (Cp)	Change in Temp (°K) (ΔT)	Heat Transfer Coefficient (W) (Qdot)
Obtained	Measured with www.wunderground.com	Measured with ruler	Calculated: η = Qdot/(IA)	Measured with flow meter	Given	Calculated: mdot = (vdot)(ρ)/60000	Given	Measured between inlet and outlet	Calculated: Qdot = (mdot)(Cp)(ΔT)
1:00pm	875	0.643	0.796	300.0	0.988	0.0049	4.18	21.7	448.09
1:10pm	868	0.643	0.847	300.0	0.988	0.0049	4.18	22.9	472.87
1:20pm	862	0.643	0.972	300.0	0.988	0.0049	4.18	26.1	538.94
1:30pm	872	0.643	0.589	300.0	0.988	0.0049	4.18	16.0	330.39
1:40pm	863	0.643	0.812	283.3	0.988	0.0047	4.18	23.1	450.50
1:50pm	860	0.643	0.645	283.3	0.988	0.0047	4.18	18.3	356.89
2:00pm	856	0.643	0.668	233.3	0.988	0.0038	4.18	22.9	367.79
2:10pm	844	0.643	0.527	150.0	0.988	0.0025	4.18	27.7	285.99
2:20pm	840	0.643	0.605	166.7	0.988	0.0027	4.18	28.5	326.95
2:30pm	830	0.643	0.615	333.3	0.988	0.0055	4.18	14.3	328.09
2:40pm	789	0.643	0.529	300.0	0.988	0.0049	4.18	13.0	268.44
2:50pm	785	0.643	0.586	333.3	0.988	0.0055	4.18	12.9	295.97

Table 9 shows the results summary for determining the efficiency, mass flow rate, and heat transfer coefficient of the solar collector. The equations for calculating these values are shown. The values calculated will determine whether or not the solar collector met the performance predictions. These results show the data that was collected for the curved pipe path on April 25th 2016. There is only one hour's worth of data, because the pump gave out. A filter was later installed and the pump now works properly. As shown, the calculated efficiency was above 50% at all points. During this test, the solar collector was only able to achieve a temperature increase of 25°K for a couple of the data points shown. This is due to the pump. The pump was not able to maintain the low flow rates necessary for the collector to achieve its maximum capacity. As shown, the flow rates were around 300mL/min, when they should have been at 150mL/min for maximum capacity.

Table 10: Collector Efficiency Testing – Manifold Path 5/1

Time	Solar Irradiance (W/m^2)	Collector Area (m^2)	Volume Flow Rate (mL/min)	Inlet Temperature (°K)	Outlet Temperature (°K)
1:30pm	875	0.643	166.7	298.6	330.1
1:40pm	872	0.643	166.7	298.6	333.1
1:50pm	873	0.643	150.0	298.9	337.7
2:00pm	861	0.643	150.0	299.7	342.2
2:10pm	847	0.643	166.7	300.1	337.1
2:20pm	841	0.643	166.7	300.3	327.3
2:30pm	833	0.643	150.0	299.3	326.2
2:40pm	814	0.643	150.0	300.0	333.3
2:50pm	805	0.643	150.0	300.3	330.3
3:00pm	798	0.643	166.7	300.9	331.6
3:10pm	775	0.643	183.3	300.3	321.1
3:20pm	760	0.643	183.3	300.0	321.2

Table 10 shows the lab data form that will be used during the lab to analyze the output efficiency of the solar collector. The solar irradiance, collector area, volume flow rate, and temperature change will all be measured. The area of the collector, the density of water, and Cp water will all be given. From there, the collector output efficiency, mass flow rate, and heat transfer coefficient can all be calculated.

Table 11: Collector Efficiency Results Summary – Manifold Path 5/1

Time	Solar Irradiance (W/m^2) (I)	Collector Area (m^2) (A)	Calculated Efficiency (η)	Volume Flow Rate (mL/min) (vdot)	Water Density (kg/m^3) (ρ)	Mass Flow Rate (kg/s) (mdot)	Cp Water (kJ/kg K) (Cp)	Change in Temp (°K) (ΔT)	Heat Transfer Coefficient (W) (Qdot)
Obtained	Measured with www.wunderground.com	Measured with ruler	Calculated: η = Qdot/(IA)	Measured with flow meter	Given	Calculated: mdot = (vdot)(ρ)/ 60000	Given	Measured between inlet and outlet	Calculated: Qdot = (mdot)(Cp) (ΔT)
1:30pm	875	0.643	0.642	166.7	.988	0.0027	4.18	31.5	361.36
1:40pm	872	0.643	0.706	166.7	.988	0.0027	4.18	34.5	395.78
1:50pm	873	0.643	0.714	150.0	.988	0.0025	4.18	38.8	400.59
2:00pm	861	0.643	0.793	150.0	.988	0.0025	4.18	42.5	438.80
2:10pm	847	0.643	0.779	166.7	.988	0.0027	4.18	37.0	424.46
2:20pm	841	0.643	0.573	166.7	.988	0.0027	4.18	27.0	309.74
2:30pm	833	0.643	0.519	150.0	.988	0.0025	4.18	26.9	277.73
2:40pm	814	0.643	0.657	150.0	.988	0.0025	4.18	33.3	343.81
2:50pm	805	0.643	0.598	150.0	.988	0.0025	4.18	30.0	309.74
3:00pm	798	0.643	0.686	166.7	.988	0.0027	4.18	30.7	352.18
3:10pm	775	0.643	0.527	183.3	.988	0.0030	4.18	20.8	262.47
3:20pm	760	0.643	0.547	183.3	.988	0.0030	4.18	21.2	267.52

Table 11 shows the results summary for determining the efficiency, mass flow rate, and heat transfer coefficient of the solar collector. These results show the data that was collected for the curved pipe path on May 1st 2016. There is only one hour's worth of data, because the pump gave out. A filter was later installed and the pump now works properly. As shown, the calculated efficiency was above 50% at all points. Furthermore, the collector was able to maintain a temperature increase of 25°K for almost all of the data points. The last two were under, due to the solar input dropping below 800W/m^2 and the flow rate increasing above 150mL/min.

Table 12: Collector Measurements

Measurement	Specification Limit	Actual
Collector Weight	25lbs	31.7lbs
Collector Width	30in	30.0in
Collector Length	36in	35.9in
Collector Depth	6in	4.3in

Table 12 shows the collector specifications that were measured during testing. As shown, the collector was within spec for size, but not for weight.

Table 13: Time Log

Description of Activity	Time Taken to Complete
Size and cut four frame sides	2 hours
Size and cut insulation	0.25 hour
Size and cut Plywood Backing	0.25 hour
Size and cut plastic cover	0.25 hour
Assemble backing, and four frame sides	2 hours
Size and cut copper sheet components	1 hour
Bend copper for curved piping path	1 hour
Size and cut large manifold header pipes	0.25 hour
Size and cut small manifold header pipes	2 hours
Assemble manifold header pipes - drill	1.5 hours
Solder manifold pipes to header pipes	1.5 hours
Size and cut collector tubing	0.5 hour
Solder pipes to copper sheet	3 hours
Size and cut manifold backing	0.25 hour
Assemble manifold piping assembly	1 hour
Cut slots in the frame	0.5 hour
Cut and bend aluminum sidings	0.25 hour
Paint collector black	1.5 hours
Attach connecting bar	0.25 hour
Solder/attach fitting to inlet and outlet collector pipes	0.25 hour
Attach the aluminum sidings to the collector	0.25 hour
Connect piping path	1.5 hours
Total	21.25 hours

Table 13 shows the list of tasks completed during the manufacturing phase, and the time it took to complete each task. The goal was for the entire construction process to take less than 20 hours, but the total time is 21.25 hours. This means that the collector failed this requirement.

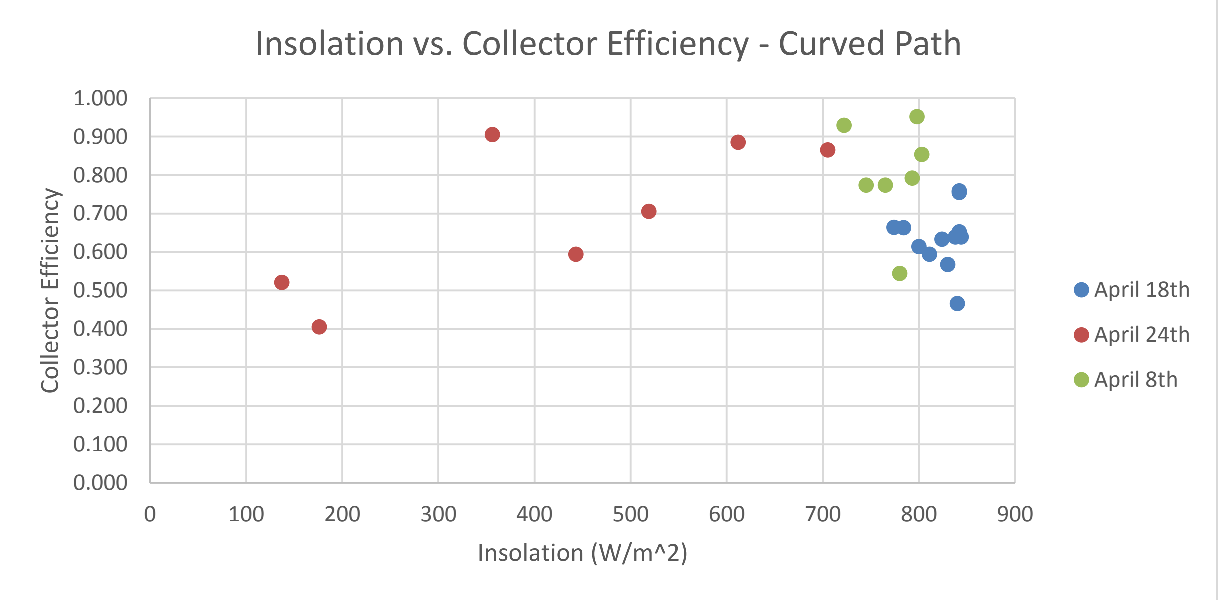


Figure 1: Insolation vs. Collector Efficiency Graph for the Curved Collector Path
Figure 1 shows that there wasn't a consistent trend between the incoming solar insolation and the collector efficiency. There is somewhat of a trend to the data from April 24th, however, there is not enough data to be conclusive. Therefore, there is no substantial evidence to show whether or not the insolation played a role solely on the collector efficiency. The graph does show that all but two of the data points demonstrate efficiencies of 50% or higher. The point on the left was below 50% due to the low insolation, and the point in the right is likely due to a high flow rate.

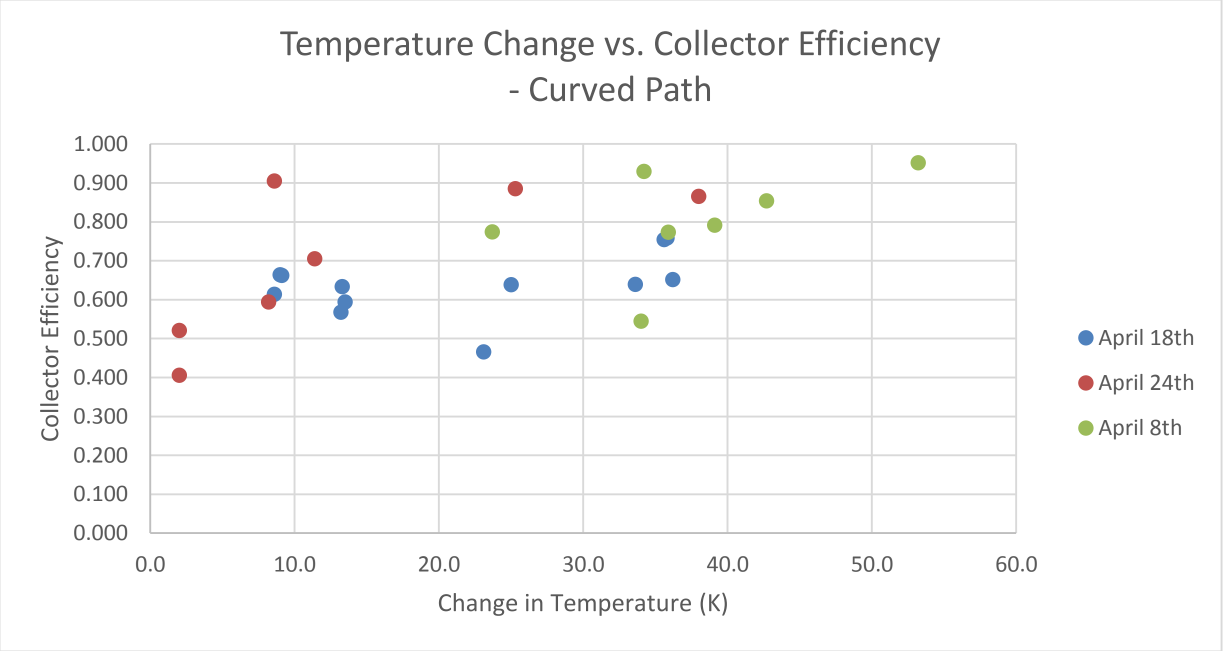


Figure 2: Temperature Change vs. Collector Efficiency Graph for the Curved Collector Path
Figure 2 shows somewhat of an upward sloping trend between the change in temperature and the collector efficiency. The graph does show that all but two of the data points achieved 50% efficiency or greater. These are the same two points mentioned with Figure 1.

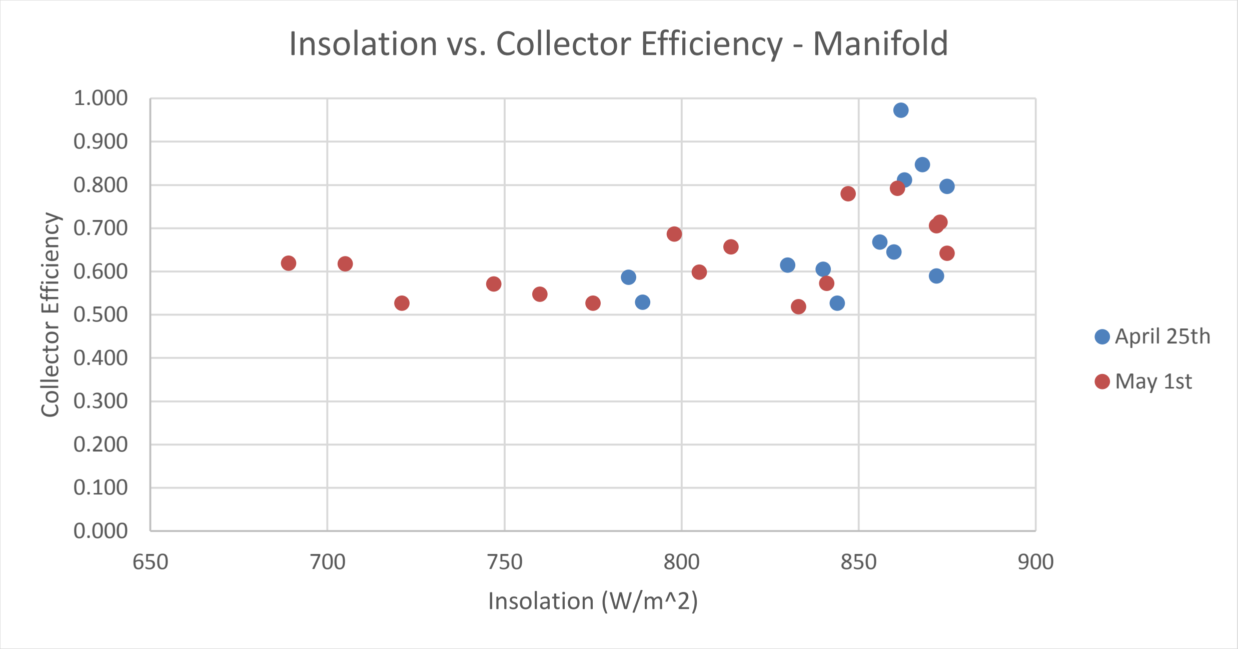


Figure 3: Insolation vs. Collector Efficiency Graph for the Manifold Path

Figure 3 shows that there is somewhat of a consistency in the collector efficiency regardless of the solar input. This was unexpected. This shows that the solar insolation may not be the largest factor in determining the collector efficiency. The collector seems to be able to maintain the same output efficiency, regardless of the input. The graph also shows that all of the recorded points show efficiencies of greater than 50% as per the success criteria.

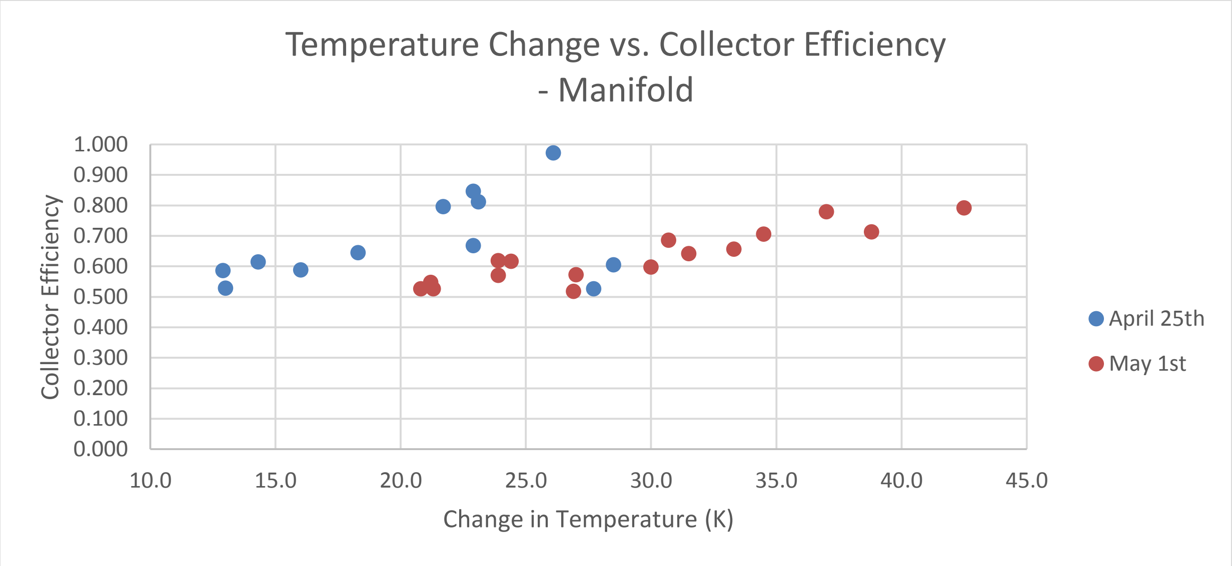


Figure 4: Temperature Change vs. Collector Efficiency Graph for the Manifold Path

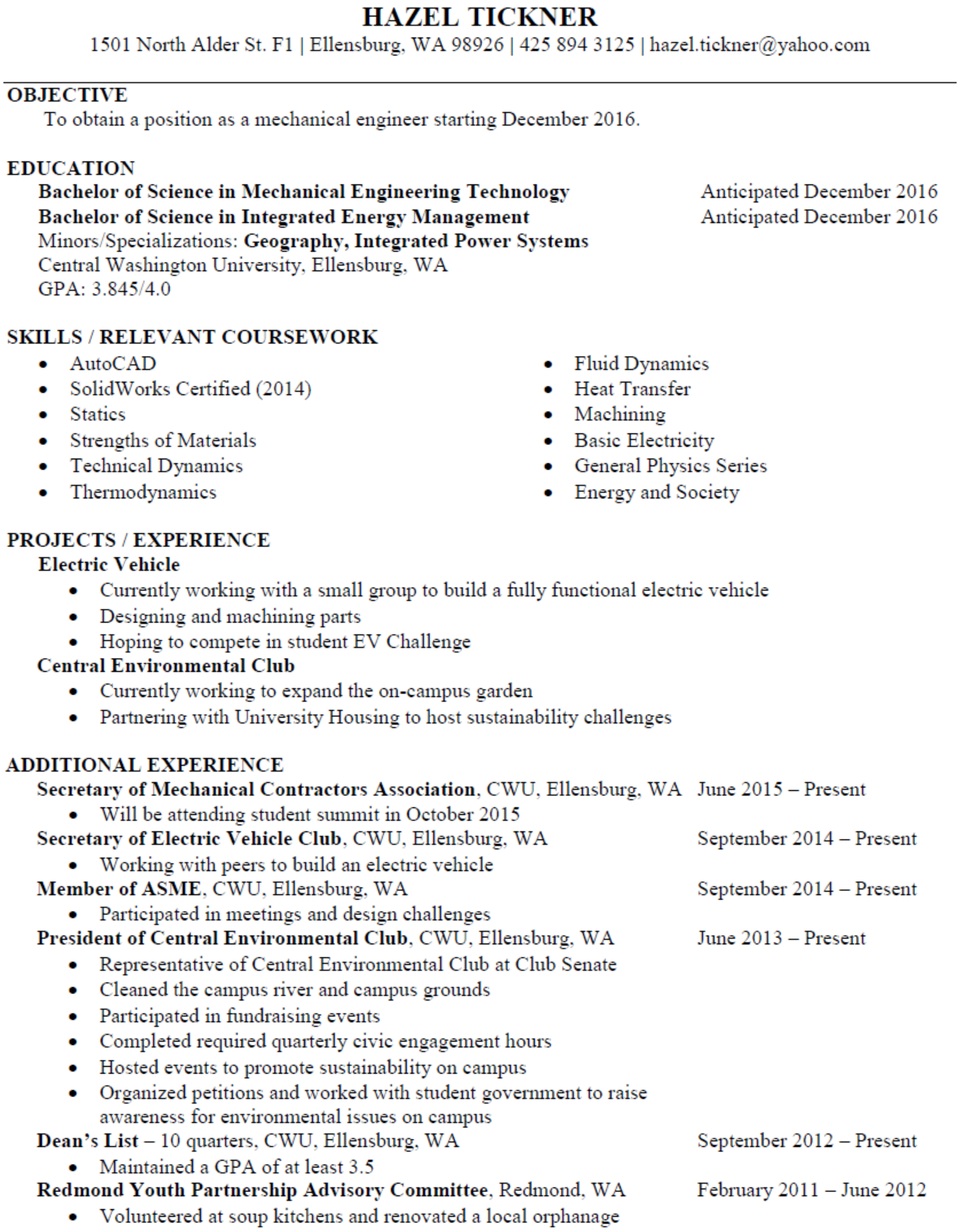
Figure 4 shows two somewhat consistent trends between the change in temperature and the collector efficiency. This is probably due to the equation Qdot = IAη = mdotCpΔT. The higher the change in temperature, the higher the heat transfer coefficient (Qdot). Flow rate also plays a part in this equation. The higher the heat transfer coefficient, the higher the efficiency, because the surface area stayed the same. The insolation played a role too, but it changed by smaller percentages of the whole than the temperature change altered throughout testing. For example, a change of 20 – 40°K is a 100% increase, but a change in insolation between 750 – 850W/m^2 is only a 13.3% increase.

Procedure Checklist:

- ☐ Gather materials.
  - Collector on stand
  - Full water tank
  - Power source
  - Extension cord
  - Thermocouples
  - Insulation – Styrofoam wrapping
  - Tape
  - Data tables
  - Stopwatch
  - Plus a couple of volunteers
- ☐ Start timer and transport collector and materials to the Hogue patio.
- ☐ Set up the collector system as outlined in the lab set up instructions above, and stop timer.
- ☐ Record transport and set up time.
- ☐ Run the pump with the collector facing the sun.
- ☐ Adjust the flow rate until it is close to 150mL/min, or 9L/hour
- ☐ Measure and record the inlet and outlet temperatures as well as the volume flow rate and Solar input every ten minutes over the course of two hours.
- ☐ Measure and record the incoming irradiance with www.wunderground.com
- ☐ Start timer and pack up the materials.
- ☐ Transport collector and materials back to the store cupboard and stop timer.
- ☐ Record clean up and transport time.
- ☐ Weigh the collector.
- ☐ Measure and record the collector dimensions.
- ☐ The time to manufacture the collector was recorded during winter quarter
- ☐ The cost of each component was recorded during winter quarter, and can be found in Appendix D in the full report.

APPENDIX J

Figure J1: Resume



HAZEL TICKNER

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OBJECTIVE

To obtain a position as a mechanical engineer starting December 2016.

EDUCATION

Bachelor of Science in Mechanical Engineering Technology Anticipated December 2016
Bachelor of Science in Integrated Energy Management Anticipated December 2016
Minors/Specializations: **Geography, Integrated Power Systems**
Central Washington University, Ellensburg, WA
GPA: 3.845/4.0

SKILLS / RELEVANT COURSEWORK

- AutoCAD
- SolidWorks Certified (2014)
- Statics
- Strengths of Materials
- Technical Dynamics
- Thermodynamics
- Fluid Dynamics
- Heat Transfer
- Machining
- Basic Electricity
- General Physics Series
- Energy and Society

PROJECTS / EXPERIENCE

Electric Vehicle

- Currently working with a small group to build a fully functional electric vehicle
- Designing and machining parts
- Hoping to compete in student EV Challenge

Central Environmental Club

- Currently working to expand the on-campus garden
- Partnering with University Housing to host sustainability challenges

ADDITIONAL EXPERIENCE

Secretary of Mechanical Contractors Association, CWU, Ellensburg, WA June 2015 – Present

- Will be attending student summit in October 2015

Secretary of Electric Vehicle Club, CWU, Ellensburg, WA September 2014 – Present

- Working with peers to build an electric vehicle

Member of ASME, CWU, Ellensburg, WA September 2014 – Present

- Participated in meetings and design challenges

President of Central Environmental Club, CWU, Ellensburg, WA June 2013 – Present

- Representative of Central Environmental Club at Club Senate
- Cleaned the campus river and campus grounds
- Participated in fundraising events
- Completed required quarterly civic engagement hours
- Hosted events to promote sustainability on campus
- Organized petitions and worked with student government to raise awareness for environmental issues on campus

Dean's List – 10 quarters, CWU, Ellensburg, WA September 2012 – Present

- Maintained a GPA of at least 3.5

Redmond Youth Partnership Advisory Committee, Redmond, WA February 2011 – June 2012

- Volunteered at soup kitchens and renovated a local orphanage