# Design, Construction, and Test of a Miniature Parabolic Trough Solar Concentrator

Donald Jeremy Gaitan

Cal Poly, San Luis Obispo, CA

Fall Quarter 2012

Project Advisor: Dr. Lanny Griffin

# Abstract

This report describes the creation of a senior project. It recounts the steps taken from the initial design stages and choice of a parabolic trough solar concentrator, through the building process, and finally through the test stages of the project. The objective of the project was to test the capabilities of a Cal Poly trained engineer by performing a completely self guided process of designing, building, and testing a parabolic solar collection trough. This particular trough was designed to utilize the energy provided by the sun to heat water. The test results were compared with a mathematical model drafted during the design stage. Due to restrictions of cost and space, a miniature version of typical parabolic troughs used today was made. Because of the small scale of the project, actual use of the parabolic trough to heat water would not be feasible, although testing showed consistency with initial mathematical modeling.

# Table of Contents

# Figures

# Background

The idea behind a concentrating solar collector is to minimize the heat losses associated with solar collection. In many instances it is desirable to deliver energy at higher temperatures than those possible with flat plate solar collectors. In this case, a parabolic "mirror" concentrates incident solar irradiation onto a much smaller receiver area, greatly decreasing heat loss and maximizing the available energy from the sun.

There are many different types of concentrating solar collectors in use today. Concentrators can be reflecting or refracting, cylindrical, spherical, parabolic, and they can be continuous or segmented. Receivers can be convex, flat, cylindrical, covered or uncovered. Because of the complexity and very wide scope of concentrators and concentrator designs, it is difficult to find developed general analyses of each specific type of concentrator. Therefore each solar concentrator design must be studied on a per case basis (Duffie, 324).

One important factor in the analysis of solar concentrators is the concentration ratio. The concentration ratio is defined as the ratio of the area of the aperture of the concentrator to the area of the receiver that is reflected upon by the concentrator. This is in essence the heart of a solar concentrator. Solar tracking is also necessary for efficient use of concentrating collectors. Without tracking the collector becomes almost useless except for a very short time period once a day. Large scale concentrators today use automated tracking systems that can track the sun on a biaxial path (Powell, 138-139). Due to cost restrictions and complexity, and the small scale of this project, manual turning of the concentrator was chosen as the preferred method of solar tracking.

The future of concentrating solar collectors will rely greatly on improved engineering, design, and materials. It is very important to maintain the quality of the optical systems of solar concentrators for long periods of time. This includes accounting for weather, dirt, and corrosion amongst other things (Eames, 748). The goal of this project is to design, build, model, and test a concentrating solar collector.

# Design

The initial plan for a solar concentrator was to use a semi-spherical surface covered with many small sections of mirror to form a segmented, spherical concentrator. Referring to the optics section of a University Physics textbook it was found that the focal point of a spherical mirror would be located at a distance of half of the radius of the spherical section, directly above the vertex of the sphere. Quite some time was spent on trying to find a way to orient the small mirror sections at the proper angles about the inner surface of the sphere. The initial thought was to take the derivative of a circular equation to find the proper incline at different points along the sphere's inner surface. These inclines would then be rotated about the origin. This was a difficult problem considering the limited resources. A different approach was taken.

After conducting more research on solar energy and solar collection, the decision was made to attempt to build a parabolic trough solar concentrator. In a parabola all of the incoming rays from a light source (in this case the sun) are reflected back to the focal point of the parabola. If the said parabola is extended along an axis (becoming a trough) the solar rays are concentrated along a line through the focal point of the trough. The focal point of a parabola is located at $1/4a$ , if the equation of the parabola is $y = ax^2$ (Young, 1157).

The parabolic trough selected fit the equation $y = .04167x^2$ from $x = -12$ inches to $x = 12$ inches. This equation was chosen to yield a focal point located at 6 inches above the vertex of the parabola, for ease of construction. Initial sketches and drawings are located in Appendix A.

A mathematical model was developed that would help determine the temperature of the water leaving the parabolic trough, knowing the temperature of the water entering the trough and the amount of insolation absorbed by the receiver. These calculations can be found in Appendix B.

The frame for the parabola was made out of plywood. It would be attached to a base which would allow for proper angling of the parabolic trough. The entire collector was small enough to allow for easy manual adjustment for solar tracking. The receiver chosen was a simple, half-inch copper pipe, painted black to absorb more incident radiation. Copper was chosen because of its high thermal conductivity and it is relatively inexpensive. The water source was planned as a reservoir located above the trough, with gravity assisted flow through the trough, to another reservoir used for collection of the heated water. These were going to be fifty gallon drums. But, based on the location of testing, a simple garden hose was used with a compression fitting to attach the hose to the copper pipe. This proved to be easier and more efficient, as well as significantly less expensive.

A piece of polished Aluminum was used for the reflective surface. A reasonably priced piece of aluminum was found at a website called OnlineMetals.com. This is a small quantity metals supplier owned by ThyssenKrupp. A 36 inch by 48 inch piece of 6061-T6 Aluminum, .020 inch thick was selected. With the design stage complete construction began.

# Construction

The plan for construction consisted of the following. Based on the initial design sketches materials were bought at Home Depot. A 4 foot by 8 foot sheet of 23/32 inch outdoor plywood, four 8 foot 2 by 4's, a five foot long piece of ½ inch copper pipe, black heat resistant spray paint, a can of spray on insulation, a carpenters square, an aluminum meter stick, measuring tape, and three boxes of different types of screws (1.25 inch wood screws, 2 inch wood screws, and 0.5 inch screws) were purchased.

The next step consisted of carefully drawing a grid of 1 inch squares on the plywood sheet, followed by a sub-grid of half inch squares. An origin and x and y axes were chosen, and the points of the parabola were plotted (Figure 1). Next the 2 by 4's were measured and marked at the proper lengths. Drawings and dimensions can be found in Appendix A.

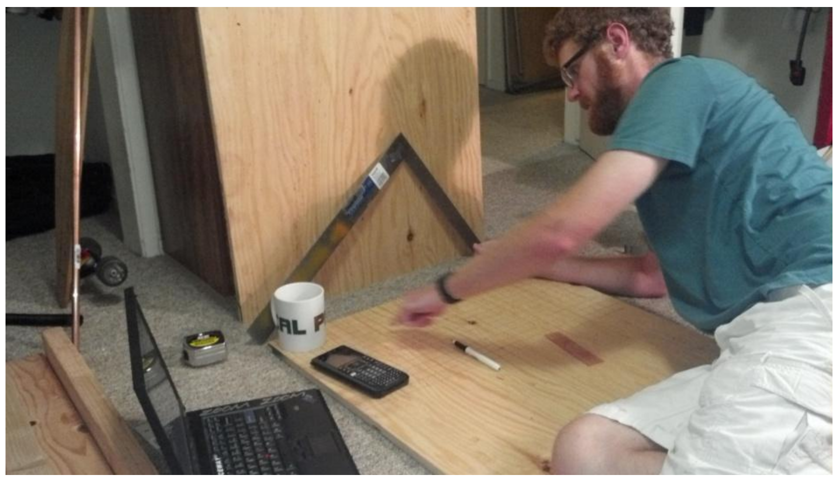


*Figure 1: Forming the grid and the parabolic shape*

The dimensioned pieces of wood were brought to the woodshop at the Cal Poly Hangar. The table saw was used to cut the plywood grid into two pieces of the same size. The plan was to attach these two pieces, one atop the other, and cut them at the same time with a band saw. Consulting with two different shop techs at the hanger, it was concluded that the best method would be to cut one piece and use that as a template for the next piece. Also, the position of the band saw would make cutting the plywood difficult, so a jigsaw was used instead. Next the 2 by 4's were cut at the proper lengths using the miter saw. Finally, the two pieces of the parabolic frame plywood were attached and sanded to achieve the best possible parabolic curve. A half inch hole was drilled in each frame piece to serve as the point of rotation for angling of the trough, and the attachment to the base.

Next an attempt was made to attach two of the 2 by 4's to the outer edges of the parabolic frame pieces. One of the 2 by 4's had warped at some point, preventing the attachment of the two frame pieces. The warped board was discarded. It was then decided to use just one 2 by 4 to attach the two parabolic frame pieces. This proved to work out well. The 2 by 4 was attached to the rectangular base of the parabolic frames with three 2 inch screws on each side. It worked out to be a strong connection.

To build the base of the solar collector two partial triangles were cut from the remaining plywood. Then, with three of the pre-cut 2 by 4's the partial triangles were attached. Two small pieces of plywood were attached to each base plywood triangle and the top 2 by 4 for extra support. To these small rectangles of plywood two more pieces of plywood were attached, each with half inch holes drilled in them. These served as the points of attachment for the parabolic frame.

To attach the Aluminum sheet to the frame, it was cut into the proper size rectangle using the hangar's sheet metal cutter. Holes were drilled along the edges at increments of 2 inches to serve as places to screw the Aluminum to the plywood frame. The Aluminum sheet's polished side was protected by a plastic film. This film was left on the Aluminum sheet until immediately before testing. Next the Aluminum sheet was manually bent down into the parabolic frame and attached with the 0.5 inch screws. Some trouble was encountered here because the Aluminum wasn't rigid enough to hold a consistent shape between the two frame pieces. It was too late to create another frame piece to help support the Aluminum, so it was decided that the Aluminum sheet could be supported in between the frames by attaching two 2 by 4's to the inside of the frame and securing them with screws. The problem was solved and the Aluminum parabola seemed to be nearly perfect.

The next items purchased included two pipe clamps, a compression fitting for the ½ inch copper pipe, a straight coupling to attach the compression fitting to a standard garden hose, PTFE thread seal tape, and two ½ inch bolts with nuts and washers. More plywood was measured and cut to attach to the sides of the parabolic frame. These pieces were for attaching the pipe clamps and running the copper pipe through the focal point of the parabola. Finally, two 1/16 inch holes were drilled in the copper pipe at the inlet and outlet for placement of thermocouples. The copper pipe was sanded lightly and sprayed with flat black paint.

*Figure 2: Completed Solar Concentrator*

Having finished the construction, all that was left was putting it all together. The pieces were brought to the test site, and using the bolts, nuts, and washers the trough was attached to the base. The pipe clamps were loosened to attach the painted copper pipe to the trough. The threading of a garden hose was wrapped with PTFE tape and attached to the compression fitting on the end of the copper pipe. The solar concentrator was ready for testing.

# Testing

*Figure 3: Vernier Lab Cradle with TI-nSpire CX CAS*

In order to test the solar concentrator testing equipment needed to be purchased. The first things needed were thermocouples. Online research led to the discovery of a company called Vernier Technology. Through this company a TI-nSpire Lab Cradle to connect with a TI-nSpire CX CAS calculator (Figure 3) were purchased. The lab cradle has five ports for different sensors. Two thermocouples to attach to the lab cradle were also purchased. The TI-nSpire CX calculator had software from Vernier pre-loaded, so all that was necessary was to attach the calculator to the lab cradle and plug in the two thermocouples. An initial experiment showed that everything seemed to be working fine. Next a pyranometer (Figure 4) and an infrared thermometer (Figure 5) were purchased from the Amazon Online Marketplace, to measure the solar intensity and the temperatures of the surfaces of the solar concentrator, respectively.


*Figure 4: Ambient Weather Pyranometer*

Upon attempting to place the thermocouples into the holes drilled in the copper pipe it was found that the tip of one of the thermocouples was slightly larger than the other, so it did not fit into the hole drilled at the outlet of the copper pipe. For the first test the thermocouple wire had to be shaped in a way that it would fit it into the end of the pipe and still be midstream in the water flow. The thermocouple was secured with tape and the previously drilled hole was sealed shut. The solar concentrator was positioned so that it was aimed directly at the sun. The two in-pipe midstream thermocouples were connected to the lab cradle/calculator set up and the Vernier software was opened. Data collection was started and the water valve was opened. Insolation values were measured at various times throughout the test. Attempts were made to measure the temperature of the surface of the pipe and the reflecting surface, but to no avail. The infrared thermometer may have been malfunctioning, as many reviews on Amazon had stated it would, or the temperatures were very widely varied on the surfaces of the concentrator.

*Figure 5: HDE Infrared Thermometer*

The day of the first test was very hot, but very windy. This may have affected the results of the test. For the second test, a larger hole was drilled at the outlet of the copper pipe to accommodate the larger thermocouple tip. This way the outlet temperature could be measured more accurately. The second test also yielded a much less windy day, which made a noticeable difference in the results.

*Figure 6: Prepping for testing*

# Results

Testing went very smoothly. The initial test was highly influenced by the strong winds present and also the misplacement of the outlet thermocouple, not to mention an inconsistent inlet temperature. The cause of this inconsistency was unknown. Therefore the results will be deemed inconclusive (Figure 7). The second test, however, with minimal wind and a properly placed outlet thermocouple proved to be quite responsive (Figure 8). The initial temperature drops noticeable on both plots are attributable to solar heating of the water sitting in the hose prior to testing.

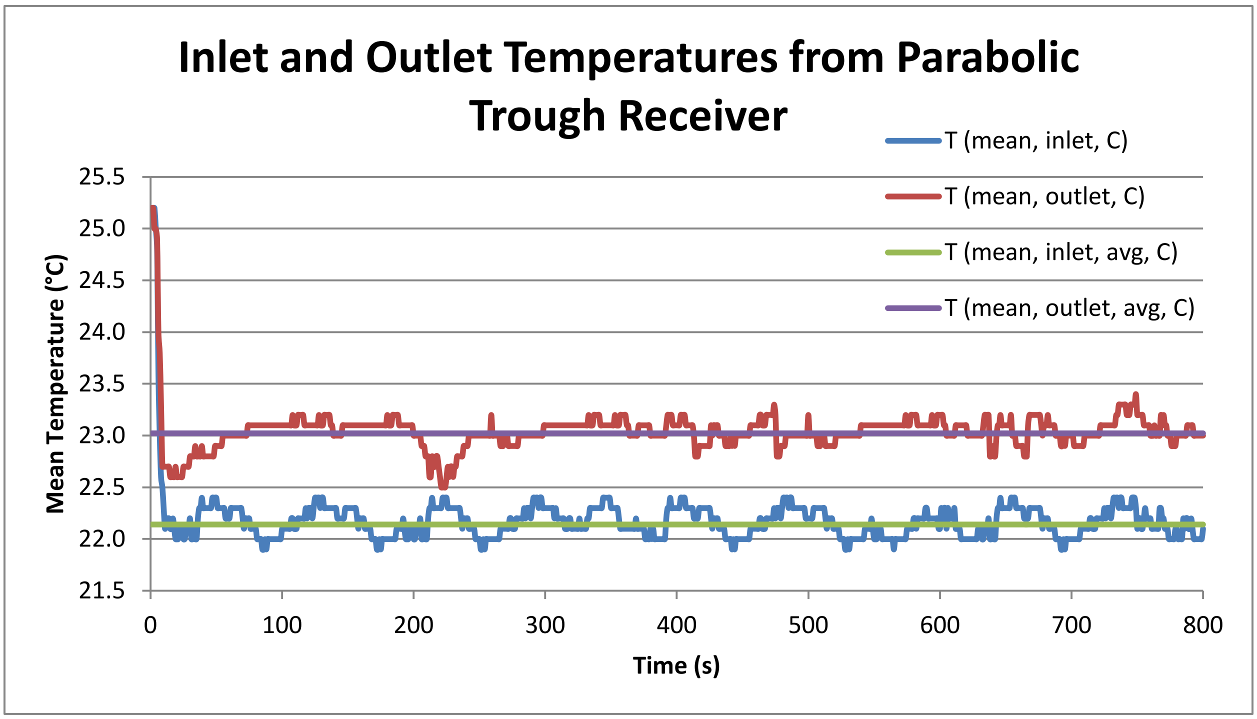



*Figure 7: Test 1 of Solar Concentrator*

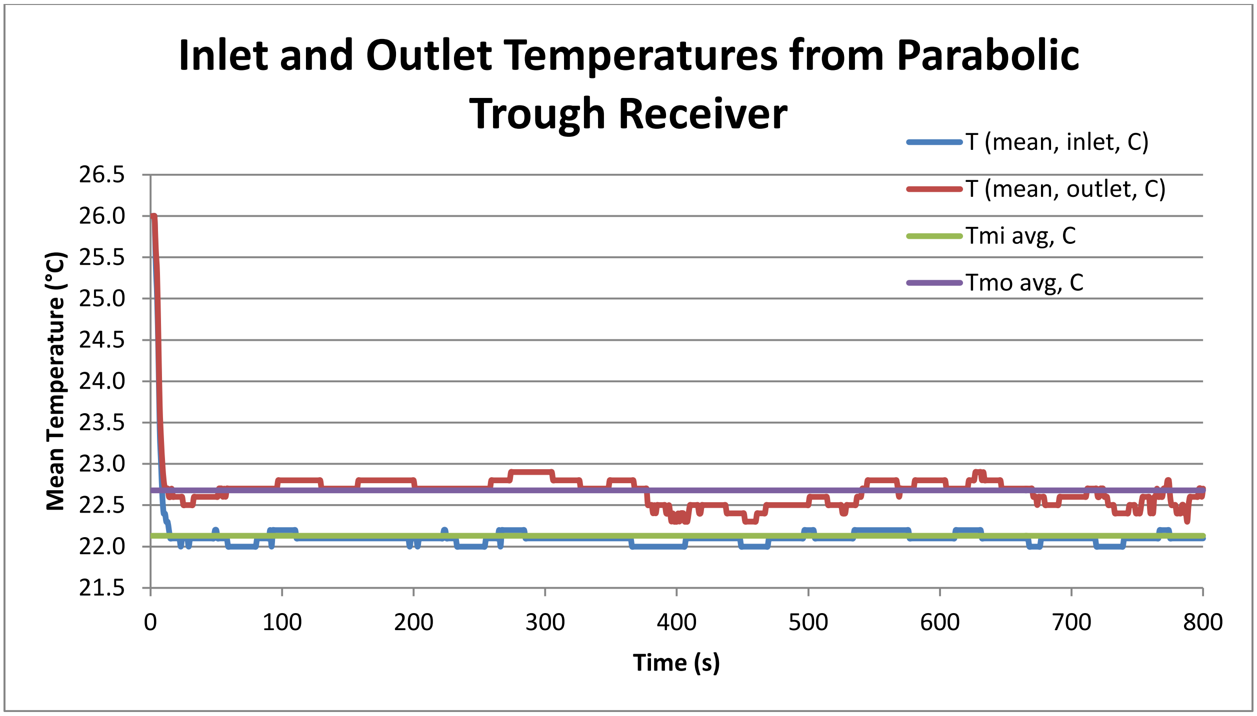



*Figure 8: Test 2 of Solar Concentrator*

The inlet and outlet temperatures were averaged across the total time of the test. The insolation measured at various times during testing was also averaged. The initial mathematical model was referred to and an expected outlet temperature was recalculated using the measured values. This model was then compared with the actual temperature recorded using the Vernier sensors. These calculations can be found in Appendix C. Data tables can be found in Appendix D.

# Conclusion

The results achieved using this miniature parabolic trough solar concentrator did not quite match up to the results expected based on the initial mathematical modeling. The differences are shown in Appendix C. The mathematical model initially proposed considered perfect conditions and a perfect parabolic trough concentrator. Thermal losses can occur through heat transfer by conduction through the surface of the parabolic trough and into the frame. Heat loss due to convection can also be a major issue on the receiver pipe surface. Fluctuation in wind speed throughout testing likely caused more heat loss than expected. This could be combated by insulating the top surface of the receiver tube, or enclosing the trough using glass or Plexiglas with high transmittance. Better insulation of the back of the reflecting surface would also help with the heat lost due to conduction. The shape of the parabola may also not have been perfect due to issues during construction, such as imperfect jigsaw cutting, sanding of the frame, and mounting of the Aluminum. These could all affect the amount of incident radiation on the copper receiver tube and thus the amount of heat transferred to the concentrator fluid. These thermal losses likely reduced the amount of useful solar gain for my concentrator. Therefore the temperature gain received in testing was significantly lower than predicted with the mathematical model. Despite the thermal losses experienced the solar concentrator did heat the water fairly consistently throughout testing. The project was a general success through the processes of designing, building, and testing.

# References


Bergman, Theodore L., et al. *Introduction to Heat Transfer*. 6th ed. Hoboken: Wiley, 2011. Print.

Duffie, John A., and William A. Beckman. *Solar Engineering of Thermal Processes*. 3rd ed. Hoboken: Wiley, 2006. Print.

Eames, P. C., et al. "Modelling Line-Axis Solar Concentrators in the Medium Temperature Range." *Renewable Energy* 16 (1999): 743-48. *Elsevier*. Web. 12 Nov. 2012.

Feuermann, Daniel, and Jeffrey M. Gordon. "Solar Fiber Optic Mini Dishes." *Solar Energy* 65.3 (1999): 159-70. Print.

Powell, Kody M., and Thomas F. Edgar. "Modeling and control of a solar thermal powerplant with thermal energy storage." *Chemical Engineering Science* 71 (2011): 138-45. *Science Direct*. Web. 12 Nov. 2012.

Sardeshpande, Vishal R., Ajay G. Chandak, and Indu R. Pillai. "Procedure for thermal performance evaluation of steam generating point-focus solar concentrators." *Solar Energy* 85 (2011): 1390-98. *Science Direct*. Web. 12 Nov. 2012.

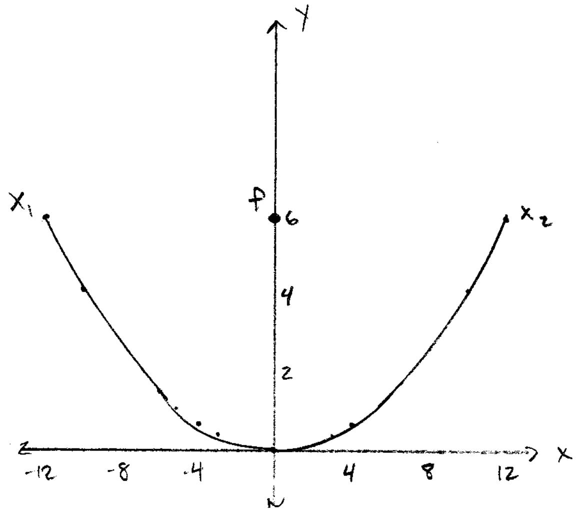
Young, Hugh, Roger Freedman, and Lewis Ford. *University Physics*. 12th ed. Boston: Addison-Wesley, 2007. Print.

# Appendix A: Design Sketches

PARABOLIC TROUGH SOLAR COLLECTOR

EQUATION OF PARABOLA: $Y = .041667x^2$ (unit = 1 in)

FOCAL POINT AT $1/4a = \frac{1}{4(.041667)} = 6$ in ABOVE ORIGIN




LENGTH OF PARABOLA FROM $X_1$ TO $X_2$, "S"

LET $t = 2f$ and $q = \sqrt{t^2 + P^2}$, P is DISTANCE FROM Y-AXIS TO POINT X

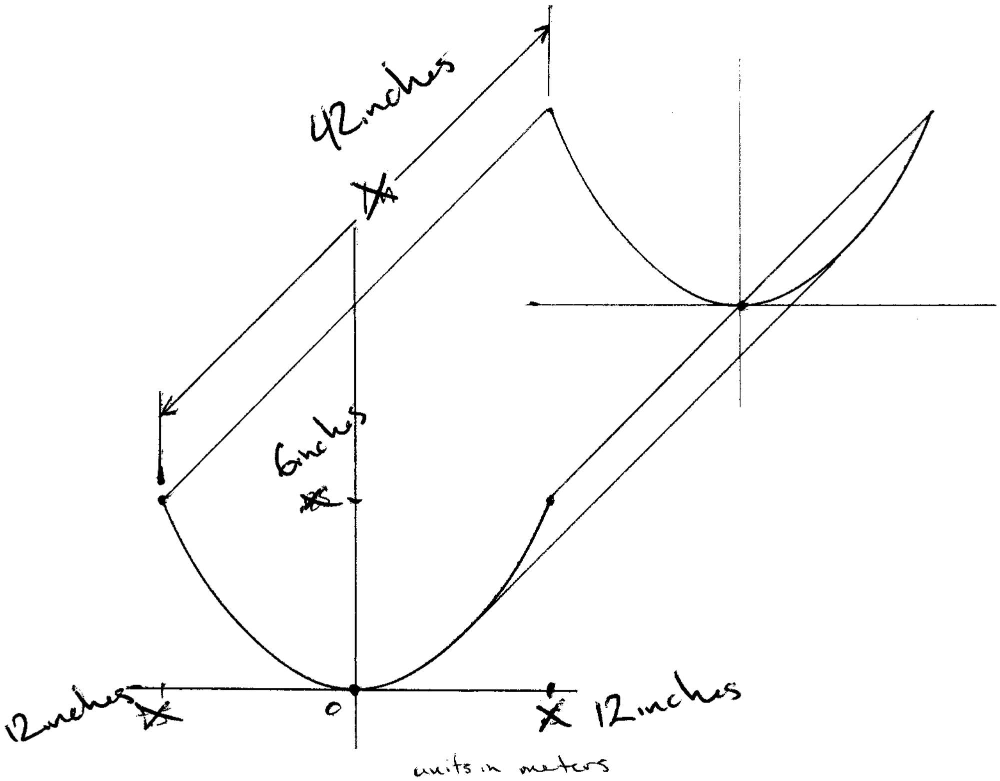
$$S = \left(\frac{Pq}{t} + t\ln\left(\frac{P+q}{t}\right)\right)$$

$$P = 12$$
$$t = 2(6) = 12$$
$$q = \sqrt{2 \cdot 12^2} = 1.697 \times 10^1$$

$$S = \left(\frac{12 \cdot 16.97}{12} + 12\ln\left(\frac{12 + 16.97}{12}\right)\right)$$

$$\boxed{S = 27.55 \text{ in}}$$

TOTAL LENGTH NEEDED FOR SHEET METAL = 27.55 in

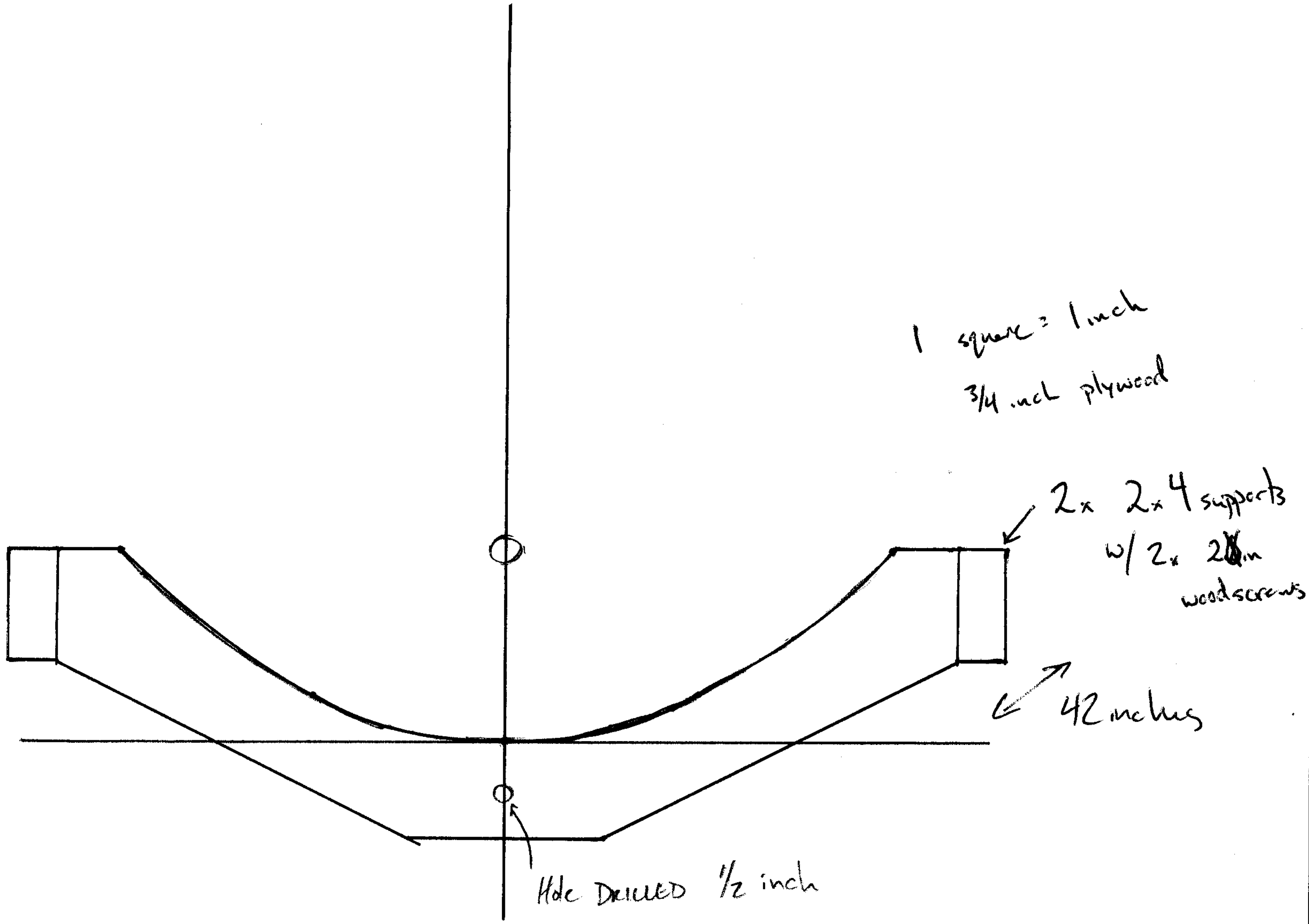



The trough will be ~~1m~~ in length as shown (not to scale)

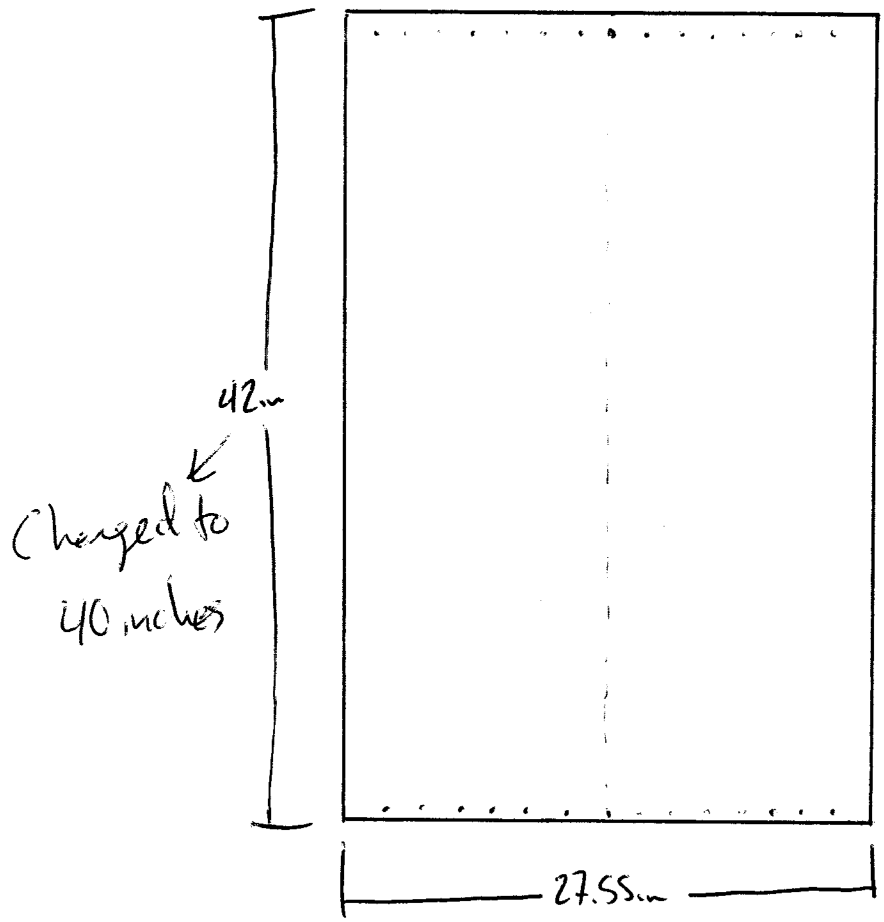
42inches

↓

Changed to 40 inches


1 square = 1 inch
3/4 inch plywood
2x 2x4 supports w/ 2x 2in woodscrews
42 inches
Hole DRILLED 1/2 inch

Drill holes every 2 inches from center line hole



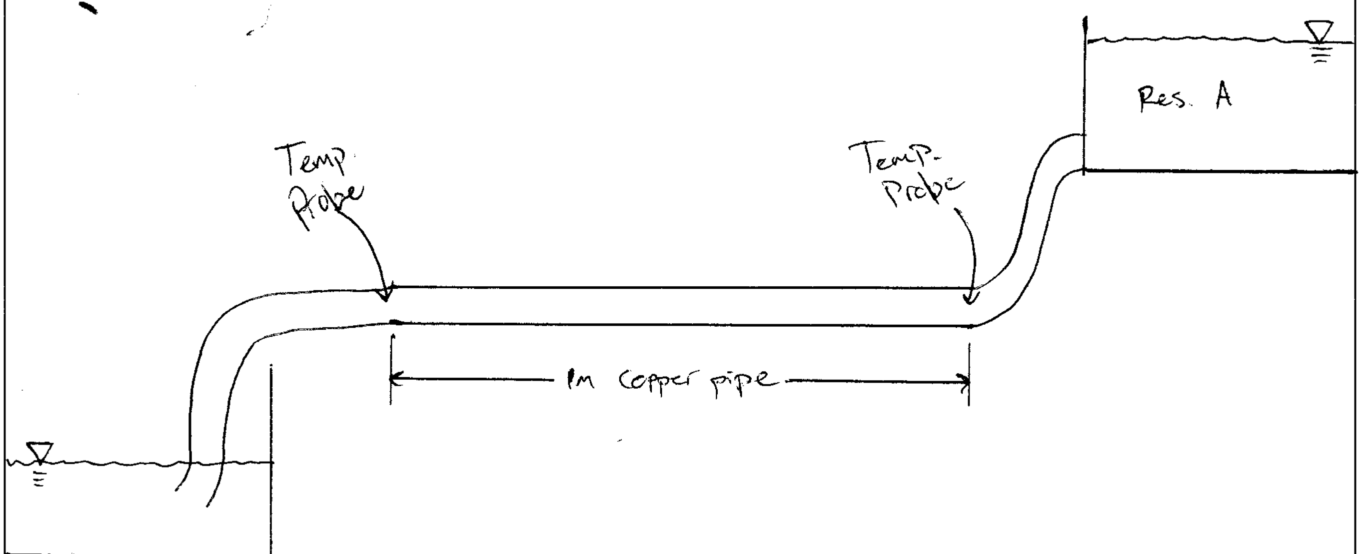

Reflective Surface

6061 T6 Aluminum

## Collector / receiver

I plan to use a ½ inch copper pipe as my receiver. The pipe will be sprayed with black heat resistant paint to maximize the energy absorbed by the copper pipe. Copper will be used for its high thermal conductivity. The pipe will be placed at the focal point of the parabolic trough, spanning the entire trough. Water will be run through the copper pipe while the temperature of the water will be measured at the inlet and outlet of the pipe.

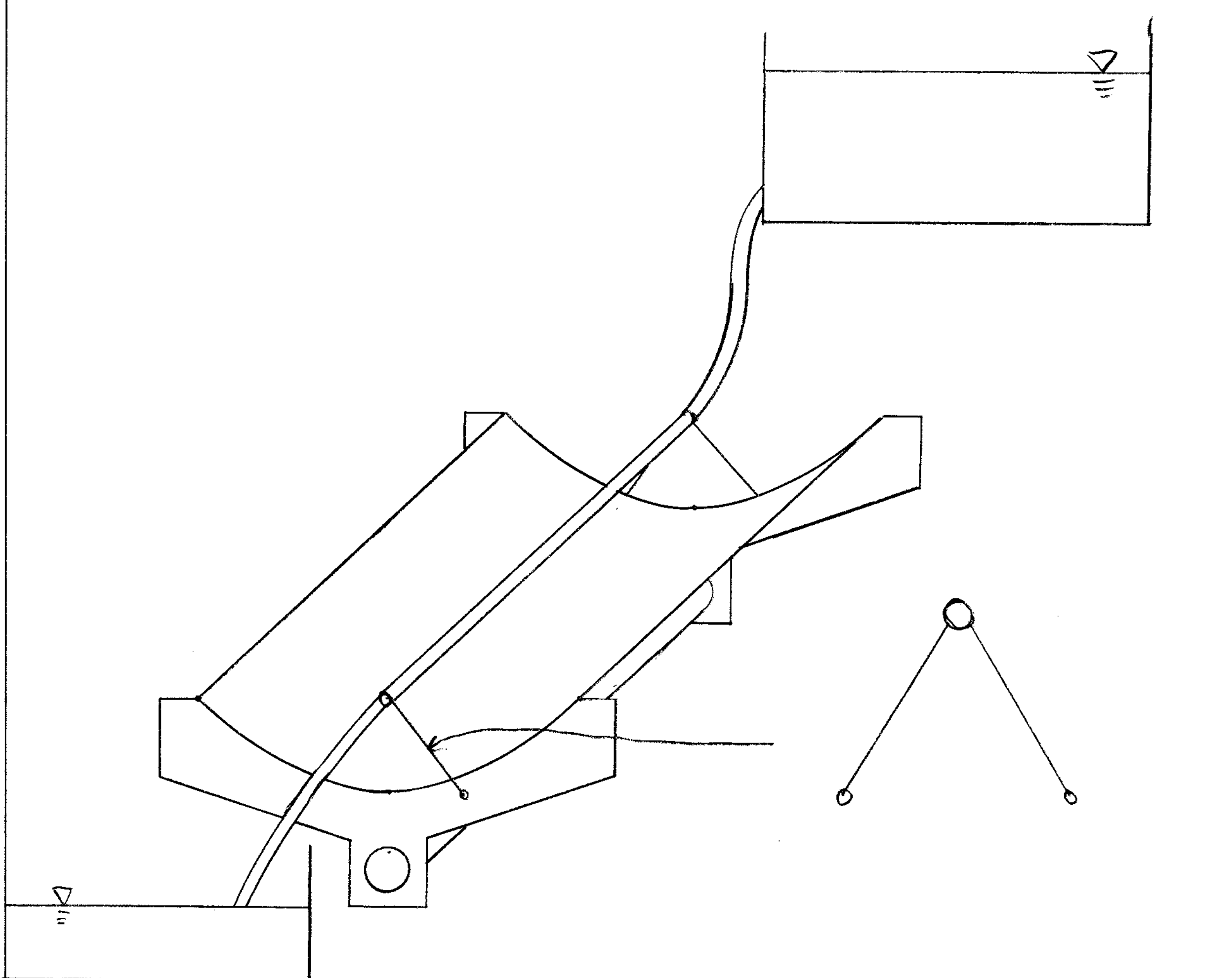
A simple siphon will be used to provide the water flow, with an upper reservoir large enough to allow ample time for testing.



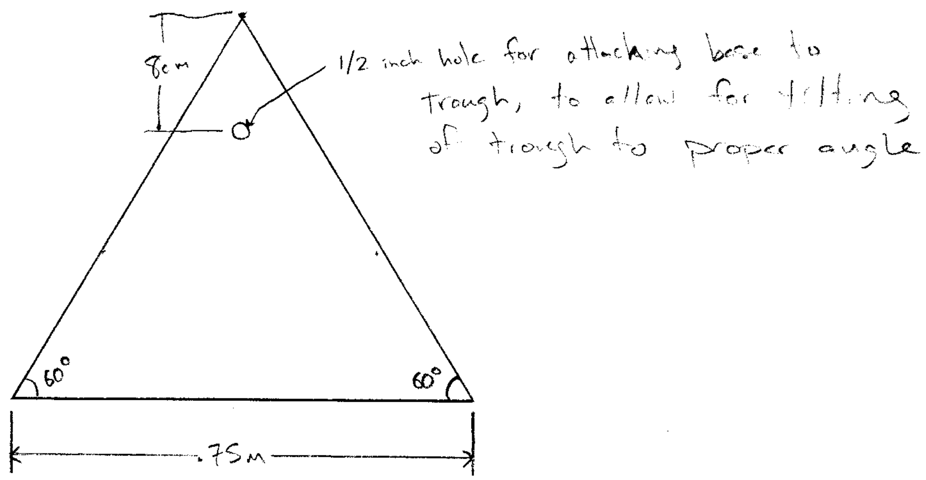
The pipes connecting the copper pipe~~s~~ to the reservoirs will be flexible, thermally resistant PEX tubing, also 1/2 inch.

My first idea for the upper reservoir A is to use a large camp cooler to attempt to keep the reservoir temperature at a constant level, hopefully this will be large enough for my purposes.

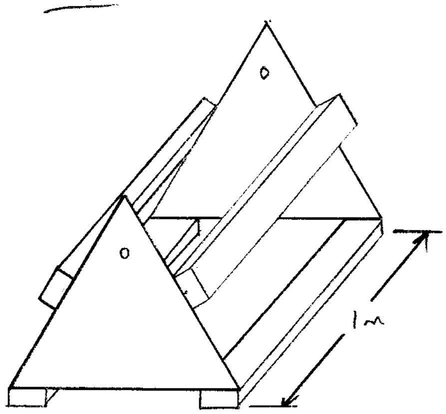
The lower reservoir is not as important, Just a tub to collect the water for retesting purposes...



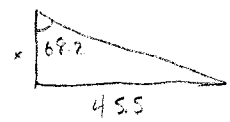
Base - Simple triangular plywood pieces (2)
Held together by 2 by 4s at base of triangle




Base:

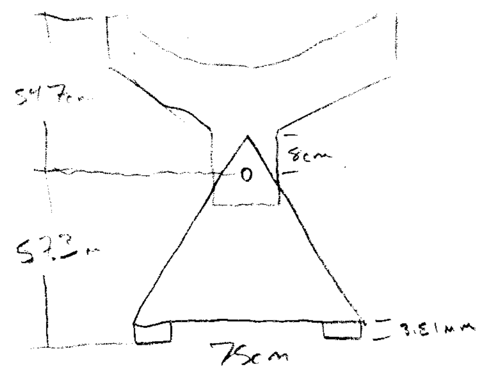


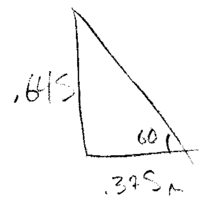
# Appendix B: Mathematical Modeling




$\tan 68.2 = \frac{45.5}{x}$

$x = 18.2\ cm$



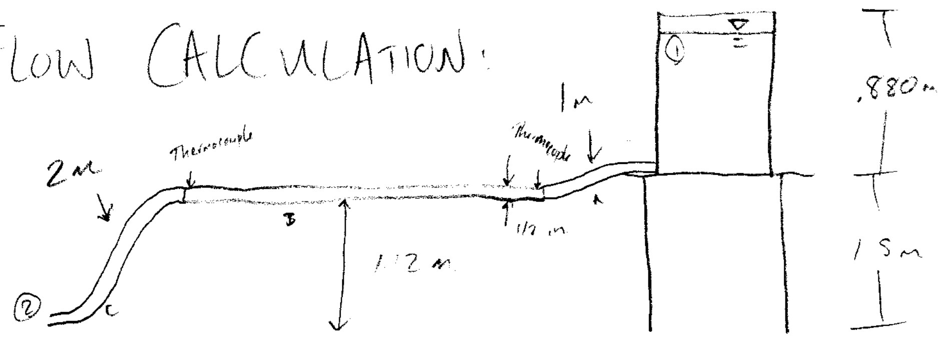




$\tan 60 = \frac{x}{.375}$

Overall height : 1.12 m

↳ Table for 55 gal drum at 1.5 m

FLOW CALCULATION:




Energy Equation

$\cancel{W_p} - \cancel{W_T} = h_{out} - h_{in} + h_{loss}$

$h_{in} = h_{out} + h_{loss}$

$\cancel{\frac{P_1}{\gamma}} + z_1 + \cancel{\frac{V_1^2}{2g}} = \cancel{\frac{P_2}{\gamma}} + z_2 + \cancel{\frac{V_2^2}{2g}} + h_{Lf} + h_{Lm}$

$z_1 = z_2 + h_{Lf} + h_{Lm}$

$z_1 = h_{Lf} + h_{Lm}$

$z_1 = f\frac{L}{D}\frac{V^2}{2g} + K\frac{V^2}{2g}$

$z_1 = f_A\frac{L_A}{D_A}\frac{V^2}{2g} + f_B\frac{L_B}{D_B}\frac{V^2}{2g} + f_C\frac{L_C}{D_C}\frac{V^2}{2g} + K\frac{V^2}{2g}$

$k_s$ for PEX Tubes: .007mm , D= 12.7mm $\frac{k_s}{D}$ = .0005

$k_s$ for copper pipe: .0015mm , D = 12.7mm $\frac{k_s}{D}$ = .0001

$$z_1 = \frac{V^2}{2g}\left(f_A\left(\frac{L_A}{D_A}+\frac{L_C}{D_C}\right)+f_B\frac{L_B}{D_B}+K\right)$$

$K = \underset{\text{unions}}{2(.08)} + \underset{\text{exit}}{1} + \underset{\text{entrance}}{.8} + \underset{\text{valve}}{2}$

$= 5.4$

guess $f_A = .02$ , $f_B = .018$

$$2.38m = \frac{V^2}{2(9.81\frac{m}{s^2})}\left[.02\left(\frac{1m}{.0127m}+\frac{2m}{.0127m}\right)+.018\left(\frac{1m}{.0127m}\right)+5.4\right]$$

$V^2 = 1.4\frac{m^2}{s^2}$

$V = 1.183$ m/s

$\hookrightarrow Re: \frac{uD}{\nu} = \frac{(1.183m/s)(.0127m)}{1.004\times10^{-6}m^2/s} = 1.5\times10^4$

assume 20°C

assume temp change in pipe affects for $\nu$ are negligible

$\hookrightarrow$ Find new friction factors on moody chart

$f_A = .029$ $f_B = .029$

$$z_1 = \frac{V^2}{2g}f\left(\frac{L_A}{D_A}+\frac{L_C}{D_C}+\frac{L_B}{D_B}+K\right)$$

$$2.38m = \frac{V^2}{2(9.81)}(.029)\left(\frac{1m}{.0127m}+\frac{2m}{.0127m}+\frac{1m}{.0127m}+5.4\right)$$

$V = 1.06$ m/s

$\hookrightarrow Re: \frac{uD}{\nu} : \frac{(1.06m/s)(.0127m)}{1.004\times10^{-6}m^2/s} = 1.34\times10^4$

f remains at .029

$\boxed{V \text{ in pipes} = 1.06 m/s}$

$Q = AV = \frac{\pi}{4}(.0127m)^2(1.06m/s) = \boxed{1.3\times10^{-4} m^3/s} \times \frac{1 gal}{.00378m^3} = \boxed{3.55\times10^{-2}\frac{gal}{s}}$

Revised Mathematical Model (After purchasing & reading solar engineering of Thermal Processes ...)

Area Concentration Ratio:

APERTURE AREA : Receiver Area

$$C = \frac{A_a}{A_r} = \frac{(\cancel{42\,in}) \times (24\,in)}{\left[\frac{\pi}{4} \times \left(\frac{5}{8}\right)^2\right] (\cancel{42\,in})}$$

$C = 78.2$

Assuming Insolation of 800 w/m²

$q_s'' = C \times I \times \rho \times K$

I = Insolation
$\rho$ = reflectivity of concentrator
K: Correction factor ≈ .7 for this

$= 78.2 \times 800 \times .8 \times .7$

$\boxed{= 35{,}000\ w/m^2}$

Assume Constant heating Condition on tube surface,

Concentrator Fluid - $H_2O$

$\rho = 1000\,kg/m^3$
$k = .58\,w/m \cdot K$
$c_p = 4210\,J/kg\,K$
$\mu = 1652 \times 10^{-6}\,N \cdot s/m^2$

Tube Diameter = 12.7 mm ($\frac{1}{2}$ inch)

Mass flow rate: from FLOW CALCULATION

$$\dot{M} = 3.55 \times 10^{-2}\,\frac{gal}{s} \times \frac{3.7854\,kg}{1\,gal} = \boxed{.1344\,kg/s}$$

Assume: Steady State, Incompressible, Constant Properties, Thin tube wall

From: INTRO TO HEAT TRANSFER

$$A_s = \pi D L = \frac{\dot{m} C_p (T_{m,o} - T_{m,i})}{q_s''}$$

$$\frac{\pi D L q_s''}{\dot{m} C_p} + T_{m,i} = T_{m,o}$$

$D = 12.7\,mm$
$L = 42\,in \rightarrow 1.066\,m$
$q_s'' = 35,000\,W/m^2$
$\dot{m} = .1344\,kg/s$
$C_p = 4210\,J/kg\,K$

$\longrightarrow$ Assume $T_{m,i} = 72°F = 22.22°C$

$$\frac{\pi(.0127\,m)(1.066\,m)(35,000\,W/m^2)}{(.1344\,kg/s)(4210\,J/kg\,K)} + 22.22°C = T_{m,o}$$

$$2.63 + 22.22 = T_{m,o}$$

$$\boxed{T_{m,o} = 24.85°C}$$

TOPS 35500

# Appendix C: Comparing Test Results to Mathematical Modeling

After building And Testing:

Area Concentration Ratio:

* During Construction length of trough changed to 40 inches

$$C = \frac{A_a}{A_r} = \frac{(\cancel{40\,in})(24\,in)}{(\pi/4 \times (\frac{5}{8})^2) \times \cancel{40\,in}}$$

$$C = 78.2$$

From Ch 7 In Solar engineering of thermal processes:

$$q_s'' = C \times I \times \rho \times K$$

I: INSOLATION
$\rho$: reflectivity of collector - Assume .8
K: Correction value - Assume .7 for average collectors

$$q_s'' = 78.2 \times 1046 \tfrac{W}{m^2} \times .8 \times .7$$

$$q_s'' = \underline{45,800} \; W/m^2$$

Still assuming Constant heating Condition on tube surface, same fluid, same Tube Diameter

Measured Mass flow rate: $3.86 \frac{oz}{s} \times \frac{.0078125\,gal}{oz}$

$$= .03016 \frac{gal}{s} \times \frac{3.7854\,kg}{gal}$$

$$= .114\,kg/s$$

TOPS 35500

Assume Steady State, Incompressible, constant properties, thin tube wall

$$A_s = \pi D L = \frac{\dot{m} C_p (T_{m,o} - T_{m,i})}{q_s''}$$ From Intro to heat transfer

$D = 12.7 mm$

$L = 40 in \rightarrow 1.016 m$

$q_s'' = 45,800 \ W/m^2$

$\dot{m} = .114 \ kg/s$

$C_p = 4210 \ J/kg K$

$\longrightarrow$ measured $T_{m,i} = 22.13°C$
$T_{m,o} = 22.68°C$

$$\frac{\pi D L q_s''}{\dot{m} C_p} + T_{m,i} = T_{m,o}$$

$$\frac{\pi (12.7 \times 10^{-3} m)(1.016 m)(45800 \ W/m^2)}{(.114 \ kg/s)(4210 \ J/kg \cdot K)} + 22.13°C$$

$3.87 + 22.13°C = T_{m,o}$

$\boxed{26°C = T_{m,o}}$

$\hookrightarrow \boxed{\text{Actual } T_{m,o} = 22.68°C}$

Calculated $T_{m,o}$ is higher than $T_{m,o}$ measured.

TOPS 35500

# Appendix D: Data Tables

## Test 1:

| Time (s) | T (mean, inlet, C) | T (mean, outlet, C) |
|---|---|---|
| 1 | 25.2 | 25.2 |
| 2 | 25.2 | 25.2 |
| 3 | 25.2 | 25.0 |
| 4 | 25.0 | 25.0 |
| 5 | 24.8 | 24.9 |
| 6 | 23.6 | 24.0 |
| 7 | 23.0 | 23.8 |
| 8 | 22.6 | 23.3 |
| 9 | 22.5 | 22.7 |
| 10 | 22.3 | 22.7 |
| 11 | 22.1 | 22.7 |
| 12 | 22.2 | 22.7 |
| 13 | 22.2 | 22.7 |
| 14 | 22.2 | 22.7 |
| 15 | 22.1 | 22.6 |
| 16 | 22.1 | 22.6 |
| 17 | 22.2 | 22.6 |
| 18 | 22.1 | 22.6 |
| 19 | 22.0 | 22.7 |
| 20 | 22.0 | 22.6 |
| 21 | 22.0 | 22.6 |
| 22 | 22.1 | 22.6 |
| 23 | 22.1 | 22.6 |
| 24 | 22.1 | 22.6 |
| 25 | 22.0 | 22.7 |
| 26 | 22.0 | 22.7 |
| 27 | 22.1 | 22.7 |
| 28 | 22.1 | 22.7 |
| 29 | 22.1 | 22.7 |
| 30 | 22.2 | 22.8 |
| 31 | 22.0 | 22.8 |
| 32 | 22.0 | 22.8 |
| 33 | 22.1 | 22.8 |
| 34 | 22.0 | 22.9 |
| 35 | 22.0 | 22.8 |
| 36 | 22.2 | 22.8 |

| | | |
|---|---|---|
| 37 | 22.3 | 22.8 |
| 38 | 22.3 | 22.8 |
| 39 | 22.4 | 22.9 |
| 40 | 22.3 | 22.8 |
| 41 | 22.3 | 22.8 |
| 42 | 22.3 | 22.8 |
| 43 | 22.3 | 22.8 |
| 44 | 22.3 | 22.8 |
| 45 | 22.3 | 22.8 |
| 46 | 22.3 | 22.8 |
| 47 | 22.4 | 22.8 |
| 48 | 22.4 | 22.8 |
| 49 | 22.4 | 22.9 |
| 50 | 22.4 | 22.9 |
| 51 | 22.3 | 22.9 |
| 52 | 22.3 | 22.9 |
| 53 | 22.3 | 22.9 |
| 54 | 22.3 | 22.9 |
| 55 | 22.3 | 23.0 |
| 56 | 22.3 | 23.0 |
| 57 | 22.2 | 23.0 |
| 58 | 22.2 | 23.0 |
| 59 | 22.2 | 23.0 |
| 60 | 22.2 | 23.0 |
| 61 | 22.3 | 23.0 |
| 62 | 22.3 | 23.0 |
| 63 | 22.3 | 23.0 |
| 64 | 22.3 | 23.0 |
| 65 | 22.3 | 23.0 |
| 66 | 22.3 | 23.0 |
| 67 | 22.3 | 23.0 |
| 68 | 22.3 | 23.0 |
| 69 | 22.3 | 23.0 |
| 70 | 22.2 | 23.0 |
| 71 | 22.1 | 23.0 |
| 72 | 22.2 | 23.0 |
| 73 | 22.2 | 23.0 |
| 74 | 22.2 | 23.1 |
| 75 | 22.2 | 23.1 |
| 76 | 22.1 | 23.1 |
| 77 | 22.1 | 23.1 |
| 78 | 22.1 | 23.1 |

| | | |
|---|---|---|
| 79 | 22.1 | 23.1 |
| 80 | 22.1 | 23.1 |
| 81 | 22.0 | 23.1 |
| 82 | 22.0 | 23.1 |
| 83 | 22.0 | 23.1 |
| 84 | 22.0 | 23.1 |
| 85 | 21.9 | 23.1 |
| 86 | 21.9 | 23.1 |
| 87 | 22.0 | 23.1 |
| 88 | 21.9 | 23.1 |
| 89 | 22.0 | 23.1 |
| 90 | 22.0 | 23.1 |
| 91 | 22.0 | 23.1 |
| 92 | 22.0 | 23.1 |
| 93 | 22.0 | 23.1 |
| 94 | 22.0 | 23.1 |
| 95 | 22.0 | 23.1 |
| 96 | 22.0 | 23.1 |
| 97 | 22.0 | 23.1 |
| 98 | 22.0 | 23.1 |
| 99 | 22.0 | 23.1 |
| 100 | 22.1 | 23.1 |
| 101 | 22.1 | 23.1 |
| 102 | 22.1 | 23.1 |
| 103 | 22.1 | 23.1 |
| 104 | 22.1 | 23.1 |
| 105 | 22.1 | 23.1 |
| 106 | 22.1 | 23.1 |
| 107 | 22.2 | 23.1 |
| 108 | 22.2 | 23.2 |
| 109 | 22.1 | 23.1 |
| 110 | 22.1 | 23.1 |
| 111 | 22.1 | 23.1 |
| 112 | 22.2 | 23.2 |
| 113 | 22.2 | 23.2 |
| 114 | 22.2 | 23.2 |
| 115 | 22.2 | 23.2 |
| 116 | 22.2 | 23.2 |
| 117 | 22.2 | 23.1 |
| 118 | 22.3 | 23.1 |
| 119 | 22.2 | 23.1 |
| 120 | 22.3 | 23.1 |

| | | |
|---|---|---|
| 121 | 22.3 | 23.1 |
| 122 | 22.3 | 23.1 |
| 123 | 22.2 | 23.1 |
| 124 | 22.3 | 23.1 |
| 125 | 22.4 | 23.1 |
| 126 | 22.4 | 23.1 |
| 127 | 22.4 | 23.1 |
| 128 | 22.4 | 23.2 |
| 129 | 22.3 | 23.1 |
| 130 | 22.4 | 23.1 |
| 131 | 22.4 | 23.1 |
| 132 | 22.3 | 23.2 |
| 133 | 22.3 | 23.2 |
| 134 | 22.3 | 23.2 |
| 135 | 22.3 | 23.2 |
| 136 | 22.3 | 23.2 |
| 137 | 22.3 | 23.1 |
| 138 | 22.3 | 23.1 |
| 139 | 22.3 | 23.0 |
| 140 | 22.3 | 23.0 |
| 141 | 22.3 | 23.0 |
| 142 | 22.2 | 23.0 |
| 143 | 22.2 | 23.0 |
| 144 | 22.2 | 23.0 |
| 145 | 22.2 | 23.0 |
| 146 | 22.2 | 23.1 |
| 147 | 22.2 | 23.1 |
| 148 | 22.3 | 23.1 |
| 149 | 22.3 | 23.1 |
| 150 | 22.3 | 23.1 |
| 151 | 22.3 | 23.1 |
| 152 | 22.3 | 23.1 |
| 153 | 22.3 | 23.1 |
| 154 | 22.3 | 23.1 |
| 155 | 22.3 | 23.1 |
| 156 | 22.3 | 23.1 |
| 157 | 22.2 | 23.1 |
| 158 | 22.1 | 23.1 |
| 159 | 22.2 | 23.1 |
| 160 | 22.2 | 23.1 |
| 161 | 22.2 | 23.1 |
| 162 | 22.2 | 23.1 |

| | | |
|---|---|---|
| 163 | 22.1 | 23.1 |
| 164 | 22.1 | 23.1 |
| 165 | 22.1 | 23.1 |
| 166 | 22.1 | 23.1 |
| 167 | 22.1 | 23.1 |
| 168 | 22.0 | 23.1 |
| 169 | 22.0 | 23.1 |
| 170 | 22.0 | 23.1 |
| 171 | 22.0 | 23.1 |
| 172 | 21.9 | 23.1 |
| 173 | 21.9 | 23.1 |
| 174 | 22.0 | 23.1 |
| 175 | 21.9 | 23.1 |
| 176 | 22.0 | 23.1 |
| 177 | 22.0 | 23.1 |
| 178 | 22.0 | 23.1 |
| 179 | 22.0 | 23.1 |
| 180 | 22.0 | 23.2 |
| 181 | 22.0 | 23.1 |
| 182 | 22.0 | 23.1 |
| 183 | 22.0 | 23.1 |
| 184 | 22.0 | 23.2 |
| 185 | 22.0 | 23.2 |
| 186 | 22.0 | 23.2 |
| 187 | 22.1 | 23.2 |
| 188 | 22.1 | 23.2 |
| 189 | 22.1 | 23.1 |
| 190 | 22.1 | 23.1 |
| 191 | 22.1 | 23.1 |
| 192 | 22.2 | 23.1 |
| 193 | 22.1 | 23.1 |
| 194 | 22.0 | 23.1 |
| 195 | 22.0 | 23.1 |
| 196 | 22.0 | 23.1 |
| 197 | 22.1 | 23.1 |
| 198 | 22.1 | 23.1 |
| 199 | 22.1 | 23.1 |
| 200 | 22.0 | 23.0 |
| 201 | 22.0 | 23.0 |
| 202 | 22.1 | 23.0 |
| 203 | 22.1 | 23.0 |
| 204 | 22.1 | 23.0 |

| | | |
|---|---|---|
| 205 | 22.2 | 23.0 |
| 206 | 22.0 | 22.9 |
| 207 | 22.0 | 22.9 |
| 208 | 22.1 | 22.9 |
| 209 | 22.0 | 22.8 |
| 210 | 22.0 | 22.8 |
| 211 | 22.2 | 22.8 |
| 212 | 22.3 | 22.6 |
| 213 | 22.3 | 22.6 |
| 214 | 22.4 | 22.8 |
| 215 | 22.3 | 22.7 |
| 216 | 22.3 | 22.7 |
| 217 | 22.3 | 22.8 |
| 218 | 22.3 | 22.8 |
| 219 | 22.3 | 22.7 |
| 220 | 22.3 | 22.6 |
| 221 | 22.3 | 22.5 |
| 222 | 22.4 | 22.5 |
| 223 | 22.4 | 22.5 |
| 224 | 22.4 | 22.5 |
| 225 | 22.4 | 22.6 |
| 226 | 22.3 | 22.7 |
| 227 | 22.3 | 22.6 |
| 228 | 22.3 | 22.7 |
| 229 | 22.3 | 22.7 |
| 230 | 22.3 | 22.6 |
| 231 | 22.3 | 22.7 |
| 232 | 22.3 | 22.7 |
| 233 | 22.3 | 22.8 |
| 234 | 22.3 | 22.8 |
| 235 | 22.3 | 22.8 |
| 236 | 22.2 | 22.8 |
| 237 | 22.1 | 22.8 |
| 238 | 22.2 | 22.9 |
| 239 | 22.2 | 22.9 |
| 240 | 22.2 | 22.9 |
| 241 | 22.2 | 22.9 |
| 242 | 22.1 | 23.0 |
| 243 | 22.1 | 23.0 |
| 244 | 22.1 | 23.0 |
| 245 | 22.1 | 23.0 |
| 246 | 22.1 | 23.0 |

| | | |
|---|---|---|
| 247 | 22.0 | 23.0 |
| 248 | 22.0 | 23.0 |
| 249 | 22.0 | 23.0 |
| 250 | 22.0 | 23.0 |
| 251 | 21.9 | 23.0 |
| 252 | 21.9 | 23.0 |
| 253 | 22.0 | 23.0 |
| 254 | 21.9 | 23.0 |
| 255 | 22.0 | 23.0 |
| 256 | 22.0 | 23.0 |
| 257 | 22.0 | 23.0 |
| 258 | 22.0 | 23.0 |
| 259 | 22.0 | 23.2 |
| 260 | 22.0 | 23.0 |
| 261 | 22.0 | 23.0 |
| 262 | 22.0 | 23.0 |
| 263 | 22.0 | 23.0 |
| 264 | 22.0 | 23.0 |
| 265 | 22.0 | 23.0 |
| 266 | 22.1 | 22.9 |
| 267 | 22.1 | 22.9 |
| 268 | 22.1 | 22.9 |
| 269 | 22.1 | 23.0 |
| 270 | 22.1 | 23.0 |
| 271 | 22.1 | 23.0 |
| 272 | 22.1 | 22.9 |
| 273 | 22.2 | 22.9 |
| 274 | 22.2 | 22.9 |
| 275 | 22.1 | 22.9 |
| 276 | 22.1 | 22.9 |
| 277 | 22.1 | 22.9 |
| 278 | 22.2 | 22.9 |
| 279 | 22.2 | 22.9 |
| 280 | 22.2 | 23.0 |
| 281 | 22.2 | 23.0 |
| 282 | 22.2 | 23.0 |
| 283 | 22.2 | 23.0 |
| 284 | 22.3 | 23.0 |
| 285 | 22.2 | 23.0 |
| 286 | 22.3 | 23.0 |
| 287 | 22.3 | 23.0 |
| 288 | 22.3 | 23.0 |

| | | |
|---|---|---|
| 289 | 22.2 | 23.0 |
| 290 | 22.3 | 23.0 |
| 291 | 22.4 | 23.0 |
| 292 | 22.4 | 23.0 |
| 293 | 22.4 | 23.0 |
| 294 | 22.4 | 23.0 |
| 295 | 22.3 | 23.0 |
| 296 | 22.4 | 23.0 |
| 297 | 22.4 | 23.0 |
| 298 | 22.3 | 23.0 |
| 299 | 22.3 | 23.1 |
| 300 | 22.3 | 23.1 |
| 301 | 22.3 | 23.1 |
| 302 | 22.3 | 23.1 |
| 303 | 22.3 | 23.1 |
| 304 | 22.3 | 23.1 |
| 305 | 22.3 | 23.1 |
| 306 | 22.3 | 23.1 |
| 307 | 22.2 | 23.1 |
| 308 | 22.3 | 23.1 |
| 309 | 22.2 | 23.1 |
| 310 | 22.2 | 23.1 |
| 311 | 22.2 | 23.1 |
| 312 | 22.2 | 23.1 |
| 313 | 22.2 | 23.1 |
| 314 | 22.2 | 23.1 |
| 315 | 22.1 | 23.1 |
| 316 | 22.1 | 23.1 |
| 317 | 22.1 | 23.1 |
| 318 | 22.2 | 23.1 |
| 319 | 22.2 | 23.1 |
| 320 | 22.1 | 23.1 |
| 321 | 22.1 | 23.1 |
| 322 | 22.1 | 23.1 |
| 323 | 22.1 | 23.1 |
| 324 | 22.1 | 23.1 |
| 325 | 22.1 | 23.1 |
| 326 | 22.2 | 23.1 |
| 327 | 22.1 | 23.1 |
| 328 | 22.1 | 23.1 |
| 329 | 22.1 | 23.1 |
| 330 | 22.1 | 23.1 |

| | | |
|---|---|---|
| 331 | 22.1 | 23.1 |
| 332 | 22.2 | 23.1 |
| 333 | 22.2 | 23.2 |
| 334 | 22.3 | 23.1 |
| 335 | 22.3 | 23.1 |
| 336 | 22.3 | 23.1 |
| 337 | 22.3 | 23.2 |
| 338 | 22.3 | 23.2 |
| 339 | 22.3 | 23.2 |
| 340 | 22.3 | 23.2 |
| 341 | 22.3 | 23.2 |
| 342 | 22.3 | 23.1 |
| 343 | 22.3 | 23.1 |
| 344 | 22.4 | 23.1 |
| 345 | 22.4 | 23.1 |
| 346 | 22.4 | 23.1 |
| 347 | 22.4 | 23.1 |
| 348 | 22.4 | 23.1 |
| 349 | 22.4 | 23.1 |
| 350 | 22.3 | 23.1 |
| 351 | 22.3 | 23.1 |
| 352 | 22.3 | 23.1 |
| 353 | 22.3 | 23.2 |
| 354 | 22.3 | 23.1 |
| 355 | 22.3 | 23.1 |
| 356 | 22.2 | 23.1 |
| 357 | 22.1 | 23.2 |
| 358 | 22.1 | 23.2 |
| 359 | 22.1 | 23.2 |
| 360 | 22.1 | 23.2 |
| 361 | 22.1 | 23.2 |
| 362 | 22.1 | 23.1 |
| 363 | 22.1 | 23.1 |
| 364 | 22.1 | 23.0 |
| 365 | 22.1 | 23.0 |
| 366 | 22.1 | 23.0 |
| 367 | 22.1 | 23.0 |
| 368 | 22.1 | 23.0 |
| 369 | 22.2 | 23.0 |
| 370 | 22.1 | 23.0 |
| 371 | 22.1 | 23.1 |
| 372 | 22.1 | 23.1 |

| | | |
|---|---|---|
| 373 | 22.1 | 23.1 |
| 374 | 22.1 | 23.1 |
| 375 | 22.1 | 23.1 |
| 376 | 22.0 | 23.1 |
| 377 | 22.0 | 23.1 |
| 378 | 22.0 | 23.1 |
| 379 | 22.0 | 23.1 |
| 380 | 22.1 | 23.0 |
| 381 | 22.0 | 23.0 |
| 382 | 22.1 | 23.0 |
| 383 | 22.0 | 23.0 |
| 384 | 22.0 | 23.0 |
| 385 | 22.0 | 23.0 |
| 386 | 22.0 | 23.0 |
| 387 | 22.0 | 23.0 |
| 388 | 22.0 | 23.0 |
| 389 | 22.0 | 23.0 |
| 390 | 22.0 | 23.0 |
| 391 | 22.0 | 23.0 |
| 392 | 22.2 | 23.1 |
| 393 | 22.3 | 23.2 |
| 394 | 22.3 | 23.2 |
| 395 | 22.4 | 23.2 |
| 396 | 22.3 | 23.2 |
| 397 | 22.3 | 23.1 |
| 398 | 22.3 | 23.1 |
| 399 | 22.3 | 23.1 |
| 400 | 22.3 | 23.1 |
| 401 | 22.3 | 23.1 |
| 402 | 22.3 | 23.1 |
| 403 | 22.4 | 23.2 |
| 404 | 22.4 | 23.2 |
| 405 | 22.4 | 23.2 |
| 406 | 22.4 | 23.2 |
| 407 | 22.3 | 23.1 |
| 408 | 22.3 | 23.1 |
| 409 | 22.3 | 23.1 |
| 410 | 22.3 | 23.1 |
| 411 | 22.3 | 23.1 |
| 412 | 22.3 | 23.1 |
| 413 | 22.2 | 23.0 |
| 414 | 22.2 | 22.8 |

| | | |
|---|---|---|
| 415 | 22.2 | 22.8 |
| 416 | 22.2 | 22.8 |
| 417 | 22.3 | 22.9 |
| 418 | 22.3 | 22.9 |
| 419 | 22.3 | 22.9 |
| 420 | 22.3 | 22.9 |
| 421 | 22.3 | 22.9 |
| 422 | 22.3 | 22.9 |
| 423 | 22.3 | 22.9 |
| 424 | 22.3 | 22.9 |
| 425 | 22.3 | 22.9 |
| 426 | 22.2 | 23.1 |
| 427 | 22.1 | 23.0 |
| 428 | 22.2 | 23.1 |
| 429 | 22.2 | 23.1 |
| 430 | 22.2 | 23.1 |
| 431 | 22.2 | 23.1 |
| 432 | 22.1 | 23.0 |
| 433 | 22.1 | 23.0 |
| 434 | 22.1 | 23.0 |
| 435 | 22.1 | 23.0 |
| 436 | 22.1 | 23.0 |
| 437 | 22.0 | 22.9 |
| 438 | 22.0 | 22.9 |
| 439 | 22.0 | 22.9 |
| 440 | 22.0 | 22.9 |
| 441 | 22.0 | 23.0 |
| 442 | 21.9 | 22.9 |
| 443 | 22.0 | 23.0 |
| 444 | 21.9 | 22.9 |
| 445 | 22.0 | 23.0 |
| 446 | 22.0 | 23.0 |
| 447 | 22.0 | 23.0 |
| 448 | 22.0 | 23.0 |
| 449 | 22.0 | 23.0 |
| 450 | 22.0 | 23.0 |
| 451 | 22.0 | 23.0 |
| 452 | 22.0 | 23.0 |
| 453 | 22.0 | 23.0 |
| 454 | 22.0 | 23.0 |
| 455 | 22.0 | 23.0 |
| 456 | 22.1 | 23.1 |

| | | |
|---|---|---|
| 457 | 22.1 | 23.1 |
| 458 | 22.1 | 23.1 |
| 459 | 22.1 | 23.1 |
| 460 | 22.1 | 23.1 |
| 461 | 22.1 | 23.1 |
| 462 | 22.1 | 23.1 |
| 463 | 22.2 | 23.2 |
| 464 | 22.2 | 23.2 |
| 465 | 22.1 | 23.1 |
| 466 | 22.1 | 23.1 |
| 467 | 22.1 | 23.1 |
| 468 | 22.2 | 23.2 |
| 469 | 22.2 | 23.2 |
| 470 | 22.2 | 23.2 |
| 471 | 22.2 | 23.2 |
| 472 | 22.2 | 23.2 |
| 473 | 22.2 | 23.2 |
| 474 | 22.3 | 23.3 |
| 475 | 22.2 | 23.2 |
| 476 | 22.3 | 22.8 |
| 477 | 22.3 | 22.8 |
| 478 | 22.3 | 22.8 |
| 479 | 22.2 | 22.9 |
| 480 | 22.3 | 22.9 |
| 481 | 22.4 | 22.9 |
| 482 | 22.4 | 22.9 |
| 483 | 22.4 | 23.0 |
| 484 | 22.4 | 23.0 |
| 485 | 22.3 | 23.0 |
| 486 | 22.4 | 23.0 |
| 487 | 22.4 | 23.0 |
| 488 | 22.3 | 23.0 |
| 489 | 22.3 | 23.0 |
| 490 | 22.3 | 23.0 |
| 491 | 22.3 | 23.0 |
| 492 | 22.3 | 23.0 |
| 493 | 22.3 | 23.0 |
| 494 | 22.3 | 23.0 |
| 495 | 22.3 | 23.0 |
| 496 | 22.3 | 23.0 |
| 497 | 22.3 | 23.0 |
| 498 | 22.2 | 23.0 |

| | | |
|---|---|---|
| 499 | 22.2 | 23.0 |
| 500 | 22.2 | 23.2 |
| 501 | 22.2 | 23.0 |
| 502 | 22.2 | 23.0 |
| 503 | 22.2 | 23.0 |
| 504 | 22.3 | 23.0 |
| 505 | 22.3 | 23.0 |
| 506 | 22.3 | 23.0 |
| 507 | 22.3 | 22.9 |
| 508 | 22.3 | 22.9 |
| 509 | 22.3 | 22.9 |
| 510 | 22.3 | 23.0 |
| 511 | 22.3 | 23.0 |
| 512 | 22.3 | 23.0 |
| 513 | 22.2 | 22.9 |
| 514 | 22.1 | 22.9 |
| 515 | 22.2 | 22.9 |
| 516 | 22.2 | 22.9 |
| 517 | 22.2 | 22.9 |
| 518 | 22.2 | 22.9 |
| 519 | 22.1 | 22.9 |
| 520 | 22.1 | 22.9 |
| 521 | 22.1 | 23.0 |
| 522 | 22.1 | 23.0 |
| 523 | 22.1 | 23.0 |
| 524 | 22.0 | 23.0 |
| 525 | 22.0 | 23.0 |
| 526 | 22.0 | 23.0 |
| 527 | 22.0 | 23.0 |
| 528 | 21.9 | 23.0 |
| 529 | 21.9 | 23.0 |
| 530 | 22.0 | 23.0 |
| 531 | 21.9 | 23.0 |
| 532 | 22.0 | 23.0 |
| 533 | 22.0 | 23.0 |
| 534 | 22.0 | 23.0 |
| 535 | 22.0 | 23.0 |
| 536 | 22.0 | 23.0 |
| 537 | 22.0 | 23.0 |
| 538 | 22.0 | 23.0 |
| 539 | 22.0 | 23.0 |
| 540 | 22.0 | 23.1 |

| | | |
|---|---|---|
| 541 | 22.0 | 23.1 |
| 542 | 22.0 | 23.1 |
| 543 | 22.1 | 23.1 |
| 544 | 22.1 | 23.1 |
| 545 | 22.1 | 23.1 |
| 546 | 22.1 | 23.1 |
| 547 | 22.1 | 23.1 |
| 548 | 22.2 | 23.1 |
| 549 | 22.1 | 23.1 |
| 550 | 22.0 | 23.1 |
| 551 | 22.0 | 23.1 |
| 552 | 22.0 | 23.1 |
| 553 | 22.1 | 23.1 |
| 554 | 22.1 | 23.1 |
| 555 | 22.1 | 23.1 |
| 556 | 22.0 | 23.1 |
| 557 | 22.0 | 23.1 |
| 558 | 22.0 | 23.1 |
| 559 | 22.0 | 23.1 |
| 560 | 22.0 | 23.1 |
| 561 | 22.0 | 23.1 |
| 562 | 22.0 | 23.1 |
| 563 | 22.0 | 23.1 |
| 564 | 22.0 | 23.1 |
| 565 | 21.9 | 23.1 |
| 566 | 22.0 | 23.1 |
| 567 | 22.0 | 23.1 |
| 568 | 22.0 | 23.1 |
| 569 | 22.0 | 23.1 |
| 570 | 22.0 | 23.1 |
| 571 | 22.0 | 23.1 |
| 572 | 22.0 | 23.1 |
| 573 | 22.0 | 23.1 |
| 574 | 22.0 | 23.2 |
| 575 | 22.1 | 23.1 |
| 576 | 22.1 | 23.1 |
| 577 | 22.1 | 23.1 |
| 578 | 22.1 | 23.2 |
| 579 | 22.1 | 23.2 |
| 580 | 22.2 | 23.2 |
| 581 | 22.2 | 23.2 |
| 582 | 22.1 | 23.2 |

| | | |
|---|---|---|
| 583 | 22.2 | 23.1 |
| 584 | 22.2 | 23.1 |
| 585 | 22.2 | 23.1 |
| 586 | 22.2 | 23.1 |
| 587 | 22.2 | 23.1 |
| 588 | 22.2 | 23.1 |
| 589 | 22.3 | 23.1 |
| 590 | 22.3 | 23.1 |
| 591 | 22.2 | 23.1 |
| 592 | 22.2 | 23.1 |
| 593 | 22.2 | 23.1 |
| 594 | 22.2 | 23.2 |
| 595 | 22.2 | 23.1 |
| 596 | 22.2 | 23.1 |
| 597 | 22.2 | 23.1 |
| 598 | 22.2 | 23.2 |
| 599 | 22.1 | 23.2 |
| 600 | 22.1 | 23.2 |
| 601 | 22.3 | 23.2 |
| 602 | 22.2 | 23.2 |
| 603 | 22.3 | 23.1 |
| 604 | 22.3 | 23.1 |
| 605 | 22.1 | 23.0 |
| 606 | 22.3 | 23.0 |
| 607 | 22.2 | 23.0 |
| 608 | 22.2 | 23.0 |
| 609 | 22.2 | 23.0 |
| 610 | 22.2 | 23.0 |
| 611 | 22.3 | 23.0 |
| 612 | 22.1 | 23.1 |
| 613 | 22.1 | 23.1 |
| 614 | 22.1 | 23.1 |
| 615 | 22.1 | 23.1 |
| 616 | 22.0 | 23.1 |
| 617 | 22.0 | 23.1 |
| 618 | 22.0 | 23.1 |
| 619 | 22.0 | 23.1 |
| 620 | 22.0 | 23.1 |
| 621 | 22.0 | 23.0 |
| 622 | 22.0 | 23.0 |
| 623 | 22.0 | 23.0 |
| 624 | 22.0 | 23.0 |

| | | |
|---|---|---|
| 625 | 22.0 | 23.0 |
| 626 | 22.0 | 23.0 |
| 627 | 22.0 | 23.0 |
| 628 | 22.0 | 23.0 |
| 629 | 22.1 | 23.0 |
| 630 | 22.1 | 23.0 |
| 631 | 22.1 | 23.0 |
| 632 | 22.0 | 23.0 |
| 633 | 22.0 | 23.1 |
| 634 | 22.1 | 23.2 |
| 635 | 22.1 | 23.2 |
| 636 | 22.1 | 23.2 |
| 637 | 22.2 | 23.2 |
| 638 | 22.0 | 22.8 |
| 639 | 22.0 | 22.8 |
| 640 | 22.1 | 22.9 |
| 641 | 22.0 | 22.8 |
| 642 | 22.0 | 22.8 |
| 643 | 22.2 | 23.0 |
| 644 | 22.3 | 23.1 |
| 645 | 22.3 | 23.1 |
| 646 | 22.4 | 23.2 |
| 647 | 22.3 | 23.1 |
| 648 | 22.3 | 23.1 |
| 649 | 22.3 | 23.1 |
| 650 | 22.3 | 23.1 |
| 651 | 22.3 | 23.1 |
| 652 | 22.3 | 23.1 |
| 653 | 22.3 | 23.1 |
| 654 | 22.4 | 23.2 |
| 655 | 22.4 | 23.0 |
| 656 | 22.4 | 23.0 |
| 657 | 22.4 | 23.0 |
| 658 | 22.3 | 22.9 |
| 659 | 22.3 | 22.9 |
| 660 | 22.3 | 22.9 |
| 661 | 22.3 | 22.9 |
| 662 | 22.3 | 22.9 |
| 663 | 22.3 | 22.9 |
| 664 | 22.2 | 22.8 |
| 665 | 22.2 | 22.8 |
| 666 | 22.2 | 22.8 |

| | | |
|---|---|---|
| 667 | 22.2 | 23.1 |
| 668 | 22.3 | 23.2 |
| 669 | 22.3 | 23.2 |
| 670 | 22.3 | 23.2 |
| 671 | 22.3 | 23.2 |
| 672 | 22.3 | 23.2 |
| 673 | 22.3 | 23.2 |
| 674 | 22.3 | 23.2 |
| 675 | 22.3 | 23.2 |
| 676 | 22.3 | 23.2 |
| 677 | 22.2 | 23.1 |
| 678 | 22.1 | 23.0 |
| 679 | 22.2 | 23.1 |
| 680 | 22.2 | 23.1 |
| 681 | 22.2 | 23.1 |
| 682 | 22.2 | 23.2 |
| 683 | 22.1 | 23.1 |
| 684 | 22.1 | 23.1 |
| 685 | 22.1 | 23.1 |
| 686 | 22.1 | 23.1 |
| 687 | 22.1 | 23.1 |
| 688 | 22.0 | 23.0 |
| 689 | 22.0 | 23.0 |
| 690 | 22.0 | 23.0 |
| 691 | 22.0 | 23.0 |
| 692 | 21.9 | 22.9 |
| 693 | 21.9 | 22.9 |
| 694 | 22.0 | 23.0 |
| 695 | 21.9 | 22.9 |
| 696 | 22.0 | 23.0 |
| 697 | 22.0 | 23.0 |
| 698 | 22.0 | 23.0 |
| 699 | 22.0 | 23.0 |
| 700 | 22.0 | 23.0 |
| 701 | 22.0 | 23.0 |
| 702 | 22.0 | 22.9 |
| 703 | 22.0 | 22.9 |
| 704 | 22.0 | 22.9 |
| 705 | 22.0 | 22.9 |
| 706 | 22.0 | 22.9 |
| 707 | 22.1 | 22.9 |
| 708 | 22.1 | 22.9 |

| | | |
|---|---|---|
| 709 | 22.1 | 22.9 |
| 710 | 22.1 | 23.0 |
| 711 | 22.1 | 23.0 |
| 712 | 22.1 | 23.0 |
| 713 | 22.1 | 23.0 |
| 714 | 22.2 | 23.0 |
| 715 | 22.2 | 23.0 |
| 716 | 22.1 | 23.0 |
| 717 | 22.1 | 23.0 |
| 718 | 22.1 | 23.0 |
| 719 | 22.2 | 23.0 |
| 720 | 22.2 | 23.0 |
| 721 | 22.2 | 23.0 |
| 722 | 22.2 | 23.1 |
| 723 | 22.2 | 23.1 |
| 724 | 22.2 | 23.1 |
| 725 | 22.3 | 23.1 |
| 726 | 22.2 | 23.1 |
| 727 | 22.3 | 23.1 |
| 728 | 22.3 | 23.1 |
| 729 | 22.3 | 23.1 |
| 730 | 22.2 | 23.1 |
| 731 | 22.3 | 23.1 |
| 732 | 22.4 | 23.1 |
| 733 | 22.4 | 23.1 |
| 734 | 22.4 | 23.2 |
| 735 | 22.4 | 23.2 |
| 736 | 22.3 | 23.3 |
| 737 | 22.4 | 23.3 |
| 738 | 22.4 | 23.3 |
| 739 | 22.3 | 23.3 |
| 740 | 22.3 | 23.3 |
| 741 | 22.3 | 23.3 |
| 742 | 22.3 | 23.2 |
| 743 | 22.3 | 23.2 |
| 744 | 22.3 | 23.2 |
| 745 | 22.3 | 23.3 |
| 746 | 22.4 | 23.3 |
| 747 | 22.4 | 23.3 |
| 748 | 22.4 | 23.3 |
| 749 | 22.3 | 23.4 |
| 750 | 22.1 | 23.2 |

| | | |
|---|---|---|
| 751 | 22.2 | 23.2 |
| 752 | 22.2 | 23.2 |
| 753 | 22.1 | 23.2 |
| 754 | 22.1 | 23.2 |
| 755 | 22.2 | 23.1 |
| 756 | 22.3 | 23.1 |
| 757 | 22.2 | 23.1 |
| 758 | 22.2 | 23.1 |
| 759 | 22.2 | 23.1 |
| 760 | 22.2 | 23.0 |
| 761 | 22.1 | 23.0 |
| 762 | 22.1 | 23.0 |
| 763 | 22.1 | 23.1 |
| 764 | 22.1 | 23.0 |
| 765 | 22.1 | 23.0 |
| 766 | 22.1 | 23.0 |
| 767 | 22.3 | 23.0 |
| 768 | 22.3 | 23.2 |
| 769 | 22.2 | 23.1 |
| 770 | 22.2 | 23.2 |
| 771 | 22.1 | 23.1 |
| 772 | 22.1 | 23.1 |
| 773 | 22.1 | 23.0 |
| 774 | 22.0 | 23.0 |
| 775 | 22.0 | 23.0 |
| 776 | 22.0 | 22.9 |
| 777 | 22.0 | 22.9 |
| 778 | 22.0 | 22.9 |
| 779 | 22.1 | 22.9 |
| 780 | 22.1 | 23.0 |
| 781 | 22.0 | 23.0 |
| 782 | 22.0 | 23.0 |
| 783 | 22.0 | 23.0 |
| 784 | 22.0 | 23.0 |
| 785 | 22.2 | 23.0 |
| 786 | 22.1 | 23.0 |
| 787 | 22.2 | 23.0 |
| 788 | 22.2 | 23.1 |
| 789 | 22.1 | 23.1 |
| 790 | 22.1 | 23.1 |
| 791 | 22.2 | 23.1 |
| 792 | 22.1 | 23.1 |

| | | |
|---|---|---|
| 793 | 22.0 | 23.0 |
| 794 | 22.0 | 23.0 |
| 795 | 22.0 | 23.0 |
| 796 | 22.0 | 23.0 |
| 797 | 22.0 | 23.0 |
| 798 | 22.0 | 23.0 |
| 799 | 22.0 | 23.0 |
| 800 | 22.1 | 23.0 |

**Test 2:**

| Time (s) | T (mean, inlet, C) | T (mean, outlet, C) |
|---|---|---|
| 1 | 26 | 26 |
| 2 | 26 | 26 |
| 3 | 26 | 26 |
| 4 | 25.4 | 25.6 |
| 5 | 25 | 25.3 |
| 6 | 24.3 | 24.5 |
| 7 | 23.4 | 23.7 |
| 8 | 23 | 23.3 |
| 9 | 22.6 | 23 |
| 10 | 22.4 | 22.8 |
| 11 | 22.4 | 22.7 |
| 12 | 22.3 | 22.7 |
| 13 | 22.3 | 22.7 |
| 14 | 22.2 | 22.6 |
| 15 | 22.1 | 22.6 |
| 16 | 22.1 | 22.7 |
| 17 | 22.1 | 22.6 |
| 18 | 22.1 | 22.6 |
| 19 | 22.1 | 22.6 |
| 20 | 22.1 | 22.6 |
| 21 | 22.1 | 22.6 |
| 22 | 22.1 | 22.6 |
| 23 | 22 | 22.6 |
| 24 | 22.1 | 22.6 |
| 25 | 22.1 | 22.5 |
| 26 | 22.1 | 22.5 |
| 27 | 22.1 | 22.5 |
| 28 | 22.1 | 22.5 |
| 29 | 22 | 22.5 |
| 30 | 22.1 | 22.5 |
| 31 | 22.1 | 22.5 |
| 32 | 22.1 | 22.5 |
| 33 | 22.1 | 22.6 |
| 34 | 22.1 | 22.6 |
| 35 | 22.1 | 22.6 |
| 36 | 22.1 | 22.6 |
| 37 | 22.1 | 22.6 |
| 38 | 22.1 | 22.6 |
| 39 | 22.1 | 22.6 |

| | | |
|---|---|---|
| 40 | 22.1 | 22.6 |
| 41 | 22.1 | 22.6 |
| 42 | 22.1 | 22.6 |
| 43 | 22.1 | 22.6 |
| 44 | 22.1 | 22.6 |
| 45 | 22.1 | 22.6 |
| 46 | 22.1 | 22.6 |
| 47 | 22.1 | 22.6 |
| 48 | 22.1 | 22.6 |
| 49 | 22.2 | 22.6 |
| 50 | 22.2 | 22.6 |
| 51 | 22.1 | 22.6 |
| 52 | 22.1 | 22.7 |
| 53 | 22.1 | 22.7 |
| 54 | 22.1 | 22.7 |
| 55 | 22.1 | 22.6 |
| 56 | 22.1 | 22.7 |
| 57 | 22.1 | 22.6 |
| 58 | 22.1 | 22.7 |
| 59 | 22 | 22.7 |
| 60 | 22 | 22.7 |
| 61 | 22 | 22.7 |
| 62 | 22 | 22.7 |
| 63 | 22 | 22.7 |
| 64 | 22 | 22.7 |
| 65 | 22 | 22.7 |
| 66 | 22 | 22.7 |
| 67 | 22 | 22.7 |
| 68 | 22 | 22.7 |
| 69 | 22 | 22.7 |
| 70 | 22 | 22.7 |
| 71 | 22 | 22.7 |
| 72 | 22 | 22.7 |
| 73 | 22 | 22.7 |
| 74 | 22 | 22.7 |
| 75 | 22 | 22.7 |
| 76 | 22 | 22.7 |
| 77 | 22 | 22.7 |
| 78 | 22 | 22.7 |
| 79 | 22 | 22.7 |
| 80 | 22 | 22.7 |
| 81 | 22.1 | 22.7 |

| | | |
|---|---|---|
| 82 | 22.1 | 22.7 |
| 83 | 22.1 | 22.7 |
| 84 | 22.1 | 22.7 |
| 85 | 22.1 | 22.7 |
| 86 | 22.1 | 22.7 |
| 87 | 22.1 | 22.7 |
| 88 | 22.1 | 22.7 |
| 89 | 22.1 | 22.7 |
| 90 | 22.1 | 22.7 |
| 91 | 22.2 | 22.7 |
| 92 | 22 | 22.7 |
| 93 | 22.2 | 22.7 |
| 94 | 22.2 | 22.7 |
| 95 | 22.2 | 22.7 |
| 96 | 22.2 | 22.7 |
| 97 | 22.2 | 22.8 |
| 98 | 22.2 | 22.8 |
| 99 | 22.2 | 22.8 |
| 100 | 22.2 | 22.8 |
| 101 | 22.2 | 22.8 |
| 102 | 22.2 | 22.8 |
| 103 | 22.2 | 22.8 |
| 104 | 22.2 | 22.8 |
| 105 | 22.2 | 22.8 |
| 106 | 22.2 | 22.8 |
| 107 | 22.2 | 22.8 |
| 108 | 22.2 | 22.8 |
| 109 | 22.2 | 22.8 |
| 110 | 22.2 | 22.8 |
| 111 | 22.1 | 22.8 |
| 112 | 22.1 | 22.8 |
| 113 | 22.1 | 22.8 |
| 114 | 22.1 | 22.8 |
| 115 | 22.1 | 22.8 |
| 116 | 22.1 | 22.8 |
| 117 | 22.1 | 22.8 |
| 118 | 22.1 | 22.8 |
| 119 | 22.1 | 22.8 |
| 120 | 22.1 | 22.8 |
| 121 | 22.1 | 22.8 |
| 122 | 22.1 | 22.8 |
| 123 | 22.1 | 22.8 |

| | | |
|---|---|---|
| 124 | 22.1 | 22.8 |
| 125 | 22.1 | 22.8 |
| 126 | 22.1 | 22.8 |
| 127 | 22.1 | 22.8 |
| 128 | 22.1 | 22.8 |
| 129 | 22.1 | 22.8 |
| 130 | 22.1 | 22.7 |
| 131 | 22.1 | 22.7 |
| 132 | 22.1 | 22.7 |
| 133 | 22.1 | 22.7 |
| 134 | 22.1 | 22.7 |
| 135 | 22.1 | 22.7 |
| 136 | 22.1 | 22.7 |
| 137 | 22.1 | 22.7 |
| 138 | 22.1 | 22.7 |
| 139 | 22.1 | 22.7 |
| 140 | 22.1 | 22.7 |
| 141 | 22.1 | 22.7 |
| 142 | 22.1 | 22.7 |
| 143 | 22.1 | 22.7 |
| 144 | 22.1 | 22.7 |
| 145 | 22.1 | 22.7 |
| 146 | 22.1 | 22.7 |
| 147 | 22.1 | 22.7 |
| 148 | 22.1 | 22.7 |
| 149 | 22.1 | 22.7 |
| 150 | 22.1 | 22.7 |
| 151 | 22.1 | 22.7 |
| 152 | 22.1 | 22.7 |
| 153 | 22.1 | 22.7 |
| 154 | 22.1 | 22.7 |
| 155 | 22.1 | 22.7 |
| 156 | 22.1 | 22.7 |
| 157 | 22.1 | 22.7 |
| 158 | 22.1 | 22.8 |
| 159 | 22.1 | 22.8 |
| 160 | 22.1 | 22.8 |
| 161 | 22.1 | 22.8 |
| 162 | 22.1 | 22.8 |
| 163 | 22.1 | 22.8 |
| 164 | 22.1 | 22.8 |
| 165 | 22.1 | 22.8 |

| | | |
|---|---|---|
| 166 | 22.1 | 22.8 |
| 167 | 22.1 | 22.8 |
| 168 | 22.1 | 22.8 |
| 169 | 22.1 | 22.8 |
| 170 | 22.1 | 22.8 |
| 171 | 22.1 | 22.8 |
| 172 | 22.1 | 22.8 |
| 173 | 22.1 | 22.8 |
| 174 | 22.1 | 22.8 |
| 175 | 22.1 | 22.8 |
| 176 | 22.1 | 22.8 |
| 177 | 22.1 | 22.8 |
| 178 | 22.1 | 22.8 |
| 179 | 22.1 | 22.8 |
| 180 | 22.1 | 22.8 |
| 181 | 22.1 | 22.8 |
| 182 | 22.1 | 22.8 |
| 183 | 22.1 | 22.8 |
| 184 | 22.1 | 22.8 |
| 185 | 22.1 | 22.8 |
| 186 | 22.1 | 22.8 |
| 187 | 22.1 | 22.8 |
| 188 | 22.1 | 22.8 |
| 189 | 22.1 | 22.8 |
| 190 | 22.1 | 22.8 |
| 191 | 22.1 | 22.8 |
| 192 | 22.1 | 22.8 |
| 193 | 22.1 | 22.8 |
| 194 | 22.1 | 22.8 |
| 195 | 22.1 | 22.8 |
| 196 | 22.1 | 22.8 |
| 197 | 22 | 22.8 |
| 198 | 22.1 | 22.8 |
| 199 | 22.1 | 22.8 |
| 200 | 22.1 | 22.8 |
| 201 | 22.1 | 22.7 |
| 202 | 22.1 | 22.7 |
| 203 | 22 | 22.7 |
| 204 | 22.1 | 22.7 |
| 205 | 22.1 | 22.7 |
| 206 | 22.1 | 22.7 |
| 207 | 22.1 | 22.7 |

| | | |
|---|---|---|
| 208 | 22.1 | 22.7 |
| 209 | 22.1 | 22.7 |
| 210 | 22.1 | 22.7 |
| 211 | 22.1 | 22.7 |
| 212 | 22.1 | 22.7 |
| 213 | 22.1 | 22.7 |
| 214 | 22.1 | 22.7 |
| 215 | 22.1 | 22.7 |
| 216 | 22.1 | 22.7 |
| 217 | 22.1 | 22.7 |
| 218 | 22.1 | 22.7 |
| 219 | 22.1 | 22.7 |
| 220 | 22.1 | 22.7 |
| 221 | 22.1 | 22.7 |
| 222 | 22.1 | 22.7 |
| 223 | 22.2 | 22.7 |
| 224 | 22.2 | 22.7 |
| 225 | 22.1 | 22.7 |
| 226 | 22.1 | 22.7 |
| 227 | 22.1 | 22.7 |
| 228 | 22.1 | 22.7 |
| 229 | 22.1 | 22.7 |
| 230 | 22.1 | 22.7 |
| 231 | 22.1 | 22.7 |
| 232 | 22.1 | 22.7 |
| 233 | 22 | 22.7 |
| 234 | 22 | 22.7 |
| 235 | 22 | 22.7 |
| 236 | 22 | 22.7 |
| 237 | 22 | 22.7 |
| 238 | 22 | 22.7 |
| 239 | 22 | 22.7 |
| 240 | 22 | 22.7 |
| 241 | 22 | 22.7 |
| 242 | 22 | 22.7 |
| 243 | 22 | 22.7 |
| 244 | 22 | 22.7 |
| 245 | 22 | 22.7 |
| 246 | 22 | 22.7 |
| 247 | 22 | 22.7 |
| 248 | 22 | 22.7 |
| 249 | 22 | 22.7 |

| | | |
|---|---|---|
| 250 | 22 | 22.7 |
| 251 | 22 | 22.7 |
| 252 | 22 | 22.7 |
| 253 | 22 | 22.7 |
| 254 | 22 | 22.7 |
| 255 | 22.1 | 22.7 |
| 256 | 22.1 | 22.7 |
| 257 | 22.1 | 22.7 |
| 258 | 22.1 | 22.7 |
| 259 | 22.1 | 22.8 |
| 260 | 22.1 | 22.8 |
| 261 | 22.1 | 22.8 |
| 262 | 22.1 | 22.8 |
| 263 | 22.1 | 22.8 |
| 264 | 22.1 | 22.8 |
| 265 | 22.2 | 22.8 |
| 266 | 22 | 22.8 |
| 267 | 22.2 | 22.8 |
| 268 | 22.2 | 22.8 |
| 269 | 22.2 | 22.8 |
| 270 | 22.2 | 22.8 |
| 271 | 22.2 | 22.8 |
| 272 | 22.2 | 22.8 |
| 273 | 22.2 | 22.8 |
| 274 | 22.2 | 22.9 |
| 275 | 22.2 | 22.9 |
| 276 | 22.2 | 22.9 |
| 277 | 22.2 | 22.9 |
| 278 | 22.2 | 22.9 |
| 279 | 22.2 | 22.9 |
| 280 | 22.2 | 22.9 |
| 281 | 22.2 | 22.9 |
| 282 | 22.2 | 22.9 |
| 283 | 22.2 | 22.9 |
| 284 | 22.2 | 22.9 |
| 285 | 22.1 | 22.9 |
| 286 | 22.1 | 22.9 |
| 287 | 22.1 | 22.9 |
| 288 | 22.1 | 22.9 |
| 289 | 22.1 | 22.9 |
| 290 | 22.1 | 22.9 |
| 291 | 22.1 | 22.9 |

| | | |
|---|---|---|
| 292 | 22.1 | 22.9 |
| 293 | 22.1 | 22.9 |
| 294 | 22.1 | 22.9 |
| 295 | 22.1 | 22.9 |
| 296 | 22.1 | 22.9 |
| 297 | 22.1 | 22.9 |
| 298 | 22.1 | 22.9 |
| 299 | 22.1 | 22.9 |
| 300 | 22.1 | 22.9 |
| 301 | 22.1 | 22.9 |
| 302 | 22.1 | 22.9 |
| 303 | 22.1 | 22.9 |
| 304 | 22.1 | 22.9 |
| 305 | 22.1 | 22.9 |
| 306 | 22.1 | 22.8 |
| 307 | 22.1 | 22.8 |
| 308 | 22.1 | 22.8 |
| 309 | 22.1 | 22.8 |
| 310 | 22.1 | 22.8 |
| 311 | 22.1 | 22.8 |
| 312 | 22.1 | 22.8 |
| 313 | 22.1 | 22.8 |
| 314 | 22.1 | 22.8 |
| 315 | 22.1 | 22.8 |
| 316 | 22.1 | 22.8 |
| 317 | 22.1 | 22.8 |
| 318 | 22.1 | 22.8 |
| 319 | 22.1 | 22.8 |
| 320 | 22.1 | 22.8 |
| 321 | 22.1 | 22.8 |
| 322 | 22.1 | 22.8 |
| 323 | 22.1 | 22.8 |
| 324 | 22.1 | 22.8 |
| 325 | 22.1 | 22.8 |
| 326 | 22.1 | 22.8 |
| 327 | 22.1 | 22.7 |
| 328 | 22.1 | 22.7 |
| 329 | 22.1 | 22.7 |
| 330 | 22.1 | 22.7 |
| 331 | 22.1 | 22.7 |
| 332 | 22.1 | 22.7 |
| 333 | 22.1 | 22.7 |

| | | |
|---|---|---|
| 334 | 22.1 | 22.7 |
| 335 | 22.1 | 22.7 |
| 336 | 22.1 | 22.7 |
| 337 | 22.1 | 22.7 |
| 338 | 22.1 | 22.7 |
| 339 | 22.1 | 22.7 |
| 340 | 22.1 | 22.7 |
| 341 | 22.1 | 22.7 |
| 342 | 22.1 | 22.7 |
| 343 | 22.1 | 22.7 |
| 344 | 22.1 | 22.7 |
| 345 | 22.1 | 22.7 |
| 346 | 22.1 | 22.7 |
| 347 | 22.1 | 22.7 |
| 348 | 22.1 | 22.7 |
| 349 | 22.1 | 22.8 |
| 350 | 22.1 | 22.8 |
| 351 | 22.1 | 22.8 |
| 352 | 22.1 | 22.8 |
| 353 | 22.1 | 22.8 |
| 354 | 22.1 | 22.8 |
| 355 | 22.1 | 22.8 |
| 356 | 22.1 | 22.8 |
| 357 | 22.1 | 22.8 |
| 358 | 22.1 | 22.8 |
| 359 | 22.1 | 22.8 |
| 360 | 22.1 | 22.8 |
| 361 | 22.1 | 22.8 |
| 362 | 22.1 | 22.8 |
| 363 | 22.1 | 22.8 |
| 364 | 22.1 | 22.8 |
| 365 | 22.1 | 22.8 |
| 366 | 22 | 22.8 |
| 367 | 22 | 22.8 |
| 368 | 22 | 22.7 |
| 369 | 22 | 22.7 |
| 370 | 22 | 22.7 |
| 371 | 22 | 22.7 |
| 372 | 22 | 22.7 |
| 373 | 22 | 22.7 |
| 374 | 22 | 22.7 |
| 375 | 22 | 22.7 |

| | | |
|---|---|---|
| 376 | 22 | 22.7 |
| 377 | 22 | 22.7 |
| 378 | 22 | 22.5 |
| 379 | 22 | 22.5 |
| 380 | 22 | 22.5 |
| 381 | 22 | 22.5 |
| 382 | 22 | 22.4 |
| 383 | 22 | 22.5 |
| 384 | 22 | 22.4 |
| 385 | 22 | 22.5 |
| 386 | 22 | 22.5 |
| 387 | 22 | 22.5 |
| 388 | 22 | 22.5 |
| 389 | 22 | 22.5 |
| 390 | 22 | 22.5 |
| 391 | 22 | 22.5 |
| 392 | 22 | 22.4 |
| 393 | 22 | 22.4 |
| 394 | 22 | 22.5 |
| 395 | 22 | 22.4 |
| 396 | 22 | 22.3 |
| 397 | 22 | 22.4 |
| 398 | 22 | 22.3 |
| 399 | 22 | 22.3 |
| 400 | 22 | 22.3 |
| 401 | 22 | 22.4 |
| 402 | 22 | 22.3 |
| 403 | 22 | 22.4 |
| 404 | 22 | 22.4 |
| 405 | 22 | 22.4 |
| 406 | 22 | 22.3 |
| 407 | 22.1 | 22.3 |
| 408 | 22.1 | 22.3 |
| 409 | 22.1 | 22.4 |
| 410 | 22.1 | 22.5 |
| 411 | 22.1 | 22.5 |
| 412 | 22.1 | 22.5 |
| 413 | 22.1 | 22.5 |
| 414 | 22.1 | 22.5 |
| 415 | 22.1 | 22.5 |
| 416 | 22.1 | 22.5 |
| 417 | 22.1 | 22.4 |

| | | |
|---|---|---|
| 418 | 22.1 | 22.4 |
| 419 | 22.1 | 22.5 |
| 420 | 22.1 | 22.5 |
| 421 | 22.1 | 22.5 |
| 422 | 22.1 | 22.5 |
| 423 | 22.1 | 22.5 |
| 424 | 22.1 | 22.5 |
| 425 | 22.1 | 22.5 |
| 426 | 22.1 | 22.5 |
| 427 | 22.1 | 22.5 |
| 428 | 22.1 | 22.5 |
| 429 | 22.1 | 22.5 |
| 430 | 22.1 | 22.5 |
| 431 | 22.1 | 22.5 |
| 432 | 22.1 | 22.5 |
| 433 | 22.1 | 22.5 |
| 434 | 22.1 | 22.5 |
| 435 | 22.1 | 22.5 |
| 436 | 22.1 | 22.5 |
| 437 | 22.1 | 22.5 |
| 438 | 22.1 | 22.4 |
| 439 | 22.1 | 22.4 |
| 440 | 22.1 | 22.4 |
| 441 | 22.1 | 22.4 |
| 442 | 22.1 | 22.4 |
| 443 | 22.1 | 22.4 |
| 444 | 22.1 | 22.4 |
| 445 | 22.1 | 22.4 |
| 446 | 22.1 | 22.4 |
| 447 | 22.1 | 22.4 |
| 448 | 22.1 | 22.4 |
| 449 | 22 | 22.4 |
| 450 | 22 | 22.4 |
| 451 | 22 | 22.4 |
| 452 | 22 | 22.3 |
| 453 | 22 | 22.3 |
| 454 | 22 | 22.3 |
| 455 | 22 | 22.3 |
| 456 | 22 | 22.3 |
| 457 | 22 | 22.3 |
| 458 | 22 | 22.3 |
| 459 | 22 | 22.3 |

| | | |
|---|---|---|
| 460 | 22 | 22.3 |
| 461 | 22 | 22.4 |
| 462 | 22 | 22.4 |
| 463 | 22 | 22.4 |
| 464 | 22 | 22.4 |
| 465 | 22 | 22.4 |
| 466 | 22 | 22.4 |
| 467 | 22 | 22.4 |
| 468 | 22 | 22.5 |
| 469 | 22 | 22.5 |
| 470 | 22.1 | 22.5 |
| 471 | 22.1 | 22.5 |
| 472 | 22.1 | 22.5 |
| 473 | 22.1 | 22.5 |
| 474 | 22.1 | 22.5 |
| 475 | 22.1 | 22.5 |
| 476 | 22.1 | 22.5 |
| 477 | 22.1 | 22.5 |
| 478 | 22.1 | 22.5 |
| 479 | 22.1 | 22.5 |
| 480 | 22.1 | 22.5 |
| 481 | 22.1 | 22.5 |
| 482 | 22.1 | 22.5 |
| 483 | 22.1 | 22.5 |
| 484 | 22.1 | 22.5 |
| 485 | 22.1 | 22.5 |
| 486 | 22.1 | 22.5 |
| 487 | 22.1 | 22.5 |
| 488 | 22.1 | 22.5 |
| 489 | 22.1 | 22.5 |
| 490 | 22.1 | 22.5 |
| 491 | 22.1 | 22.5 |
| 492 | 22.1 | 22.5 |
| 493 | 22.1 | 22.5 |
| 494 | 22.1 | 22.5 |
| 495 | 22.1 | 22.5 |
| 496 | 22.1 | 22.5 |
| 497 | 22.2 | 22.5 |
| 498 | 22.2 | 22.5 |
| 499 | 22.2 | 22.5 |
| 500 | 22.2 | 22.5 |
| 501 | 22.2 | 22.6 |

| | | |
|---|---|---|
| 502 | 22.2 | 22.6 |
| 503 | 22.2 | 22.6 |
| 504 | 22.2 | 22.6 |
| 505 | 22.1 | 22.6 |
| 506 | 22.1 | 22.6 |
| 507 | 22.1 | 22.6 |
| 508 | 22.1 | 22.6 |
| 509 | 22.1 | 22.6 |
| 510 | 22.1 | 22.6 |
| 511 | 22.1 | 22.6 |
| 512 | 22.1 | 22.6 |
| 513 | 22.1 | 22.6 |
| 514 | 22.1 | 22.6 |
| 515 | 22.1 | 22.5 |
| 516 | 22.1 | 22.5 |
| 517 | 22.1 | 22.5 |
| 518 | 22.1 | 22.5 |
| 519 | 22.1 | 22.5 |
| 520 | 22.1 | 22.5 |
| 521 | 22.1 | 22.5 |
| 522 | 22.1 | 22.5 |
| 523 | 22.1 | 22.5 |
| 524 | 22.1 | 22.5 |
| 525 | 22.1 | 22.5 |
| 526 | 22.1 | 22.4 |
| 527 | 22.1 | 22.4 |
| 528 | 22.1 | 22.4 |
| 529 | 22.1 | 22.5 |
| 530 | 22.1 | 22.5 |
| 531 | 22.1 | 22.5 |
| 532 | 22.1 | 22.5 |
| 533 | 22.1 | 22.5 |
| 534 | 22.1 | 22.5 |
| 535 | 22.2 | 22.5 |
| 536 | 22.2 | 22.5 |
| 537 | 22.2 | 22.6 |
| 538 | 22.2 | 22.6 |
| 539 | 22.2 | 22.6 |
| 540 | 22.2 | 22.6 |
| 541 | 22.2 | 22.7 |
| 542 | 22.2 | 22.7 |
| 543 | 22.2 | 22.7 |

| | | |
|---|---|---|
| 544 | 22.2 | 22.7 |
| 545 | 22.2 | 22.8 |
| 546 | 22.2 | 22.8 |
| 547 | 22.2 | 22.8 |
| 548 | 22.2 | 22.8 |
| 549 | 22.2 | 22.8 |
| 550 | 22.2 | 22.8 |
| 551 | 22.2 | 22.8 |
| 552 | 22.2 | 22.8 |
| 553 | 22.2 | 22.8 |
| 554 | 22.2 | 22.8 |
| 555 | 22.2 | 22.8 |
| 556 | 22.2 | 22.8 |
| 557 | 22.2 | 22.8 |
| 558 | 22.2 | 22.8 |
| 559 | 22.2 | 22.8 |
| 560 | 22.2 | 22.8 |
| 561 | 22.2 | 22.8 |
| 562 | 22.2 | 22.8 |
| 563 | 22.2 | 22.8 |
| 564 | 22.2 | 22.8 |
| 565 | 22.2 | 22.8 |
| 566 | 22.2 | 22.8 |
| 567 | 22.2 | 22.8 |
| 568 | 22.2 | 22.7 |
| 569 | 22.2 | 22.6 |
| 570 | 22.2 | 22.7 |
| 571 | 22.2 | 22.7 |
| 572 | 22.2 | 22.7 |
| 573 | 22.2 | 22.7 |
| 574 | 22.2 | 22.7 |
| 575 | 22.2 | 22.7 |
| 576 | 22.2 | 22.7 |
| 577 | 22.1 | 22.7 |
| 578 | 22.1 | 22.7 |
| 579 | 22.1 | 22.7 |
| 580 | 22.1 | 22.7 |
| 581 | 22.1 | 22.8 |
| 582 | 22.1 | 22.8 |
| 583 | 22.1 | 22.8 |
| 584 | 22.1 | 22.8 |
| 585 | 22.1 | 22.8 |

| | | |
|---|---|---|
| 586 | 22.1 | 22.8 |
| 587 | 22.1 | 22.8 |
| 588 | 22.1 | 22.8 |
| 589 | 22.1 | 22.8 |
| 590 | 22.1 | 22.8 |
| 591 | 22.1 | 22.8 |
| 592 | 22.1 | 22.8 |
| 593 | 22.1 | 22.8 |
| 594 | 22.1 | 22.8 |
| 595 | 22.1 | 22.8 |
| 596 | 22.1 | 22.8 |
| 597 | 22.1 | 22.8 |
| 598 | 22.1 | 22.8 |
| 599 | 22.1 | 22.8 |
| 600 | 22.1 | 22.8 |
| 601 | 22.1 | 22.8 |
| 602 | 22.1 | 22.8 |
| 603 | 22.1 | 22.8 |
| 604 | 22.1 | 22.8 |
| 605 | 22.1 | 22.7 |
| 606 | 22.1 | 22.7 |
| 607 | 22.1 | 22.7 |
| 608 | 22.1 | 22.7 |
| 609 | 22.1 | 22.7 |
| 610 | 22.1 | 22.7 |
| 611 | 22.1 | 22.7 |
| 612 | 22.2 | 22.7 |
| 613 | 22.2 | 22.7 |
| 614 | 22.2 | 22.7 |
| 615 | 22.2 | 22.7 |
| 616 | 22.2 | 22.7 |
| 617 | 22.2 | 22.7 |
| 618 | 22.2 | 22.7 |
| 619 | 22.2 | 22.7 |
| 620 | 22.2 | 22.7 |
| 621 | 22.2 | 22.7 |
| 622 | 22.2 | 22.8 |
| 623 | 22.2 | 22.8 |
| 624 | 22.2 | 22.8 |
| 625 | 22.2 | 22.8 |
| 626 | 22.2 | 22.8 |
| 627 | 22.2 | 22.9 |

| | | |
|---|---|---|
| 628 | 22.2 | 22.9 |
| 629 | 22.2 | 22.9 |
| 630 | 22.2 | 22.9 |
| 631 | 22.2 | 22.9 |
| 632 | 22.1 | 22.8 |
| 633 | 22.1 | 22.9 |
| 634 | 22.1 | 22.8 |
| 635 | 22.1 | 22.8 |
| 636 | 22.1 | 22.8 |
| 637 | 22.1 | 22.8 |
| 638 | 22.1 | 22.8 |
| 639 | 22.1 | 22.8 |
| 640 | 22.1 | 22.8 |
| 641 | 22.1 | 22.8 |
| 642 | 22.1 | 22.8 |
| 643 | 22.1 | 22.8 |
| 644 | 22.1 | 22.8 |
| 645 | 22.1 | 22.8 |
| 646 | 22.1 | 22.8 |
| 647 | 22.1 | 22.7 |
| 648 | 22.1 | 22.7 |
| 649 | 22.1 | 22.7 |
| 650 | 22.1 | 22.7 |
| 651 | 22.1 | 22.7 |
| 652 | 22.1 | 22.7 |
| 653 | 22.1 | 22.7 |
| 654 | 22.1 | 22.7 |
| 655 | 22.1 | 22.7 |
| 656 | 22.1 | 22.7 |
| 657 | 22.1 | 22.7 |
| 658 | 22.1 | 22.7 |
| 659 | 22.1 | 22.7 |
| 660 | 22.1 | 22.7 |
| 661 | 22.1 | 22.7 |
| 662 | 22.1 | 22.7 |
| 663 | 22.1 | 22.7 |
| 664 | 22.1 | 22.7 |
| 665 | 22.1 | 22.7 |
| 666 | 22.1 | 22.7 |
| 667 | 22.1 | 22.7 |
| 668 | 22 | 22.7 |
| 669 | 22 | 22.7 |

| | | |
|---|---|---|
| 670 | 22 | 22.7 |
| 671 | 22 | 22.6 |
| 672 | 22 | 22.6 |
| 673 | 22 | 22.6 |
| 674 | 22 | 22.5 |
| 675 | 22 | 22.6 |
| 676 | 22 | 22.6 |
| 677 | 22.1 | 22.6 |
| 678 | 22.1 | 22.6 |
| 679 | 22.1 | 22.6 |
| 680 | 22.1 | 22.5 |
| 681 | 22.1 | 22.5 |
| 682 | 22.1 | 22.5 |
| 683 | 22.1 | 22.5 |
| 684 | 22.1 | 22.5 |
| 685 | 22.1 | 22.5 |
| 686 | 22.1 | 22.5 |
| 687 | 22.1 | 22.5 |
| 688 | 22.1 | 22.5 |
| 689 | 22.1 | 22.5 |
| 690 | 22.1 | 22.5 |
| 691 | 22.1 | 22.6 |
| 692 | 22.1 | 22.6 |
| 693 | 22.1 | 22.6 |
| 694 | 22.1 | 22.6 |
| 695 | 22.1 | 22.6 |
| 696 | 22.1 | 22.6 |
| 697 | 22.1 | 22.6 |
| 698 | 22.1 | 22.6 |
| 699 | 22.1 | 22.6 |
| 700 | 22.1 | 22.6 |
| 701 | 22.1 | 22.6 |
| 702 | 22.1 | 22.6 |
| 703 | 22.1 | 22.6 |
| 704 | 22.1 | 22.6 |
| 705 | 22.1 | 22.6 |
| 706 | 22.1 | 22.6 |
| 707 | 22.1 | 22.6 |
| 708 | 22.1 | 22.6 |
| 709 | 22.1 | 22.6 |
| 710 | 22.1 | 22.6 |
| 711 | 22.1 | 22.6 |

| | | |
|---|---|---|
| 712 | 22.1 | 22.7 |
| 713 | 22.1 | 22.7 |
| 714 | 22.1 | 22.7 |
| 715 | 22.1 | 22.7 |
| 716 | 22.1 | 22.7 |
| 717 | 22.1 | 22.7 |
| 718 | 22.1 | 22.7 |
| 719 | 22 | 22.7 |
| 720 | 22 | 22.6 |
| 721 | 22 | 22.6 |
| 722 | 22 | 22.7 |
| 723 | 22 | 22.7 |
| 724 | 22 | 22.7 |
| 725 | 22 | 22.6 |
| 726 | 22 | 22.6 |
| 727 | 22 | 22.6 |
| 728 | 22 | 22.5 |
| 729 | 22 | 22.5 |
| 730 | 22 | 22.5 |
| 731 | 22 | 22.5 |
| 732 | 22 | 22.5 |
| 733 | 22 | 22.4 |
| 734 | 22 | 22.4 |
| 735 | 22 | 22.4 |
| 736 | 22 | 22.4 |
| 737 | 22 | 22.4 |
| 738 | 22 | 22.4 |
| 739 | 22 | 22.4 |
| 740 | 22.1 | 22.4 |
| 741 | 22.1 | 22.4 |
| 742 | 22.1 | 22.4 |
| 743 | 22.1 | 22.4 |
| 744 | 22.1 | 22.5 |
| 745 | 22.1 | 22.5 |
| 746 | 22.1 | 22.5 |
| 747 | 22.1 | 22.5 |
| 748 | 22.1 | 22.5 |
| 749 | 22.1 | 22.4 |
| 750 | 22.1 | 22.4 |
| 751 | 22.1 | 22.4 |
| 752 | 22.1 | 22.4 |
| 753 | 22.1 | 22.5 |

| | | |
|---|---|---|
| 754 | 22.1 | 22.6 |
| 755 | 22.1 | 22.6 |
| 756 | 22.1 | 22.6 |
| 757 | 22.1 | 22.6 |
| 758 | 22.1 | 22.6 |
| 759 | 22.1 | 22.6 |
| 760 | 22.1 | 22.4 |
| 761 | 22.1 | 22.5 |
| 762 | 22.1 | 22.4 |
| 763 | 22.1 | 22.6 |
| 764 | 22.1 | 22.6 |
| 765 | 22.1 | 22.7 |
| 766 | 22.1 | 22.6 |
| 767 | 22.2 | 22.6 |
| 768 | 22.2 | 22.6 |
| 769 | 22.2 | 22.6 |
| 770 | 22.2 | 22.7 |
| 771 | 22.2 | 22.7 |
| 772 | 22.2 | 22.7 |
| 773 | 22.2 | 22.8 |
| 774 | 22.2 | 22.8 |
| 775 | 22.1 | 22.6 |
| 776 | 22.1 | 22.5 |
| 777 | 22.1 | 22.5 |
| 778 | 22.1 | 22.5 |
| 779 | 22.1 | 22.5 |
| 780 | 22.1 | 22.4 |
| 781 | 22.1 | 22.4 |
| 782 | 22.1 | 22.4 |
| 783 | 22.1 | 22.4 |
| 784 | 22.1 | 22.5 |
| 785 | 22.1 | 22.5 |
| 786 | 22.1 | 22.4 |
| 787 | 22.1 | 22.4 |
| 788 | 22.1 | 22.3 |
| 789 | 22.1 | 22.5 |
| 790 | 22.1 | 22.6 |
| 791 | 22.1 | 22.6 |
| 792 | 22.1 | 22.6 |
| 793 | 22.1 | 22.6 |
| 794 | 22.1 | 22.6 |
| 795 | 22.1 | 22.6 |

| | | |
|---|---|---|
| 796 | 22.1 | 22.6 |
| 797 | 22.1 | 22.7 |
| 798 | 22.1 | 22.7 |
| 799 | 22.1 | 22.6 |
| 800 | 22.1 | 22.7 |

# Appendix E: Time Sheet and Costs

## Hours:

| | |
|---|---|
| Research and Design: | 30 hours |
| Construction: | 24 hours |
| Testing: | 2.5 hours |
| Typing: | 16 hours |

**Total: 72.5 hours**

## Cost:

| | |
|---|---|
| Building Materials, Home Depot | $138.78 |
| 6061-T6 Aluminum Sheet .020 inch, OnlineMetals.com: | $84.96 |
| Vernier Lab Cradle, Vernier Technologies: | $155.00 |
| Vernier Thermocouples, Vernier Technologies: | $120.00 |
| Pyranometer, Amazon.com: | $94.14 |
| Infrared Thermometer, Amazon.com: | $25.00 |
| Solar Engineering of Thermal Processes Textbook, Amazon.com: | $76.99 |
| Introduction to Heat Transfer Textbook, Cal Poly University Store: | $163.99 |
| Printing and Binding, Poly Prints: | $13.19 |

**Total: $872.05**