Formula SAE Cooling System Design

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The complete senior project report was submitted to the project advisor and sponsor. The results of this project are of a confidential nature and will not be published at this time.

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Executive Summary

The overall objective of this senior project is to develop, via testing and analysis, a guided process that will aid the Cal Poly Formula SAE team in designing their cooling system. More specifically, a set of designed tests will yield the results necessary in determining a combination of fan and radiator that will achieve appropriate cooling.

A test section that has the capability of interfacing with both the wind tunnel in the Thermal Science Lab and a radiator will be used to facilitate the necessary experiments. The wind tunnel is powered by fan controlled by a variable frequency drive that can induce a range of air flow rates through the duct and radiator. Five tests will be performed, whose goals are as follows:

1. Determine mass flow rate of the cooling water as a function of the crank shaft rotational speed.
2. Determine heat rejected from the engine to the cooling water as a function of crank shaft rotational speed.
3. Determine the mass flow rate of air through the core as a function of car speed.
4. Determine static pressure drop of the air across the radiator core at varying air mass flow rates.
5. Determine the heat rejection rate associated with a test radiator as a function of both the mass flow rate of air through the core and the mass flow rate of cooling water.

These tests will develop relationships that will ultimately allow the formula team to predict the heat rejection necessary at every car speed as well as the ability of a particular radiator to reject heat at those speeds. A guided process will be presented that will aid the team in designing the cooling system to be used on the formula competition car. By performing these tests, the FSAE team can choose an appropriate radiator type and face area for the racecar's specific cooling needs each year. This process will allow the team to minimize the radiator's size and optimize cooling to increase performance.

The following report will detail background information regarding a car's cooling system, a description of conceptual designs, the final design process, the test procedures and finally sample results produced via testing.

Chapter1: Introduction

1. Sponsor Background and Needs

Cal Poly's Formula SAE team needs a method of correctly and easily sizing the radiator for their racecar each year. Currently, radiators are chosen based on previous radiators that the team has used that have adequately cooled the engine but without the analysis of the cooling system to correctly choose the face area, type of radiator and manufacturer of the radiator for each car. Although the cooling systems in the past have worked, they lack true engineering justification. In developing this test method, we will aid the FSAE team in the process of choosing a radiator and fan to minimize the size and weight of the radiator for their application.

2. Formal Problem Definition

The Formula SAE team at Cal Poly sponsored us in our development of a process that will aid them in designing the formula car's cooling system each year. In the past, there has been no formal engineering design that has gone into developing the cooling system, so we have developed a test procedure that will guide them through a design process that is based on engineering principles in fluids and heat transfer.

Chapter 2: Background

Background research spanned the following topics: the FSAE rules regarding keeping the engine cool, the components and plumbing used in cooling systems, methods of sizing a radiator, the variables that affect the engine cooling and how these variables can be manipulated in the system, as well as measurement techniques. A detailed explanation of the background research that was performed follows.

1. FSAE Rules

Because we are working with FSAE, the cooling system of the car must comply with the FSAE Rules. In the 2013 FSAE Rules, the specifications relating to the cooling system are that there must be a "firewall to separate the driver compartment from all the components of the fuel supply, the engine oil, the liquid cooling systems and any high voltage system" (T4.5.1. 2013fsaerules), the "cooling or lubrication system must be sealed" (T8.2.1 2013fsaerules), "any catch can on the cooling system must vent through a hose with a minimum internal diameter of 3 mm" (T8.2.4 2013fsaerules), and "no power device may be used to move or remove air from under the vehicle except fans designed exclusively for cooling" (T9.4 2013fsaerules). Also, "water-cooled engines must only use plain water. Electric motors, accumulators or HV electronics can use plain water or oil as the coolant. Glycol-based antifreeze, "water wetter", water pump lubricants of any kind, or any other additives is strictly prohibited" (T8.1 2013fsaerules). Thus, the details within the cooling system such as the number, size, type, and orientation of the radiators or whether oil coolers and fans are necessary are left to the team to decide. This leaves our team a lot of freedom to change and test some of these variables in order to optimize the system.

2. Initial Meetings

We first met with John Waldrop at the Hangar on the California Polytechnic University campus who gave us an introduction to the FSAE team, showed us the car that would be used at competition in June 2013, showed us the current cooling system components, informed us of what testing they have done already, and described some of the significant variables. John described the dynamometer and the way it worked to measure the torque at different speeds and tune the engine by determining a correct gas/air mixture for the combustion process. The engine is cooled with a radiator-fan combination on the dynamometer. A dynamometer, or "dyno," is an instrument used to measure torque. In the case of the Formula SAE team, it is used as a way of tuning their engine and will be used in our testing as described in *Test Descriptions* (*Chapter 6, Section 1*). A diagram of a typical dyno can be observed in *Figure 1* below. In the figure, the engine's drive shaft is coupled to a shaft on the dyno. A tachometer is used to measure the

rotational speed of the shaft and the torque arm, which is generally resisted with some sort of fluid inside the housing, is used to measure torque. The torque is displayed on the scale and the housing is supported in trunnion bearings.

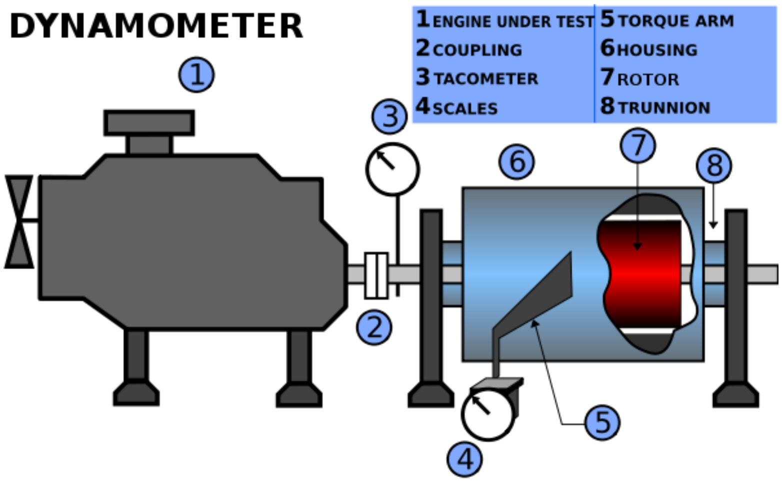


Figure 1. *Diagram of a typical dynamometer coupled to an engine*

The test setup on the wind tunnel will mimic heat generated in the engine by using a hot water source in the lab to fill the radiator. The water will need to be 180°F because when the water flowing into the radiator reaches this temperature, the radiator fan on the car is set to turn on to increase heat rejection and maintain this inlet temperature. We also met with Matt Roberts and Eric Griess (two engine specialists on the FSAE team) to determine specific requirements for our project proposal and gain some general knowledge regarding the engine.

Information on the FSAE car for June 2013 race from John Waldrop and Matt Roberts:

- The fuel is gas
- The coolant is water
- Engine: Yamaha WR450F from 2003
- Optional use of a turbo-charger
- They provided a histogram to show the number of occurrences of the various speeds of the racecar during a typical race. Refer to Figure 2.
- The fan turns on when the temperature of the water entering the engine is greater than or equal to 180 °F, and the fan turns off when the water entering the engine reaches 160°F. The temperatures are measured within 6-12 inches before and after the engine (we can assume there is negligible heat loss between the inlet/outlet of the engine's cooling system and where the temperature is measured).
- The water pump is engine-driven

The FSAE team provided a histogram (see *Figure 2*) which describes the number of instances when the car travels at a particular speed (in ft/s) over the course of the autocross event. This is important because we can see the range of speeds spans a minimum speed of 35 ft/s to a maximum speed of 95 ft/s and that a speed of 40 ft/s occurs most often in a typical race. This will aid the team in choosing a design point which correlates to a particular car speed where they will perform the guided radiator sizing process. During this process, they will be able to measure the heat transferred from the engine to the cooling water over a range of mass flow rates of air through the radiator core. It is important to realize that the speed of the car is not equal to the average speed of the air that will move through the radiator plane due to the effects of friction and drag in the radiator core. A method of developing relationship between the two to account for the air velocity changes through the radiator core will be provided.

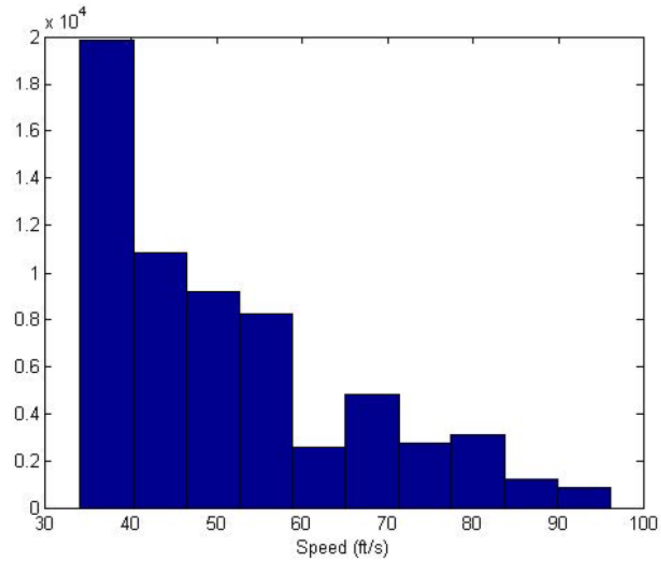


Figure 2. *Histogram describing the number of instances when the car travels at a particular speed*

We also had some helpful meetings with Cal Poly Professors Patrick Lemieux, John Fabijanic, Kim Shollenberger, and Glen Thorncroft. From these meetings, we came up with a list of variables that should be considered. These variables are as follows:

- Mass flow rate of the water and air
- When in the race (idle or high speed) is the engine the hottest
- Type of radiator: Downflow/Cross-flow
- Aluminum/Brass/Copper Core and the difference it makes for heat transfer
- Orientation of the Radiator (heat transfer or packaging reasons)
- Number of radiators
- Fan (how to size, when necessary, how many, where placed)
- Ducting in and out of the radiator (how diffusion affects the flow)
- Pressure Drop Across the Radiator/Rise across the Fan
- Accuracy of the equipment used

3. Engine Used on the Car

The engine used on the 2013 formula car was a 2003 Yamaha WR450F engine, which is a 40-horsepower, single-cylinder, water-cooled, engine. As in almost all ground vehicle engines, the engine is cooled using a radiator, where the cooling water flows through canals in the engine to remove heat, then heat is transferred to the air when the cooling water flows through the radiator core. The engine from a very similar 2007 model of the same dirt bike is depicted in *Figure 3* below. The engine and the tip of the bottom tank of one of the radiators can be observed.

Figure 3. *Yamaha WR450F engine, used by Cal Poly FSAE in 2013*

The method for sizing the radiator via testing will allow the formula team to size their radiator in the event that they decide to use a different engine. For instance, they could use the engine from a Honda CBR600F4i or CBR900RR. Honda's CBR600F4i is a 90.1-hp, 4-cylinder engine and Honda's CBR900RR engine is 128-hp and 4-cylinder as well. In this case, it is predictable that more heat would need to be rejected from each of these engines because they would produce more waste heat. This is due to the fact that the waste heat produced by the engine is proportional to the power that the engine produces. The process for sizing the radiator or radiators that will be provided allows the team to take measurements to determine the amount of heat that their engine rejects to the cooling water. Similarly, if the team decides to use a turbocharger and oil cooler, more heat would need to be rejected from the system.

4. Types of Radiators

In the recent past, the FSAE team has used dirt bike engines to power their cars, and they have used the OEM radiators that were used with the corresponding engine on the stock dirt bike. In knowing how much heat transfer area the radiator needs to have to achieve adequate cooling, the team can get more creative with the types of radiators they use. Radiators exist as either

crossflow or downflow radiators. A crossflow radiator has tanks on the left and right sides of the radiator core and the cooling fluid travels parallel to the ground. Conversely, a downflow radiator has tanks above and below the core and cooling fluid moves down towards the ground through the core. In terms of performance, it is believed that there is no real difference between the two types of radiators. Radiators also exist as single or dual pass radiators. In a single pass radiator, the cooling fluid crosses the core once, while it crosses the core twice in a dual pass radiator. *Figure 4* depicts these characteristics. Typically, the team uses single pass radiators which are more conventional, generally cheaper, and good for low flow/low pressure pumps. The dual pass radiators are typically used for higher flow/higher pressure pump systems where a single pass would not cool the coolant enough and a second pass is necessary.

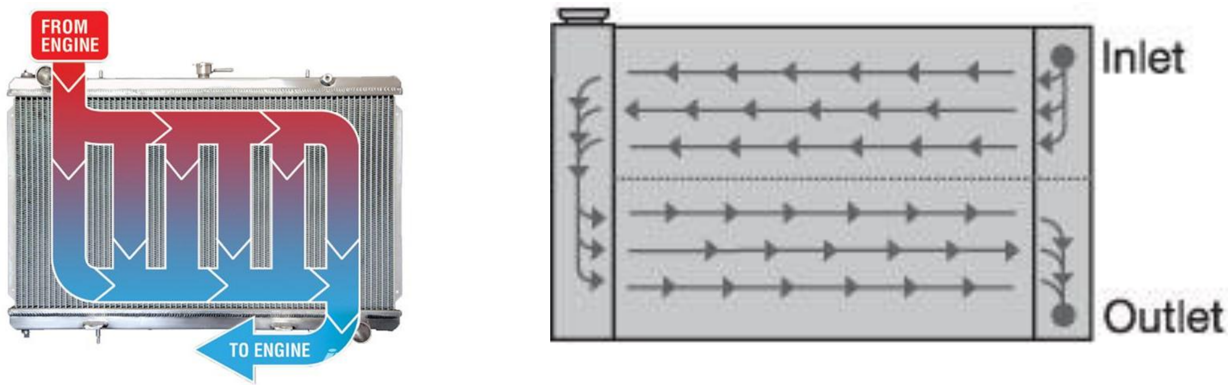


Figure 4. *Diagrams of single pass, downflow (left) and dual pass, crossflow (right) radiators*

5. Radiator Installation in FSAE Application

There are no FSAE regulations concerning where to mount the radiators or how many radiators to use, but typically, the radiators are side-mounted as depicted in *Figure 5*. They are often mounted at an angle, but this is only a product of packaging concerns. The angle at which they are mounted should be minimized because the air streamlines won't be guided evenly through the tubes and there can be uneven cooling across the radiator. In the case of the 2013 Cal Poly FSAE car, the two relatively smaller OEM radiators, have been side-mounted. It is also worth-

Figure 5. *This FSAE team has installed their radiator such that it is side-mounted at an angle*

while to note that when two radiators are used, they can be connected either in parallel or series. It may be more efficient to connect them in parallel because high temperature cooling water directly from the engine would flow to both radiators as opposed to having lower temperature water flow to one of the radiators. The larger temperature gradient between cooling air and hot water yields greater heat transfer. However, the distribution of the coolant must be split evenly to both radiators to be effective, which is difficult to accomplish and risky as well. If the amount of cooling fluid supplied to each radiator is not split evenly, it is possible that one radiator could be doing almost none of the cooling in which case, the engine is at risk of overheating. As a result, it is most common to connect two radiators in series in this application.

6. Fan Sizing

In a manner similar to a pump, a fan can pull or push air so that it travels at a flow rate specific to a pressure drop. That pressure drop is a product of the system design, and the system pressure drop varies with the velocity of the flow. As a result each fan-system combination has an equilibrium point at which it will operate, as depicted in *Figure 6*. The figure also shows a stall region where the flow separates from the fan blades, which create vortices. These vortices result in a back pressure, which is reflected in the figure.

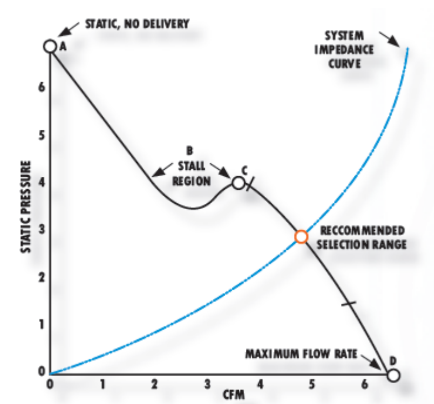


Figure 6. *Typical fan-system curve*

The formula team will be able to determine the static pressure drop across the radiator so that they can choose a fan, based on the manufacturer’s fan curve, if they decide to use one.

Initially, when a flow bench was going to be built to facilitate testing, an estimate the system pressure loss (losses due to ducting, duct components, and radiator core) was needed to size the fan that would be used on the flow bench. We were provided a sample data point which indicated the static pressure drop across a radiator core at a given speed: 50 ft/s and 57 psi pressure drop. With this data, the loss coefficient of a typical radiator core could be estimated. In estimating the major losses in the ducting and minor losses in the duct components at the maximum speed at which the flow bench would be operated, we could choose a fan. The fan should have been able to operate such that air would flow at the necessary maximum speed and overcome the calculated system back pressure.

When we decided to conduct testing on the wind tunnel in the Thermal Science Lab, we assumed that the fan on the wind tunnel would be adequate. That wind tunnel is capable of pulling air at a

velocity of up to 200 mph with no added loss elements in the ducting. We concluded that it would be adequate to get our desired air speeds.

7. Measuring the Mass Flow Rate of Air

It is important to be able to measure the mass flow rate of the air in the wind tunnel duct because heat transfer is highly dependent on the mass flow rate of the fluids involved. Once the average velocity of the flow is determine, it is very easy to determine the mass flow rate of the fluid. It will be assumed that air density is constant as it pertains to the application of flow through a hot radiator. Proof of the validity of this assumption is described in *Supporting Preliminary Analysis* (*Chapter 3, Section 3*). The mass flow rate of air is determined using the equation below:

$$\dot{m} = \rho v A \tag{1}$$

where $\dot{m}$ is the mass flow rate of the air, ρ is the density of air, V is the average velocity of the air through the duct, and A is the cross-sectional area of the duct. We assume the duct area is equal to the face area of radiator tested if the radiator is mounted normal to the duct without any air leaks around the radiator. The mass flow rate is conserved before and after the radiator as well as before and after the fan. The velocity can be measured with different methods and instruments, each with different accuracies. Some of these methods are as follows.

<u>Method 1: Laminar Flow Element (LFE)</u>

In an LFE, the static pressure drop is measured across a loss element with a calculated loss coefficient. With the, loss coefficient, k, the static pressure drop, Δp and the density of the fluid, the following equation can be used to find the average velocity of the air.

$$\Delta p = k 0.5 \rho v^2 \tag{2}$$

Laminar flow elements can be a very accurate method of measuring air velocity in a duct. Cal Poly has two LFE's in the storage room in the Thermal Science Lab, one of which can be interfaced with the wind tunnel in the lab. The LFE that can be interfaced with the wind tunnel is depicted in *Figure 7.* The two LFEs are both made by Meriam. The smaller LFE (from *Figure 7*) with part number 50MC2-04, is approximately 4" in diameter at the inlet and outlet and can measure flow rates up to 400 CFM. The

Figure 7. *Meriam 50MC2-04 LFE*

larger LFE, with part number 50MC2-08, is approximately 8” in diameter at the inlet and outlet and can measure flow rates up to 2200 CFM.

It was determined that the LFE would not be used during testing because it is very likely that it needed to be calibrated. Further, it is typically used to measure flow rates that are less than 2 m/s, which is not adequate in the case of the necessary test procedure.

Method 2: Pitot-Static Tube Array to produce Average Velocity

An array of pitot-static tube readings can be used to produce an average air velocity through the core of the radiator. Pitot-static tubes measure both the total pressure and static pressure using to separate ports on the pitot tube. In general, pitot static tubes are composed of two separate, concentric tubes: one which measures static pressure with a port perpendicular to the flow, and one which measures total pressure parallel to the flow. This is illustrated in *Figure 8* on the right. The digital readout that the pitot-static tube is connected to can then use the static pressure (P_1 in the figure), total pressure (P_2 in the figure), and fluid density to deduce the dynamic pressure and the velocity component of the dynamic pressure that follows. This is obtained theoretically via the following equation.

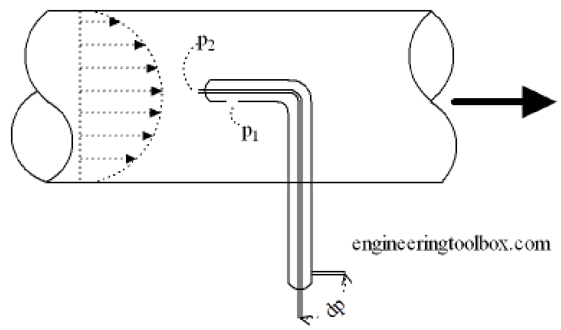


Figure 8. *Diagram of a pitot-static tube in a duct with air flow*

$$v = \sqrt{\frac{2(p_t - p_s)}{\rho}} \tag{3}$$

A pitot-static tube only has the ability to determine the velocity of the flow along a streamline. It is highly unlikely that the velocity of the flow will be the same over the entire face of the radiator core. Due to the fact that the goal is to eventually determine the mass flow rate of air through the radiator core, an array of measurements will need to be taken and averaged to determine an average velocity of air through the core. This array of measurements should be taken in a manner similar to the one shown in *Figure 9.*

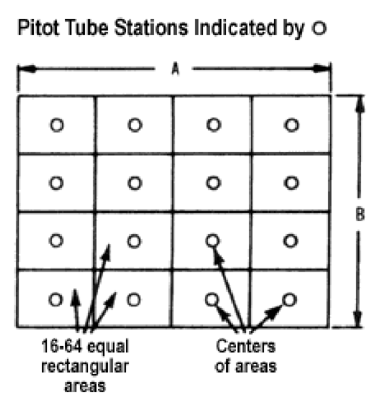


Figure 9. *Example of the way an array of measurements may be taken with a pitot-static tube*

There are some drawbacks involved in using this method. First, the pitot-static tube needs to be oriented so that the port that measures total pressure needs to be oriented so that it is parallel to the flow along a streamline. This is difficult to do even in developed flow where the flow is

uniform and flowing along one axis in the duct. Second, because the pitot-static tube would be used behind the radiator, the flow may not be developed until well after it has passed through the radiator core.

Method 3: Pressure Differential in Venturi Section

Using a Venturi section is a simple and fairly accurate way of determining the mass flow rate of the airflow in a duct directly, as opposed to determining the velocity, then using the velocity to find the mass flow rate according to *Equation 1*. A Venturi, or contraction area in the duct, can be used to find the velocity of the air through the pressure drop from the large to small diameter cross sections. This is illustrated in *Figure 10* below.

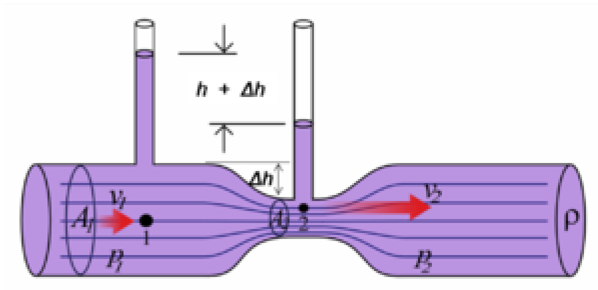


Figure 10. *A venturi section with a liquid column manometer*

A manometer is used to determine the difference in pressure between the two sections. The difference in liquid column heights is then used to determine the differential pressure ($P_1 - P_2$ where P_1 and P_2 are as they appear in *Figure 10*). This is accomplished using the following equation.

$$h = \frac{P_1 - P_2}{\gamma} \quad (4)$$

Once the pressure differential has been determined, the following equation can be used to determine the mass flow rate of the air in the duct.

$$Q = A_1 \sqrt{\frac{2}{\rho} \times \frac{(P_1 - P_2)}{\left({}^{A_1}/_{A_2}\right)^2 - 1}} = A_2 \sqrt{\frac{2}{\rho} \times \frac{(P_1 - P_2)}{1 - \left({}^{A_2}/_{A_1}\right)^2}} \quad (5)$$

The caveat to using this method is that the Venturi section requires a gradual expansion after the reduced area region, or the flow will separate from the duct walls. This is not something that would be practical to install on the wind tunnel in the Thermal Science Lab.

Method 4: Measuring Static Pressure Rise Across the Fan

In a manner similar to the process that accompanies the use of the Venturi section, the velocity can be determined by measuring the pressure rise across the fan. A U-tube manometer could be used to determine the pressure differential across the fan. The pressure differential would be determined using the difference in height via *Equation 4*. This measurement could then be used with the manufacturers fan curve to determine the corresponding mass flow rate of air. Reference *Figure 6* in *Fan Sizing* from this chapter to see how a fan curve could be used to find the mass flow rate of the air based on the pressure rise.

8. Effectiveness-NTU Method of Determining Heat Transfer Characteristics

In *Chapter 6*, the Formula SAE team will be led through the process of determining the rate at which heat must be rejected from the radiator, and the mass flow rates of both of the fluids. They can choose an inlet air temperature, which will be equal to the ambient air temperature they want to design for and a desired temperature for the cooling water that will enter the radiator, then use the Effectiveness-NTU method to determine a theoretical solution to the problem.

To begin, they would want to select a radiator that is typical of the type of radiator they would use on the car. This is the radiator they would be used to determine the effectiveness of that particular type of radiator. That effectiveness will then be used to find an NTU value for the design point. The equations and descriptions below explain how to find the NTU value.

All of the following equations are taken from *Introduction to Heat Transfer*, 6th Edition by David Dewitt.

1. Determine the heat capacities, C_c for air, and C_h for the cooling water. The subscripts *c* and *h* are used for the cold fluid (air) and the hot fluid (cooling water), respectively.

$$C_c = \dot{m}_c * c_{p,c} \quad (6)$$
$$C_h = \dot{m}_h * c_{p,h} \quad (7)$$

   Where $\dot{m}$ denotes the mass flow rate and c_p is the constant pressure specific heat of the respective fluids. Then whichever heat capacity is lower becomes C_{min} and the corresponding fluid becomes the "minimum fluid."

2. Determine the maximum possible heat transfer. Note that T_i denotes the inlet temperature of the hot or cold fluid.

$$q_{max} = C_{min}(T_{h,i} - T_{c,i}) \quad (8)$$

3. Calculate the actual heat transfer that is occurring via testing. This will be accomplished using the inlet and outlet temperatures of the cooling water: $T_{h,i}$ and $T_{h,o}$, respectively.

$$q = C_h(T_{h,i} - T_{h,o}) \tag{9}$$

4. Determine the effectiveness of the heat exchanger: the ratio of the actual heat transfer to the maximum possible heat transfer.

$$\varepsilon = \frac{q}{q_{max}} \tag{10}$$

5. Determine the NTU via the following equations.

$$C_r = {C_{min}}/{C_{max}} \tag{11}$$

$$\varepsilon = 1 - exp\left[\left(\frac{1}{C_r}\right)(NTU)^{0.22}\{exp[-C_r(NTU)^{0.78}] - 1\}\right] \tag{12}$$

At this point, the following equation would be used to predict the required heat transfer area.

$$NTU = \frac{UA}{C_{min}} \tag{13}$$

However, there is no easy way predict the overall heat transfer coefficient, *U*, for the radiator that would be used. One way to abate this problem would be to develop a method of predicting the overall heat transfer coefficient for a type of radiator based on the overall heat transfer area, *A*. At this point, they could substitute the expression describing this relationship into *Equation 13* above, which would eliminate all the variables except, *A,* the heat transfer area needed.

9. Literature Review for Testing Procedure Formulation

In *The Design of Automobile and Racing Car Cooling Systems* (Callister), the first goal in the design of a cooling system should be to find out how much heat the engine rejects. He recommended testing the engine on the dynamometer and calculating the heat rejection of the coolant at wide open throttle. He said this can be done in two different ways: the one is by measuring the flow rate of the coolant and the temperature differences of the coolant at the inlet and outlet of the radiator to find the rate at which heat is rejected to the cooling water, *Q*, via the following equation:

$$Q = \dot{m}c_p(T_{in} - T_{out}) \tag{14}$$

where $\dot{m}$ is the mass flow rate, c_p is the specific heat of the coolant, and T_{in} and T_{out} are the temperatures of the cooling fluid entering and exiting the radiator.

It is also possible to determine the heat rejection from the engine is by measuring the heat added to the air flowing through the radiator core. This is more difficult to do because the process of measuring the temperature of the air exiting the radiator core is much more convoluted than measuring the temperatures of the cooling water.

According to Callister, the next step is to find the pressure drop in the air flowing through the radiator versus the air velocity (or mass flow rate). He also recommended finding the air flow rate delivered by a fan as a function of pressure drop; however, ideally, the fan manufacturer would provide a fan curve. The final goal would be to have a fan curve, a radiator air-side flow curve and a heat transfer rate curve.

10. Equipment Available at Cal Poly

The following is equipment that is available on campus and is necessary to perform the testing described later in *Chapter 6*.

- Wind Tunnel: The wind tunnel is equipped with a fan and variable frequency drive so that the speed of the fan is adjustable. At the system load incurred solely due to the ducting on the wind tunnel, the fan is capable of pulling air at speeds of up to 200 mph. The wind tunnel ducting is broken up into different sections, so adding and removing sections is relatively easy.

- The Laminar Flow Element: An LFE in the Thermal Science Lab can be used to obtain very accurate pressure readings at air flow rates lower than 2 m/s. Because the test procedures require flow rates above 2 m/s, the LFE will be replaced by a straight duct.

- Liquid Column Manometer: A liquid column manometer is installed on the back wall near the test section of the wind tunnel where the radiator will be placed. It is inclined when the pressure differential is less than 1 inch of water.

- Thermocouple Wire & Digital Readouts: Thermocouple wire and digital readouts are readily available in the Thermal Science Lab.

- Hose Coupling w/ Embedded Thermocouple: There are hose couplers with embedded thermocouples that can be used with the hoses that go into and out of the radiator to measure the temperature of the cooling water.

- Heat Bath w/ Pump: There is hot water bath that has a capacity of up to 7 gallons. It is equipped with a 1000-watt heater and a pump. The pump could achieve a maximum flow rate of about 5 gpm when the radiator was connected for testing. Another pump added in series will add energy to the system in the form of the head lost to tubing and radiator. However 5 gpm, may be sufficient in replicating the flow rate from the water pump on the engine. Testing could not be performed to determine the flow rate of the engine's water pump.

11. Test Equipment Requirements

Requirements have been established for the test equipment to be used over the course of the data collection. These requirements are as follows.

- Wind Tunnel: The wind tunnel will provide the air flow through the radiator core, which will remove heat from the hot water.
    - Must have the ability to be fitted with the test section that will allow the radiator to interface with the wind tunnel
    - Must be airtight at each section connection to ensure that air mass is conserved in each section of the ducting
    - Flow must have the ability to become fully developed where air flow tests are performed
    - Radiator interface cannot be permanent, i.e. the test section needs to accommodate testing with different radiators
    - Hot water must be available near the wind tunnel
    - Must be able to pull air through the radiator core speeds of up to 30 mph (14 m/s)
    - Fan speed must be variable so that a range of air velocities can be achieved
    - Test section must be able to accommodate use of a pitot static tube in the ducting
    - Must accommodate static pressure measurements on either side of radiator

- Water Pump: The water pump will provide the hot water flow through the radiator.
    - Must be able to achieve flow rates of up to 5 gpm. One source indicated that the maximum cooling water flow rate in the Yamaha WR450F engine is 19 liters per minute, ~5.0 gpm. Water pump flow rate testing could not be performed to verify the cooling water flow rate due to lack of engine availability, but 0-5 gpm will provide a solid range over which data can be collected either way.
    - Flow rate must be variable, by valve or otherwise.

- Radiator: A radiator will interface with the wind tunnel in the Thermal Science Lab. The wind tunnel will be used to pull air through the radiator core and hot water will be pumped through the radiator to simulate its on-car function as heat is rejected from the water to the air.
    - The fins should be intact and undamaged.
    - The tanks and plumbing should not leak.
    - When fitted with aluminum foil tape (see test description in *Chapter 6*), air should not leak from the radiator core.
    - Core must be at least 5.8" long and 5.8" wide to interface with test section ducting.

- Liquid Column Manometer: The liquid column manometer will be used to measure the static pressure on either side of the radiator. This static pressure drop will correlate to a mass flow rate of air in the ducting, and therefore, through the core.
    - Must be level, so points where the height of the column is the same in each case.
    - Should be able to be easily read at eye-level.

- Thermocouples: Thermocouples will be used to read the inlet and outlet temperatures of the water, as well as the ambient air temperature.
    - There must be a way of ensuring that the thermocouple can be used in the hoses while maintaining a water-tight seal.

- Pitot-Static Tube: A pitot-static tube will be used to measure the velocity of the air in the ducting.
    - Tip of pitot-static tube must be parallel to the airflow to ensure that it is not just a component of the total pressure that is being measured.

Chapter 3: Design Development

It was determined that the formula team needs to be able to predict the necessary size of their radiator based on testing. This is beneficial both as a hands on learning experience for the formula team and as a way to generate data that can be presented at competitions. This was chosen over development of a more theory-based method. Dates of completion of each step in the process of arriving at this decision, developing tests, designing test rigs, and testing is outlined in the “Radiator Sizing Project Timeline” in *Appendix A*. The rough outline is broken up into three quarters. The first quarter was spent gathering background information, then determining the equipment and tests necessary in obtaining pertinent data. The second quarter was used to design and build the test fixture (test section) and order other components needed to facilitate testing. The last quarter was dedicated to testing and compiling and analyzing the data to create a guided process with sample data for the formula team.

1. Conceptual Designs

The initial plan to perform testing involved building a wind tunnel (or flowbench) that would be reserved for use exclusively by the formula team. The design was meant to replicate a flowbench that was designed by engineers at All American Racers to perform similar radiator testing. A schematic of the AAR radiator flowbench can be observed in *Figure 11* below. The main components include the intake duct, test radiator, LFE, fan, and gate valve at the exhaust.

Eventually it was determined that it would be more economically feasible to perform testing on an existing wind tunnel on campus and the decision was eventually made to use the wind tunnel in the Thermal Science Lab on campus at Cal Poly. Using the wind tunnel in the Thermal Science Lab made the most sense because the ducting was composed of various sections, so it would be easy to incorporate a new section that facilitated the project needs.

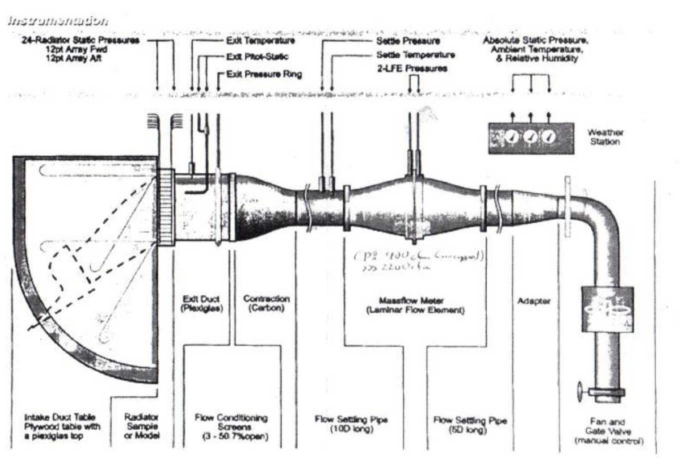


Figure 11. *AAR radiator flowbench schematic*

The following will detail the various conceptual designs that were formulated before ultimately pursuing the final design.

Concept 1: Build a Flowbench w/ LFE, Use in Coordination w/ Engine on Dyno
This concept featured 4" diameter, circular cross-section ducting that would be connected to the LFE. The radiator would interface with the ducting directly after a bell mouth inlet, which minimized pressure losses and allowed the largest amount of air to enter the duct. A flow conditioning screen would be installed before the LFE to straighten the flow. The LFE would measure the pressure drop across the LFE's loss element which would provide a very accurate measurement of the mass flow rate of the air in the duct. The airflow would be throttled using a gate valve. A schematic of this conceptual design can be observed below in *Figure 12*. All testing would be performed in coordination with the dyno. Heat rejection from the radiator would be measured over range of engine output power magnitudes.

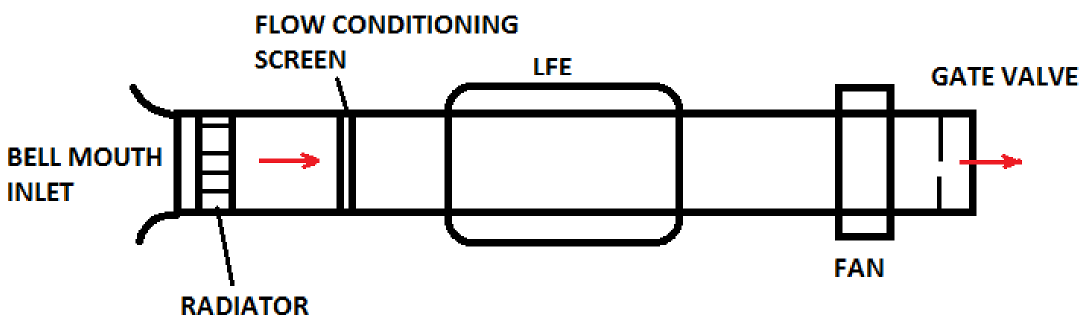


Figure 12. *Conceptual design used for radiator testing, LFE configuration*

There were a few issues with this concept. First, the LFE could not be borrowed for any extended period of time. According to Meriam's LFE User Manual, it is recommended that the LFE has 10 times the diameter of piping in front of the LFE and 5 diameters after the LFE. As a result, the flowbench would need to be relatively long, which brought up questions regarding its storage.

Concept 2: Build a Flowbench w/ Contraction Area, Use in Coordination w/ Engine on Dyno
This concept was largely the identical to *Concept 1*; however, it incorporated the use of a contraction area rather than the LFE to determine the mass flow rate of the air in the duct. *Figure 13* depicts a schematic of this concept.

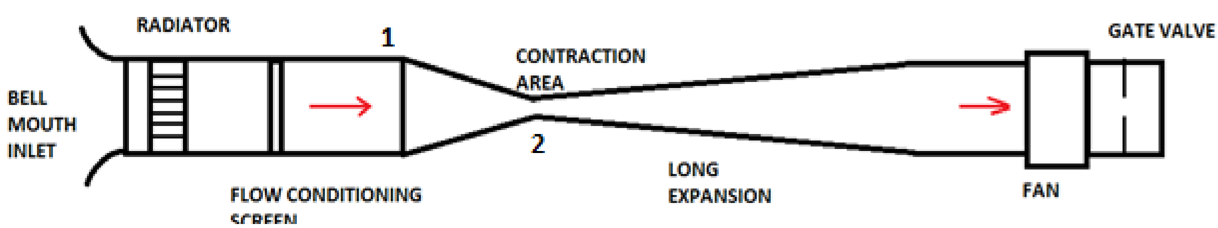


Figure 13. *Conceptual design used for radiator testing, contraction area configuration*

The mass flow rate of the air in the duct could be determined by measuring the pressure at points 1 and 2 (refer to *Figure 13*). The mass flow rate would be determined using *Method 3* described in *Measuring Mass Flow Rate of Air* (*Chapter 2, Section 7*).

This design had some issues as well. One problem with finding the mass flow rate using a Venturi section is that the contraction and expansion must occur very gradually to keep the air flow from separating and swirling, as depicted in *Figure 14*, on the right. This would necessitate long ducting, which brought up the storage issues explained in *Concept 1*. Another issue is that it would be very difficult to find off-the-shelf ducting that expanded or contracted, and fabrication would not be trivial. On the other hand, this was a cheap alternative that avoided the use of the LFE, so the flowbench would be indefinitely operational.

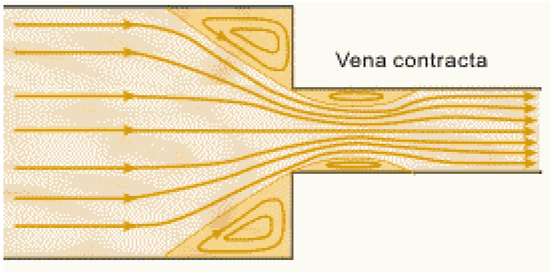


Figure 14. *Swirling and vortexing that occurs without gradual contraction*

<u>Concept 3: Build a Flowbench, Measure Pressure Rise Across Fan to Determine Mass Flow Rate</u>

Again, this conceptual design is very similar to the first one. However, there were no additions to the working ducting that would be necessary to determine the mass flow rate of the air. This design features a constant diameter cross section throughout the length of the ducting. The mass flow rate could be determined by measuring the pressure rise across the fan, as described in *Method 4* described in *Measuring Mass Flow Rate of Air*. This would require one static pressure port before the fan, then the pressure on the other side of the fan would be atmospheric. The design for this was much simpler for a few reasons. First, the flow conditioning screen would not be required because the flow need not be straight upon entering the radiator core as it did in the case of the LFE. The radiator fins would cause the flow to straighten. Second, the ducting would be much shorter because fully developed flow was not required at any point in the ducting. This conceptual design was taken slightly further due to its increased feasibility. As can be observed in *Figure 15* on the right, the radiator is surrounded in a radiator box to insulate it and ensure that heat transfer did not occur in fins outside the ducting. The figure does not depict the fan and valve that would be attached at the end where it is indicated that the fan would be.

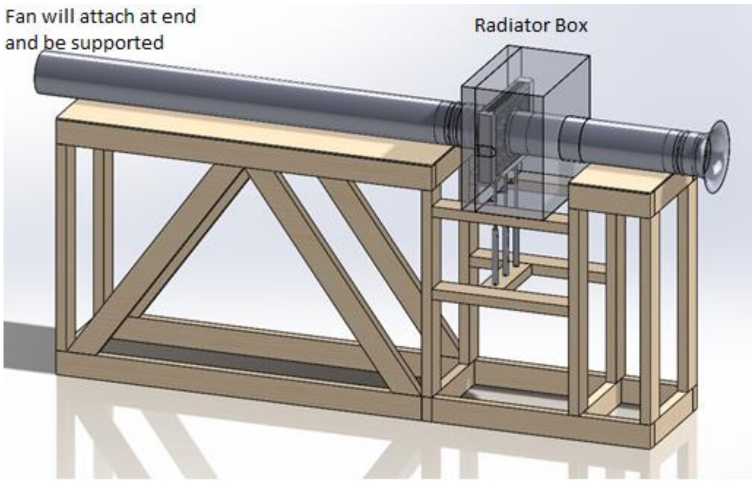


Figure 15. *Conceptual design used for radiator testing, pressure rise across fan*

Concept 4: Use Existing Wind Tunnel w/ Pumped Hot Water & Existing Dyno Measurements

This concept incorporates use of the wind tunnel in the Thermal Science Lab. The wind tunnel would be modified with a test section that would allow it to interface with a radiator and facilitate testing. In this case, radiator testing would occur separate from any testing done with the engine on the dyno. This seemed like a good idea because it would the engine could be run for significantly less time, limiting engine wear due to radiator sizing. In summary, the testing would consist separate heat generation tests and heat rejection tests to determine the necessary heat transfer area. A model of the conceptual design is depicted in *Figure 16* below. *Figure 16* also aims to illustrate where the test section would be interface with the existing ducting on the wind tunnel.

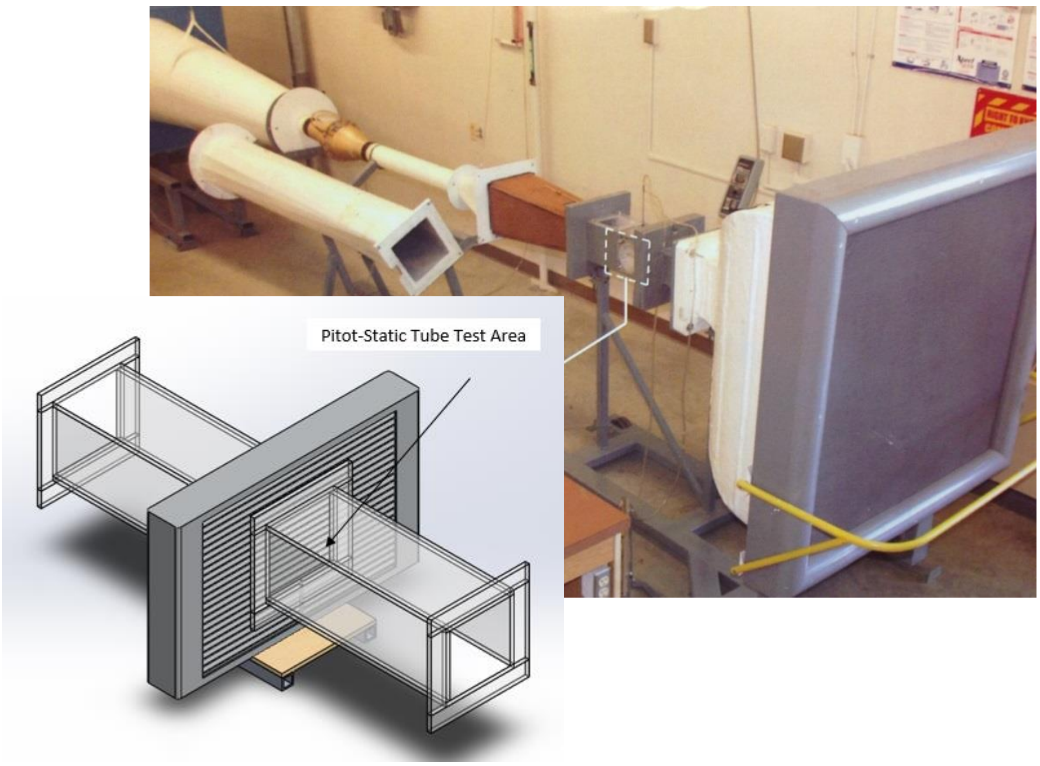


Figure 16. *Conceptual design used for radiator testing, radiator interfaces with test section on existing wind tunnel*

The test section would be constructed using polycarbonate. A pitot-static tube would be used measure air velocity in the ducting. Clear polycarbonate would make it easy to ensure that the pitot-static tube was oriented so that it was pointed parallel to the direction of air flow. The test section would feature static pressure ports on either side of the radiator that would be used with a liquid column manometer, and holes to facilitate use of a pitot static tube in the duct. It also featured a height adjustable radiator support. Telescoping tubing allowed the support to move along the vertical axis. The support would be secured in place using a plastic head thumb screw that would function as a set screw. *Figure 17* depicts the conceptual test section unobstructed by

a radiator. *Figure 18* aims to depict incorporation of the static pressure ports and adjustable radiator support. Hoses would be attached to the inlet and exit of the radiator and hot water, heated with immersion heaters, would be pumped through the radiator.

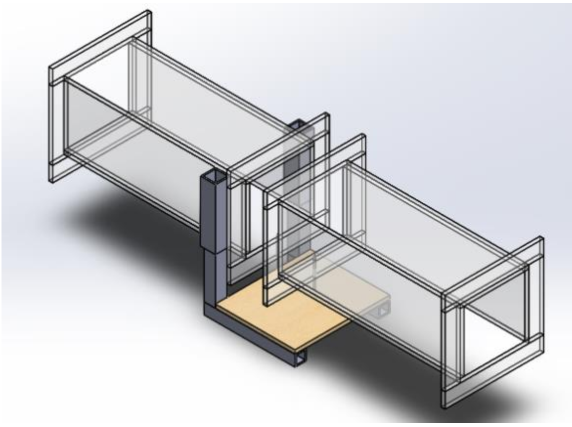


Figure 17. *Unobstructed view of the test section*

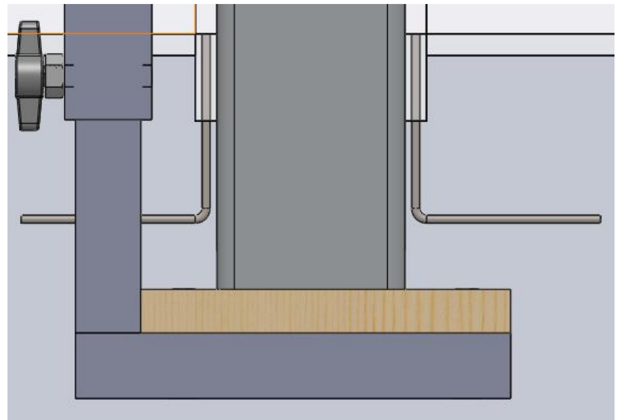


Figure 18. *View of the thumbscrew for height adjustment of the radiator support and steel tube static pressure ports*

While the formula team would not have their own wind tunnel to use at the Hangar, there were many benefits associated with this concept. Constructing the test section would be significantly less expensive than building an entirely new wind tunnel, and budget became a significant issue in the other conceptual designs. Additionally, many of the other components necessary would be readily available in the Thermal Science Lab with the wind tunnel, including: liquid column manometers, thermocouples, and a pitot-static tubes.

2. Concept Selection

Out of the various concepts listed in the previous section, *Concept 4* was chosen. It was concluded that the benefits associated with time, cost saving, and the guarantee of a working wind tunnel outweighed the fact that the formula team would not have a wind tunnel to use simultaneously with the dyno at the hangar. Decision matrices to choose between the 4 concepts and a QFD to determine which components should be considered with the most care can be referenced in *Appendix B.* Heat generated by the engine and heat rejected by the radiator will be measured separately. In testing heat generation, the engine will be used on the dyno and the cooling water temperature will be measured at the inlet and exit of the radiator. *Equation 14* from *Chapter 2*, *Section 9* will be used to determine heat generation (or heat rejected to the cooling water) based on mass measured mass flow rate and temperature differential. In testing heat rejection, hot water will be pumped into the radiator at varying mass flow rates and heat rejection will be measured over a range of air velocities. In a manner similar to determining heat generation, heat rejection will be determined by measuring the cooling water temperature at the inlet and exit of the radiator. The radiator will interface with the test section as illustrated in

Figure 16. Any part of the radiator core that is not contained within the ducting will be sealed off using aluminum foil tape to prevent air leaks.

3. Supporting Preliminary Analysis

Preliminary analysis included the following was performed to determine approximate sizing for some of the components necessary in the test procedure. This analysis included:

- Approximate fan sizing.
- Approximate heater sizing.
- Consideration of ability of measurement tools to be used.

<u>Fan Sizing</u>

The fan must be sized such that it can pull air through the test radiator at a speed equal to or greater than the speed at which air would flow the core on the car. It can be observed in *Figure 2*, the histogram that describes the number of instances when the car is traveling at a particular speed, that the maximum speed is 95 ft/s (~65 mph). Testing was performed to determine to the approximate speed of the air along a streamline as it flows through the radiator. This was accomplished using a vane type anemometer behind the radiator core. The test process is described in detail in *Chapter 6, Section 1* and the results are outlined in *Chapter 6, Section 3*. The maximum necessary velocity in the duct was determined to be 14 m/s. These results were used to estimate the maximum pressure rise and mass flow rate conditions at which the fan must be able to operate.

It was determined that the fan must be able to pull air at a mass flow rate of 0.25 kg/s and induce a pressure rise of about 400 Pa. The fan on the wind tunnel in the Thermal Science Lab is very nearly capable of achieving this operating point and it can be used to adequately model the on-car air flow conditions. The calculations used in these estimations are available in *Appendix C: Fan Sizing Program*.

<u>Heater Sizing</u>

A calculation was performed to explore the amount of time it would take to heat up different amounts of water with different combinations of heating power. Affordable heaters available with McMaster-Carr were rated at 1.15 kW, so the heating power would be some multiple of this power. A reservoir in the Thermal Science Lab was found that would hold about 17 gallons of water. It was also determined that the only source of a, for all intents and purposes, limitless water was available at an initial temperature of 100˚F.

Based on the previously listed values and the fact that it was necessary to heat the water to 180˚F, different multiples of 1.15 kW heaters could be used to predict the amount of time it

would take to heat the water with that particular number of heaters. When the 3 heaters were used, it was predicted that it would take about 57 minutes for the water to heat up. The equations used in these estimations are available in *Appendix D: Heater Sizing Program*. Note that in reality, heating would take slightly longer due to heat loss from the hot water reservoir.

<u>Measurement Instrument Consideration</u>

The static pressure drop across the radiator core will be measured over a range of air velocities. In order to measure the static pressure drop, a liquid column manometer will be used. There will be a slight difference in the static air pressure drop measurement when the radiator is being used to reject heat as compared to when it is cold. This is due to the change in air density that results from the increased temperature. A program was created to determine the pressure change that would result from the changing air density. The program was used to determine that an approximated maximum temperature rise in the air would be about 18˚C. Then the liquid column height gradient in the manometer was plotted as a function of temperature. The plot can be observed in *Figure 19* on the right.

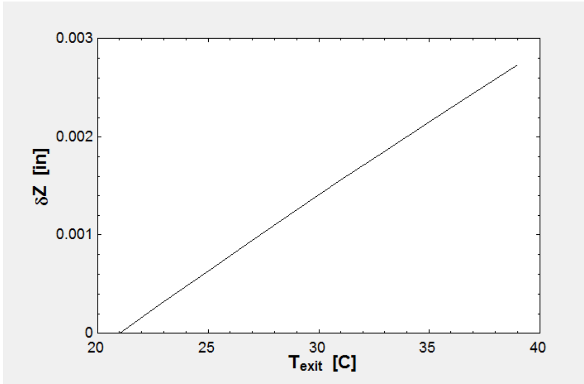


Figure 19. *Plot of the effect of exit air temperature on manometer liquid column height differential*

The important idea to recognize in the plot in *Figure 19* is that the change in air exit temperature (in the most severe case) will be responsible for a liquid column height change of no more than 0.003 inches. It would be near impossible to recognize a change in height this small, so it is safe to assume that the changing air density has no effect on the liquid column manometer reading which predicts static pressure drop across the radiator. The calculations used in this estimation are available in *Appendix E: Temperature Effects on Manometer Reading Program*.

Chapter 4: Final Design Description

In order to fulfill the project requirements, this senior project involved both designing experiments to collect data that would help predict the necessary radiator size, and designing the equipment necessary to facilitate the experimentation. In the case of this project, a test section was built that would interface with a radiator and the wind tunnel in the Thermal Science Lab so that heat transfer experiments could be performed with automotive radiators. The on-car cooling system conditions would be replicated in the Thermal Science Lab to determine the ability of different radiators to reject heat. In summary, heat generated in the engine can be predicted as a function of engine power on the dyno, then the ability of a radiator to reject heat over the entire operating range of the car can be tested using the test section on the wind tunnel. Using this data, the necessary size of the radiator can be predicted. This chapter will describe the process by which the experiments and wind tunnel test section were designed.

1. Overall Description- Testing

The goal of the project was to provide the FSAE team at Cal Poly with a guided process that will allow the team to perform heat generation and heat rejection testing. Heat rejection testing can be performed on a wide variety of radiators so that the formula team can determine the radiator characteristics they determine to be valuable (i.e. fin density, core thickness, manufacturer, etc.) based on heat rejection achieved. Once they have chosen a type of type of radiator that they would like to use, they can perform heat generation and heat rejection testing on the dyno and wind tunnel, respectively to determine how large a radiator they need. The test procedure will be developed in the following pages of this section. The formula team will be provided with an Excel program where they can enter data and all pertinent plots will change to reflect the data they collect. A summary of the tests that must be performed is as follows.

- **Test 1**: Determine mass flow rate of the cooling water as a function of the crank shaft rotational speed
- **Test 2**: Determine heat rejected from the engine to the cooling water in as a function of crank shaft rotational speed
- **Test 3**: Determine the mass flow rate of air through the core as a function of car speed
- **Test 4**: Determine static pressure drop in air across the radiator core at different air mass flow rates
- **Test 5**: Determine heat rejected by radiator as a function of both the mass flow rate of air through the core and the mass flow rate of cooling water through the radiator

The first three tests were designed so that the formula team could generate curves to predict the mass flow rates of both air and water through the radiator as well as the heat rejected to the

cooling water at each crankshaft rotational speed. This crankshaft rotational speed will correlate to a specific car speed in each gear. Since the formula team knows the speed at which the car should be traveling at each point on the FSAE autocross track, they can determine values for each of the mass flow rates and the heat rejected into the cooling water. The fourth test was designed for a couple of reasons. First, it was designed to determine the pressure drop across the radiator at different mass flow rates, to aid the formula team in choosing a cooling fan. Second, it was used to characterize the mass flow rate of air through the radiator core at different fan speeds so that the average velocity did not need to be determined with the pitot-static tube each time the fan speed was adjusted. This way, the mass flow rate of air through the core could be measured simply using the liquid column manometer. The last test was designed so that the formula team could generate a curve to predict the heat rejected from the cooling water by the radiator at air and water mass flow rates that correspond to different car speeds as determined in the first two tests. Procedural instructions for each of these five tests as well as the process by which they are used to size the radiator are described in detail in *Chapter 6*.

2. Detailed Design Description- The Test Section

The design of the radiator test section was governed by design requirements as well as cost constraints because of the budget uncertainty. The final design of the test section was slightly different from the one described in *Concept Selection* (*Chapter 3, Section 2*) almost entirely due to budget constraints. It was much more cost efficient to make two major design iterations. First, the test section would be constructed using sealed and painted plywood instead of polycarbonate. Second, the height adjustable radiator support would be eliminated in favor of a sawhorse with pieces of wood stacked to an appropriate height as a free alternative to purchasing the materials necessary to construct the radiator support. What follows will describe the final design of the test section used to facilitate the tests described in the previous section. The final design was governed by the following design requirements.

- Section must interface with automotive radiators
- Section must interface with the existing ducting on the wind tunnel
- Test assembly must be airtight
- Section must accommodate static pressure measurement with a liquid column manometer
- Section must accommodate use of a pitot-static tube

<u>Radiator Interface</u>

In order to allow radiators to interface with the test section, the test section needed to be designed so that it is two separate pieces. This way a radiator can be placed between the two pieces of the test section and air can be directed through the radiator core. Any portion of the radiator core that is not contained within the test section ducting will be blocked off with aluminum tape so that no

forced convection can occur outside of the ducting. *Figure 20* aims to illustrate the way a radiator will fit between two separate pieces of the new test section. The downstream and upstream pieces of the section will be mounted to the front and back portions of the wind tunnel, respectively. The radiator and sawhorse should be placed so that the radiator fits snug against the downstream piece of the test section, then the front portion of the wind tunnel can be pushed back so that the radiator fit snug between the two pieces of the test section. Closed cell foam would be used as a gasket material at the interface between each piece of the test section and the radiator to create an airtight seal.

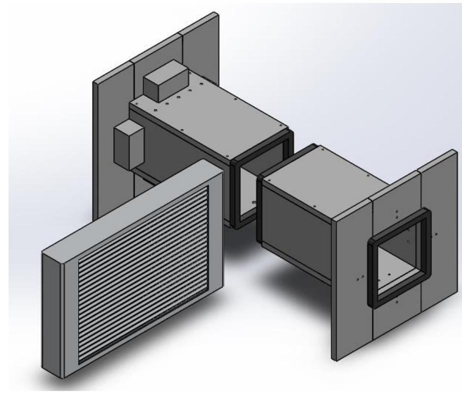


Figure 20. *The radiator will be secured between two pieces of the new test section*

Wind Tunnel Interface

It was a goal to interface the wind tunnel and the new test section while minimalizing and alterations to the wind tunnel. As a result, the inside dimensions of the new test section were made to be 4.8 x 4.8 inches—the same inside dimensions of the ducting on either side of the test section. The only change that was made to the existing wind tunnel sections had to do with the brown expansion section that is directly downstream of the original test section. In contrast to the original test section which is one solid piece, the new test section is two pieces, so each needed to be supported by the existing sections on either side. The front portion of the wind tunnel can be pulled away from the rest of the ducting. This front portion originally consisted of the brown expansion section and each section of ducting that is upstream of it. There was a foam gasket at the end of the brown expansion section so that it was airtight when the front portion of the wind tunnel was pushed up against the back portion. This created an issue in that section of ducting that comes after the radiator wouldn't be connected to anything. To abate this issue, flanges were added to the wide end of the brown expansion section and it was connected to the back portion of the wind tunnel (see *Figure 21*). The newly added flange on the brown expansion section was connected to the flange on the adjacent downstream duct section using screws and nuts at each corner of the flanges. In effect, the expansion became part of the back portion of the wind tunnel ducting.

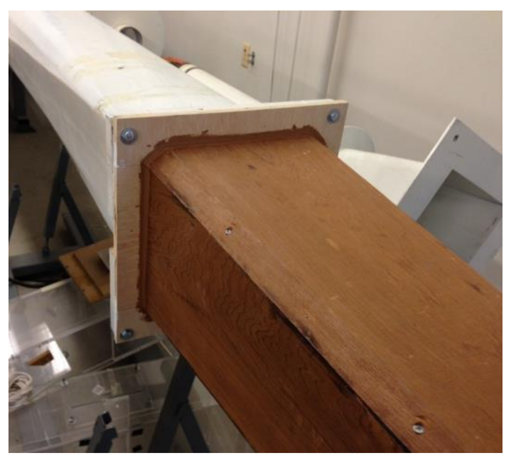


Figure 21. *Method of mounting brown expansion section to adjacent downstream wind tunnel section*

Next, the downstream piece of the new test section was mounted to the brown expansion section in a manner similar to the one used in mounting the original test section. Four L-brackets on each side of the square duct were used to fasten the expansion section to a flange on the new test section. In effect, the downstream piece of the new test section also became part of the back portion of the wind tunnel. *Figure 22* depicts the way L-brackets were used to attach the two sections to one another.

Figure 22. *Method of mounting downstream piece of test section to brown expansion section*

Lastly, the upstream piece of the test section was connected in the same way the original test section was connected. Two screw-nut pairs were used to connect a flange on the upstream piece of the test section to the flange on the adjacent contraction section on the front portion of the wind tunnel. In *Figure 23* on right, one of the nuts used to connect the upstream piece of the test section to the existing wind tunnel section can be observed on the left side flange. Another screw-nut pair was used in the same manner on the right side flange.

Figure 23. *Method of mounting upstream piece of test section to adjacent section of the wind tunnel*

<u>Airtight Ducting</u>

In order to ensure that the ducting is airtight, strips of closed-cell foam were used around the duct between each section of ducting. When adjacent sections of ducting are connected, the foam compresses, creating an airtight seal around the wind tunnel duct. Similarly, foam was used on the end of each piece of the test section so that the interface between the radiator and each piece of the test section is airtight when the front and back portions of the wind tunnel are pressed together with the test radiator between them.

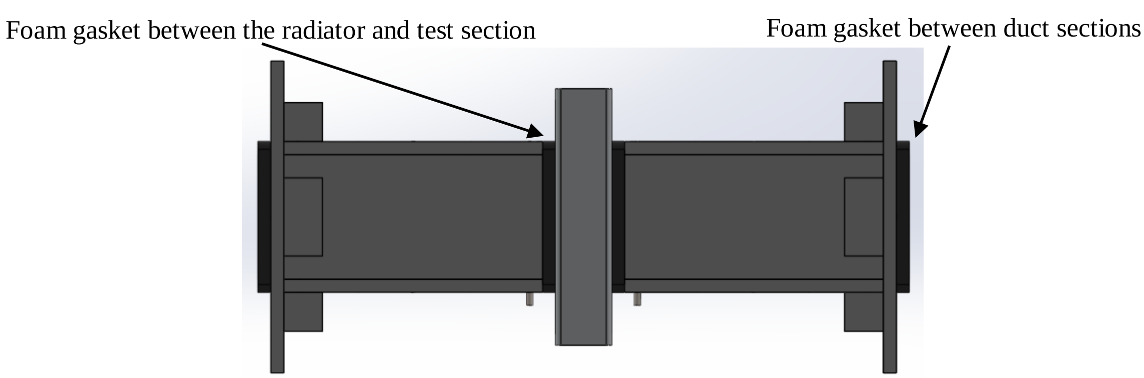


Figure 24. *SolidWorks model of the test section depicts the use of closed-cell foam gasket material and metal tube location*

Liquid Column Manometer Accommodation

In order to accommodate the use of a liquid column manometer to determine the static pressure drop across the radiator core, a metal tube was placed in the bottom of each piece of the test section downstream and upstream of the radiator core. The metal tubing can be observed on the bottom of each piece of the test section on either side of the radiator in *Figure 24*. The barb fittings on the liquid column manometer are meant to be used with ¼-inch ID tubing. In order to be sure that there is a good seal between the metal tubing on the test section and the tubing that goes to the liquid column manometer, the test section was designed so that there was be an interference fit between the metal and rubber tubing to create a tight seal. To create this interference fit, 0.259-inch OD metal tubing was used on the test section.

Pitot-Static Tube Accommodation

In order to allow a pitot static tube to be used in the ducting, holes were drilled through the top of the downstream piece of the test section. These holes are 3/16-inch in diameter—just large enough so that the elbow of the pitot-static tube can fit through them. The holes were placed as far downstream as possible to allow as much as distance as possible for the flow to develop once it passed through the radiator core. These holes can be observed on the downstream piece of the test section in *Figure 22*.

3. Cost Analysis

Table 5 in *Appendix F* details each material that was used for testing throughout the senior project. A number of materials could be borrowed; those materials have dashes in the cost columns to indicate that they didn't cost anything. They are listed in the table to acknowledge that they were used during testing and may need to purchased in the future if they are no longer available. The total cost incurred throughout the project was $479.00. The heaters used to heat the water accounted for almost 50% of the cost of the project. Initially, the plan was to use hot water from the boiler in the Thermal Science Lab, but the boiler turned out to be unavailable. This would not have influenced the decision to perform testing by simulating different engine operating points on the existing wind tunnel in the Thermal Science Lab because this option would have still more than likely been the most cost effective way and practical way of performing the testing

4. Geometry, Material, and Component Selection

The geometry of the test section was largely dictated by the fact that it needed to interface with both the existing wind tunnel sections and a radiator. It is in two separate pieces so that a radiator could be placed between the two pieces. Then flanges function to interface each section of

ducting with the adjacent section. Geometry has been described in greater detail in *Detailed Design Description- The Test Section* (*Chapter 4, Section 2*).

There were four main considerations that needed to be kept in mind in choosing materials and components to complete the testing. First, it was important to realize that many of these materials or components would be subject to high temperatures. Second, because of the prevalent use of water throughout testing, it was also important to realize that there was a possibility of the components getting wet at one point or another. Third, care needed to be taken to make sure that every portion of the ducting was airtight. The fourth and last consideration had to do with the budget. A low cost component was valued more highly than a higher cost component that may have otherwise been more appropriate in its respective application. The following bulleted points will list materials and components and describe why they were chosen.

- Closed-Cell Foam Gasket Material: The closed-cell foam weather stripping that was used as a gasket material to maintain an airtight seal between ducting components would come into direct contact with the hot radiator. Water would enter the radiator at about 180˚F, so a foam that was rated up to a maximum temperature of 200˚F was chosen.
- Rubber Heater Hose: Rubber heater hose was used to plumb the test setup. This hose would be subject to 180˚F water, and needed to be rated to be able to withstand that high temperature. The hose used was rated to be used at 212˚F.
- Wood: Wood was used to build the test section instead of polycarbonate because it was significantly less expensive than polycarbonate.
- Spackling Compound: When each piece of wood is screwed together, there are still small gaps between each piece of wood. These gaps would need to be filled using spackling compound so that the test section would be airtight.
- Primer/Sealer: A water-proof primer/sealer needed to be used on the wood because wood is not particularly resistant to wear due to water.
- Hot Water Bath: The Cole-Parmer hot water bath was used because it is was something that could be borrowed from the Mechanical Engineering department, thus saving money. It was used solely for its pump and the fact that the pump could withstand high water temperatures. It would have been much easier to use a pump that could have been submerged directly into the hot water reservoir, but the opportunity to save money made the Cole-Parmer hot water bath the best option.
- Immersion Heaters: The immersion heaters were chosen because they provided the highest heating power for the least amount of money. Three 1.15 kW heaters would be sufficient to heat 17 gallons of water in about an hour and a half.
- Sawhorse Radiator Support: The sawhorse was chosen to be used as the radiator support because it was a zero-cost option that outweighed the benefits of building a radiator support onto the test section.

5. Manufacturing Drawings

See *Appendix G* for manufacturing drawings and vendor catalog descriptions. *Appendix G* is organized so that there is some sort of bill of materials for each system that needed to be constructed. Vendor catalog pages appear in the order that they are listed in *Table 13* with manufacturing drawings and schematics for those systems that needed to be constructed preceding catalog pages. Construction instructions for those systems can be found in *Manufacturing Process* (*Chapter 5, Section* 2).

6. Maintenance and Repair Considerations

The wind tunnel and a large majority of the measurement equipment used in testing is property of Cal Poly and maintained by the Mechanical Engineering department. However, proper care should be taken so that equipment is in similar or better order than it was before use. The formula team will only be responsible for maintaining or repairing the test section. Each time the test section is used on the wind tunnel, the closed cell foam that is being used as gasket material becomes compressed. If the foam does not return to its original shape, it should be replaced to maintain an airtight seal. The same goes for the foam used between the test section and the radiator. If the foam becomes excessively deformed, it should be replaced. Nothing else should require regular maintenance; however, if something breaks it should be replaced. The information in *Manufacturing Process* contains any information the formula team might need to replace any part that has failed.

Chapter 5: Product Realization

The products of this project were the test results and the test section that would need to be manufactured to facilitate testing. This chapter will describe everything about the process of manufacturing the test section. *Chapter 6* will detail the test procedure as well as the results of the tests that were performed.

1. Description of Design Iteration

Looking at the finished test section, the most obvious design iteration to the conceptual design is that it was constructed from ½” plywood instead of polycarbonate. This was a decision that was made with the budget in mind as the polycarbonate accounted for a significant portion of the cost. The sheet of plywood that was used for construction was half the price of the polycarbonate that would have been required. Then, with the same goal of saving money, a decision was made to eliminate the radiator support from the design. Instead, a sawhorse separate from the test section was used as a more cost effective alternative. The test section ended up being more of an extension to the existing wind tunnel ducting that allowed for interface with a radiator and use of a liquid column manometer and pitot-static tube.

2. Manufacturing Process

The manufacturing process can be broken up into three separate processes. First, the test section needed to be manufactured to perform *Test 4* and *Test 5* described in *Overall Description-Testing* (*Chapter 4, Section 1*). Once the test section had been built, it would need to be mounted on the wind tunnel and then the plumbing would need to be connected. These were the second and third processes in manufacturing. The following paragraphs will describe these three processes in detail. *Appendix G* includes vendor catalog descriptions for all materials referenced.

<u>The Test Section</u>
The test section is in two separate pieces that interface with the wind tunnel on either side of the radiator. Each duct is composed of twelve individual pieces of wood. The first four pieces are for the four sides of the duct and the next four are used to construct the flange. Both the duct portion and the flange constructed are constructed from a ½”- thick sheet of plywood. The last four pieces of wood were used like brackets in order to ensure that the flanges formed a 90 degree angle with the duct portion. The manufacturing process will be described in the following paragraphs.

To begin the manufacturing process, the wood was cut using the table saw in the hangar. *Table 1* that follows will detail the function of each piece of wood and its dimensions.

Table 1. *Description of each piece of wood that would be used in the construction of the test section*

Item No.	Description	Dimensions (in)	Quantity	Initial Material
1	Duct Top- Upstream	10 x 5.8 x 0.5	1	1/2"-Thick Sandeply Plywood
2	Wood Bracket	3 x 1.5 x 1.5	8	2x2 Stud
3	Duct Side	10 x 4.8 x 0.5	4	1/2"-Thick Sandeply Plywood
4	Duct Bottom	10 x 5.8 x 0.5	2	1/2"-Thick Sandeply Plywood
5	Large Flange Piece- Upstream	4.8 x 3.6 x 0.5	2	1/2"-Thick Sandeply Plywood
6	Short Flange Piece	12 x 3.6 x 0.5	4	1/2"-Thick Sandeply Plywood
7	Duct Top- Downstream	10 x 5.8 x 0.5	2	1/2"-Thick Sandeply Plywood
8	Large Flange Piece- Downstream	4.8 x 3.6 x 0.5	2	1/2"-Thick Sandeply Plywood

Part drawings completed in SolidWorks detail hole locations and dimensioning and can be observed in *Appendix G*. A more detailed bill of materials is also included in *Appendix G*. 1/8" pilot holes were drilled so that pieces could easily be fastened to one another with #6, 1-1/4" flathead screws. A table saw was used to cut the wood to size and holes were made with a drill.

With the wood cut, construction would begin by using screws to fasten wood brackets (*Item No. 2)* to each piece of the duct (*Item No.'s 1, 3, 4 & 7*). These wood brackets were attached so that they were flush with the edge of the duct. This provided a larger surface area to attach each piece of the flange and ensure that it formed a 90˚ angle with the duct portion. *Figure 25* to the right illustrates this process with exploded view route lines representing where screws were used to fasten the bracket to the side of what would eventually be the duct.

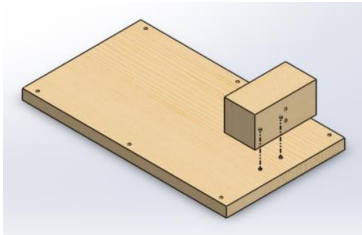


Figure 25. *First step: fasten wood brackets to each side of ducting*

The duct portion was constructed from four pieces of wood similar to what is shown in *Figure 25*. The duct sides were sandwiched between the top and bottom of the upstream and downstream ducting. The downstream duct top (*Item No. 1*) differed from the upstream duct top (*Item No. 7*) in that it had holes drilled across to accommodate use of a pitot-static tube in the duct. *Figure 26* to the right illustrates the process by which each side of the duct portion was connected to the adjacent side. With the completion of this step, the duct portion of the test section would be finished.

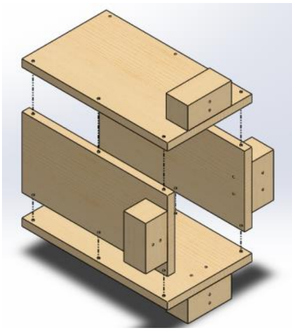


Figure 26. *Second step: construct duct portion*

The third and final step in the construction process involved attaching the each piece of the flange to the duct portion that was constructed in the two previous steps. Once again, the flange was constructed using four separate pieces of wood: two smaller pieces and two larger pieces where the smaller pieces were sandwiched between the large pieces and attached on the end of the duct. The flanges on the upstream and downstream portions of the test section differed in that holes were drilled in the upstream large flange piece (*Item No. 5*) to mount the test section on the existing ducting on the wind tunnel. *Figure 27* at right illustrates the way each part of the flange was fastened to the wood brackets. *Figure 27* illustrates construction of the downstream piece of the test section that did not require mounting holes so it could be mounted with a nut and bolt. Instead, L-brackets would be attached and it would be mounted with L-brackets onto the brown expansion section as detailed in *Detailed Design Description- The Test Section*.

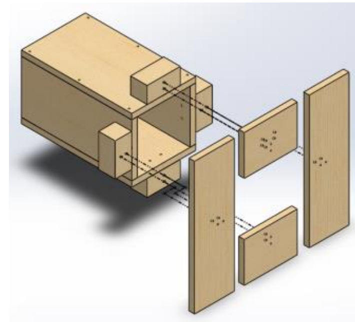


Figure 27. *Third step: attach each part of the flanges*

Upon completing the structural construction of each duct, the spaces between each piece of wood needed to be filled with spackling compound. For the sake of ease, caulking was used on the outside of the duct, rather than on the inside. Once the gaps had been filled caulk in fashion that was adequate to prevent air leaking from inside the duct, the test section was sanded, sealed, and painted. At this point, 1" long, ¼"-OD metal tubing was inserted into the holes that were drilled to facilitate the static pressure ports, and the tubing was secured using epoxy. Lastly, weather stripping was fitted around on either end of the duct to create an air-tight seal between ducting components and between the test section and the radiator. *Figure 28* on the left illustrates what the finished test section should look like.

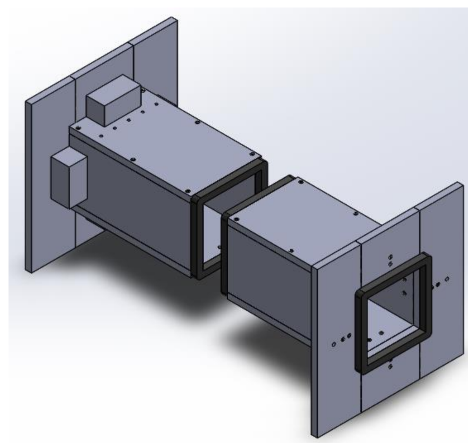


Figure 28. *SolidWorks model of the finished test section*

<u>Mounting the Test Section on the Wind Tunnel</u>

As described in *Detailed Design Description- The Test Section*, the brown expansion section needed to be modified for the test section to interface with the wind tunnel properly. A flange needed to be added so that the large end of the expansion section could be attached to the wind tunnel. A table saw was used to cut the 4 pieces of wood that the flange would be constructed with: 2 small pieces (7-3/4" x 2-1/8") and 2 large pieces (12" x 2-1/8"). These were cut from the same ½" plywood used to build the test section. Then each piece of the flange was glued to the large end of the brown expansion section using wood glue. To finish the addition of the flange, the gaps were filled with silicon caulking and 3/8" holes were drilled 10-3/4" from each other at

each corner of the flange. Finally, closed cell foam was fitted around the duct opening on the flange. *Figure 21* depicts the flange that was added to the expansion section.

Before the expansion section was mounted on the wind tunnel, L-brackets were used on each of the 4 sides of the duct to mount the downstream piece of the test section to the expansion section. The test section was placed in the proper position on top of the expansion section and the L-brackets were fastened to each of the two components using the screws that were provided with the brackets. See *Figure 22* to observe the way the L-brackets were attached.

Once the test section was mounted on the expansion section, this assembly could be mounted on the wind tunnel. 2"-long, ¼" bolts were used with washers and nuts to mount the assembly on the wind tunnel. Again, this mounting can be observed in *Figure 21*.

Mounting the upstream piece of the test section on the wind tunnel was much more straight-forward than mounting the downstream piece. In this case, the holes on the flange of the upstream piece of the test section were lined up with the holes on the existing contraction section on the wind tunnel. Then ¼" bolts, washers and nuts were used to mount this piece of the test section on the wind tunnel in a manner similar to the way the expansion section was mounted on the wind tunnel. The method for mounting the upstream piece of the test section on the wind tunnel can be observed in *Figure 23*.

<u>The Plumbing</u>

Two sets of fittings were needed in the plumbing. First, fittings were needed to accommodate a component with an embedded thermocouple and two ¾" FPT threads on either side. See *Figure 58* and *Table 14* in *Appendix G* to see a list of the fittings needed and a schematic of the way they should be connected. A valve was also used on the discharge side of the assembly described above so that the flow of water could be stopped and hot water could be retained in the radiator. This kept the radiator hot between tests and minimized the time settling time of the water temperature coming out of the radiator. Teflon tape was used on each set of threads to prevent leaks between threaded fittings. The length of hose between the radiator discharge and this set of fittings should be minimized to minimize the potential for heat to escape through the hose. Then the length of hose between this set of fittings and the valve is not significant. Hose on the discharge side of the valve should be just long enough to reach a cold water reservoir on the ground. The length of the hose should always be minimized to minimize head losses.

Then fittings were needed to go from the ¼" FPT threads on the hot water bath pump discharge to the 1" barb used in the hose. See *Figure 59* and *Table 15* in *Appendix G* to see a list of the fittings needed and a schematic of the way they should be connected. Again Teflon tape was used on each set of threads. The length of the hose at the discharge of the pump should be just enough to reach the inlet of the radiator.

Chapter 6: Testing

Initially testing was going to be performed to verify the legitimacy of the theoretical process developed to predict radiator size necessary in achieving adequate cooling. However, the engine was not available to us throughout the entirety of the senior project. As a result, only testing that did not require use of the engine could be performed. This meant that three of five tests could be completed. In the sections in this chapter, the tests will be described (with a list of the necessary materials and detailed process description) then a detailed discussion of the test results will follow.

1. Test Descriptions

There are five tests that need to be performed so that the formula team will be able to determine the size of the radiator necessary in achieving adequate cooling. A summary of the tests that must be performed is as follows.

- **Test 1**: Determine mass flow rate of the cooling water as a function of the crank shaft rotational speed
- **Test 2**: Determine heat rejected from the engine to the cooling water in as a function of crank shaft rotational speed
- **Test 3**: Determine the mass flow rate of air through the core as a function of car speed
- **Test 4**: Determine static pressure drop in air across the radiator core at different air mass flow rates
- **Test 5**: Determine heat rejected by radiator as a function of both the mass flow rate of air through the core and the mass flow rate of cooling water through the radiator

The data collected during these tests will be entered into the Excel program that the formula team will be provided, and any necessary secondary variables or plots will be generated automatically. Relevant portions of the spreadsheets from the Excel program where collected data will be entered to determine significant results can be observed in *Appendix H*. The following pages describe the test procedures in detail. Data collected can be used to determine the necessary size of a particular radiator to achieve adequate cooling according to the process described in the flowchart in *Appendix I*. The process by which the data can be used to determine the necessary radiator size will be described following the description of the test procedures.

Test 1

The formula team will need to develop a relationship that describes the mass flow rate of the cooling water as a function of the of the driveshaft's rate of rotation. With this, the formula team will be able to predict the mass flow rate of the water at any car speed. In order to develop this plot, testing will be performed to measure the mass flow rate of the cooling water over a range of driveshaft rotational rates. The impeller in the water pump is geared to the crankshaft, so the rate of rotation of the impeller is directly proportional to the rate of rotation of the crank. As a result, the mass flow rate of the water is dependent on the rotational speed indicated by the tachometer, and this relationship should not change from gear to gear. This test can be performed with or without the dyno, but the radiator hoses should not be connected as part of a normally closed system. The system should be plumbed according to the diagram depicted in *Figure 29*.

Materials:

- Desired Test Radiator
- Radiator Hose
- Garden Hose
- Engine
- 3 5-Gallon Buckets
- Water Source
- Stopwatch
- Scale

Setup:

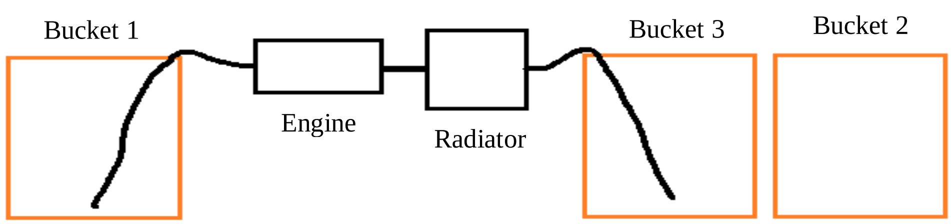


Figure 29. *Experimental setup for Test 1*

Plumb the cooling system so that radiator hose goes from a cold water reservoir ("Bucket 1") to the cooling water inlet on the engine, as illustrated in *Figure 29* above. The water pump will draw water in through the cooling canals in the engine block. Plumbing will then travel from the cooling water exit on the engine though the radiator and to a hot water reservoir bucket ("Bucket 2" or "Bucket 3"). A conscious effort should be made to be sure that the length of the hose used to plumb the experimental setup is similar to the length of the plumbing on the car. The length of the hose will affect the flow rate in that the flow rate is a function of the pressure drop in the system, which is affected by the length of hose used. "Bucket 1" and "Bucket 3" should be maintained at similar heights so that there is no significant amount of head added to the system, but it is very important that the water pump does not run dry. Additionally, the water level relative to the engine should be about equal to that of the on-car condition so that this gravitational head will not affect the predicted relationship. "Bucket 3" will be used to measure the weight of the water and determine the mass flow rate.

Procedure:

1. Weigh the empty "Bucket 3" to determine its weight, in kg.
2. Enter the weight of "Bucket 3" into the Excel spreadsheet.
3. Fill "Bucket 1" with water using a regular garden hose connected to a water spigot.
   NOTE: Keep the hose next to the cold water reservoir so that the bucket can be refilled if the water level becomes too low. Do not let the water pump run dry so as to avoid cavitation in water pump and overheating in the engine.
4. With the hose coming from the radiator discharge and directing water into "Bucket 2", start the engine and allow the water pump to draw water from the cold water reservoir. Throttle the engine so that it is operating at a continuous driveshaft rotational rate.
5. Once water starts flowing into "Bucket 2," move the hose from to "Bucket 3" and simultaneously begin timing with the stopwatch.
6. Allow the water pump to fill "Bucket 3" for 20 seconds.
   NOTE: If the bucket fills up too quickly in 20 seconds, test mass flow rate for less time and change the test time in the Excel spreadsheet.
7. Simultaneously move the hose back to "Bucket 2" and stop the stopwatch.
8. Stop the engine.
9. Weigh "Bucket 3" again to determine its weight with water, in kg.
10. Enter the weight in the Excel program in the cell that corresponds to the driveshaft rotational rate in the spreadsheet labeled "Cooling Water Mass Flow Rate."

Analysis:

The Excel program determines the mass flow rate of the water used in the cooling system according to *Equation 1* defined below. Sample data for this test could not be collected because the engine was never available for testing over the course of the senior project. However, *Figure 30* predicts the general trend that will characterize the relationship.

$$\dot{m} = \frac{m_{water+bucket} - m_{bucket}}{t_{test}} \quad (1)$$

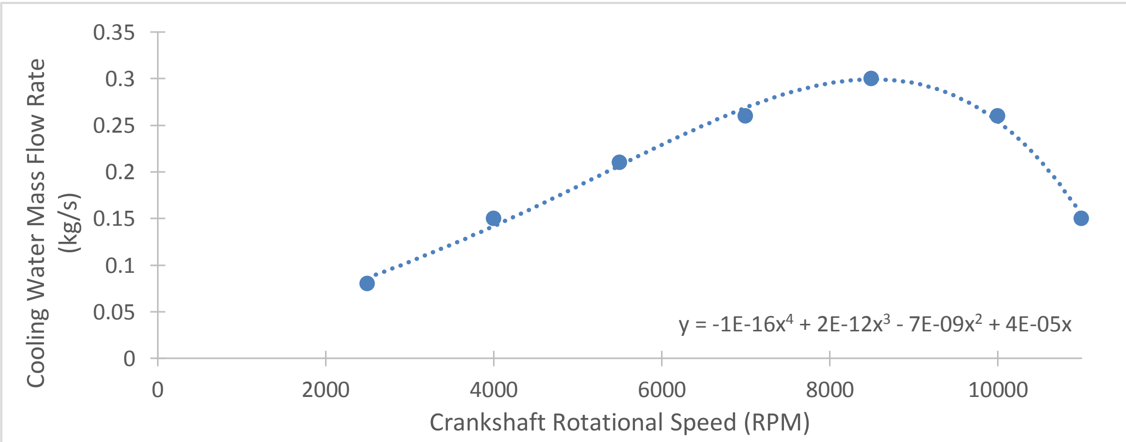


Figure 30. *Example of what the plot generated with completion of Test 1 may look like*

Test 2

In the second test, the formula team will develop a relationship between the heat rejected to the cooling water in the engine and the rotational speed of the crankshaft. This information will be used to predict the rate at which heat is rejected to the cooling water at every car speed. To develop a plot of the heat rejected to the cooling water as a function of the crank speed, the temperature of the cooling water will be measured as it goes into the engine and travels out of the engine. This test will be performed on the dyno. The FSAE team's dyno is already fitted with thermocouples at the inlet and exit of the engine and the tachometer on the dyno also allows the rotational speed of the crankshaft to be measured. Details of the test are as follows.

Materials:

- Cal Poly FSAE Dyno/Engine
- Thermocouple Readouts

Setup:

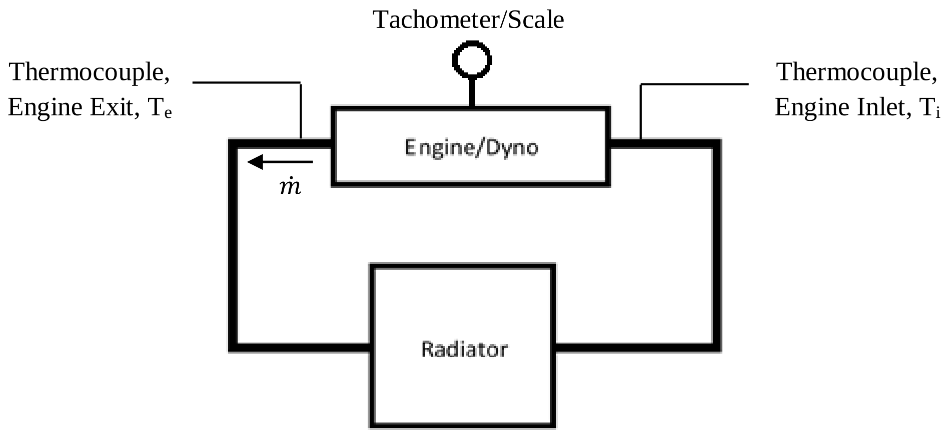


Figure 31. *Experimental setup for Test 2*

There is minimal setup associated with this test because the dyno is already equipped with the instruments necessary in gathering the useful data in this test. The engine and cooling system must be connected on the dyno. Measurements will be taken using the tachometer on the dyno and the thermocouples at the cooling water inlet and exit on the engine.

Procedure:

1. Start the engine, allowing the cooling water to flow through the radiator.
2. Wait for the engine to get hot.
3. Throttle the engine so it is operating with the crankshaft at a constant rotational speed.
4. Measure the T_i and T_e, once these temperatures have reached steady state.
5. Enter the inlet and exit temperatures of the cooling water into the Excel program under the tab labeled "Heat Generation."
6. Record the crankshaft rotational rate and repeat this process over a range of crank speeds.

   NOTE: The range of crankshaft rotational rates over which the test is performed should be the same as the range from *Test 1*.

Analysis:

The Excel program will use the mass flow rate of the cooling water determined in *Test 1*, the specific heat of water and the temperature measurements taken in this test to determine the heat generated in the cooling water according to *Equation 2* that follows.

$$Q = \dot{m} c_p (T_e - T_i) \tag{2}$$

This equation is evaluated where $\dot{m}$ is the mass flow rate of the cooling water and c_p is the specific heat of water. Again, sample data for this test could not be collected because the engine was not available for testing over the course of the senior project. The plot depicted *Figure 32* below is an example of what the plot of heat generated in the cooling water over the range of crank speeds may look like.

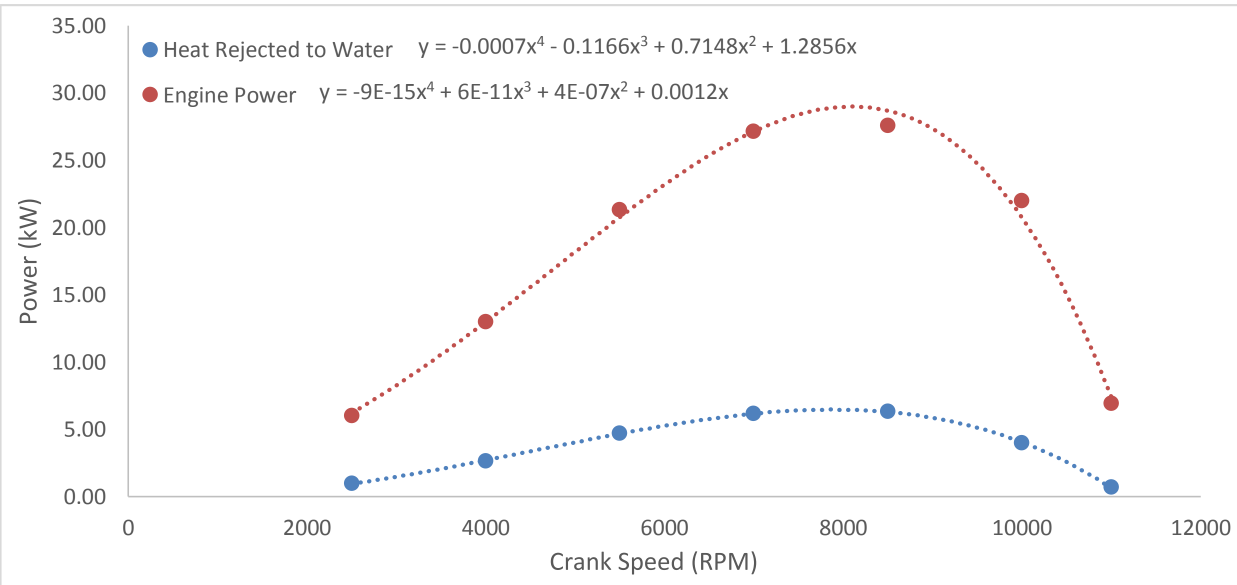


Figure 32. *Example of what the plot generated with completion of Test 2 may look like*

The dependent variable is heat generated in the cooling water per unit time, so it is labeled "Power" on the y-axis. The engine power is plotted on the same graph. Measuring the torque off the scale on the dyno at each data point to produce the engine power curve is optional. However, it may be useful to be able to see the engine power and the heat rejected to the cooling water on the same plot.

Test 3

A relationship between the car speed and the average velocity (and mass flow rate) of the air flowing through the radiator core must also be developed. In order to develop this relationship, a test was performed where a radiator core was held outside the window of a car and a vane type anemometer was used to take an array of air velocity measurements behind the radiator. Using this array, an average velocity was determined. The average velocity of the air through the core can be used with the face area of the radiator core to determine the mass flow rate of the air that flows through the radiator core. This test was performed while the car was traveling at a range of speeds from 0-60 mph. Details are as follows.

Materials:

- Test Radiator
- Car
- Vane Anemometer

Setup:

There is no real setup required to perform this test. If the test is performed in the same manner as it was performed to collect the data for this senior project, three people would be required to collect data. One person will drive the car, then one person will hold the radiator outside of the window while another person held the anemometer behind the radiator to collect data.

Ideally, the test would be performed on the formula car with a fixture to hold the anemometer behind the radiator in different positions along the face of the radiator to collect an array of velocity values over a range of car speeds. This is the ideal due to the fact that it is possible that the relative air velocity is slightly different at different points around the car.

Procedure:

1. The car should be driven at a constant speed.
2. Record the car speed.
3. One person will hold the radiator away from the car while another person holds the anemometer behind the radiator core.
4. Record data for an array of velocities in different positions over the face of the core.
5. Enter the data into the spreadsheet labeled “Core Air Flow.”

Analysis:

The Excel program will find the average air velocity based on the array of air velocities measured. Then it will determine the mass flow rate of the air that flows through the core at each car speed based on *Equation 3* below.

$$\dot{m}_{air} = \rho v_{avg} A \tag{3}$$

Equation 3 is evaluated where ρ is the density of air. The density of air assumed to be constant and equal to its published value of 1.18 kg/m^3 at 25˚C. *A* is the area of the face of the radiator core. The program will then plot both the average air velocity and the mass flow rate of the air through the core as a function of the speed of the car. The Excel program was used to develop this plot for sample data collected that was collected. The results are depicted in *Figure 33* below.

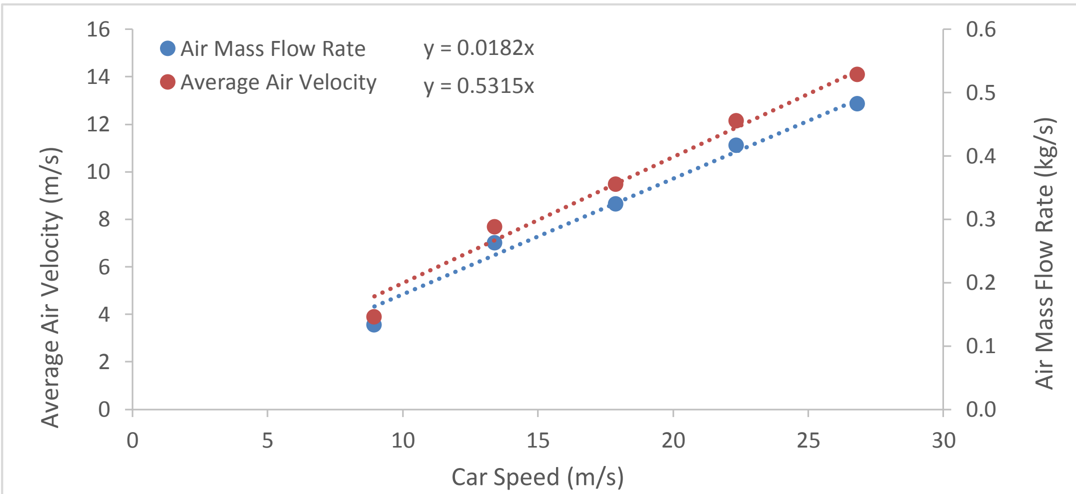


Figure 33. *Plot of results from completion of Test 3*

Both the average air velocity and the mass flow rate of the air through the core are plotted on the graph using the Excel program. It will be helpful to know both the average air velocity and the mass flow rate of the air through the core to correlate data points in the results of *Test 4* and *Test 5* to actual car speeds. Results from the test will be discussed in depth in the *Test Results* (*Chapter6, Section 3*).

Test 4

This test is the first of two tests to be performed on the wind tunnel in the Thermal Science Lab. A relationship between the average air velocity through the radiator core and the static pressure drop across the core will be established. This relationship will be used in two ways: first it will be helpful in measuring the mass flow rate of air through the core in *Test* 5, and second it will be helpful in choosing a fan to be used on the formula car. In order to develop this relationship, the radiator to be tested will be mounted in the test section, then a pitot-static tube will be used to determine the velocity of the air over an array of positions on the face of the radiator core. A liquid column manometer will be used to determine the pressure drop across the radiator. The details of this test will be described in the next few paragraphs.

<u>Materials</u>:

- Wind Tunnel w/ Test Section
- Aluminum Foil Tape
- Test Radiator
- Saw Horse
- Inclined Liquid Column Manometer
- ¼" ID Flexible Plastic Tubing
- Pitot-Static Tube w/ Readout
- Square Ruler

<u>Setup</u>:

Figure 34. *Experimental setup for Test 4- ensuring the core is airtight*

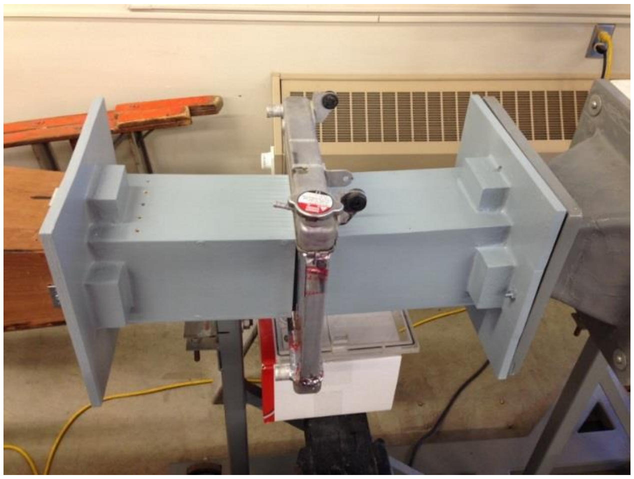


Figure 35. *Experimental setup for Test 4- securing the radiator between the two test section pieces*

To prepare for data collection in *Test 4*, the radiator core needs to be covered with aluminum foil tape on both sides where it will not be contained within the wind tunnel ducting, as depicted in *Figure 34*. This to ensure that the core is airtight; air should only pass through the fins contained within the wind tunnel ducting. The face area tested will be used to predict the necessary face area of the radiator core to achieve adequate cooling on the formula car. If more fins are rejecting heat, the face area reference used in these tests will be meaningless and the necessary face area predicted will be wrong. Additionally, the aluminum foil tape

should not cover any part of the core that is contained within the ducting. Once the face area outside of the duct has been covered with aluminum foil so no air can escape the core, the radiator can be mounted in the test section, as depicted in *Figure 35*. The front end of the wind tunnel where air enters is on wheels while the back with the fan is stationary. The saw horse should be positioned so that it will be underneath the radiator when the front end of the wind tunnel has been pushed against the radiator. If the saw horse is too short, boxes or other materials can be used on top of the sawhorse to support the radiator in the test section. It can be observed in *Figure 35* that a box was used on top of the sawhorse to support the radiator in the proper vertical position. Once the proper vertical position is achieved, the front end of the wind tunnel can be pushed against the radiator core. Check around the foam gasket to be sure that no fins are visible.

Lastly, use two pieces of rubber tubing to connect the static pressure ports on the test section to the inclined liquid column manometer mounted on the wall behind the wind tunnel. Connect one end of the tubing to the test section as depicted in *Figure 36* to the right. The other end of the tubing will be connected to the barb fitting on top of the liquid column manometer. The tubing should be placed such that the static pressure port in front of the radiator is connected to the barb fitting on the left side of the manometer. The static pressure port behind the radiator will be connected to the barb fitting on the right side of the manometer. As a result, the higher pressure that exists in front of the radiator will push the height of the inclined liquid column down with resistance from the lower pressure on the other side of the column.

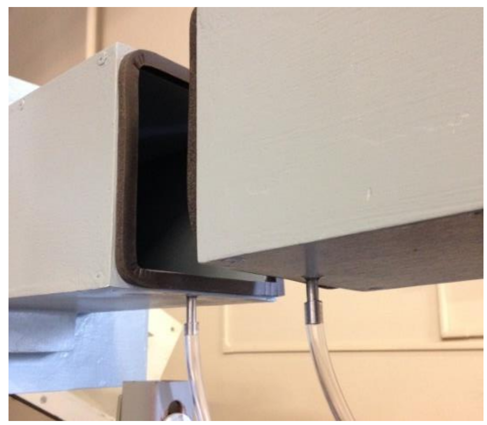


Figure 36. *Experimental setup for Test 4-connecting the tubing to the static pressure ports on the test section*

Procedure:

1. Move the lever on the circuit breaker for the wind tunnel (located behind the wind tunnel) to the "On" position.
2. Set the fan to a low speed using the variable frequency drive (VFD, located on the wind tunnel near the test section).
3. Flip the switch on right on the VFD to the "Start" position.
4. Insert the pitot-static tube into one of the holes on top of the test section and pull up so that the tip of the pitot-static tube is at the top of the duct. This will measure the velocity of the incoming/outgoing air at that point on the face. Use a square ruler to be sure the pitot-static tube is straight up and down and the tip is pointed directly towards the incoming air flow (See *Figure 37*).

5. Record the velocity measurement in the Excel program using the spreadsheet labeled "Core Pressure Drop."
6. Use the ruler to move the pitot-static tube down 1-1/8 inches and measure the velocity at that point on the radiator face and record the measurement in the Excel program.
7. Repeat *Step 6* until 5 measurements have been taken in that hole.
8. Repeat *Step 4* through *Step 7* until measurements have been taken in each of the 5 holes along the top of the test section.
9. Observe the difference in the difference in height of the two oil columns in the inclined liquid column manometer on the wall and record the value in the Excel program.
10. Repeat *Step 4* through *Step 9* over a range of fan speed settings.

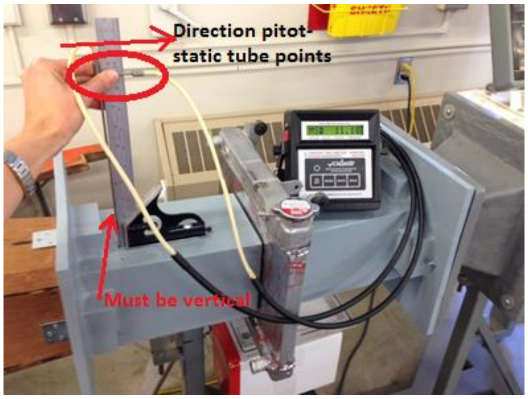


Figure 37. *Orientation of the pitot-static tube in the test section during Test 4*

<u>Analysis</u>:

The Excel program will use the values from each array of measurements to determine the average velocity of the air that passes through the core. From this average velocity, the mass flow rate of the air in the duct can be determined in the same way it was determined in *Test 3* using *Equation 3*. It will then plot both the velocity of the air in the duct and the mass flow rate of the air in the duct as a function of the pressure drop reflected by the change in height of the liquid column manometer. The first plot generated by the Excel program with results from testing performed can be observed in *Figure 38* below.

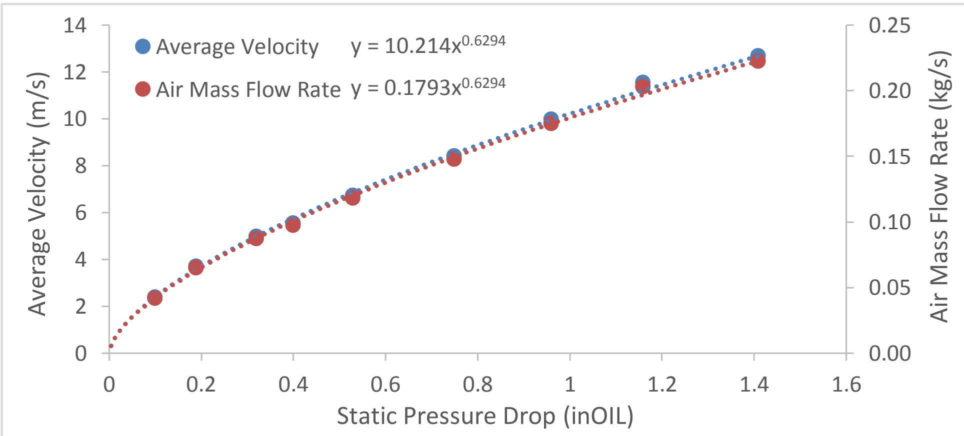


Figure 38. *Plot of results from Test 3- average air velocity and mass flow rate associated with static pressure drop*

This plot can be used as a calibration curve to determine the average velocity of the flow in the duct. This will be valuable in *Test 5*, so that mass flow rate at any fan speed can be determined using the liquid column manometer.

The spreadsheet for this test will produce another plot. This plot develops a relationship between the mass flow rate of the air through the core and the static pressure drop associated with it for the radiator core as a loss element. This information will be valuable in selecting a fan if the formula team determines a fan is necessary to keep the engine cool. The second plot generated using the Excel program with results from testing performed can be observed in *Figure 39* below.

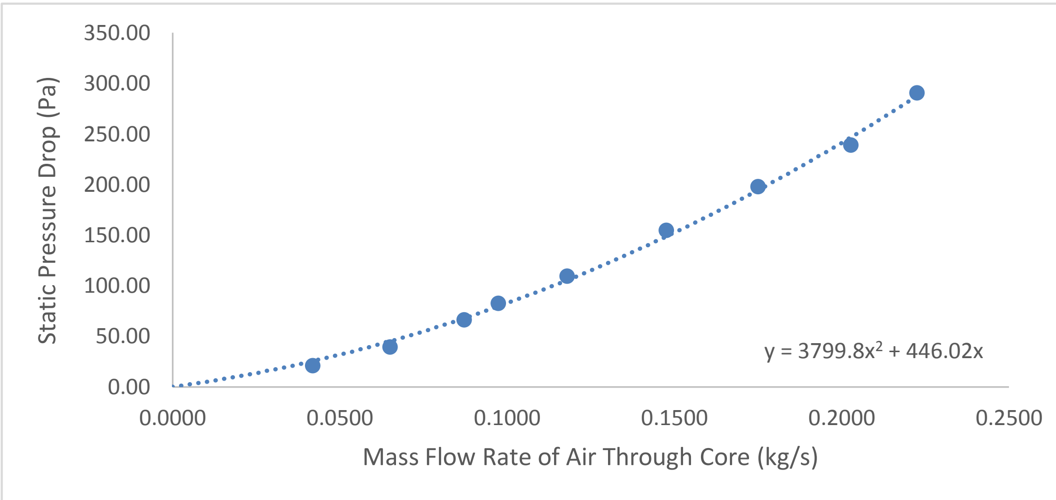


Figure 39. *Plot of results from Test 3- static pressure associated with mass flow rate of air through the core*

Test 5

This test is the second of the two tests that are performed on the wind tunnel in the Thermal Science Lab. A relationship between the flow rates of air and water and the heat rejected by the radiator will be established. In order to develop this relationship, the radiator to be tested will be mounted in the test section, then thermocouples will be used to measure the temperature of the water at the inlet and outlet of the radiator. The temperature drop across the radiator can be used to find the heat rejected by the radiator over a range of mass flow rates of both air and water. This data will generate a curve that will allow the formula team to predict the heat rejected by their radiator per unit area over the car's operating range. Details are as follows.

Materials:

- Plumbing Assemblies from *Appendix G*
- Cole Parmer Hot Water Bath
- ¼" Brass Pipe Plug Fitting
- 2-Quart Pot w/ Handle
- Aluminum Foil Tape
- 20-Gallon Reservoir
- Immersion Heaters
- 2 Extension Cords
- 2 Surge Strips
- Test Radiator
- Inclined Liquid Column Manometer
- ¼" ID Flexible Plastic Tubing
- Wind Tunnel w/ Test Section
- Type K Thermocouple Wire
- 2 Thermocouple Readouts
- Thermocouple Jack
- 2 5-Gallon Buckets
- Stopwatch
- Sawhorse
- Stir Stick

Setup:

Setup should begin almost exactly as *Test 4* was set up. The test radiator needs to be covered with aluminum foil so that no air will escape the test section and the covered radiator needs to be secured between the two pieces of the test section on a sawhorse. Then two lengths of flexible plastic tubing need to be attached between the static pressure port tube on bottom of the test section and the barb fittings on the liquid column manometer. Again, this tubing should be attached so that the tubing attached to the upstream piece of the test section goes to the barb fitting on the left side of the liquid column manometer near the 0" designation. The tubing attached to the downstream piece of the test section will go to the barb on the right side of the liquid column manometer. Place the hot water bath in the spot where it will stay during testing.

Next the plumbing needs to be set up. Begin by using the brass pipe plug described in *Appendix G* to plug the hot water bath's pump suction. Next, construct the pump discharge assembly described in the *Figure 59* and *Table 15,* in *Appendix G*. Apply Teflon tape to all external threads. The ¼" MPT nipple on this assembly should be threaded into the hot water bath discharge on the right side of the back of the hot water bath. At this point, the heater hose can be fitted on the barb at the other end of the pump discharge assembly. Use a hose clamp to secure

the hose on the barb. The other end of the heater hose should be cut so that it just reaches the radiator inlet. Place the hose over the radiator inlet and use a clamp to secure the hose around the inlet. Similarly, construct the thermocouple assembly described in *Figure 58* and *Table 14*, in *Appendix G*; again, using Teflon tape on all male threads. Cut a 3" long piece of heater hose and use clamps to attach one end to the radiator outlet and the other end to a barb on the thermocouple assembly. Cut another piece of heater hose about 6" long. Attach one end of the hose to the other end of the thermocouple assembly and the other end to one end of the valve. Use clamps to secure each end of the hose. Cut another piece of heater hose that is just long enough to go from the other end of the valve to the furthest of two discharge water reservoir buckets on the ground. Use a clamp to attach one end of the heater hose to the discharge end of the valve.

Plug the banana plugs from the embedded thermocouple into the thermocouple jack and then plug the wire from the jack into a thermocouple readout. Similarly, plug the thermocouple wire into the other thermocouple readout. The thermocouple wire can be placed inside the red hole on the back right corner of the hot water bath. *Figure 40* below depicts the way the test should be set up.

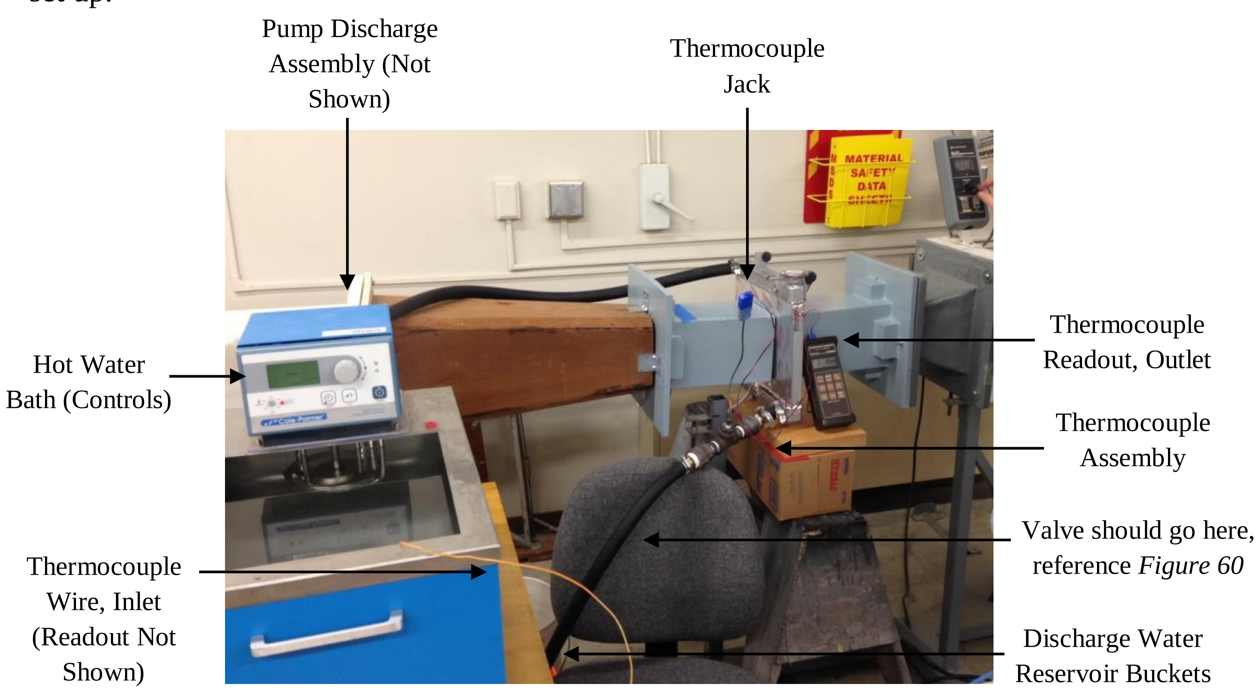


Figure 40. *Experimental setup for Test 5*

The valve at the radiator outlet, and the pump discharge assembly are not visible in the figure above, but should absolutely be implemented. The thermocouple wire that is used to measure the inlet water temperature in the hot water bath can be placed in the red hole at the back right corner of the hot water bath as described above. Again the figure above does not depict this implementation.

Procedure (Heating the Water):

1. Begin by filling the 20-gallon reservoir with about 17 gallons of water. The hotter the water begins, the faster the water will heat up to the appropriate temperature, so a water source with the hotter water should be used.
2. Place the immersion heaters in the reservoir.
   NOTE: Do not allow the bottom of the black plastic at the top of the heater dip below the water level.
3. Plug the extension cords into the wall and the surge strips into the extension cords. Then plug the immersion heaters into the surge strips. Turn the surge strips on.
   NOTE: Plug no more than two heaters into one of the surge strips.
4. Allow the water to heat up to 180˚F (or whatever the target temperature for the cooling fluid flowing into the radiator is determined to be). Stir the water every 10 minutes because the water will stratify and take excessively long to reach the target temperature. While the water is heating up, continue with the procedures below.

Figure 41. *Heating water using immersion heaters*

Procedure (Measuring Water Flow Rates):

1. Weigh one of the buckets being used at the radiator outlet to determine its weight, in kg.
2. Enter the weight of the bucket into the Excel spreadsheet titled "Heat Rej. from Rad."
3. Fill the hot water bath with tap water.
4. Move the outlet hose to the bucket that was not weighed.
5. Be sure that the valve at the radiator outlet is open and turn the hot water bath pump on using the power button on the control panel.
   NOTE: The hot water bath is only being used for its pump, it is not being used to heat up water at any time.
6. Adjust the pump speed by pressing down on the knob until you have reached pump speed selection and turn the knob to select the pump speed. When the desired pump speed is selected, press the knob down again.
7. Turn the pump off.
8. Refill the hot water bath, if necessary.
9. Turn the pump back on and allow water to flow into the bucket.
10. Move the hose into the bucket that was weighed and simultaneously begin timing with the stopwatch.
11. Allow the pump to fill the bucket for 20 seconds.
12. At the end of the 20 seconds move the outlet hose back to the other bucket.
13. Turn the pump off.
14. Weigh the bucket again to determine its weigh with water, in kg.
15. Enter the weight into the Excel spreadsheet to produce water mass flow rate.

16. Repeat this process to determine mass flow rates at 4 pump speeds (slow, medium, fast, and maximum).

Procedure (Measuring Air Mass Flow Rates):

1. Make 5 marks with pencil on the variable frequency drive on the wind tunnel. These will be the air speeds at which testing is performed.
2. At each of these 5 speeds, record the pressure drop across the radiator, in inches of oil.
3. Record these values in each of the 4 tables in the Excel spreadsheet.
4. Change the equation in the "Air Mass Flow Rate" column to correspond to the relationship between air mass flow rate and static pressure drop (in inches of oil) to produce air mass flow rates specific to the system setup at each of the 5 speeds.

Procedure (Measuring Heat Rejection):

1. Use the pot to transfer hot water into from the hot water reservoir into the hot water bath.
2. Be sure that the valve at the radiator outlet is open and the end of the heater hose is in a bucket. Turn the pump on and allow it to run until water begins to flow into the bucket.
3. Turn the pump off and close the valve to allow the hot water trapped in the radiator to heat up the radiator.
4. Wait about 5 minutes then begin testing by opening the valve and allowing the water that was trapped in the radiator to flow out. This will heat up the radiator.
5. Set the fan to one of the predetermined speeds then simultaneously turn the fan and the pump on.
6. Watch the thermocouple readout at the radiator outlet. Once, the outlet temperature has reached steady state, record the inlet and outlet water temperatures.
7. Change the fan and pump speeds and repeat this process 19 times for each combination of fan and pump speeds.
8. Enter the inlet and outlet water temperatures into the appropriate cells in the Excel spreadsheet to determine the relationship between fluid mass flow rates and heat rejected from the radiator.

Analysis:

The Excel program will use the inlet and outlet water temperature values and the mass flow rate of the water to determine the heat rejected from the water via the radiator. This heat can be predicted using to the aforementioned inputs via *Equation 4* below.

$$Q = \dot{m} c_p (T_o - T_i) \tag{4}$$

Where the outlet and inlet temperatures are T_o and T_i, respectively. Then $\dot{m}$ is the mass flow rate of the water and c_p is the specific heat of the water at an average temperature.

The Excel spreadsheet will then produce two different plots. It will produce two plots where heat rejection rate, in kW, is plotted on the y-axis with two independent variables. The first plot has 5 different graphs with water mass flow rate on the x-axis. Each of the 5 graphs correspond to a different air mass flow rate. *Figure 42* contains a plot generated with real test data.

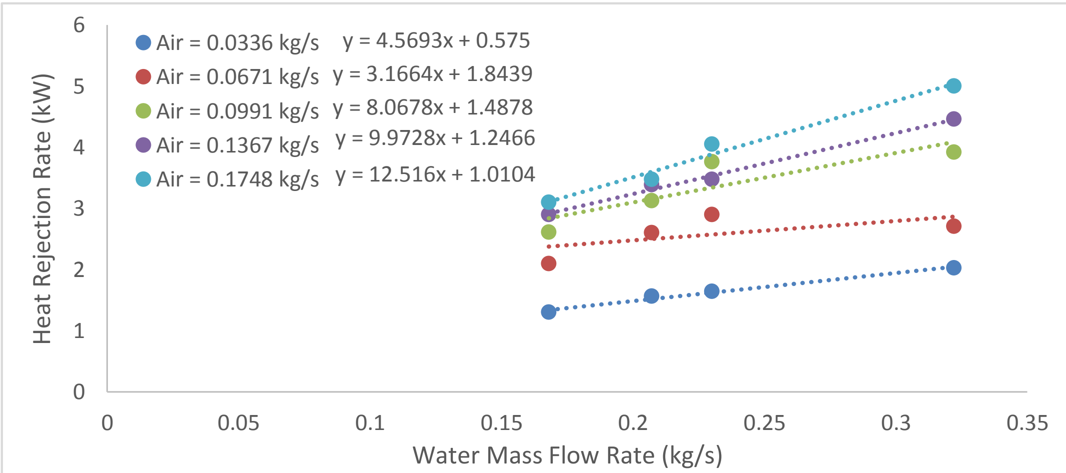


Figure 42. *Heat rejection rate as a function of water and air mass flow rates- water mass flow rate on the x-axis*

The next plot is very similar to the first plot, except in this case, there are 4 different graphs with air mass flow rate on the x-axis. Each of the 4 graphs correspond to a different water mass flow rate. Another plot generated with real test data can be observed in *Figure 43* below.

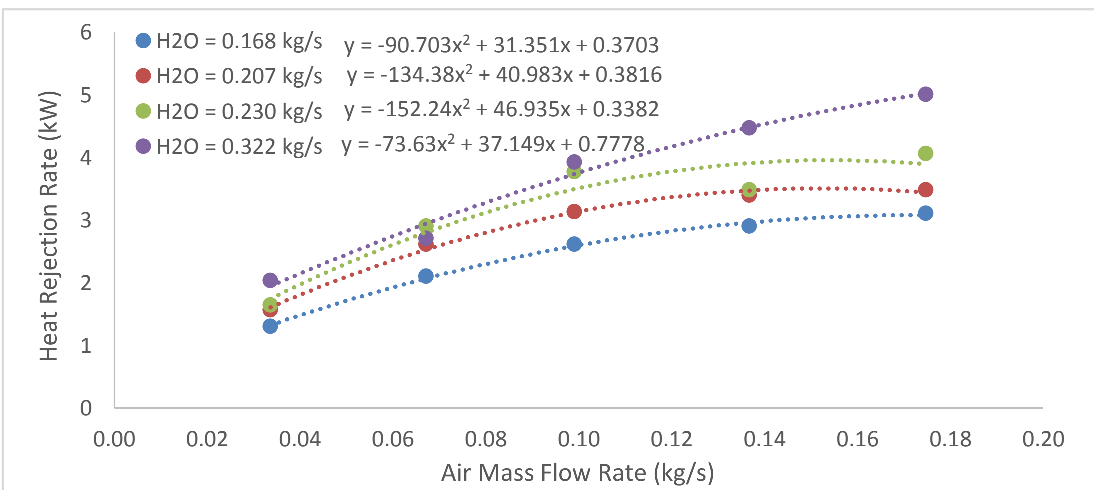


Figure 43. *Heat rejection rate as a function of water and air mass flow rates- air mass flow rate on the x-axis*

Predictably, the rate at which heat is rejected from the radiator increases as the mass flow rates of either of the fluids increases. The data indicates that the heat rejection increases at a decreasing rate as the mass flow rate of air increases. Conversely, the data suggests that the heat rejection rate increases linearly as the mass flow rate of water increases.

Using Experimental Results to Size the Radiator

The flowchart in *Appendix I* will walk the user through the process of using the experimental results to size the radiator. To begin, the user must select a type of radiator that they want to use. This type of radiator should be characterized by its fin density, its depth, and the material that it is made from. Then the user must select a "worst-case scenario" that they would like to use as a design point. This "worst-case scenario" is the operating point that results in a high rate of heat rejection from the engine to the cooling fluid and a low rate of heat rejection from the cooling fluid to the air via the radiator. This will most likely come in low gears (i.e. first gear) at high engine outputs. At this point, the car will not be going very fast, so the mass flow rate of air through the core is low, resulting in a low rate of heat rejection from the cooling fluid to the air. There is still a maximum engine output in first gear around 8500 RPM, so if the car will ever operate in first gear at 8500 RPM, this may be the worst case scenario. The formula team will need to determine on their own whether or not this is truly the worst case scenario that they will use as a design point. If the cooling water flow rate changes significantly as the crank speed increases, this may not be the worst case scenario because the water flow rate is so high. Determination of the "worst case scenario" will necessitate some exploration. For the purpose of describing the process of sizing the radiator, the max engine output in first gear will be treated as the design point.

The formula team will use the equations of the curves generated by the plot from *Test 1* (*Figure 32*) and the plot from *Test* 2 (*Figure 32*) to determine the mass flow rate of the cooling water and the rate at which heat is rejected to the cooling water, respectively, at the design point. They will also use the gear ratio and the radius of the tire to determine the speed of the car at this point. The speed of the car will can be determined according to *Equation 5* below

$$v = \left(N_e * \frac{2\pi}{60}\right)\frac{1}{\xi_t \xi_a} r_w \tag{5}$$

where v is the velocity of the car, N_e is the rate of revolution of the crankshaft (RPM), ξ_t and ξ_a are the gear ratios for the transmission reduction and the drive axle, respectively, and r_w is the radius of the tire.

Once the formula team has determined the speed of the car at the design point, they will use equation of the curve generated by the plot from *Test 3* (*Figure 33*) to determine the mass flow rate of air through the core at the design point. This mass flow rate of air and the determined mass flow rate of water will be used with either of the plots from *Test 5* to determine the rate at which heat will be rejected from the cooling water via the radiator. The heat rejection rate measured in *Test 5* can be viewed as the heat rejection rate per heat transfer area (or the surface area of the fins contained within the duct during testing). To determine the surface area necessary to achieve adequate cooling, simply divide the rate at which heat is rejected from the engine to

the water by the rate of heat rejection from the water to the air per unit area, according to *Equation 6* as follows.

$$A_{req} = A_{ht} * \frac{Q_2}{Q_5} \quad (6)$$

In the above equation, A_{req} is the required heat transfer area (the surface area associated with the sum of the fins in the core), A_{ht} is the heat transfer area as previously described—the surface area of the fins contained within the duct during testing, then Q_2 and Q_5 are the heat rejection rates determined in *Test 2* and *Test 5*, respectively.

If the necessary radiator size determined is acceptable, then the radiator sizing is completed; however, it could be beneficial to use a fan to increase the mass flow rate of air at your design point, thus lowering the necessary heat transfer area. If this is the case, the user should continue as the flowchart suggests. They will choose an area where they believe this would be beneficial and use the results from *Test 5* to determine the mass flow rate of air associated with adequate cooling using the heat transfer area that has been chosen. They will then use the results from *Test 4* (*Figure 39*) to determine the static pressure drop associated with the new and old air mass flow rates. Then a fan must be chosen that can supply the difference in the static pressure drop at the mass flow rate chosen.

The formula team may also decide that a fan is necessary because the worst case scenario is when the car is idling. If this is the case, the process above should be performed where the design point are the conditions at idle. The mass flow rate of air through the core is zero when the car is idling, so a fan will be necessary. They would need to choose a fan and radiator size combination that would satisfy the cooling requirements as described above.

2. Safety Considerations

This section contains a discussion regarding safety considerations that should be made throughout the testing process. It describes the consequences of failing to use proper care during testing as well as the severity if that consideration is not heeded, and methods of avoiding potentially dangerous situations.

1. The valve at the outlet of the radiator needs to be opened before the pump is turned on.
   Consequences: The clamps could fail and water could be sprayed on the user. The user could be burnt by hot water or slip in a puddle.
   Severity: Severe
   Solution: The user should always be sure the valve is open before the pump is turned on.

2. Any material making contact with the radiator in testing should be resistant to burning.
   Consequences: The radiator will be hot, if plastic is used to as a support, it could burn, resulting in potentially toxic fumes.
   Severity: Moderately severe
   Solution: Only burn-resistant materials (i.e. wood, 180˚ rated foam) should come in contact with the radiator.

3. Do not touch the radiator, hoses, hot water, hot water reservoir, or engine during testing as they will all be very hot.
   Consequences: The user runs the risk of being burnt by hot materials.
   Severity: Severe to very severe
   Solution: Care should be taken during testing to be sure that the user does not come into contact with any of the aforementioned objects. Wear pants, long sleeves, and gloves when necessary.

4. The plumbing should not leak.
   Consequences: The user runs the risk of being burnt by hot water that drips from plumbing and slipping in a puddle of water that has gone unnoticed.
   Severity: Moderately severe to severe
   Solution: The user should be aware of their surroundings and check the plumbing before each test to be sure that hot water is not leaking.

5. Water should not be spilled when it is being transferred.
   Consequences: If water is spilled, the user may be burnt by hot water, or slip in the resulting puddle.
   Severity: Moderately severe to severe
   Solution: The user should exercise care when transferring water.

6. Any buckets used as reservoirs should not be allowed to overflow.
   Consequences: If water spills, the user runs the risk of slipping in the resulting puddle. If hot water is spilled, the user could be burnt.
   Severity: Moderately sever to severe
   Solution: The user needs to pay special attention to be sure that the buckets never overflow.

7. When performing *Test 3*, the users should exercise caution throughout the entire test.
   Consequences: The driver could become distracted and hit something. If the user holding the radiator drops it, it could hit another user.
   Severity: Moderately severe to very severe
   Solution: The driver needs to always pay attention to the road and other users should firmly grasp any object being held outside of a moving car.

8. The immersion heaters should not be allowed to short circuit.
   Consequences: If the heaters short circuit, the heaters could be damaged or the user could be electrocuted.
   Severity: Very severe
   Solution: The user should always be careful to keep any surge strips outlets well out of the way of water.

9. The radiator should be properly supported from below.
   Consequences: The radiator could fall from between the two pieces of the test section. If the radiator falls, it is possible that they plumbing detaches from adjacent components, resulting in hot water being spilt and the potential for users to be burnt. The radiator may be damaged as well.
   Severity: Very severe
   Solution: The radiator support should be stable.

3. Test Results

This section will discuss the results of the sample testing that was performed. As a result of the fact that the engine was unavailable for testing, the first two tests could not be performed. However, sample data was acquired for the last three tests. The results that would have been expected from *Test 1* and *Test 2* as well as the results from the last three tests will be detailed.

Test 1

In *Test 1*, the relationship between the rate of rotation of the crankshaft and the mass flow rate of the cooling fluid (which, in this case will be water) is established. This test is performed so that the formula team will be able to predict the mass flow rate of the water, which will be dependent on the power delivered to the system by the pump's impeller. Since the impeller is connected to the crankshaft and power delivered to the crankshaft will increase from idle until the engine's maximum power output at about 8500 RPM, the mass flow rate of the water should increase from idle to 8500 RPM, then begin to dip back down at higher crank speeds. Results should be characterized by a plot similar to the one shown below in *Figure 44*.

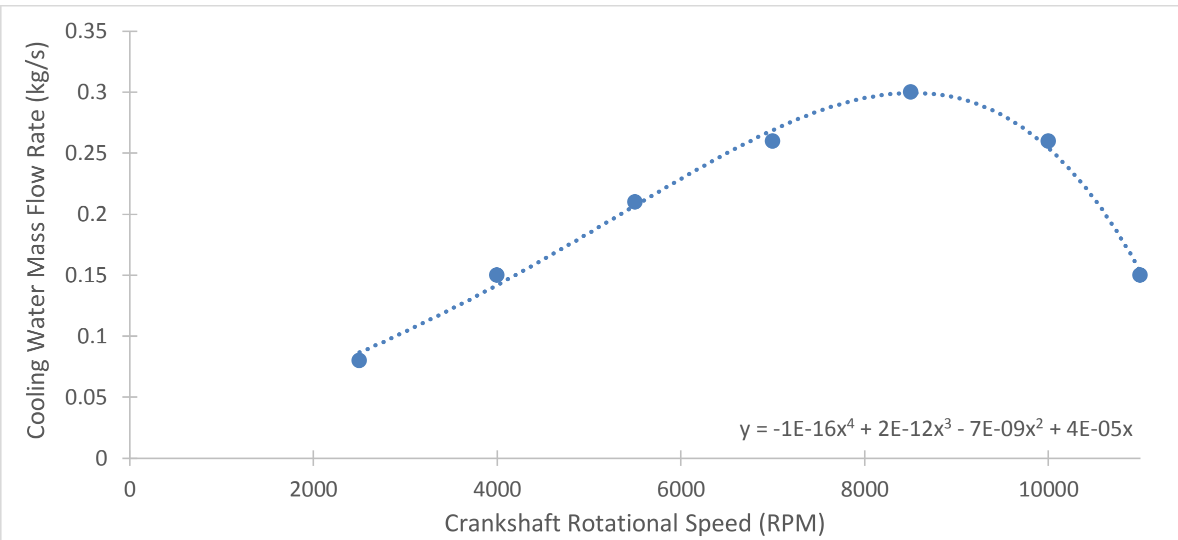


Figure 44. *Predicted relationship between cooling fluid mass flow rate and crank speed from Excel program*

Test 2

In *Test 2*, the relationship between the rate of rotation of the crankshaft and the rate at which heat is rejected from the engine to the cooling water is established. Theoretically, about 30% of the engines rated power is rejected to the cooling water in the form of heat. This theory establishes a proportional relationship between the engine's output power and the rate at which heat is rejected to the cooling water. As a result, the trend that predicts the rate at which heat is rejected to the cooling fluid should be similar to the plot of the results from *Test 1*. Results should be characterized by a plot similar to the one shown below in *Figure 44*.

Both the engine power and the rate at which heat is rejected to the cooling fluid as a function of crankshaft rotational speed are plotted in the Excel program. It is not necessary to collect data to plot engine power, but it may be interesting to test the theory that predicts that 30% of the engines rated power is rejected to the cooling water in the form of heat. Theoretically predicted results are plotted in *Figure 45* that follows.

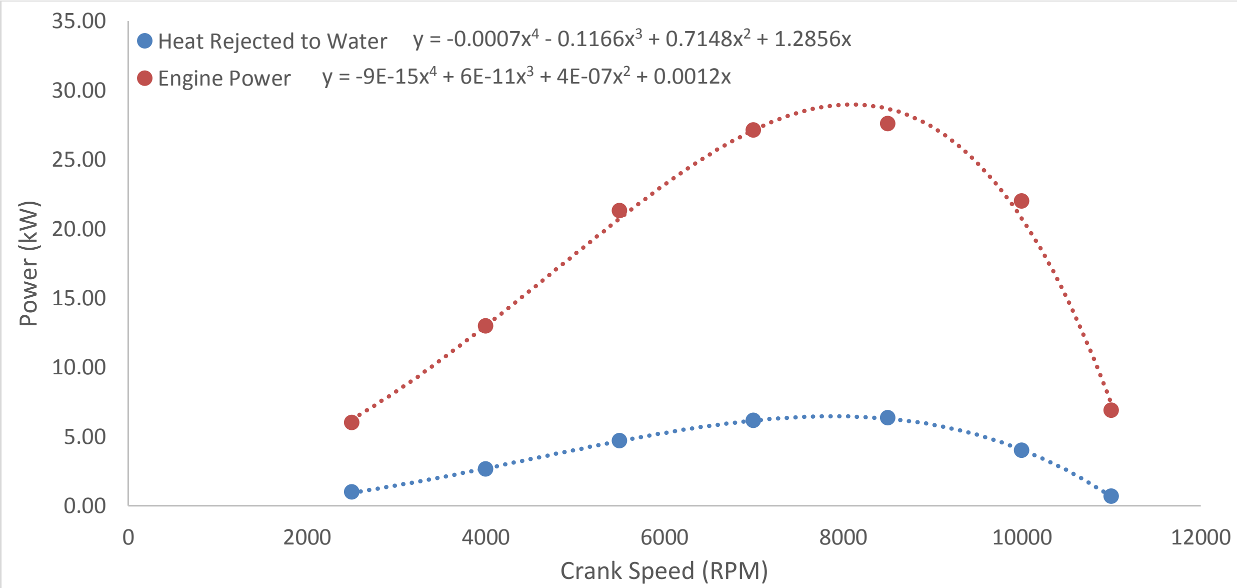


Figure 45. *Predicted relationship between rate of heat rejection to the cooling fluid and crank speed from Excel program*

<u>Test 3</u>

From this point on, sample data was collected. In *Test 3*, the relationship between car speed and the mass flow rate of air through the radiator core was predicted. As described in *Test Descriptions*, the velocity of air was measured at different points along the face of a radiator that was being held out of window. This data yielded an average velocity of air through the core, from which the mass flow rate of air through the core could be determined. The raw data results are can be observed in the tables below.

Table 2. *Array of measurements of air velocity through core, car speed = 20mph*

	Horizontal Position		
Vertical Position	8	10	8
	8	10	8

Table 3. *Array of measurements of air velocity through core, car speed = 30mph*

	Horizontal Position		
Vertical Position	15	18	17
	19	17	17

Table 5. *Array of measurements of air velocity through core, car speed = 40mph*

	Horizontal Position		
Vertical Position	23	20	21
	20	22	21

Table 4. *Array of measurements of air velocity through core, car speed = 50mph*

	Horizontal Position		
Vertical Position	26	28	27
	26	29	27

Table 6. *Array of measurements of air velocity through core, car speed = 60mph*

	Horizontal Position		
Vertical Position	33	31	32
	30	31	32

Contrary to what was expected, there was not a major difference in the velocity along the edges of the radiator core. In the case of the radiator that was tested, the average velocity of air through the radiator core could have almost been predicted by measuring the velocity at an arbitrary point along the face because there was such insignificant variance.

The data from the tables was used to generate the plot in *Figure 46* below. This plot displays the relationship between car speed, the average velocity through the radiator core and the mass flow rate of air that results.

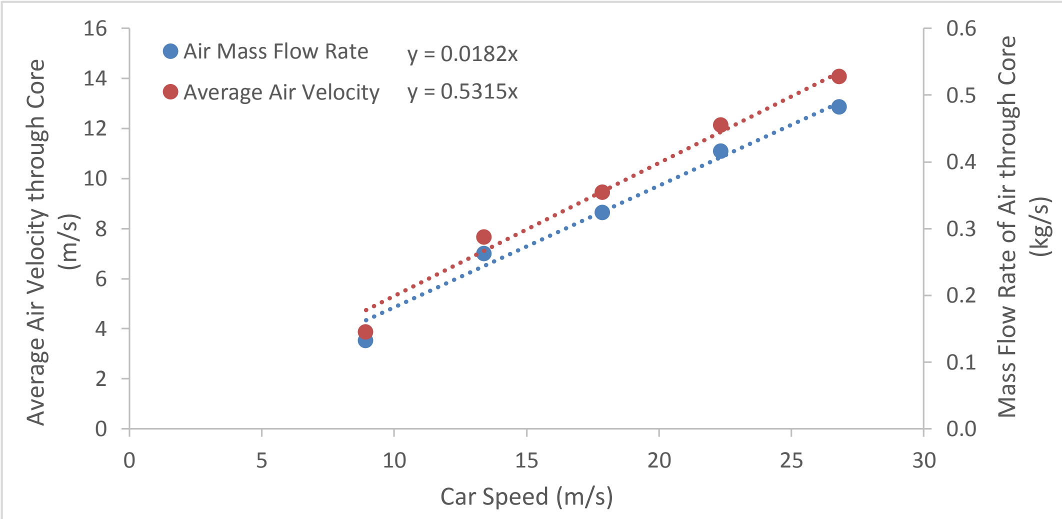


Figure 46. *Measured relationship between the average air velocity and mass flow rate of air through the core and car speed*

Since the density of the air is constant along at each car speed, the mass flow rate and average velocity of air through the radiator core are directly proportional. The trendlines on the plot are not perfectly parallel because they are plotted on different scales. The plot suggests that the relationship between the speed of the car and the average velocity (and thus the mass flow rate) of air through the core is quite linear. The measurements beyond 15 mph suggest that the relationship is almost perfectly linear. This is most likely due to measurement error and the effect of wind being more significant at lower speeds. This seems to be the most likely cause of the drop in average velocity through the core at low speeds because when the trendline is forced through the origin, the resulting trendline almost perfectly intersects every point at speeds above 15 mph. The trendline should intersect the origin because the velocity of air through the car should be zero when the car is idle. However, the accuracy of the trendline is appropriate in these circumstances and it can be assumed that there is a linear relationship between the velocity of air through the core and the car speed. In other words, as the speed of the car increases, the velocity of the air that passes through the radiator increases proportionally.

Test 4

In *Test 4*, the relationship between the mass flow rate of air through the core and the static pressure drop across the core was established. This was useful for a few reasons. First, it made it so that the average velocity of air in the duct could be predicted using the static pressure drop indicated by the liquid column manometer any time the fan speed was changed. Second, it aided in choosing a fan. This way, the formula team would know the back pressure associated with a mass flow rate of air through the radiator. They can choose a fan based that can generate enough head to overcome the pressure drop across the radiator at their desired mass flow rate. As described in *Test Descriptions*, the average velocity of air through the core was predicted using a pitot-static tube to find the air speed at 25 different points along the face of the radiator. These 25 points made for a nice average that would negate the effects of any human error during testing.

This test was performed for two different radiators. The first radiator was a radiator provided by the formula team that was a downflow radiator with a 1" thick core. The second radiator was a C&R racing radiator. It was a crossflow radiator with a 1.35" thick core with a higher fin density. *Figure 47* on the right depicts the radiator that was borrowed from the formula team for testing. *Figure 48* and *Figure 49* depict the two sides of the C&R racing radiator core. The radiator received from the formula team has a significantly lower fin density as compared to that of the C&R core. Notice that one can see straight through the fins on this radiator, while this is not the case for the C&R core.

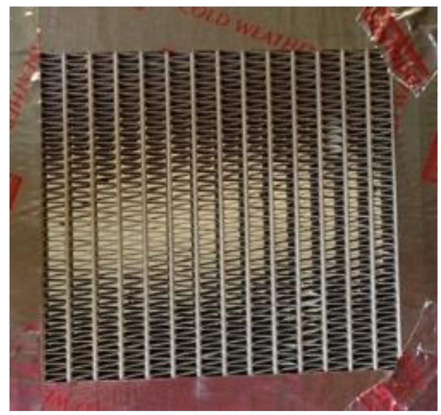


Figure 47. *Core of radiator borrowed from the formula team*

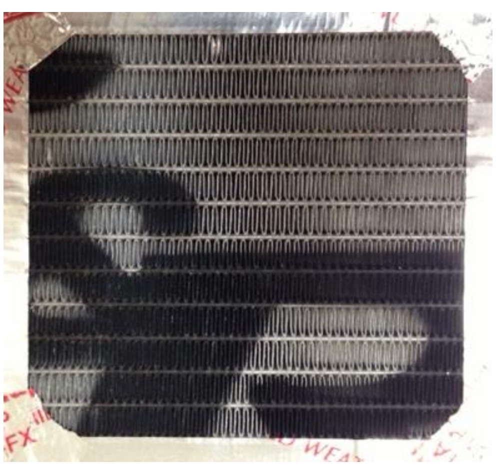


Figure 49. *C&R racing radiator, undamaged fins*

Figure 48. *C&R racing radiator, notice damaged fins in the top right hand corner of the exposed area*

Test 4 was performed on both radiators. The tables below contain raw data collected during the experiment. The test was performed at 9 different air speeds in the case of the formula team's radiator and 6 different speeds in the case of Professor Fabijanic's radiator. The trends were relatively similar over the range of airspeeds for each respective radiator.

Table 7. *Array of air velocity measurements behind the radiator in the wind tunnel ducting, formula team's radiator core*

	Horizontal Position				
Vertical Position	6.49	7.27	6.14	5.04	4.57
	6.43	7.08	6.26	7.21	6.75
	7.31	8.02	7.12	7.87	7.48
	7.54	6.63	7.6	6.3	6.69
	5.64	7.43	6.14	7.61	5.65

Table 8. *Array of air velocity measurements behind the radiator in the wind tunnel ducting, C&R racing radiator core*

	Horizontal Position				
Vertical Position	0	0	8.78	10.47	10.7
	0	0	7.87	9.66	10.37
	0	5.61	8.47	8.89	10.51
	0	6.91	9.4	9.64	10.01
	1.67	4.72	9.61	10.65	11.24

Table 7 indicates that there is some disparity between the velocity readings taken in the middle of the duct and those taken at the corners of the duct. This is to be expected as a result of the formation of a boundary layer inside the ducting. The velocity should be at a maximum in the center of the duct and then eventually go to zero at a point infinitely close to the duct wall. The evidence of a boundary layer was not significant at middle positions along the edges, but was very apparent at the corner positions.

Table 8 contains raw data taken from testing on the thicker racing radiator. At every velocity, there was a region in the top left portion of the ducting where the air velocity was zero. This was due to what seemed to be relatively minor damage to the fins (see *Figure 49*). This relatively minor fin damage proved to be very significant. It wouldn't be as significant in the case of heat rejection on the wind tunnel as it would be on the car. On the wind tunnel, the same mass flow rate of air will be forced through a smaller area. There would only be a small dip in the mass flow rate of air due to the increased system back pressure. The most significant cause of reduced heat rejection would be due to the fact that there are fins that are not being used to reject heat, not the slightly reduced mass flow rate of air through the core. However, on the car, it will be as

though that entire area didn't exist. Not only would those fins not reject heat, but a large portion of the air that would have gone through that area would just go around the radiator.

The data collected was used to produce two different plots for each radiator. One plotted the mass flow rate and the average velocity of the air through the radiator core against the difference in height of the liquid columns on the inclined manometer. This plot was used mainly as a calibration curve to predict the average velocity and mass flow rate of air through the duct at different fan speeds based on the manometer measurement. These calibration plots can be observed in *Figure 50* and *Figure 51* below. The liquid column manometers measure the pressure drop in inches of oil. The oil used in the liquid column manometer has a specific gravity of 0.826.

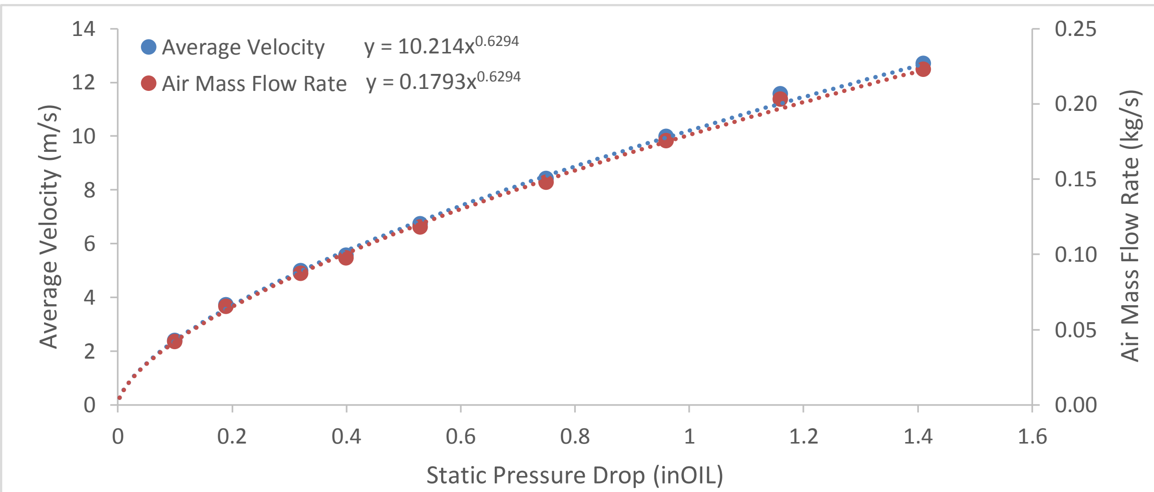


Figure 50. *Calibration curve for radiator from formula team- average velocity and mass flow rate of air through core as a function of static pressure drop*

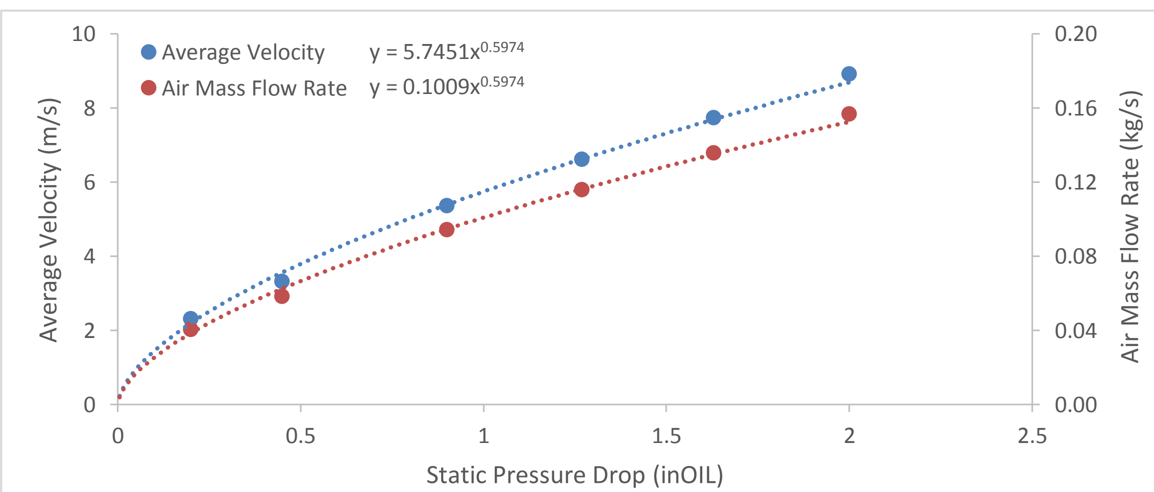


Figure 51. *Calibration curve for C&R radiator- average velocity and mass flow rate of air through core as a function of static pressure drop*

The calibration curves above suggest that the pressure drop across the C&R core is significantly higher than the pressure drop across the other radiator at an equivalent air mass flow rate. This is due to higher fin density associated with the C&R core. There are more fins and thus more drag resulting in more significant head losses across the core. This is reflected by a loss in static pressure between the two sides of the core.

The second plot was more of a system curve for the radiator. It plotted the static pressure drop as a function of static pressure drop to predict the back pressure associated with varying air mass flow rates. The system curves for each of the radiators can be observed in *Figure 52* and *Figure 53* below.

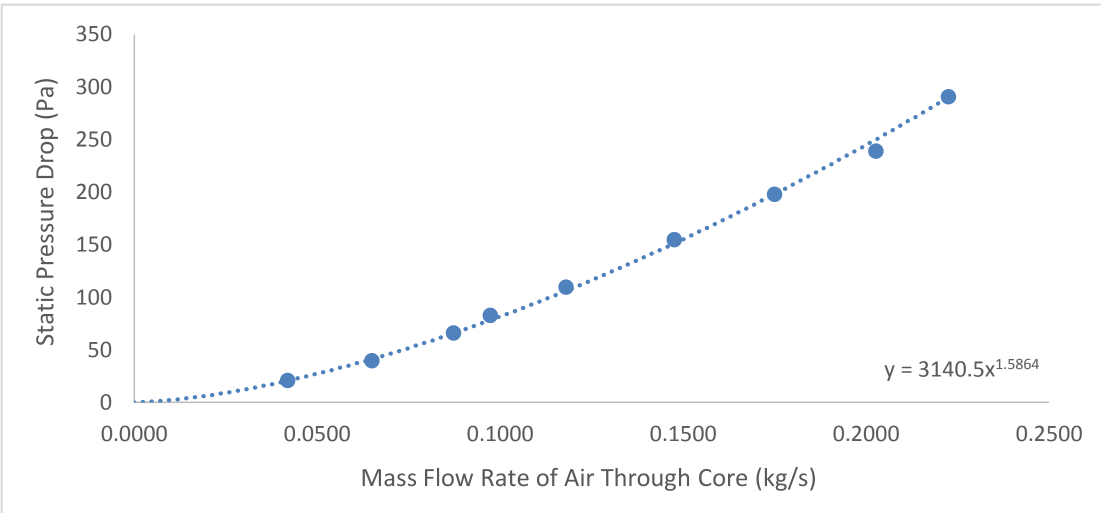


Figure 52. *System curve for radiator borrowed from formula team*

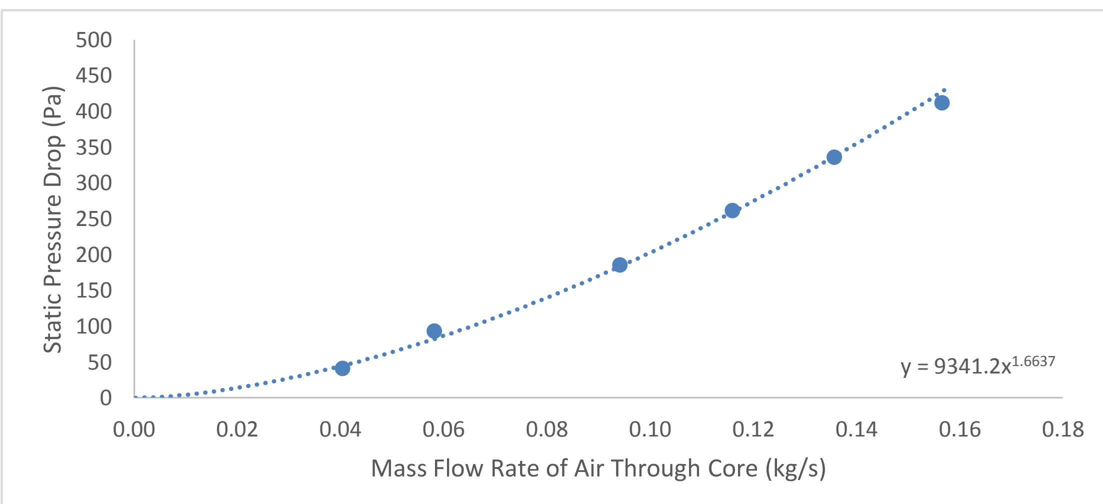


Figure 53. *System curve for C&R radiator*

In both radiator cases, the system curve looks the way it would be expected to look. There should be an exponential relationship between the mass flow rate of air and the pressure drop across the system. The pressure drop across the system should increase exponentially as the mass flow rate of air through the system increases. The plots in the figures reflect this relationship.

Test 5

In *Test 5*, a relationship between the mass flow rates of each fluid and their effect on the rate at which heat is rejected by the radiator was established. This test was performed on both the C&R racing radiator and the radiator borrowed from the formula team. There was one subtest associated with *Test 5* that was performed as a precursor to heat rejection testing. In this subtest, the mass flow rate of water was measured at the 4 pump speeds described in *Test Descriptions*. *Table 9* below contains data that describes the water mass flow rates at each of the 4 speeds for each radiator.

Table 9. *Water mass flow rates at different pump speeds for each radiator*

Pump Speed	Mass Flow Rate (kg/s)	
	FSAE	C&R
Slow	0.168	0.168
Med.	0.207	0.18
High	0.23	0.212
Max	0.322	0.286

The mass flow rate of the water through the radiator borrowed from the formula team was higher at every pump speed after the lowest speed. This suggests that the pressure drop across the system where the C&R radiator was installed was higher. There is a larger difference between the two mass flow rates as the mass flow rate increases. This is consistent with what would be expected because the system curve that plots the relationship between the mass flow rate of water and the backpressure in the system is exponential. The C&R radiator is a larger radiator which means that the channels in the radiator are longer. The pressure losses due to friction in a longer system can account for the increased backpressure in the case of the C&R radiator.

Once the mass flow rates had been determined, the temperature drop across the radiator could be measured at different water and air mass flow rates to develop a relationship between the heat rejection rate and the mass flow rates of the fluids involved. The data collected was used to develop two plots involving heat rejection. The first plot developed relationships between the mass flow rate of the air through the core and the heat rejection rate at 4 different water mass flow rates. Data was collected using both the C&R radiator and the radiator that was borrowed from the formula team. Sample data was used to create these plots, which can be observed in *Figure 56* and *Figure 57* on the following page.

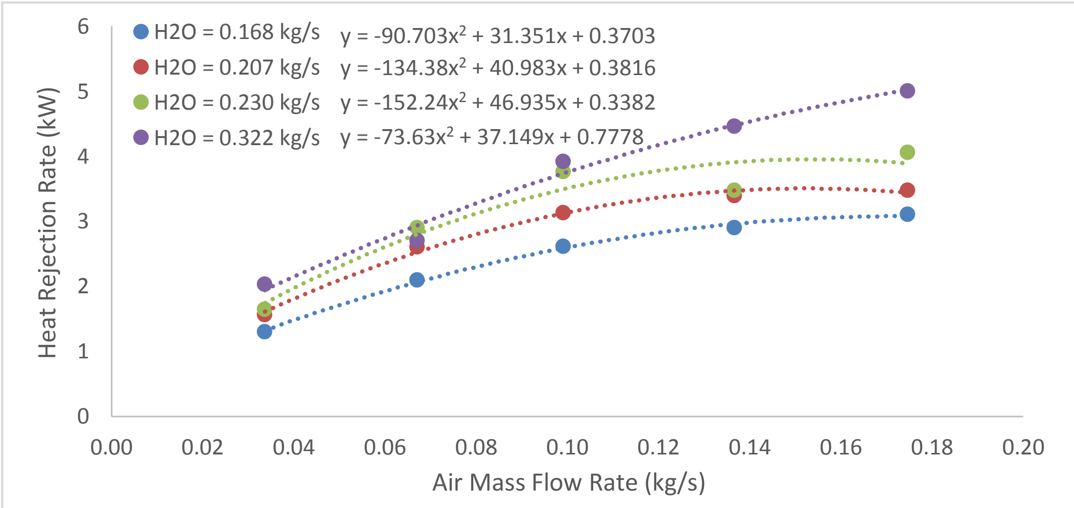


Figure 54. *Heat rejection as a function of the mass flow rate of air, radiator borrowed from formula team*

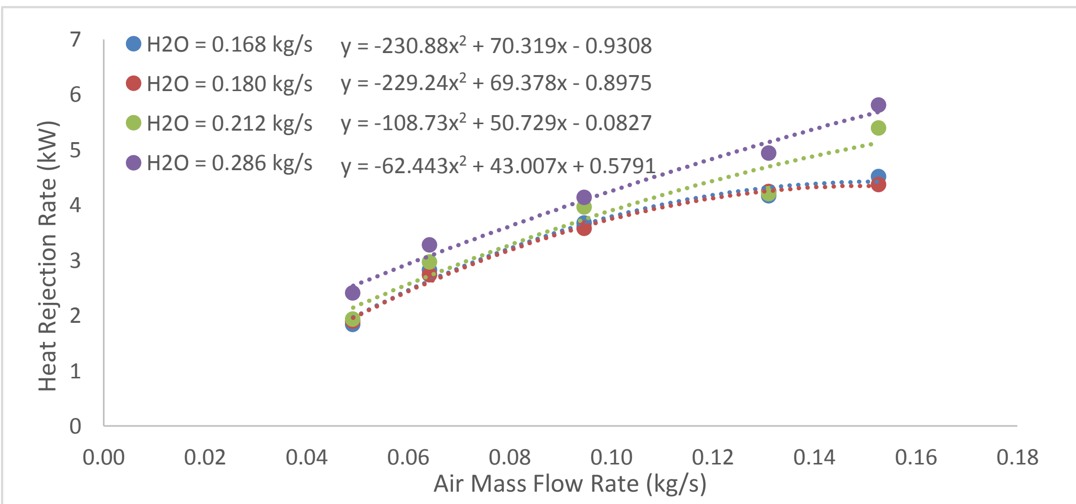


Figure 55. *Heat rejection as a function of the mass flow rate of air, C&R radiator*

The plots above suggest that the heat rejection rate increases at a decreasing rate as the mass flow rate of air increases. It is apparent from the figures above that the C&R radiator is better-suited for rejecting heat from the cooling water. The C&R radiator achieves a higher rate of heat rejection in spite of the fact that the mass flow rates of both the air and the water are lower. This is undoubtedly due its high fin density.

The second plot that is generated in the Excel program is very similar to the first plot (the two plots in the figures above). It still deals with heat rejection rate; however, the mass flow rate of water is plotted on the x-axis for five separate air mass flow rates. Again, data was collected using both radiators and the plots described above were generated. These plots can be observed in *Figure 58* and *Figure 59* on the following page.

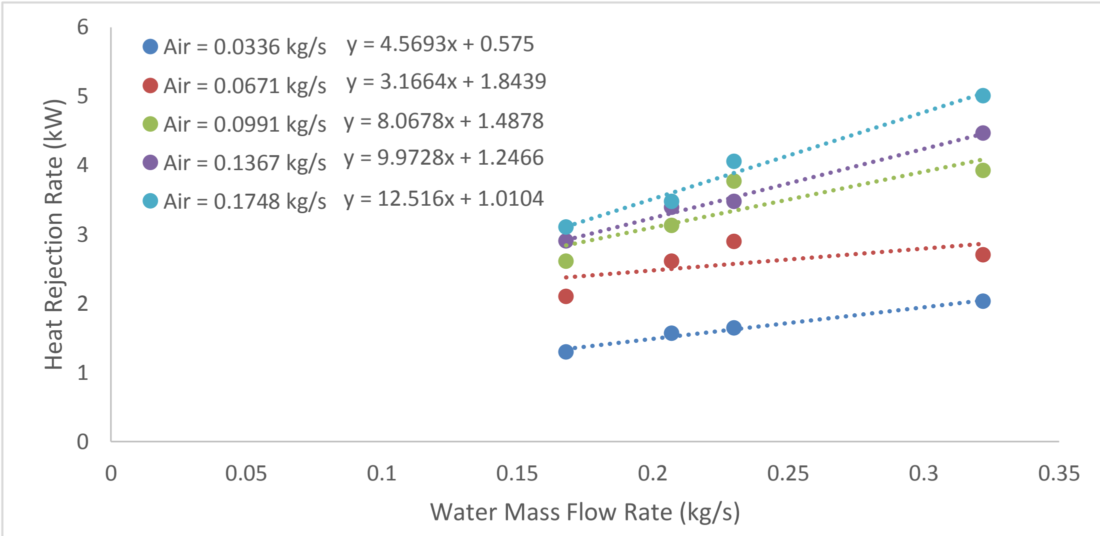


Figure 56. *Heat rejection as a function of the mass flow rate of water, radiator borrowed from formula team*

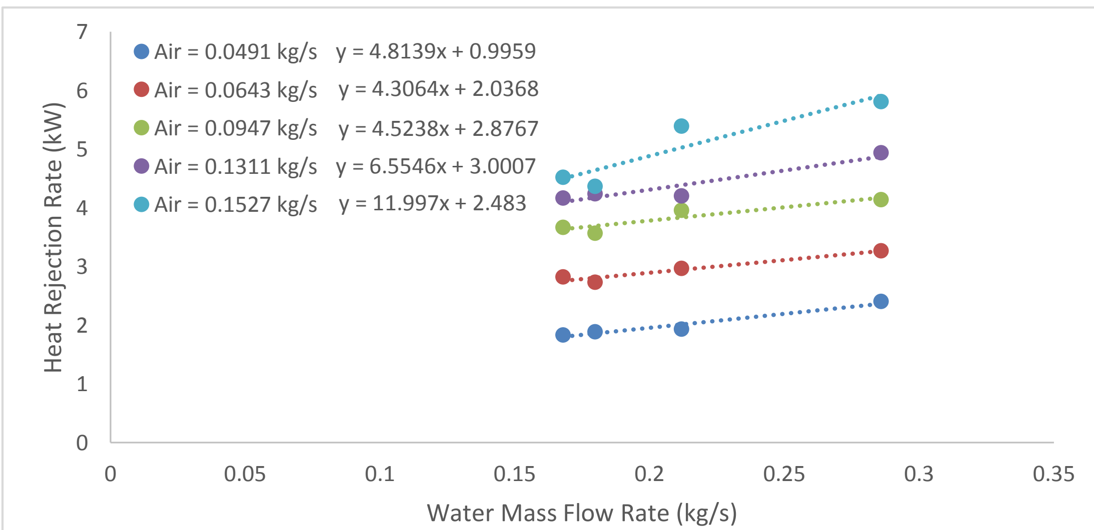


Figure 57. *Heat rejection as a function of the mass flow rate of water, C&R radiator*

The figures above suggest that heat rejection rate increases linearly as the mass flow rate of water increases. The lines are relatively flat, which means that the mass flow rate of water does not play as crucial a role in heat rejection as air flow through the core. The mass flow rate of air is a much more significant variable with respect to heat rejection, especially at low flow rates.

4. Specification Verification Checklist or DVP&R

The following section details specifications that each component should be capable of meet to develop an accurate model that can be used to predict the size a radiator must be to achieve adequate cooling. It also details appropriate operating conditions for each of the components.

Dynamometer:

- Thermocouples must be present on either side of the radiator to measure the temperature drop in the cooling fluid across the radiator.
- The dyno must be operable in an open loop where water is pumped from one reservoir to the other, as opposed to a closed loop where the same water is continually pumped through the system.

Cole-Parmer Hot Water Bath:

- The pump's flow rate must be variable up to 8 GPM (or the max flow rate of the water pump in the formula car's engine).
- The water level should never dip below the top of the impeller in the hot water bath. Water needs to be continually fed into the hot water bath to prevent cavitation.
- The suction side of the pump should be plugged with a brass pipe plug. This pump will be operated in an open loop, the same way the dyno will.

Test Section:

- Closed cell foam must exist at the interface between the test section and each adjacent object to maintain airtight characteristics (even with presence of vibration).
- Static pressure ports should be within half an inch of the radiator core to eliminate effects of major head losses in the ducting from the static pressure drop measurement.
- Should be mounted securely, and level, so that each piece of the test section encloses the same space on either side of the radiator.

Radiator Setup:

- The radiator fins should be in good condition to measure radiator performance. Performing measurements with a radiator with damaged fins will measure the performance of a damaged radiator, and the radiator should not leak.
- The radiator face outside of the test section ducting should be completely covered with aluminum foil. No air should leak from the radiator core.

Fan:

- Should be appropriate for testing in the entire range of airspeeds through the core that the car will operate at.

Measuring Devices:

- Verify that all equipment has been calibrated recently.
- Make sure the liquid column manometer reaches equilibrium at 0" when both sides are subject to atmospheric air pressure.
- The pitot-static tube must be held vertically against the direction of airflow.
- Allow thermocouple reading to reach steady state before recording values.

Chapter 7: Conclusions and Recommendations

The purpose of this senior project was to develop a method of aiding the Formula SAE team at Cal Poly in designing the cooling system that will be used on the competition car. In order to serve this purpose for years to come as cooling requirements may change, a method that could be used in this event was chosen. The most effective way of making the aid dynamic was to design a series of tests to determine heat rejection requirements and the ability of a hypothetical system to reject that heat. The following conclusions and recommendations can be made based on the process of designing and completing the tests that will be used to aid the cooling system design.

The results from testing a couple radiators can be used to conclude a few things. First, fin density is a very significant characteristic. A radiator with a high fin density achieved higher rates of heat rejection at equivalent fan powers. It becomes important to know the mass flow rate of the air through the core at equivalent car speeds when determining whether to use a radiator with a high or low fin density. The results on the wind tunnel are heavily based on the fan's ability to overcome the pressure drop across the radiator. If the results from *Test 3* suggest that the difference in mass flow rate of air through the two different cores are similar to the difference on the wind tunnel, a radiator with a higher fin density may be the best option. However, if the goal is to minimize weight, this not be beneficial because the increased fin density may increase weight proportionally resulting in no performance gain. If a larger radiator results in higher drag forces and the goal is to minimize drag, it may be beneficial to use a radiator with a higher fin density. It is all very dependent on the design goals, but the testing described in this report will be very helpful in making these decisions.

On the topic of *Test 3*, it is worthwhile to note that the method of developing a relationship between the car speed and the mass flow rate of air through the core that has been developed is not the most effective method. It is possible that the velocity profile of the air where the radiator will go on the formula car is completely different from the velocity profile of the air where the test was performed on a different car. It could be beneficial to develop a new method of developing this relationship on the car. A test fixture capable of translating and anemometer along the face of the radiator core could be developed and used on the formula car to collect the data needed to develop this relationship. The method that has been developed is effective, but is slightly unorthodox and isn't the easiest way of collecting the necessary data. The newly developed method could be used with the radiator mounted in different locations on the car to see if the higher mass flow rates can be achieved at slightly different spots around the car. It could also be used to determine whether or not mounting the radiator at different angles makes a significant difference in the mass flow rate of air through the core.

While the mass flow rate of the air through the radiator core may or may not be heavily affected by unique velocity profiles around the car, it was very much so affected by damaged fins. Results

from *Test 4* suggest that damaged fins can entirely eliminate air flow through the core. This would be highly problematic with respect to cooling as that entire area of the radiator would be rendered useless. This goes to show the extent of the benefit of having a higher fin density. Higher rates of heat rejection were achieved in the case of the C&R radiator even with 1/3 of the heat transfer area eliminated. While the mass flow rate of air through the core wouldn't change as much, the effective heat transfer area was significantly lower, so it can be concluded that the C&R core is undoubtedly markedly more effective than the other radiator tested.

It can be concluded from the data that heat rejection rates are highly dependent on the mass flow rate of air through the core; it is more dependent on the mass flow rate of the air than the flow rate of the water. As such, it is possible that the worst case scenario exists at an engine power below the maximum when the speed of the car is especially low. Data should be taken at all crank speeds from idle to max power. It is also very likely that the worst case scenario exists at idle and a fan will need to be use. In that case the radiator should be sized with this fact in mind. The mass flow rate necessary to achieve adequate cooling can be determined and a fan chosen. Then the decision to run the fan during the race must be used. If the fan is run during the race, power from the engine will go to running the fan as opposed to turning the wheels. It will need to be determined if the extra mass flow rate or the extra engine power is more highly valued.

The process of sizing the radiator by determining the necessary rate of heat rejection and the heat rejected per unit of heat transfer area is based on the assumption that the rate at which heat is rejected from the radiator increases linearly with heat transfer area. The validity of this assumption could be tested by using aluminum foil to block off a portion of the fins in the duct while performing *Test 4* and *Test 5*. This would effectively test the effect relationship between heat transfer area and heat rejection. It could also be interesting to block off horizontal then vertical areas to determine whether the radiator orientation effects the heat rejection rate.

Finally, it should be noted that in general, if two radiators are being used they should be plumbed in series. As detailed, in *Radiator Installation in FSAE Application* (*Chapter 2, Section 5*) when two radiators are connected in parallel, one must pay special attention to be sure that the fluid resistance of the two paths to each of the radiators is equal. This is the only way that the mass flow rate of cooling water to each of the two radiators will be equal. If there is a large disparity in the fluid resistances associated with the two parallel paths, the mass flow rate to one of the radiators can be limited to the point of that radiator becoming extremely ineffective, vastly prohibiting the cooling systems proficiency. This is an issue that the formula team encountered in 2014 when two radiators were working together in a parallel configuration. While two radiators in parallel can work more effectively, it can cause issues if not implemented properly, and a series configuration is generally recommended.

Appendix A: Gantt Chart

Table 10. *Gantt chart describing project timeline*

	Spring Quarter 2013										Fall Quarter 2013										
Week	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	11
Task / **Date**	4/1	4/8	4/15	4/22	4/29	5/6	5/13	5/20	5/27	6/3	9/23	9/30	10/7	10/14	10/21	10/28	11/4	11/11	11/18	11/25	12/2
Background Research	■	■	■	■	■	■															
Write Project Requirements Doc.				■	T																
Develop Method of Testing				■	■	■	■														
Write Conceptual Design Report						■	■	■	■	T											
Develop Conceptual Model						■	T	■	■	■	■	■	■								
Write Final Design Report											■	■	■	■	■	T					
Prepare Critical Design Review														■	T						
Meet w/ Andrew for Purchasing																	■	■			
Purchase Heaters																	■	■			
Compile Sr. Project Expo Materials																		■	■	■	■
Build Test Section																		■	■	■	■

	Winter Quarter 2014									
Week	1	2	3	4	5	6	7	8	9	10
Task / **Date**	1/6	1/13	1/20	1/27	2/3	2/10	2/17	2/24	2/3	3/10
Conduct Tests Done on Wind Tunnel		■	■	■	■	■	■			
Compile/Reduce Data		■	■	■	■	■	■	■		
Final Report/Data Presentation					■	■	■	■	■	T

Notes: ■ denotes time spent working on task
T denotes that a task is due Tuesday of the indicated week

Appendix B: Decision Matrices, QFD

The decision matrix in *Table 2* below was used to verify that choosing *Concept 4* described in *Conceptual Designs* (*Chapter 3, Section 1*) was the most practical option. Each concept was graded for the given characteristic on a scale from 1-4. They were essentially ranked from best to worst for each of the 4 concepts. When a concept was no more effective than one of the other concepts for a particular characteristic, they were given the same scores.

Table 11. *Decision matrix used in concept selection*

Characteristic	1) LFE	2) Contraction Area	3) Fan Pressure Rise	4) ME Wind Tunnel
Ease of Use	4	3	2	2
Availability	1	4	4	3
Air Speed Measurement Accuracy	4	3	2	2
Large Range of Air Speeds Measured	1	2	2	4
Number of Parts Needed	2	1	3	4
Ease of Fabrication	3	1	2	4
Low Cost	1	2	3	4
Ease of Maintenance	1	2	2	4
Ease of Storage	1	1	1	4
Total	18	19	21	31

Table 2 indicates that using the wind tunnel in the Thermal Science Lab was the most practical option by a wide margin. For this reason, there was no reason to add weight to each of the characteristics. The reasons for the grades are quite predictable except for in the case of the air speed measurement range characteristic. The LFE can only read very low air speeds in the case of the necessary measurement range, so *Concept 1* was assigned a grade of 1. Then *Concept 2* and *Concept 3* were assigned a grade of 2 based on the fact that there was no chance that a fan as large as the one used on the wind tunnel in the Thermal Science Lab could be used on a flow bench constructed for the formula team. For this reason, those two concepts would not allow for as large a range of air speed operation. *Concept 4* was assigned a grade of 4 because it was clearly the best option in the case of this characteristic by a fairly significant margin.

A QFD that outlines the dependency of certain operating characteristics on overall design performance can be observed on the following page. A grade of 9 indicates a strong correlation between a characteristic and performance while, a grade of 3 indicates a medium correlation, a grade of 1 indicates a small correlation, and a blank cell indicates no correlation.

Table 12. *QFD for use of the ME Thermal Science Lab wind tunnel to perform radiator characterization testing*

	Weighting (Total 100)	Actual-Theoretical Error (%)	Time Engine Must be Used (hrs)	Cost to Maintain ($)	Time to Set Up (hrs)	Time to Break Down (hrs)	Time to Perform Tests (hrs)	Radiators that will Fit (%)	Fan Performance (CFM/inH2O @ Max)	Tests to Perform (#)	Steps to Set Up (#)	Steps to Break Down (#)	Additional Floor Space Required (ft^2)	Time to Maintain (hrs/year)	Time Available (hrs/week)	Cost to Fabricate ($)	Cost to Run ($/hr)	Time to Fabricate (hrs)	**ME TSL Wind Tunnel (1-3)**	**Weighted ME TSL Wind Tunnel**
Functional Performance																				
Accurate Measurements	17	9						1	1										3	51
Low Engine Wear	10		9	3						3							3		3	30
Quick Use	5		1		9	9	9			3	3	3		3	1				2	10
Accomodates Most Radiators	10	3			3	3		9	3							1		1	2	20
Wide Range of Performance	8								9							3			3	24
Human Factors																				
Ease of Use	5		3				3			9					1				1	5
Easy Setup	5				3						9								1	5
Easy Breakdown	5					3						9							1	5
Easy Storage	8												9			3		3	3	24
Low Maintenance	5	1	3	9	1	1					1	1		9		3			3	15
High Availability	5				1	1					1	1			9				1	5
Low Cost	12												1			9		1	3	36
Quick Fabrication	5															3		9	3	15
ME TSL Wind Tunnel		95	4	0	0.5	0.5	24	95	200	5	5	5	0	0	30	280	0	20		245
Target		98	4	0	0.4	0.4	24	95	100	3	2	2	8	5	30	300	0	40		

Appendix C: Fan Sizing Program Calculations

The following equations were used to determine the necessary pressure rise across the fan used in testing that correlates to the maximum air mass flow rate to be tested. Equations and further description of the way they were used follow.

This program will predict the pressure rise and mass flow rate capabilites of the fan used to replicate the on-car conditions. The velocity requirement is derived from the results referenced in Fan Sizing in Chapter 3, Section3. Major losses in the ducting will be ignored because of the very large diameter ducting.

$K_{L1} = 0.5$ [-] *Loss coefficient of the flow screen*

$K_{L2} = 0.05$ [-] *Loss coeffcient- large radius inlet bend*

$K_{L3} = 0.2$ [-] *Loss coefficient- small radius inlet bend*

$K_{L4} = 1$ [-] *Loss coefficient of radiator core*

The loss coefficient of the radiator core was predicted by assuming that it would be similar to that of the flow screen, but definitely higher. It was assumed that it would not be twice as high as that of the flow screen.

$v_d = 14$ [m/s]

$v_i \cdot A_i = v_d \cdot A_d$ *Velocity in inlet, conservation of mass, constant density*

$A_d = 0.122^2$ *Cross sectional area of inlet*

$A_i = 1.5^2$ *Cross sectional area of duct*

$v_{rad} = v_d \cdot \dfrac{A_d}{A_{rad}}$ *Velocity through radiator, onservation of mass, constant density*

$A_{rad} = 2 / 3 \cdot A_d$ *Approximate ratio of open core area to duct area*

$$\delta_P = 0.5 \cdot \rho \cdot v_d^2 + 0.5 \cdot [K_{L1} + K_{L2}] \cdot \rho \cdot v_i^2 + 0.5 \cdot K_{L3} \cdot \rho \cdot v_d^2 + 0.5 \cdot K_{L4} \cdot \rho \cdot v_{rad}^2$$

$\rho = \rho[Air_{ha}, T=21, P=101.325]$

$\dot{m}_{air} = \rho \cdot v_d \cdot A_d$

Solution

Main

Unit Settings: SI C kPa kJ mass deg

$A_d = 0.01488$ [m^2]	$A_i = 2.25$ [m^2]	$A_{rad} = 0.009923$	$\delta_P = 405.8$ [Pa]
$K_{L1} = 0.5$ [-]	$K_{L2} = 0.05$ [-]	$K_{L3} = 0.2$ [-]	$K_{L4} = 1$ [-]
$\dot{m}_{air} = 0.2501$ [kg/s]	$\rho = 1.2$ [kg/m^3]	$v_d = 14$ [m/s]	$v_i = 0.09261$ [m/s]
$v_{rad} = 21$			

Appendix D: Heater Sizing Program

The most cost effective heater that could be purchased provided a heating power of 1.15 kW. Equations were used to determine the amount of time it would take to heat water with different numbers of 1.15 kW heaters. Equations and further description of the way they were used follow.

This program is used to predic the number of heaters that are needed to heat the water to 180 degrees F in a timely manner. The whole number next to the 1.15 in the heater power in the inputs section can be changed and the variable t_{min} observed to predict the amount of time it will take for the water to reach the desired temperature.

Inputs

$\dot{Q} = 3 \cdot 1.15$ [kW] *Heater power*

$V = 17$ [gal] *Volume of reservoir*

$T_{1f} = 100$ [F] *Initial water temperature*

$T_{2f} = 180$ [F] *Final water temperature*

$cp = \mathbf{Cp}[water, T=60, P=101.325]$ *Specific heat of water*

Temperature Conversion

$T_{1c} = [T_{1f} - 32] \cdot 5 / 9$ *Convert water temperature to C*

$T_{2c} = [T_{2f} - 32] \cdot 5 / 9$ *Convert water temperature to C*

Determining Mass of Water

$V_{met} = V \cdot 0.00378541$ [m^3/gal] *Convert volume to metric units*

$\rho = \rho[water, T=60, P=101.325]$ *Density of water*

$m = \rho \cdot V_{met}$ *Water mass in reservoir*

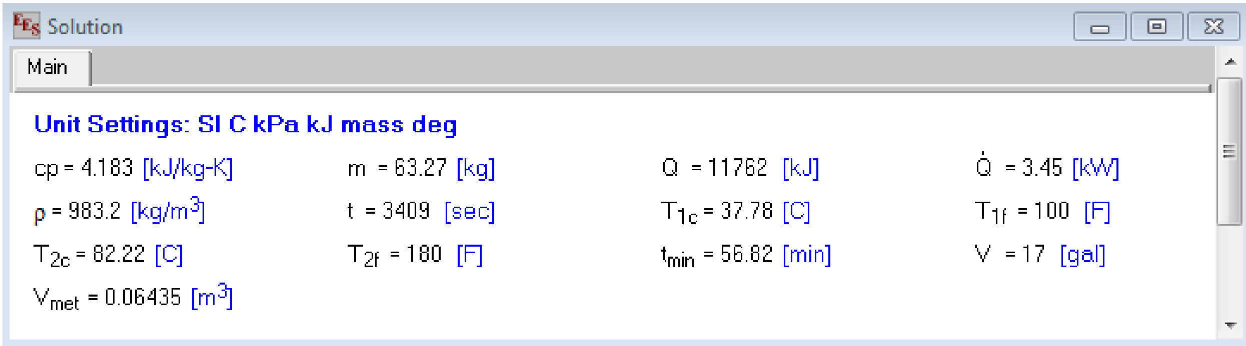
Calculation of Time to Heat

$Q = m \cdot cp \cdot [T_{2c} - T_{1c}]$ *Heat required to get the water to desired temperature*

$Q = \dot{Q} \cdot t$ *Time required to supply necessary heat*

Time Converstion (s-min)

$$t_{min} = \frac{t}{60 \text{ [sec/min]}}$$


Solution
Main
Unit Settings: SI C kPa kJ mass deg
cp = 4.183 [kJ/kg-K]
m = 63.27 [kg]
Q = 11762 [kJ]
Q̇ = 3.45 [kW]
ρ = 983.2 [kg/m3]
t = 3409 [sec]
T1c = 37.78 [C]
T1f = 100 [F]
T2c = 82.22 [C]
T2f = 180 [F]
tmin = 56.82 [min]
V = 17 [gal]
Vmet = 0.06435 [m3]

Appendix E: Temperature Effects on Manometer Reading

Analysis was performed to determine if the changing in the density of air due to temperature rise across the radiator core would have a significant effect on the liquid column manometer height. The following equations were used to generate the plot shown in *Figure 21*.

This program is used to determine the effect of varying exit air temperatrures on the liquid column height

$\dot{q}_w = \dot{m}_w \cdot c_{pw} \cdot \delta T_w$ *Heat rejected from fluid based on predicted temperature change*

$\dot{m}_w = 0.168$ [kg/s] *Prediceted mass flow rate of water, 5 gpm*

$c_{pw} = \mathbf{Cp}[\text{water}, T = 88, P = 101.325]$ *Specific heat of water*

$\delta T_w = 4.4$ [C] *Predicted temperautre change in cooling water*

$\dot{q}_w = \dot{q}_a$ *Heat rejected from water=heat rejected to air*

$\dot{q}_a = \dot{m}_a \cdot c_{pa} \cdot \delta_{T,a}$ *Heat rejected to air to find air temperature change*

$\dot{m}_a = 0.17472$ [kg/s] *Mass flow rate of air maximum flow rate*

$T_{am} = T_{amb} + \frac{\delta_{T,a}}{2}$ *Average air temp to predict specific heat of air*

$T_{amb} = 21$ [C] *Ambient air temperature*

$c_{pa} = \mathbf{Cp}[\text{Air}_{ha}, T = T_{am}, P = 101.325]$ *Specific heat of air*

$\rho_1 = \rho[\text{Air}_{ha}, T = 21, P = 101.325]$ *Density of inlet air*

$\rho_2 = \rho[\text{Air}_{ha}, T = T_{exit}, P = 101.325]$ *Density of exit air for table, T_{exit} will vary*

$\delta P = v \cdot [\rho_1 - \rho_2]$ *Pressure differential*

$v = \frac{\dot{m}_a / \rho_1}{0.122^2}$ *Air velocity*

$\delta Z_m = \frac{\delta P}{\gamma_w}$ *Change in liquid column height*

$\rho_w = \rho[\text{water}, T = 21, P = 101.325]$ *Density of liquid column water*

$\gamma_w = 9.81 \cdot \rho_w$ *Specific gravity of liquid column water*

$\delta Z = \delta Z_m \cdot 39.3701$ *Change in liquid column height converted to inches of water*

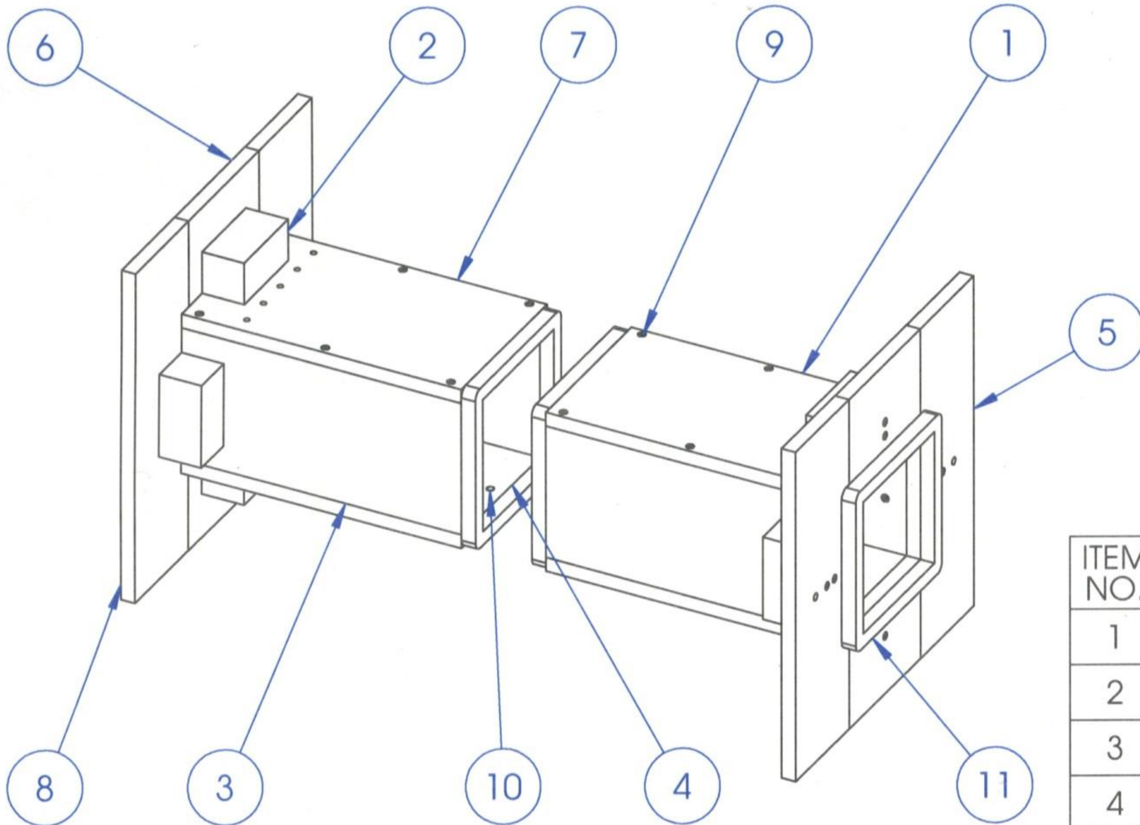
Appendix F: Cost Analysis Table

Table 13. *Cost of each component used throughout the project- "cost" column includes 8.0% tax*

Purpose	Description	Qty	Ea. Cost	Cost
Test Section	Plywood	1	$37.97	$41.01
	2"x2"x8"Strip Board	1	$1.81	$1.95
	Flat Head Phillips Screw #6, 1-1/4" L	1	$7.75	$8.37
	Precision SS Tubing, .259" OD, .239" ID, 1' L	1	$8.24	$8.90
	3/8" x 7/16" x 10' Rubber Foam Tape	2	$3.48	$7.52
	Zinsser Spackling Compound (1 Qt.)	1	$35.88	$38.75
	Primer White Paint	1	$14.98	$16.18
	Gray Gloss Paint	1	$3.87	$4.18
	Liquid Column Manometer	1	--	--
	Sawhorse	1	--	--
Test Section-Wind Tunnel Interface	Zinc corner Braces 1.5" Dbl Wide	2	$3.97	$8.58
	1/4" x 2" Hex Bolts	6	$0.18	$1.17
	1/4" Cut Washers	12	$0.11	$1.43
	1/4" Hex Nuts	6	$0.06	$0.39
	Aluminum Foil Tape, 2.5" Wx 60 Yrd L	1	$24.68	$26.65
	Wind Tunnel	1	--	--
Heating	Immersion Heaters, 1150 W, 11-1/2" Lg	1	$73.12	$78.97
	Immersion Heater, 1150 W, 5-1/2" Lg	2	$68.82	$148.65
	20 Gallon Hot water Reservoir	1	--	--
	Metal Stir Stick	1	--	--
Plumbing	3/4" FPT - 3/4" FPT coupling w/ embedded thermocouple	1	--	--
	3/4" MPT - 3/4" MIP brass nipple	2	$9.23	$19.94
	3/4 FPT - 1" FIP galvanized iron coupling	2	$3.77	$8.14
	1" MPT - 1" brass barb	3	$5.23	$16.95
	3/4" solder brass ball valve	1	$0.98	$1.06
	1/4" galvanized steel nipple	1	$1.54	$1.66
	3/4" MPT - 1/4" FPT galvanized iron bushing	1	$2.37	$2.56
	3/4" FPT - 3/4" FPT galvanized iron coupling	1	$2.40	$2.59
	1" OD x 3/4" ID x 10' rubber heater hose	1	$21.47	$23.19
	1/2" - 1-1/4" stainless steel hose clamp	7	$0.98	$7.41
	1/4" Brass Pipe Plug	1	$2.61	$2.82
	Cole-Palmer Hot Water Bath	1	--	--
	5-Gallon Bucket	2	--	--
		Total Cost		$479.00

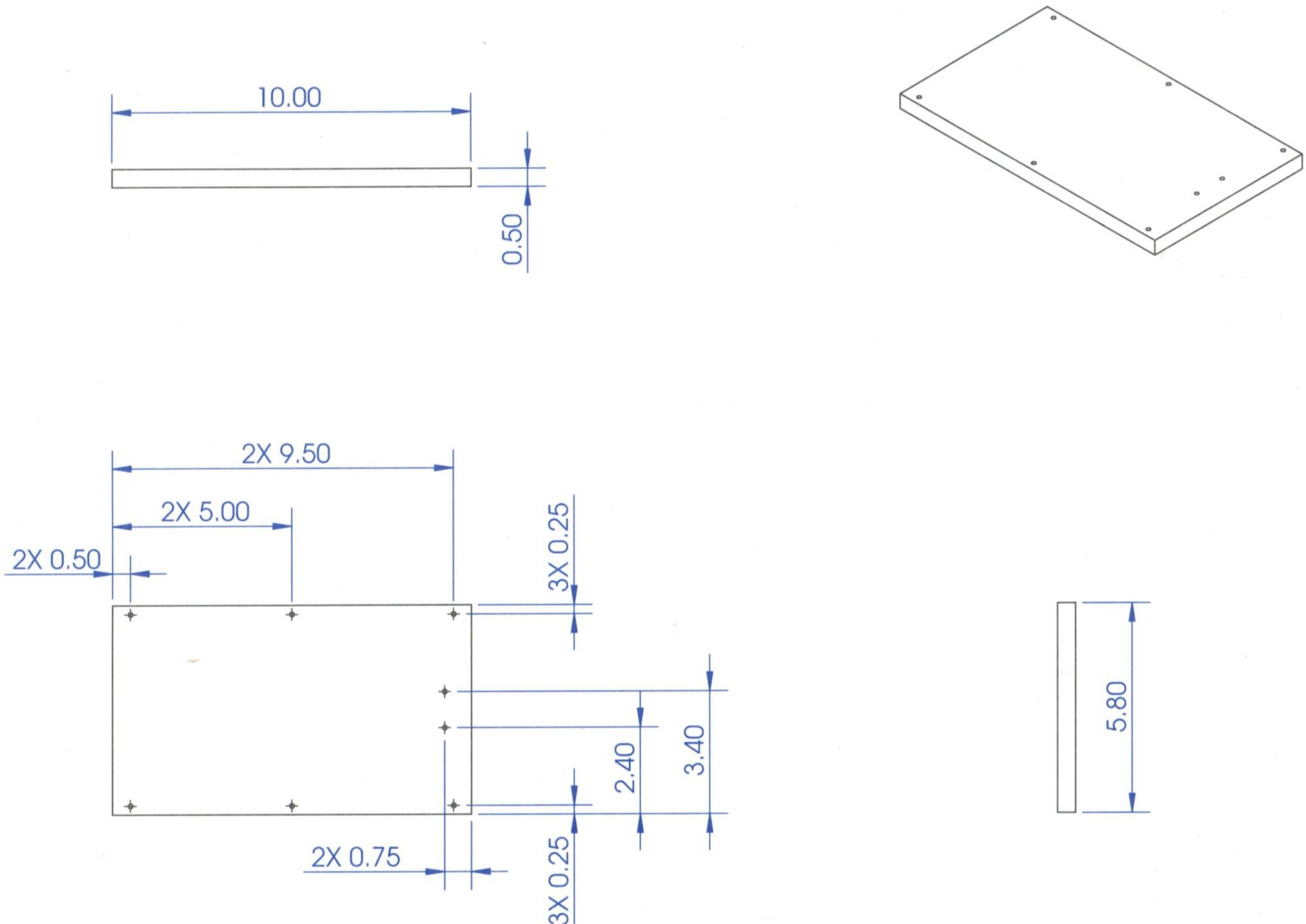
Appendix G: Bills of Materials & Manufacturing/Vendor Drawings

Bill of Materials, manufacturing/vendor drawings, and vendor catalog pages will begin on the following page.

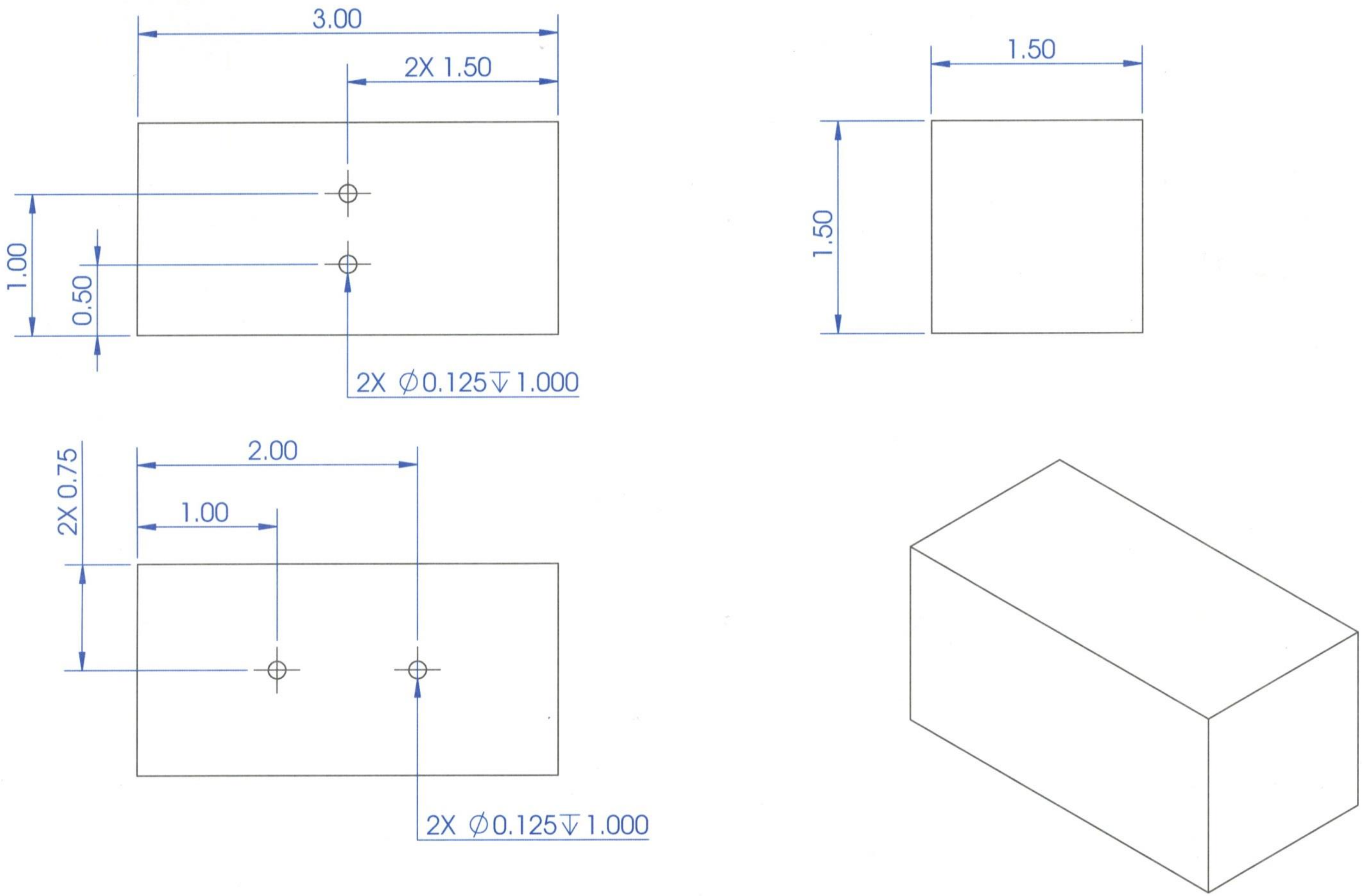


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	DT-U-1	DUCT TOP, UPSTREAM	1
2	WB-8	WOOD BRACKET	8
3	DS-4	DUCT SIDE	4
4	DB-2	DUCT BOTTOM	2
5	LF-U-2	LONG FLANGE, UPSTREAM	2
6	SF-4	SHORT FLANGE	4
7	DT-D-1	DUCT TOP, DOWNSTREAM	1
8	LF-D-2	LONG FLANGE, DOWNSTREAM	2
9	90198A182	#6 SHEET METAL SCREW, 1-1/4"	56
10	PP-2	STATIC PRESSURE PORT TUBE	2
11	R534H	RUBBER FOAM TAPE	4

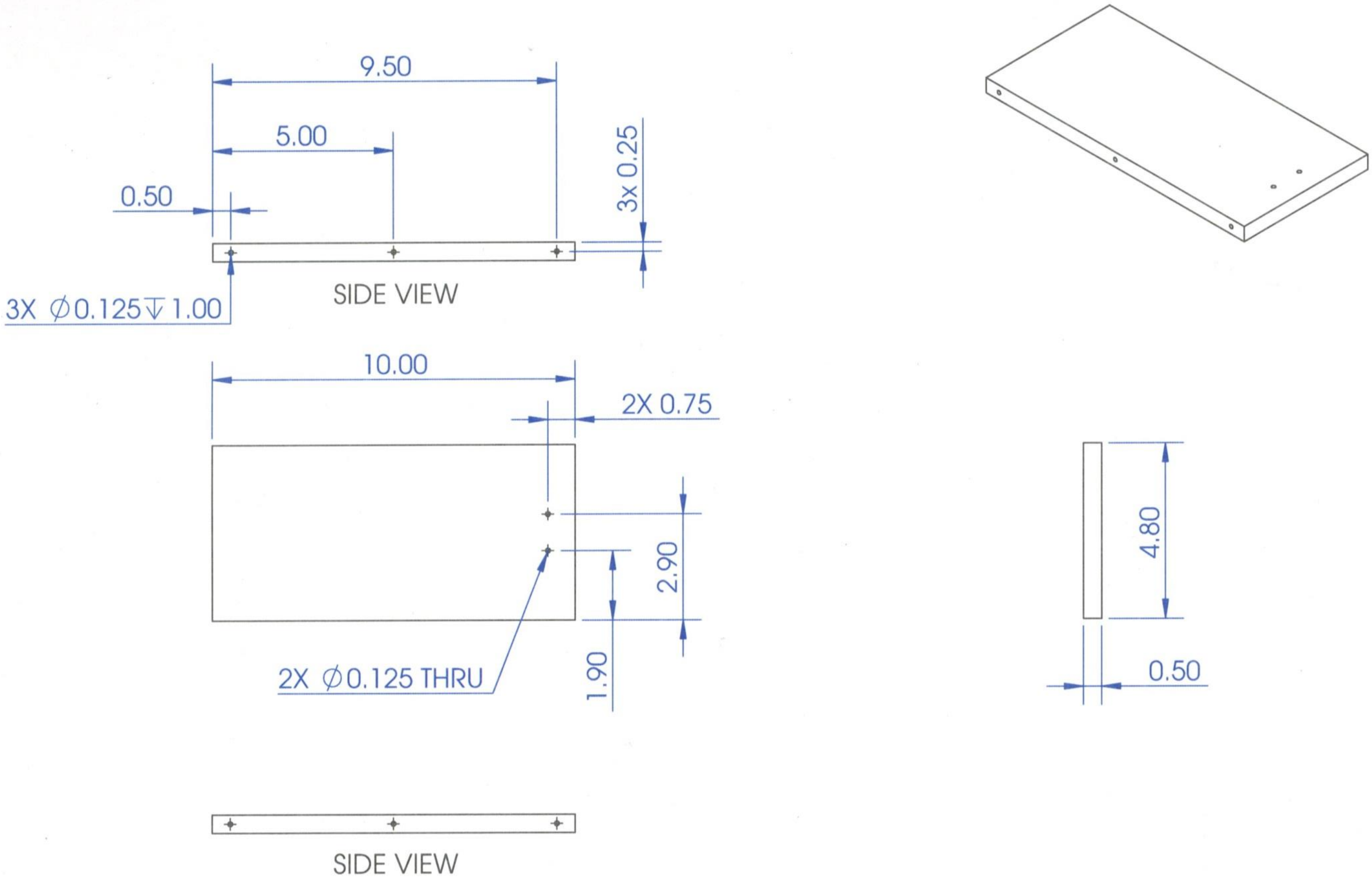
CAL POLY SAE	ASSY: TEST SECTION	UNITS: INCHES	TITLE: TEST SECTION ASSEMBLY	DRAWN BY: LISA VAN DEN BERG
	PART #: N/A	TOLERANCE: N/A	DATE: 4/9/2014 / SCALE: 1:6	MATERIAL: N/A



CAL POLY SAE	ASSY: TEST SECTION	UNITS: INCHES	TITLE: DUCT TOP, UPSTREAM	DRAWN BY: LISA VAN DEN BERG
	PART #: DT-U-1	TOLERANCE: ±1/32	DATE: 4/9/2014 SCALE: 1:4	MATERIAL: 1/2" PLYWOOD

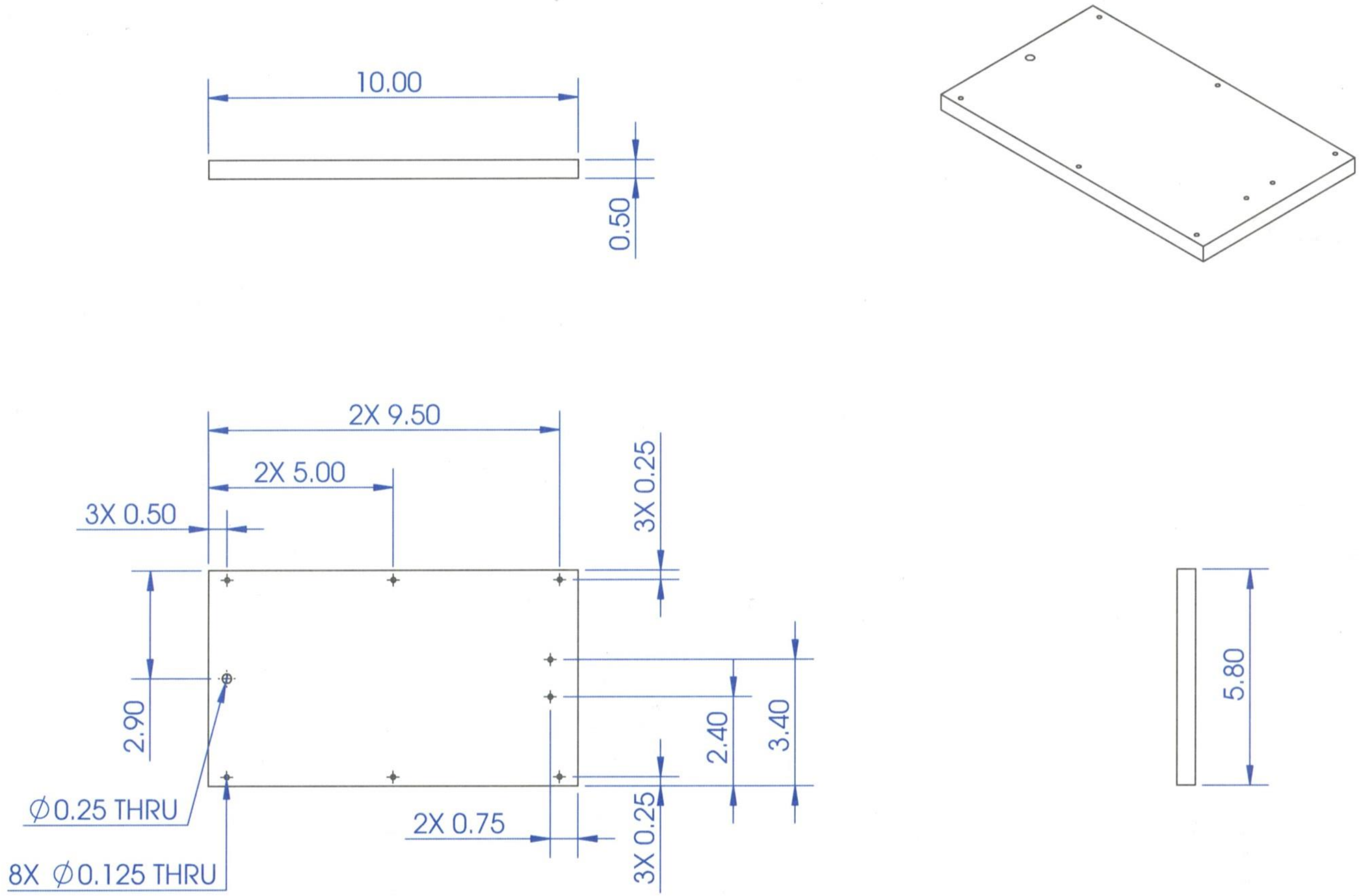


CAL POLY SAE	ASSY: TEST SECTION	UNITS: INCHES	TITLE: WOOD BRACKET	DRAWN BY: LISA VAN DEN BERG
	PART #: WB-8	TOLERANCE: ±1/32	DATE: 4/9/2014 — SCALE: 1:1	MATERIAL: 2X2 STUD

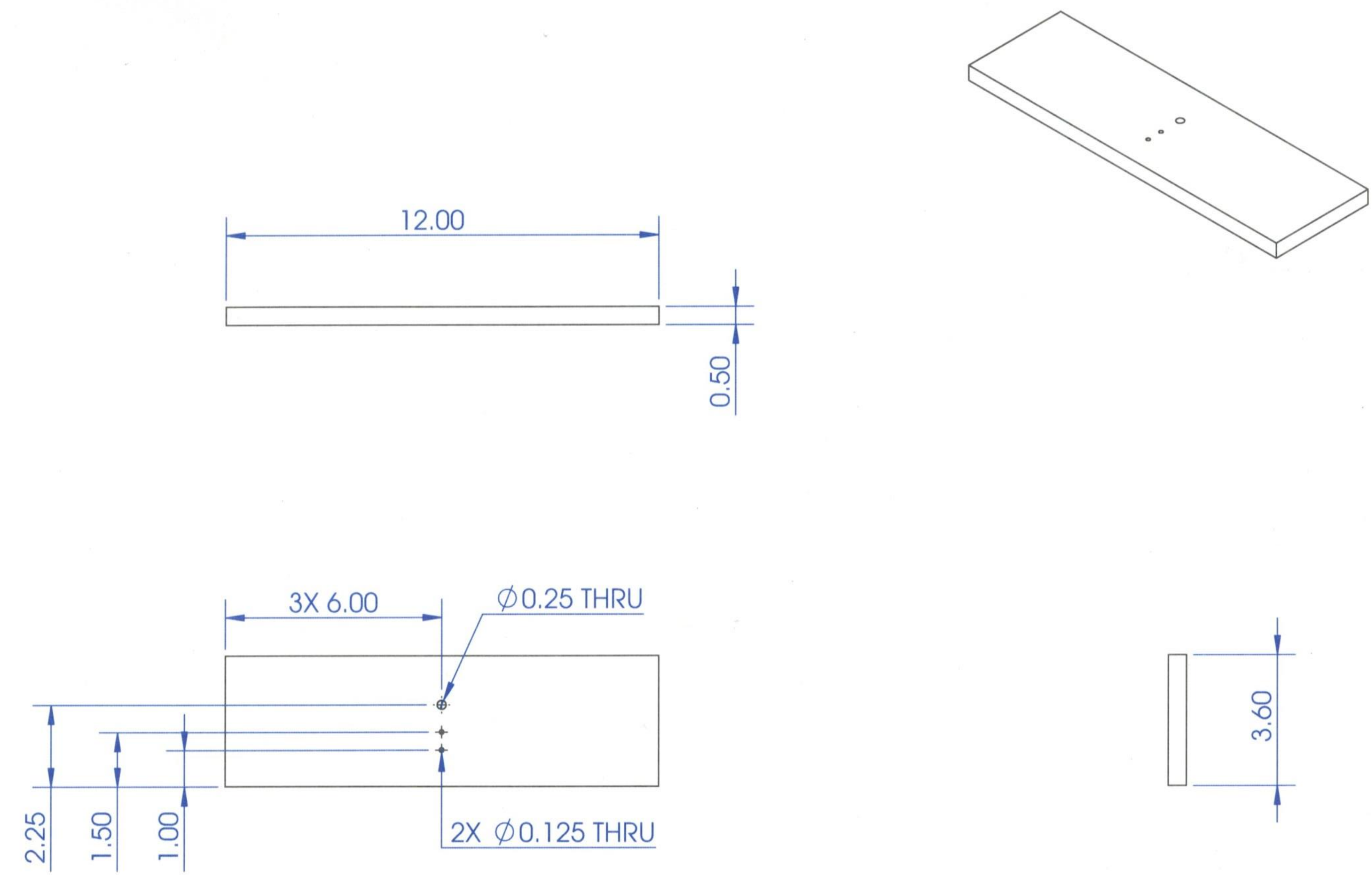


NOTE: SIDE VIEW DIMENSIONS ARE TYPICAL

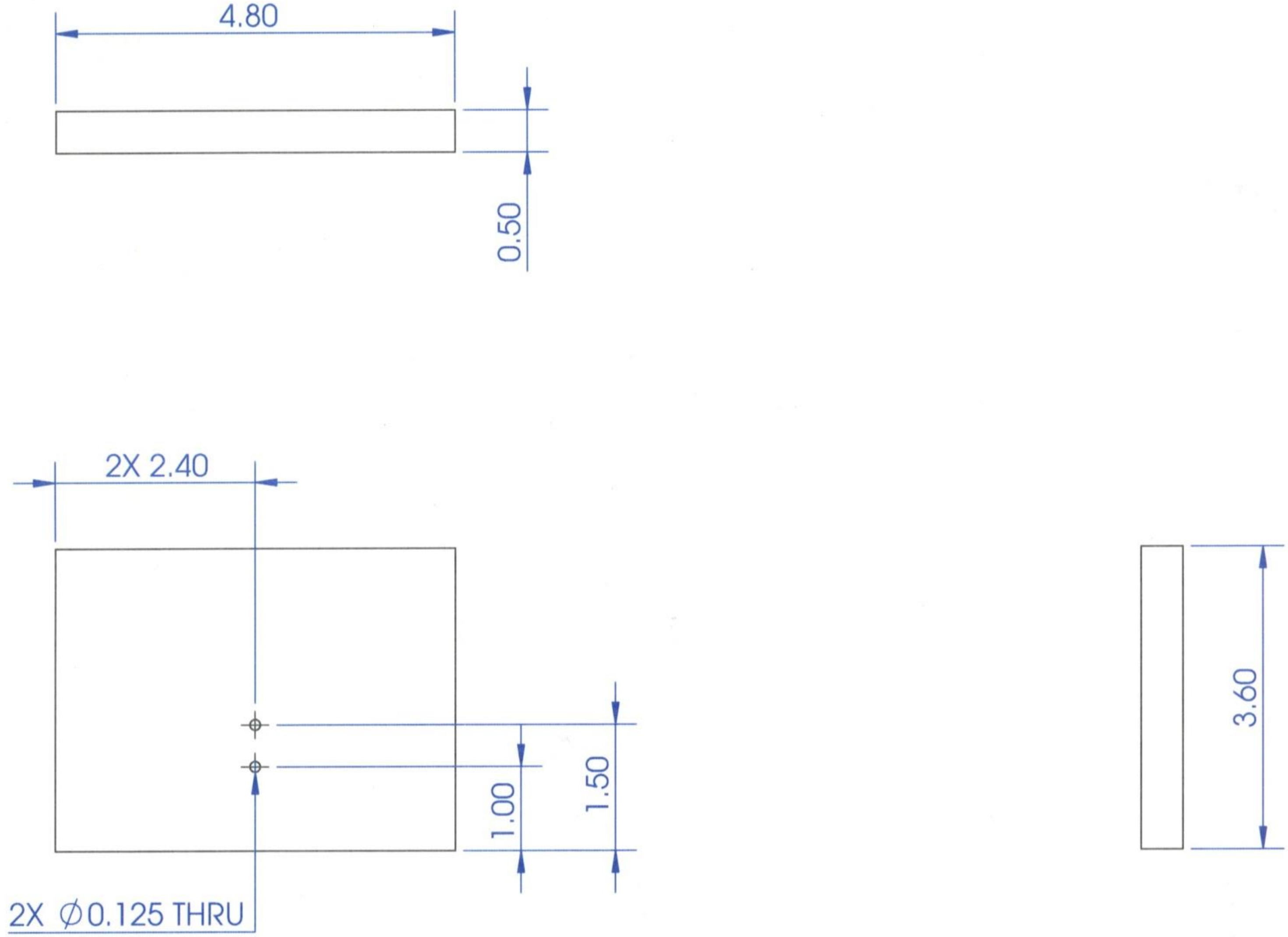
CAL POLY SAE	ASSY: TEST SECTION	UNITS: INCHES	TITLE: DUCT SIDE	DRAWN BY: LISA VAN DEN BERG
	PART #: DS-4	TOLERANCE: ±1/32	DATE: 4/9/2014 — SCALE: 1:4	MATERIAL: 1/2" PLYWOOD



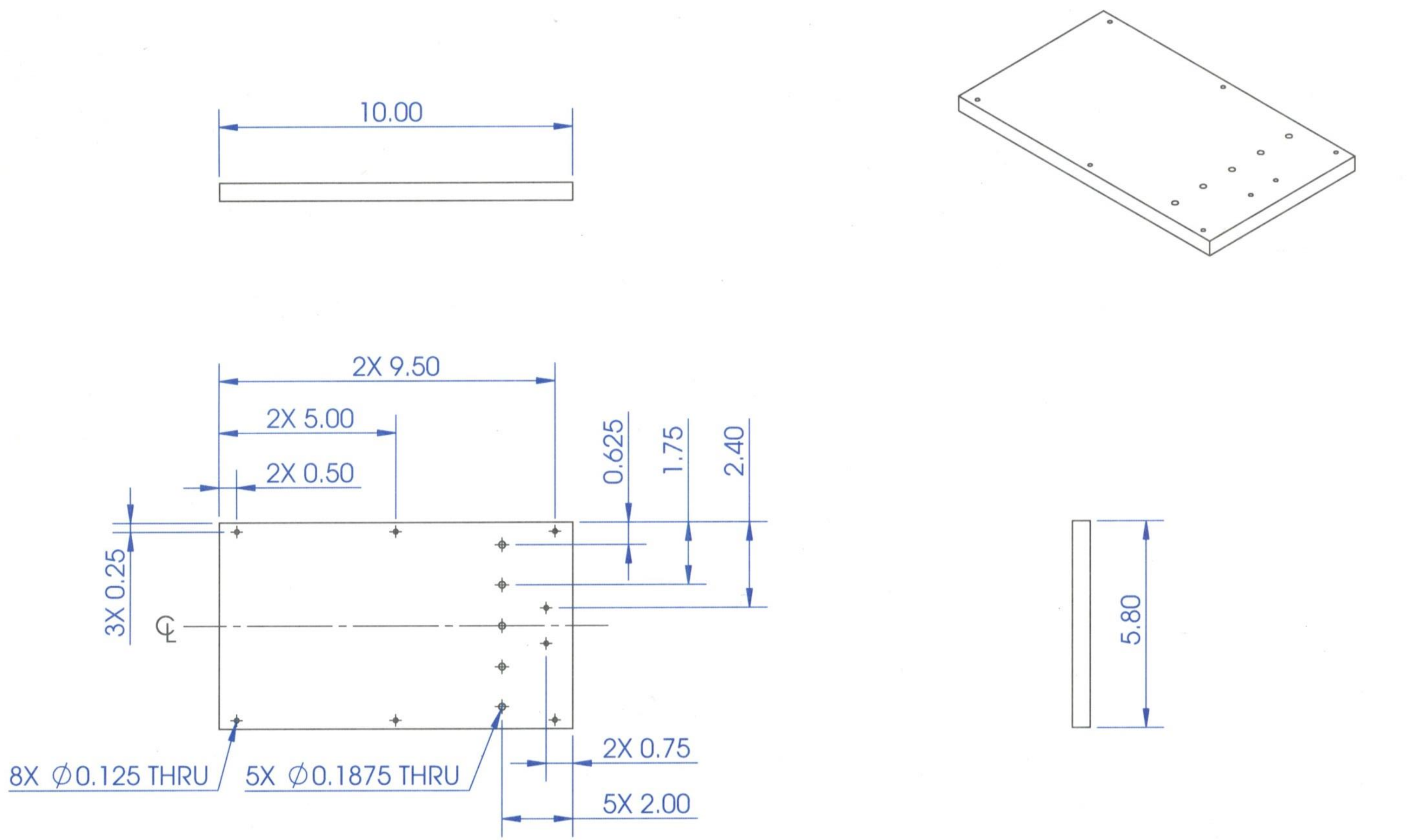
ASSY: TEST SECTION	UNITS: INCHES	TITLE: DUCT BOTTOM		DRAWN BY LISA VAN DEN BERG
PART #: DB-2	TOLERANCE: ±1/32	DATE: 4/9/2014	SCALE: 1:4	MATERIAL: 1/2" PLYWOOD



CAL POLY SAE	ASSY: TEST SECTION	UNITS: INCHES	TITLE: LONG FLANGE, UPSTREAM	DRAWN BY: LISA VAN DEN BERG
	PART #: LF-U-2	TOLERANCE: ±1/32	DATE: 4/9/2014 SCALE: 1:4	MATERIAL: 1/2" PLYWOOD

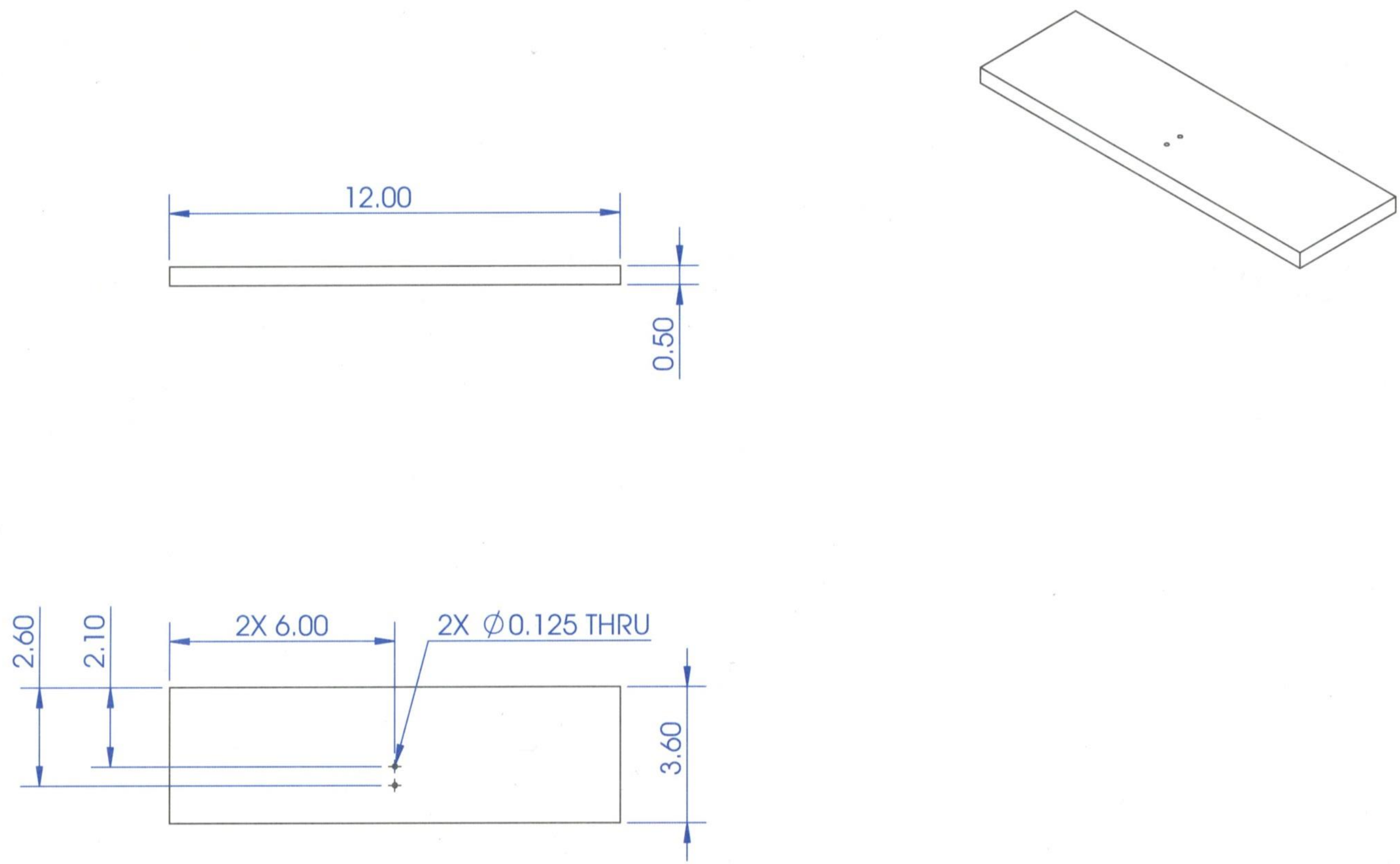


CAL POLY SAE	ASSY: TEST SECTION	UNITS: INCHES	TITLE: SHORT FLANGE	DRAWN BY: LISA VAN DEN BERG
	PART #: SF-4	TOLERANCE: ±1/32	DATE: 4/9/2014 · SCALE: 1:2	MATERIAL: 1/2" PLYWOOD

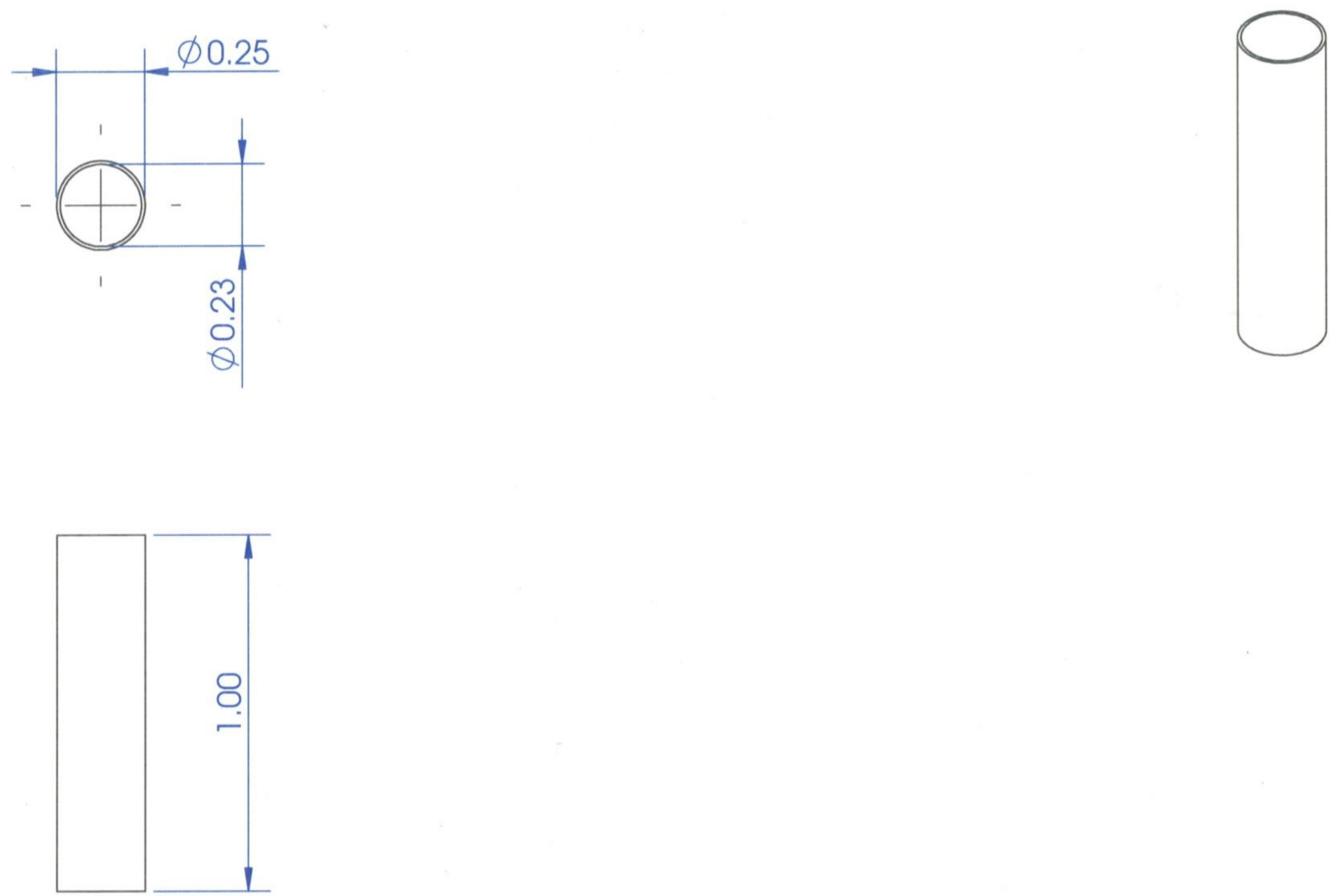


NOTE: THERE IS SYMMETRY ABOUT ℄

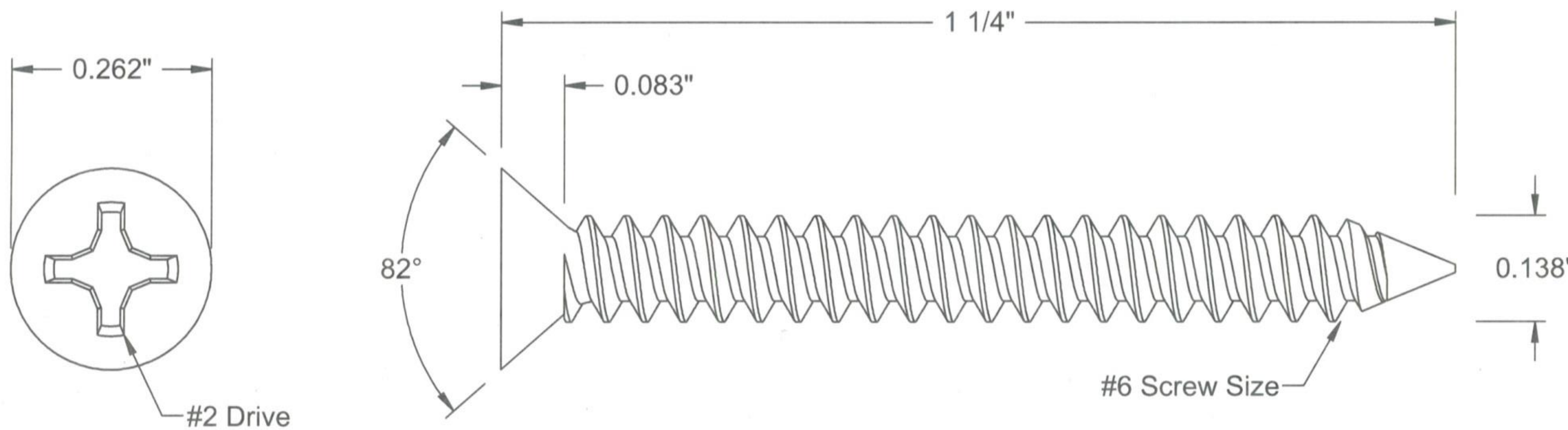
CAL POLY SAE	ASSY: TEST SECTION	UNITS: INCHES	TITLE: DUCT TOP, DOWNSTREAM		DRAWN BY: LISA VAN DEN BERG
	PART #: DT-D-1	TOLERANCE: ±1/32	DATE: 4/9/2014	SCALE: 1:4	MATERIAL: 1/2" PLYWOOD



CAL POLY SAE	ASSY: TEST SECTION	UNITS: INCHES	TITLE: LONG FLANGE, DOWNSTREAM	DRAWN BY: LISA VAN DEN BERG
	PART #: LF-D-2	TOLERANCE: ±1/32	DATE: 4/9/2014	SCALE: 1:4	MATERIAL: 1/2" PLYWOOD



CAL POLY SAE	ASSY: TEST SECTION	UNITS: INCHES	TITLE: STATIC PRESSURE PORT TUBE	DRAWN BY: LISA VAN DEN BERG
	PART #: PP-2	TOLERANCE: ±1/32	DATE: 4/9/2014 / SCALE: 2:1	MATERIAL: MCMASTER PN 5560K1- STAINLESS STEEL TUBING



McMASTER-CARR® CAD	PART NUMBER	90198A182
http://www.mcmaster.com © 2013 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Flat Head Phillips Screw for Sheet Metal	

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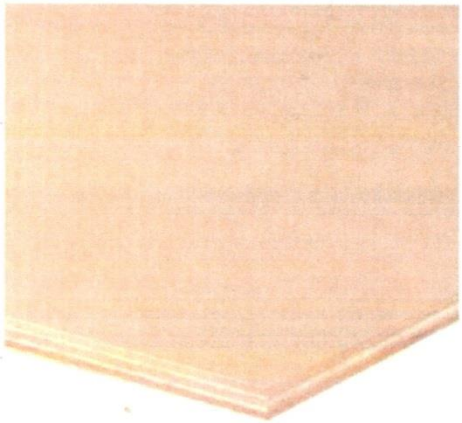

12mm, (1/2 in), 4ft x 8ft, Sandeply Hardwood Plywood

Model # 454532 Store SKU # 454532

★★★★ (6) Write a Review

$37.97 / each

35 in Stock at San Luis Obispo #1052
Aisle 22 Bay 002
(change pick up store)

PRODUCT SOLD : In Store Only

PRODUCT OVERVIEW

Sandeplywood is a Home Depot Exclusive. Every piece meets the highest grading standards for strength and appearance.

California residents: see Proposition 65 information

- Key Attributes:- Minimal core veneer voids - a quality core helps eliminate chip out that can damage or destroy the work piece when sawn or routed- Minimal core veneer overlaps - a quality core helps eliminate telegraphing to the face/back which can cause an uneven stain appearance when a stain is applied- Calibrated panel - provides a uniform thickness to the panel from end/end that insures that all cut pieces of the project fit properly
- Sandeplywood delivers durable beauty in cabinets, furniture, shelving, wall panels, entertainment centers, tables and various interior projects.
- Sandeplywood can be painted, stained or laminated.
- Other products needed with Sandeplywood projects: saw blades, screws, hardware (Knobs, hinges and handles), wood conditioner, sealers, stain, paint, edgebanding, sand paper, tack clothes and brushes.
- 1/2 in. x 4 ft. x 8 ft.

SPECIFICATIONS

Actual product thickness (in.)	0.47	Actual product width (in.)	48
Assembled Depth (in.)	96 in	Assembled Height (in.)	.47 in
Assembled Width (in.)	48 in	Manufacturer Warranty	No
Plywood Type	Hardwood Plywood	Pressure Treated	No
Product Length (ft.)	8 ft	Product Thickness (in.)	1/2 in
Tounge and Groove	No		

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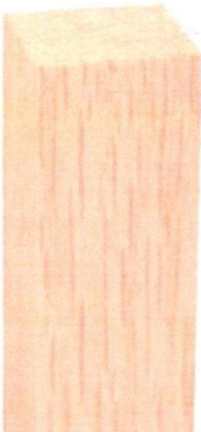


2 x 2 x 8 Hem-Fir Furring Strip Board

Model # 165360 Store SKU # 165360

★★★★★ (1) Write a Review

$1.81 / piece

642 in Stock at San Luis Obispo #1052
Aisle 21 Bay 001
(change pick up store)

PRODUCT SOLD : In Store Only

PRODUCT OVERVIEW

These Furring strips are smooth and provide a solid nailing surface. These nonstructual strips of wood are most commonly attached to walls and ceilings and used as a base for paneling, drywall, tile or other similar material installations.

California residents: see Proposition 65 information

- Kiln dried, untreated
- Can be painted or stained
- Made of white fir
- Light, easy to cut and handle
- Exterior and interior use
- Note: Product may vary by store.

SPECIFICATIONS

Actual product thickness (in.)	1.5	Actual product width (in.)	1.5
Assembled Depth (in.)	1.5 in	Assembled Height (in.)	96 in
Assembled Width (in.)	1.5 in	Manufacturer Warranty	No Warranty
Nominal Product H x W (In.)	2x2	Nominal Product Height (In.)	2
Nominal Product Length (ft.)	8	Nominal Product Length (in.)	8
Nominal Width	2 in	Nominal product width (in.)	2
Primed	No	Product Length (ft.)	8 ft
Product Length (in.)	96	Texture	Smooth
Water Resistant	No		

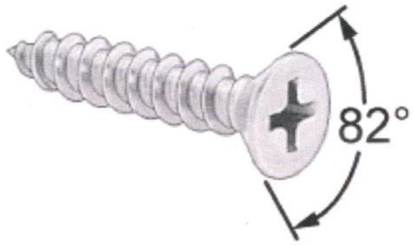
MCMASTER-CARR. HOME

(562) 692-5911
(562) 695-2323 (fax)
la.sales@mcmaster.com
Text 75930

Flat Head Phillips Screw for Sheet Metal

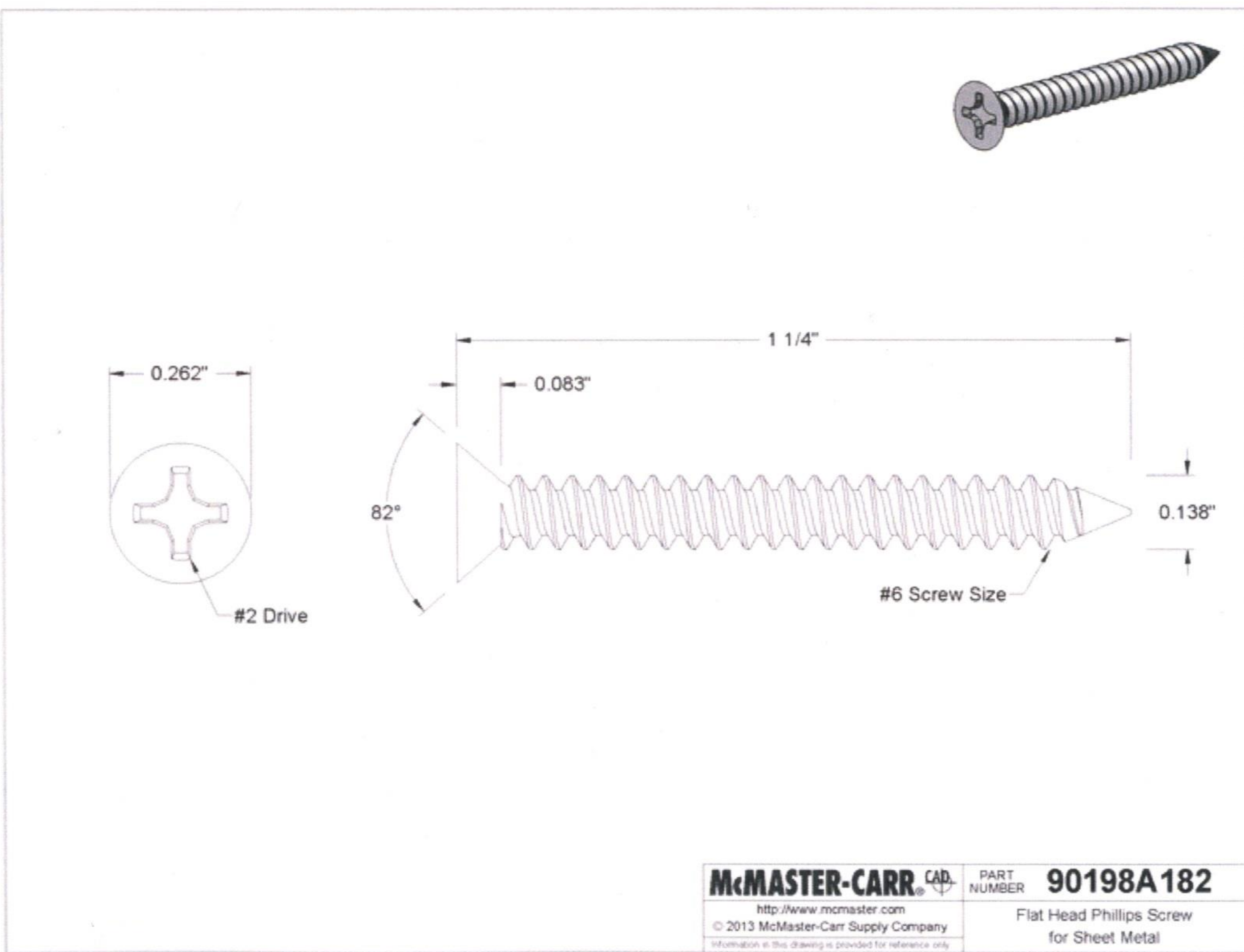
316 Stainless Steel, Number 6 Size, 1-1/4" Length

In stock
$7.75 per pack of 50
90198A182



Length	1 1/4"
Additional Specifications	Type 316 Stainless Steel No. 6—#2 Drive

Screws are beveled under the head for use in countersunk holes. Length is measured from the top of the head. Sizes noted have an undercut head that allows for more threading.



The information in this 3-D model is provided for reference only.

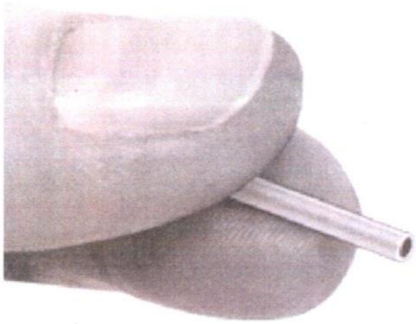
McMASTER-CARR. OVER 555,000 PRODUCTS

(562) 692-5911
(562) 695-2323 (fax)
la.sales@mcmaster.com
Text 75930

Precision Miniature Stainless Steel Tubing

304 Stainless Steel, 3 Gauge, .259" OD, .239" ID, .01" Wall

In stock
$8.24 Each
5560K1



Material	Type 304 Stainless Steel
Gauge	3
OD	0.259"
Wall	0.01"
ID	0.239"
OD Tolerance	±0.002"
Maximum psi @ 72° F	2,000
Length	1 ft.
Temperature Range	
Elbows	Not rated
Short Straight Lengths	Not ratedStraight Lengths
Additional Specifications	Straight Lengths Bend with a bending tool Connect by welding

Made to tight tolerances, this small-diameter tubing has thin walls for use in precision applications such as needles and instruments. Also known as hypodermic tubing, use with water, air, natural gas, and oil. Tubing meets ASTM A908. It has a hard temper and welded construction with a smoothed weld bead, which provides a smooth interior. It can be sterilized with steam (autoclaving). Straight lengths also meet Fed. Spec. GG-N-196.

Type 304 stainless steel has good corrosion resistance for an economical alternative to Type 316.

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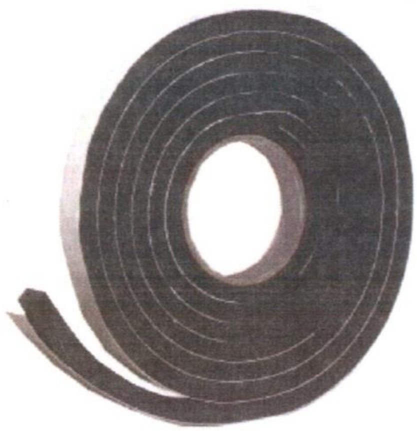

Frost King E/O 3/4 in. x 10 ft. Rubber Foam Tape

Model # R534H Internet # 202262324 Store SKU # 518425

★★★★★ (2) Write a Review | Ask a Question

$3.48 / each

14 in Stock at San Luis Obispo #1052
Aisle 30 Bay 003
(change pick up store)

PRODUCT SOLD : Online & In Store
Item cannot be shipped to the following state(s): GU,PR,VI

PRODUCT OVERVIEW

Use Thermwell Products Co., Inc. E/O 3/4 in. x 10 ft. Rubber Foam Tape during your next home project. This self-sticking tape can be used as a gasket, for insulating, for cushioning and for creating a tight seal around air conditions, windows and appliances. It is weatherproof and features memory foam construction for a tight seal.

- Self-sticking tape can be used as Weather-Stripping, cushioning around air conditioners, doors, lamps, windows, appliances and as a seal or gasket
- Helps prevent vibration noise on cars, trucks and boats
- Includes 10 ft. of 3/4 in. W x 5/16 in. T tape
- Memory foam construction for a tight seal
- Weatherproof

SPECIFICATIONS

Assembled Depth (in.)	.75 in	Assembled Height (in.)	10.5 in
Assembled Width (in.)	8.5 in	Builders Hardware Product Type	Foam Tape
Color	Black	Color Family	Blacks
Density	4.0	Manufacturer Warranty	5 Years
Material	Polyurethane	Product Height (in.)	0.4375
Product Width (in.)	.75 in	Returnable	90-Day
Unspooled Length (ft.)	10.0		

FREE SHIP TO STORE† OR HOME* ON OVER 400,000 ITEMS*. NEED IT NOW? BUY ONLINE AND PICK UP IN STORE†.

Zinsser 1-Qt. Ready Patch Spackling and Patching Compound (6-Pack)

Model # 04424 Internet # 202058891

★★★★½ (4) | Write a Review

$35.88 / case

PRODUCT SOLD : Online Only
Item cannot be shipped to the following state(s): AK,GU,HI,PR,VI

PRODUCT OVERVIEW

The Zinsser 1-qt. Ready Patch Spackling and Patching Compound is a spackling paste for interior and exterior applications. The Silica-free formula resists shrinkage and will not sag or crack. This product is sandable and paintable.

California residents: seeProposition 65 information

- Silica-free formula for indoor and outdoor applications
- For wood, metal and masonry
- Off white color when dried; dries fast and cures hard
- Coverage is depending on surface porosity
- Shrink resistant, won't sag or crack

SPECIFICATIONS

Applicator included	No	Assembled Depth (in.)	4.25 in
Assembled Height (in.)	4.25 in	Assembled Width (in.)	5 in
Color When Dry	Off White	Interior/Exterior	Interior/Exterior
Paint Product Type	Spackling Paste	Paintable	Yes
Patching & Repair Product Type	Spackling Paste	Product Depth (in.)	4.25
Product Height (in.)	5.0	Product Size (oz.)	32.0
Product Weight (lb.)	3.46	Product Width (in.)	4.25
Ready To Use	Yes	Returnable	90-Day
Sandable	Yes	Tintable	No

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San Luis Obispo #1052 (Change)

Zinsser 1-gal. White PrimeCoat 2 Water Interior Primer and Sealer

Model # 1811 Store SKU # 840741

★★★☆☆ (8) | Write a Review

$14.98 / each

13 in Stock at San Luis Obispo #1052
Aisle 09 Bay 003
(change pick up store)

PRODUCT SOLD : In Store Only
Item cannot be shipped to the following state(s):
AK,CA,CT,GU,HI,OR,PR,VI

PRODUCT OVERVIEW

The Zinsser PrimeCoat 2 1-Gallon Water White Interior Primer and Sealer is great for use on interior surfaces and is guaranteed under any topcoat. Its low-odor, tintable water-based formula blocks common stains and graffiti and will not raise the grain on new wood. The primer dries to the touch in just 30 minutes and should be reapplied after 1 hour. The 1-gallon container provides coverage for areas up to 593 sq. ft.

California residents: seeProposition 65 information↗

- Great for priming and sealing interior surfaces
- Guaranteed under all topcoats
- Can be used in low temperatures
- Will not raise grain on new wood
- Low-odor, tintable water-based formula blocks common stains and graffiti
- Dries to the touch in just 30 minutes
- Recoat after 1 hour for best results
- Covers areas up to 593 sq. ft.
- Subject to or will include a recycling fee in the following states: CA, OR, CT
- Actual paint colors may vary from on-screen and printer representations

SPECIFICATIONS

Application Method	Spray, Roller or Brush	Assembled Depth (in.)	6.625 in
Assembled Height (in.)	7.65 in	Assembled Width (in.)	6.625 in
Cleanup	Mineral Spirits	Color Family	Whites
Color/Finish	White	Dry to touch (min.)	30.0
Inverted spray ability	No	Manufacturer Warranty	Satisfaction Guaranteed
Paint Product Type	Primer Sealer	Primer Purpose	Color Changing,Odor Blocking,Stain Blocking
Product Size (oz.)	128	Sheen	Flat/Matte
Type	Oil	UV Resistant	No
Waterproof	No		

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Rust-Oleum Painter's Touch 2X 12-oz. Gloss Winter Gray General Purpose Spray Paint

Model # 249089 Store SKU # 619026

Write the First Review

$3.87 / each

Aisle 11 Bay 005

PRODUCT SOLD : In Store Only
Item cannot be shipped to the following state(s): AK,GU,HI,PR,VI

PRODUCT OVERVIEW

Painter's Touch Ultra Cover 2X 12-oz. general purpose spray paint delivers twice the coverage as other competitive brands. Our Double Cover Technology provides ultimate hiding power, which allows projects to be completed faster and easier. A great value.

California residents: see Proposition 65 information

- An any-angle spray feature that allows you to spray in any direction, even upside down, comfort spray tip with a wider finger pad reduces finger fatigue cause by continuous spraying
- Made with double cover technology, which provides twice the coverage of competitive brands
- Dries to the touch in 20 minutes
- Covers up to 50 sq. ft.
- Glossy gray finish
- Cleans up with Mineral Spirits
- Subject to or will include a recycling fee in the following states: CA, OR, CT

SPECIFICATIONS

Assembled Depth (in.)	2.625 in	Assembled Height (in.)	7.875 in
Assembled Width (in.)	2.625 in	Cleanup	Mineral Spirits
Color Family	Grays	Color/Finish	Gloss Winter Gray
Coverage Area (sq. ft.)	50 ft²	Dry to touch (min.)	20
Interior/Exterior	Interior/Exterior	Inverted spray ability	No
Manufacturer Warranty	Satisfaction Guaranteed	Paint Product Type	General Purpose Spray Paint
Primer required	No	Product Size (oz.)	12
Sheen	Gloss	Spray Paint/Stain Type	General Purpose
Spray Product Type	General Purpose	Type	Oil

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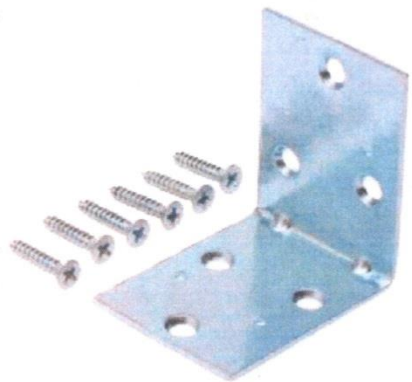

Everbilt 2-1/2 in. Zinc Plated Double-Wide Corner Braces (2-Pack)

Model # 15052 Internet # 202034033 Store SKU # 151557

★★★★★ (1) Write a Review

$3.97 / package

10 in Stock at San Luis Obispo #1052
Aisle 29 Bay 012
(change pick up store)

PRODUCT SOLD : Online & In Store
Item cannot be shipped to the following state(s): AK,GU,HI,PR,VI

PRODUCT OVERVIEW

The Everbilt 2-1/2 in. Double-Wide Corner Braces (2-Pack) are ideal reinforcement of right and corner joints. Double wide design adds extra support and durability. Easy to install.

- Made of steel
- Zinc plated finish
- Ideal for use with wood on indoor and outdoor applications
- Screws included
- 6 hole design

SPECIFICATIONS

Assembled Depth (in.)	1.50 in	Assembled Height (in.)	2.50 in
Assembled Width (in.)	2.50 in	Builders Hardware Product Type	Braces
Gauge	3	Manufacturer Warranty	none
Material	Steel	Material	Steel
Number of Pieces	2	Number of mounting holes	6
Product Height (in.)	2.5	Product Thickness (in.)	0.0625 in
Product Weight (lb.)	0.3125	Product Width (in.)	2.5
Returnable	30-Day	Type	Double wide corner brace

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Your Store:
San Luis Obispo #1052 (Change)

1/4 in.-28 tpi x 2 in. Zinc-Plated Grade-5 Cap Screw (1-Piece/Pack)

Model # 807228 Store SKU # 219985

Write the First Review

$0.28 / each

5 in Stock at San Luis Obispo #1052
Aisle 19 Bay 005
(change pick up store)

PRODUCT SOLD : In Store Only
Item cannot be shipped to the following state(s): AK,GU,HI,PR,VI

PRODUCT OVERVIEW

Cap Screws, or Hex Bolts, have hexagonal heads and are for general purpose applications with a socket type installation tool or standard wrench. The standard bolt is compatible with standard nuts and washers of the same thread pitch, grade, and finish.

California residents: seeProposition 65 information

- 1-piece per pack
- Steel construction
- Zinc-plated finish
- 1/4 in.-28 tpi x 2 in.

SPECIFICATIONS

Assembled Depth (in.)	2 in	Assembled Height (in.)	0.25 in
Assembled Width (in.)	0.25 in	Drive Style	Hex
Fastener Thread Type	Coarse	Fastener Type	Hex Bolt
Fastener length (in.)	2	Head diameter (in.)	.2
Manufacturer Warranty	None	Package Quantity	1
Product Weight (lb.)	.2	Returnable	90-Day

FREE SHIP TO STORE† OR HOME* ON OVER 400,000 ITEMS*. NEED IT NOW? BUY ONLINE AND PICK UP IN STORE†.

Everbilt 1/4 in. Zinc-Plated Flat Washer (25-Pieces)

Model # 08034 Internet # 100338073 Store SKU # 327915

Write the First Review

$2.46 / package

7 in Stock at San Luis Obispo #1052
Aisle 19 Bay 013
(change pick up store)

PRODUCT SOLD : Online & In Store
Item cannot be shipped to the following state(s): AK,GU,HI,PR,VI

PRODUCT OVERVIEW

This flat washer provides a larger circular bearing surface which helps prevent a nut or bolt head from pulling through the material. It is round with a hole in the center and can also be used as a spacer. Flat washers are commonly used in any application using a bolt where two pieces are being drawn together. The package size designates the inner diameter of the washer. Used in applications with nuts and bolts of any kind as well as screw products. Available in various materials and finishes.

California residents: see Proposition 65 information

- 25-pieces per pack
- Steel construction
- Zinc-plated
- 1/4 in.

SPECIFICATIONS

Assembled Depth (in.)	0.7340 in	Assembled Height (in.)	0.07 in
Assembled Width (in.)	0.7340 in	Fastener Type	Flat Washer
Finish Family	Metallic	Inside Diameter	.25 in
Manufacturer Warranty	None	Material	Steel
Outside diameter (in.)	0.625	Package Quantity	25
Product Weight (lb.)	0.0064	Returnable	90-Day

FREE SHIP TO STORE† OR HOME* ON OVER 400,000 ITEMS*. NEED IT NOW? BUY ONLINE AND PICK UP IN STORE†.

1/4 in.-28 tpi Zinc Grade 5 SAE Hex Nut

Model # 94888 Internet # 203538349 Store SKU # 576321

Write the First Review

$0.07 / bag

Item Not Sold at San Luis Obispo #1052

Check nearby stores to confirm availability and pick up options.

PRODUCT SOLD : Online & In Store

Item cannot be shipped to the following state(s): AK,GU,HI,PR,VI

PRODUCT OVERVIEW

Crown Bolt's hex nuts are internally threaded and have a hex drive for nearly all general applications. The most commonly used nut, hex nuts are used in any application with a mating male threaded machine bolt or screw. Can be used with any fastener with a machine screw thread. Hex nuts are used with bolts and washers of the same diameter, material, and finish. The package size designates the inner diameter and the number of threads per inch or thread pitches.

California residents: see Proposition 65 information

- 1-piece per bag
- Steel construction
- Zinc plated finish
- 1/4 in.-28
- Grade 5

SPECIFICATIONS

Assembled Depth (in.)	.15 in	Assembled Height (in.)	4.25 in
Assembled Width (in.)	2 in	Color Family	Metallics
Fastener Type	Specialty Fastener	Manufacturer Warranty	None
Package Quantity	1	Product Weight (lb.)	.5
Returnable	90-Day		

McMASTER-CARR. OVER 555,000 PRODUCTS
(562) 692-5911
(562) 695-2323 (fax)
la.sales@mcmaster.com
Text 75930

Aluminum Foil Tape

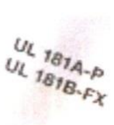
Printed UL, 2-1/2" Wide x 60 Yrd Length, .004" Thick

In stock
$24.68 per roll
76145A33

Width	2 1/2"
Thickness	0.004"
Liner	Yes
Length, yds.	60
Additional Specifications	Tape Long Rolls Printed UL

This flexible aluminum foil tape conforms to irregular and curved surfaces. Color is shiny silver.

Printed UL—UL 181A-P and UL 181B-FX flexible duct standards are printed on this tape for easy identification. Tape has 0.002" thick acrylic adhesive. Temperature range is -30° to 300° F.



Printed UL

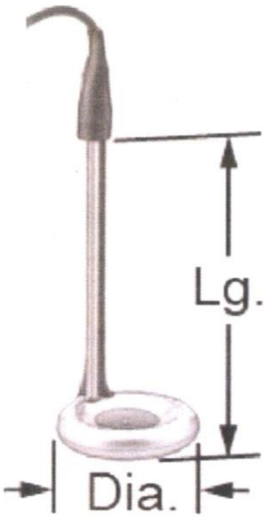
McMASTER-CARR. OVER 555.000 PRODUCTS

(562) 692-5911
(562) 695-2323 (fax)
la.sales@mcmaster.com
Text 75930

Side-Mount Immersion Heater with Incoloy Element

1150 Watts, 11-1/2" Long Element, Fits 5 Gallon Drum

In stock
$73.12 Each
3583K92



Fits Drum Size, Gallon	5
Watts	1,150
AC Voltage (Phase)	120 (1)
Amps	9.6
Element	
Diameter	5"
Length	11 1/2"
Minimum Liquid Level	1 1/2"
Mount Type	Hanging
Temperature Controller	None
Additional Specifications	Incoloy Element for Water

Attach these heaters to the side of your drums to warm their contents. Note: All heaters must be immersed in liquid up to at least the minimum liquid level. They are not for use in plastic drums.

Heaters with Incoloy element are not for use with acid, alkaline, or caustic solutions.

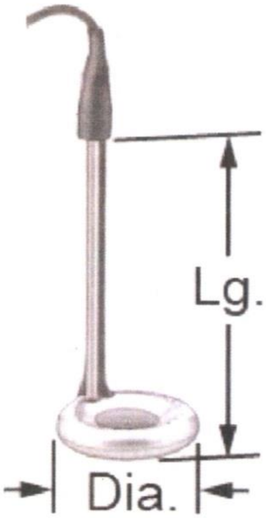
Style E—Have a circular base that sits in your tank—good when there's nothing to clip onto. Remove from water when desired temperature is reached. All have a 5 1/2-ft. long power cord. UL listed. 120V AC heaters have a standard three-prong plug; 240V AC heater has a NEMA 6-15 plug.

McMASTER-CARR. OVER 555,000 PRODUCTS
(562) 692-5911
(562) 695-2323 (fax)
la.sales@mcmaster.com
Text 75930

Side-Mount Immersion Heater with Incoloy Element

1150 Watts, 5-1/2" Long Element, Fits 5 Gallon Drum

In stock
$68.82 Each
3583K91



Fits Drum Size, Gallon	5
Watts	1,150
AC Voltage (Phase)	120 (1)
Amps	9.6
Element	
Diameter	5"
Length	5 1/2"
Minimum Liquid Level	1 1/2"
Mount Type	Hanging
Temperature Controller	None
Additional Specifications	Incoloy Element for Water

Attach these heaters to the side of your drums to warm their contents. Note: All heaters must be immersed in liquid up to at least the minimum liquid level. They are not for use in plastic drums.

Heaters with Incoloy element are not for use with acid, alkaline, or caustic solutions.

Style E—Have a circular base that sits in your tank—good when there's nothing to clip onto. Remove from water when desired temperature is reached. All have a 5 1/2-ft. long power cord. UL listed. 120V AC heaters have a standard three-prong plug; 240V AC heater has a NEMA 6-15 plug.

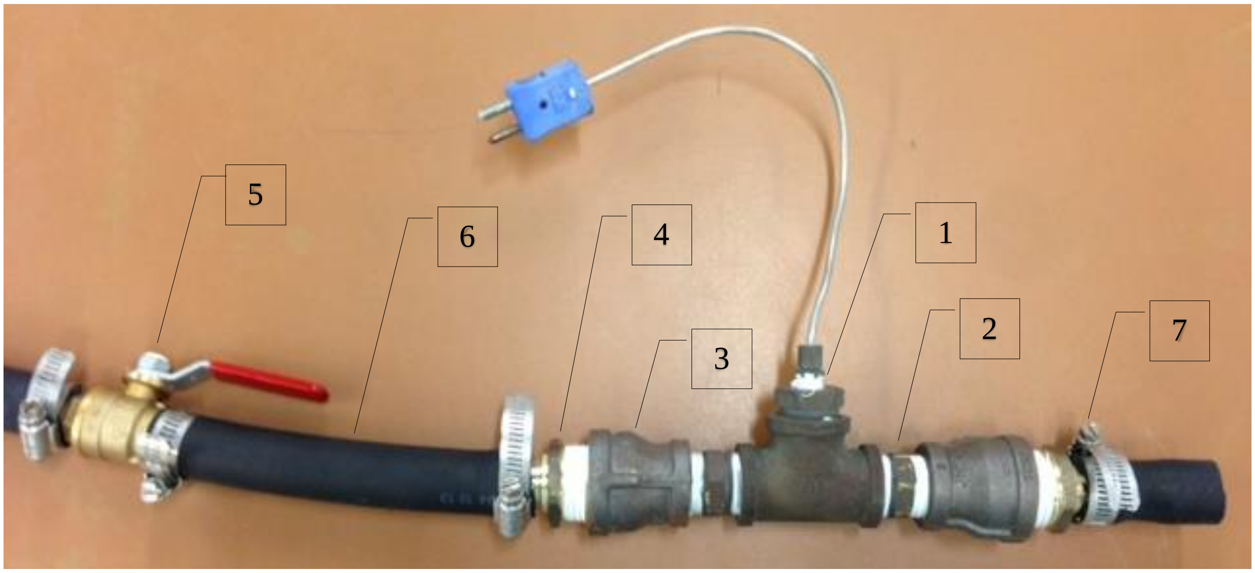


Figure 58. *Plumbing at radiator outlet- thermocouple and valve*

Table 14. *Bill of materials corresponding to above figure*

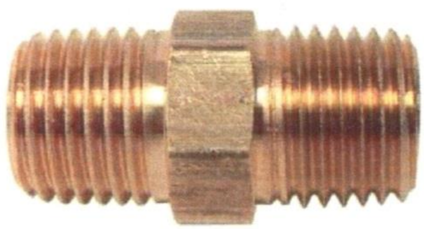
Item No.	Manufacturer	Part No.	Description	Qty.
1	--	--	3/4" FPT - 3/4" FPT coupling w/ embedded thermocouple	1
2	Watts	LFA-875	3/4" MPT - 3/4" MIP brass nipple	2
3	LDR Industries	311 RC-134	3/4 FPT - 1" FIP galvanized iron coupling	2
4	SharkBite	UC140LFA	1" MPT - 1" brass barb	2
5	Mueller	107-454	3/4" solder brass ball valve	1
6	Watts	SHNL10	1" OD x 3/4" ID x 10' rubber heater hose	1
7	Glacier Bay	6712595	1/2" - 1-1/4" stainless steel hose clamp	5

Vendor catalog pages descriptions are included in the following pages.

FREE SHIP TO STORE† OR HOME* ON OVER 400,000 ITEMS*. NEED IT NOW? BUY ONLINE AND PICK UP IN STORE†.

Watts 3/4 in. Lead-Free Brass Hex Nipple

Model # LF A875 Internet # 202254974 Store SKU # 784343



Write the First Review | Ask a Question

$9.23 / each

17 in Stock at San Luis Obispo #1052
Aisle 33 Bay 018
(change pick up store)

PRODUCT SOLD : Online & In Store
Item cannot be shipped to the following state(s): AK,GU,HI,PR,VI

PRODUCT OVERVIEW

Durable, lead-free brass is an excellent choice, with all tapered pipe threads manufactured to highest quality standards and tolerances. Lead-free brass is not more than a weighted average of 0.25% lead when used with respect to the wetted surfaces of pipes and pipe and plumbing fittings and fixtures. This pipe fitting is easy to use for both contractors and the do-it-yourselfer.

- Ideal for use with copper, brass, iron pipe on oil, natural gas, water and air lines
- Tapered pipe threads are manufactured to exacting quality and standards
- Manufactured to industry standards for lead free pipe fittings
- Not for underground use

SPECIFICATIONS

Assembled Depth (in.)	2.5 in	Assembled Height (in.)	1 in
Assembled Width (in.)	1 in	Compatible pipe material	Brass
Fitting 1 size	3/4"	Fitting 2 size	3/4"
Fitting or Connector Type	Nipple	Manufacturer Warranty	Watts (the "Company") warrants each product to be free from defects in material and workmanship under normal usage for a period of one year from the date of original shipment.
Material	Brass	Maximum working pressure (psi)	1200
Pipe or Fitting Product Type	Fittings & Connectors	Product Height (in.)	1
Product Length (in.)	2.5 in	Product Weight (lb.)	0.19
Product Width (in.)	1	Push to connect	No
Returnable	90-Day		

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Your Store:
San Luis Obispo #1052 (Change)

LDR Industries 1 in. x 3/4 in. Galvanized Iron Reducing Coupling

Model # 311 RC-134 Store SKU # 182281

Write the First Review

$3.77 / each

11 in Stock at San Luis Obispo #1052
Aisle 33 Bay 014
(change pick up store)

PRODUCT SOLD : In Store Only

PRODUCT OVERVIEW

When selecting water pipe for your home, LDR pipe and fittings are the way to go. The durable galvanized iron is 100% pressure tested and protected right at the factory. Fittings and pipe come in an array of sizes for residential water applications.

- Galvanized malleable iron construction
- Maximum working pressure of 150 psi
- For use with residential drinking water applications
- Galvanizing meets ASTM A-123 standards
- Zinc applied by hot dip process
- Hydrostatically tested
- Note: Product may vary by store.

SPECIFICATIONS

Assembled Depth (in.)	1.75 in	Assembled Height (in.)	1.75 in
Assembled Width (in.)	1.75 in	Compatible pipe material	Galvanized malleable iron
Connection	FPT x FPT	Fitting 1 size	1"
Fitting 2 size	3/4"	Fitting or Connector Type	Adapter or Coupling
Manufacturer Warranty	Limited Lifetime	Material	Iron
Maximum working pressure (psi)	150	Pipe or Fitting Product Type	Fittings & Connectors
Product Height (in.)	1.75	Product Length (in.)	1.75 in
Product Weight (lb.)	0.42	Product Width (in.)	1.75 in
Push to connect	No	Underground rated	No

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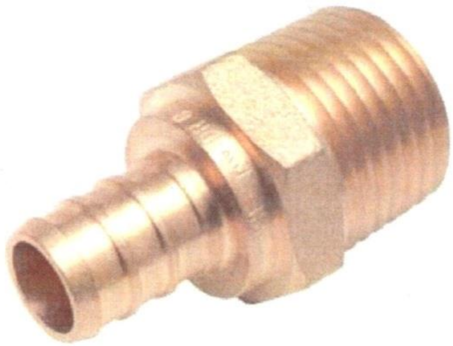


SharkBite 1 in. Brass Barb x Male Threaded Adapter

Model # UC140LFA Internet # 202270622 Store SKU # 307104

Write the First Review | Ask & Answer (1)

$5.23 / each

5 in Stock at San Luis Obispo #1052
Aisle 33 Bay 015
(change pick up store)

PRODUCT SOLD : Online & In Store
Item cannot be shipped to the following state(s): AK,GU,HI,PR,VI

PRODUCT OVERVIEW

The SharkBite 1 in. Brass Barb x MPT Male Adapter can be used with crimp-ring or clamp connections. The adapter can be used underground with PEX tubing (not included).

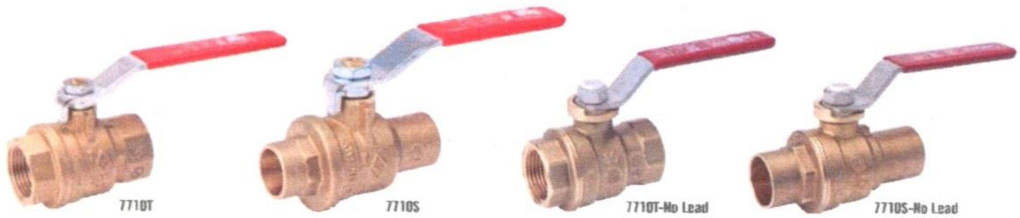
California residents: see Proposition 65 information

- Dezincification Resistant Brass construction is durable and corrosion resistant
- Compatible with PEX tubing (not included)
- Rated for underground use
- Use with clamp or crimp-ring connections
- 200 psi maximum working pressure
- Meets ASTM F1807 requirements and is listed to the NSF 14 Standards

SPECIFICATIONS

Assembled Depth (in.)	1 in	Assembled Height (in.)	1 in
Assembled Width (in.)	2 in	Compatible pipe material	PEX
Fitting 1 size	1"	Fitting 2 size	1"
Fitting or Connector Type	Adapter or Coupling	Manufacturer Warranty	For warranty information on this product, please call our Internet Customer Service Center at 1-800-435-4654.
Material	Brass	Maximum working pressure (psi)	160.0
Pipe or Fitting Product Type	Fittings & Connectors	Product Height (in.)	1.0
Product Length (in.)	1.29 in	Product Weight (lb.)	0.195
Product Width (in.)	1.0 in	Push to connect	No
Returnable	90-Day	Type	Male
Underground rated	Yes		

ProLine® SERIES Ball Valves



SERIES 7710 • BALL VALVE • FULL PORT • 600 PSI FORGED BRASS

Item No.	Size	Connection	Inner Qty.	Master Qty.	Each Wt.
STYLE 7710T – THREADED					
107-401*	1/4"	FPT x FPT	20	200	0.16
107-402*	3/8"	FPT x FPT	10	100	0.36
107-403*	1/2"	FPT x FPT	10	100	0.43
107-404*	3/4"	FPT x FPT	10	100	0.63
107-405*	1"	FPT x FPT	5	50	1.02
107-406*	1-1/4"	FPT x FPT	4	20	1.65
107-407*	1-1/2"	FPT x FPT	2	20	2.27
107-408*	2"	FPT x FPT	2	10	3.89

- 600 PSI WOG/150 PSI WSP
- -20°F to 300°F temperature range
- Full port for maximum flow rate
- Packing Gland - blowout-proof stem design
- PTFE seat and packing
- Frost-proof stainless steel ball design
- Rust-resistant heavy-duty handle with vinyl grip
- CSA ANSI Z 21.15 (1/2 PSIG)
- CSA Certified to ASME B16.33 (5G)
- CSA Certified to ASME B16.44 (125G)
- CSA tamper proof (T)
- UL Gas Shutoff valve (YRPV)
- UL Manual valves (MHKZ)
- UL Compressed Gas Shutoff valve (YQNZ)
- UL Flammable liquid Shutoff valve (YRBX)
- UL LP-Gas Shutoff valve (YSDT)
- FM Approved - Fire Protection
- Conforms to MSS-SP-110
- Meets Fed Spec WW-V-35, Type II, Class A Style 3
- Threaded ends comply with ANSI B1.20.1
- Certified to NSF 61

Item No.	Size	Connection	Inner Qty.	Master Qty.	Each Wt.
STYLE 7710S – SOLDER					
107-453*	1/2"	C x C	10	100	0.39
107-454*	3/4"	C x C	10	50	0.70
107-455*	1"	C x C	6	30	1.13
107-456*	1-1/4"	C x C	4	20	1.75
107-457*	1-1/2"	C x C	2	20	2.43
107-458*	2"	C x C	2	10	3.92

- 600 PSI WOG/150 PSI WSP
- -20°F to 300°F temperature range
- Full port for maximum flow rate
- Packing Gland - blowout-proof stem design
- PTFE Packing
- Frost-proof stainless steel ball design
- Rust-resistant heavy-duty handle with vinyl grip
- CSA Certified
- CSA tamper proof (T)
- UL Listed
- FM Approved - Fire Protection
- Conforms to MSS-SP-110
- Meets Fed Spec WW-V-35, Type II, Class A Style 3
- Solder ends comply with ANSI B16.18
- Certified to NSF 61

Item No.	Size	Connection	Inner Qty.	Master Qty.	Each Wt.
STYLE 7710T – THREADED – NO LEAD					
107-401NL	1/4"	FPT x FPT	-	20	0.16
107-402NL	3/8"	FPT x FPT	-	20	0.36
107-403NL	1/2"	FPT x FPT	-	15	0.43
107-404NL	3/4"	FPT x FPT	-	15	0.63
107-405NL	1"	FPT x FPT	-	10	1.02
107-406NL	1-1/4"	FPT x FPT	-	4	1.65
107-407NL	1-1/2"	FPT x FPT	-	4	2.27
107-408NL	2"	FPT x FPT	-	2	3.89

- 600 PSI WOG/150 PSI WSP
- -20°F to 300°F temperature range
- Full port for maximum flow rate
- Double Viton O-ring - blowout-proof stem design
- PTFE Discs and Seats
- Internal & External anit-friction stem washers
- Hollow ball for lighter weight and longer seat life
- Corrosion-resistant Dacromet-coated steel handle
- CSA ANSI Z 21.15 (1/2 PSIG)
- CSA Certified to ASME B16.33 (5G)
- CSA Certified to ASME B16.44 (125G)
- CSA tamper proof handle
- UL Gas Shutoff valve (YRPV)
- UL Manual valves (MHKZ)
- UL Compressed Gas Shutoff valve (YQNZ)
- UL Flammable liquid Shutoff valve (YRBX)
- UL LP-Gas Shutoff valve (YSDT)
- FM Approved - Fire Protection
- Conforms to MSS-SP-110
- Meets Fed Spec WW-V-35, Type II, Class A Style 3
- Threaded ends comply with ANSI B1.20.1
- Certified to NSF 61-G
- "Lead-Free" Compliant

Item No.	Size	Connection	Inner Qty.	Master Qty.	Each Wt.
STYLE 7710S – SOLDER – NO LEAD					
107-453NL	1/2"	C x C	-	15	0.39
107-454NL	3/4"	C x C	-	15	0.70
107-455NL	1"	C x C	-	10	1.13
107-456NL	1-1/4"	C x C	-	5	1.75
107-457NL	1-1/2"	C x C	-	5	2.43
107-458NL	2"	C x C	-	2	3.92

- 600 PSI WOG/150 PSI WSP
- -20°F to 300°F temperature range
- Full port for maximum flow rate
- Double Viton O-ring - blowout-proof stem design
- PTFE Discs and Seats
- Internal & External anit-friction stem washers
- Hollow ball for lighter weight and longer seat life
- Corrosion resistant Dacromet coated steel handle
- CSA Certified
- CSA tamper proof handle
- UL Listed
- FM Approved - Fire Protection
- Conforms to MSS-SP-110
- Meets Fed Spec WW-V-35, Type II, Class A Style 3
- Solder ends comply with ANSI B16.18
- Certified to NSF 61-G
- "Lead-Free" Compliant

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Your Store:
San Luis Obispo #1052 (Change)

Watts 1 in. OD x 3/4 in. ID x 10 ft. Rubber Heater Hose

Model # SHNL10 Internet # 100131884 Store SKU # 302571

Write the First Review | Ask a Question

$21.47 / each

13 in Stock at San Luis Obispo #1052
Aisle 33 Bay 018
(change pick up store)

PRODUCT SOLD : Online & In Store
Item cannot be shipped to the following state(s): AK,GU,HI,PR,VI

PRODUCT OVERVIEW

This rubber heater hose is manufactured with lightweight EPDM rubber reinforced with multiple textile piles. It has excellent resistance to heat, ozone, and weather conditions. It is designed for use with automotive coolant under standard operating pressures and temperatures.

- Can also be used as a dishwasher or washing machine discharge hose
- Made of durable, reinforced rubber
- Working pressure is 80 - 105 PSI
- Maximum operating temperature is 212 degrees Fahrenheit

SPECIFICATIONS

Actual inside diameter (in.)	.75	Actual outside diameter (in.)	1
Assembled Depth (in.)	3 in	Assembled Height (in.)	10.5 in
Assembled Width (in.)	10.5 in	Certifications and Listings	No Certifications or Listings
Coiled	Yes	Manufacturer Warranty	Watts (the "Company") warrants each product to be free from defects in material and workmanship under normal usage for a period of one year from the date of original shipment.
Material	Rubber	Maximum working pressure (psi)	105
Maximum working temperature (F)	212	Minimum working temperature (F)	33
Pipe & Tubing Product Type	Specialty	Pipe Size	3/4"
Pipe or Fitting Product Type	Pipe & Tubing	Product Length (ft.)	10 ft
Product Weight (lb.)	3.16	Rating	Water
Recommended function	Water Supply	Returnable	90-Day
Wrapped	No		

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PRO Site | Tool & Truck Rental | Installation Services and Repair | Gift Cards | Help

More saving. More doing.

Your Store:
San Luis Obispo #1052 (Change)

Glacier Bay 1/2 - 1-1/4 in. Hose Repair Clamp

Model # 6712595 Store SKU # 100589

★★★★★ (1) | Write a Review | Ask a Question

$0.98 / each

106 in Stock at San Luis Obispo #1052
Aisle 33 Bay 018
(change pick up store)

PRODUCT SOLD : In Store Only

PRODUCT OVERVIEW

The Glacier Bay 1/2 - 1-1/4 in. Hose Repair Clamp features a stainless-steel finish. The clamp is recommended for use with various hose materials and sizes.

- Stainless steel finish
- Use for hose repairs
- Suitable for use with multiple hose materials
- Compatible with 1/2 - 1-1/4 in. hose sizes

SPECIFICATIONS

Assembled Depth (in.)	.375 in	Assembled Height (in.)	.875 in
Assembled Width (in.)	.5 in	Finish Family	Silver Metallic
Maintenance, Repair & Supplies Product Type	Repair Clamps	Manufacturer Warranty	1 year
Maximum hose size compatibility (in.)	1.25	Minimum hose size compatibility (in.)	0.5
Product Height (in.)	8	Product Width (in.)	5.625 in
Repair Clamps Type	For Hoses		

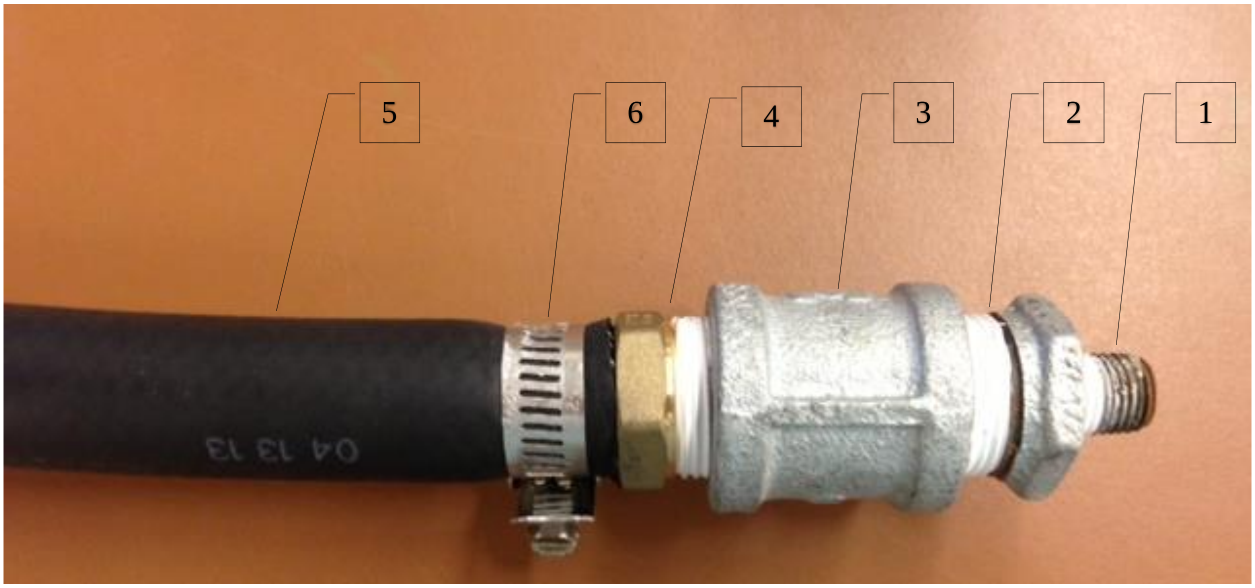

Figure 59. *Plumbing at pump discharge to couple pump discharge fitting to hose*

Table 15. *Bill of materials corresponding to above figure*

Item No.	Manufacturer	Part No.	Description	Qty.
1	Mueller	561-001HN	1/4" galvanized steel nipple	1
2	Mueller	511-941HN	3/4" MPT - 1/4" FPT galvanized iron bushing	1
3	Mueller	511-204HN	3/4" FPT - 3/4" FPT galvanized iron coupling	1
4	SharkBite	UC140LFA	1" MPT - 1" brass barb	1
5	Watts	SHNL10	1" OD x 3/4" ID x 10' rubber heater hose	--
6	Glacier Bay	6712595	1/2" - 1-1/4" stainless steel hose clamp	2

Vendor catalog pages descriptions are included in the following pages.

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PRO Site | Tool & Truck Rental | Installation Services and Repair | Gift Cards | Help

More saving. More doing.

Your Store:
San Luis Obispo #1052 (Change)

Mueller Global 1/4 in. Galvanized Steel Nipple

Model # 561-001HN Store SKU # 179078

Write the First Review

$1.54 / each

8 in Stock at San Luis Obispo #1052
Aisle 33 Bay 012
(change pick up store)

PRODUCT SOLD : In Store Only

PRODUCT OVERVIEW

Use the MUELLER GLOBAL 1/4 in. Galvanized Steel Nipple for residential potable water applications. This nipple is suitable for repairing pipe or extending an existing pipe and should be installed according to your local code.

- Galvanized steel
- Use for residential potable water and drainage applications
- Use to repair pipe or make an extension from a fitting or existing pipe
- Male threaded connection
- Threads comply with ansi b1.20.1
- Install according to your local building codes
- Note: Product may vary by store.

SPECIFICATIONS

Assembled Depth (in.)	0.83 in	Assembled Height (in.)	0.54 in
Assembled Width (in.)	0.54 in	Compatible pipe material	Steel
Fitting 1 size	1/4" x close	Fitting 2 size	1/4" x close
Fitting or Connector Type	Nipple	Manufacturer Warranty	1 Year Warranty
Material	Steel	Material	Steel
Maximum working pressure (psi)	700.0	Pipe or Fitting Product Type	Fittings & Connectors
Product Height (in.)	0.54 in	Product Length (in.)	0.83 in
Product Weight (lb.)	0.02 lb	Product Width (in.)	0.54 in
Push to connect	No		

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Your Store:
San Luis Obispo #1052 (Change)

Mueller Streamline 3/4 in. x 1/4 in. Galvanized Malleable Iron MPT x FPT Hex Bushing

Model # 511-941HN Store SKU # 832863

Write the First Review

$2.37 / each

4 in Stock at San Luis Obispo #1052
Aisle 33 Bay 012
(change pick up store)

PRODUCT SOLD : In Store Only

PRODUCT OVERVIEW

Connect pipes of different sizes with the Mueller Global 3/4 in. x 1/4 in. galvanized iron MPT x FPT hex bushing. Used in potable water and drain applications, the reliable, galvanized hex bushing meets ASTM and ASME standards and has ANSI B 1.20.1 approved threads. The bushing's Class 150 lb. malleable iron construction makes it durable.

- Inserts into female threading of a fitting to reduce size of a pipe or fitting
- For use with potable water and drainage applications
- Galvanized malleable iron class 150 lb.
- Meets astm and asme standards
- Threads comply with ansi b 1.20.1
- Note: Product may vary by store.

SPECIFICATIONS

Assembled Depth (in.)	1.5 in	Assembled Height (in.)	1.5 in
Assembled Width (in.)	1.5 in	Compatible pipe material	Galvanized malleable iron
Connection	MPT x FPT	Fitting 1 size	3/4"
Fitting 2 size	1/4"	Fitting or Connector Type	Bushing
Manufacturer Warranty	1 Year Warranty	Material	Iron
Material	Malleable Iron	Maximum working pressure (psi)	300.0
Pipe or Fitting Product Type	Fittings & Connectors	Product Height (in.)	1.5 in
Product Length (in.)	1.5 in	Product Weight (lb.)	0.14 lb
Product Width (in.)	1.5 in	Push to connect	No
Underground rated	No		

FREE SHIP TO STORE† OR HOME* ON OVER 400,000 ITEMS*. NEED IT NOW? BUY ONLINE AND PICK UP IN STORE†.

3/4 in. Galvanized Malleable Iron FPT x FPT Coupling

Model # 511-204HN Store SKU # 181870

Write the First Review

$2.40 / each

43 in Stock at San Luis Obispo #1052
Aisle 33 Bay 012
(change pick up store)

PRODUCT SOLD : In Store Only

PRODUCT OVERVIEW

Zinc coated for use with potable water and drainage applications, the Mueller Global 3/4 in. galvanized iron coupling can be used to connect 2 pieces of same sized piping in a straight, in-line run.

- For use with potable water and drainage applications
- Use to connect 2 pieces of pipe of the same size in a straight, in-line run
- Galvanized malleable iron class 150 lb. Construction
- Female threaded connections comply with ansi b 1.20.1
- Note: Product may vary by store.

SPECIFICATIONS

Assembled Depth (in.)	1.9 in	Assembled Height (in.)	1.9 in
Assembled Width (in.)	1.9 in	Compatible pipe material	Galvanized malleable iron
Connection	FPT x FPT	Fitting 1 size	3/4"
Fitting 2 size	3/4"	Fitting or Connector Type	Adapter or Coupling
Manufacturer Warranty	1 Year Warranty	Material	Iron
Material	Malleable Iron	Maximum working pressure (psi)	500.0
Pipe or Fitting Product Type	Fittings & Connectors	Product Height (in.)	1.9 in
Product Length (in.)	1.9 in	Product Weight (lb.)	0.29 lb
Product Width (in.)	1.9 in	Push to connect	No
Underground rated	No		

FREE SHIP TO STORE† OR HOME* ON OVER 500,000 ITEMS*. NEED IT NOW? BUY ONLINE AND PICK UP IN STORE†.

Watts 1/4 in. Lead-Free Brass MPT Square-Head Plug

Model # LF A737 Internet # 202254918 Store SKU # 709568

Write the First Review | Ask a Question

$2.61 / each

18 in Stock at San Luis Obispo #1052
Aisle 33 Bay 018
(change pick up store)

PRODUCT SOLD : Online & In Store
Item cannot be shipped to the following state(s): AK,GU,HI,PR,VI

PRODUCT OVERVIEW

Durable, lead-free brass is an excellent choice, with all tapered pipe threads manufactured to highest quality standards and tolerances. Lead-free brass is not more than a weighted average of 0.25% lead when used with respect to the wetted surfaces of pipes and pipe and plumbing fittings and fixtures. This pipe fitting is easy to use for both contractors and the do-it-yourselfer.

- Ideal for use with copper, brass, iron pipe on oil, natural gas, water and air lines
- Tapered pipe threads are manufactured to exacting quality and standards
- Manufactured to industry standards for lead free pipe fittings
- Not for underground use

SPECIFICATIONS

Assembled Depth (in.)	.5 in	Assembled Height (in.)	.65 in
Assembled Width (in.)	.5 in	Compatible pipe material	Brass
Connection	MPT	Fitting or Connector Type	Plug
Manufacturer Warranty	Watts (the "Company") warrants each product to be free from defects in material and workmanship under normal usage for a period of one year from the date of original shipment.	Material	Brass
Maximum working pressure (psi)	1200.0	Pipe or Fitting Product Type	Fittings & Connectors
Product Height (in.)	0.5	Product Length (in.)	1 in
Product Weight (lb.)	0.05	Product Width (in.)	0.5
Push to connect	No	Returnable	90-Day
Temporary or permanent	Temporary or permanent	Threaded	Yes
Underground rated	No		

Appendix H: Excel Program Tables

Instructions: Input measured weights from Test 1 in cell corresponding to appropriate crankshaft rotational rate.

Green fill indicates that a cell needs a measured input value.

Bucket Weight (kg) =	0.745
Test Time (s) =	20

RPM of engine	Weight of Water + Bucket (kg)	Cooling Water Mass Flow Rate (kg/s)
2500	2.345	0.08
4000	3.745	0.15
5500	4.945	0.21
7000	5.945	0.26
8500	6.745	0.3
10000	7.345	0.26
11000	7.745	0.15

Figure 60. *Screenshot of "Cooling Water Mass Flow Rate" spreadsheet in Excel program*

Instructions: Enter tmeperatures of the cooling water into and out of the engine in the appropriate cells. It is not required that you enter the torque to determine the power curve, but it can be useful to compare the engine power and the amount of heat being rejected to

Green fill indicates that a cell needs a measured input value.

Specific Heat of water (kJ/kg*C) = 4.2

Crankshaft Rotational Rate RPM	Cranskshaft Rotational Speed (rad/s)	Torque (Nm)	Engine Power (kW)	Cooling Water Mass Flow Rate (kg/s)	Temperature Into Engine (C)	Temperature Out of Engine (C)	Differential Temperature (C)	Heat Rejected to Water (kW)
2500	261.80	23	6.02	0.08	165	168.0	3.0	1.00
4000	418.88	31	12.99	0.15	165	169.2	4.2	2.66
5500	575.96	37	21.31	0.21	165	170.3	5.3	4.69
7000	733.04	37	27.12	0.26	165	170.6	5.6	6.17
8500	890.12	31	27.59	0.30	165	170.0	5.0	6.35
10000	1047.20	21	21.99	0.26	165	168.7	3.7	3.99
11000	1151.92	6	6.91	0.15	165	166.1	1.1	0.69

Figure 61. *Screenshot of "Heat Rej. to Water" spreadsheet from Excel program*

Instructions: While the radiator core is held outside the window of a car, use a vane anemometer to tak an array of velocity measurements aft of the radiator core. Take an array of measurements. The positions in the tables correspond to positions on the back of the radiator, for the sake of consistency. Enter the measurements in the tables below. Also enter the the face area of the radiator and the speed of the car.

Green fill indicates that a cell needs a measured input value.

Air Density (kg/m^3) = 1.18
Core Face Area (m^2) = 0.02903

Car Velocity (mph) = 20

	Horizontal Position		
Vertical Position	8	10	8
	8	10	8

Avg Velocity through Core (mph) = 8.6666667

Car Velocity (mph) = 30

	Horizontal Position		
Vertical Position	15	18	17
	19	17	17

Avg Velocity through Core (mph) = 17.166667

Car Velocity (mph) = 50

	Horizontal Position		
Vertical Position	26	28	27
	26	29	27

Avg Velocity through Core (mph) = 27.166667

Car Velocity (mph) = 60

	Horizontal Position		
Vertical Position	33	31	32
	30	31	32

Avg Velocity through Core (mph) = 31.5

Figure 62. *Screenshot of "Core Air Flow" spreadsheet from Excel program*

Instructions: Enter pitot-static tube measurements in the cells. Measurements should be taken in m/s. As described in the procedure, take an array of measurements. For the sake of consistency, the top left position in the table will correspond to the top left position as though you are looking down the ducting of the wind tunnel from its front. Enter the pressure differential reading from the liquid column manometer. This pressure differential has the units, inches of oil, where the oil has specific gravity = 0.826.

Green fill indicates that a cell needs a measured input value.

Air Density (kg/m^3) = 1.18
Core Face Area (m^2) = 0.01488
Manometer Oil Denisty (kg/m^3) = 826

	Horizontal Position				
Vertical Position	2.39	2.32	2.31	1.67	2.13
	2.48	2.08	2.09	2.51	2.22
	2.48	3.02	2.37	2.18	2.67
	2.81	2.43	2.91	2.32	3.06
	1.77	1.84	2.58	2.64	2.57

Average Velocity (m/s): 2.39
Differential Pressure (inOIL): 0.1

	Horizontal Position				
Vertical Position	3.79	3.99	3.42	3.24	2.28
	3.65	3.44	3.58	3.81	3.34
	4.25	3.77	3.84	4.21	3.83
	3.71	3.69	4.02	3.82	4.07
	3.11	3.85	4.75	3.23	4.1

Average Velocity (m/s): 3.71
Differential Pressure (inOIL): 0.19

	Horizontal Position				
Vertical Position	5.82	6.11	4.97	3.87	3.7
	5.14	5.52	5.53	6.1	5.48
	6.54	6.11	5.61	6.53	5.85
	6.12	5.45	6.96	5.69	5.58
	4.27	5.33	5.13	6.43	4.97

Average Velocity (m/s): 5.55
Differential Pressure (inOIL): 0.4

	Horizontal Position				
Vertical Position	6.49	7.27	6.14	5.04	4.57
	6.43	7.08	6.26	7.21	6.75
	7.31	8.02	7.12	7.87	7.48
	7.54	6.63	7.6	6.3	6.69
	5.64	7.43	6.14	7.61	5.65

Average Velocity (m/s): 6.73
Differential Pressure (inOIL): 0.53

Figure 63. *Screenshot of "Core Pressure Drop" spreadsheet from Excel program*

Instructions: Perform a test similar to the one performed when determining the mass flow rates of the water pump in the engine. Enter the bucket weight, length of the test, and then enter the weights of the water in the bucket. This weight will be the weight of the water and the weight of the bucket combined. Next you will choose 5 different speeds at which the wind tunnel fan will be run for 4 different mass flow rates. Mark these setting on the VFD knob so that you can use this speed at each of the 4 water flow rates. Record the height that the oil in the liquid column drops at each speed. Change the equation in the "Air Mass Flow Rate" colum to correspond to the relationship derived in Test 4 that will predict the air mass flow rate that results from a pressure drop in inches of oil. Run the test and record the temperatures into and out of the radiator in the appropriate boxes.

Green fill indicates that a cell needs a measured input value.

$T_{ambient}$ = 22˚C

Bucket Weight (kg) = 0.745
Test Time (s) = 20

Specific Heat of Water (kJ/kg*C) = 4.2

Pump Setting	Weight of Water + Bucket (kg)	Water Mass Flow Rate (kg/s)
Slow	4.105	0.168
Medium	4.885	0.207
Fast	5.345	0.23
Maximum	7.185	0.322

Water Mass Flow Rate (kg/s) = 0.168

Static Pressure Drop (inOIL)	Air Mass Flow Rate (kg/s)	Temp Into Radiator (C)	Temp Out of Radiator (C)	Temperature Drop (C)	Heat Rejection Rate (kW)
0.07	0.0336	83.9	81.4	2.5	1.76
0.21	0.0671	82.4	79.2	3.2	2.26
0.39	0.0991	82.5	78.8	3.7	2.61
0.65	0.1367	78.9	74.4	4.5	3.18
0.96	0.1748	80.6	76.2	4.4	3.10

Figure 64. *Screenshot of "Heat Rej. from Radiator" spreadsheet from Excel program*

Appendix I: Testing Flowchart

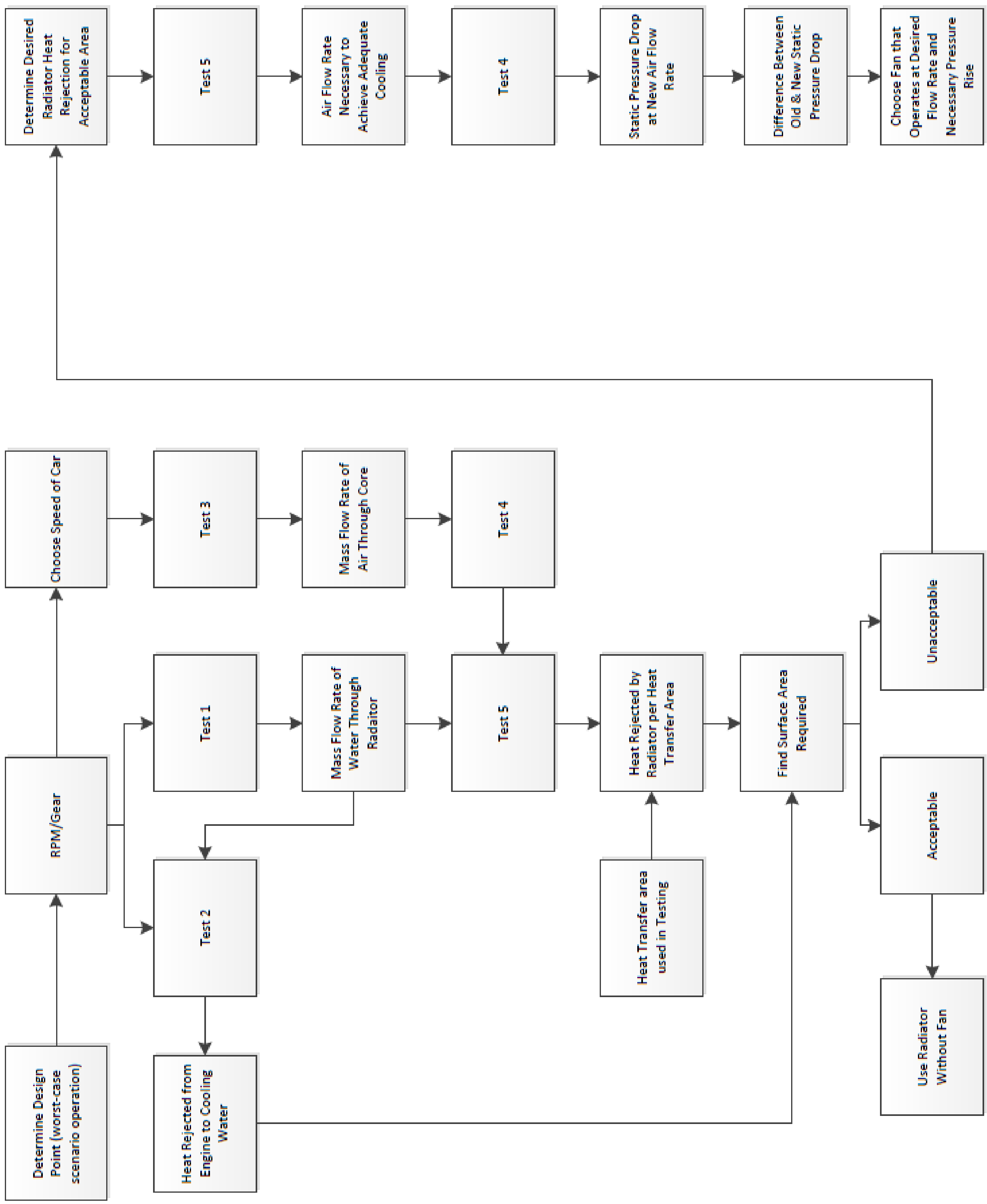

Figure 65. *Flowchart to guide user through application of test results*

Appendix J: References

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