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Thermal Resistance Test Station

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Abstract

Parker Hannifin’s Division of Cooling has requested the design of a test station to validate the thermal resistance performance of a combined cold plate-thermal interface material used in two-phase evaporative cooling applications. This test station should be more accurate than the testing system currently in place. The engineering design process for this project is divided into two semesters, where the design process performed during the first semester has already been outlined in the first report. The intent of this document is to illustrate the building, testing and analysis of the primary design chosen to best address the problem statement. This report outlines the completed design from last semester, the building process and design changes done prior to testing, all tests completed, and a full evaluation of the design. Based on the results and evaluations of the completed tests, the design meets all of the specified requirements from Parker Hannifin. Additionally, recommendations for a better design or changes that may be implemented in the future are also detailed in the report.
Section 1: Detailed Design Description
Section 1.1 Initial Design

Last semester it was agreed upon that the primary concepts would be sufficient to proceed with: the cart, ceramic heating element, direct temperature readings for configuration of instrumentation, the heating element and cold plate enclosure and the manually operated screw clamp. Once the design was approved, the team began detailing the process for the concepts chosen. The final assembly can be seen below in Figure 1. It should be noted that this assembly does not depict the configuration of instrumentation.
Section 1.2 Requirements and Specifications

Many of the products that Parker Hannifin manufactures aid in the cooling of electronic devices such as computer chips. Often cold plates are used as a heat sink in the cooling process of these electronic devices. In order to properly use these plates, Parker must know the thermal resistance of the plates and the thermal interface material. For this reason, the following requirements and specifications are crucial and will be used to judge the success of the design.

- The design must be able to determine the combined thermal resistance of the cold plate-thermal interface material system.
- The design must incorporate Parker’s existing data acquisition system.
- The test station must be easily moved around a lab.
- The thermal resistance measured results should be accurate within 10%.

Section 1.3 Parameters/Fixed Variables

Design parameters and fixed variables are established by Parker Hannifin to aid in the design and development of the mobile Thermal Resistance Test Station. These design constraints are not to be modified under any condition by the design team.

- Cold Plate Size – The size of the cold plate which is being measured for thermal resistance will be 2.5” x 3.5” x 0.3”.
- Heat Input – The heat input into the testing station may vary between 0 to 1,000 W.
- Thermal Interface Materials – The design must be built to accommodate any thermal interface materials used by Parker Hannifin.
- Force – The design must be able to mechanically apply a force of 500 lbs on the sample being tested.
- Data will be collected by Parker’s data acquisition system.

Section 1.4 Design Variables

The design variables are the qualitative values that can be altered within the project in order to meet the specifications. The best design to meet these variables will be chosen by the design team based on tradeoffs.

- Cart Material – Fabrication materials for the mobile test station cart shall be established by the design team.
• Heating Element Enclosure – Material selection for the heating element enclosure shall be determined by the design team.

• Heating Element Insulation – The insulating material utilized in the design of the heating element enclosure shall be selected by the design team.

• Force Applying Mechanism – The material for the force applying mechanism will be selected by the design team.

Section 1.5 Limitations and Constraints

Limitations and constraints must be taken into account to properly design a Thermal Resistance Test Station for Parker Hannifin. Limitations and constraints are anything that could potentially inhibit the system and must be properly accounted for in order to model the system correctly. Listed below are the parameters that are limiting factors.

• Test Station Size – In order for the unit to be mobile enough to move between testing locations it must meet the following size constraints:
  - Table top unit – 12” x 24” footprint, 45 lbs maximum
  - Rolling unit – 24” x 36” footprint, 38” table height

• Cost – Parker Hannifin will be funding this project and has set a final project cost of $5,000.

• Maximum Temperature Output – The design should have a maximum operating temperature of 80°C

Section 1.6 Additional Considerations

Additional considerations establish pertinent design intents that may not be portrayed in previous sections. These worthwhile considerations could enhance safety, versatility, and longevity of the test station, as well as present industry standard test methods and certifications. Although these design considerations are desirable, they are not contributing factors in assessing the success of the project.

• Safety – Comply with industry standards set forth by the Occupational Safety and Health association (OSHA) to diminish the opportunity for recordable injuries in the work environment. Incorporate maximum operating condition fail safe controls in the design.

• Standards – Comply with industry standards established by the American Society for Testing and Materials (ASTM) during material testing procedures.

• Sustainability – Comply with the Environmental Protection Agency in dealing with material design selection and methods of waste removal.
• Reparability – The unit should be completely repairable in the case of component failure.
• Cold Plate Sizes – The design may be adjustable to incorporate additional sizes of cold plates.
• Thermal Interface Application – The design may include an additional device for the consistent application of the thermal interface materials.

Section 1.7 Design Revisions

Upon completion of the final design, a few design changes needed to be made before moving onto the build process. This included mainly included changing the type of heaters being used as well as the data acquisition system. Changing the heaters affected the size of the copper plate as well as the opening for the copper plate within the insulated enclosure. Additionally, one of the machined insulated enclosures was modified to test the temperatures reached at each point of the outside of the enclosure to ensure that heat loss may be neglected.

Section 1.7.1 Heating Element Design Revision

Parker Hannifin suggested using several cartridge heaters as opposed to the ceramic heater in order to cut costs and still be compatible with the given power supply. Three power supplies each with 150 VDC and 10 A maximums were available to use to power the heaters. O.E.M. Heaters was chosen as the supplier since they provided heaters that could use either AC or DC power. Three 400 W heaters were purchased in order to meet the 1000 W maximum power input required by Parker Hannifin (six total were purchased, and three will be used at a time). These heaters are two inches long and have a 0.50 inch diameter. They also have a maximum voltage intake of 120 volts, but in order to promote a longer life for the heaters it is suggested that the voltage should not exceed 110-115 volts.

Figure 2: O.E.M. Heaters high watt density cartridge heaters
Two different configurations were used in order to make sure that the heaters did not exceed the voltage or current that could be supplied, one with the heaters connected in parallel to one power supply and another with each heater being connected to its own power supply.

By connecting the three heaters in parallel, one power supply could be used to power the heaters more efficiently. With this setup, each heater will have the same current and voltage and thus the same amount of power will be coming from each heater. However, this does not necessarily mean that each heater will be running at the same temperature due to an inconsistency in the size of the cold plate. This setup was originally done using a circuit board purchased from RadioShack. However, after a longer testing at an 800 watt output, some of the wires melted and the board was ruined. So, a larger wire gauge was used and the heater leads were then soldered together in parallel and a wire nut was placed on top to secure the connection. Below is a schematic of the heaters in the setup along with some of the equations used to determine the maximum voltage and current, and thus power, from each individual heater.

\[ Q = IV = I^2R \]  

Here, the maximum power is 400 watts, and voltage is 120 volts. This means that the maximum current that can be drawn from one heater is 3.33 amps. This can then be used to find the internal resistance of each heater, which results in 36 ohms. So, if the heaters are placed in parallel this means that each will have the same voltage drop across as well as current flowing through each branch since they have equivalent resistances. As was previously stated, for the heaters to have a longer life it is recommended that the current is not maximized, which requires keeping the voltage below 120 V. Running at a maximum of 110 V ensures that the current going through each heater is only 3.056 amps, so each heater is not running at full capacity. This also means that the total, idea power output is 1008 watts. Realistically, there will be some losses and so the actual wattage output will most likely be within the 1000 watt maximum as listed in the given limitations. Figure 3 shows a schematic of this setup using 110 V power supply, and Figure 4 shows the parallel set up using the circuit board.

![Figure 3: Parallel heater circuit design schematic](image-url)
Figure 4: Parallel heater design using circuit board

By connecting the heaters in series to an individual power supply, the heaters could be run more accurately. This allows the user to set the voltage and current of the power supply for each individual heater in order to maintain the desired wattage and temperature output at that given heater. The total wattage that is being supplied is then simply the sum of each heater’s individual power.

\[ Q_{total} = (IV)_{heater\ 1} + (IV)_{heater\ 2} + (IV)_{heater\ 3} \] (2)

Section 1.7.2 Configuration of Instrumentation Design Revision

It was also determined that creating a separate LabVIEW program for acquiring the data was unnecessary. It was possible for all data to be collected with the in-house program already in use, and then extracting the required measured values from the program and inputting them into an Excel spreadsheet. This spreadsheet calculates the amount of heat lost based on the temperatures on the outside of the enclosure, and the ambient temperature. Using the actual amount of heat that is going into the cold plate, the thermal resistance of the cold plate, the thermal interface material, and the cold plate-TIM combination is calculated. An example of this spreadsheet and the calculations for it may be found in the Appendix.

Furthermore, several more holes were drilled into the enclosure in order to account for any heat lost from every side of the enclosure. Originally, only eight ports for thermocouples were offered
by Parker Hannifin, but after further discussion a total of sixteen were offered. This allowed the team to drill holes in the front, bottom, one of the sides and halfway down the back of the enclosure to study the heat flow through the enclosure. The back thermocouples would be used to determine if the heat was flowing from the heaters through the insulation in an even manner. The remaining thermocouples on the outside of the enclosure were used to compare to the ambient temperature in order to calculate the amount of heat lost from the system. The original thermocouple placement still includes three across the top of the copper plate, one in the bottom of the cold plate, the top of the enclosure, one side, and the back of the enclosure. A visual of the placement of all of these holes can be seen in the following figures, and a detailed drawing of this can be found in the Appendix. Note that all of these holes were only drilled in one of the made enclosures in order to determine the amount of heat lost from the system. Once it has been determined that the heat loss is negligible, this enclosure does not necessarily have to be used every time.

In the figure below, the holes that are circled in red are the ones that were added manually at Parker Hannifin. Figures 6 and 7 show the actual enclosure with all of the thermocouples in place.

![Figure 5: Added holes for thermocouples in enclosure](image-url)
Figure 6: Back view of all thermocouples

Figure 7: Back and side view of all thermocouples in place
The size of the thermocouple also varied for each location. The thermocouple used for the cold plate has a 0.02” diameter as designated by Parker Hannifin. To have the least invasive type of design as possible, the thermocouples used across the copper plate have a 0.04” diameter. Since drilling near the edges of the calcium silicate enclosure proved difficult, a larger diameter was chosen for these. The sixteenth inch drill bit was used for the additional holes, and three purchased thermocouples with a 0.0625” diameter were used for the top and sides of the enclosure. Four thermocouples were made at Parker Hannifin and tested by placing them in boiling water and comparing them to the purchased thermocouples to ensure accuracy. These thermocouples were small enough to fit into the drilled holes at a tight tolerance.

Section 1.7.3 Heating Element and Cold Plate-Thermal Interface Material Enclosure Design Revision

In order for the new heaters to be put in place, the copper plate also had to be adjusted. Parker also expressed concerns about the ceramic heaters not being able to withstand the 500 pound force being applied to the set up. The new cartridge heaters require being enclosed within a stronger material so that the heaters are not damaged. So, the dimensions of the copper plate were made larger so that the heaters could be placed into the copper plate at a tight tolerance and disperse the heat. The new copper plate dimensions are 2.36” x 2.15” x 0.88”. The three holes are drilled 2” deep with a 0.5” diameter and a distance of 0.33” in between each heater. Three thermocouples will still be placed across the top of the copper plate to ensure that the cold plate is being evenly heated. Figure 8 is a back view of the new copper plate design with drilled holes for the placement of the cartridge heaters.

So the new copper plate could properly fit into the enclosure, the center opening for the placement of the enclosure also had to be modified. This part of the enclosure’s new dimensions are 2.45” x 2.25” x 0.865” with corner radii of 0.863”.
An additional removable piece was added to the back of the design so that the leads from the heaters could fit through the back of the enclosure and reach the power supply while still insulating as much of the system as possible. The dimensions of this piece are 2.15” x 0.7” x 0.5” with 0.125” corner radii and a hole cut out from the center with a 0.375” diameter.

The material of the enclosure was also modified to a stronger version of calcium silicate known as Super FireTemp “Type L” calcium silicate and ordered from Industrial Insulation Group LLC, and manufactured by Basic Resources Inc. A second enclosure made of wear resistant, easy to machine cast nylon with less ideal thermal properties was also constructed for testing in case of any complications with the calcium silicate. This plastic enclosure was machined by Parker Hannifin. All detailed drawings for the copper plate and enclosure may be found in the Appendix.
Section 1.7 Final Design

After all modifications have been taken into consideration, the final design includes three cartridge heaters, a slightly larger copper plate, modified enclosure, and added thermocouples for more accurate heat loss calculations. Additionally, the data acquisition has been simplified to an Excel spreadsheet that will input all necessary measurements and calculate the thermal resistance of the cold plate and thermal interface material system. Below includes a picture of the final cart assembly, as well as the final assembly with the cold plate and enclosure set in place.

Figure 11: Final assembly of the cart and attached screw jack
Figure 12: Final configuration of enclosure with thermocouples in place, refrigerant connections, and force being applied
Section 2: Building Process
Section 2.1 Building Process

Step one in the building process is erecting the mobile cart frame. The framing members are constructed from IPS, an extruded aluminum profile system manufactured by Parker Hannifin. Framing members were fabricated and installed by employees of Parker per the fabrication drawings furnished by the design team provided in Appendix A. The stainless counter top is then secured in place at each corner of the frame by specially designed t-nuts and screws used in the extruded profile.

Step two is to assemble components of the manually operated screw jack then position and secure it into place. A male-female threaded adaptor was screwed to the leading end of the ACME screw followed by a rotating flange nut, both secured with Loctite adhesives to prevent backing out. Finally the jack is positioned between two horizontal members running parallel to each other at the top of the cart and secured with two t-nut and screw combinations. Figure 13 shows the assembled cart frame with quarter inch thick stainless steel countertop, lockable caster wheels for mobilization, and installed screw jack.

Figure 13: Final assembled cart
Step three involves the assembly of the refrigerant piping and hoses that connect the thermal resistance test bench with Parker’s test bench refrigerant loop. Brass flare fittings and 0.25”O.D. copper tubing connections were fabricated and brazed to the cold plate by employees of Parker per the fabrication drawings furnished by the design team provided in Appendix X. Figure 14 shows 0.375” diameter hoses connected to the inlet (left) and outlet(right) of the cold plate. On either side of the inlet or outlet tubing to the cold plate a flow through manifold with three additional ports was used for measuring pressure and temperature of the system. A flare fitting was fitted to one of the three ports that have additional hose connecting to Parkers work bench pressure transmitters. The second port was plugged for future use while the third port housed the thermocouple to measure inlet and outlet temperatures. Figure 15 shows a typical arrangement of connections to the mono block.

![Figure 14: Refrigerant connections to cold plate](image1)

![Figure 15: Thermocouples and pressure port on the mono block](image2)

The last step in the building process deals mainly with electrical components. The cartridge style heating elements were wired individually by soldering extended lead wires from each heater to a L6-30P twist lock plug that are connected directly to Parker’s test bench. As previously mentioned this allows for variable voltage and current inputs to each heater through the use of individual direct current power supplies. The load cell was powered by an additional 5Vdc power supply provided by Parker. A multi meter was then connected to the output of the load cell to measure mV DC that was used to determine the applied force equivalent. Several thermal couples were inserted into various parts of the insulation enclosure, copper block, and cold plate and connected to the test bench through the internal DAQ.
Section 2.2 Difficulties

The first issue encountered was the configuration and location of the countertop center frame member. Due to changes in the perimeter countertop member the inner support was unable to align with the top of the members supporting the counter. The issue was resolved by adding an additional member and orienting them vertically to be flush with the perimeter members. Figure 16 provides a side-by-side comparison of the issue.

Figure 16: Comparison of the original and modified cart to solve the countertop issue

Section 2.3 Completed Build

The fabrication and assembly of the thermal resistance test station was primarily performed by members on the team with the assistance of employees at Parker Hannifin who completed the initial assembly of the cart. Although assembly was performed in two days at the New Haven Parker Hannifin facility, additional changes were implemented throughout several weeks as testing was conducted. Figure 17 shows the completed test station as intended for testing. Additionally, an operation manual has been included in Appendix C which describes the full set up for the testing procedure.
Section 2.4 Budget

Laboratory Equipment
Laboratory equipment utilized during this build were components like; Parker Hannifin’s test bench, power supplies, digital multi meter, Yellow Jacket refrigerant hose, brass hose fittings, miscellaneous wires and connectors. These components had no cost impact on the build budget but were required to complete the build.

Standard Parts
Standards parts were components of the system that were supplied directly from various manufacturers that require minimal to no customization.

Fabrication
Cart materials were selected from the vast line of Parker Hannifin’s IPS products and will be constructed by employees at the New Haven facility. Resources from the IPFW Department of Engineering were utilized to fabricate the force distribution plate machined from raw metal materials. Additional machining was performed by Lomar Machine Co. for the copper plate that housed the heaters, while Stamets Tool and Engineering Inc. performed machining on the torsion plate and countertop. CNC machining of the Type ‘L’ calcium silicate material for the enclosure was performed at Basic Resources Inc. based in Humboldt Tennessee.

Overall Cost
The final build cost to create and assemble the Thermal Resistance Test Station was $4,439.82 which was $894.84 over the projected cost from fall semester. The final cost is still under the $5,000 budget set by Parker by $560.18. Table 1 provides a breakdown for cost of each subsystem of the design. Table 1 located in Appendix C gives a detailed list of part descriptions, manufacturers, suppliers, part numbers, cost and quantity for the Thermal Resistance Test Station.
Table 1: Final Budget per Item

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating Element</td>
<td>$241.74</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>$548.60</td>
</tr>
<tr>
<td>Enclosure</td>
<td>$1,603.54</td>
</tr>
<tr>
<td>Clamping Mechanism</td>
<td>$1,096.32</td>
</tr>
<tr>
<td>Mobilization System</td>
<td>$949.62</td>
</tr>
<tr>
<td><strong>Total Build Cost:</strong></td>
<td><strong>$4,439.82</strong></td>
</tr>
</tbody>
</table>
Section 3: Testing
Section 3.1 Testing Overview

The thermal resistance test station was used to test the cold plate provided by Parker. As stated in the design requirements, the test station must be able to determine the combined thermal resistance of the cold plate-thermal interface material system with an accuracy of 10% or better.

Section 3.2 Testing Performed

In order to ensure the data being collected was consistent and accurate, the tests listed below were conducted along with comparisons to previous test data from Parker.

- **Steady State Test:** The steady state test was performed on the cold plate provided by Parker with at heat loads of 500 W and 800 W with an applied force of 533 lbs for two hours in order to determine a reasonable wait time before being able to record values at steady state with confidence. As it can be seen in Figure 18, the temperature across the copper plate as well as the cold plate and the fluid in settles after approximately 20 minutes on the test with the 500 W heat load.

![Steady State Test for 500 W](image)

Figure 18: The temperature across the copper plate, along with the temperature of the cold plate and the fluid in, is plotted versus time to show the amount of time that is required for the system to reach steady state.

Figure 19 shows the temperatures of the cold plate, fluid in and across the copper plate settle after 10 minutes.
Figure 19: The temperature across the copper plate, along with the temperature of the cold plate and the fluid in, is plotted versus time to show the amount of time that is required for the system to reach steady state.

- **Repeatability Test:** A tests were conducted to ensure that similar results are able to be attained consistently under the same testing conditions in order to demonstrate consistency in the test station. Two separate tests were conducted on the cold plate. The tests shown for comparison in Table 3 had a heat load of 800 W and an applied force of approximately 493 lbs. The tests that were conducted were set up to run with the most conditions that were able to be replicated. Both tests had heat inputs, fluid temperatures, flow rates and forces applied as close as possible in order to demonstrate repeatable results. Table 3 shows the thermal resistance of the Cold Plate-TIM is well within the 10% uncertainty value that was calculated in the uncertainty analysis.

**Table 2:** Comparison of separate 800 W tests conducted.

<table>
<thead>
<tr>
<th>Test Date</th>
<th>4/12/2014</th>
<th>04/25/14</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Input to Cold Plate (W)</td>
<td>800</td>
<td>800</td>
<td></td>
</tr>
<tr>
<td>Fluid Flow Rate (gph)</td>
<td>10.20</td>
<td>10.20</td>
<td></td>
</tr>
<tr>
<td>Fluid In (°C)</td>
<td>35.03</td>
<td>34.06</td>
<td>2.85%</td>
</tr>
<tr>
<td>Fluid Out (°C)</td>
<td>41.41</td>
<td>41.16</td>
<td>0.61%</td>
</tr>
<tr>
<td>Cold Plate (°C)</td>
<td>53.74</td>
<td>53.52</td>
<td>0.41%</td>
</tr>
<tr>
<td>Copper Plate (TC-1) (°C)</td>
<td>76.05</td>
<td>75.21</td>
<td>1.12%</td>
</tr>
<tr>
<td>Copper Plate (TC-2) (°C)</td>
<td>75.90</td>
<td>76.24</td>
<td>0.45%</td>
</tr>
<tr>
<td>Copper Plate (TC-3) (°C)</td>
<td>75.71</td>
<td>76.68</td>
<td>1.26%</td>
</tr>
<tr>
<td>Force Applied to Cold Plate (lbs)</td>
<td>493.33</td>
<td>493.33</td>
<td></td>
</tr>
</tbody>
</table>
• **Uncertainty Analysis:** To ensure the data being collected had an accuracy of 10% or better an uncertainty analysis was derived for the different components of the test station that collect data vital to the calculation of the thermal resistance of the cold plate-thermal interface material. The uncertainty of the thermal resistance was calculated using Equation 3.

\[
\begin{align*}
\text{Uncertainty of} & \quad \text{Cold Plate-TIM} \\
\text{Thermal Resistance} & \quad u_R = \sqrt{(u_p)^2 + \left(\frac{T_1}{(T_1 - T_2)}u_{T_1}\right)^2 + \left(\frac{T_2}{(T_1 - T_2)}u_{T_2}\right)^2}
\end{align*}
\]

Table 2 displays the uncertainty of each test, respectively. The uncertainty of the thermal resistance was calculated to be less than 10% for all of the tests that were conducted. Because tests with lower heat loads tend to have smaller temperature differences their uncertainty values will be among the highest, nearing 10%. Therefore it can be stated that the accuracy of the thermal resistance of the Cold Plate-TIM is within 10%.

**Table 3:** The uncertainty of the thermal resistance for each tests displayed.

<table>
<thead>
<tr>
<th>Heat Load (W)</th>
<th>Quality (%)</th>
<th>Thermal Resistance (°C/W)</th>
<th>(u_R) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>35</td>
<td>0.0498</td>
<td>8.17%</td>
</tr>
<tr>
<td>200</td>
<td>70</td>
<td>0.0511</td>
<td>7.89%</td>
</tr>
<tr>
<td>500</td>
<td>35</td>
<td>0.0516</td>
<td>4.75%</td>
</tr>
<tr>
<td>500</td>
<td>70</td>
<td>0.0516</td>
<td>4.16%</td>
</tr>
<tr>
<td>800</td>
<td>35</td>
<td>0.0513</td>
<td>3.48%</td>
</tr>
<tr>
<td>800</td>
<td>70</td>
<td>0.0512</td>
<td>3.00%</td>
</tr>
<tr>
<td>1000</td>
<td>35</td>
<td>0.0509</td>
<td>3.18%</td>
</tr>
<tr>
<td>1000</td>
<td>70</td>
<td>0.0508</td>
<td>2.88%</td>
</tr>
</tbody>
</table>

• **Comparison to Parker Test Data:** Data for cold plate tests at 500 W with qualities at 35% and 70% was compared to data obtained with the thermal resistance test station at 500 W with qualities also at 35% and 70%. When Parker’s test data was compared to the data obtained using the thermal resistance test station there was an average difference of 13.7% between the 35% quality tests and a 12.8% difference between the 70% quality tests.

• **Comparison to Analytical Model:** A comparison was also made to an analytical model based on the research published in the article, “Two-Phase Liquid Cooling for Thermal Management of IGBT Power Electronic Module.” The main components for the thermal model include the temperature of the heat sink, pressure of the fluid at the inlet, and several other liquid and vapor properties. Most of these properties are dependent on the temperature and pressure of the system and so will change with every test. This thermal model creates a convective heat transfer coefficient based on the two phase refrigerant flow. This resistance is calculated by taking the inverse of the convective area through
the fins of the heat sink and multiplying it by the heat two phase heat transfer coefficient. Again, a detailed view of the equations used can be found in the article listed above.

As is noted in the paper, this analytical model does state that there is a 20% error in calculating the heat transfer coefficient when compared to other available data. Overall the comparison was favorable to some of the tests conducted, namely those where the quality of the test was 35%. When the quality of the refrigerant was greater than 35%, the analytical model data varied from the measured cold plate thermal resistance by 50% or more. Table 4 shows the differences in the analytical model used and the measured thermal resistances of the cold plate for the various tests conducted. Overall, the results seem more favorable with the lower qualities meaning that the model is more useful when it is closer to being a single phase fluid. Further studying of the analytical process is required to confirm the accuracy of the model.

**Table 4: Comparison of Analytical Model with Test Station Cold Plate Resistances**

<table>
<thead>
<tr>
<th>Test</th>
<th>Test Parameters</th>
<th>Thermal Model Resistance (K/W)</th>
<th>Measured Thermal Resistance (K/W)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200 W x = 0.35</td>
<td>0.0874</td>
<td>0.086</td>
<td>1.63</td>
</tr>
<tr>
<td>2</td>
<td>200 W x = 0.7</td>
<td>0.0367</td>
<td>0.089</td>
<td>58.76</td>
</tr>
<tr>
<td>3</td>
<td>500 W x = 0.35</td>
<td>0.0559</td>
<td>0.0597</td>
<td>6.37</td>
</tr>
<tr>
<td>4</td>
<td>500 W x = 0.7</td>
<td>0.0228</td>
<td>0.068</td>
<td>66.47</td>
</tr>
<tr>
<td>5</td>
<td>800 W x = 0.35</td>
<td>0.0451</td>
<td>0.051</td>
<td>11.57</td>
</tr>
<tr>
<td>6</td>
<td>800 W x = 0.5</td>
<td>0.0318</td>
<td>0.053</td>
<td>40.00</td>
</tr>
<tr>
<td>7</td>
<td>800 W x = 0.7</td>
<td>0.0187</td>
<td>0.059</td>
<td>68.31</td>
</tr>
</tbody>
</table>
Section 4: Evaluations and Recommendations
Section 4.1 Analysis of Data

Additional tests were conducted to confirm that the trends created by the new data from the thermal resistance test station were correct.

- **Effects of Increasing the Applied Force:** Two separate tests were conducted with an applied heat load of 800 W, each set to a fixed refrigerant quality of 35% and 70%. A force was then applied to the cold plate to increase contact area between the copper plate and the thermal interface material (TIM) and also the TIM and the cold plate, thus reducing the contact resistance between them. As Figure 19 shows, as the applied force increases the thermal resistance of the TIM decreases.

![Thermal Resistance vs Applied Force with 800 W Heat Load](image)

Figure 20: This figure shows the relationship between the contact resistance and the amount of force applied between the surfaces.

- **Thermal Resistance of Cold Plate-TIM:** Several tests were conducted to show different relationships of thermal resistance of the cold plate, TIM, and the combination of the cold plate-TIM. Figure 20 shows the thermal resistance of the cold plate and the cold plate-TIM combination decreasing as the heat load increases while the refrigerant is at a fixed flow rate of 5.4 gph. The thermal resistance of the cold plate and cold plate-TIM is decreasing as the quality of the fluid mixture is increasing along with the heat load. The thermal resistance of the TIM remains relatively constant throughout the test.
Figure 21: This figure shows the thermal resistance of the TIM, cold plate and cold plate-TIM as the heat load increases while the refrigerant flow rate is constant at 5.4 gph.

The focus of the previous test was to show the effects of a constant flow rate through the cold plate on the thermal resistance of the cold plate as the heat load increased. The following test was focused to show the effect of constant quality in the cold plate as the heat load increased. Figure 21 shows how the thermal resistance of the cold plate-TIM decreases for both 35% and 70% qualities in a similar manner as the heat load increases. The thermal resistance of the TIM remains relatively constant as it did in the previous test with constant flow rate. The thermal resistance of the TIM only varied with the variation of the applied force.

Section 4.2 Recommendations

After completion and evaluation of the test results, the design team would like to recommend a few changes to the test station and data collection. The first recommendation is to neglect heat loss. The results presented above accounted for the heat lost to the ambient air. The percent heat loss is most at lower heat settings and is never more than .2%. It is with this the design team recommends that the heat lost be neglected to simplify the calculations of thermal resistance. The second recommendation is that a more accurate readout be provided for the load. The multi-meter used to show the mili-volts that would be converted to the load was only accurate to a tenth of a mili-volt. This lead to a 13 pound uncertainty and a readout that would read more accurately would decrease the uncertainty of the load applied to the cold plate. The third and final recommendation the design team suggests is implementing means of measuring the thickness of the Thermal Interface Material. By being able to measure the thickness of Thermal Interface Material to some degree of uncertainty would allow for the operator to calculate what the thermal resistance across the thermal interface material is and compare it to the
manufacturer’s published values. This, assuming that the thermal interface material has microscopic air bubbles, would also allow for the effect that the air bubbles have on the result.
Conclusions

After building the thermal resistance test station, testing the combination of cold plate and thermal interface material and the evaluation of the test data the design team has successfully meet all of the following requirements, limitations and constraints:

- **Requirements**
  - Determining the thermal resistance of the cold plate-thermal interface material combination
  - Incorporating the existing data acquisition system currently used by Parker
  - Making the thermal resistance test station mobile
  - The test station is able to output up to 1000 W of heat
  - A load of up to 500 lbf can be applied to the cold plate
  - Various types of thermal interface materials can be used during testing

- **Limitations and Constraints**
  - Maximum temperature of 80 °C across the copper plate
    - The maximum temperature across the copper plate can be maintained below 80 °C. The temperature across the copper plate is dependent upon the temperature and flow rate across the cold plate as well as the force applied on the cold plate.
  - The total cost of the test station came in at $4439.82, below the project budget of $5000
  - The maximum footprint of the test station is 24” x 36” and the table height is 38”, which is the same as the size constraints set by Parker
References


Appendix A: Detailed Drawings

Detailed Drawings
The following pages contain all of the detailed design drawings for parts that must be fabricated.
Copper Plate

Dimensions are in inches.
Tolerances:
- Angular: ±0.001
- Linear: ±1.18

Material: Copper C110
Finish: As Per

Weights:
- Length: 2.15" (54.61 cm)
- Width: 2.36" (59.94 cm)

Tolerances:
- Two Place Decimal
- Three Place Decimal
- Interpreted Geometrically

Not to Scale Drawing

Comments:
- UNLESS OTHERWISE SPECIFIED:
- SCALE NTS
- REPRODUCTION IN PART OR AS A WHOLE PROHIBITED.
- PROPRIETARY AND CONFIDENTIAL
- NEXT ASSY USED ON <INSERT COMPANY NAME HERE>.
- ANY <INSERT COMPANY NAME HERE> IS REVDRAWING IS THE SOLE PROPERTY OF
- THE INFORMATION CONTAINED IN THIS SHEET 1 OF 1

<table>
<thead>
<tr>
<th>UNLESS OTHERWISE SPECIFIED</th>
<th>NAME</th>
<th>DATE</th>
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</thead>
<tbody>
<tr>
<td>DRAWN</td>
<td>CHECKED</td>
<td></td>
</tr>
<tr>
<td>ENG APPR.</td>
<td>MFG APPR.</td>
<td></td>
</tr>
<tr>
<td>Q.A.</td>
<td>CONCLUDING</td>
<td></td>
</tr>
</tbody>
</table>

Title: Copper C110
Removable Insulation Piece

Dimensions are in inches. Tolerances: Angular — ±0.01, Linear ±0.005, Surface Finish: Calcium Silicate

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- Reproduction in part or as a whole prohibited.
- Proprietary and Confidential
- The information contained in this drawing is the sole property of the manufacturer. Reproduction in part or as a whole without the written permission of the manufacturer is prohibited.

Material: Calcium Silicate

Application: Removable Insulation Piece

NOTES:

- Thru All

- Dimensions are in inches. Tolerances: Angular — ±0.01, Linear ±0.005, Surface Finish: Calcium Silicate

Title: Removable Insulation Piece

Title: Removable Insulation Piece

Scale: 1/27/14

Drawing Date: 1/27/14

Drawn By: M. Flenniken

The information contained in this drawing is the sole property of the manufacturer. Reproduction in part or as a whole without the written permission of the manufacturer is prohibited.

Dimensions are in inches. Tolerances: Angular — ±0.01, Linear ±0.005, Surface Finish: Calcium Silicate

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Appendix B: Operation Manual

Preparing the Apparatus

Before preparing the apparatus, be sure that all of the components have been obtained. Table 1 lists out the equipment you will need to prepare the apparatus.

Table 1: List of Items Needed to Prepare the Apparatus

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machined Insulation Box</td>
<td>1</td>
</tr>
<tr>
<td>Resistance Heaters with separate power connectors</td>
<td>3</td>
</tr>
<tr>
<td>Machined Copper Plate</td>
<td>1</td>
</tr>
<tr>
<td>Thermal Grease</td>
<td>As Needed</td>
</tr>
<tr>
<td>Machined Cold Plate</td>
<td>1</td>
</tr>
<tr>
<td>Machined Distribution Plate</td>
<td>1</td>
</tr>
<tr>
<td>Machined Torsion Plate</td>
<td>1</td>
</tr>
<tr>
<td>Load Cell</td>
<td>1</td>
</tr>
</tbody>
</table>

Installing the Heaters

1. Obtain the thermal grease and apply to the resistance heaters indicated in Figure 1. The fit for the resistance heaters is tight so any excess thermal grease will be pushed out so only a small amount of thermal grease is needed to reduce mess and clean up.

![Figure 1: Applying the thermal grease to the heaters](image)

2. Apply thermal grease to inside of copper plate’s machined holes. Insert each heater into the machined holes of the copper plate and twist to grease the inside of the copper plate to ensure a uniform layer and then remove. The
thermal grease will provide a layer between the heater and the surface of the copper plate to keep air from insulating the heaters and restricting heat flow.

3. Place the Copper Plate into the slot for the insulation. 
   It is important that the copper plate be placed with the machined holes for the thermocouples on top of the holes for the resistance heaters and pointed toward the back of the insulation block, otherwise the heaters and thermocouples will not fit.

4. Place Heaters into copper plate through the hole in the back of the insulation as seen in Figure 2. 
   Make sure the heaters are pushed in all the way by using a screwdriver or something similar to push the heaters in.

![Figure 2: Inserting the cartridge heaters into the copper plate](image)

**Installing the Cold Plate**

The cold plate will be placed on the copper plate with a thin layer of thermal grease to eliminate air pockets between the pieces. In order to obtain accurate readings, the thermal grease applied to the copper plate must be uniform.

1. Obtain scotch tape and apply to edge of copper plate. See Figure 3.

   Scotch tape applied to the edge of the copper plate provides a uniform height to ensure uniform coverage of the thermal grease. It is recommended that three layers of tape be applied to provide enough grease to guarantee that the air pockets are eliminated.
Figure 3: Placing the tape onto the copper plate

2. Apply thermal grease to top surface of copper plate.
   Apply thermal grease directly to the top surface of the copper plate. Using a putty knife, spread thermal grease around, applying more if necessary. Make sure that the entire surface of the copper plate is covered.

3. Scrape off excess thermal grease and remove tape. Figures 4 shows scraping the excess grease off and Figure 5 shows what the copper plate should look like when the tape is removed.
   Once thermal grease covers open surface of the copper plate, scrape off excess grease with the putty knife. The raised height of the tape will keep from taking all of the thermal grease off.
4. Place cold plate on copper plate and thermal grease.
   In order to obtain accurate results the bottom surface of the cold plate must be in line with copper plate. This can be done by placing the back of the cold plate against the insulation.

5. Place top insulation pieces, distribution plate, load cell and torsion plate.
The insulation pieces are required to reduce the heat loss to ambient and the distribution plate is required to protect the insulation. Without the distribution plate, the force applied could damage the insulation. The torsion plate must be applied to keep the load cell from rotating while the force is applied.

**Installing the Thermocouples**

Be sure that all thermocouples are available and obtained. Figures 6 and 7 shows the insulation and the sizes of thermocouples required for each hole location. Table 2 shows the list of required thermocouples, as well as the location in the system. It is strongly recommended that each thermocouple be labeled to ensure the correct temperature is captured.

**Table 2: List of Thermocouples Used**

<table>
<thead>
<tr>
<th>Thermocouple Type/Size (in)</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchased, 0.02</td>
<td>Bottom of Cold Plate</td>
</tr>
<tr>
<td>Purchased, 0.04</td>
<td>Top of Copper Plate</td>
</tr>
<tr>
<td>Purchased, 0.04</td>
<td>Top of Copper Plate</td>
</tr>
<tr>
<td>Purchased, 0.04</td>
<td>Top of Copper Plate</td>
</tr>
<tr>
<td>Purchased, 0.0625</td>
<td>Top of Enclosure</td>
</tr>
<tr>
<td>Purchased, 0.0625</td>
<td>Left Side of Enclosure</td>
</tr>
<tr>
<td>Purchased, 0.0625</td>
<td>Right Side of Enclosure</td>
</tr>
<tr>
<td>Made, approx. 0.125</td>
<td>Front of Enclosure</td>
</tr>
<tr>
<td>Made, approx. 0.125</td>
<td>Back of Enclosure</td>
</tr>
<tr>
<td>Made, approx. 0.125</td>
<td>Bottom of Enclosure</td>
</tr>
<tr>
<td>Made, approx. 0.125</td>
<td>Center of Enclosure</td>
</tr>
</tbody>
</table>
1. Apply thermal grease to thermocouples being placed in the copper plate and cold plate and install.
   This again does not require a large amount of grease as the fit is tight and will cause excessive squeeze out. The thermal grease will again provide a layer between the thermocouple and the surface of the copper plate to keep air from insulating the thermocouples and tainting the readings. The thermocouples used are small and excessive force while installing them could damage them and affect the readings. Take caution when installing these thermocouples.
2. Install all other thermocouples into machined insulation holes. These thermocouples can be ordered thermocouples or thermocouples made by hand. Caution should be taken again with these thermocouples so as to not damage the thermocouples or the insulation when installing them.

**Connecting the Apparatus to the Refrigeration Cycle**

All connections and hoses will be DASH-4 unless otherwise noted. Be sure, before connecting the apparatus to the cycle, that none of the connections have Schrader valves in them as these valves cause inconsistencies in the pressure of the fluid. At this time no thermocouples or heaters should be connected to readers or power.

1. Connect one end of two hoses to the inlet and outlet of the cold plate and connect the other ends to a copper block. See Figures 8 and 9. This copper block will be responsible for taking temperature and pressure readings of the inlet and outlet flow.

![Figure 8: Connections to the cold plate](image)

2. Connect two more hoses to the top of the copper blocks, one on each and connect the other ends to the refrigeration table as seen in Figures 9 and 10. These will be connected to the refrigeration cycle table to measure the pressure of the flow in and out of the cold plate.
3. Connect two in-line thermocouples to the top of the copper blocks, one on each. See Figure 10. These will be used to measure the temperature of the flow in and out of the cold plate.

4. Connect one end of another hose to the empty end of the copper block on the inlet side. See Figure 10. This will serve as the connection from the table to the apparatus.

5. Connect one end of a DASH-6 hose to the empty end of copper block on the outlet side. See Figure 10.

6. Connect the remaining free ends to the refrigeration table as seen in Figure 11.
Connecting the Load Cell and Running Test

1. Connect the black and red colored wires of the load cell to the respective black and red ports on the power supply. Set the Power supply to supply 5V and 1A.

2. Connect the white and the green colored wires to the red and black ports on the multi meter. The multi meter should be set to read millivolts. The Load Cell is calibrated so that 7.5mV is 1000 Lbs.

3. Plug each heater into the ports on the refrigeration table shown in Figure 12, crank the press so that the desired reading is displayed on the multi meter and begin testing.
Cartridge Heater Power Supply

Figure 12: Power supply ports for cartridge heaters
<table>
<thead>
<tr>
<th>Part Description</th>
<th>Manufacturer</th>
<th>Supplier</th>
<th>Part Number(s)</th>
<th>Cost</th>
<th>Quantity</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless Plate 304</td>
<td>Stamets</td>
<td>Stamets</td>
<td>1-M-F13-1</td>
<td>$516.00</td>
<td>1</td>
<td>$516.00</td>
</tr>
<tr>
<td>Extruded Aluminum 40mm x 40mm x 21*</td>
<td>Parker</td>
<td>Parker</td>
<td>10-040</td>
<td>$5.13</td>
<td>8</td>
<td>$41.04</td>
</tr>
<tr>
<td>Extruded Aluminum 40mm x 40mm x 50*</td>
<td>Parker</td>
<td>Parker</td>
<td>10-040</td>
<td>$12.22</td>
<td>4</td>
<td>$48.88</td>
</tr>
<tr>
<td>Extruded Aluminum 40mm x 80mm x 21*</td>
<td>Parker</td>
<td>Parker</td>
<td>10-080</td>
<td>$9.67</td>
<td>6</td>
<td>$58.02</td>
</tr>
<tr>
<td>1.5&quot; Gusset Bracket, Aluminum</td>
<td>Parker</td>
<td>Parker</td>
<td>20-440</td>
<td>$4.70</td>
<td>20</td>
<td>$94.00</td>
</tr>
<tr>
<td>3.0&quot; Economy Gusset Bracket Aluminum</td>
<td>Parker</td>
<td>Parker</td>
<td>28-608</td>
<td>$6.94</td>
<td>2</td>
<td>$13.88</td>
</tr>
<tr>
<td>0.625&quot; 5/16-18 Button Head Screw</td>
<td>Parker</td>
<td>Parker</td>
<td>25-110-5</td>
<td>$-</td>
<td>30</td>
<td>$-</td>
</tr>
<tr>
<td>0.750&quot; 5/16-18 Button Head Screw</td>
<td>Parker</td>
<td>Parker</td>
<td>25-112-5</td>
<td>$-</td>
<td>80</td>
<td>$-</td>
</tr>
<tr>
<td>0.875&quot; 5/16-18 Button Head Screw</td>
<td>Parker</td>
<td>Parker</td>
<td>25-114-5</td>
<td>$-</td>
<td>8</td>
<td>$-</td>
</tr>
<tr>
<td>2.0&quot; Dia. Rubber Caster Black, Non-marking</td>
<td>Parker</td>
<td>Parker</td>
<td>21-301</td>
<td>$4.85</td>
<td>4</td>
<td>$19.40</td>
</tr>
<tr>
<td>1.5&quot; Profile End Cap Glass-filled Nylon, Black</td>
<td>Parker</td>
<td>Parker</td>
<td>18-913</td>
<td>$0.34</td>
<td>4</td>
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</tr>
<tr>
<td>40mm T Joining Plate Anodized Aluminum</td>
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<td>$8.72</td>
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<td>Parker</td>
<td>20-307</td>
<td>$8.33</td>
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<td>$16.66</td>
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<td>5/16-18 Standard T-Nut, Steel</td>
<td>Parker</td>
<td>Parker</td>
<td>25-002</td>
<td>$0.90</td>
<td>10</td>
<td>$9.00</td>
</tr>
<tr>
<td>5/16-18 Double T-Nut, Steel</td>
<td>Parker</td>
<td>Parker</td>
<td>25-041</td>
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<td>64</td>
<td>$115.20</td>
</tr>
<tr>
<td>0.625&quot; 5/16-18 Button Head Screw</td>
<td>Parker</td>
<td>Parker</td>
<td>25-110-5</td>
<td>$-</td>
<td>30</td>
<td>$-</td>
</tr>
<tr>
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<td>$-</td>
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<td>$-</td>
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<td>Parker</td>
<td>25-114-5</td>
<td>$-</td>
<td>8</td>
<td>$-</td>
</tr>
<tr>
<td>2.0&quot; Dia. Rubber Caster Black, Non-marking</td>
<td>Parker</td>
<td>Parker</td>
<td>21-301</td>
<td>$4.85</td>
<td>4</td>
<td>$19.40</td>
</tr>
<tr>
<td>1.5&quot; Profile End Cap Glass-filled Nylon, Black</td>
<td>Parker</td>
<td>Parker</td>
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<td>4</td>
<td>$1.36</td>
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<tr>
<td>40mm T Joining Plate Anodized Aluminum</td>
<td>Parker</td>
<td>Parker</td>
<td>20-110</td>
<td>$4.36</td>
<td>2</td>
<td>$8.72</td>
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<tr>
<td>3&quot; T Joining Plate Anodized Aluminum</td>
<td>Parker</td>
<td>Parker</td>
<td>20-307</td>
<td>$8.33</td>
<td>2</td>
<td>$16.66</td>
</tr>
<tr>
<td>5/16-18 Standard T-Nut, Steel</td>
<td>Parker</td>
<td>Parker</td>
<td>25-002</td>
<td>$0.90</td>
<td>10</td>
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<td>$115.20</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J363 Rugged Transition Joint Probe Type ‘T’, 0.040&quot; x 6.0&quot;</td>
<td>Omega</td>
<td>Omega</td>
<td>J363-CPSS-040U-6-SMPW-M</td>
<td>$33.00</td>
<td>4</td>
<td>$132.00</td>
</tr>
<tr>
<td>J363 Rugged Transition Joint Probe Type ‘T’ 0.0625&quot; x 6.0&quot;</td>
<td>Omega</td>
<td>Omega</td>
<td>J363-CPSS-0625U-6-SMPW-M</td>
<td>$42.00</td>
<td>3</td>
<td>$126.00</td>
</tr>
<tr>
<td>TJ36 Rugged Compact Transition Joint Probe Type ‘T’, 0.020&quot; x 6.0&quot;</td>
<td>Omega</td>
<td>Omega</td>
<td>J363-CPSS-020U-6-SMPW-M</td>
<td>$38.00</td>
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<td>$76.00</td>
</tr>
<tr>
<td>TC Rugged Pipe Plug Thermocouple probe Type ‘T’ 1/4&quot; mounting thread</td>
<td>Omega</td>
<td>Omega</td>
<td>TC-T-NPT-U-72</td>
<td>$38.00</td>
<td>2</td>
<td>$76.00</td>
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<tr>
<td>Brass Manifold (2) 3/8 inlets, (3) 1/4 outlets</td>
<td>McMaster Carr</td>
<td>McMaster Carr</td>
<td>5627K505</td>
<td>$68.03</td>
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<td>Brass Hex head plug 1/4&quot;</td>
<td>McMaster Carr</td>
<td>McMaster Carr</td>
<td>50785K22</td>
<td>$1.27</td>
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<td>Enclosure</td>
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<tr>
<td>Super Firetemp ‘L’ Flat Calcium Silicate Block</td>
<td>Industrial Insulation Group, LLC</td>
<td>Basic Resources Inc.</td>
<td>45-IIG-F13-1</td>
<td>$565.50</td>
<td>2</td>
<td>$1,131.00</td>
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<tr>
<td>Copper Flat Bar C110 0.375&quot;x2.0&quot;x6.0&quot;</td>
<td>Lomar</td>
<td>Lomar</td>
<td>45-M-F13-1</td>
<td>$345.00</td>
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<td>Wear Resistant Easy to Machine Cast Nylon 4&quot;x6&quot;x6&quot; (45-IIG-F13-1)</td>
<td>McMaster Carr</td>
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<td>8505K117</td>
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<td>Wear Resistant Easy to Machine Cast Nylon 0.75&quot;x6&quot;x6&quot; (45-IIG-F13-2 &amp; 45-IIG-F13-5)</td>
<td>McMaster Carr</td>
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<td>8505K112</td>
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<td>Wear Resistant Easy to Machine Cast Nylon 1.5&quot;x6&quot;x6&quot; (45-IIG-F13-3)</td>
<td>McMaster Carr</td>
<td>McMaster Carr</td>
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<td>5/8-11 Swivel Nut</td>
<td>CarrLane</td>
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<td>CL-10-SN</td>
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<td>Stainless Sheet 304</td>
<td>Stamets</td>
<td>Stamets</td>
<td>6-M-F13-1</td>
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<td>Male-Female Thread adapter 3/8&quot;-16 male, 3/8&quot;-24 female</td>
<td>McMaster Carr</td>
<td>McMaster Carr</td>
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<td>Rotating Flange Nut 3/8&quot;-16</td>
<td>McMaster Carr</td>
<td>McMaster Carr</td>
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<td>Metal Super Markets/IPFW</td>
<td>Metal Super Markets/IPFW</td>
<td>6-M-F13-2</td>
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<td>Miniature High-Capacity Top Hat Load Cell, 1,000 lbf</td>
<td>Omega</td>
<td>Omega</td>
<td>LC307-1K</td>
<td>$385.00</td>
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<td>Total Build Cost:</td>
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