Disc Brake Energy Conversion

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Statement of Disclaimer

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Executive Summary

The original goal of this project was to complete the design and building of a disc brake energy conversion project started by a former senior project team, and then spend a majority of the year performing testing in order to see if the device could be used to accurately calculate the Joule's constant. However, due to unforeseen complications and obstacles, the design and manufacturing portion of the project ended up taking much longer than anticipated. A majority of this time was spent designing the hydraulic plumbing system that would actuate the brakes. The previous team purchased some hydraulic parts and left them unassembled with no hydraulic schematic, and in order to save money, one of our goals was to use as many of the previous team's purchased parts as possible. This led to us attempting to complete their hydraulic design using the few parts they had left behind. However, after some time we discovered that the parts they had purchased would not work with the system we were trying to create. After discussion with multiple professors and shop techs, we discovered a hydraulic schematic created by W.C. Branham that would be perfect for our device. After making a few changes to the design, we were able to start manufacturing the hydraulic system using hand-held tube benders and tube cutters. Once the tubing was assembled, we bled the air out of the hydraulic portion of the system and filled it with hydraulic fluid. Then, in order to measure the temperature of the thermistor in the copper brake pads, we programmed an Arduino read the thermistor and collect data. This left us with only three weeks to test; however, through our testing and analysis, we were able to calculate a Joule's constant within 35% of the accepted value. The error in the calculated value came from heat loss that was not accounted for by our thermal model for the system. In an attempt to reduce the heat loss, we insulated the rear of the thermistor using Styrofoam and improved the thermal conductivity between the thermistor and copper pad using thermal paste. Although this improved our measured temperature, we believe we were still losing a lot of heat out of the back of the copper pad. Even though we had limited time to test, we believe that we proved that with further testing and analysis this device can be used to accurately and consistently calculate the Joule's constant.

1. Introduction

The goal of this project is to complete the building of a Joule's Constant Experiment for the California Polytechnic State University-San Luis Obispo Thermal Science Laboratory. Joule's constant, which is equal to 4186 Joules kg^{-1}, is the numerical value for the amount of mechanical work required to produce a unit of heat. This project will be used to replace the current experiment used in the lab, and will provide students with a more accurate and exciting way to learn about Joule's constant. This project is a continuation of a previous senior project. Our first step is to complete the building and assembly of all the parts. Then we will run and test the experiment in order to help gain a better understanding of issues with the experiment that could potentially be fixed or explained as errors in the lab experiment. Once thorough testing has been performed, we will produce a laboratory experiment write-up for the future students that will be using this particular lab. This write-up will be complete with background, theory, safety, procedure, deliverables, and sources. The goal is that students will be able to safely and accurately perform an experiment that will help teach them the fundamentals of Joule's constant. In order to more effectively reach this goal, we first performed thorough background research to help us gain a better understanding of heat transfer occurring in disc brake systems and similar experiments that could be useful in the design of our experiment. Then, through communication with our sponsor, known requirements for the finished experiment, and specifications from the original senior project, we created a specification list to help define concrete requirements for our finished product. We then performed brainstorming techniques to help us come up with improvements to the current device and decide if they were worthwhile to implement. Using a decision matrix, we decided on a final concept. Lastly, we mapped out a detailed schedule of when different tasks will be completed in a Gantt chart.

1.1. Sponsor Background and Needs

During the 2012-13 school year, a senior project team attempted to replace the current Joule's constant experiment in the Cal Poly Thermal Science Lab by designing, building, and installing a new experiment. However, they were unable to finish building and installing their machine. Dr. Shollenberger was the sponsor for that project as well, and she needs the project to be completed. This involves finishing the building of the machine as needed, installing the machine, and drafting a lab manual for the experiment as well as thoroughly testing the experiment to ensure the experiment meets the original requirements and solves the original problem. The original problem was the inaccuracy and danger of the current Joule's experiment at Cal Poly which has significant human error and exposes students to a crushing hazard and to a risk of lead poisoning. Dr. Shollenberger needed a new experiment that would allow students to measure the Joule's constant accurately and safely, and she desired the experiment to be relevant and interesting to students to make the experiment more educational.

Dr. Shollenberger, this projects sponsor, now needs the previous team's work towards a safe, accurate, and relevant experiment to be finished and tested thoroughly.

1.2. Formal Problem Definition

A previous project was unable to finish the building and installation of an experiment that safely and accurately measures the Joule's constant, and Dr. Shollenberger needs the experiment to be finished so that future Cal Poly mechanical engineering students can perform the Joule's constant experiment accurately without being exposed to lead and crushing hazards.

1.3. Objective and Specification Development

The overall goal of this project is to deliver a safe and operational laboratory experiment that future students can use to accurately measure and gain a better understanding of Joule's constant. In order to more effectively reach this goal, we created a specification list that provides a detailed breakdown of every task we need to deliver and how we will accomplish each task. Each of the specifications were created through communication with the project sponsor, known requirements for the finished experiment, and from the original senior project. Due to the fact the former students already finished most of the design and build phase of the project, we cited a lot of their specifications in our list. We did however add many more specifications regarding the finished lab experiment, in particular focusing on safety, energy, maintenance, and ergonomics.

The most important section in our specification list is safety. This project is eventually going to be run by students almost every day for many years, so this device must be very safe and reliable to use. Some of the hazards with this device include the electrical supply, nitrogen supply, high speed rotation of parts, brake pad compression, high pressure lines and failure of parts. Because of the design of this experiment, there are a lot of potential hazards for the students that will be operating it. In an attempt to minimize the students' exposure to a lot of these hazards, we will enclose the rotating machinery and most of the high pressure lines in safety glass. The only exposed parts that will leave the shielding will be the ball valve so students can activate the brakes, the accumulator, the check valve and the pressure relief valve. All of these will be placed on the back side of the device except for the ball valve. This will help the students remain minimally exposed to the equipment. The nitrogen tank will be secured against the wall, and will have a pressure regulator on it. If the pressure in the lines gets too high, the pressure relief valve will open and release fluid. Also, the electrical wiring will be done by an electrician to ensure it is properly wired.

Another specification that is critical to the project is the maximum temperature of the brake pad. This is important because the thermistors that we have are more accurate in different temperature ranges. We can adjust this change in temperature based on the pressure applied to the disc and the speed at which the disc is rotating. Because the components are only rated to certain pressures and spinning the shaft at too high of a speed would be dangerous, we must be able to create the desired temperature rise within these constraints. These variables will be critical when running the experiment and will have a very large effect on how close the experimental Joule's constant is to the true value.

One important specification for our device that we took from the original senior project specifications list is the geometry, or size of the device. Although there is a lot of room in the lab, especially because the old HVAC experiment will be taken out of the lab, it is important that this experiment does not take up to much space. The device must be able to fit on the table near where the nitrogen tank will be secured. It is also important to keep the plumbing and wires coming off the device compact and properly secured in order to avoid people in the lab from damaging the device or hurting themselves while moving around the lab.

Keeping the spending to a minimum is very important for this project as the previous team used most of the budget while they were building the device. Although the device is completed for the most part, the electrical wiring still needs to be done along with the plumbing for the hydraulic and pneumatic lines. The plumbing will prove to be the most expensive of these expenditures because the lines will be operating at high pressures. To ensure the safety of the students and people in the lab, very high quality tubing must be purchased to ensure it does not leak or fail. Although these known expenditures will keep us near our budget, it is very possible that there will be unforeseen problems in the future that will require more spending. To help prevent these future problems from arising, we must be very thorough in the design, building and testing of the experiment.

This device should be simple and easy to use for the students. If they are unable to turn on the motor or read the data from the DAQ system, it will make it very difficult for the students to run the experiment. They also must be able to complete the experiment during the allotted laboratory time, which is three hours long. However, knowing that often professors will lecture at the beginning of lab, or unforeseen problems can arise while performing an experiment, we decided that the students must be able to finish performing our experiment in under 1.5 hours. This will hopefully give the students plenty of time to perform the experiment, and if needed they can redo trials that resulted in faulty data. It is important that students can perform an adequate number of trials and get the data they need to calculate the Joule's constant.

Lastly, we decided that maintenance and long term reliability were very important for this project. This experiment will be used by students multiple times a week for the entire school year. It is also meant to be a long-term replacement for the old Joule's Constant experiment, so it should last for many years. Due to the high usage of this device, maintenance should only need to be performed on it annually, meaning that it must be durable and reliable. Also, if a part has to be fixed or replaced, it should be easy to do so that the experiment is not out of operation for a long time. A large part of this is keeping proper documentation of everything we do and the parts we use. This will help enormously in the future when repairs need to be made or parts need to be replaced.

Table 1: Design Specifications

Spec. #	Parameter Description	Requirement or Target (units)	Tolerance	Demand or Wish	Risk	Compliance
1	Machine height	4	MAX	D	L	I
2	Machine width	3	MAX	D	L	I
3	Machine length	4	MAX	D	L	I
4	Motion type	Rotational		D	L	I
5	Additional mass attached to shaft	100 kg	MAX		L	I
6	Power	Ability to receive power in the Thermal Science Lab	-	D	M	I
7	Pages in experiment manual	15 pages	MAX	D	M	I
8	Pressure supplied to disc brakes	1500 psi	MAX	D	L	T
9	Change in temperature	100 K	MAX	D	M	T
10	Energy conversion	Kinetic to thermal	-	D	L	T
11	Controls for motor	On, off, and speed adjustment	-	D	L	T
12	Controls for brake	Engaged and disengaged	-	D	L	T
13	Output from experiment	Temperature measurements for brake pad	-	D	L	T
14	Method of measurement recording	DAQ system	-	D	L	T
15	Wire safety	No loose wires are within 10 inches of moving parts	-	D	L	I
16	Instruction safety	Safety warnings about machine operation posted on the machine.	-	D	L	I
17	Operational safety	Ensure machine cannot be operated during brake pad replacement.	-	D	M	T
18	Time to complete experiment	1.5 hours	MAX	D	L	T
19	Colors of experiment	3	MIN	W	L	I

Spec. #	Parameter Description	Requirement or Target (units)	Tolerance	Demand or Wish	Risk	Compliance
20	Number of custom parts	0 parts	MAX	W	H	I
21	Tolerance of temperature measurement	1 %	MAX	D	M	T, A
22	Tolerance of thermistor	0.2 %	MAX	D	M	I, A
23	Steps in the manual's procedure	14	MAX	D	M	I
24	Actions in each step in the manual	2	MAX	W	M	I
25	People required to lift the device	2	MAX	W	M	T
26	Noise	90 dB	MAX	D	L	T
27	Time before brake pad replacement is required	10 years	MIN	D	M	A
28	Time before maintenance is required	1 year	MIN	D	L	A
29	Time needed to replace both brake pads	10 minutes	MAX	W	M	T
30	Spending for project	$500	MAX	D	L	I
31	Completion of project	May 2016	MAX	D	L	I
32	Accuracy of Joule's constant	95 %	MIN	D	M	T, A
33	Changes allowed to current design	0	MAX	W	M	I

1.4. Project Management

The Project team was composed of Jeffrey Powell and Coleman Badgley. Badgley and Powell shared responsibilities during the project, but each focused on different areas of work. Powell was responsible for communication and acted as the point of contact for the team. Furthermore, Powell was responsible for designing the hydraulic circuit and the control panel for the machine. Badgley was responsible for thermally modeling the experiment and analyzing the experiment data. In addition, Badgley was responsible for programming the variable frequency drive for the experiment.

The Gantt chart for the project went through several revisions due to delays with connecting the motor to its power supply and delays with correctly designing the hydraulic circuit. Designing the hydraulic circuit took several iterations because of the team was learning about hydraulics during the design. And the motor could only be connected to its power supply by a certified electrician, and it was difficult to find a school certified electrician who had the time to connect motor. These setbacks led to most of the machine testing and assembly occurring in the final quarter of 2016 (the spring quarter).

The spring quarter will consist of finishing the assembly of the machine. After the machine is fully assembled, the team will focus on verification of the theory as well as refining the theory while drafting a lab manual. The middle of spring quarter will involve testing of our experiment and refinement of our manual and theory as necessary. The end of spring quarter will be the project demonstration the experiment, and the experiment will be completed by week 19, along with a rough draft or outline of the manual for the experiment.

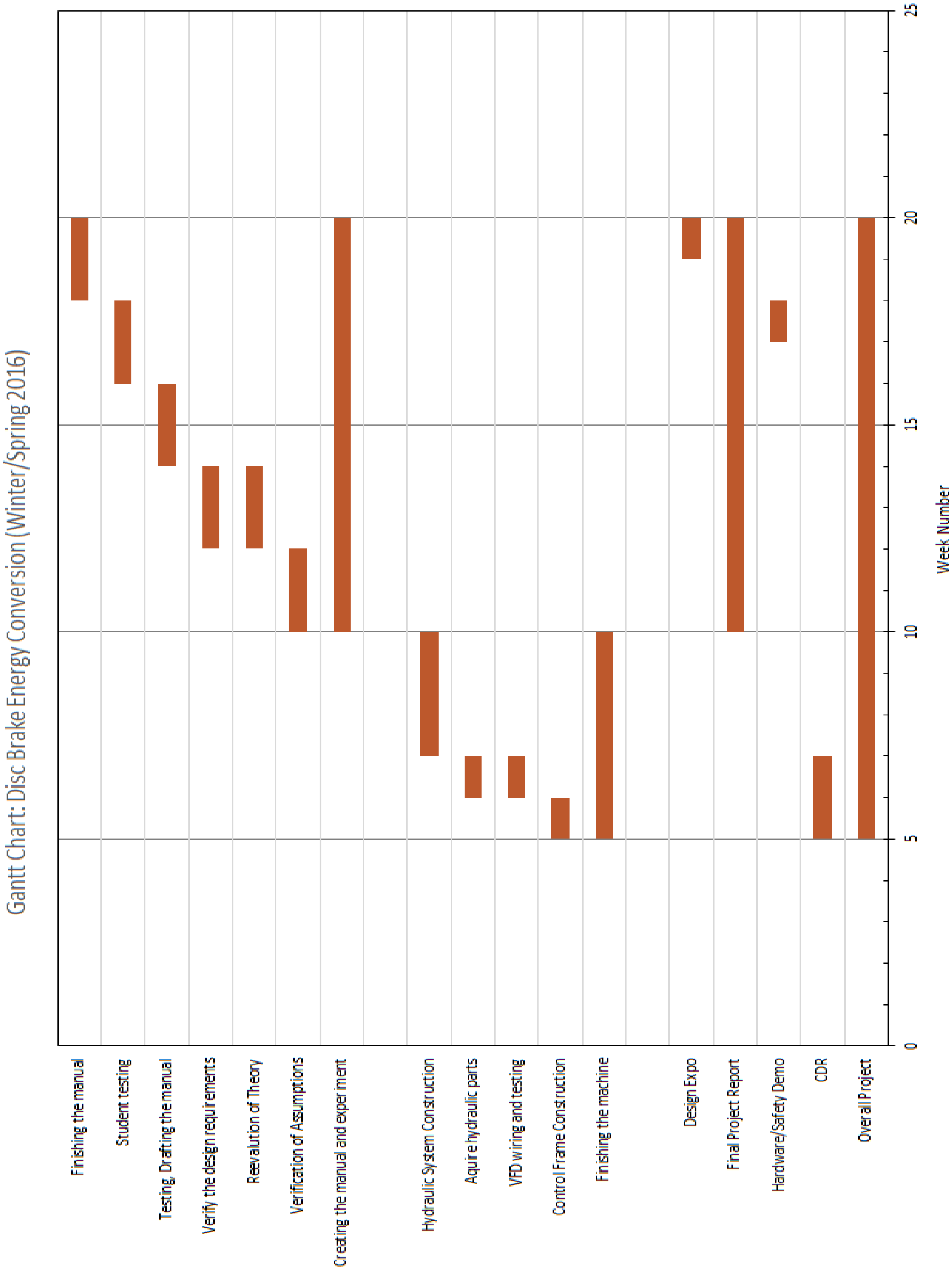


FIGURE 1. DISC BRAKE CONVERSION GANTT CHART FINAL VERSION

2. Background

The point of this project is to replace the current Joule's Constant experiment in the Thermal Science Laboratory. The current experiment is designed to convert potential energy into thermal energy through the release of two pendulums that have heavy steel weights on the end (Thermal Sciences Laboratory, 2nd Edition). These weights swing down and collide with a piece of lead that is positioned at the impact point. This piece of lead is wrapped around a thermocouple, and it allows the user to see the change in temperature of the lead after the steel weights hit it. However, this experiment has a lot of issues problems: inaccurate measurement of the initial height of the weights, thermocouples that are simply wrapped in lead and do not provide an accurate reading of temperature rise, and pieces of the lead mass falling off through the many trials of the experiment. After recently performing this experiment and reading through the laboratory manual write-up for the lab, we have a good understanding of the issues with this particular experiment. This will be very useful in completing the new equipment and laboratory write-up, as we can hopefully improve upon some of the areas where the old experiment is lacking.

2.1. Existing Products

The project we are working on is a continuation of a previous Senior Project. This project utilizes the conversion of kinetic energy to thermal energy through the application of brake pads to a spinning disc (Ward, Wallace and Waltman). The change in temperature of the brake pads will be measured using thermistors, allowing the students to calculate the gain in thermal energy. An electric motor is used to rotate a shaft at high rotational velocity. Using a variable frequency drive, the speed at which the shaft spins can be varied, allowing the students to perform multiple runs at varying speeds. Also, a 60-pound flywheel was attached to the shaft to increase the kinetic energy of the shaft during rotation. This will allow for a greater change in temperature of the brake pads. The group of students whom began this project left a long project write-up, including the materials they used to build the device, calculations to prove that the device will not fail, and many other things that will be helpful while finishing the experiment. Although they did not begin the actual write-up of the laboratory experiment, they provided a lot of information that will help us in the design of the experiment. Therefore, many of the specifications we decided to use in our specification list came from specifications from the original project, or were derived through information found in their final project write-up.

While performing our background research, we attempted to find similar Joule heating experiments that would assist in the creation of our experiment. We discovered that there are multiple other variations to the Joule heating experiment. One of the most common we found was an apparatus where the student raises and lowers a weight on a rope by turning a crank (Mechanical Equivalent of Heat Apparatus: PASCO). These devices are produced and sold through companies such as PASCO. The device also comes with a laboratory manual that includes the modeling theory, procedure, and deliverables needed to perform the experiment. The device by PASCO is capable of determining Joule's constant, or the Mechanical Equivalent of Heat, to within 5% of the accepted value. This is possible because the amount of work performed by turning the crank is measurable. As the crank is turned, an aluminum cylinder rotates as well. The aluminum cylinder has a nylon rope wrapped around it and a weight attached to the end of the rope. As the crank is turned, the friction between the rope and the cylinder is enough to support the hanging weight, which allows for the torque acting on the cylinder to be constant and measurable. Also, there is a counter that keeps track of the number of turns.

FIGURE 2. PASCO MECHANICAL EQUIVALENT OF HEAT APPARATUS

As the cylinder rotates, the friction between the cylinder and the nylon ropes changes the work into thermal energy, and in turn causes a temperature rise in the aluminum cylinder. This rise in temperature is measured using thermistors in the aluminum cylinder. Then, this change in temperature can be used to calculate the thermal energy transferred into the cylinder. The ratio between the work performed to lift the mass and the thermal energy transferred into the cylinder determines the Joule's constant, or mechanical equivalent of heat.

This experiment is quite simple and requires very few calculations. It allows for the user to solve for the Joule's Constant by simply recording the following variables: mass hanging from the rope, radius of the cylinder, number of rotations of the cylinder, final and initial temperature. Then, all that is needed is the acceleration due to gravity and the specific heat of the aluminum, both of which are known values or can be found easily. The positive things about this experiment is that it requires very little setup. The students simply must make sure the mass is roughly 10 kilograms and then measure the actual mass. They must raise and lower the mass by turning the crank. Also, they must cool down the aluminum to room temperature in-between trials. This easy setup allows the students to learn the fundamentals of Joule's constant without worrying about how to perform the experiment. It also allows for multiple trials due to the short amount of time it takes to run one trial. It also requires no regular maintenance, except to lubricate the aluminum cylinder periodically. This low maintenance is also associated with the low number of parts in the design of this experiment. The design is very basic and only consists of 8 total parts. This is helpful when parts need to be replaced or maintenance needs to be performed.

The downside to this experiment is that it requires very little calculation and would be far too easy for third year mechanical engineering students to perform. Also, there is some error associated with the experiment. The thermistor that is imbedded in the cylinder only measures the temperature in one location on the cylinder. Since the size of the cylinder is not taken into account, it must be assumed that all of the temperature rise occurs in the location of the thermistor. Also, it must be assumed that there is no heat lost to the surroundings, as none of the equations take into account the error associated with heat lost to the environment from the cylinder.

The laboratory manual for PASCO's Mechanical Equivalent of Heat experiment was very helpful for the modeling of the laboratory manual that we will have to create. It begins by walking through the experimental apparatus and the basic idea of how it will be used to find Joule's constant. It also gives a detailed description of the equipment that is included on the device, what it is used for and if there is any error associated with that particular piece of equipment. These sections are followed by a history of the theory behind the experiment and how Joule's constant originally came to be derived. After the students have a good idea of the equipment being used and the theory behind the experiment, then the laboratory manual provides a detailed procedure and then calculations section.

Another helpful laboratory experiment that we were able to find was an experiment that is performed at the University of Mary Hardin-Baylor's Department of Computer Science and Engineering. The objective of this experiment is to calculate the Joule's constant through the use of the bicycle front caliper brake (Mullison). The concept is that the calorimeter friction pads rub on the front tire, bringing the bicycle to a stop. However, the rubbing of these pads on the front tire causes the pads to heat up. The loss in the kinetic energy of the bicycle and rider is equal to the gain in thermal energy of the friction pad. The ratio of change in kinetic energy to change in internal energy is equal to Joule's constant.

FIGURE 3. EXPERIMENTAL SETUP OF COPPER CALORIMETER FRICTION PAD

The mechanism that applies friction to the front tire is a pivoting beam with one end connected to a hand-operated brake cable and the other end carrying the copper calorimeter friction pad. The type K thermocouple is soldered in a small hole on the back surface of the friction pad. They try to eliminate heat loss from the friction pad by insulating it with a thick piece of balsa wood on the back of the pad and on all of the exposed sides of the copper. Also, phenolic washers are used to thermally isolate the mounting screws from the pivoting beam.

Unlike the experiment designed by PASCO, this experiment attempts to account for as many of the losses as possible. The main losses accounted for are: bicycle aerodynamic drag, rolling friction, and heat loss into the front tire. The runs were first performed with no braking. A speedometer was mounted on the bicycle handlebars, which provided them with speed versus time data. With the final speed of zero, the speedometer provided the initial velocity of the bike and how long it took to come to a stop without braking. Performing these no braking runs allows the determination of the losses in kinetic energy due to aerodynamic drag and rolling friction. Then, they applied the first law of thermodynamics to the bicycle in a control volume consisting of its initial velocity at state 1 and where it comes to rest as state 2.

$$\underset{(1)}{[Q_{1-2}]_{rubber}} = \underset{(2)}{\left[\frac{m}{2g_c}(V_2^2 - V_1^2)\right]_{bike}} + \underset{(3)}{\left[\frac{mg}{g_c}(z_2 - z_1)\right]_{bike}} + \underset{(4)}{(U_2 - U_1)_{Cu}} + \underset{(5)}{W_{1-2}}$$

FIGURE 4. FIRST LAW OF THERMODYNAMICS

Then, they proceeded to walk through the steps of how to calculate the heat lost to the rubber tire, as this is the biggest loss of heat in the experiment. This was followed by a section that showed how the work due to aerodynamic drag and rolling friction could be calculated. By subtracting the work losses in kinetic energy from the theoretical value of the kinetic energy and the heat losses to the tire from gain in thermal energy, a more accurate value of the Joule's constant can be calculated.

These already made laboratory write-ups helped us while making our specifications list, as they gave us good guidelines for what should be included in our experiment and write-up. Since these experiments were designed to be used by students, each one included a big emphasis on safety in the procedure section. They also included a long section that gives the students background on the theory and modeling of the particular experiment. We decided to adopt both of these ideas into our specification list. One thing that was lacking from the PASCO experiment was a section on the theory of losses and error in the experiment. There will always be mechanical and heat losses in an experiment such as this, however PASCO did not include any information on how to reduce the error caused by these losses. The bicycle brake experiment included a thorough and detailed section on the major losses in the experiment and how to calculate them. This is something that we need to adopt in our experiment. Including a section on losses helps provide students with a better understanding of the experiment and where the error in the results come from. However, it is also very important because if we can minimize the error due to losses in the results of our experiment, it will help us achieve our goal of a Joule's constant within 5% of the accepted value.

2.2. Theory

Another area that we researched heavily was the theory of brake pad and disc brake heating. We were able to find a lot of articles on the theory and derivations equations regarding disc brake heat transfer. This largely due to the fact that overheating of disc brakes is a big issue in the automotive industry, so it is widely researched. One of the most helpful articles we found was called "Analysis of heat conduction in a disk brake system” (Talati and Jalalifar). This article provided insight and derivations on how to calculate the heat flux in both the brake pads and the disc brakes. These calculations were performed using the uniform pressure theory, with heat flux as a function of time and the distance at which the brake pad is applied from the center of the disc.

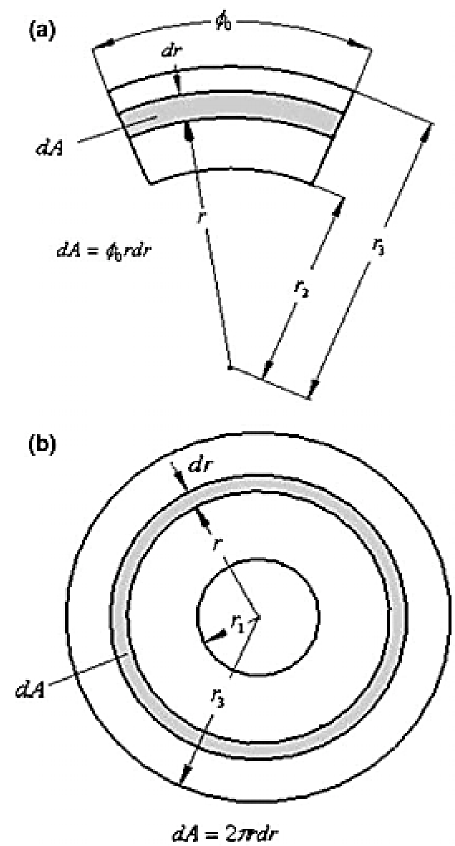


FIGURE 5. CONTACT SURFACE ELEMENT OF THE BRAKE PAD AND DISK COMPONENTS

Another helpful source that we were able to find on disc brake heating was "Thermo-mechanical Analysis of a Disc Braking System" (Chan). This article also covers the heat flux into the brake pads and the disc brake, along with the heat transfer to these components. It also provides the equations for the heat transfer on the different surfaces of the brake pads and disc brake. This allows for a more complete understanding of where the heat is going in the system and where the most amount of heat will be lost to the surroundings. Along with the equations provided in this article, it discusses other topics that could be helpful to our experiment. One such topic is the formation of hot spots and where they may form. These hot spots could lead to issues in the system, including potential disc failure after many thermal cycles. This is something that cannot happen in our system, as a failure in a component spinning at high velocity could be very dangerous for the people operating the experiment or other people in the laboratory. It also discusses ways of reducing the thermal gain in the disc, such as the use of vented rotors or fans in the system. Cooling down the brake pad and disc will be very important because the students will be running multiple trials. This will require cooling of components in between trials to make sure that overheating does not occur and that the students get the most accurate results.

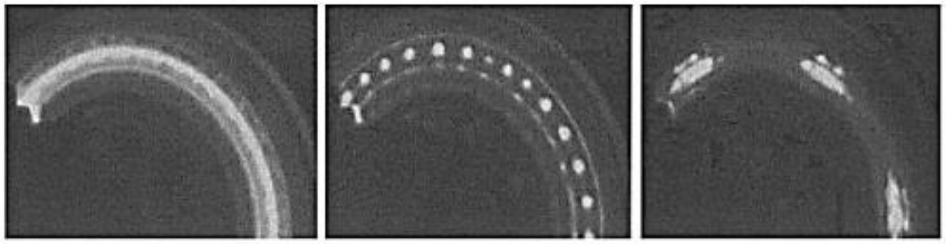


FIGURE 6. HOT SPOTS ON DISC

This theory will be very important while we are writing the new laboratory experiment, as it is important to give the students a good background and base knowledge before asking them to perform the experiment. It will also help us better understand where some assumptions will need to be made or where possible errors will arise when going from theory to experimental data. The bicycle braking experiment and the mechanical equivalent of heat apparatus discussed earlier will provide a good starting point into the theory and calculations. Because of their similarity to the experiment we are designing, a lot of the content in the experimental write-up will be useful. In particular, the bicycle braking experiment has a lot of likeness to our experiment. The losses that are seen in that experiment will provide us with a good initial understanding of where we are losing heat and kinetic energy. This experiment also provides a detailed discussion of how to account for these losses, which will hopefully reduce the error of the Joule's constant value calculated. With a good base understanding of the issues that will arise while performing the experiment, we should be able to begin the actual process of testing our experiment. Then, once we have tested our experiment, if we are still not getting a Joule's constant value that is satisfactory, then we may need to turn to the braking system analysis articles. These articles provide a much more in-depth look at heat transfer occurring in a disc brake system. These articles provide additional insight at where thermal losses are occurring in the system, which will prove to be one of the biggest sources of error.

3. Design Development

Ideation and concept selection is discussed in this section

3.1. Discussion of Conceptual Designs

The machine for the experiment was mostly completed. So ideation focused on the changes that could improve the experiment as well as the changes that must be made in order for the experiment to function. The changes that need to be made were quickly identified as: equipping the thermistors to a data acquisition (DAQ) system, writing a manual, tightening the nuts on the brake calipers to secure the calipers in place, and designing and installing a plumbing system for actuating the hydraulic disc brakes during the experiment. Tightening the nuts for the brake calipers will not be a difficult task, so ideation for how to tighten them was ignored. In addition, the thermistors are already installed in the brake pads and the wires for the thermistors are ready to be attached to a DAQ system. Since attaching the thermistors wires to a DAQ system will require little to no ideation and will occur after the experiment is operational, its ideation was ignored as well. The manual format was designed during the creation of the specification list for the experiment. The manual will follow the format of the current lab manual, so the ideation for the manual was postponed. Of the necessary changes, the plumbing design and installation is the highest priority and requires ideation. The ideation and concept selection for the plumbing system is discussed below in the "Plumbing Ideation," "Concept Selection,", and "Concept Evaluation" sections.

After thinking of possible changes to the current machine that might be necessary or might improve the machine, the most feasible changes were selected and considered. The changes considered were:

1. Controller: Addition of a single unit controller
2. Clutch: Replacing the coupler with a clutch.
3. Fail-Proof Brakes: Forcing brakes to normally be engaged
4. Fail-proof Motor: Keeping motor normally disconnected from the flywheel's shaft
5. Emergency Shutoff: Addition of an emergency shutoff for the motor

3.1.1. Change 1: Controller

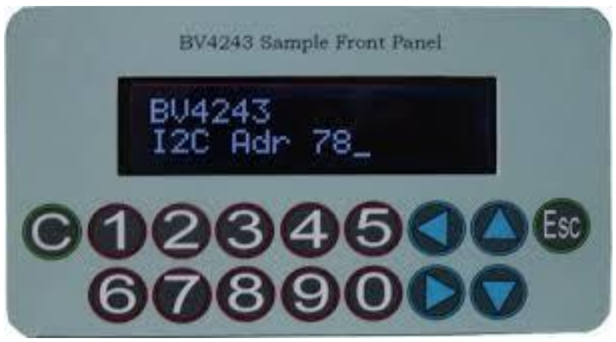


FIGURE 7. EXAMPLE INTERFACE FOR CONTROL SYSTEM

One idea to improve the experiment was to simplify the controls for the experiment to improve the experiment's user interface. The idea was to switch from a manual ball valve to a hydraulic solenoid valve, and then to equip the frequency drive and the solenoid valve to a micro controller that would be attached to a keypad and LCD display or lights. This would allow the students to operate the motor and the hydraulic brakes using one keypad and to receive feedback about what actions the system Is performing through the LCD display (the LCD display could display whether or not the motor is on or off, the motor speed, whether or not the brakes are actuated, or other characteristics that could improve user interface). The benefit of this change is a more user friendly experiment. The disadvantages of this change is the cost of the components that are required to install the control system.

3.1.2. Change 2: Clutch

During initial examination of the machine, the effect the motor would have on the shaft during braking arose as a concern. If the motor added resistance to shaft rotation when turned off, then the kinetic energy would not be completely transferred to thermal energy. Some of the energy would be consumed by the motor. To ensure that this will not be problem, we considered replacing the coupler in between the motor and the main shaft with a clutch. This would allow the motor to be completely disconnected from the main shaft during braking and would therefore isolate the shaft, ensuring that the hydraulic brakes are the only significant resistance to shaft rotation during braking. Figure 8 shows the location where a clutch would be implemented, which is the current location of the motor coupler. The benefit of this change is the certainty that the motor will not bias the experiment's data. The disadvantage of this change is the significant cost to implement a clutch into the experiment.

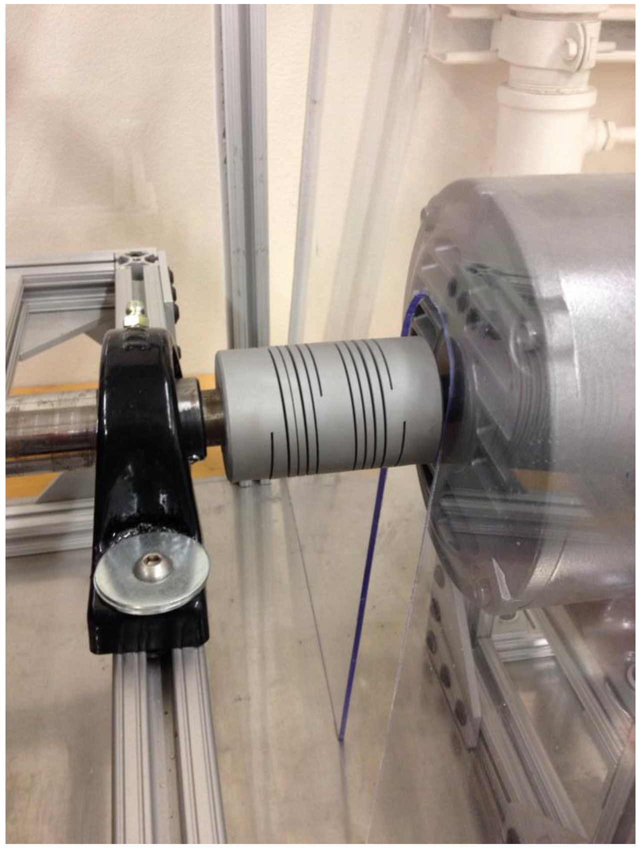


FIGURE 8. COUPLER BETWEEN THE MOTOR AND MAIN SHAFT

3.1.3. Change 3: Fail-Proof Brakes

While considering changes to improve the experiment's safety, fail-proof brakes (which are normally engaged to prevent the rotation of the shaft) were considered. These brakes would require the student to open a valve in order to release the brakes instead of opening a valve to actuate the brakes. The benefit of this change would be the decreased risk of injury or harm caused by accidentally turning on the motor or spinning the shaft. The disadvantage of this change, which was quickly realized, is the need to store high pressure in the system's tubing in order to keep the brakes normally actuated.

3.1.4. Change 4: Fail-Proof Motor

Another safety feature considered was disconnecting the motor from the main shaft and requiring the student to hold down a switch in order to attach the motor shaft to the main shaft. This would likely be accomplished through a clutch, and this change would reduce the chance that the main shaft accidentally starts spinning. The benefit of this change is reduced risk of injury, and the disadvantage of this change is that is requires a clutch (which would be a significant expense).

3.1.5. Change 5: Emergency Shutoff

An emergency shut off button was considered as a safety option to ensure that the motor could be quickly shut down in the event of a system failure or another emergency. This design would require a change in the electrical schematics and additional electrical components. However, the benefit would be an easy to press button to deactivate the machine in the event of an emergency.

3.2. Plumbing ideation

The previous senior project team did not leave behind a plumbing schematic to describe how to attach the hydraulic disc brakes to a power source for the disc brakes. They did, however, leave behind a physical plumbing system. This system appeared to be for display purposes since the fittings and the layout of the system were not acceptable. But this system did exhibit how they had planned to attach the disk brakes to the brake's power source. The system form the previous project is shown in Figure 9 below.

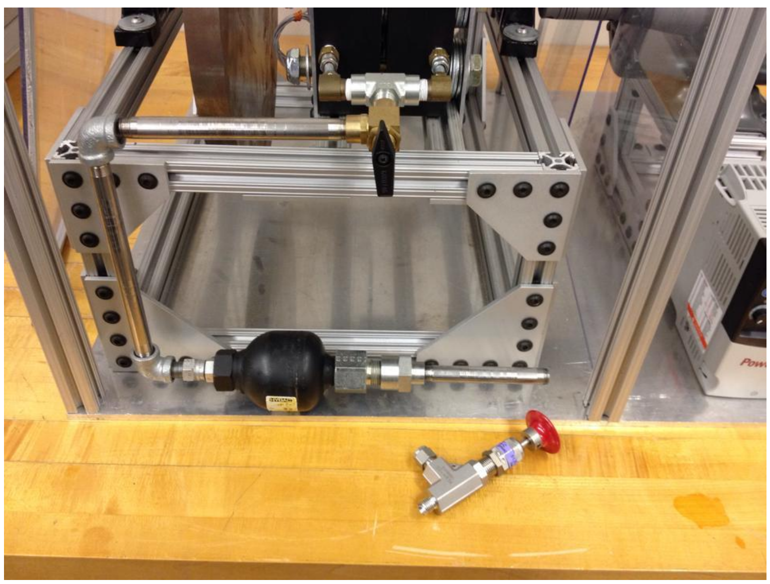


FIGURE 9. PREVIOUS PROJECT'S PLUMBING SYSTEM

After examining this system, initial plumbing schematics were drawn, specifications for the plumbing system were determined, and then ideation for the plumbing format (how the tubing would be placed) occurred. The specifications for the plumbing system is listed in

Table 2 below.

TABLE 2. PLUMBING SPECIFICATIONS

Spec. #	Parameter Description	Requirement or Target (units)	Tolerance	Demand or Wish	Risk	Compliance
1	Accumulator Position	Vertical (hydraulic port towards ground)	-	D	L	I
2	Plumbing components	Swagelok manufactured (unless not possible)	-	D	L	I
3	Proximity to student	Plumbing is behind or inside shielding	MAX	W	L	I
4	Length of tubing that can be unbraced	5 in	MAX	W	L	I
5	Cost	$ 500	MAX	D	H	I

After reviewing the specifications and the previous senior project's plumbing system, a series of conceptual sketches were created for the format of the plumbing. Most sketches were discarded because there is little free space inside the framing, and most sketches involved placing the tubing somewhere inside the framing where a structure currently existed. The top sketches from ideation are shown and described below. For all sketches shown below, the knob for the ball valve sticks outside the shielding to allow the student to access the ball valve without moving the plumbing in front of the front Plexiglas wall. Figure 10 displays the entire machine to help with visualizing where the plumbing formats would run the tubing with respect to the machine.

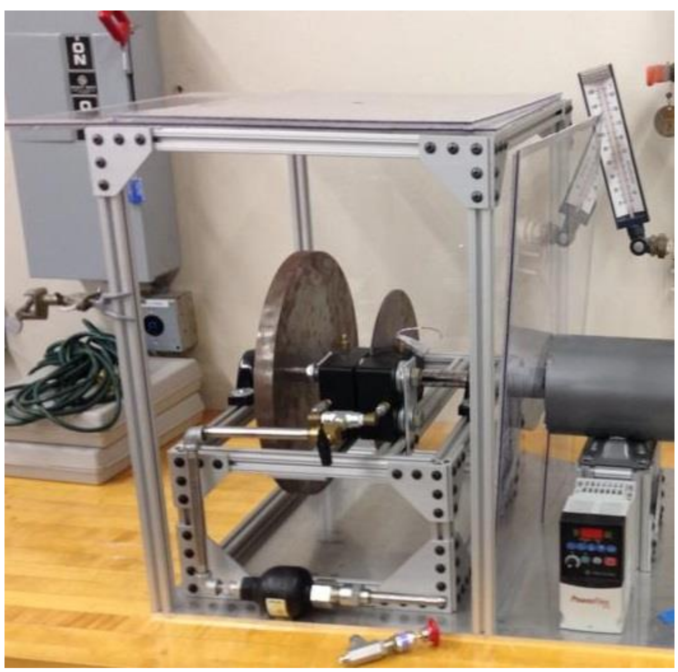


FIGURE 10. OVERVIEW OF THE CURRENT MACHINE

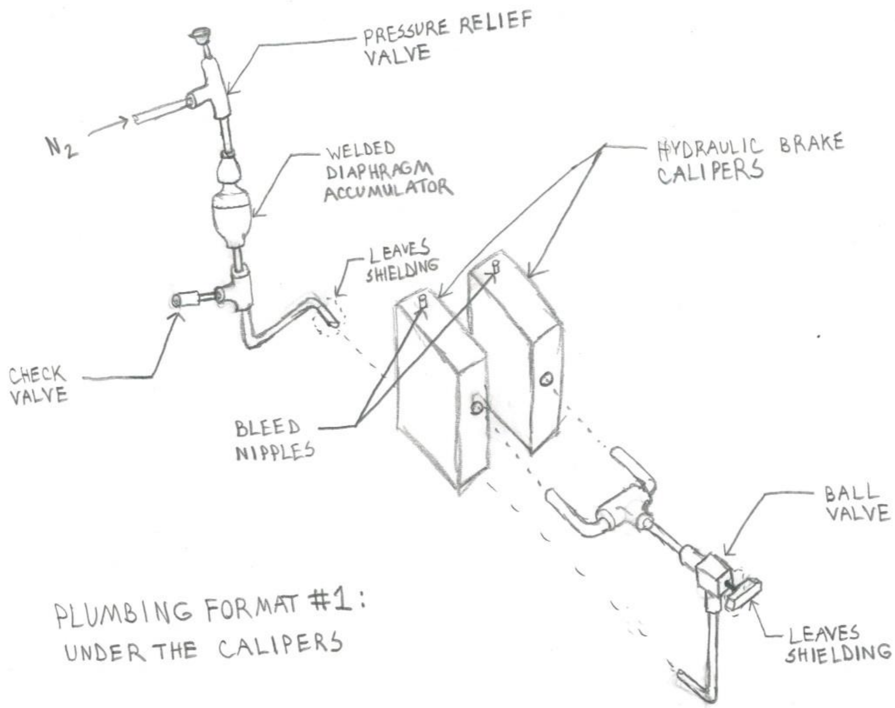


FIGURE 11. PLUMBING FORMAT 1: UNDER THE CALIPERS

**NOTE: The relief valve in the drawing represents a T joint with a relief valve connected to its third end.

The first plumbing format, shown in Figure 11, involves running the tubing from the calipers to a T joint, then to a ball valve and then running the tubing below the brake calipers to the rear shield wall. At the rear shield wall, the tubing exits the shielding and then move vertically. This idea involved the least amount of tubing to reach the rear shield wall. However, this idea runs the tubing under rotating components.

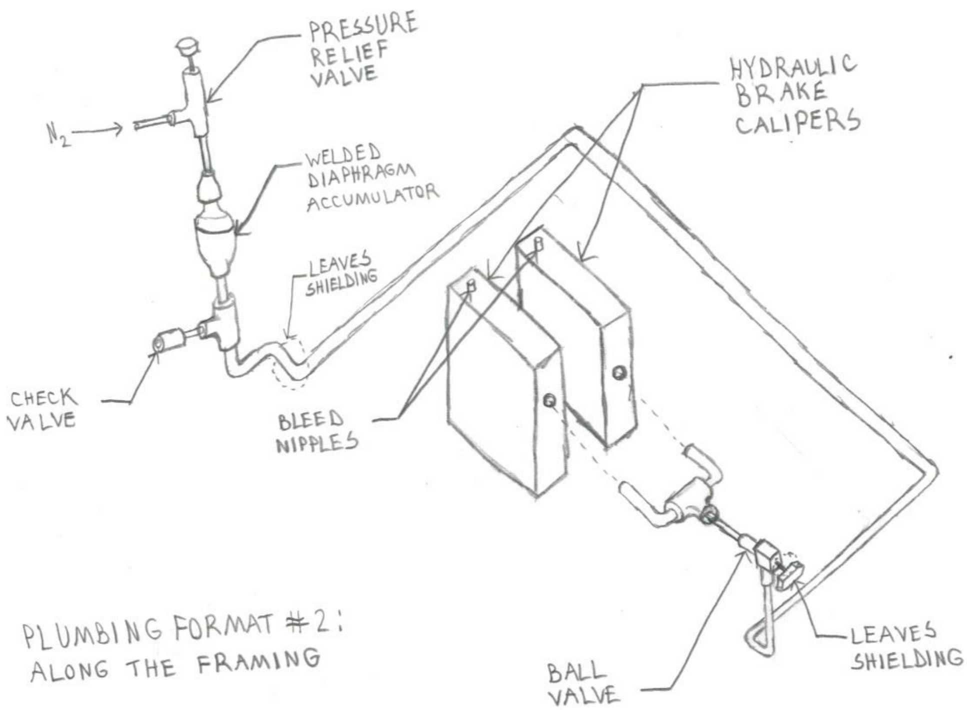


FIGURE 12. PLUMBING FORMAT 2: ALONG THE FRAMING

**NOTE: The relief valve in the drawing represents a T joint with a relief valve connected to its third end.

Plumbing format 2, shown in Figure 12 is identical to the previous plumbing format, except the tubing does not below any rotating components. Instead, the tubing runs along the framing to reach the rear shield wall, where it exits and then runs vertically (next to rear left aluminum framing, which is not shown in the format drawing) identically to plumbing format 1. This idea involves more tubing, but this idea does not run any tubing under rotating components.

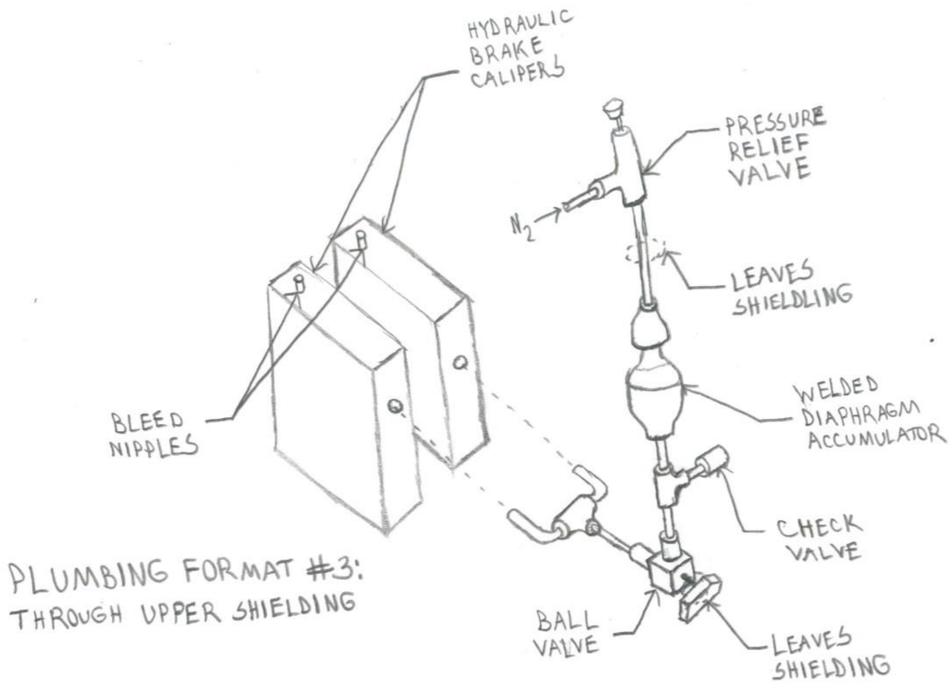


FIGURE 13. PLUMBING FORMAT 3: THROUGH UPPER SHIELDING

**NOTE: The relief valve in the drawing represents a T joint with a relief valve connected to its third end.

Plumbing format 3, shown in Figure 13, was an attempt to create a format that used the least amount of tubing and fittings. While this idea uses the least amount of piping, and keeps the components mostly inside the shielding, it does not allow for the tubing to be braced along the aluminum framing because the tubing runs next to the Plexiglas shield wall and does not run next to any framing.

3.3. Concept Selection

Concept selection for the overall experiment followed a form of morphological analysis. Except only the change and the current design were examined. And for each change, the benefit of the change was compared to the cost and the need for that change was assessed as well. Then the decision whether or not to implement the change was made. Of the changes considered, no changes were implemented.

The addition of a controller would not significantly improve the user interface in comparison to the cost of the components and the time that would be required to install the controller. In addition, the controller is not a necessity but is a wish, so the controller will not be added to the current design. The next change, implementing a clutch, was opposed because of similar reasons. The cost of a clutch is significant, being in the magnitude of hundreds of dollars to a couple thousand dollars. And after further examining the machine, no noticeable resistance by the unpowered, unwired motor was observed on the shaft when the shaft was spun by hand and then let go of. So it is assumed that the clutch is not a necessity. Since the clutch would be a significant, unnecessary cost, the clutch was opposed. However, this change will be reconsidered after operation and testing of the experiment to verify our assumption. The fail-proof motor was not implemented because it requires a clutch, and the design will not be changed to implement a clutch. Therefore the fail-proof motor will not be implemented either. Granted, if a clutch is later implemented, then the fail-safe motor will be implemented since it would then provide increased safety at minimal cost. The fail-proof brakes were opposed because of the increased risk that would occur if the tubing were to be normally pressurized. Keeping the system pressurized is a greater risk than having the brakes normally disengaged. So the fail-proof brakes will not be implemented into the design. The last change considered, the emergency shut off valve, will not be implemented because the frequency drive already allows students to quickly shutoff the motor in case of an emergency. And emergency shut off switches are usually implemented when the controls to shutoff the machine are not near the machine operators reach during operation. But the frequency drive is within short reach of the student during the experiment's operation, making an emergency shutoff switch unnecessary.

To select the final plumbing design, a decision matrix was created to compare the safety (how much of the tubing is inside or behind the shielding), cost (measured by length of tubing required), and bracing (how easily the tubing can be secured) of each top concept. This decision matrix is shown in Table 3.

TABLE 3. DECISION MATRIX FOR PLUMBING DESIGN

Plumbing Format	Safety	Cost	Bracing	Total
1	1	3	3	7
2	3	2	4	8
3	3	4	0	7

From this decision matrix, we selected Plumbing Format 2 as the plumbing format to be implemented.

3.4. Concept Evaluation

The previous design has already met the concept requirements of the previous senior project. In addition, it currently meets the current design requirements except the current design does not include a manual. However, we will be adding a manual after testing the machine and manipulating the experiment to ensure that the experiment can be used to reliably calculate the joules constant within 95% of the published value.

The plumbing design has met our specifications, and the design was shown to Cal Poly technicians Mr. Gerhardt and Mr. Leone for critique. This critique was applied to create a semifinal plumbing system that meets our requirements and is considered acceptable to Mr. Gerhardt and to Mr. Leone. The plumbing schematic below is what we considered the semifinal plumbing schematic; however, after talking to Dr. Owen, the schematic was altered to use an intensifier (a device that uses area ratios to turn low pressure air into high pressure hydraulic fluid). This will prevent students from working with high pressure gas, which Dr. Owen, Mr. Gerhardt, and Dr. Shollenberger strongly advised against. All of them emphasized that high pressure gas can be extremely dangerous and that a leak in a high pressure gas line can be much more catastrophic than a leak in a hydraulic line.

Although the below information is not the semifinal design and is now obsolete, it is included because it is the basis for the altered design and because money was spent for parts on this design. Luckily, many of the parts could still be used in the new design.

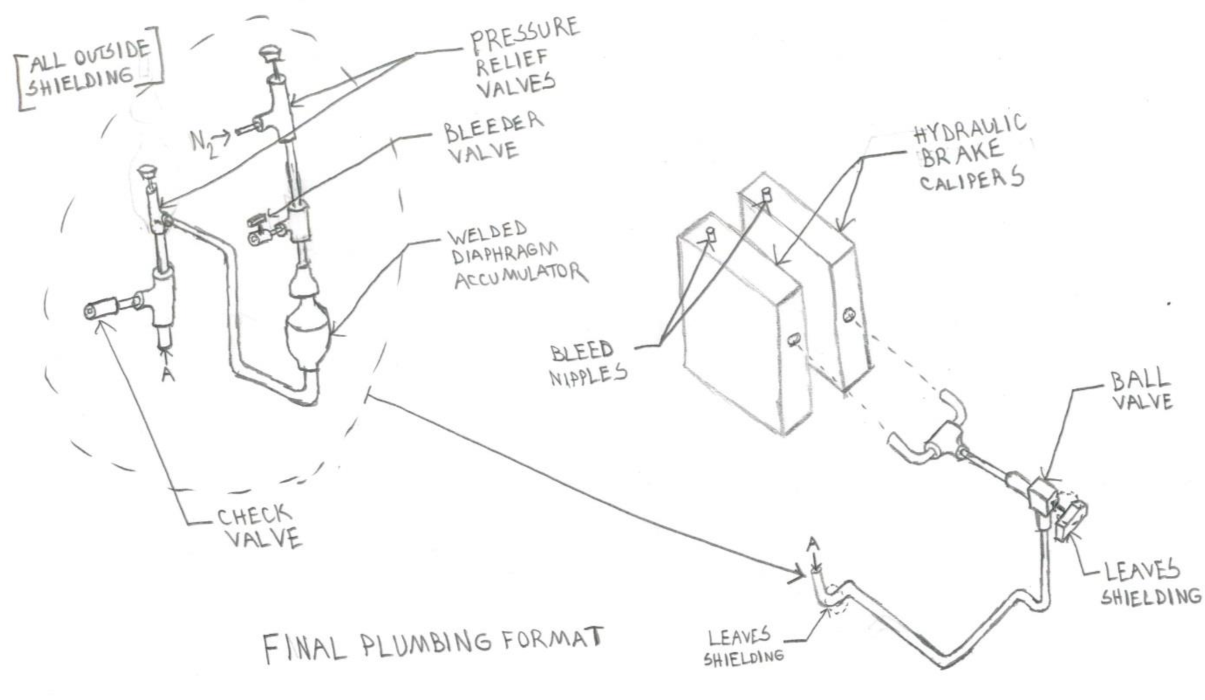


FIGURE 14. SEMIFINAL PLUMBING FORMAT (AFTER FEEDBACK)

**NOTE: The relief valves in the drawing represent a T joint with a relief valve connected to its third end.

The plumbing system, shown in Figure 14, will allow for the hydraulic side of the system to be charged through the check valve in the line, and then bled through the bleed nipples on the brake calipers. The brakes can be actuated by setting the nitrogen tank's regulator to the appropriate pressure (assumed to be 500 psi but this set pressure may be changed after testing) and then by opening the ball valve. The system's pressure can be returned to atmospheric pressure by closing the nitrogen tank's regulator and then bleeding the pneumatic side through the bleeder valve attached to the line. This will allow the students to operate the disk brakes during the experiment.

This design requires the plumbing to run outside of the shielding and to be near the student (so that the student can access the bleeder valve), so there is no significant benefit to keep the ball valve inside the shielding as well. Because of this, a slight modification was made to the design before creating the semifinal plumbing schematic. The ball valve was moved from the hydraulic side of the plumbing system, to the pneumatic side of the plumbing system. The semifinal plumbing schematic with this change incorporated can be seen in Figure 15.

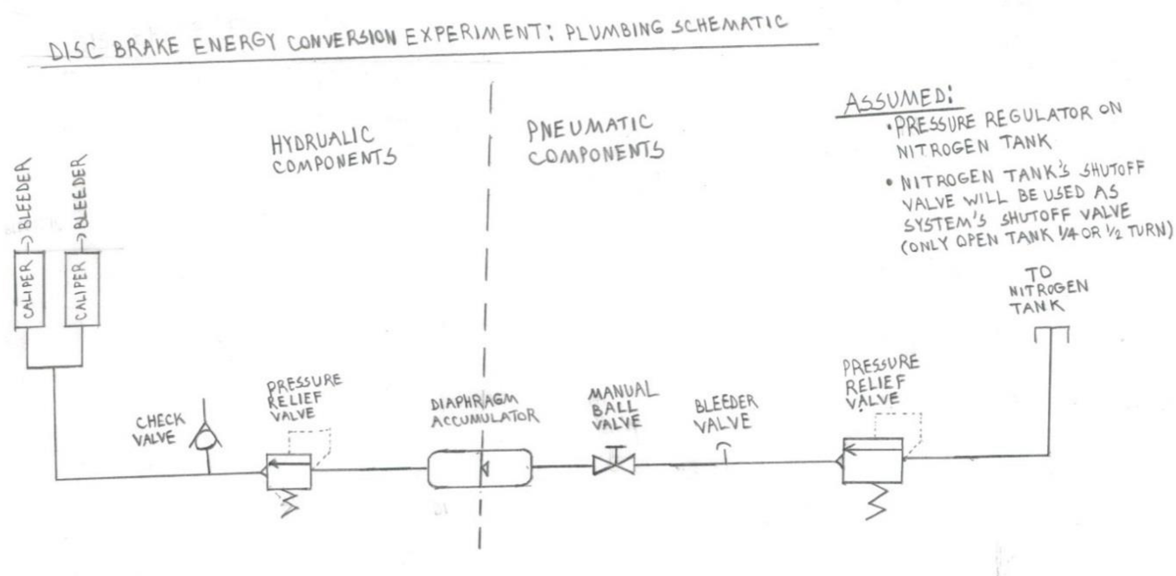


FIGURE 15. DETAILED PLUMBING SCHEMATIC OF SEMIFINAL SYSTEM

Parts for the plumbing components have been found in Swagelok catalogs except for the fitting which connects the accumulator to the diaphragm accumulator. This fitting needs to be a connection between ¼" tubing and a male M28X1.5 thread, which could not be found in any Swagelok catalogs. The first idea to solve this problem was to purchase an adapter for the male M28X1.5 threads that would reduce to a smaller male threads which could fit a Swagelok component to connect to the ¼" tubing. However, after browsing catalogs from other manufacturers, we were unable to find an adapter to reduce the M28X1.5 threads to fit a Swagelok adapter. The next idea was to manufacture our own adapter or to take to adapters that fit the ¼" tubing and the M28X1.5 thread and weld those adapters together. However, the sponsor expressed a desire to not manufacture any parts of the plumbing by ourselves. This is desired to ensure that the parts used in the plumbing are certified and reliable, and this is the same reason behind the sponsor's requirement to construct the plumbing using Swagelok components. With this new information, our idea transitioned back to using adapters to connect the accumulator to the pneumatic side of the plumbing system. After browsing through fittings from several different manufacturers, a possible solution was found. Five adapters were found that could connect from the male M28X1.5 thread to the ¼" Swagelok tubing. However, this would cost approximately $250 in the adapters alone. And using five adapters in series to form one connection is not acceptable, even though it would work. Because of this, we are continuing to search for a valid solution to this connection and will be seeking advice from local pneumatic supply companies (such as Airgas) about how to connect the accumulator's male M28X1.5 threads to the ¼" tubing. This means the bill of materials for the plumbing is incomplete. The current bill of materials is shown in

Table 4. Plumbing BOM as of 11/19/15

Qty	Part number	Manufacturer	Purchased?	Description	Cost ($ USD)
1	SS-42GS4-A	Swagelok	NO	Manual Ball Valve	99.16
1	SS-4C-1	Swagelok	NO	Check Valve	52.60
4	316L-400-3	Swagelok	NO	T Joint (to connect tubing to check and relief valves)	26.68
1	SS-400-3TTF	Swagelok	NO	T Joint (to connect bleeder valve to tubing)	30.05
2	316L-400-1-2	Swagelok	NO	Adapter for Calipers (Between tubing and female caliper connection)	8.09
1	SS-400	Swagelok	NO	Adapter from tubing to hydraulic port of accumulator	16.17
1	304L-T4-S-035-20-S	Swagelok	NO	20 ft of 1/4" tubing (smallest increment for ordering)	86.20
1	SS-BVM2-SH	Swagelok	NO	Bleed Valve for pneumatic side	58.13
1	NA	NA	NO	Adapter from tubing to pneumatic port of accumulator	NA
1	SS-4R3A-MO	Swagelok	YES	Pressure relief valve	[208.26]
1	SS-4R3A-MO	Swagelok	NO	Pressure relief valve	208.26
1	SBO 250	Hydac	YES	Welded Diaphragm Accumulator	[274.00]
				Total Price ($ USD)	673.47

4. Description of Final Design

4.1. Overall Description

The previous design involved a 60 lb. flywheel attached to a shaft that was equipped with a disk situated in between two hydraulic disk brake calipers. This shaft would be connected to a motor through a coupler/ For measurement, the previous team planned on measuring brake pad temperature through thermistors attached to the rear face of the brake pads, and we presume they planned on measuring the shaft speed through the frequency of the variable frequency drive (VFD). The previous team managed to build most of their design.

The final design will remain similar to the previous design, and the physical aspects of the design are mostly assembled. The following improvements will be made to the previous team's design: 1) A control panel will be added, 2) A hydraulic system will be added, 3) If necessary, the aluminum framing will be switched for steel framing, and 4) If (3) was necessary, a cage will be placed around the flywheel for added safety and the frame will be bolted to the floor.

4.2. Detailed Design Description

The previous team gives a detailed description of their final design in their senior project report which is available online (Ward, Wallace and Waltman). Therefore, we will give a detailed description of the changes that will be made to their design. And later, in section 7. Conclusions and Recommendations, we will review the entire design.

4.2.1 Control Panel

A control panel will be added so that both the VFD and the plumbing components can be mounted securely, and so that the student has easy access to the controls for the experiment. The figure below shows the experiment with the frame for the control panel attached. The orange section represents the occupied space of the experiment, and the grey section represents the control panel frame constructed of 1.5" X 1/8" angled steel beams welded together. This panel will support the VFD on the top right of the panel, and will support most of the hydraulic components on the rear of the panel. The manual ball valves and the manual override pressure relief valves will be placed on the front, left of the control panel so that students can access these components.

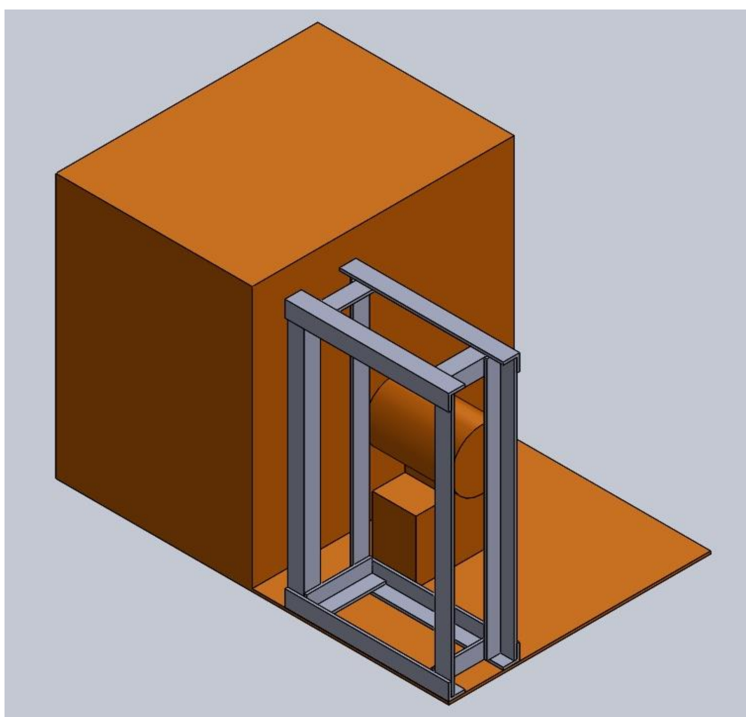


FIGURE 16. CONTROL PANEL FOR EXPERIMENT

4.2.2 Plumbing System

Besides a control panel, a hydraulic system will be added as well. The previous team did not have a hydraulic schematic or design for their experiment. They did attempt to attach some plumbing to the hydraulic disk brake calipers, as seen below.

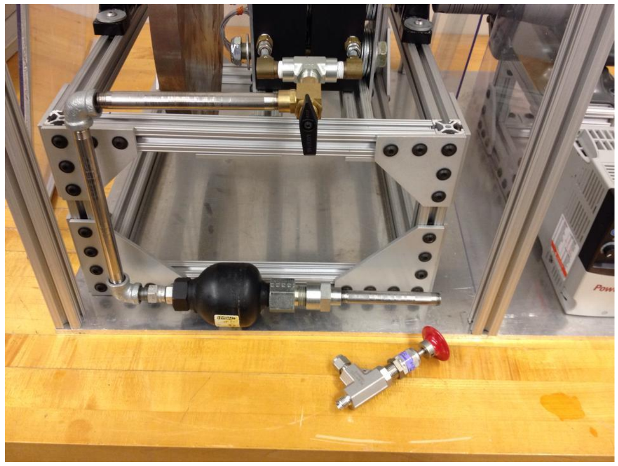


FIGURE 17. PREVIOUS TEAM'S PLUMBING

This plumbing must have been for presentation purposes since the piping machined and threaded by the students, and the connections between some of the hydraulic components were loose and could not be threaded fully. However, this plumbing led to the eventual design of the hydraulic system for this experiment. A W.C. Branham plumbing schematic for hydraulic brakes was found, and this was used to design the final plumbing schematic. The W.C. Branham schematic and the final plumbing design can be seen in the figures below.

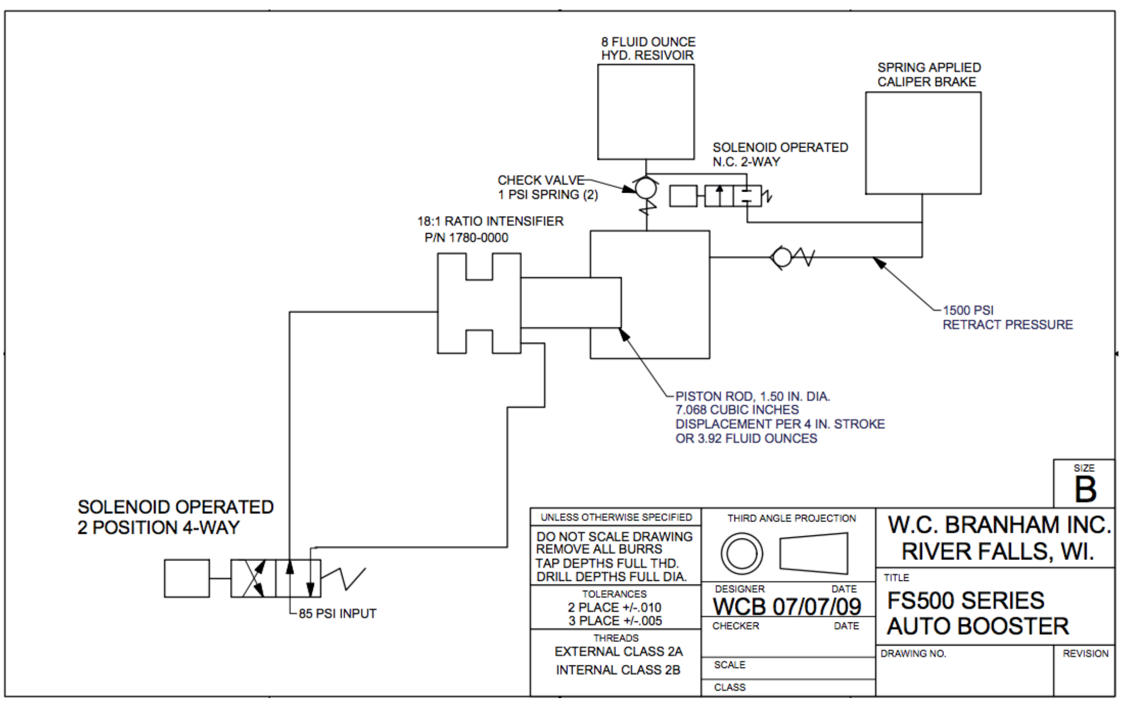


FIGURE 18. W.C. BRANHAM SCHEMATIC

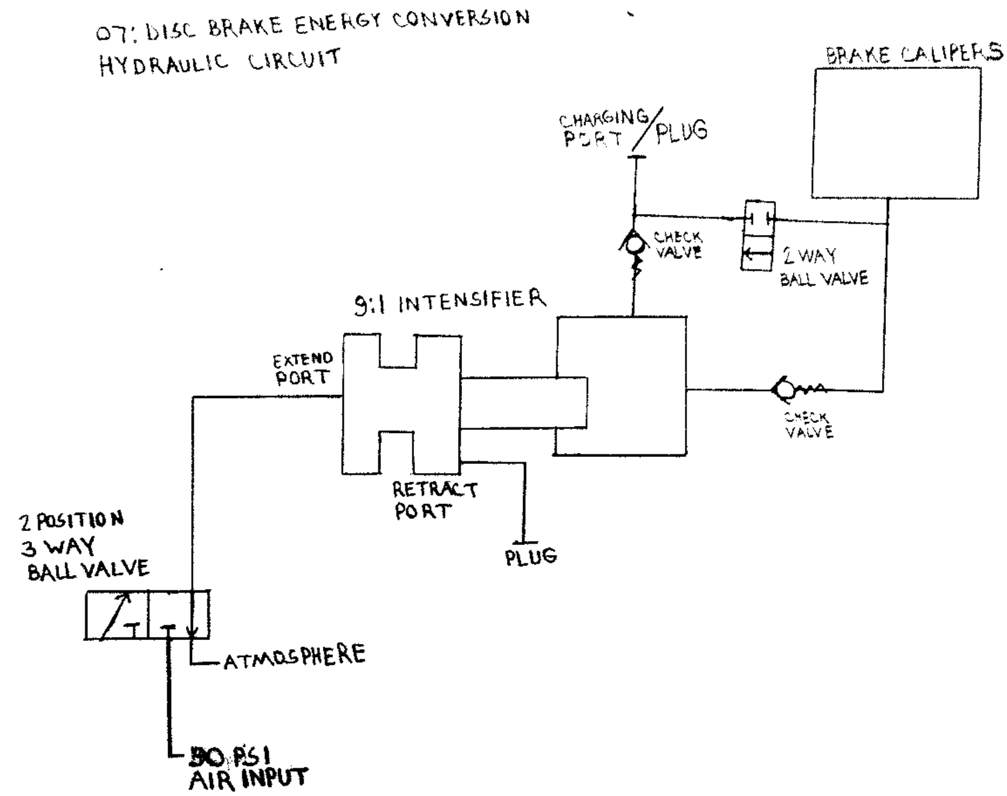


FIGURE 19. FINAL PLUMBING SCHEMATIC

After several iterations of the plumbing design, the above design was found on W. C. Branham's website, and it matches our final plumbing iteration almost exactly (the only difference being the solenoid valves, the intensifier ratio, and the input air pressure). This schematic will therefore be our final design schematic for the plumbing. Since W. C. Branham is a trusted manufacturer and this schematic is from them, we are able to trust that are final plumbing design is correct. The first component to fail in this design will be the hydraulic disk brake calipers, which have a maximum operating pressure of 1500 psi. A pressure relief valve will be placed into the system to ensure that pressures above 750 psi result in hydraulic fluid being expended into the hydraulic reservoir. This will prevent the system from failing.

During braking, the students will move the 4 way valve so that shop air at 120 psi enters the system and, through the intensifier (which will be discussed in the next section), pressurizes the hydraulic oil to a greater pressure (around 500 psi, but this is dependent on the intensifier ratio). This pressure will push the brake pads against the brake disc and cause the main shaft to stop. After braking is finished, the student will open the two way ball valve so that the pressurized hydraulic fluid can enter the hydraulic reservoir. Then the student will move the 4 way valve so that the shop air leaves the system and relieves the pressure on the intensifier so that the brake pads retract and the system returns to its normal state.

4.2.3 Intensifier

The intensifier is a mechanism that uses a cylinder and a difference in area ratios to convert low pressure air into high pressure hydraulic oil. This schematic for an intensifier is shown below.

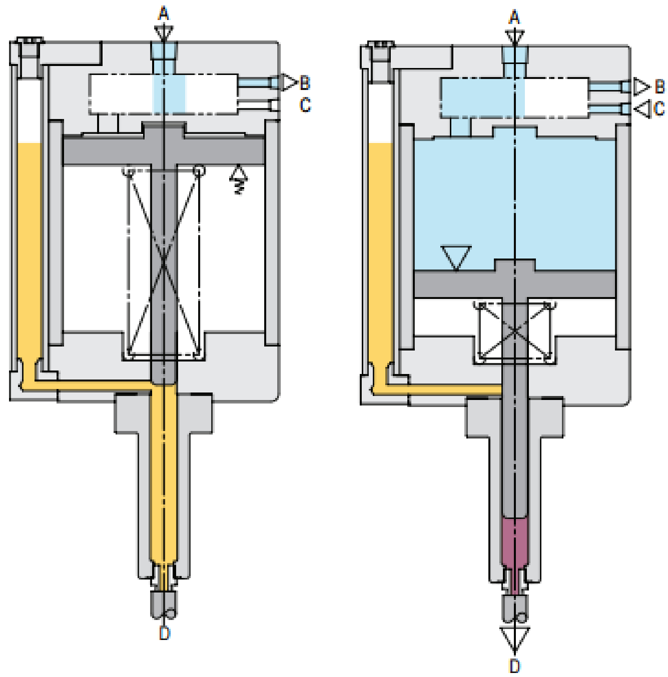


FIGURE 20. SCHEMATIC OF INTENSIFIER

FIGURE 21. PICTURE OF INTENSIFIER

The intensifier, also called a booster, was recommended to us by Dr. Owen. This device will allow us to achieve high pressure oil without using high pressure gas. This will make the experiment significantly safer; however, intensifiers are expensive and range in price from $300 to $600, or even in the thousands of dollars. Even though this component is expensive, it is necessary for a safe experiment that uses an air to oil hydraulic brake system. The other recommendations to improve the safety of the experiment from the previous high gas plumbing system, was to use air brakes and to combine multiple low pressure lines to achieve the equivalent braking force of a higher pressure. Another suggestion was to use multiple bicycle brakes to brake the main shaft. However, the intensifier is the final decision since the other recommendations would require significant changes to the current design, and we do not have time to make those changes.

4.2.4. Steel Frame

The building of the experiment is still being finished, and we are waiting to test the machine for rotational imbalance or structural issues (such as the machine jumping when the brakes are applied) before we determine whether or not the current aluminum frame must be replaced with a steel frame. If the machine needs additional stiffness and support in order for the experiment to be safe, then the aluminum frame will be replaced with a steel frame, and then the steel frame will be bolted to the floor of the Thermal Science Lab. But until we are able to test the machine, we will be operating under the assumption that a steel frame is not needed.

4.2.5. Experiment and Manual

The manual for the experiment has not been designed or brainstormed because the format and outline for the manual has already been determined by the existing experiments. The existing experiments have manuals already In place that have a specific format, and we wish our manual to match this format (Since changing the format may confuse students who are used to the standard lab manual format).

The experiment will be adjusted and designed more fully later during testing. But for now, it consists of the students first checking the equipment to ensure the experiment is safe and operational, perhaps performing a trial run without data to help ensure the experiment is functional and to allow the students to become familiar with the controls for the experiment. Next, the students will gather data for the experiment. We expect to have students running one run and gather data once every 10 minutes at least. Lastly, the students will Make a record of the uncertainty of the measuring equipment, and will generate results and answer discussion questions. The results so far will require the students to calculate the Joule's constant for each run, and to take the statistical average of them and compare both the run values and the averaged value with the published value. The discussion so far will require the students to discuss sources of error in the experiment, to discuss how more accurate results could be obtained, and how increasing the speed of the shaft, decreasing pressure to the brakes, and changing the disk brake material would affect the experiment results.

4.3. Analysis Results

While most of the analysis was performed by the previous senior project team, we performed some analysis for the control frame, the plumbing, and for measuring the Joule's constant.

4.3.1 Control Frame Analysis

The control panel frame was too complex to perform accurate deflection and strength analysis, so we instead analyzed the deflection of an individual vertical, flat beam of ¼" thickness fixed to the baseplate. According to our calculations, a single flat beam will experience a maximum deflection of .002 inches if the panel components way 25 lb.s and create a center of mass 1 in away from the surface of the frame. This means that the panel components will not cause the frame to significantly deflect since the frame will be several beams connected together, and the deflection of one beam was not significant.   Furthermore, if a 200 lb. force is applied perpendicularly to the single, vertical beam, it will experience a maximum deflection of .25 inches. This is a significant deflection for a single beam; however, the actual frame will consist of angled beams and will consist of several beams connected together as well. So the deflection of the frame will be much less than the deflection of a single beam. Since the deflection of the frame will be much less than .25 inches under a 200 lb. force, the frame will not significantly deflect under a 200 lb. Force.

4.3.2. Plumbing Analysis

Most of the plumbing analysis was verification rather than calculations. The manufacturers' information about the operating pressure for the tubing, fittings, and other components were found and compared to our operating pressure. As long as a component's maximum operating pressure exceeds our design operating pressure, that component is acceptable. This method of analysis was preferred to calculations since the manufacturer's information is more reliable than the results of calculations we perform for maximum operating pressure. So we relied on the manufacturers' data sheets for determining which plumbing components to include in the design. The component that has the closest operating pressure to the design operating pressure of 500 psi is the hydraulic disk caliper, which has a maximum operating pressure of 1500 psi.

4.3.3 Measurement Analysis

In order to achieve the most accurate results, we first performed thermal analyses using both EES and SolidWorks Thermal Simulator. These tools help provide us with an idea of what type of thermal gain we will be able to achieve at a given speed and pressure. Both of these values can easily be adjusted, and therefore it will allow us to fine tune our experiment before we even begin testing. Once testing actually begins, we will be testing the device to see what value we get for Joule's constant. This is an easy calculation, simply the change in kinetic energy of the device over the change in thermal energy. However, this value will most likely not be very accurate at first. Therefore a large part of testing will be identifying the sources of error and accounting for losses in the calculations.

4.4. Cost Analysis

Below is the Bill of Materials (BOM) for the entire project which lists the costs required to build and assemble the final design. Some components from this BOM were not used (such as the hydraulic reservoir) because of changes to the final design near the end of the project.

TABLE 5. BILL OF MATERIALS FOR FINAL DESIGN

Vendor	Part Number	Description	Price per unit	Qty	Line Price	Contact info
Swagelok	SS-42GS4-A	Manual Ball Valve	$92.00	1	$92.00	(805)384-1060
Swagelok	SS-4C-1	Check Valve	$49.05	1	$49.05	(805)384-1060
Swagelok	SS-400-3	T Joint (to connect tubing to check and relief valves)	$23.34	4	$93.36	(805)384-1060
Swagelok	SS-400-1-2	Adapter for Calipers (Between tubing and female caliper connection)	$7.13	2	$14.26	(805)384-1060
Swagelok	304L-T4-S-035-20-S	20ftof 1/4" tubing (smallest increment for ordering)	$86.20	1	$86.20	(805)384-1060
Swagelok	SS-4R3A-MO	Pressure relief valve	$208.26	1	$208.26	(805)384-1060
Swagelok	SS-41GXS2	3 way Ball Valve	$120.00	1	$120.00	(805)384-1060
Summit Racing	AAF-ALL42046	Hydraulic Reservoir	$60.00	1	$60.00	1(800)230-3030
ACE Hardware		Angled Steel Framing	$28.00	3	$84.00	1(888)827-4223
ACE Hardware		Fasteners (1/4" bolts, washers, nuts)	$10.00	1	$10.00	1(888)827-4223
W.C. Branham		Air/Oil Intensifier	$536.00	1	$536.00	(715)426-2000
Swagelok	SS-41GXS2	3 way Ball Valve	$120.00	1	$120.00	(805)384-1060
Summit Racing	AAF-ALL42046	Hydraulic Reservoir	$60.00	1	$60.00	1(800)230-3030
W.C. Branham		Air/Oil Intensifier	$536.00	1	$536.00	(715)426-2000
TOTAL					**$2,069.13**	

4.5. Material, Geometry, Component Selection

Steel was selected for the control panel because it offered more stiffness and strength than aluminum, and is widely available so it could be acquired from a local hardware store. The shape of the frame was selected as a box to make the frame stiff and resistant to deflection.

Swagelok components were selected for the plumbing by sponsor request. Swagelok components are certified, trusted, and well known for their reliability. And since this experiment will be used by students for upcoming years at Cal Poly, it is essential that this experiment be as safe and reliable as possible. For this reason, the Sponsor strongly suggested we use Swagelok tubing and fittings when possible.

The intensifier was selected to reduce the pressure of the air during the experiment, and thus make the experiment safer for students. The other components being used (such as the previous team's pressure relief valve) was not selected. We attempted to design around the previous team's components as much as possible to avoid further spending on this project. In fact, the high pressure air design (the SEMIFINAL PLUMBING DESIGN) was inspired by a desire to salvage all of the previous team's purchased parts. However, the high pressure gas plumbing design is too dangerous to implement, so we will need to purchase additional components.

4.6. Flowcharts, Schematics, and Wiring Diagrams

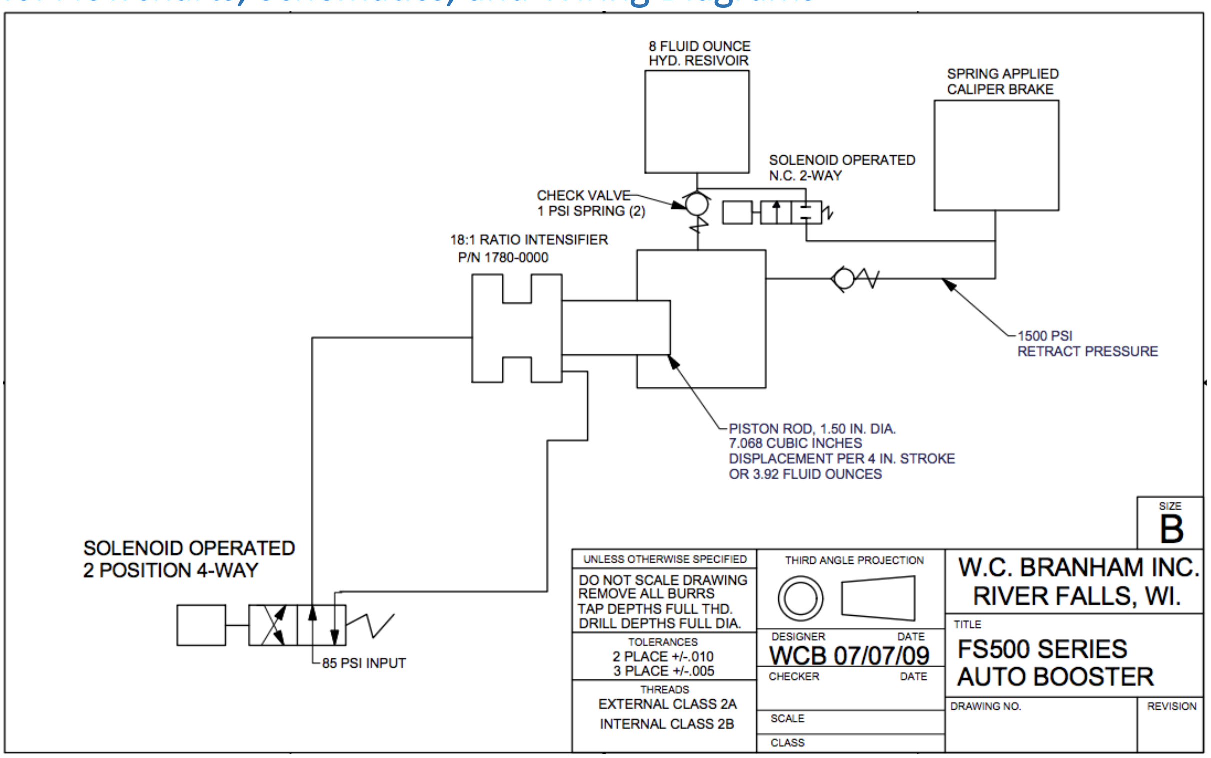


FIGURE 22. W.C. BRANHAM SCHEMATIC

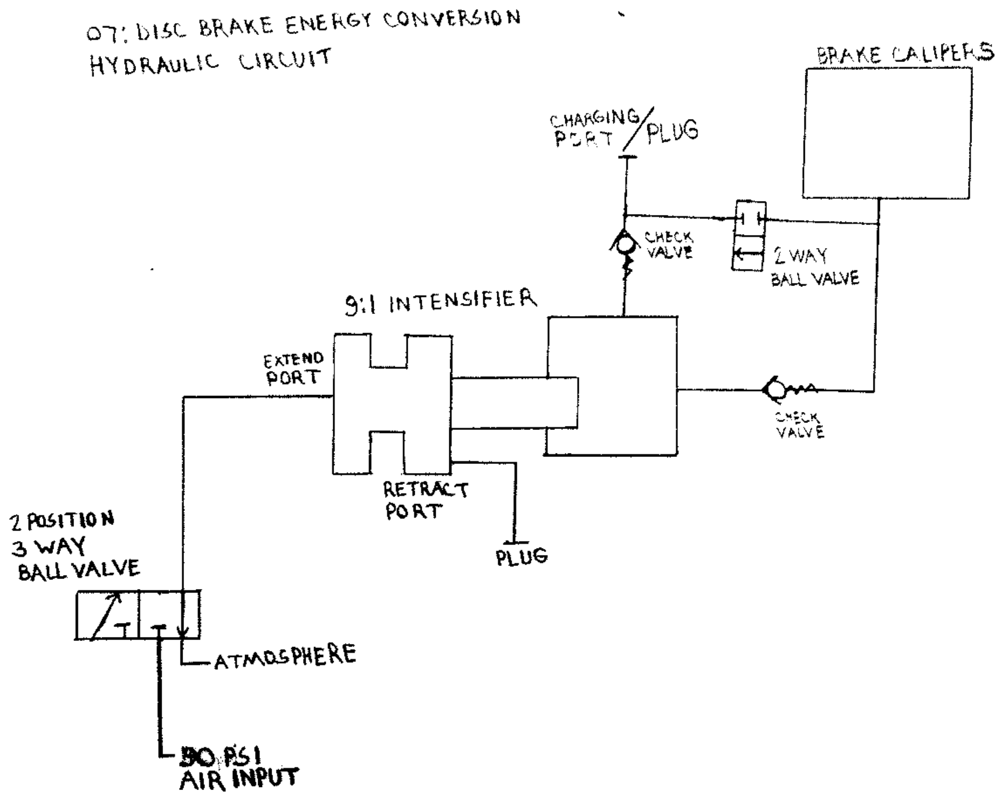


FIGURE 23. FINAL PLUMBING SCHEMATIC

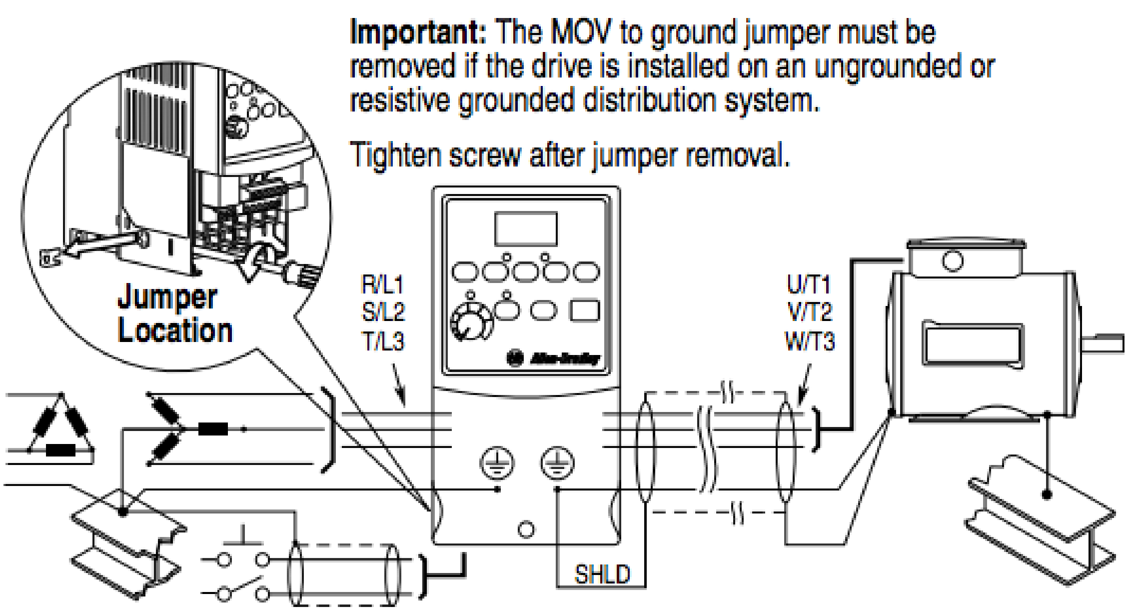


FIGURE 24. WIRING SCHEMATIC

4.7. Special Safety Considerations

The greatest risks in this experiment were or are the high pressure gas and the high speed, heavy flywheel. The high pressure gas is no longer a serious concern because the new plumbing design has removed the use of high pressure gas. The high speed flywheel is still a concern though, and we will take steps to more rigidly secure the flywheel and to place a cage around the flywheel if testing the machine shows that the flywheel has any noticeable (to the human eye) rotational imbalance. Below is the safety checklist for the experiment, as well as the FMEA table for the experiment. Besides the flywheel and the high pressure gas, the next highest concerns were the coupler not being securely attached or the disk brake over heating because the user did not turn off the power before braking the motor. The recommended action to solve most of the failure modes, including the coupler not being securely attached, is to require the students to perform a pre-experiment check on the machine to ensure it is fully operational. The recommended action to prevent the disk brake from overheating and warping is to makes notes both in the manual and on the control panel that brakes should not be applied unless the motor power is turned off. While a more effective action would be a control system that turn off the motor whenever the brakes are applied, such a control system is beyond the scope of this budget. And notes will be sufficient enough to reduce the risk of the disk brake overheating.

ME428/429/430 Senior Design Project 2015-2016

SENIOR PROJECT CONCEPT DESIGN HAZARD IDENTIFICATION CHECKLIST

Team: ______________________________________ Advisor: ____________________

Y	N	
☐	☐	Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
☐	☐	Can any part of the design undergo high accelerations/decelerations?
☐	☐	Will the system have any large moving masses or large forces?
☐	**☐**	Will the system produce a projectile?
☐	**☐**	Would it be possible for the system to fall under gravity creating injury?
☐	**☐**	Will a user be exposed to overhanging weights as part of the design?
☐	☐	Will the system have any sharp edges?
☐	**☐**	Will any part of the electrical systems not be grounded?
☐	☐	Will there be any large batteries or electrical voltage in the system above 40 V either AC or DC?
☐	☐	Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
☐	**☐**	Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
☐	**☐**	Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
☐	**☐**	Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
☐	**☐**	Can the system generate high levels of noise?
☐	**☐**	Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
☐	☐	Is it possible for the system to be used in an unsafe manner?
☐	☐	Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses, add a complete description, list of corrective actions to be taken, and dates to be completed on the reverse side.

FIGURE 25. SAFETY CHECKLIST FOR EXPERIMENT

TABLE 6. FAILURE MODES AND EFFECT ANALYSIS (FMEA)

Component / Function	Potential Failure Mode	Potential Cause(s) Mechanism(s) of Failure	Local Effects of Failure	Next higher level effect	System level end effect	Probabil.	Severity	Detection	Detection Dormacy	Risk priority number	Recommended Action(s)	Responsibility & Target Completion Date
Screw for lower framing	(a)Coming Loose; (b)Shearing at the shaft or at the head	(a) Not tightened fully during installation; (b)Tightened too much during	(a) and (b): Bracket and Aluminum brace are no longer connected	(a) and (b): The other screws will take more of the	No effect	4	1	1	Every time machine is turned on	4	Define a required torqure for pre-stress of the screw during installation.	
3 Screws for lower framing	(a) All screws come loose or shear	(a)significant load applied to the frame; All screws not tightened properly	(a) Bracket and framing become completely disconnected	(a) Framing leans on one side and is no longer horizontal	(a) Calipers scrape against disk brake	1	7	1	Immediately	7	Require screws to be checked before operations and set maximum operating	
Motor	(a) Will not rotate output shaft	(a) Wiring short; Broken internatl component, incorrect wiring	(a) Output shaft will not turn	(a) Flywheel is not energized	Experiment cannot be completed	1	7	1	1 week	7	Have certified personell check the wiring for the motor.	Coleman and Jeff; 1/30

General Framing	(a) fatigue fracture, (b) Static load fracture	(a) Stresses over time cause a frame meber to fracture; (b) A large load is applied to a	(a) and (b) Frame can no longer support a load or link other	(a) and (b) Other frame members or fasteners	(a) and (b) Framing for the macine is weaker, and may hinder	1	4	1	Immediately	4	Use thicker framing or a stronger material for the framing.	
Mainshaft with keys.	(a) Shaft shears; (b)Shaft deflects during spinnign (c)Keys shears;	(a) Shaft becomes held at one endwhile motor supplies power; (b) Shaft is spun at or near its critical speed; (c)Shaft is held in place while powered or fatigue.	(a) Shaft is split into two sides; (b) Shaft deflects while spinning; (c)Shaft is not connected to shaft a	(a) Components may fall off shaft, and only one side will spin; (b) Significant vibration may	(a) Experiment cannot be ompleted, Possible projectiles	1	10	1	Immediately	10	Advise a maximum operating speed and also advise user to slowly speed up the shaft to ensure no sudden forces /impulses	
Coupler	Coupler slips on one fo the shafts	Coupler is not properly installed (setscrews are not tightened down enough)	The motor shaft and mainshaft are no longer attached.	Power is no longer supplied to the mainshaft.	The experiment is no able to be completed.	4	7	1	Immediately	28	Advise a torque to apply to the coupler setscrew during installation of	
Bearing A (far from motor)	(a) Bearing failure; (b) Bearing shears from framing	(a) Foreign material enters bearing; Improper installation; (b) Excessive axial load is placed onto bearing	(a) Bearing makes noise or can no longer spin freely;	(a) Shaft is unable to spin freely or squeaks during rotation; (b) Shaft can move freely on one side	The user may not be able to perform the experiment; the results may not be accurate	4	7	4	1 day	112	Advise students to test the bearings before the experiment to ensure they can spin freely; Ensure bearing are installed by someone with experience installing	

Bearing B (close to motor)	(a) Bearing failure; (b) Bearing shears from framing	(a) Foreigh material enters bearing; Improper installation; (b) Excessive axial load is placed onto bearing	(a) Bearing makes noise or can no longer spin freely;	(a) Shaft is unable to spin freely or squeaks during rotation; (b) Shaft can move freely on one side	The user may not be able to perform the experiment; the results may not be accurate	4	7	4	1 day	112	Advise students to test the bearings before the experiment to ensure they can spin freely; Ensure bearing are installed by someone with experience installing	
Flywheel	Flywheel fractures or shears from shaft	Fatigue, Excessive RPM, Flywheel Imbalance	Flywheel is no longer attached to shaft	Flywheel becomes a heavy metal projectile	Possible serious personal injury, experiment cannot be performed	4	10	7	Immediately	280	Build metal cage around device that will stop flywheel even if it becomes a projectile. Advise students to not operate above a certain RPM to reduce risk	
Disc Brake	(a) Disk Brake warps	(a) Brakes applied while shaft is powered.	(a) Disk brakes surface is no longer consistent/u	(a) Braking becomes inconsiste nt	(a) Inaccurate results	7	7	4	1 day	196	Warn user not to power the shaft when the disk brakes are	
Frequency drive	(a) Malfunction of frequency drive; (b) Frequency drive overloaded	(a) Improperly manufactured frequency drive; (b) Improper installation	(a) and (b) Frequency drive does not function	(a) and (b) Motor does not turn the mainshaft	(a) and (b) Experiment cannto be performed	1	7	1	Immediately	7	Test frequency drive after installation, and ensure an experienced installer installs the frequency	

Framing for shaft	Fracture	Fatigue or excessive static load.	Shaft is no longer vertically supported on one end.	Coupler experiences excessive moment and shaft will not turn properly	Experiment cannot be performed accurately, or possibly at all	1	7	1	Immediately	7	Directly brace the shaft bearing underneath the bearing itself. And/or specify maximum operating speed	
Framing for motor	Fracture	Fatigue or excessive static load.	Motor may no longer be secured	Motor wmay turn itself instead of the shaft, possible may become a projectile.	Experiment cannot be perofrmed, and possible user injury.	1	10	1	Immediately	10	Specify maximum operating speed. Add safety wiring that will short the motor should it leave its mounting position	
Calipers	Does not actuate	Excessive leakage in the hydraulic system or inside the calipers	Brake pads are not extended.	Brake pads never engage and stop the disc brake	Experiment cannot be performed	1	7	1	immediately	7	Advise students to check the hydraulic brakes before beginning the experiment (test brake)	
Brake Pads	Fracture	Excessive force when engaging disk brake	Brake pads may become projectiles when engaged with spinning disk	Disk does not stop.	Possible injury and inability to complete the experiment.	4	10	1	immediately	40	Ensure spacing between calipers is not excessive, and specify a maximum actuating pressure	

Screws/braces for calipers	Axial moment induced fracture	Fatigue, excessive braking force.	Calipers are no longer held in place.	Disk brake does not stop, and possible projectile	Possible injury and inability to complete the experiment.	4	10	1	immediately	40	Specify maximum actuating pressure. Reinforce caliper bracing	
Bolts for calipers	Shearing at caliper surface	Fatigue, excessive braking force.	Calipers are no longer held in place.	Disk brake does not stop, and possible projectile	Possible injury and inability to complete the experiment.	4	10	1	immediately	40	Specify maximum actuating pressure. Reinforce caliper bracing for	
Baseplate	Fracture	Possibly by dropping the machine	Worst case scenario, motor is thrown out of line (or	Shaft cannot turn properly.	Experiment cannot be performed	1	7	1	immediately	7	Specify required method to transport the machine.	
Shielding	Fractures	Excessive impact	Shield is no longer intact or in place.	Object that impacted the shield continues, and parts of the shield	Injury and inability to complete the experiment.	4	10	1	immediately	40	Use thicker shielding and/or ensure rotating components are extremely well secured	
Diaphragm accumulator	Leakage/Explosion of accumulator	Accumulator is supplied with a pressure above 1500 psi, or experiences a significant impact.	Accumulator no longer transfers pressure.	High velocity gas escapes from the accumulator.	Personal injury and experiment cannot be performed	1	10	1	immediately	10	Place protective shielding around the accumulator and advise user not to work near the	

Pressure relief valve (pneumatic side)	Failure to exhaust gas when pressure exceeds the maximum pressure.	Valve failure (faulty valve) or release pressure was set improperly.	Plumning is exposed to excessive pressure.	If high enough, the accumulat or or calipers will fail.	Personal injury and experiment cannot be performed	1	10	1	immediately	10	Ensure pressure relief valves are properly installed and set. (experienced installer)	
Pressure relief valve (hydraulic side) [both valves]	Failure to exhaust fluid when pressure exceeds the maximum pressure.	Valve failure (faulty valve) or release pressure was set improperly.	Plumning is exposed to excessive pressure.	If high enough, the accumulat or or calipers will fail.	Personal injury and experiment cannot be performed	1	10	1	immediately	10	Ensure pressure relief valves are properly installed and set. (experienced installer)	
Tubing	Tubesburst/ detach from a fitting	Improper installation	High velocity fluid leaves the system.	No power to hydraulic brakes. High velocity fluid.	Personal injury and experiment cannot be performed	1	10	1	immediately	10	Check fittings after installations and ensure installation is done by experienced	
tube braces on frame	Braces detach/brea k off of frame	Improper mounting or braces are not strong enough	Tubing no longer secured to the frame.	Larger forces applied to the tubing and fittings. More range of motion. Tubing/fitti	Personal injury and experiment cannot be performed.	1	10	1	immediately	10	Check bracing after installation to make sure it is secure. Regular inspection of braces can be done quickly and easily	

Tube braces on shielding	Braces detach/break off of shielding, or shielding breaks.	Braces not mounted properly or shielding gets broken from operator or piece of equipment.	Tubing no longer secured to the frame.	Larger forces applied to the tubing and fittings. More range of motion.	Personal injury and experiment cannot be performed.	1	10	1	immediately	10	Check bracing after installation to make sure it is secure. Regular inspection of braces can be done quickly	
Wiring to Frequency drive	Wiring becomes loose/undone, exposed wiring.	Wires are not secured well enough and get pulled out of the frequency drive.	Exposed wires to the operators of the device.	Still high voltage running in the wires while it is exposed to the students.	Personal injury and experiment cannot be performed.	4	10	1	immediately	40	Make sure wires are installed by professional with solid connections. Regular inspection of cables before operating	

4.8. Maintenance and Repair Considerations

Maintenance and Repair is not difficult, but is inconvenient to the technician performing the repair. The motor and the main framing is connected to the baseplate through bolts. The head of these bolts are on the bottom surface of the baseplate, which requires the technician to lift the sixty plus pound experiment in order to access those bolts. We attempted to make this slightly less inconvenient by adding a foam pad underneath the experiment. This foam pad will facilitate technicians in lifting one side of the machine because it will be less difficult to separate the Aluminum baseplate from the foam than it would be to separate the aluminum baseplate from the wooden table. However, it will be more difficult to slide the aluminum off the foam than it would be to slide the aluminum off the wooden table because of the foams less slippery surface (the foam's higher coefficient of friction). But this is a benefit to the experiment and will not hinder repairs

The control panel was designed with repair and modification in mind, so the nuts of its bolts are accessible from the top of the baseplate. This makes removal of the control panel much simpler and faster than removal of the other components attached to the baseplate.

5. Product Realization

The control panel and the hydraulic circuit were the only aspects of the design that had yet to be manufactured. The control panel was manufactured in the Hangar during the winter quarter of 2015. And the hydraulic circuit was manufactured in the beginning of the spring quarter of 2016.

5.1. Manufacturing Processes

The control panel framing was constructed out of steel with an aluminum plate connected to the front. ¼” thick angled steel beams 1.5” by 1.5” were used to construct the control panel. A horizontal band saw was used to cut the steel beams into various predetermined lengths. Each segment was cut slightly longer than necessary. The next step involved trimming the steel beam segments to exact length using a mill. This was the most time consuming manufacturing process for the control panel manufacturing. After the steel beam segments were cut and trimmed to their specified lengths with a tolerance of +/- .10 inches, the segments were prepared for welding by cleaning and sanding the edges of the segments. After welding preparation was completed, the steel beams were welded together in the designed formation using MIG welder. The final step in manufacturer the control panel frame involved drilling holes into the bottom of the frame to allow the frame to connect to the baseplate of the machine for the experiment. And then drilling holes into the front of the frame to allow the control panel to be connected to the frame.

An aluminum sheet was sheered to fit the front of the control frame and to serve as the control panel. This control panel had multiple holes drilling into it in order to attach the control panel to the control frame and to attach the support for the hydraulic lines to the control panel. The control panel was fastened to the control frame using ¼” machine bolts.

The hydraulic lines were manufactured in the thermal science lab with handheld tube benders, tube cutters, a crescent wrench, Swagelok tubing and fittings, and a No-go gauge for Swagelok fittings. The lines were installed starting at the brake calipers and moving toward the intensifier. Each segment began with a starting point and a desired end point on the frame, with the starting point based on the previous segment installed, and the end point based on the desired position for the next segment to start. Measurements were taken to determine the X, Y, and Z lengths to reach the desired end point from the specified starting point (X and Y were considered parallel to the front of the baseplate, where the control panel faces, and parallel to the side of the baseplate respectively). After this, the segments were bent into shape using the tube benders and then cut from the tube stock, as shown in the figures below.

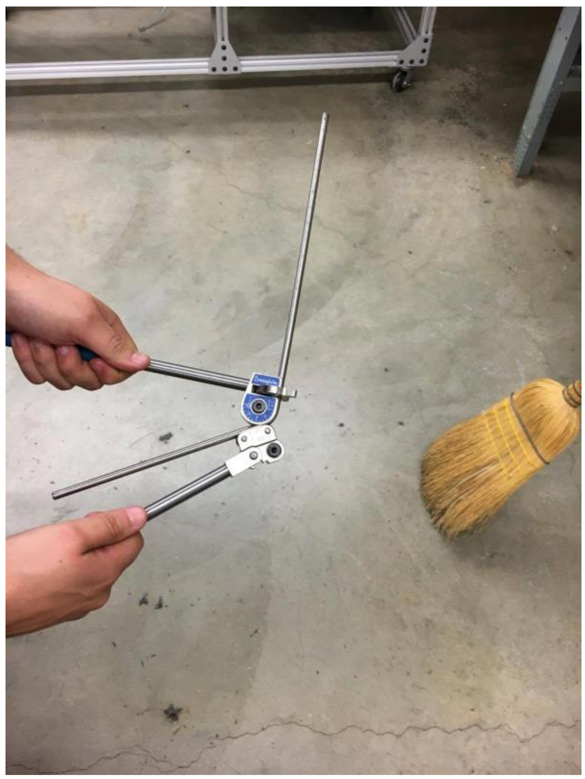


FIGURE 26. BENDING A TUBE

FIGURE 27. CUTTING A TUBE

Each hydraulic line (tube) was cut to its desired shape, and then the tubes were placed together to ensure that all of the tubes fit in the system and were the correct shape and size. After this was verified, the tubes were taken down to the workshop in Mr. Gerhardt's office in room 13-128. Here, the end of the tubes were ground flat and slightly chamfered. The tubes were then taken back to the thermal science room and installed, with supports attached to the tubing as much as possible. The installation involved tightening the Swagelok fittings and then checking the all the fittings with the no-go gauge to ensure the installation was performed correctly. The fittings installation and check can be seen in the figures below.

FIGURE 28. INSTALLING AND TIGHTENING A SWAGELOK FITTING

FIGURE 29. CHECKING SWAGELOK FITTING WITH NO-GO GAUGE

After the hydraulic lines were fully installed, the hydraulic system was then charged with hydraulic fluid using a charging set supplied by Mr. Gerhardt. The charging set consisted of a handheld cylindrical vessel which was used to push oil into the system. This vessel, once filled approximately ¾ full of hydraulic fluid, was pressurized to 10 psi. After pressurization, the vessel was connected to the hydraulic system through tubing between the vessel and the charging port of the system near the top on the control frame. The vessel was then inverted so that the oil rested at the bottom of the vessel and the pressurized air was at the top of the vessel. The vessel was then opened to allow the air to push the oil out of the bottom of the vessel and into the system. The bleed ports on the brake calipers were opened to allow air to leave the system and be replaced by the hydraulic fluid. This process was repeated until only oil came out of the bleed ports on the calipers. Then the bleed ports were closed, and the charging port for the system was plugged. The final step was verifying that the hydraulic system was functional by actuating the brakes. The hydraulic system being charged using the vessel and the air being bled out of the calipers can be seen in the figures below.

FIGURE 30. USING THE VESSEL TO CHARGE THE SYSTEM

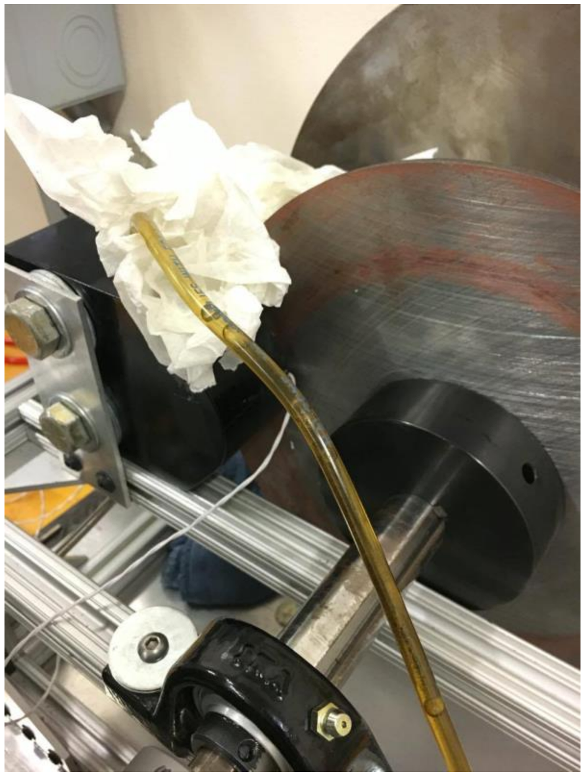


FIGURE 31. AIR BEING BLED FROM THE SYSTEM THOUGH THE BRAKE CALIPERS

5.2. Comparison of Prototype and Planned Design

The prototype constructed mostly matches the final design. The hydraulic circuit is identical to the final hydraulic circuit schematic, but the control frame constructed is slightly different in length than the planned control frame. This likely occurred from human error when cutting and welding the steel beam segments for the control frame. Furthermore, the original idea of attaching a hydraulic reservoir to the system (at its charging port) was abandoned when the purchased oil reservoir failed to work as expected. After this failure, the reservoir was removed from the prototype and the design, since it was an unnecessary addition.

The prototype differed from the previous team's design as well. The setscrews that attached the inner race of the bearing to the main shaft (the bearing closest to the motor) had to be removed in order to reduce the rotational imbalance in the system. Rotational imbalance in the system ceased to occur at low speeds when these setscrews were removed, and these setscrews were not significant since the worst case scenario caused by removing them would be the main shaft slipping inside the bearing, which has no significant effect on the experiment. Another change to the previous team's design was the addition of thermal paste inside the brake calipers. This paste was included to improve the thermistor measurements, and a Styrofoam backing was placed inside the calipers to add insulation while pressing the thermistor firmly against the copper brake pad. This addition can be seen in the figure below.

FIGURE 32. BRAKE PAD WITH THERMAL PASTE AND STYROFOAM BACKING ADDED

The last significant change to the previous team's design was changing motor mount frame's position. The framing that the motor is mounted on was moved farther away from the main shaft and was realigned to ensure that the motor shaft was no longer touching the main shaft and that the motor shaft was collinear with the main shaft.

5.3. Future Manufacturing Recommendations

It is recommended that assembly of the machine be performed by professionals, especially for the hydraulic system. Having the hydraulic system assembled by students was not dangerous during the project because Swagelok fittings were used (and it is difficult to install Swagelok fittings incorrectly) and the project team constantly asked for help in assembling the hydraulic system when they were not certain about how they should proceed. Another recommendation would be to use calipers instead of measuring tape when making measurements for bending and cutting the hydraulic lines to shape.

6. Design Verification Plan

6.1. Test Descriptions

The first test that will be performed on the device will be the flywheel imbalance test. The reason for performing this test is that to ensure the safe use of the device, the flywheel cannot show any signs of imbalance. During this test, we will operate the device at very low velocities at first, and then slowly increase the speed. Slowly increasing velocity will allow us to see if resonance is caused at any speed. Imbalance can lead to movement of the device as it is simply sitting on top of a table and not mounted to the floor in any way. Also, rotating a 60-pound flywheel at high velocities while it is imbalance can cause damage to the rest of the device and potentially break other parts of the device. The flywheel could even potentially fly off of the shaft, so if there is any imbalance seen in the flywheel, it must be sent back to be rebalance or a new flywheel will need to be ordered. The next test to be performed is the motor braking test. Often motors have a built in braking system so they do not continue to spin a long time after the device is turned off. However, since the students will be asked to turn off the motor before applying the brakes, the motor cannot cause significant braking immediately after it is turned off or the velocity value used in the calculation of Joule’s constant will be wrong. Therefore, we will turn the motor off and time how long it takes to stop the rotating shaft on its own. It must continue to rotate for at least 10 seconds after the motor is turned off.

Another test that we will perform is that the brake pads operate as they should and properly brake the spinning disc. This test will be performed after the hydraulic plumbing system is installed, and will ensure that the plumbing system can deliver the necessary pressure to the brakes. This is an important test not only for the proper operation of the device, but for the safety of the people using the device. Once it is confirmed that the brake pads operate properly, we will begin testing the temperature gain that can be achieved by the braking process. Based on thermal calculations done in EES and SolidWorks Simulation, we will have a good estimation of the necessary velocity for the shaft to spin to achieve the desired temperature gain of 10 degrees Celsius. If this gain is not achieved, the speed of the motor will be adjusted until we get the desired value. This is an important test because if we cannot reach the desired temperature gain at a safe rotational velocity, we will have to investigate other ways of achieving our goal. This temperature gain is required to get a more accurate reading from the thermistors. After we have met our goal for temperature gain, we will perform our final test in calculating the Joule’s constant. This test will give us feedback as to where the error in our experiment is coming from. If the previous test is successful, then the temperature gain should not cause an issue. However, assumptions were made in the thermal analysis we performed, such as neglecting the mass of the shaft. However, if we are not achieving a high level of accuracy in our Joule’s constant value, within 5% of the accepted value, we will have to reevaluate assumptions made in our calculations and make adjustments.

6.2 Detailed Results

In order to test our device, we started by running our device at low speeds, and then braking it and measuring the temperature change in the brake pads. We then used this change in temperature to calculate the Joule's constant using our analysis in EES (see Appendix E). However as we predicted in our analysis, in order to achieve a temperature change of 10 degrees Celsius or greater the device had to be run at higher speeds. When run at 900 RPM, we achieved a temperature change of 13 degrees. This large increase in temperature becomes very important when performing the Joule's constant calculations. It helps reduce the measurement error in the thermistors and makes the minor losses in heat less significant. Due to safety concerns and issues that arose with the Arduino we were using to measure temperature, we were not able to test the device at speeds higher than 900 RPM. However, at this speed we were able to calculate the Joule's constant within 35% of the accepted value. Although this is not the accuracy we were originally hoping for, we believe that calculating the Joule's constant within 5% of the accepted value is possible using this device with further testing and analysis (see Conclusions and Recommendations). To see the results from testing and analysis, refer to Appendix E.

6.3 DVPR

TABLE 7. DVPR

TEST PLAN									
Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsi	Test Stage	SAMPLES		TIMING	
						Quantity	Type	Start date	Finish date
1	Flywheel	Flywheel imbalance at various rotational speeds	Flywheel must not show any imbalance or cause movement of device	Jeffrey Powell	PV	1	C	2/9/2016	2/17/2016
2	Motor	Motor braking once motor is turned off	Motor braking continues for 10 seconds after turn off	Coleman Badgley	PV	1	C	2/9/2016	2/16/2016
3	Brake Pads	Brake Pad piston operation once plumbing system is installed	Pads brake the disc in one second or less	Coleman Badgley	PV	4	C	3/1/2016	3/5/2016
4	Thermal Gain	Brake the disc at desired speed and pressure to ensure proper temperature gain of pads	10 degree Celcius minimum rise in temperature	Coleman Badgley	PV	5	C	3/6/2016	3/10/2016
5	Joule's Constant	Measure the thermal gain in the thermistors and perform Joule's constant calculation to ensure accuracy	Within +/- 5% of accepted Joule's constant value	Jeffrey Powell	PV	10	C	3/11/2016	3/18/2016

7. Conclusions and Recommendations

The goal of this experiment is to allow students to safely and accurately calculate the Joule's constant. It is meant to provide students with a better understanding of the first law of thermodynamics and how it applies to real world engineering applications. After performing testing and analysis, we have concluded that this experiment can be used to accurately calculate the Joule's constant. Through our analysis, we calculated the Joule's constant to within 35% of the accepted value when the motor was run at 900 RPM. Although we were not able to achieve our goal of calculating the Joule's constant to within 5% of its accepted value, we believe that this goal is achievable with further testing and analysis. In order to further improve both the design of the experiment and the accuracy of the calculated Joule's constant value, we have included the following recommendations:

1. **Mount the device to a stiffer frame:** The first major step that has to be taken to improve the safety of this experiment is to mount it to a stiffer frame. The aluminum base plate that it is currently mounted to is able to flex far more than is desired. This flexibility can be damaging to the hydraulic lines, and also allows for a lot of vibration when the motor is running. From what we observed, the shaft was well balanced, however the flexibility of the base plate allowed the frames that the motor and shaft were mounted on to move, causing significant vibration at higher speeds. In order to fix these issues, the device should be mounted to a steel frame that is bolted to the floor. This will reduce vibration while the motor is running and prevent damage to the device from the base plate flexing.
2. **Replace Plexiglas with steel cage:** Another safety concern with the current design of the experiment is the safety shield that surrounds the spinning components. This thin Plexiglas sheet will most likely not protect the user if something were to break or fly off of the shaft. That is why we recommend mounting a steel cage around the spinning components. This will assure that even if the experiment did critically fail, no harm would come to the user.
3. **Replace disk with less conductive material:** Although copper is much more thermally conductive than steel, steel is still a good conductor of heat. Therefore, when the brakes are

applied, there is a significant portion of the heat being lost to the disk. Although most of this heat can be accounted for using a heat ratio with the properties of the two materials, if a less conductive material were used, or if the steel disk was coated in rubber, this would allow for a greater rise in temperature on the brake pad.

4. **Move thermistor closer to contact surface:** One idea that we were not able to get to during testing was moving the thermistor location closer surface where the brake pad contacts the disk to stop the shaft. Copper is a good thermal conductor, and through our SolidWorks Thermal analysis, we saw no noticeable difference in temperature between the current thermistor location and the contact surface. However, this change in measurement location could have a large effect on the measured temperature change. The issue with this is that it would require machining of the copper brake pad. Although this would not be too difficult to perform, the copper pads are replaceable, and therefore would have to be re-machined every time they are replaced.
5. **Run the experiment at higher speeds:** During our testing and analysis, the highest speed we ran the machine at was 900 RPM. This was due to safety concerns with the shielding and measurement issues. At this speed we were able to calculate the Joule's constant within 35% of the accepted value. However, if the machine were run at higher speeds it would increase the change in temperature in the brake pads, which in turn would decrease the significance of the minor losses in the system. Therefore, we believe that if the device were tested at higher speeds, the calculated Joule's constant could be calculated more accurately.
6. **Use better thermal insulation:** The main reason why we were not able to achieve a more accurate calculation of the Joule's constant was due to losses in heat. In order to help reduce these losses and improve the accuracy of the experiment, the thermal insulation around copper pads must be improved. Currently, there is polycarbonate behind the copper pad with a slot machined in them for the thermistors. Then, we packed Styrofoam into these slots to better insulate the back of the thermistor, while applying thermally conductive paste in between the thermistor and the copper pad to eliminate air gaps and improve heat transfer between the two. However, the back of the copper pad can be insulated further. Also, we believe there is a significant amount of heat being lost to the two screws in the brake pads. To improve this, we suggest either using thermal insulating paste around the screws or finding screws made out of a material that is less thermally conductive.

References

Appendix A: Decision Matrices

TABLE 8. PLUMBING DECISION MATRIX

Plumbing Format	Safety	Cost	Bracing	Total
1	1	3	3	7
2	3	2	4	8
3	3	4	0	7

*NOTE: 1, 2, and 3 refer to specific plumbing formats. These formats can be found in appendix B.

Appendix B: Drawing Packet

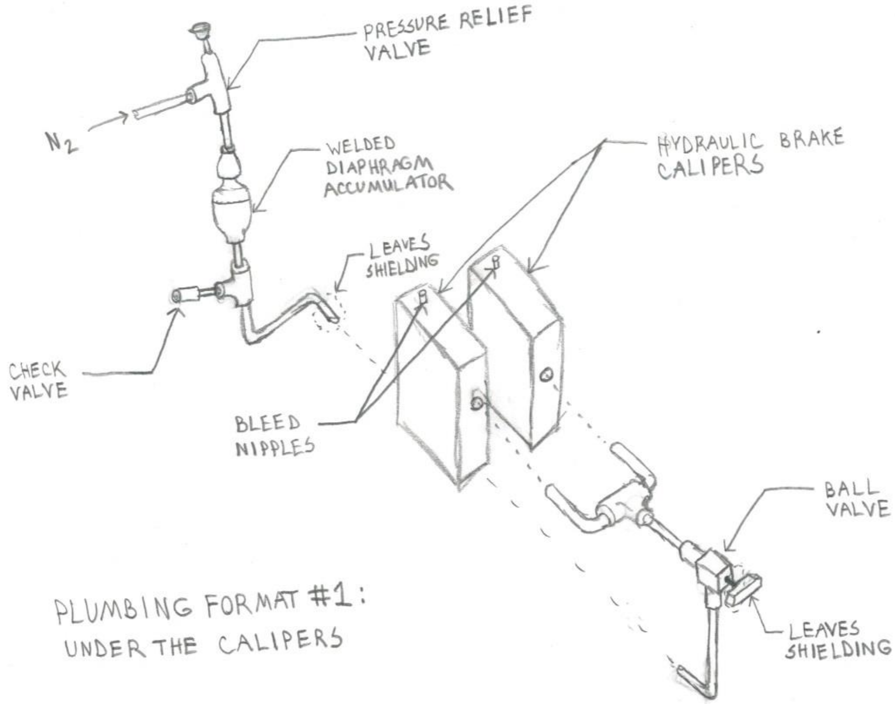


FIGURE 33. PLUMBING FORMAT 1: UNDER THE CALIPERS

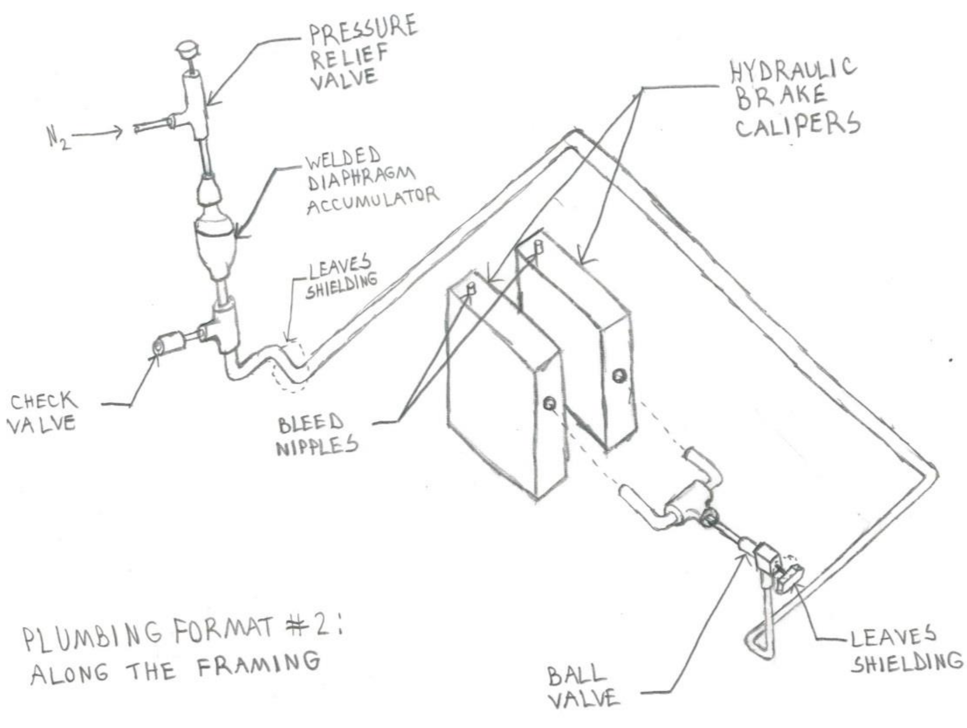


FIGURE 34. PLUMBING FORMAT 2: ALONG THE SHIELDING

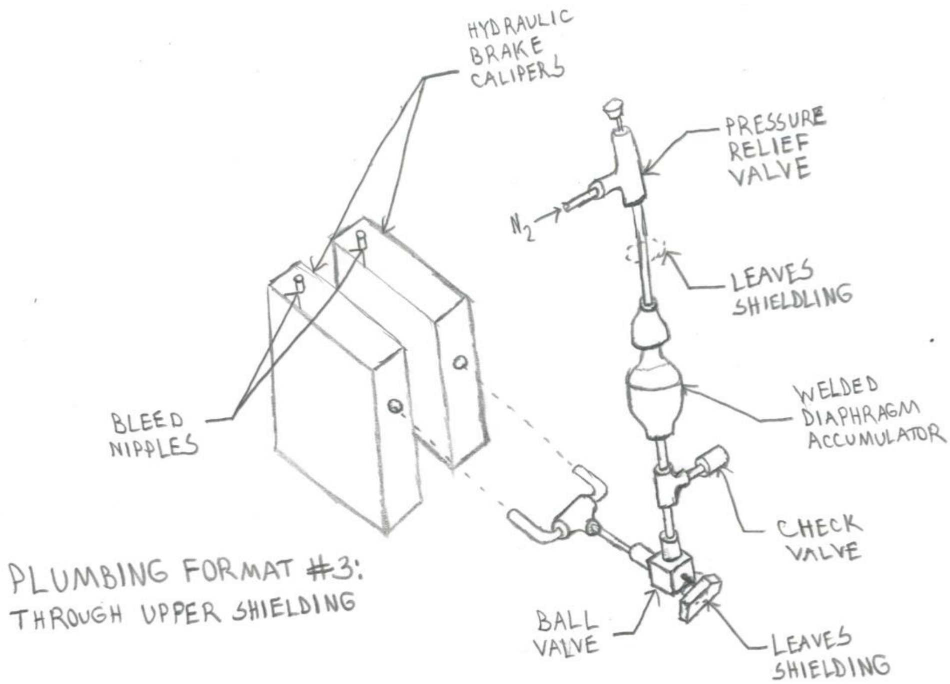


FIGURE 35. PLUMBING FORMAT 3: THROUGH UPPER SHIELDING

Appendix C: List of Vendors, Contact Information, and Pricing

TABLE 9. BILL OF MATERIALS FOR THE PROJECT

Vendor	Part Number	Description	Price per unit	Qty	Line Price	Contact info
Swagelok	SS-42GS4-A	Manual Ball Valve	$92.00	1	$92.00	(805)384-1060
Swagelok	SS-4C-1	Check Valve	$49.05	1	$49.05	(805)384-1060
Swagelok	SS-400-3	T Joint (to connect tubing to check and relief valves)	$23.34	4	$93.36	(805)384-1060
Swagelok	SS-400-1-2	Adapter for Calipers (Between tubing and female caliper connection)	$7.13	2	$14.26	(805)384-1060
Swagelok	304L-T4-S-035-20-S	20ftof 1/4" tubing (smallest increment for ordering)	$86.20	1	$86.20	(805)384-1060
Swagelok	SS-4R3A-MO	Pressure relief valve	$208.26	1	$208.26	(805)384-1060
Swagelok	SS-41GXS2	3 way Ball Valve	$120.00	1	$120.00	(805)384-1060
Summit Racing	AAF-ALL42046	Hydraulic Reservoir	$60.00	1	$60.00	1(800)230-3030
ACE Hardware		Angled Steel Framing	$28.00	3	$84.00	1(888)827-4223
ACE Hardware		Fasteners (1/4" bolts, washers, nuts)	$10.00	1	$10.00	1(888)827-4223
W.C. Branham		Air/Oil Intensifier	$536.00	1	$536.00	(715)426-2000
Swagelok	SS-41GXS2	3 way Ball Valve	$120.00	1	$120.00	(805)384-1060
Summit Racing	AAF-ALL42046	Hydraulic Reservoir	$60.00	1	$60.00	1(800)230-3030
W.C. Branham		Air/Oil Intensifier	$536.00	1	$536.00	(715)426-2000
TOTAL					**$2,069.13**	

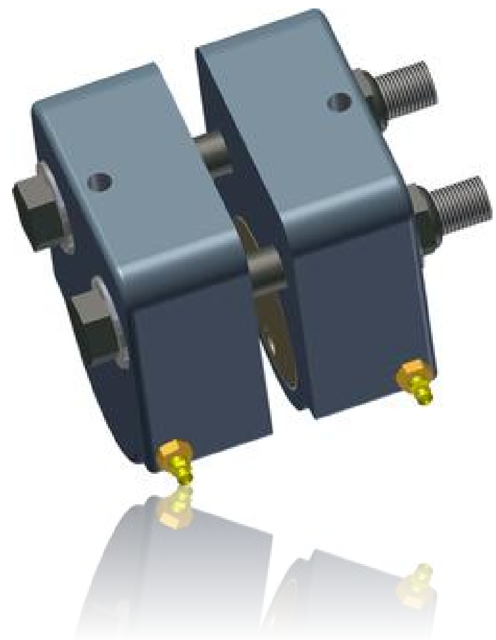
Appendix D: Vendor supplied Component Specifications and Data Sheets

H491D Caliper Disc Brake NEW!

Attributes | Quote | Options | Downloads | Related

4251-0000

491 series, hydraulic double acting caliper disc brake. Customer supplied spacer for brake disc thicknesses up to 2.0 inches.



- Aluminum Construction
- Hardcoated
- Fits on Brake Discs with Unlimited Diameter
- Replaceable Friction Pads (WCB p/n 4000-1014)
- Bolts are for Brake Discs up to 1/2 in. Thick.
- Advise Brake Disc Thickness When Ordering to Ensure Correct Bolts
- Dynamic torque (inch/lb): 353.5 lbf per 100 psi x braking radius
- Parking/static torque (inch/lb): 211 lbf per 100 psi x braking radius
- Power Factor: **491 Series 5X**, 38 Series 1X, 47 Series 2X, 200 Series 4X, 962 Series 10X

Attributes

Description	Double Acting, Fixed Mount. Use Fixed or Floating Disc
Additional Info	Dual Non-Retractable Pistons
Disc Thick. (in.)	Custom
Fluid Type	Hydraulic Oil
Max. Pressure, PSI	1500
Seals	Buna-N
Wearable Friction Material	3.80 cu. in.
Piston Dia.	2.5 In.
Total Pad Area	9.14 sq. in.
Fluid Displacement	0.147 cu. in.

FIGURE 36. DATASHEET; H491D CALIPER DISC BRAKE

8.0 Dia.

Attributes | Quote | Downloads | Related

4802-0016

8.0 in. diameter fixed hub and disc assembly, 1.0 inch bore. Fits all W.C. Branham and T-O-M Brand caliper disc brakes with 'A' brake spacer designator.

- Carbon 1010 steel
- Flat to within .020 inch
- Stress Relieved
- Blanchard ground 80 RMS finish
- Rated up to 300° F.
- 1215 Cold rolled steel hub material
- Socket head cap screws
- Keyway set screws

Attributes

Description	Fixed Disc/Hub Assy
Bore Dia. (in.)	1.000
Disc Thick. (in.)/Spacer	5/32 / A
Key Size (in.)	1/4 x 1/4

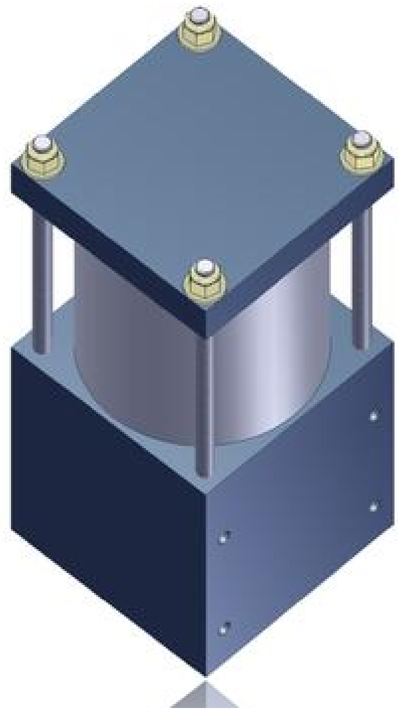
FIGURE 37. DATASHEET; DISC FOR DISC BRAKES

Model 1781 9:1 Air/Oil Intensifier NEW!

Attributes | Quote | Downloads

1781-0000

Model 1781, 9:1 Air/Oil Intensifier. Use with W.C. Branham hydraulic caliper disc brake H491, H493, H962 series AND hydraulic spring applied FS38, FS47, FS200, FS400, FS500 series.



Attributes

Hyd Fluid Displacement	7.068 cu. in. per stroke
Max Input Pressure	100 psi
Max Output Pressure	900 psi
Piston Seal	Quad Seal
Construction Tube	Aluminum Hardcoat ID/OD
Construction Base	Aluminum Anodized
Port Size	1/8 NPTF
Physical Size	5.0 x 5.0 x 11.631 in.

FIGURE 38. DATASHEET; AIR/OIL INTENSIFIER

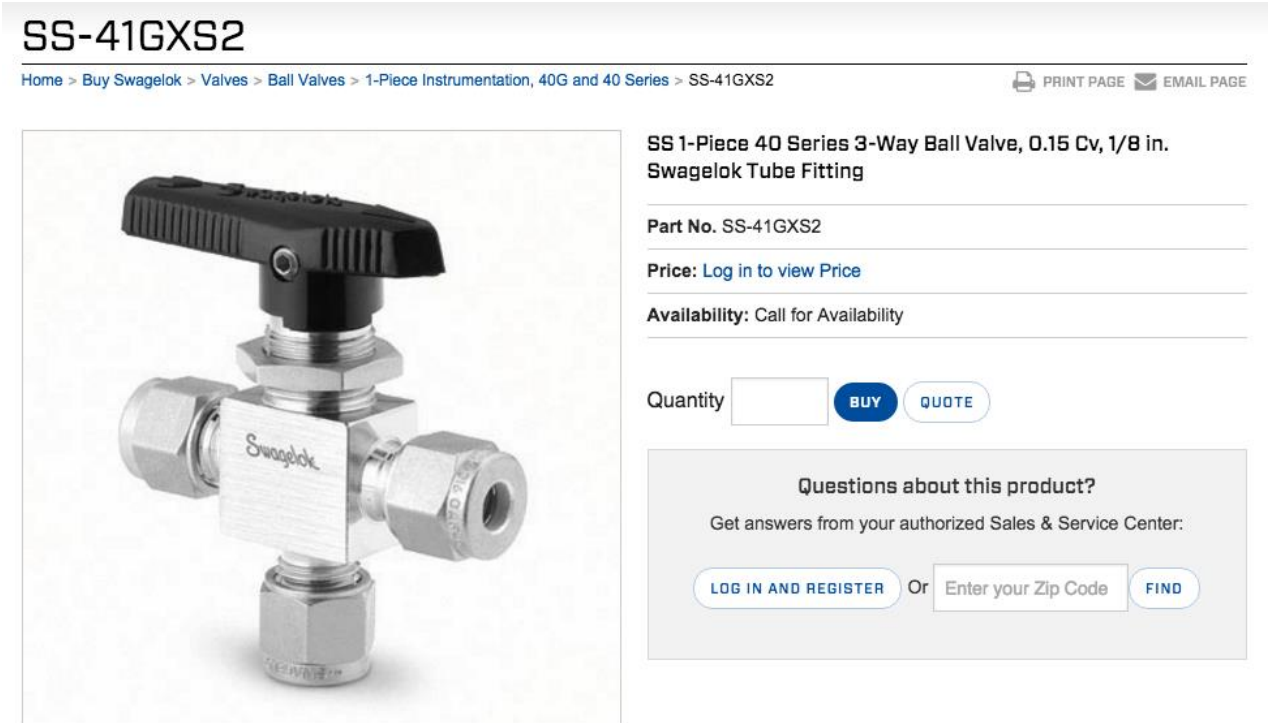


FIGURE 39. 3-WAY BALL VALVE

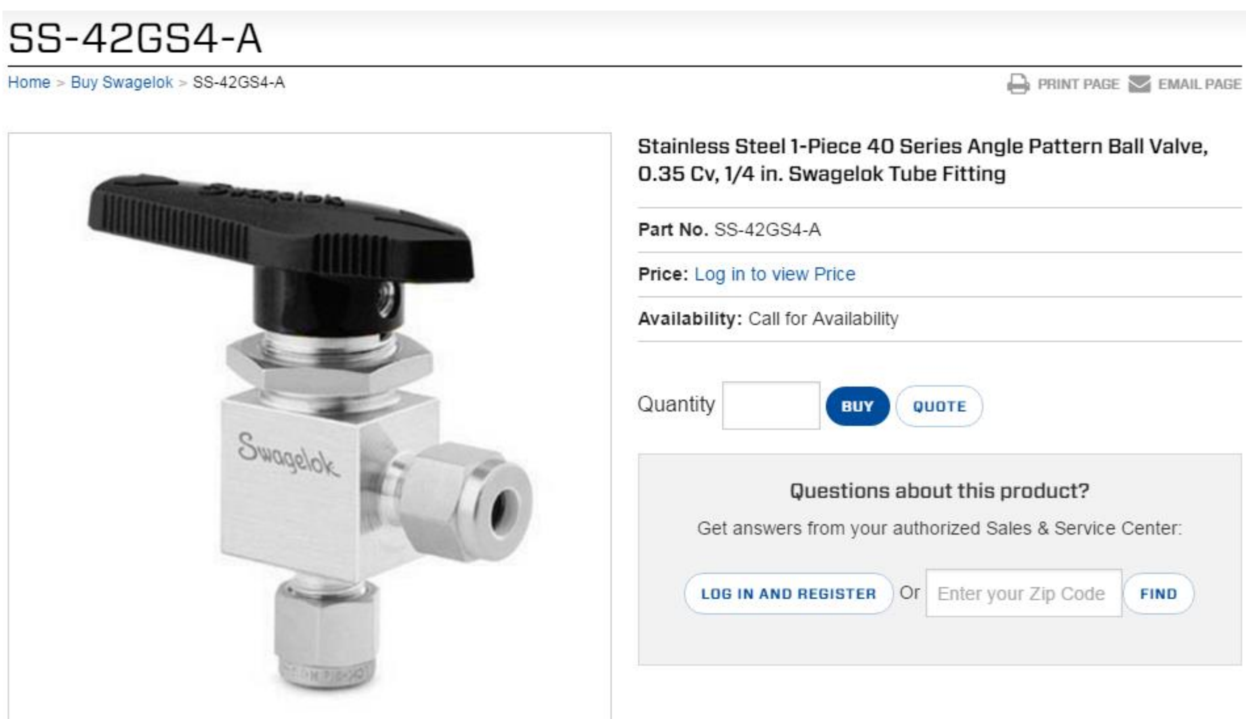


FIGURE 40. 2-WAY BALL VALVE

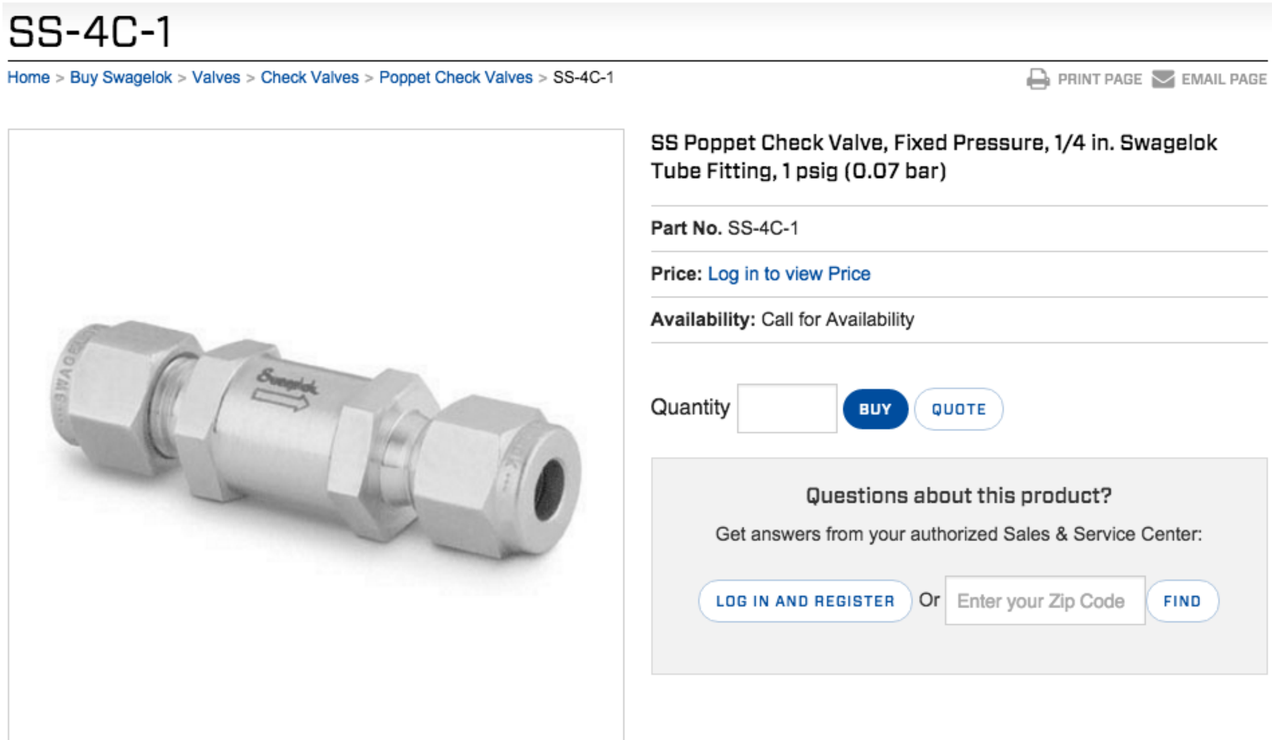


FIGURE 41. CHECK VALVE FOR PLUMBING

Figure 42. Regulator

Appendix E: Detailed Supporting Analysis

EES Thermal Calculations

Convection Coefficient Calculations

Boundary Conditions:

$$R = 10 \quad [in] \cdot \left| 0.0254 \cdot \frac{m}{in} \right|$$

$$N_{max} = 2000 \quad [rev/min]$$

$$\omega_{max} = N_{max} \cdot \frac{\left| 6.283 \cdot \frac{rad}{rev} \right|}{\left| 60 \cdot \frac{s}{min} \right|}$$

Properties of Air:

$$T_{atm} = 20 \quad [C]$$

$$P_{atm} = 101.325 \quad [kPa]$$

$$v = \textbf{KinematicViscosity} (Air , T = T_{atm} , P = P_{atm})$$

$$k = \textbf{k} (Air , T = T_{atm})$$

$$Pr = \textbf{Pr} (Air , T = T_{atm})$$

Correlations for Nusselt Number for Turbulent and Laminar Bounary Layers:

$$Re_{t1} = \left[\frac{0.365}{8.98 \times 10^{-14}} \right]^{\left[\frac{1}{2.3} \right]}$$

$$Re_{t2} = \left[\frac{0.0183}{8.98 \times 10^{-14}} \right]^{(1 / 2)}$$

$$N_{pts} = 200$$

$$N_i = \frac{i}{N_{pts}} \cdot N_{max} \qquad \text{for } i = 1 \text{ to } N_{pts}$$

$$\omega_i = \frac{i}{N_{pts}} \cdot \omega_{max} \qquad \text{for } i = 1 \text{ to } N_{pts}$$

$$U_i = \omega_i \cdot R \qquad \text{for } i = 1 \text{ to } N_{pts}$$

$$Re_i = \omega_i \cdot \frac{R^2}{v} \qquad \text{for } i = 1 \text{ to } N_{pts}$$

$$NuR_{lam,i} = 0.365 \cdot Re_i^{(1 / 2)} \cdot Pr^{(1 / 3)} \qquad \text{for } i = 1 \text{ to } N_{pts}$$

$$NuR_{lam,i} = \frac{h_{lam,i} \cdot R}{k} \qquad \text{for } i = 1 \text{ to } N_{pts}$$

$$NuR_{trans,i} = 8.98 \times 10^{-14} \cdot Re_i^{2.8} \cdot Pr^{(1 / 3)} \qquad \text{for } i = 1 \text{ to } N_{pts}$$

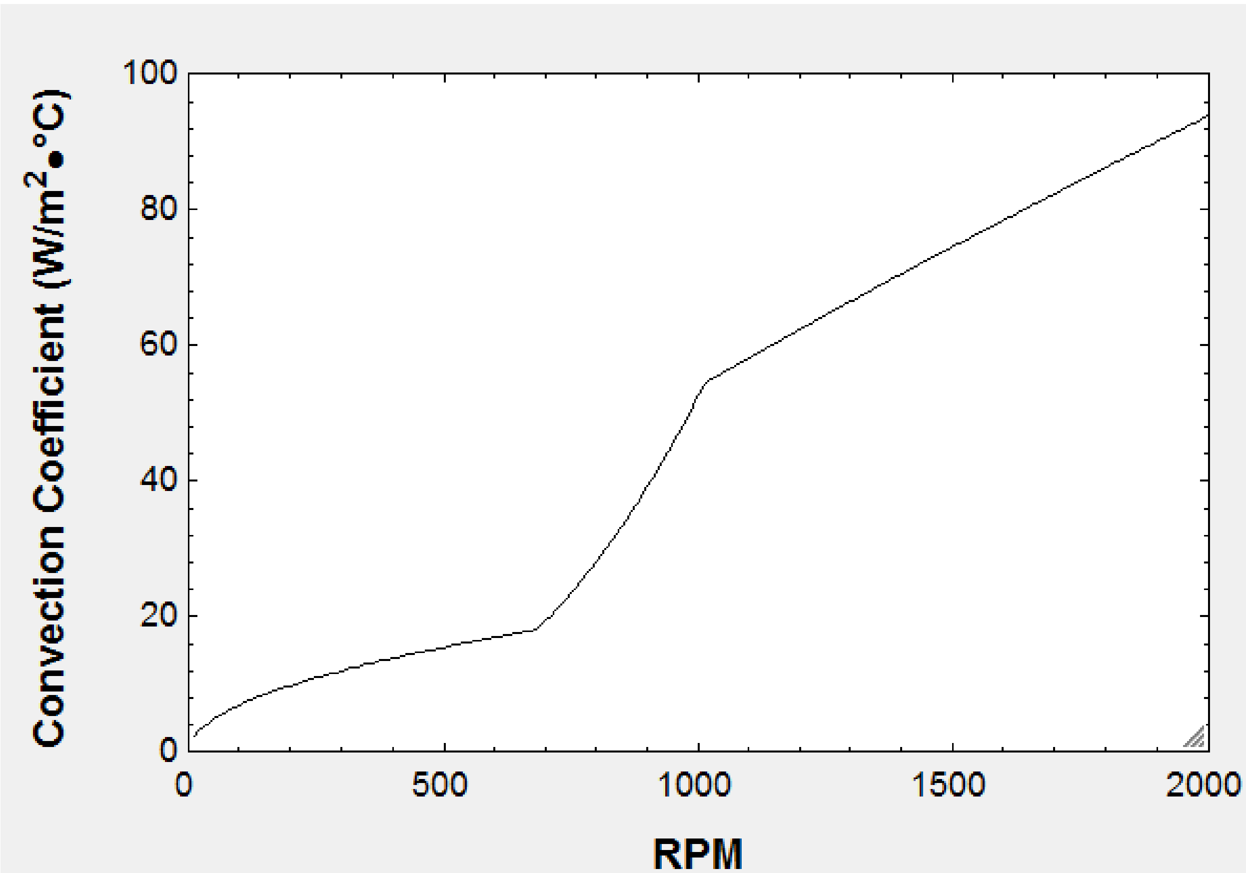
$$NuR_{trans,i} = \frac{h_{trans,i} \cdot R}{k} \qquad \text{for } i = 1 \text{ to } N_{pts}$$

$$NuR_{turb,i} = 0.0183 \cdot Re_i^{(4/5)} \cdot Pr^{(1/3)} \quad \text{for } i = 1 \text{ to } N_{pts}$$

$$NuR_{turb,i} = \frac{h_{turb,i} \cdot R}{k} \quad \text{for } i = 1 \text{ to } N_{pts}$$

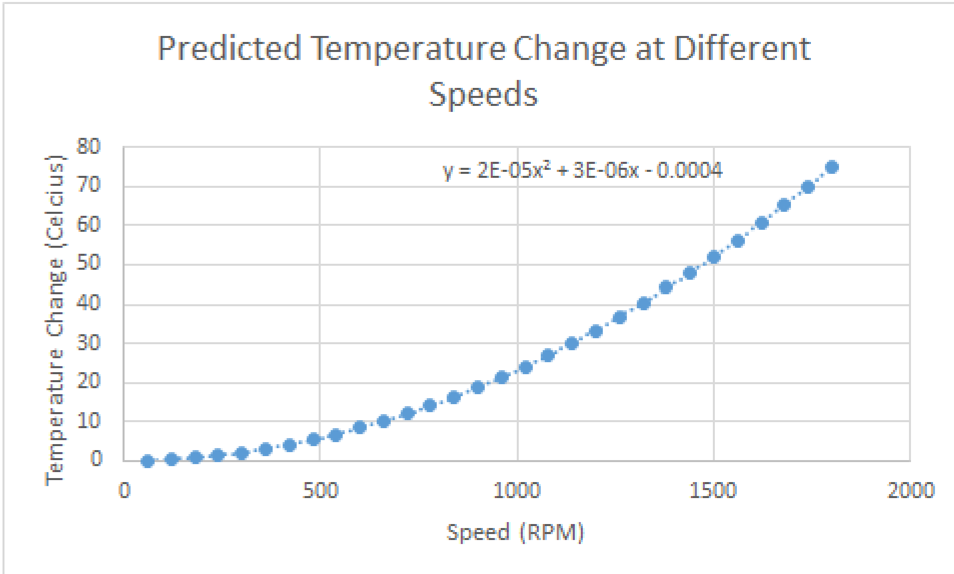
$$NuR_i = \textbf{If}\ (Re_i,\ Re_{t1},\ NuR_{lam,i},\ NuR_{lam,i},\ \textbf{If}\ (Re_i,\ Re_{t2},\ NuR_{trans,i},\ NuR_{trans,i},\ NuR_{turb,i})) \quad \text{for } i = 1 \text{ to } N_{pts}$$

$$NuR_i = h_i \cdot \frac{R}{k} \quad \text{for } i = 1 \text{ to } N_{pts}$$

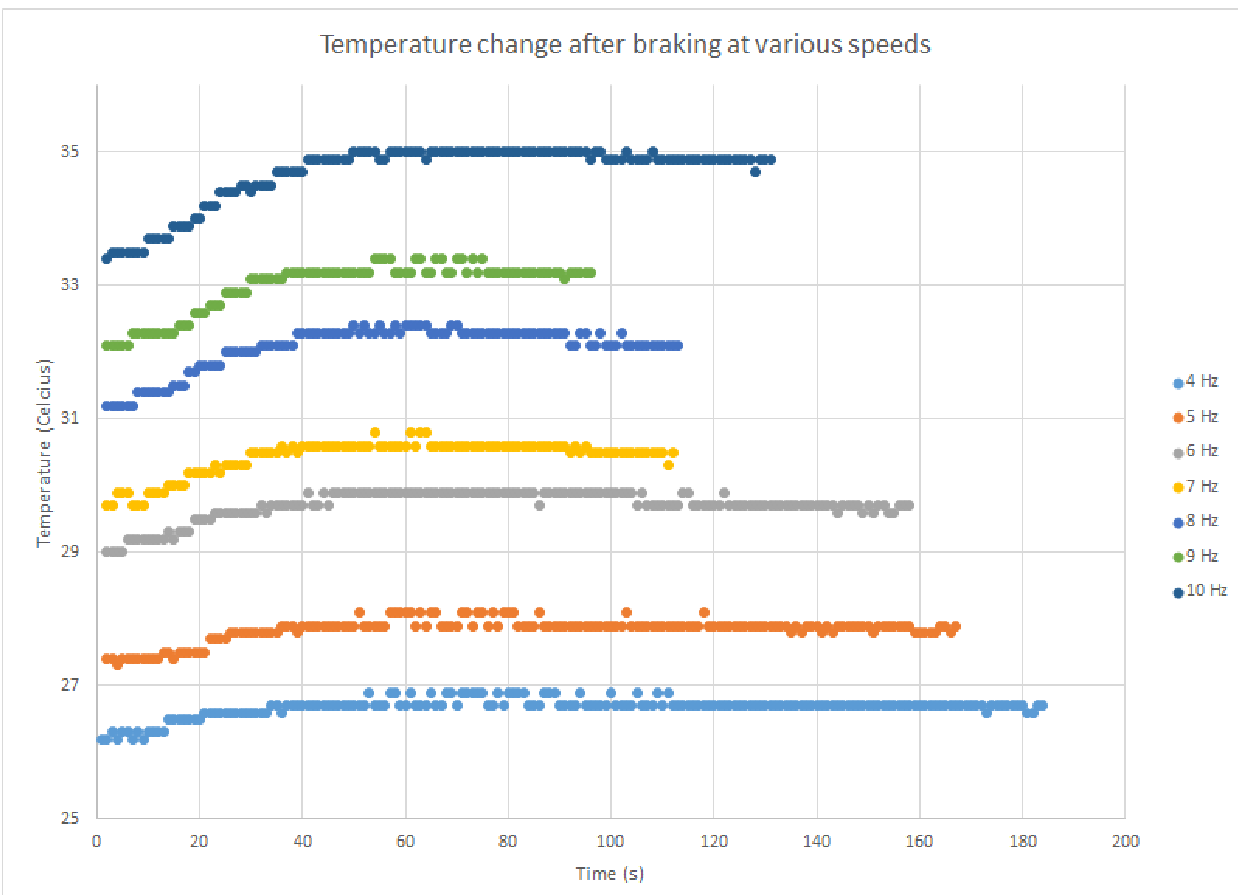


Predicted Total Temperature Change of Brake Pads at Various Speeds

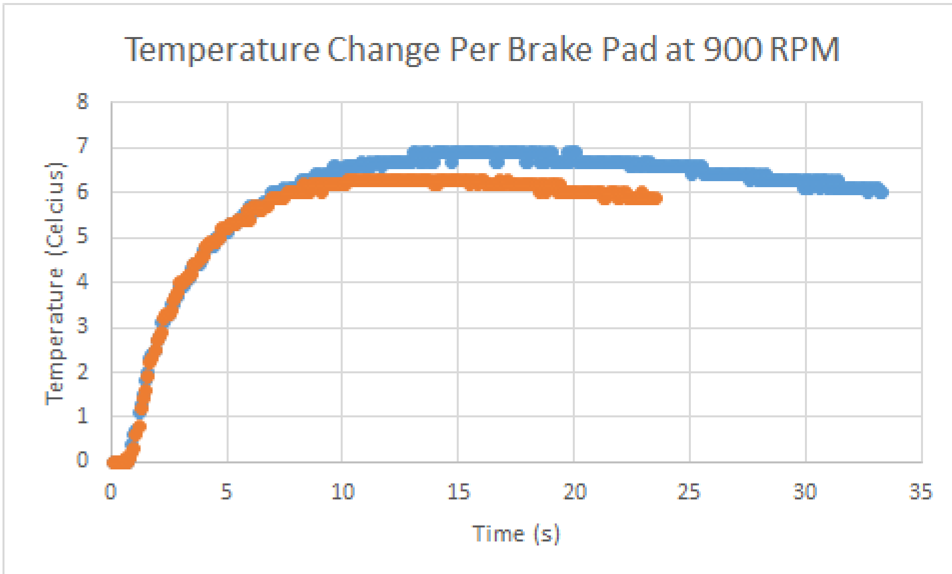
1..30	n_{disk} [revolutions/min	δ_T [C]
Run 1	60	0.08336
Run 2	120	0.3334
Run 3	180	0.7502
Run 4	240	1.334
Run 5	300	2.084
Run 6	360	3.001
Run 7	420	4.084
Run 8	480	5.335
Run 9	540	6.752
Run 10	600	8.336
Run 11	660	10.09
Run 12	720	12
Run 13	780	14.09
Run 14	840	16.34
Run 15	900	18.76
Run 16	960	21.34
Run 17	1020	24.09
Run 18	1080	27.01
Run 19	1140	30.09
Run 20	1200	33.34
Run 21	1260	36.76
Run 22	1320	40.34
Run 23	1380	44.1
Run 24	1440	48.01
Run 25	1500	52.1
Run 26	1560	56.35
Run 27	1620	60.77
Run 28	1680	65.35
Run 29	1740	70.1
Run 30	1800	75.02



Measured Temperature Change of Single Brake Pad at Various Speeds (Thermal Paste and No Styrofoam)



Measured Temperature Change of Brake Pads at 900 RPM (Thermal paste and Styrofoam insulation added)



Thermal calculations at 900 RPM

Heat Transfer Calculations

Known Values

$T_1 = 20 + 273$ [K]

$T_2 = 26.9 + 273$

$n_{disk} = 900$

$P = 500$ [psi]

$\delta_T = 2 \cdot (T_2 - T_1)$

$radius_{additional} = 7$ [inch]

$mass_{additional} = 25.8 + 1.447$ [kg]

$t_{disk} = 0.156$ [inch]

$D_{disk} = 8$ [inch]

$\rho_{steel} = 7750$ [kg/m^3]

$$A_{pads} = 2 \cdot \pi \cdot \left[\frac{2.5}{2}\right]^2 \cdot 1 \quad [in^2]$$

$h = 15$ [W/(m^2*C)]

$$A_{disk} = 2 \cdot \pi \cdot \left[\frac{D_{disk}}{2}\right]^2$$

$$m_{disk} = \rho_{steel} \cdot \frac{A_{disk}}{2} \cdot t_{disk}$$

$A_{padsouter} = 1.96 \cdot 2$

$A_{diskouter} = 3.92$

Thermal Properties

Copper

$c_{CU} = 0.39$ [kJ/(kg*K)]

$\rho_{CU} = 8940$ [kg/m^3]

$k_{CU} = 353$ [W/(m*K)]

Steel Disk

$c_{disk} = 0.49$ [kJ/(kg*K)]

$\rho_{disk} = 8050$ [kg/m^3]

$k_{disk} = 65.2$ [W/(m*K)]

1st Law of Thermodynamics

$deltaU_{CU} + Q_{disk} + Q_{padtoair} + Q_{disktoair} = deltaKE_{assembly}$

$$Q_{disk} = \frac{1}{HeatRatio} \cdot \delta U_{CU}$$

$$T_{2,disk} = \frac{Q_{disk}}{m_{disk} \cdot c_{disk}} + T_1$$

$$Volume_{CU} = 2 \cdot \pi \cdot \left[\frac{2.5}{2}\right]^2 \cdot 0.125 \cdot 0.0000163871 \quad [m^3]$$

Heat Ratio

$$HeatRatio = \left[\frac{c_{CU} \cdot \rho_{CU} \cdot k_{CU}}{c_{disk} \cdot \rho_{disk} \cdot k_{disk}}\right]^{0.5}$$

Heat Transfer to Air

$$Q_{padtoair} = \frac{(h \cdot (A_{pads} + A_{padsouter}) \cdot 0.00064516 \cdot (T_2 - T_1)) \cdot 15}{1000}$$

$$Q_{disktoair} = \frac{(h \cdot (A_{disk} + A_{diskouter}) \cdot 0.00064516 \cdot (T_{2,disk} - T_1)) \cdot 15}{1000}$$

Internal Energy Copper

$$\delta U_{CU} = m_{CU} \cdot c_{CU} \cdot \delta_T$$

$$m_{CU} = \rho_{CU} \cdot Volume_{CU}$$

Kinetic Energy

$$\delta KE_{assembly} = 0.5 \cdot I_{Total} \cdot (n_{disk} \cdot 0.1047)^2 \cdot 0.001$$

$$I_{disk} = 0.5 \cdot \rho_{steel} \cdot Volume_{disk} \cdot (0.5 \cdot D_{disk} \cdot 0.0254)^2$$

$$I_{additional} = 0.5 \cdot mass_{additional} \cdot (radius_{additional} \cdot 0.0254)^2$$

$$Volume_{disk} = \frac{\pi}{4} \cdot D_{disk}^{\ 2} \cdot t_{disk} \cdot 0.0000163871$$

$$I_{Total} = I_{disk} + I_{additional}$$

$Q_{disk}+Q_{padtoair} + Q_{disktoair}$

$$J = \frac{\delta KE_{assembly}}{\delta U_{CU} + Q_{disk} + Q_{padtoair} + Q_{disktoair}}$$

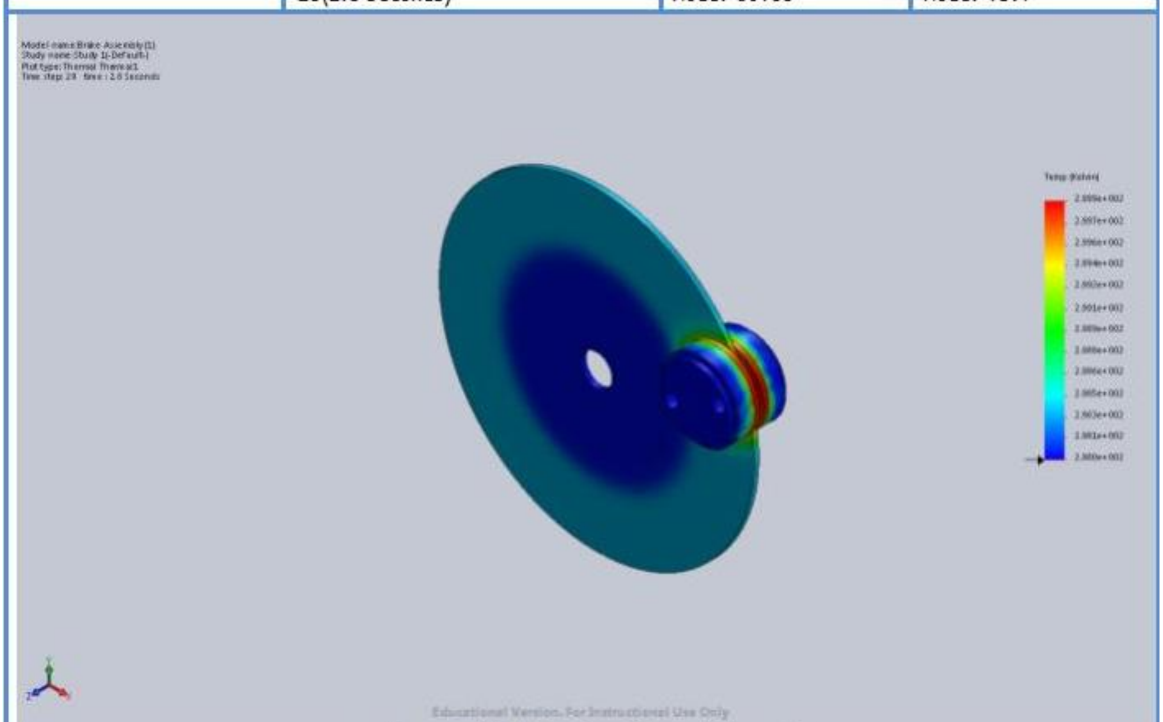
$$Error = -\left[\frac{1 - J}{1}\right] \cdot 100$$

A_{disk} = 100.5 [in^2]	$A_{diskouter}$ = 3.92 [in^2]	A_{pads} = 9.817 [in^2]
$A_{padsouter}$ = 3.92 [in^2]	c_{CU} = 0.39 [kJ/(kg*K)]	c_{disk} = 0.49 [kJ/(kg*K)]
$\delta KE_{assembly}$ = **1.935** [kJ]	δU_{CU} = **0.9676** [kJ]	δ_T = 13.8 [C]
D_{disk} = 8 [inch]	Error = 35.91 [%]	h = 15 [W/(m^2*C)]
HeatRatio = 2.188 [-]	$I_{additional}$ = 0.4307 [m^4]	I_{disk} = 0.00514 [m^4]
I_{Total} = 0.4358 [m^4]	J = 1.359 [-]	k_{CU} = 353 [W/(m*K)]
k_{disk} = 65.2 [W/(m*K)]	$mass_{additional}$ = 27.25 [kg]	m_{CU} = 0.1798 [kg]
m_{disk} = 60771 [kg]	n_{disk} = 900 [revolutions/minute]	P = 500 [psi]
Q_{disk} = **0.4423** [kJ]	$Q_{disktoair}$ = **2.252E-07** [kJ]	$Q_{padtoair}$ = **0.01376** [kJ]
$radius_{additional}$ = 7 [inch]	ρ_{CU} = 8940 [kg/m^3]	ρ_{disk} = 8050 [kg/m^3]
ρ_{steel} = 7750 [kg/m^3]	T_1 = 293 [K]	T_2 = 299.9 [K]
$T_{2,disk}$ = 293 [K]	t_{disk} = 0.156 [inch]	$Volume_{CU}$ = 0.00002011 [m^3]
$Volume_{disk}$ = 0.0001285 [m^3]		

SolidWorks Thermal Simulation

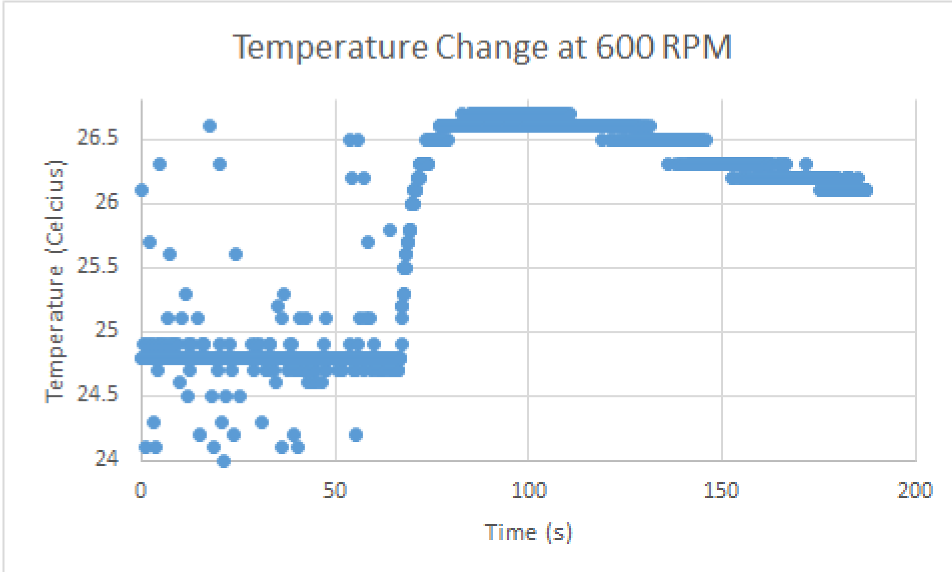
Thermal Analysis performed on the disc and copper brake pad with shaft spinning at 600 revolutions per minute.

Name	Type	Min	Max
Thermal1	TEMP: Temperature at Step No: 28(2.8 Seconds)	297.977 Kelvin Node: 30163	299.876 Kelvin Node: 1597

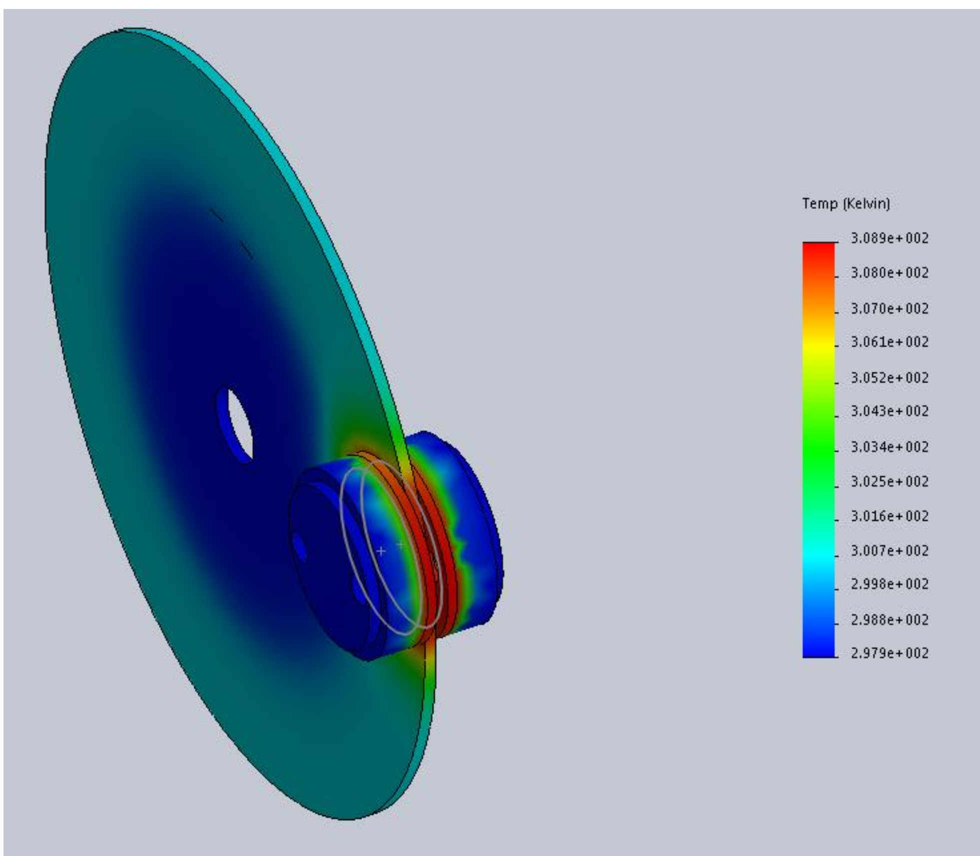


Brake Assembly (1)-Study 1-Thermal-Thermal1

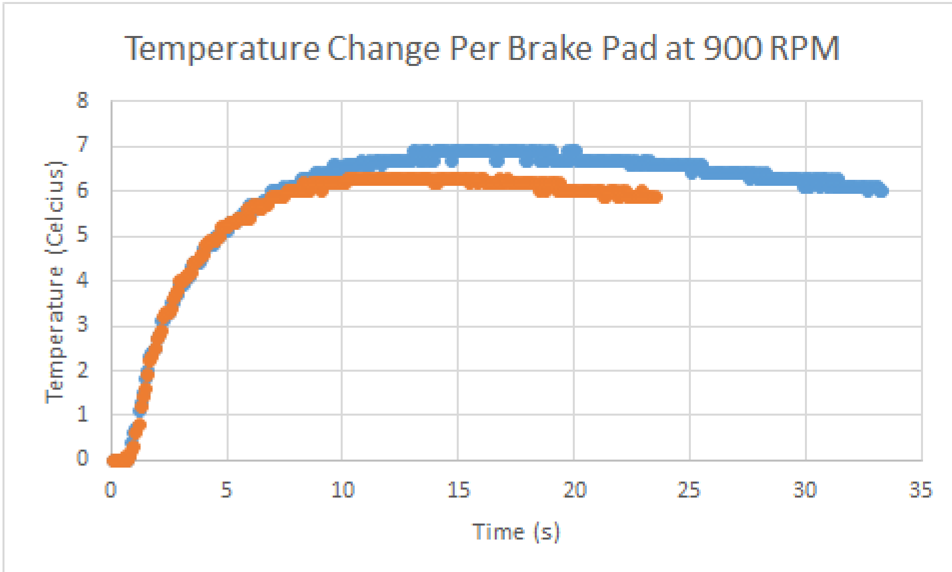
Measured Temperature Change at 600 RPM (thermal paste and no Styrofoam)



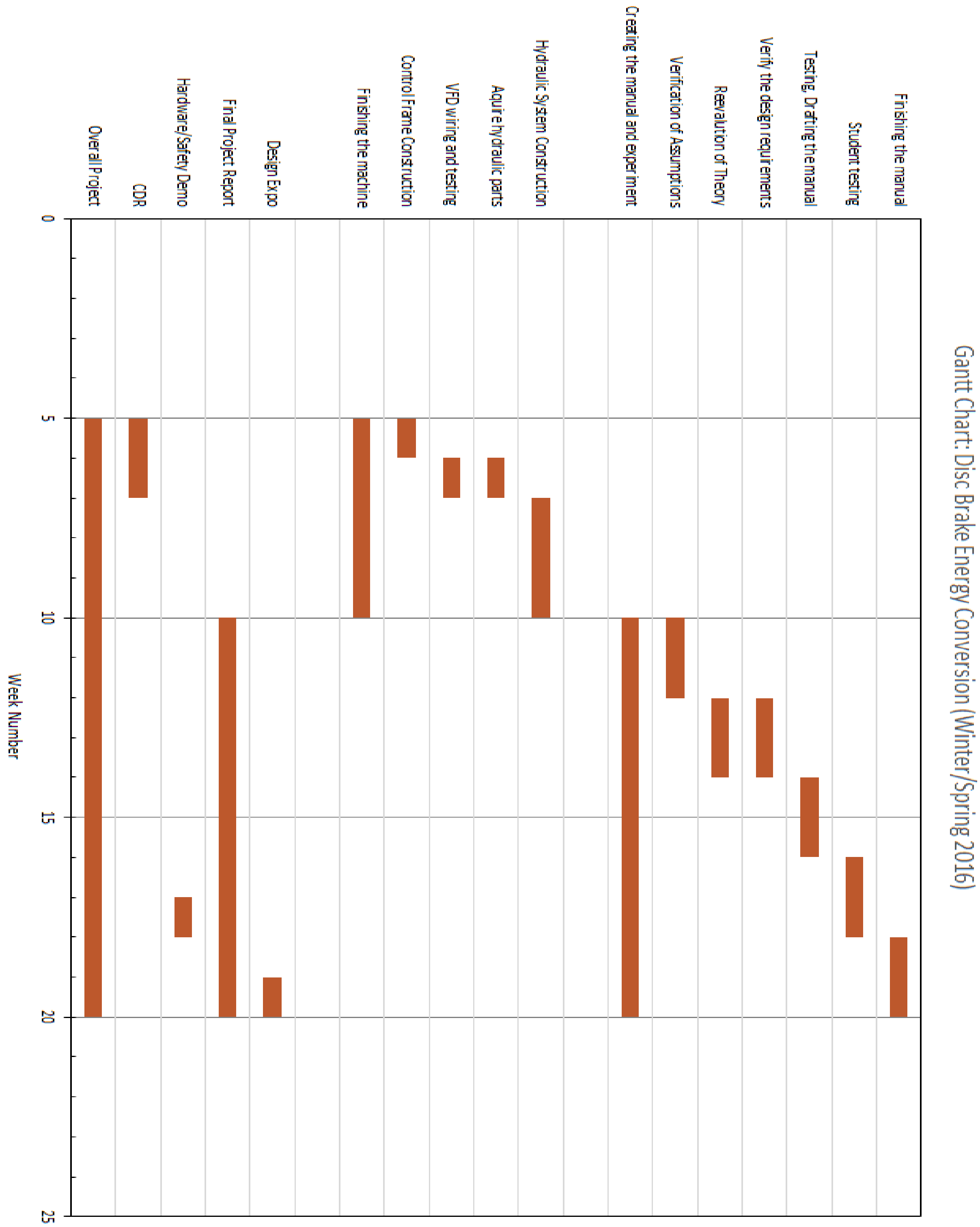
Thermal Analysis performed on the disc and copper brake pad with shaft spinning at 900 revolutions per minute.



Measured Temperature Change of Brake Pads at 900 RPM (Thermal paste and Styrofoam insulation added)



Appendix F: Gantt Chart



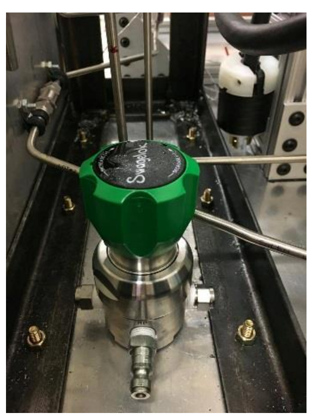
Appendix G: Machine Operation Procedure

Procedure

1. Open the bottom (three-way) valve to atmosphere (pointed to the right). Close the top ball valve (pointed up to the right). Initial position of ball valves pictured below.

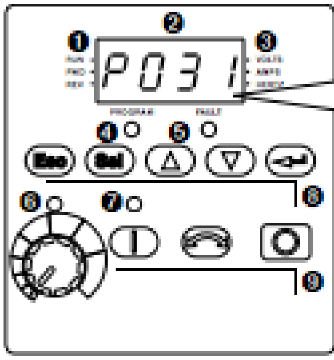
2. Make sure regulator is turned all the way clockwise (increased all the way) (regulator will regulate incoming air to 100 psi MAX)

3. Attach pressurized air to port on regulator



4. Press the start button on the variable frequency drive

Integral Keypad



Menu	Description
d	**Display Group (View Only)** Consists of commonly viewed drive operating conditions.
P	**Basic Program Group** Consists of most commonly used programmable functions.
A	**Advanced Program Group** Consists of remaining programmable functions.
F	**Fault Designator** Consists of list of codes for specific fault conditions. Displayed only when fault is present.

No.	LED	LED State	Description
1	Run/Direction Status	Steady Red	Indicates drive is running and commanded motor direction.
		Flashing Red	Drive has been commanded to change direction. Indicates actual motor direction while decelerating to zero.
2	Alphanumeric Display	Steady Red	Indicates parameter number, parameter value, or fault code.
		Flashing Red	Single digit flashing indicates that digit can be edited. All digits flashing indicates a fault condition.
3	Displayed Units	Steady Red	Indicates the units of the parameter value being displayed.
4	Program Status	Steady Red	Indicates parameter value can be changed.
5	Fault Status	Flashing Red	Indicates drive is faulted.
6	Pot Status	Steady Green	Indicates potentiometer on Integral Keypad is active.
7	Start Key Status	Steady Green	Indicates Start key on Integral Keypad is active. The Reverse key is also active unless disabled by A095 [Reverse Disable].

No.	Key	Name	Description
8	Esc	Escape	Back one step in programming menu. Cancel a change to a parameter value and exit Program Mode.
	Sel	Select	Advance one step in programming menu. Select a digit when viewing parameter value.
	△ ▽	Up Arrow Down Arrow	Scroll through groups and parameters. Increase/decrease the value of a flashing digit.
	↵	Enter	Advance one step in programming menu. Save a change to a parameter value.
9		Potentiometer	Used to control speed of drive. Default is active. Controlled by parameter P038.
		Start	Used to start the drive. Default is active. Controlled by parameter P036.
		Reverse	Used to reverse direction of the drive. Default is active. Controlled by parameters P036 and A095.
		Stop	Used to stop the drive or clear a fault. This key is always active. Controlled by parameter P037.

5. Increase the frequency using the knob on the variable frequency drive to desired speed

Frequency (Hertz)	Speed (RPM)
1	60
2	120
3	180
4	240
5	300
6	360
7	420
8	480
9	540
10	600
11	660
12	720
13	780
14	840
15	900
16	960
17	1020
18	1080
19	1140
20	1200

6. Allow motor to reach desired speed
7. Press stop button on variable frequency to turn off power to motor, allowing shaft to spin freely
8. Immediately after turning off power to motor, actuate the bottom ball valve by rotating it clockwise until it points to the left. This actuates intensifier, pressurizing the hydraulic lines and actuates the brakes.

9. Observe measured temperature increase from the thermistors in the brake pads
10. Once temperature has reached steady-state, record temperature change.
11. Then, rotate the bottom ball valve counter-clockwise until it points to the right again. This will relieve pressure in the hydraulic lines, and release pressurized air behind the control panel.
12. Then, rotate the top ball valve counter-clockwise to fully relieve pressure in the lines

13. Repeat the procedure above.

Appendix H: Other supporting information

1. Cal Poly University Store, *Thermal Sciences Laboratory*, 2nd Edition, Cal Poly University Store Publications, 2014

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