Abstract:

Proof of Concept Pyrolysis System Design

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There is currently a need to design new energy and waste management systems which are capable of mitigating climate change while maintaining commercial viability. This report documents the overall system design and subsequent detailed design undertaken in the development of a proof of concept (POC) pyrolysis bioenergy system in the context of an undergraduate mechanical engineering CAPSTONE project. The project was selected based on the current need to design new energy and waste management systems capable of mitigating climate change while maintaining commercial viability. This report along with the manufactured POC will be used as a stepping stone towards the ultimate goal of manufacturing a fully functional prototype capable of mitigating climate change through the production of sustainable energy carriers from organic waste. The commercially viability of this project will depend on the trend in global markets to start pricing externalities such as carbon dioxide emissions. If this trend continues carbon markets will continue to develop and mature over time. Once these markets are fully integrated into our economic system companies will be aggressively seeking new forms of energy in order to avoid the cost of carbon dioxide emissions. The energy carriers generated through pyrolysis can be sold as sustainable energy sources, or in the case of Biochar, can be used as a carbon sink. Pyrolysis systems can thus produce sustainable sources of energy while simultaneously sequestering carbon from the atmosphere. Early entry into this underdeveloped market is critical for strategic placement and future commercial success.

Keywords: Biochar; Waste Management; Pyrolysis; Energy; Proof of Concept;

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Proof of Concept Pyrolysis System Design:

FINAL REPORT

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1. INTRODUCTION

Current markets do not account for many externalities such as the long term economic cost of global warming and pollution. Governments around the world are looking at policy options that will provide individuals with incentives to reduce greenhouse gas (GHG) emissions. The most promising are market-based incentives such as emissions trading schemes which place a cost on those who emit polluting substances and reward those who reduce emissions [1]. The European Union and the United States of America have already started experimenting with carbon markets, where carbon credits can be traded. In Canada, the provincial government of British Columbia introduced a provincial carbon tax in 2008. Continued economic success in British Columbia may provide the ground for the adoption of a nationwide carbon tax in the years to come [2].

The increased price of fossil fuels and the luring climate crisis will drive significant investment in renewable energies. Pyrolysis bioenergy systems will potentially attract investment by producing sustainable energy and by sequestering carbon from the atmosphere. It has been estimated that pyrolysis bioenergy systems can reduce up to 12% of current anthropogenic CO_2 emissions [3].

Pyrolysis is the process of anoxic thermal decomposition of carbon bearing compounds at high temperatures into various energy carriers, most notably volatile gases and Biochar. Organic waste is mainly composed of cellulose, hemicellulose and lignin. Each of these materials begins to thermally decompose at different temperatures and rates, resulting in a series of different products. Hemicellulose generates non-condensable gases dominated by CO, CO_2, H_2 and CH_4, carboxylic acids, aldehydes, alkanes, ethers, and water vapor. Cellulose generates Biochar, CO_2, H_2O and small quantities of CH_4 and CO. Lignin produces C_2H_4, CH_4, CO, and pyroligeneous acid (methanol, acetic acid, acetone and tar) [3].

Biochar, an energy carrier produced by pyrolysis bioenergy systems is a substance similar to charcoal. It can be valued as an energy carrier, carbon sink, or soil amendment. Studies have found that Biochar, when used as a soil amendment improves the following: soils absorption of water, reduces soil strength, reduces GHG emissions from natural soil processes, increases nutrient retention thus fertilizer requirements, stimulate bacterial growth, and sequester carbon in a highly stable form [3]. Biochar's effect on temperate soils is not fully understood and is currently the focus of a three year joint study between the universities of McGill and Laval.

This report documents the overall system design and subsequent detailed design undertaken in the development of a proof of concept (POC) pyrolysis bioenergy system in the context of an undergraduate mechanical engineering CAPSTONE project. The project was selected based on the current need to design new energy and waste management systems capable of mitigating climate change while maintaining commercial viability. This report along with the manufactured POC will be used as a stepping stone towards the ultimate goal of manufacturing a fully functional prototype capable of mitigating climate change through the production of sustainable energy carriers from organic waste.

1.1. Pyrolysis Overview

The pyrolysis system design required: first, a substantial literature review regarding the fundamental principles of pyrolysis systems. Second: a review of some of the already existing technologies before delving into the detailed design of the conceived system components. The following section will review the pyrolysis process and the parameters that affect by-product production. In order to effectively pyrolyze biomass, it needs to go through a pyrolysis unit that subjects the material to elevated temperatures and variable pressures depending on the system design. Typical pyrolysis units have three major components: the feed processor, system core, and a process extraction system.

The feed processor permits the entry of feed stock into the system. It is designed according to the mode of operation (continuous, batch), type and quality of feedstock, and typically differ from one application to another. The system core can generally be subdivided into the combustion chamber, heating system, and pyrolysis chamber as shown in Figure 1 below. The combustion chamber encloses both the heating system and pyrolysis chamber and is used to control emissions and reduce thermal losses. The heating system may vary from system to system depending on the energy source selected. The pyrolysis chamber is the component where in the anoxic decomposition of the feedstock occurs. It needs to be sealed in such a manner so that little or no oxygen enters from the atmosphere.

As seen in Figure 1, there are four major energy carriers that can be generated through pyrolysis. The first three: bio-oil, none-condensable gases and aqueous pyroligenous solution are produced by condensing the volatile gases released during the pyrolysis process. In some units, the gases extracted from the process are circulated to the combustion chamber to provide the unit with its own energy requirements. The fourth energy carrier is Biochar that must be extracted by a solid extraction unit.

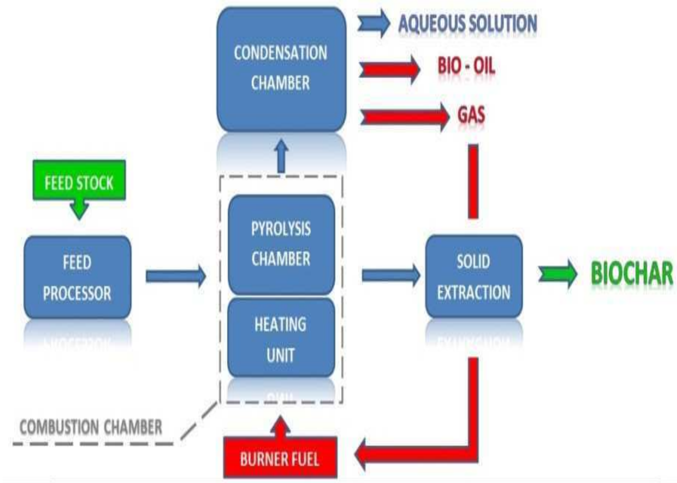


Figure 1: Typical components of pyrolysis system

1.2. Process Parameters

1.2.1. Heating Rates

There are two major classifications for the rate of pyrolysis: fast and slow pyrolysis. They are differentiated based on their heating rates of the material to be pyrolyzed. Each type of pyrolysis produces different ratios of bio-oil, gas and Biochar.

Slow pyrolysis systems have material heating rates of 5-7˚C/min, converting 30-50% of feed mass into a dual liquid phase (pyroligenous water and bio-oil) and 25-35% of feed mass to Biochar with the remainder converted into a gas phase. These systems typically operate at a design temperature of 400-500˚C, and are designed to operate with relatively large feedstock particles typically greater than 2mm in diameter [3].

Fast pyrolysis systems have material heating rates of approximately 300˚C/min, converting 75-85% of feed mass into liquid phase, 10-15% of feed mass into Biochar and the remaining feed mass into gas phases. These systems typically operate at a design temperature of 500˚C, and are designed to operate with relatively small feedstock particles of less than 2mm, in diameter, in order to achieve elevated heating rates [3].

1.2.2. Heating Method

There are three different types of heating method that are commonly used in the pyrolysis industries [4].

1) Auto-thermal process:

   Limited amount of oxygen is allowed to enter the pyrolysis chamber. This oxidizes the biomass generating combustion, which provides the heat required to pyrolyze the remainder of the biomass.

2) Direct heating through inert gas:

   An inert gas is heated and injected into the pyrolysis chamber. Heat is transfered form the gas to the biomass until pyrolysis occurs.

3) Indirect heating:

   Energy is added indirectly through the pyrolysis chamber walls, or radiator system. Heat carriers may also be used such as pre-heated steel balls, sand, or molten salt, which are mixed to the biomass.

1.2.3. Pressure & Gas Purge Rate

Pressure and purge gas rate have an effect on both the yield rates of pyrolysis by-products and the energy required for the pyrolysis to occur. It has been found that by raising the process pressure within the pyrolysis chamber Biochar yields increase and the enthalpy of pyrolysis decreases. In other words, pyrolysis has been found to be either exothermic or endothermic depending on the reactor pressure under which the process is initiated. Recall that exothermic reactions release energy while endothermic reactions absorb energy. These two effects can be seen in Figure 2.

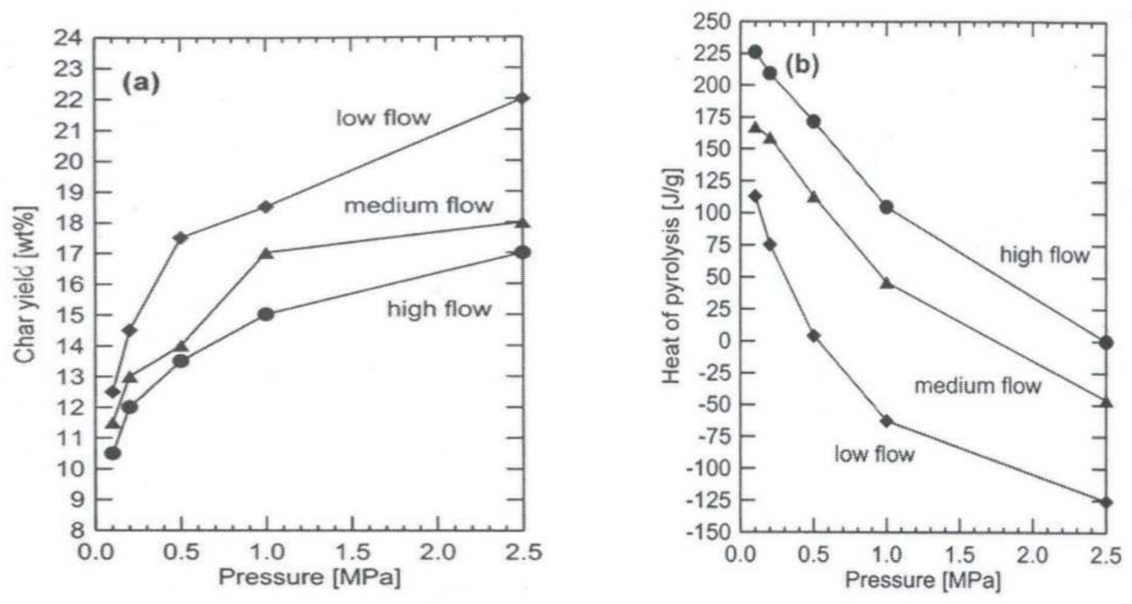


Figure 2:Effect of pressure and purge gas flow rate (low, medium, high) on Biochar yield (left) and heat of pyrolysis (right) [3]

It is thought that pressure has a kinetic effect on vapor molecules, that prologue their intra-particle residence time and increases the rate of thermal decomposition. Similarly, purge gas flow rate dictates the residence time of pyrolysis vapors within the chamber. Thus a high flow rate of vapor out of the unit will decrease the residence time by reducing the duration that the vapor was in within the chamber [3].

Several reaction pathways are thought to exist for cellulose decomposition through pyrolysis. The various paths use differing chemical mechanisms that are beyond the scope of this paper and help explain the variation in pyrolysis byproduct yields. To summarize, the vapor purge rate, pressure and heating rate will affect the decomposition pathway favoured by the cellulose, and each factor will push the reaction towards a specific by-products production ratio [3].

1.3. Mode of operation

The following section will describe the two modes of operation that are typically utilized by current commercial pyrolysis systems.

1.3.1. Batch Operation

Pyrolysis systems designed for smalls scale production are typically designed for batch operation. These units are first loaded with biomass, then, sealed properly so little oxygen enters the process. Lastly the pyrolysis chamber is heated to initiate pyrolysis reactions. After the process is complete and the pyrolysis vapors have been extracted, the system is unloaded. In order to run the process another time, the same steps should be repeated from the start. It is for this reason that this mode of operation is considered to be by batches and there are several disadvantages related to it. First, after each batch a cool down period is required for the Biochar before it is discharged. Second, there is a relatively large amount of labour required to load and unload units. Both these factors increase the overall operating time and cost [4]. An advantage to batch operation lies in the systems relatively simply design when compared to continuous operation.

1.3.2. Continuous Operation

The second mode of operations is continuous and is usually used for large scale productions. The unit runs continuously over time and is stopped only for maintenance. This operating mode permits the addition of biomass to the system as required without stopping the process. These systems are designed in such a way as to permit the intake and extraction of feedstock while maintaining operating conditions within the pyrolysis chamber. In other words the anoxic environment and process pressure must be maintained. The complexity of these systems is thus apparent when designing an intake and outtake system that is capable of maintaining process parameters. In terms of thermal losses continuous pyrolysis systems tend to be more efficient since significant energy is lost during the cool down of the batch systems [4].

1.4. Existing System Designs

This section will provide a brief description of some existing pyrolysis system designs.

1.4.1. The Mitsui Rotary Drum Pyrolyzer

The Mitsui rotary drum pyrolyzer shown in Figure 3 consists of an externally heated rotating horizontal cylindrical shell. Within the shell biomass is moved from inlet to outlet through mechanical paddles that push the biomass. The material inside the unit is heated indirectly with hot gases. The advantage of this pyrolysis unit is that it becomes energy independent after the starting phase. The system is heated by high temperature fumes that are generated by the process, and that flow counter current from the biomass. The main disadvantage of this type of pyrolyzer is that there might be an overheating of the pyrolysis vapors that result in the change of the vapors into solid carbon and non-condensable gases. To solve this problem, some of the rotary drum pyrolyzers use burners to maintain an optimum wall temperature, which yields to the production of bio-oil and Biochar. Also, it requires multiple burners for uniform heating and two sets of blowers to recycle product gases and to supply

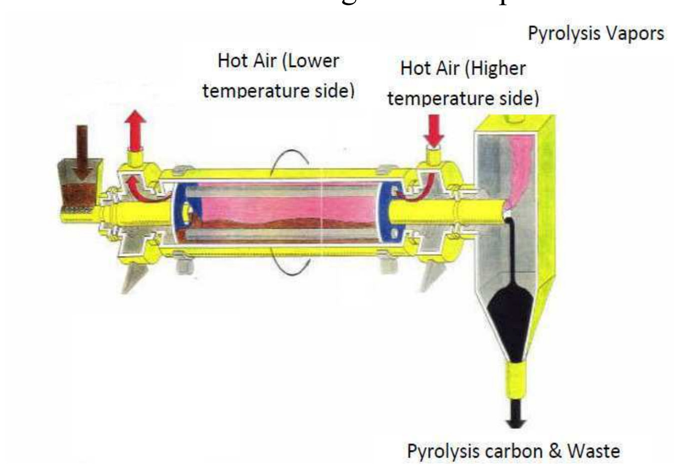


Figure 3: Mitsui Recycling Rotary Drum Pyrolyzer [4]

air to the burners respectively. This type of unit is complex to build due to the rotary vessel heat circulation and is composed of elements that increase the risk of hazards [4].

1.4.2. The inclined Rotary Kiln Pyrolyzer

The rotary kiln uses a rotating, externally heated inclined cylindrical shell instead of a horizontal one and it operates at atmospheric pressure. It is similar to the drum pyrolyzer except that the inclination allows gravity to draw the biomass from the inlet to the outlet instead of using paddles. In the design shown in Figure 4, a burner near the lower end provides auto-thermal heating. Hot flue gases flow counter current of the moving biomass. The advantage of this system is its simplicity and lack of moving parts. On the other hand, the disadvantages are the same as the rotary drum pyrolyzer, that include difficulty to control process temperature accurately [4].

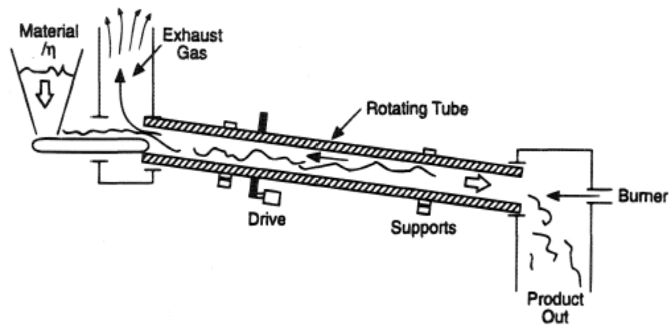


Figure 4: Inclined rotary kiln pyrolyzer

1.4.3. The Screw Pyrolyser

The screw pyrolyser uses an Archimedes screw, to move the biomass continuously along a heated cylindrical vessel. The gases and vapors are taken to a condenser to produce bio-oil, none-condensable gases and Biochar, that falls out from the vessel through an extraction system.

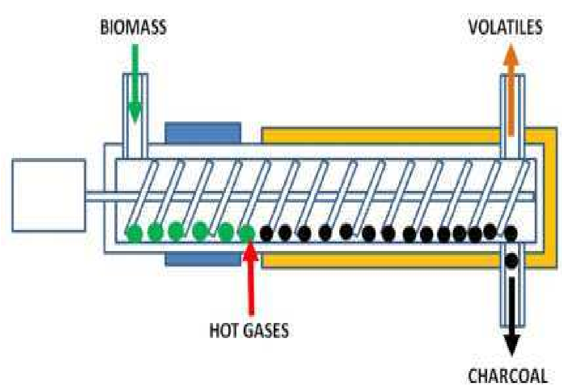


Figure 5: Schematic of screw pyrolyzer [4]

The heating system is placed at the lower part of the structure to provide heat to the area where most of the material will be touching. The heating system is usually composed of gas burners that provide indirect heating through the walls. Some systems require blowers for both air supply and gas circulation. Disregarding the heating system, this type of unit is relatively simple. This system has been proven to function for small and large scale operations. [4].

1.4.4. Vessel Pyrolyzer

The static vessel pyrolyser is in essence a pressure vessel which is loaded, sealed, and then heated. Pyrolysis is allowed to reach completion and then the system is unloaded, and the process is started once again. This type of unit is easy to build and doesn't have any complex part to it. It is a batch type system. The main advantage of this type of unit is that the sealing is easily done and there is no problem in maintaining the inside pressure and temperature of the pyrolysis chamber. This type of unit typically entails significantly more thermal losses during the heating and cooling cycles. These units also have the disadvantage that they cannot generate power in a continuous manner [4].

1.5 Design Applications

Versions of the four designs outlined in the previous section are currently being used by various industries. They are applied for: waste management, torrefaction, production of chemical derivatives, energy carriers and Biochar. Waste management applications range from hazardous waste disposal to municipal waste management. Mitsui rotary drum pyrolyzer is currently being used in Japan to dispose of electronic waste, and tires. The system heats the waste to extreme temperatures that thermally decomposes them. The pyrolysis vapors are then burned and the excess energy is used to power electric generators.

Commercialized torrefaction pyrolysis units are being used to produce energy dense wood products for pelletized wood power stations. The process of torrefaction leaves wood extremely dry reducing its weight and tendency to decompose. These two factors facilitate the distribution of pelletized wood for energy production.

Most pyrolysis systems have the ability to condense from the pyrolysis vapors various bio-oils, or other chemical compounds that through further processing can be converted to a multitude of chemical products ranging from plastics, fertilizers, and other synthetic compounds. Of significant interest is the growing trend to design pyrolysis systems for the production of Biochar that can provide the following benefits as a soil amendment:

1. Improved water absorption in soils reduces the duration and frequency of irrigation, which in turn reduces energy costs and GHG emissions associated with pumping water. A reduction in soil strength facilitates soil manipulation and reduces tractor fuel consumption [3].

2. The microstructure of Biochar foments bacterial growth though the mechanism through which this is achieved in not well understood. It is thought that the porous microstructure provides shelter for bacteria which would normally suffer predation in soil environments. Microbial activity is essential for plant health and nutrient absorption [3].

3. Biochar tends to have surface charges that effectively attract soluble ions in soils. This in turn increases fertilizer retention in soils that have Biochar amended to them along with reducing run off; a leading cause of eutrophication of waterways[3].

4. The addition of Biochar and organic materials to soils increases their carbon content, which results in the sequestration of carbon. The difference between an increase due to regular organic material and Biochar is that Biochar is stable. This means that the carbon re-enters the carbon cycle within hundreds of years versus 10 to 20 years for regular organic matter. This delayed re-entry can be considered as an avoided CO_2 emission [3].

5. Studies have found that the addition of Biochar to soils can significantly reduce N_2O and CH_4 emissions from soils. One study found a 50% reduction in N_2O and a complete elimination of CH_4 emissions. Methane and nitrous oxide both have 25 and 298 times the global warming potential of carbon dioxide (CO_2) respectively[3].

The previous five benefits described above are of particular interest both from an environmental and business point of view as developments in economic incentives continue to develop. It is for these reasons that Concordia's Sustainable Action Fund (SAF) showed interest in this design project, as an innovative solution to today's environmental concerns.

1.6. Expected Results and Contributions

This project will provide SAF with a functional POC pyrolysis unit, along with a technical report outlining the design process, considerations, and methods used throughout the project. The project will also include manufacturing drawings used. Our proposed solution to the global waste management problem is directly applicable within the university. This is because Concordia University has seen a yearly increase of 24% in its waste disposal costs. These unsustainable figures along with environmental concerns provide a serious incentive to reduce the amount of waste leaving the University. This document along with the POC will provide a preliminary feasibility study of the technology for a wide range of applications both within and beyond the confines of the university.

The POC subsystems will be clearly identified in the following chapter, along with the required controls. This report will be accessible to the general public and thus all our designed components can be easily improved by others. Another benefit of this work will lie in the systems scale. Its low cost and mobility will allow others to apply the technology easily to meet a variety of needs.

2. PROPOSED SOLUTION

The following three sections list the project's objectives, constraints and system specifications. They were generated from a review of existing technical literature on pyrolysis bioenergy systems. From the existing pyrolysis systems, it was deemed imprudent to design an operational pyrolysis unit that could generate hazardous flammable gases. As a result, a POC pyrolysis system was deemed as the ideal test bench for future prototype development.

2.1. Objectives

The system will be designed in such a way that the following objectives will be met:

1) The system will be able to monitor and control process pressure and temperature.
2) The system should attain temperatures and pressures required for pyrolysis.
3) The system will be flexible enough as to accept various kinds of feedstock.
4) The system must be hermetic, thus having no leakage of the gases generated within the pyrolysis chamber.
5) The system will be designed in such a manner as to minimize the amount of energy losses.

2.2. Constraints

1) The POC pyrolysis unit must be able to fit within the fume hood from the Multiphase Flow & Thermal Spray Laboratory. The entry window is 128.5cmx72cm, with a back geometry of 128.5cm x58cm x120cm.
2) The system should be designed as a scaled down version of a larger mobile system.

3) The system must avoid the production of hazardous gases due to safety concerns at Concordia University. Thus limiting the feedstock to a none-organic source.

4) The project must be completed within a 36 week period.

5) The project must not exceed the funding obtained from Concordia's Sustainable Action Fund.

2.3. Preliminary System Description and Specifications

The proposed system is a POC pyrolysis unit, seeing as it will be using wetted sand instead of organic material as feedstock. This will avoid the production of hazardous gases and reduce complexity of the safety and mechanical systems required for operation. The use of biomass was ruled out early on in the conception of the project after concerns were raised regarding the production of flammable and hazardous gases. The system as a whole will be designed as if to function with organic material. The pyrolysis chamber and other subsystems will thus be designed to operate at temperatures and pressures required to achieve pyrolysis.

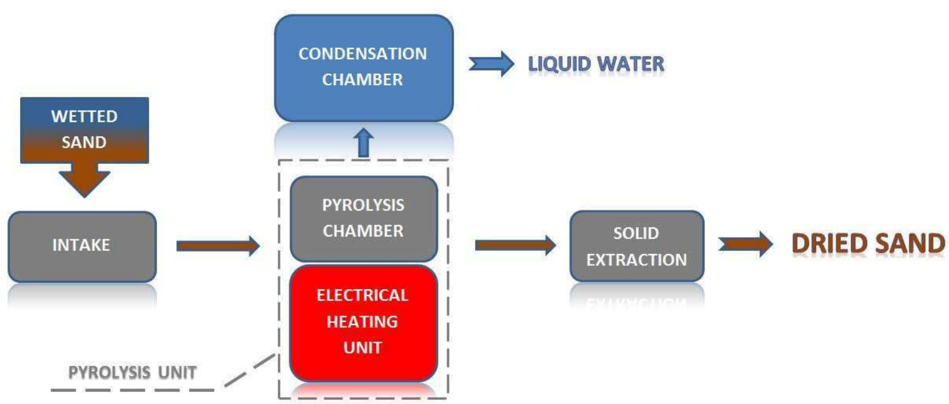


Figure 6: Preliminary schematic of proposed POC unit

In the schematic of Figure 6, the feed processor and solid extraction will insert and extract wetted sand into the pyrolysis chamber. The chamber will be operating at non atmospheric pressures, and must be designed to be air tight. Note that selecting a design pressure of 0.5MPa as shown in Figure 6 was desired since the resulting pyrolysis process would theoretically require zero energy input. Since the pyrolysis chamber would be both pressurized and heated it was deemed prudent to cut the operating pressure in half, targeting a design pressure of 0.25MPa (~38psi). The target design temperature was selected to be 400^0C as this is the minimum temperature at which the building blocks of organic material, cellulose, hemicellulose, and lignin thermally decompose. The targeted heating rate will be slow, since the production of Biochar favored by slow pyrolysis is desired. The feedstock will be pushed along the chamber by a drive system. A heating system must be devised that will provide the energy needed to heat the system to the selected temperature of 400^0C.

The purpose of the POC is to demonstrate that an effective mechanical and control system, capable of monitoring and controlling both pressure and temperature has been designed. Major flaws such as leaks or malfunctioning components can also be identified while avoiding the presence of flammables and hazardous gases. The design process undertaken during this project will provide a technical reference along with lessons learned for the development of a subsequent working prototype.

3. IDEA GENERATION

Once a preliminary design was determined, as described in Section 2, the POC system was broken down into five major subsystems: intake, extraction, drive, pressure vessel and controls. Technical considerations for each subsystem were considered and a brainstorming session was done regarding possible design alternatives for each subsystem.

3.1. Pyrolysis Chamber

The pyrolysis chamber is an important subsystem of a pyrolysis unit where the process occurs. The intake and extraction systems will be connected to it and the whole chamber will be heated. A drive system will be installed in order to carry the biomass through the vessel. Since the process is carried at a different pressure than the atmospheric pressure, the pyrolysis chamber can be referred to as a pressure vessel. Pressure vessels can be designed to be any shape desired, but as the shape gets more complex the required analysis becomes increasingly difficult. The most common shapes that are usually used are cylinders, spheres and cones. Spherical vessel can withstand higher pressure difference than cylindrical vessels, but are harder to manufacture and thus more expensive. Note that a section of industrial process piping, closed off on each end can be considered a cylindrical pressure vessel. This design option was selected as it was found to be the most economical. The material normally used for pressure vessel can vary from one to another depending on their use, operating conditions and tensile properties. These materials and their specifications are all listed in the 1992 ASME Boiler & Pressure Vessel Codes (ASME B&PV). The main concern regarding the cylindrical vessel is to design the appropriate end caps to close the vessel.

3.1.1. Domed end caps

The first choice of end caps are the domed end caps. They are more expensive than most end caps due to their manufacturing techniques to obtain a perfect round shape.These are used for high pressure difference vessels. Due to symmetry, the pressure within a spherical vessel is distributed equally in all directions perpendicularto the vessel surface. On the right, Figure 7 shows the stress distribution inside a half sphere and the stresses that the wall is subjected to. The domed end caps are simply considered as half spheres. The vessel undergoes two types of stresses: the cylindrical stress (hoop stress) and a longitudinal stress. The hoop stress is caused by forced applied to the cylinder wall due to pressure differential. The longitudinal stress is the one that will act on the end caps and is caused by the pressure inside the vessel as seen in Figure 8. The stress domed end caps are subjected to in a cylindrical vessel behaves the same way as the stress present in a half sphere [5].

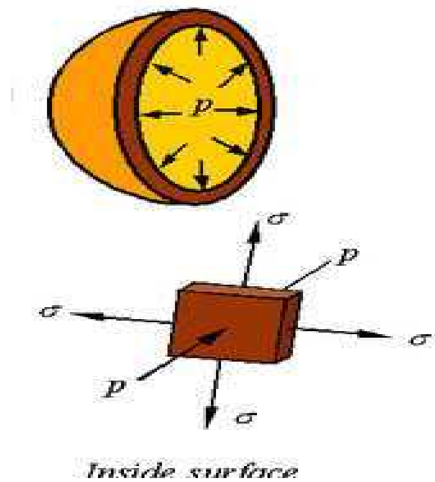


Figure 7: Schematic of domed end cap and stresses

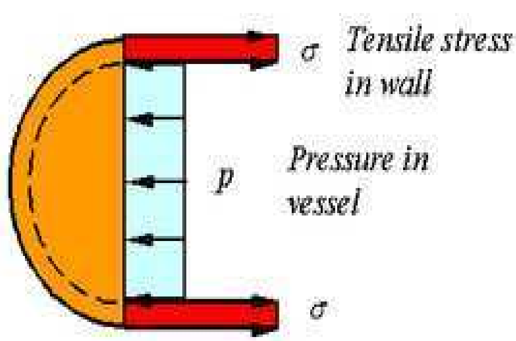


Figure 8: Longitudinal stresses on domed end cap

Vessels using half spheres as end caps have less chances of failing than when using other types of end caps. This is due to the fact that the longitudinal stress is distributed equally creating a uniformly distributed stress in all directions. The manufacturability of these end caps is really constrained. Due to their round shape, drilling holes or making any changes to their shape will alter significantly the stress distribution which will diminish their working temperature and pressure. In fact, stress concentrations near the holes made on spherical surfaces are higher than around those made on flat surfaces [5].

3.1.2. Flat end caps

The second type of end caps considered is the flat end caps. The pressure vessel will undergo hoop stress and the end caps a longitudinal stress, both explained previously. On the other hand, a third stress arises when using flat ends. When applying a pressure longitudinally to the ends, a perpendicular axial stress is induced. This is why the vessel with flat ends has more chances to fail at the ends than along the cylinder. This is due to the fact that the stresses at the ends are not distributed uniformly anymore. There will be an increase of stress concentration at the junction of the flange and the cylinder. This makes this type of end caps less safe than the domed end caps. When designing a pressure vessel operating at relatively low temperature and pressure flat end caps can be used. A close look needs to be addressed to specific standards from the ASME BPVC when choosing the end caps to make sure they are capable to withstand the working pressure and temperature. Flat end caps are easy to manufacture due to their flat surface, which makes processes like drilling, boring and welding easier. This is an important advantage for the design because some modifications to the initial shape are required in order to build the prototype properly. The safest way to install end caps is first to weld on the cylinder flanges (that must also meet ASME BPVC standards) and then bolt on the flat end caps. A flange gasket is placed between the two mating surfaces to prevent leakage during the process while under compression [5].

In summary, the pyrolysis chamber will be constituted of a cylinder that will serve as a pressure vessel. This vessel will be closed on both ends using flat end caps. This choice was made because this type of end caps is less expensive than the domed end cap and because machining a flat surface, with the tools available in the EDML, is easier than on a curved surface. Details about the type of flanges, end caps and the material used are discussed in Section 4.2.

3.2 Intake and Extraction Systems

For continuous type pyrolysis designs such as the one being documented in this report, the intake and extraction system must be designed to allow material to enter and leave the chamber with minimal loss in pressure. The design of the intake and extraction system thus needs to fulfill the following requirements:

1. Allow material to enter and exit the chamber without interrupting the pyrolysis process.
2. Minimize the pressure loss of the system.

From these requirements a couple alternative solutions were generated.

3.2.1. Pressure Door System

This solution required the use of gasketed doors and an actuator to force material through the pressure lock section and into the chamber.

This door and piston system requires a sequence of three steps:

1. The piston, with a hollow "push loop" pierces through the material and forces the doors to the pressure vessel open. The piston rings around the piston prevent gas and material from escaping upwards.

2. Once the material has been pushed through the pressure doors, the shape of the push loop ensures that the doors close in the correct sequence. This is necessary for the doors, as seen in Figure 9, are overlapped and gasketedin order to lock in the pressure. If the doors close out of sequence, a large gap would allow pressure to escape.
3. The final stage is when the doors close in proper sequence, locking in the pressure. The piston recedes and fresh material is allowed to enter the pressure lock.

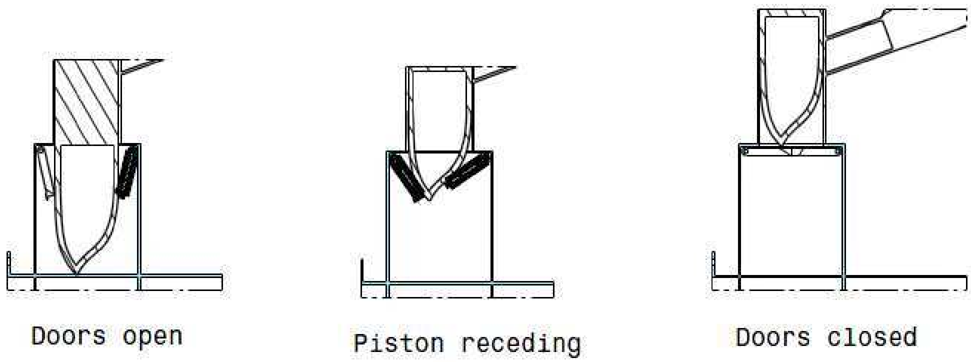


Figure 9: Gasketed door and piston preliminary design solution

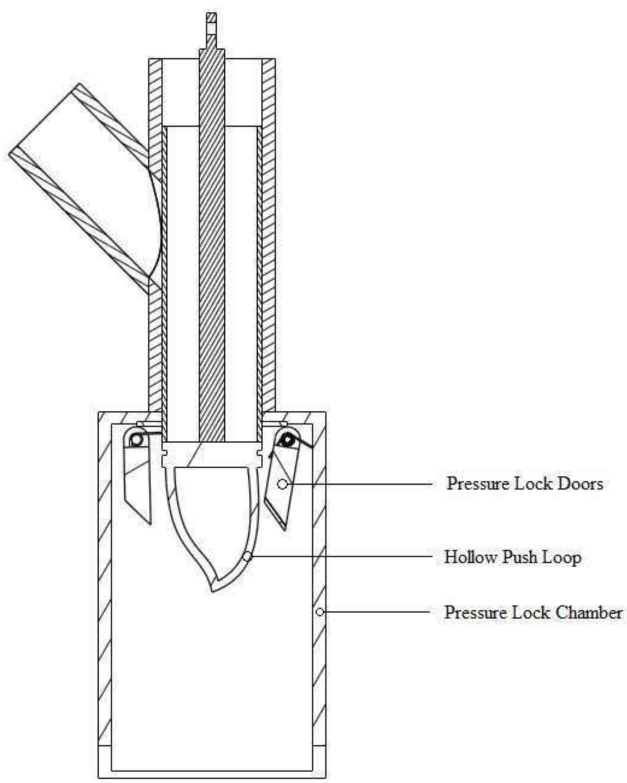


Figure 10: Overall view of gasketed door and piston design

The main advantage of this design is that as the pressure in the chamber increases, so would the pressure acting to close the doors. This increase in pressure would act to compress the gasket further, increasing the effectiveness of the seal as the pressure builds. However, the complexity of the design would lead to many problems with manufacturing and respecting tolerances. Problems such as machining internal features of the pressure lock chamber, doors and the hollow push loop would only increase the likelihood of delays and would not necessarily add to the effectiveness of the design. To insure the air tightness of the overall system would require very strict tolerance around the doors and the piston to ensure that the gaskets would function correctly in blocking the escape of pressure. Also, by design the piston would be forcing against the internal pressure of the system. While permissible at the scale of the current model, the forces that would ultimately be subject to the piston, doors, and driving mechanism would not become feasible if this were to be scaled.

3.2.2. Sliding Piston Extraction

As with the criteria of the intake system the extraction system needs to respect the same objects. For the extraction stage, a piston type pressure lock is also designed to extract material from our chamber and maintain pressure throughout the pyrolysis process. Figure 11 shows the two positions of the pistion gone through during the operation.

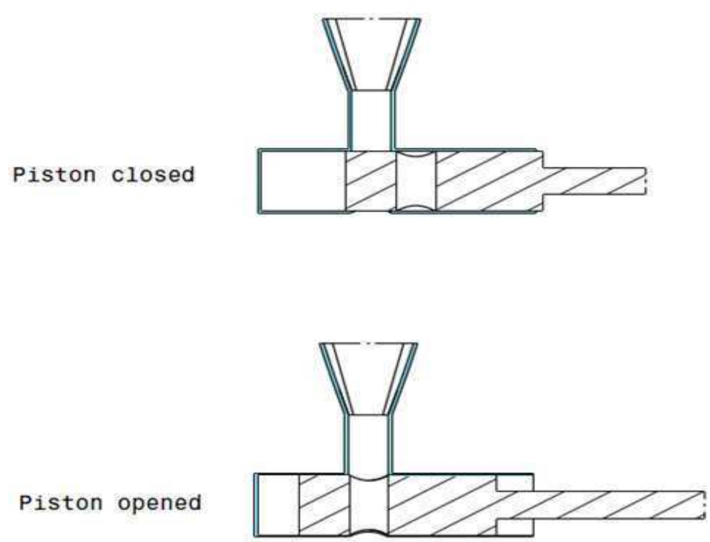


Figure 11: Open and closed position of sliding piston extraction

This extraction process requires 2 stages:

1. When the piston is closed the piston blocks the material and gases from escaping the chamber.
2. When the piston is open, the material is free to escape.

The main advantage of this system is simplicity. The internal pressure works to extract the pyrolyzed material as soon as the hole in piston lines up with the hole in the pressure vessel. With this design there is no need to force the material out, but only to control the flow of material by varying the size of the passage during the alignment of the holes. As the gas generated in the chamber will rise to the top, the extraction system will be placed on the underside of the chamber and therefore should extract only the solid by products of pyrolysis. Overall this design is simple, but manufacturability is an issue again due to the tight tolerances that would be required to make a tight seal between the piston in the extraction housing.

3.2.3. Draw String Tooth Gate (Extraction)

A very early design was based on a pressure barriers found in nature. The system in Figure 12 shows a draw string that closes and opens a gate. When the tension in the string is loosened the internal pressure would force the material out and when the draw string is tightened the teeth on the gate would close. This is a system that is similar to the way your mouth closes, and blood vessels in your body constrict.

This design is also fairly complicated to manufacture and put into operation as the tolerance on the teeth dimensions would need to be very accurate. There are also serious concerns that this design is only well suited for very low pressure and dry, solid material.

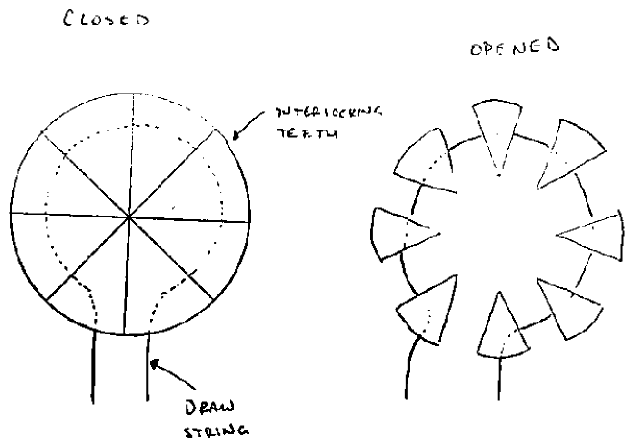


Figure 12: Draw string stooth gate

3.2.4. Dual Disk Lock (Extraction)

This design is inspired by a simple gumball machine which is constructed from one rotating disc and another non rotating disc. When the holes in the disc line up the material is allowed to evacuate the chamber. Like the previous design, the internal pressure will force out the material and all that is required is the control of the material flow rate through the adjustment of the hole size. Figure 13 and 14 provide a cross section view of both open and closed positions of the disk lock and isometric view respectively.

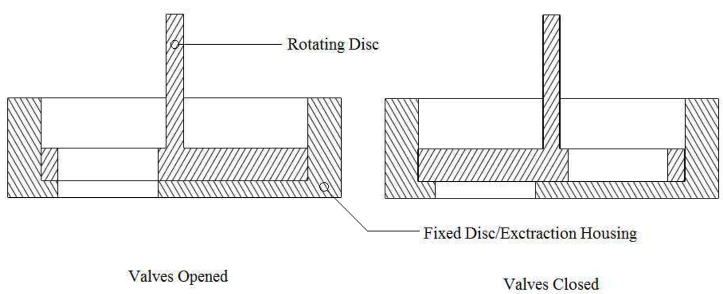


Figure 13: Cross section of dual disk lock extraction

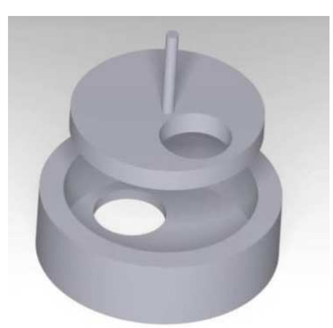


Figure 14: Isometric view of exploded dual disk lock

This design is simple, effective and easy to implement into any pyrolysis design. Like the sliding piston design however, this design is simply a more complex version of commercially available vales that offer the same benefits without the manufacturing issue.

3.2.5. Ball Valves System - Intake & Extraction

Ball valves offer many of the benefits that were desirable in other solutions, such as simplicity and easy implementation while guaranteeing that the pressure loss will be at a minimum if properly fastened. Figure 15 illustrates the type of valve considered.

Figure 15: Standard brass ball valve

For the purposes of the extraction system the ball valve would satisfy the requirements outlined above, as only the flow of material leaving the unit needs to be controlled, however the same isn't true of the intake system.

For the intake, there needs to be a mechanism that opposes the pressure and pushes the material into the chamber, or the pressure needs to be equalized so that the material can freely drop into the pressurized chamber. The first idea (Pressure Lock Doors) used a piston to push material through a pressure locking system which added complexity without adding integrity to the design. Therefore, a simpler design is needed. By setting up a series of ball valves and operating them in specific sequence, a pressure lock can be created. In Figure 16 the intake system is illustrated using a 4 ball valve setup with one side dedicated to the input of material, and the other side used to equalize the pressure through the process. Section 4.3 further explains the correct sequence of the opening and closing of the valves to achieve a pressure lock.

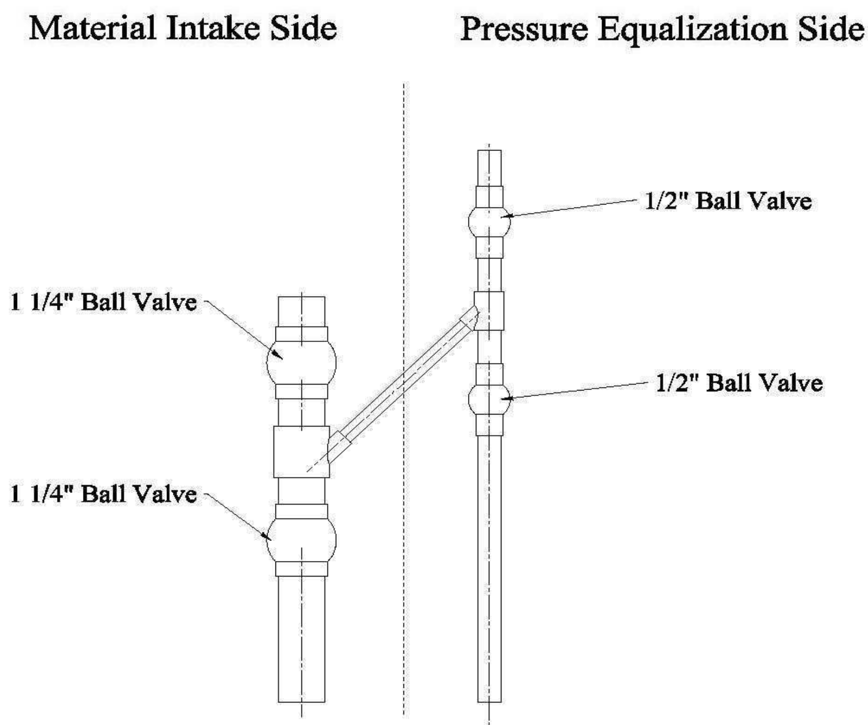


Figure 16: Illustration of ball valve intake system

The idea generation stage of the project was lengthy and continuously revisited. In total two designs for the intake and four for the extraction were considered. All of these designs in theory meeting the objectives outline previously. The advantages and disadvantages that led to the selection of the simple ball valve pressure lock system are summarized in Table 1.

Table 1: Summary of advantages and disadvantages for intake & extraction

		Advantages	Disadvantages
Intake System	**Pressure Doors**	• Pressure would help the sealing	• Extremely complex • Difficult to manufacture • Low chance of success • Not easily scalable
	Ball Valves Lock	• Pre-manufactured to exact tolerance • Guaranteed sealing if operated within limits • Easy to implement into any design • Easy to operate or automate if need	• Costly to buy • Only come in standard sizes
Extraction Systems	**Sliding Piston**	• Simple design • Easy to manufacture • Easy to implement	• Tight tolerances on design
	Draw String Tooth Gate	• Supports a wide range in flow rates	• Hard to create airtight seal • Will be difficult to operate (or automate)
	Two Disc Lock	• Simple to build • Easy to operate • Easy to implement	• Fairly tight tolerances
	Ball Valves Lock	• Pre-manufactured to exact tolerance • Guaranteed sealing if operated within limits • Easy to implement into any design • Easy to operate or automate if need	• Costly to buy • Only come in standard sizes

In summary, the intake and extraction system would be centered on using ball valves to hold pressure. This is because ball valves met all the advantages of the other designs that were considered while drastically reducing manufacturing time, increasing safety, effectiveness and dependability.

3.3. Drive System

The main purpose of the drive system is to act as a mechanism to move material across the pyrolysis chamber. One of the constraints of the drive system is the speed at which material is moved. As explained in Section 1.2.3, the residence time of the feedstock within the chamber is crucial to the production of Biochar. In Section 1.4 *Existing System Designs*, four different types of drive systems were identified. While brainstorming a fifth novel idea was generated, the pyrolysis belt drive system.

3.3.1. Pyrolysis Belt Drive System

The concept was to use a V-shaped belt within the unit that would be driven by a chain attached to a main gear and sprocket, all powered by a motor. Due to the amount of the parts, this option comes with high manufacturability and cost, but remains an effective method of moving material across the pyrolysis chamber.

3.3.2. Selection of Drive System

The following is a list of the possible drive systems considered during the conception phase of the POC:

1. *The Rotary Drum Pyrolyser:*
2. *The Inclined Rotary Kiln Pyrolyser:*
3. *The Screw Pyrolyzer:*
4. *Static Vessel Pyrolyzer:*
5. *Belt Pyrolyzer:*

These five listed systems were then systematically analyzed through the use of a decision matrix, using specifically identified criteria. The decision matrix has been provided in the Figure 17 below. It must be stressed that a decision matrix is only a tool to guide the decision process and does not provide definitive answers. Any decision made through the decision matrix must be re-evaluated to ensure that it meets current and future design considerations.

Taking the decision matrix into consideration, the design alternatives were narrowed down to the top rated three: pot, screw and inclined rotary kiln. The pot scored the highest though it was disregarded since it requires batch operation. As previously discussed, the downside of producing non-continuous by-products along with the incurred thermal losses of batch operations, lead to its dismissal as a design alternative. The inclined rotary kiln was also disregarded, since feeding material into a rotating cylinder seemed almost impossible, unless an auto-thermal mode of operation as shown in Section 1.4.2 was used. This mode of operation was undesirable as it oxidized the material being pyrolyzed and thus yielded less by-products. This final additional analysis led the design team to favor the selection of the screw as the preferred drive system.

	Criteria	MANUFACTURABILITY		Cost			Engineering		Simplicity					
	Sub-criteria	Labour Time	Skill Level	Hardware	Materials	Maintenance	Quality of analysis	Validation	Pressure system	Feed system	Heating system	Control systems	Drive systems	
	Coarse weight	40		30			20		10					
	Fine weight	15	25	12	12	6	12	8	2	2	2	2	2	
	Percentage	15	25	12	12	6	12	8	2	2	2	2	2	
option	Option description													SCORE
A	Belt	9	15	7	9	3	9	6	1	2	2	2	2	67
B	Screw	10	18	9	8	4	7	5	2	2	2	2	2	71
C	Inclined rotary kiln	12	18	8	7	6	6	6	1	2	1	1	2	70
D	Pot	14	22	10	10	6	11	7	2	0	2	2	2	88
E	Vaned rotary kiln	11	17	8	7	5	6	6	1	1	2	1	2	67

Figure 17: Decision matrix Decision matrix of five drive systems considered during conception of the POC

* For a description of the definitions of the decision matrix criteria used please refer to the Appendix D.

3.4. Sealing the Drive System

In order to rotate the screw, a drive shaft would need to be connected through the pyrolysis chamber. A pressure seal is thus required to maintain the pyrolysis chambers pressure and temperature. The following sealing methods were identified as possible candidates for the drive shaft seal: O-rings, bushings, mechanical seals, retaining rings, labyrinth seal, and fan seal.

A combination of O-rings, bushings, and retaining rings, was selected as the preferred method of sealing. The design was based on typical drive shaft sealing methods referred [6]. This preferred method was abandoned late in the design schedule for a design solution that the design team did not know existed, the Pump Packing Seal. A description of the abandoned design along with its replacement can be found in the detailed design section of this report.

3.5. Control Systems

The pyrolysis unit should be designed to be operating continuously with minimal human supervision. The desired control system will need to perform the following tasks:

- Monitor the temperature and pressure.
- Control the heat input from the heating unit.
- Safely handle situations resulting in dangerous temperatures and pressure.
- Control the mass flow through the intake and extraction system.

3.5.1. Sensors

Pressure

To measure the pressure inside a pyrolysis unit there are two main pieces of hardware, a pressure transducer and a pressure gauge. A pressure transducer can produce either a voltage or a current output signal. This signal can then be converted into a digital reading by means of an analog to digital (A/D) converter. The signal can be used to determine when the target pressure is reached, turning on the pressure regulating system. It can also be used to turn off the overall system when pressure exceeds the maximum limit. The pressure gauge, on the other hand, offers greater reliability and is relatively inexpensive. The disadvantage of a pressure gauge is that the readings are not recorded automatically and no automation can be achieved. Due to budgetary constraints the pressure gauge was selected in favor of the transducer.

Temperature

The challenge of selecting the proper temperature sensor is the linearity of the sensor at the working temperature. There are 3 types of temperature sensors that can produce a voltage output to the A/D converter. They are thermocouples, thermistors and RTDs; each of them has advantages and disadvantages for different types of applications. Thermocouples offer a large sensing temperature range well above 500˚Cand able withstand rough environment. The other two types of sensors are limited to temperature reading below 400˚C and offer no linearity on reading for higher temperature[7].For the rugged reason, the team have selected the thermocouple as the ideal temperature sensor for the pyrolysis unit.

3.5.2. Heater tubular, inside, wrap

Section 1.2.2., reviewed the three heating methods typically used in pyrolysis systems. From the review the auto-thermal process was deemed undesirable since the part of the material to be pyrolyzed underwent oxidation. This means that production rates of energy carriers would be lower depending on the amount of material oxidized. Direct heating through inert gases, heated steel balls, or molten sand would require a level of complexity beyond the scope of a 32 week project. One direct heating method was explored that required the insertion of electric heaters within the pyrolysis chamber. It was determined that this was un-acceptable since the element surfaces would be subjected to substantial fouling which would quickly reduce their thermal efficiency during the pyrolysis process.

Having ruled out two of the three heating methods, the design team then considered indirect heating. Two relatively simple methods were identified. The first, a gas burner design, would use re-circulated pyrolysis gas in order to heat the unit. This design was abandoned after the H&SD, raised several hazard issues that were insurmountable. The second solution, electric heaters, did not raise serious safety concerns with the H&SD. Having ruled out all other options the electric heaters were thus selected for the design.

3.5.3. Pressure regulator

Solenoid valves can be used to regulate the pressure inside the pyrolysis unit by venting its contents. The solenoid valve would be controlled by a computer that receives a signal from a pressure transducer. This system would be capable of maintaining the desired design pressure. The disadvantage of such a system is its reliance on electrical and software components and its elevated cost. Compared to the solenoid valve, a mechanical back pressure regulating valve is simpler, more reliable, and much less expensive. It is for these reasons that the mechanical back pressure regulating valve was selected.

3.5.4. Motor

The selection of motor for the drive system depends mainly on the RPM and the required torque of the system to move biomass through the process.

3.5.5. DAQ system & Software selection

The data acquisition (DAQ) system for the pyrolysis unit has to be able to perform the task of an A/D converter, display the temperature and pressure signal when voltage/current output is used and perform digital and pulse-width modulation (PWM) signal output to control the actuator and motor. The following are the potential DAQ boards that can be used for the system: Mbed NXP LPC1768, Arduino Uno and NI USB-6008 represented in Figure 18 [8].

The microcontroller Mbed and Arduino are well known to be inexpensive and provide a large variety of libraries for the software developer to perform digital input and output (I/O) and A/D converter. The NI USB-6008 manufactured by national instrument offers a faster sampling rate and compatibility with LabView software to monitor the sensor signal and perform digital I/O. Various software's can be used for developing the control system for the project. LabView can be used as the software to monitor and control the system, and since the Arduino microcontroller has gained popularity, the LabView developers have produced title blocks that are compatible for Arduino users. The second choice of software to develop the control system is to use MatLab Simulink, which is also compatible with NI DAQ Board and Arduino. The third possibility is to write the control system in C++ source code and upload the code onto the microcontroller Mbed or Arduino. In order to improve the freedom of programming the control loop software, the Arduino Uno was selected and the programming loop was designed using C++ language.

NI USB-6008 Arduino Uno Mbed NXP LPC1768

Figure 18: DAQ Boards & Microcontrollers

4. DESIGN

It is recommended that the reader review the design CAD drawings in Appendix G to get a full and clear understanding of the unit designed. Figure 19 shows the final POC along with labels for key components.

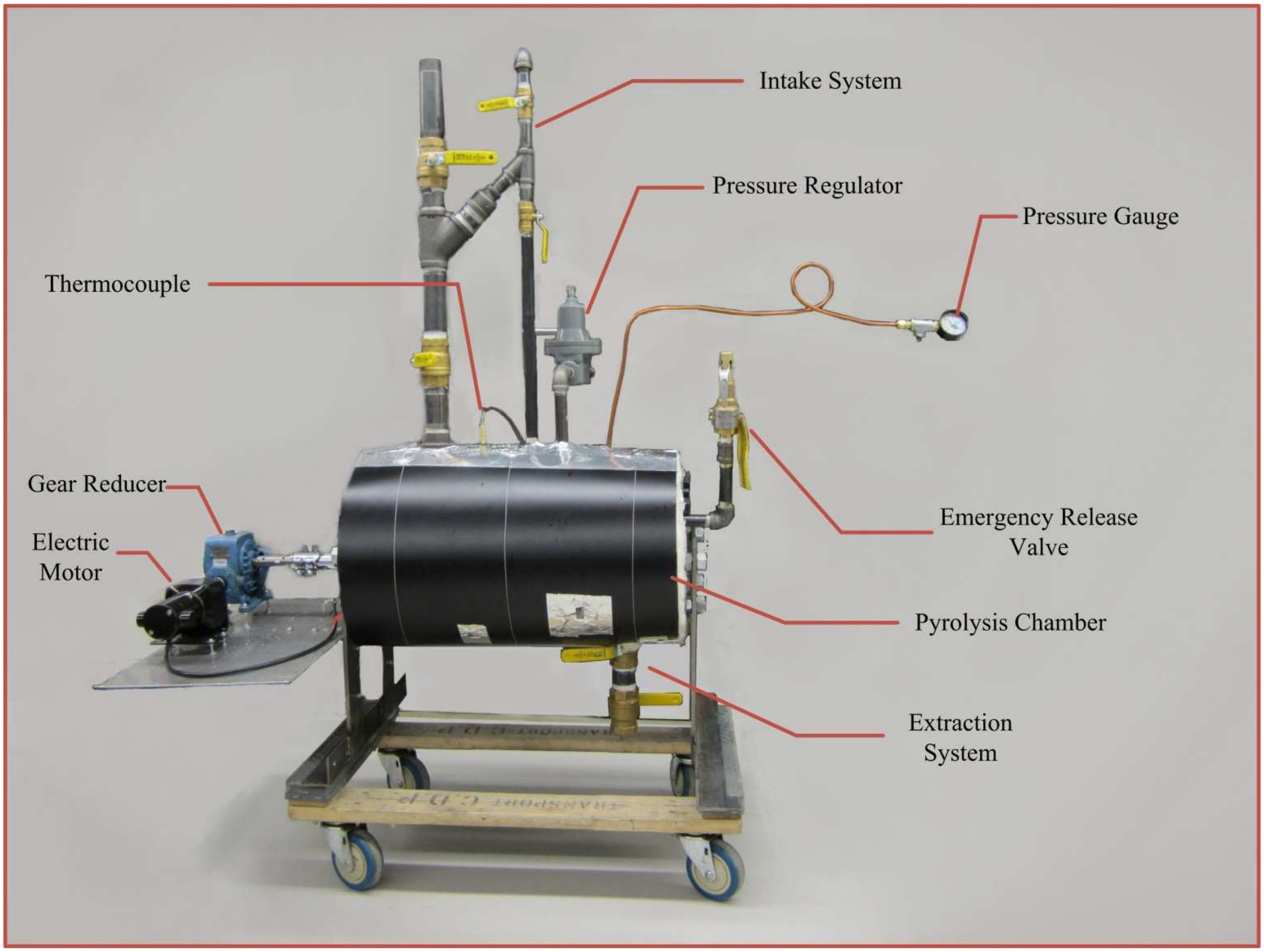


Figure 19: System Overview

4.1. Codes and Standards

The following section provides a review of the 1992 ASME Boiler & Pressure Vessel Codes (ASME B&PV) for Power Boilers (PB) [9]. These standards were found to be best suited for the design of the POC. It must be noted that these standards are not the most recent, though due to budgetary constraints newer standards were not obtained. A revision of up-to-date standards would be needed to continue further development of a pyrolysis unit. Another issue that must be addressed in future works is the following: individual provinces within Canada select which sections of the ASME B&PV are adopted within their jurisdictions. These locally adopted provincial codes were not reviewed.

4.1.1. Design Assumptions

It was assumed that the sand component of the feedstock would be inert, and thus would only absorb heat as the unit operated. The water fraction of the feedstock, once within the pyrolysis chamber, would undergo a phase change to steam through the absorption of heat. A device that employs a source of energy to convert water to steam is typically considered a boiler. It was using this justification that the ASME B&PV Standards were identified as suitable standards to review for the design of the POC in question.

Throughout the following section initial assumptions needed to be made regarding components, thicknesses etch, in order to verify that they withstand the design operating conditions within the selected safety factor. These assumptions were based on research that indicated that these components were acceptable or commonly used in industry. In other words, the design method utilized was one of general selection based on rules of thumb, and simplified calculations, and then leading to a detailed design to verify that the components desired would in fact be satisfactory.

4.1.2. Boiler Terminology

The language and writing style used in the ASME B&PV standards is difficult and dense to read, having many terms which were unfamiliar to the uninitiated reader. Definitions and explanations for terms and equations are not always provided within the standards as its target audience is assumed to be well versed in pressure vessel design. The following is a list of some terms that undergraduate readers may have difficulty with:

- **Water Tube Boilers**: A type of boiler in which water is circulated within tubes that are externally heated by flue/combustion gases.
- **Flue Tube/Shell Type Boilers**: Flue/combustion gases are channeled within tubes that are submerged in water.
- **Expanded Tube Connection:** Boiler tubes connected with tube expanders are called expanded tube connection. The tube is deformed by a mandrel to fill the gap between tube and the tube hole.
- **Stays:** Used to provide structural reinforcement to pressurized components of boiler. They typically are dilled through the member they support, or may be similar to welded support bars.
- **Ligaments:** Refers to the area of metal between the holes in a tubesheet. Three types of ligaments exist: longitudinal, circumferential and diagonal
- **Tubesheet**: Usually flat plates, part of the boiler drum.
- **Safety valve**: used for gas or vapor service
- **Relief valve**: uses primarily for liquid service
- **Safety relief valve**: suitable for use as wither safety or relief valve.

4.2 Cylindrical Component Equations

The equations used to determine the minimum thickness required to withstand the design pressure, and to determine the maximum pressure allowable for a specific thickness are presented below. These equation are valid for cylindrical components and were selected from section *PG-27 Cyclindrical Components Under Internal Pressure* from the ASME B&PV PB standard and have been provided in a similar format[9].

<u>Tubing - up to and including 5in outside diameter</u>

Eq. 1 $$\boldsymbol{P = S\left[\frac{2t-0.01D-2e}{D-(t-0.005D-e)}\right]}$$

$$\boldsymbol{t = \frac{PD}{2S+P} + 0.005D + e}$$

<u>Note</u>:

- For tubes expanded into drums, or headers a Table PWT-10 provides minimum wall thickness of tubes. Table is recommended instead of equations.
- For the tubing equation provided above please refer to the Notes 2, 4, 8 and 10, provided below.

<u>Piping, Drums, and Headers</u>

Eq. 2 $$\boldsymbol{t = \frac{PD}{2SE+2yP} + C or \frac{PR}{SE-(1-y)P} + C}$$

$$\boldsymbol{P = \frac{2SE(t-C)}{D-2y(t-C)} or \frac{SE(t-C)}{R+(1-y)(t-C)}}$$

Where:

t = minimum required thickness, in (Refer to PG-27.4, Note 7)

P = Maximum allowable working pressure, psi (Refer to PG-21)

D = Outside diameter, in

R = Inside radius of cylinder, in

E = Efficiency (Refer to PG-27.4, Note 1)

S = Maximum allowable stress value at the operating temp.of the metal, psi
(Refer to PG-27.4, Note 2)

C = minimum allowance for threading and structural stability, in
(Refer to PG-27.4, Note 3)

e = Thickness factor for expanded tube ends (Refer to PG-27.4, Note 4)

y = Temperature coefficient (Refer to PG-27.4, Note 6)

The above layout, as given within the ASME standard did not have equation numbering. This suggested that for *Tubing* and *Piping* there was two or more independent equations, both functions of P and t. Attempts were made to solve these equations simultaneously through iterations in MatLab. It was later found that these equations are not independent but dependent, meaning that both equations can be obtained through the algebraic manipulation of one.

4.2.1 Initial Selection of Process Piping for Pressure Vessel

Pipes are typically rated in terms of their schedule, which is the ratio of the internal pressure to allowable fiber strength, as shown in equation Eq. 1.

Eq. 3 $$Schedule = \frac{Internal\ Presssure\ (PSI)}{Allowable\ Fiber\ Stress\ (PSI)} x1000$$

Selecting an internal pressure of five times the design pressure, 185psi, and a steel yield stress of 36,000psi the schedule was determined to be 10. A schedule of 40 was selected to be conservative since temperature was not accounted and since most industrial process pipes are manufactured for a schedule of 40.

Knowing the required schedule a candidate 6in nominal diameter pipe was found in the universities machine shop, EDML B. As the pipe had no specifications or markings of any kind that would indicate what type of pipe it was, a couple of measurements needed to be taken in order to determine if the pipe would be able to withstand the temperature and pressure of the project. The first measurement was of the pipe's internal and outer diameter. The outer and inner diameter measurements were 6.625" and 6.065" respectively. These measurements where consistent with a schedule 40 pipe, which indicated that this pipe was in fact manufactured as a pipe and not simply a structural tube member with no associated pressure rating standard.

In order to calculate the pressure that this pipe could withstand, the yield strength needed to be estimated. To test the hardness of the pipe, a section was cut and tested on the 10^{th} floor of the Hall Building in the Properties and Failure of Materials laboratory with the supervision of Robert Olivier. The section used for the test is shown in Figure 20. The hardness test indicated that the pipe that was found in the EDML had a hardness of 60B on the Rockwell Hardness Test. Using the hardness conversion chart of Figure 20, the Rockwell value was converted to 115 on the Brinell Scale.

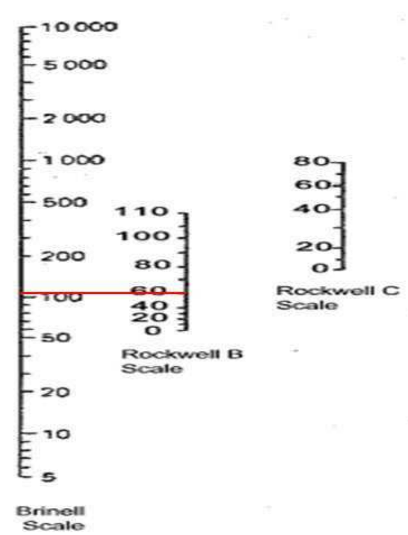


Figure 20: Picture of the sample of pipe that was tested for hardness (left) – Conversion scale used to determine BrinellHardness (right) [10]

The tensile strength was determined using the Brinell harness through Eq. 4 below [10]

Eq. 4 $$T_s(MPa) = 3.45 \times HB$$

Where:

T_s = Tensile strength, MPa

HB = Brinell hardness

The tensile strength was found to be 396.75MPa. It was found that ASTM A53B steel, has a tensile strength of approximately 415 MPa[10], and is commonly used in the production of industrial process equipment. The result of the Rockwell hardness test also indicates that the pipe was relatively soft and would be good for welding. Using the pipe of the EDML would greatly reduce spending that could be used in other components of the project.

4.2.2. Identification of Copper Tubing

The tubing used to connect the pressure gauge was stock tubing from the machine shop used to repair an old heat exchanger. From this information, along with the geometric measurements of the tubing, it was found that ASTM B280 was the most likely match. This type of tubing was made in the correct size, 0.25in OD and 0.065in ID and was commonly used to repair HVAC systems. The ASTM B280 standard met UNS 10200, 12000, 12200.

Since the material was thought to be ASTM B280 but there was no guarantee regarding this hypothesis, the ASME Non-Ferrous Materials standards were looked up. A list of five other possible candidates was made:

- SB-75
- SB-111
- SB-251
- SB-315
- SB-359

4.2.3. Component Parameters Used

To determine the maximum allowable stress (S) at 400C, use Tables 1A and 1B from Section II part D of the ASME B&PV Standards [9]. In order to use these tables the component material must be first identified, as is given in Table 2 below.

Table 2: Component description and material identification used to determine S from ASME standard

Component	Component Description	Material Identification
Pyrolysis Chamber	Seamless welded back steel pipe	ASTM A53B* ASME SA-53*
Flanges	Forged carbon steel	ASTM A105* ASME SA-105*
Piping	Seamless welded back steel pipe	ASTM A53B* ASME SA-53*
Tubing	Annealed copper tube – used in AC	Unknown

* Standard identification are identical over the year verified 1992, though may change from year to year. It must be noted that ASME and ASTM generally try to maintain standard compatibility unless major conflict arises.

Note: Since the copper tubing had a range of possible materials from which it could be made the maximum acceptable stress values were obtained for each of the five materials, the lowest of which was taken as the assumed value for the material and is tabulated in Table 3 below. The following table provides the values obtained for all the parameters:

Table 3: Value obtained for maximum allowable stress

	Pyrolysis Chamber	Piping 1-¼”	Piping ½”	Tubing 1
S, psi	17100	17100	17100	3000
D, in	6.625	1.660	0.84	0.25
R, in	3.0325	0.69	0.311	0.095
E*	0	1	1	1
C*, in	0	0.0696	0.065	0.065
e*	0	0	0	0
y*	0.4	0.4	0.4	0.4

*A brief description as to how the values of these parameters were determined will be provided at the end of this section within Notes 1-8, along with the referenced sections of the ASME B&PV Standard.

The values in Table 3 were used in conjunction with Eq.1-2 to determine minimum thickness required for a maximum pressure five times the design operating pressure. Note that it is customary in boiler design to work with a safety factor of four to five. The same equations were used to work backwards from the selected material, to determine the maximum pressure they would accept, these results have been tabulated below in Table 4.

Table 4: Results for minimum thickness and maximum pressure of current design compared to POC

	Pyrolysis Chamber*	**Piping 1-¼" ***	**Piping ½" ***	**Tubing 1**
t_{min}, in	0.0763	0.0788	0.0696	0.0089
t_{actual} , in	0.28	0.14	0.109	0.0925
P_{max}, psi	714	1501	1869	3448
P_{design}, psi	38	38	38	38

*Eq.2 was used to determine the value of t_{min} and P_{max} for these components. Pipes can be differentiated from tubes in that their inside diameter is close to the nominal diameter whereas for tubing the nominal diameter refers to the outside diameter of the tube.

Where:

t_{min} = Minimum thickness required for $5P_o$

t_{actual} = Actual thickness of component of POC

P_{max} = Maximum pressure for selected component thickness

P_{design} = Design pressure 38psi

4.2.3 Bolt loading

The following section used the ASME VIII standard method to determine the load on the flange bolts required to seal the pyrolysis chamber [9]. Several other more complex calculation methods exist that were not within the ASME VIII standard. These methods take into account various geometric, metallurgical, and loading effects; these include DIN 2505, PVRC, CEN, and others. No attempt was made to review these complex methods as they fell outside the scope of the ASME requirements.

Bolts are typically loaded for two distinct usages. The first, gasket seating conditions, refers to the axial bolt loading used to assemble the joint (flange). This loading is done under atmospheric conditions and room temperature. The second, operating conditions, refers to the axial bolt loading present experienced by the bolt while it resists the hydrostatic end force of the design pressure, while keeping sufficient compression on the gasket to maintain seal. The following two equations, A and B, provide the total force experienced by all the bolts on the flange under both seating and operating conditions.

Initial Load Requirement: (Seating Conditions)

Eq. 5 $$\boldsymbol{W_{m1} = \pi b G y}$$

Operating Load Requirement:

Eq. 6 $$\boldsymbol{W_{m2} = \frac{\pi G^2 P}{4} + 2b\pi G m P}$$

Initial Seating Stress:

Eq. 7 $$\boldsymbol{y = 180(2m - 1)^2}$$

Determination of Effective Width:

If the basic width is found to be greater than ¼” then:

Eq. 8 $$\boldsymbol{b = \sqrt{\frac{b_o}{2}}}$$

If the basic width is found to be less than ¼” then:

Eq. 9 $$\boldsymbol{b = b_o}$$

Where:

W_{m1}, W_{m2} = Load for Seating and operating conditions respectively
b = Effective width, in
G = Effective diameter, in
P = System design pressure, psi
R = Flange raised lip outside diameter, in
B = Flange raised lip inside diameter, in
N = Flange raised lip OD – Flange
n = Flange number of bolts
b_o = Basic width, in

m = Gasket factor

y = Initial seating stress, psi

The overall load requirement needed is taken to be the larger of the two values obtained from Eq. 5 and 6. To determine the load on an individual bolt the overall load is then divided by the number of bolts. A maximum allowable pressure of five times the operating pressure was used in order to maintain a factor of safety of 5. ASME B&PV design standards recommend the use safety factor values between 4 and 5. The gasket factor for the *Novatech Premium II Gasket* was selected from the literature provided by the gasket manufacturer, and is consistent with the recommended value found in the ASME Section VIII Standard [9].

$P = 190$ psi
$N = 1.78$ in
$b_o = 0.89$ in
$b = 0.6671$in
$m = 2.75$
$n = 8$

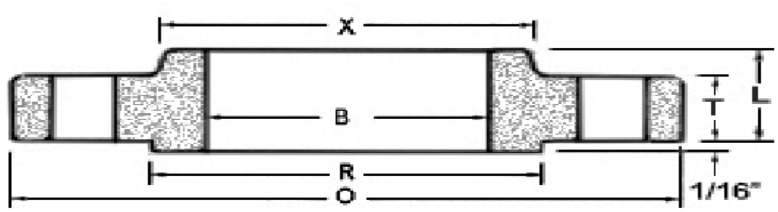


Figure 21: Slip on flange geometric identification used for calculation [12]

$R = 8.5$ in
$B = 6.72$ in
$O = 11$ in
$X = 7.56$ in

Results

$y = 3645$ psi

$W_{m1} = 41105$lb

$W_{m2} = 20422$lb

Overall Load = 41105lb

Bolt Load = 41105lb/8 = 5138lb

Having determined the amount of loading required to seal the vessel, an equivalent torque was determined using the following simplified equation:

Eq. 10 $$\boldsymbol{T = 0.2(BoltLoad)(BoltDiameter)}$$

Note: *To obtain ft-lb remember to convert the bolt diameter from in toft, by dividing by 12.*

Another more complex torque equation existed though it included the friction coefficients under the head of the nut and threads, which were difficult to determine [9]. It was deemed impractical to use this equation, since the added accuracy would be as good as the friction coefficients that were obtained, that depend on several conditions including lubrication. The simplified equation can provide an error of up to ±60% [12].

To determine the torque the cross sectional area of the bolts was required. It was found Class 150lb flanges were customarily fastened using Class 5 Medium Strength Bolts [12]. These bolts with a nominal cross section of ¾" were rated to be torque to a maximum of 288ft-lb for plain black steel and 200ft-lb for plated finish.

The local supplier we contacted did not have in stock the plain black steel finish of the required length needed, thus a mix of plated and black steel were used.

The torque was thus found to be:

$$T = 0.2(5138lb)(0.0625ft) = 64ft \cdot lb$$

To account for the ±60% error and thus assuring a conservative design the following calculation was done in order to determine the final bolt torque:

$$T_{final} = 0.6(64) + 64 = 103ft \cdot lb$$

The final torque required was then determined to be 36% less than the maximum allowable torque of the weakest bolt. The literature reviewed indicated that this margin was acceptable as it was customary to torque bolts no more than 80% of their maximum allowable torque spec [12].

4.2.4 Flange end cap requirements

The following equations were taken from section *PG-31: Unstayed Flat Heads and Covers* from the ASME B&PV PB standards [11]. The equation used to determine the minimum thickness of a flange circular head cover connected to a vessel by bolts in such a manner as to create edge moments, is provided below:

Eq. 11 $$\mathbf{t = d\sqrt{CP/S + 1.9Wh_g/Sd^3}}$$

Where:

C = Factor that accounts for attachment method to chamber (As given in Figure PG-31)

d = Mean diameter of flange raised lip (See Figure PG-31)

h_g = Gasket moment arm; measured from the centerline of bolts to the line of gasket reaction. (See Figure PG-31)

P = Maximum allowable working pressure, psi

S = Maximum allowable stress value, psi

W = Total bolt load, lb

Eq. 11 must be used to determine the thickness under both gasket seating and operating conditions. The values to be used for the equation parameters change with the type of operations and are provided below. Note that the larger of the two values calculated must be used as the minimum thickness.

Operating Conditions:

P = Maximum allowable working pressure

S = Value at design temperature

W = Sum of the bolt loads required to maintain flange secure and sealed

Gasket Seating Conditions:

P = Zero

S = Value at atmospheric temperature used

W_{avrg} = Average of the required bolt load and the load available from the bolt area actually used.

Note: A value of C = 0.3, is recommended for flat circular head covers bolted a flange.

The following will clearly show the steps taken to determine the minimum thickness of the end cap. Justifications will be provided for values, and assumptions. Using the flange geometric lengths given above in Figure 26 the mean diameter and moment arm were found to be:

Eq. 12 $$\mathbf{d = \frac{(R+B)}{2} = 7.61}$$

Eq. 13 $$\mathbf{h_G = \frac{(O+R)-(R+B)}{4} = 1.07}$$

Operating Conditions:

$$P = 190 \text{ psi}$$

The maximum allowable working pressure was chosen to be five times the design pressure. This was done in order to give the flange a factor of safety of 5.

$$S = 20000 \text{ psi}$$

The maximum allowable stress was obtained from ASME B&PV Table 1A Section II, Part D, for the material SA-105. It was taken at the operating temperature of 400C.

$$W = 41105\text{lb}$$

This value is the same as the one calculated in the bolt load section.

Eq. 14 $$t_{operating} = d\sqrt{\frac{CP}{S} + 1.9\frac{Wh_g}{Sd^3}} = 0.84in$$

Gasket Seating Conditions:

P = 0

As prescribed by ASME standard

S = 20000psi

Maximum allowable stress taken at room temperature value did not change.

W_{avrg} = 65353lb

Thus the required minimum thickness under gasket seating conditions was found to be:

Eq. 15 $$t_{seating} = d\sqrt{1.9\frac{W_{avrg}h_g}{Sd^3}} = 0.934in$$

The average value (W_{avrg}) was determined through the following:

The maximum allowable torque on a Class 5 ¾" plated bolt was found to be [11]:

T = 200ft-lb

Using the bolt torque equation Eq. 10 the axial force generated by this torque on a bolt can be found through:

$$W_{max,load} = \left(\frac{T}{0.2(Bolt\ diameter)/12}\right) = 16000lb$$

$$W_{avrg} = \frac{W_{max,load} + {}^{W}/_{8}}{2} = 65353\text{lb}$$

From these calculations it was observed that the maximum thickness required for the flange occurred under seating conditions, resulting in a thickness of 0.934in. Using this thickness the ASME recommended B16.5 type flanges were looked up. The thickness that came closest to the calculated thickness was the Class 150 B16.5 flange, with thickness of 1in [11].

4.2.5 Openings and Compensation

Sections PG-32 to PG-39 provide the rules for all openings and compensations in shells, headers, and heads [9]. These rules omit effects of external loads such as thermal expansion and unsupported weight of connecting piping. For a detailed design of a unit, these effects should be evaluated, but due to time constrains this topic was not investigated.

To summarize, these sections provide information regarding permissible opening sizes, spacing, and material compensation. Depending on the size and spacing of openings, the ASME B&PV PB standards recommend thickening a prescribed area around the opening. This thickness is determined through the calculation of ligament efficiency, which is then used in conjunction with Eq. 1 and Eq. 2. Recall that these equations were used to determine the minimum thickness required for the components.

As can be seen the design process is an interactive one. As openings are selected and located, one needs to calculate the new efficiency depending on the size and space of the openings, and then determine the required thickness within the compensation area.

Section PG-32 stipulates that no material compensation is required as long as:

- The openings are below the maximum opening requirements of Eq. 16.
- Welded connections are not larger than 2in. in pipe diameter.

- Threaded, studded, or expanded connections do not use openings greater than 2in. pipe size.
- Openings have a minimum center to center distance as stipulated by Eq. 18 below.

The maximum permissible opening diameter can be determined through Eq. 16 below:

Eq. 16 $$\boldsymbol{d = 2.75[Dt(1-K)]^{1/3}}$$

Eq. 17 $$\boldsymbol{K = \frac{PD}{1.82St}}$$

The minimum center to center distance between adjacent openings should not be less than the value L obtained through Eq. 18 below:

Eq. 18 $$\boldsymbol{L = \frac{A+B}{2(1-K)}}$$

Where:

P = Maximum allowable working pressure, psi
d = Maximum allowable diameter of openings, in
(Obtained from Figure PG-32)
D = Outer diameter of shell, in
t = Actual thickness of the shell, in
S = Maximum allowable stress value, psi
(Obtained from Table 1A and 1B of Section II, Part D)

Using Eq. 16 and Eq. 17 the values of K and d were determined and have been tabulated in Table 5 below.

Table 5:Values for K and maximum permissible opening diameter (d).

	K	**d(in)**
Pyrolysis Chamber	0.145	3.20
End Cap (Flat Head)	0.0574	5.99

It was thus deemed desirable to ensure that the process piping and external features requiring openings into the pyrolysis POC unit would have diameters less than those determined in Table 5 above.

Using Eq. 18 the minimum center-to-center distances for the selected pipe sizes were determined and were compared in Table 7below with the design center-to-center distances. Note: refer to Figure 22 and Table 6 for design spacing and hole dimensions.

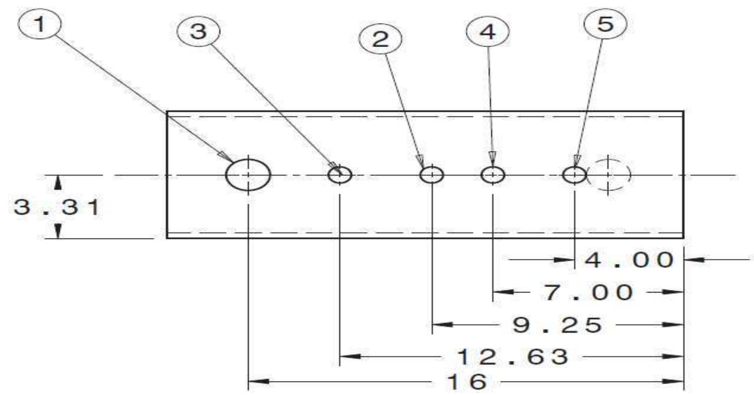


Figure 22: Pyrolysis chamber designed process openings with opening identification

Table 6 : Pyrolysis chamber and end cap process opening dimensions as indicated by Figures 23, 24, 25

	Identification No.	Opening Diameter (in)
Pyrolysis Chamber	1	1.67
	2	0.84
	3	0.84
	4	0.84
	5	0.84
Right Flange	Process Opening	0.694
	Bolt Hole	0.88
Left End Cap	Process Opening	1.125
	Bolt Hole	0.88

For the end caps the minimum length between the desired process opening and the already existing flange openings was taken as the design length to compare to the computed L_{min}.

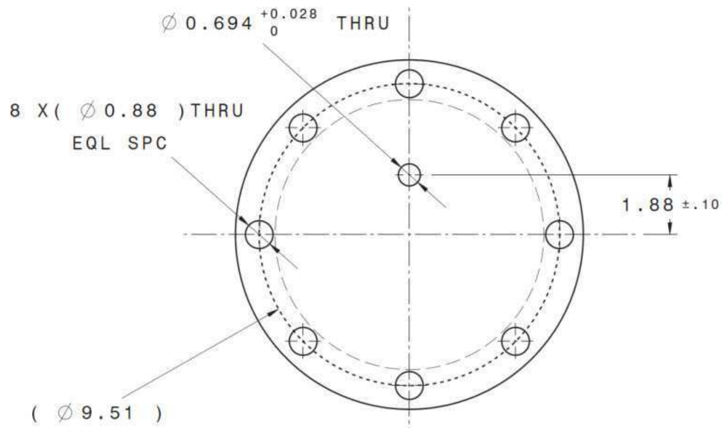


Figure 23: Right end cap

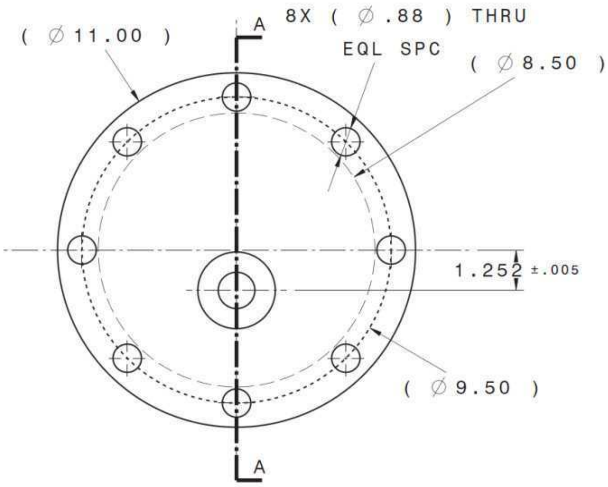


Figure 24: Left end cap

Table 7: Minimum center-to-center distances for adjacent openings and designed distances

	Adjacent Openings	**L_{min}(in)**	**L_{design}(in)**
Pyrolysis Chamber	1&3	1.467	3.37
	3&2	0.982	3.38
	2&4	0.982	2.25
	4&5	0.982	3
End Cap (Flat Head)	Right End Cap:	0.835	2.884
	Left End Cap:	1.064	3.498

From Table 7 it is apparent that the desired location and sizing of the designed process openings conform to the requirements stipulated in section PG-32 and thus no further calculations or material compensation is required.

4.3. Design of Intake & Extraction System

The intake is designed as a pressure and gravity feed system. This means that no external components such as actuators or pumps are required to move material into the chamber. Because of this, the intake system is required to be installed above the pressure chamber so that the material can drop downwards. Figure 25 illustrates the overall dimension of the designed intake system.

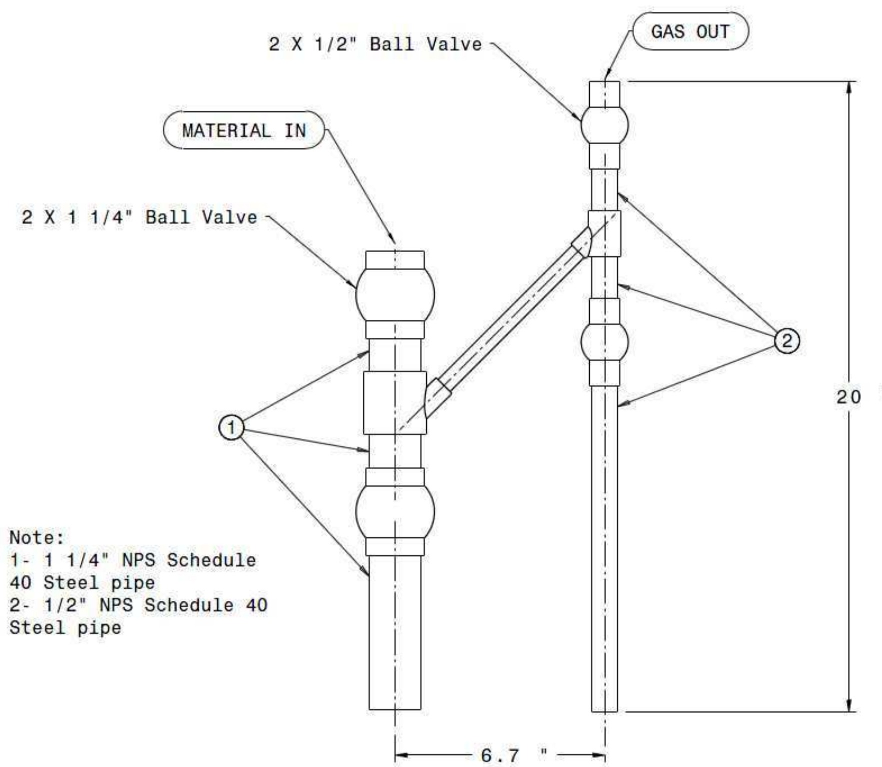


Figure 25: Intake Layout

All connections between components are threaded according to National Pipe Thread (NPT) standards. The exact dimension of the final system is slightly different after the components are tightened into place. However Figure 25 offers a good idea of the size of the assembled system.

The middle unifying pipe between the left and right vertical pipe section has been places at an angle to minimize the possibility that material will contaminate the right *gas extraction* side while the material is being collected in the left end.

Note: High temperature ball valves capable of operating at 400ºC had been found from local suppliers. These valves were not selected for the design as budgetary constraints were not permitting. The selected valves were generic brass ball valves with maximum operating temperature rated at 185ºC.

Extraction System

Like the intake system the most efficient method to extract material out of the pressure chamber is to use a series of valves that are operated in sequence as to minimize the amount of pressure loss from the chamber. The extraction does not need to be as complex as the intake system as the internal pressure is aiding the extraction of material. Only the quantity of material removed needs to be regulated.

The extraction uses one 3" 1 ¼" NPT pipe and two NPT ball valves mounted to the underside of the chamber. The pressure and temperature constraints are the same for the extraction system as the intake system.

The sequence for the extraction is short and logical:

1. With the bottom valve closed, the top valve is opened
2. The top valves is closed once the material has a chance to flow through the pipe
3. The bottom valve is opened carefully into the collection pan.

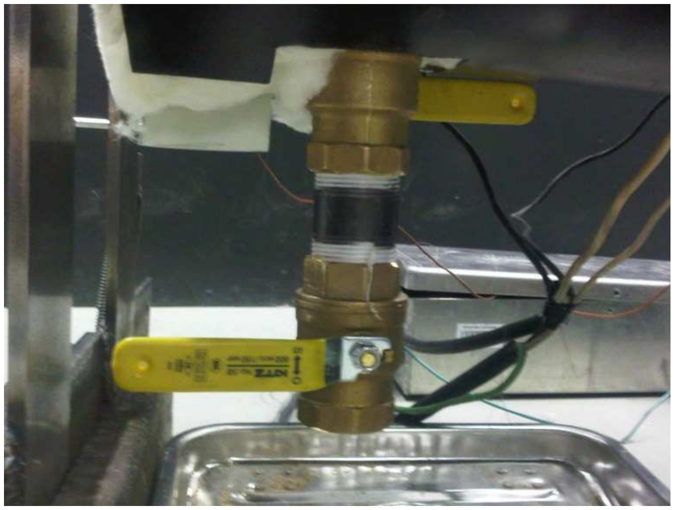


Figure 26 : Extraction System

Note: Since the design will be using whetted sand as feedstock, there is no need to allow the exiting material to cool. For a functional prototype the Biochar would be exiting at temperatures that could cause it to ignite upon contact with oxygen. Thus a prototype would require a cooling section to be devised.

4.3.1 Intake Sequence

The sequence of the opening and closing of the valves in the intake system is crucial to the design of the system. The four valves used in the intake process will be operated in accordance with Figure 27 and will insure that material enters the chamber with minimal loss of pressure or gas exfiltration. The six stages of the intake process are as follows:

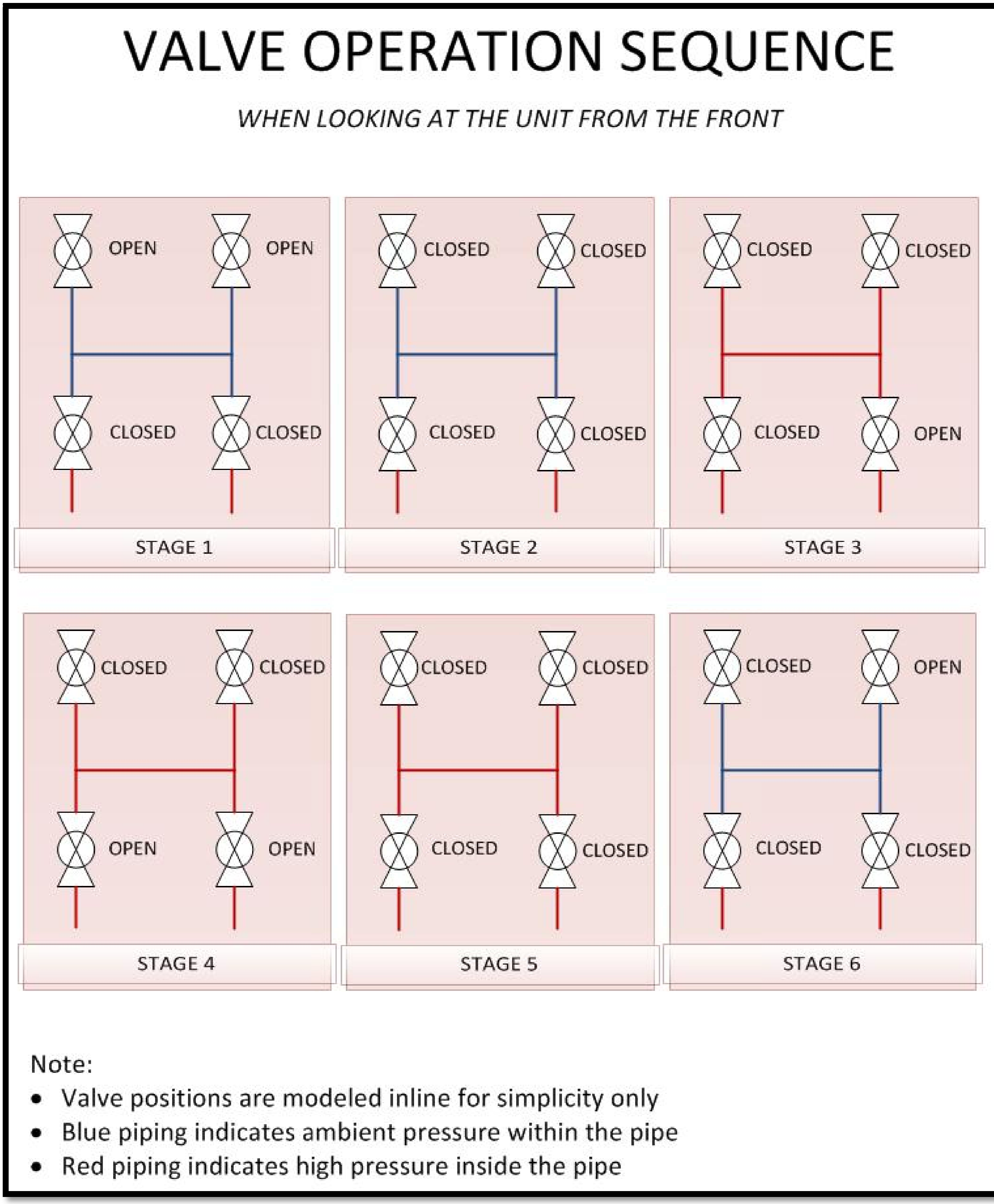


Figure 27: Intake Sequence

4.4. Design Drive System

The following section is a more elaborate explanation of the design and thought process behind the creation of the drive system. Figure 28 is a sectional view of the pressure vessel, enabling one to fully see the drive system. The red rectangle envelopes all the components that are part of the drive system and will be further discussed in this section.

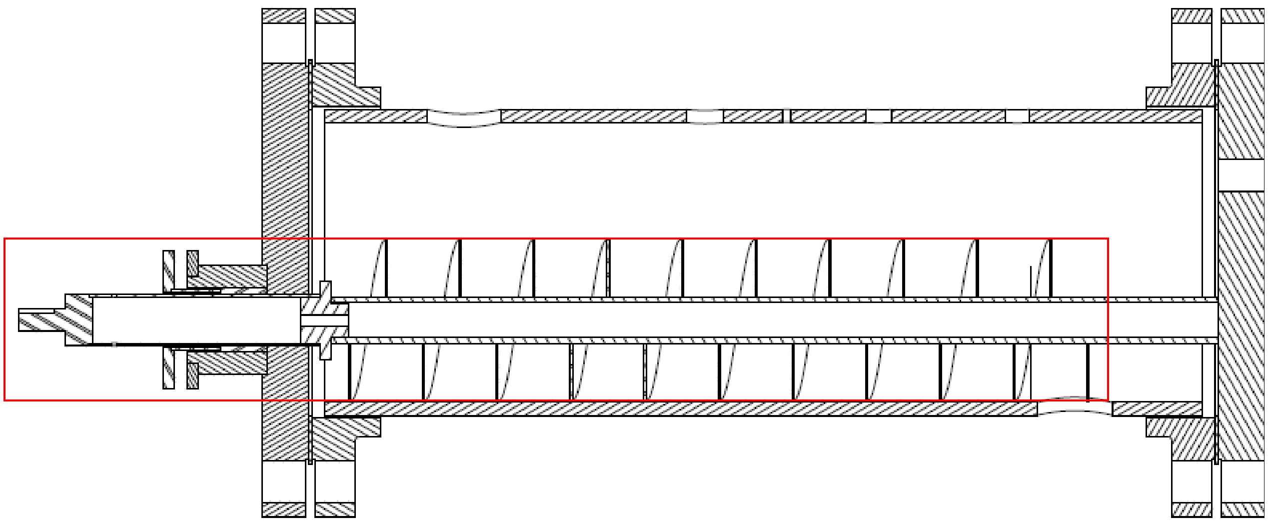


Figure 28 : Section View of the Vessel

4.4.1. The Auger

The initial idea was to manufacture an Archimedes screw that would force the feedstock across the pressure vessel. The screw was to use a parametric design, based on the work of Chris Rorres [13]. This meant that certain parameters would be selected and from these given parameters the rest of the unknowns would be obtained through ratios and easy to use equations. Once the screw design was complete, having determined optimal screw pitch, length, inner and out radiuses, manufacturability was then considered. It would take a highly skilled craftsman to shape the blades of the designed screw. The cost of which was deemed unacceptable.

Purchasing an ice fishing auger reduced the cost and the need for manufacturing. The auger was made out of steel able to withstand high temperature and high pressure. The auger is 0.52m in length (where 0.42 meters of that is bladed) with an outer blade radius of 0.04m, an inner blade radius of 0.013m which also corresponds to the outer radius of the drive shaft. The shaft is placed horizontally in the machine. Due to the inclination of the blades on the auger creat a helix that enables the translation of material from one end to the other. The drawing purchased auger can be seen in Figure 29.

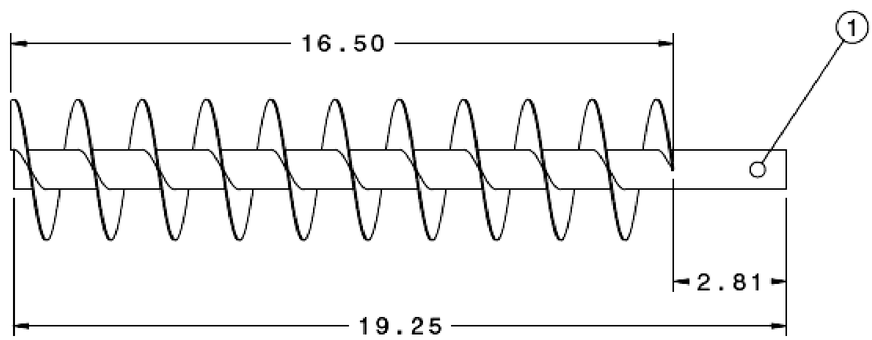


Figure 29: Illustration of ice fishing auger purchased

4.4.2. Original Sealing Design

To connect the auger to the motor while keeping a pressure seal within the pyrolysis chamber the following design in Figure 30 below was developed. The design shown was conceived over several weeks and required multiple iterations.

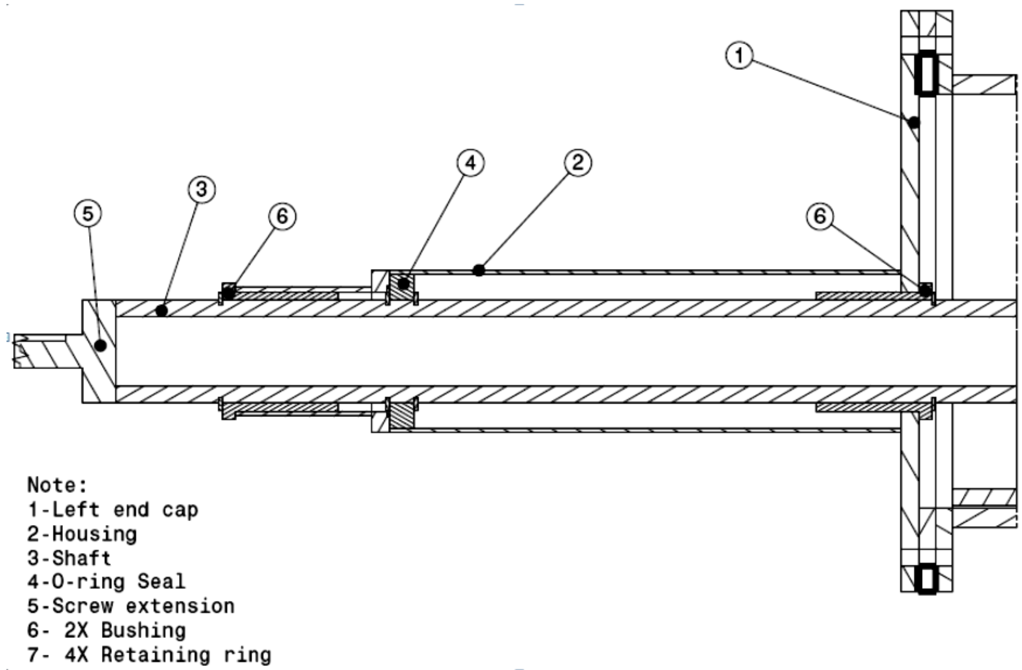


Figure 30: Original Idea for the Drive Shaft Extension

During this period it was though that O-rings and bushings capable of operating at 400ºC would be found. High temperature bushings and bearings had been found during this period capable of withstanding the temperatures, though no O-ring or O-ring substitute were found. The design team was about to lower the operating temperature when a solution was discovered in an unexpected place. While calling suppliers and companies for sealing ideas and solutions, an engineer from John Crane commented on pump sealing packing's that were subjected to extreme temperatures.

4.4.3. Pump Packing Seal Design

Reviewing literature on pump packing's lead to the design shown in Figure 31 that would allow the auger drive shaft to enter the pyrolysis chamber while maintaining process pressure. The design was also capable of withstanding the extreme temperature of 400ºC. It must be noted due to the low RPM of the shaft, determined in Section 4.4.4, no bushing or bearing were used. Instead the packing provided a tight running fit used as a bearing.

The packing is essentially a composite fibrous material that is wound about the drive shaft and is squeezed by the packing insert into a cavity, the housing extension. The squeeze prevents the contents within the chamber to escape while allowing the shaft to rotate.

In Figure 31 the numbering elements refer to the following:

1- Packing insert
2- Housing extension
3- Flange end cap
4- Packing

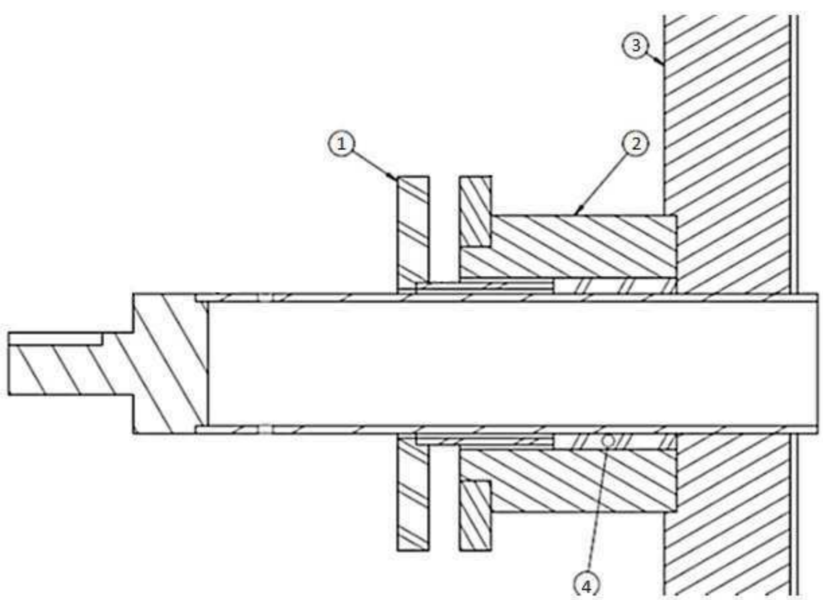


Figure 31 : Working Model of Drive Shaft Extension

The packing seal is a crucial element in the drive system, was donation from John Crane and can be seen in Figure 32, it is a simple metallic rope that is meant to be wrapped around the drive shaft.

The following Figure 32 notes the specifications of the packing seal that is used in the design. Important features can be seen underlined in red. These features mark that the chosen packing seal can withstand the pressure and temperature characteristics of the vessel.

Figure 32: Packing Seal Specifications [14]

4.4.4. The Motor

Selection of the motor is directly dependent on the geometry of the auger, the torque required to move the feedstock, and the residence time desired for pyrolysis. It was estimated that the feedstock would need have a residence time of approximately 1hr in order to achieve slow pyrolysis. The residence time was based on calculations performed in Section 4.2.3.

Equation 19 was used to determine the value of the volume displaced per screw rotation and was obtained from [13]:

Eq. 19 $$\mathbf{Vt} = \left(\frac{2\pi^2 Ro^3}{K}\right)\boldsymbol{\lambda\nu}(\mathbf{N}, \boldsymbol{\rho}, \boldsymbol{\lambda})$$

Where:

Vt = Volume of material moved per turn of the screw

Ro = Outer diameter of the blade on the screw

K = Number of blades on the screw

λν(N,ρ,λ) = Volume per turn ratio

λν(N,ρ,λ) is dependent on the chosen number of blades (N=1) that is directly taken from an optimization [13]. The value obtained from this table was 0.0361. From Eq. 19 the volume of material moved per turn of the auger was found to be 4.78E-5m^3. With this value the amount of material that would move in an hour could be determined by setting the motor RPM.

The maximum capacity of material that the auger can hold is 60% of its complete volume. Therefore a functional volume illustrates the maximum amount of feedstock that can be held within the screw at one time needed to be established. Under the assumption that the blades are extremely thin, the function is based on the inner and outer radius, as well as the length of the screw, and treated as a cylinder, found in Eq. 20.

Eq. 20 $$\mathbf{Vf} = \boldsymbol{\pi}(\mathbf{r_o^2} - \mathbf{r_i^2})\mathbf{L} * (\mathbf{60}\%)$$

Where:

Vf = Functional volume of material in the auger

r_o = Outer radius of the auger's blades

r_i = Inner radius of the auger's blades

L = Length of the bladed region of the auger

The functional volume of the auger is 1.46E-3 m^3. With this value, a flow rate is found by dividing the functional volume by the time constraint.

Eq. 21 $$\mathbf{Q} = \frac{\mathbf{Vf}}{\mathbf{t}}$$

Where:

Q = flow rate of the system.
Vf = functional volume of the auger.
t = desired amount of time the material is to stay in the vessel.

The residence time was determined to be, t = 3600s. With this value a flow rate of $4.063\text{x}10^{-7}\,\frac{m^3}{s}$ was found. From there, an angular velocity could be obtained using the flow rate and dividing it by the amount of volume that is moved per turn of the auger. As seen in Eq22.

Eq. 22 $$\boldsymbol{\omega} = \frac{\mathbf{Q}}{\mathbf{Vt}}$$

Where:

ω = angular velocity of the auger.

Q = flow rate of the material in the auger.

Vt = volume per turn of the screw.

An angular velocity of 8.49E-3 turns per second (approximately 0.5 rpm) was found.

Having determined the RPM the torque was found using Eq. 22. Note that the design includes the composite packing therefore the motor must be able to overcome the resulting friction. The friction factor used was selected to be extremely conservative, since a friction factor for the packing could not be obtained.

Eq. 23 $$\mathbf{T}_{\boldsymbol{u}} = \boldsymbol{T}_{\boldsymbol{su}} + \boldsymbol{T}_{\boldsymbol{seal}} = \frac{\mathbf{Fdp}}{\mathbf{2}}\frac{\boldsymbol{\mu\pi}\mathbf{dp+L}}{\boldsymbol{\pi}\mathbf{dp}-\boldsymbol{\mu}\mathbf{L}} + \frac{\boldsymbol{\mu}*\mathbf{F}*\mathbf{dp}}{\mathbf{2}}[5]$$

Where:

T_u = Minimum amount of torque required from the motor

T_{su} = Torque needed for the dead weight

T_{seal} = Torque needed to work against the seals

F = Forces acting on motor (weight of the motor and the feedstock) see equation 24

μ = Friction factor for metal on metal with a value of 0.8 [15]

L = Pitch of the screw dp is the diametric pitch of the screw found from equation 23 (below) is 0.0876 m.

To use Eq22, one needs to know how to calculate the diametric pitch of the auger:

Eq. 24 $$dp = 2*\left(\frac{\mathbf{Ro-Ri}}{\mathbf{2}} + Ri\right)$$

Along with calculating the diametric pitch of the auger, the force caused by the mass of the auger itself and the sand used must be calculated.

Eq. 25 $$F = g(M_{screw} + M_{sand})$$

Where:

$M_{screw}$is the mass of the screw weighing 2 kg

M_{sand} is the maximum amount of sand that can be used, 2.81 kg respectively.

g is the gravitational acceleration taken as 9.81 m/s^2. [15]

Resulting in a minimum torque required of 1.82 N*m. This value, along with the minimum required speed became the two constraining factors in choosing a motor. A motor was found in the EDML with the capability of running at 7.1 N*m and 208 rpm. In order to get the required speed, the motor was attached to a 70:1 gear reducer (Figure 34 below) and was driven by speed controller (Figure 33).

Figure 34 : Motor Speed Controller

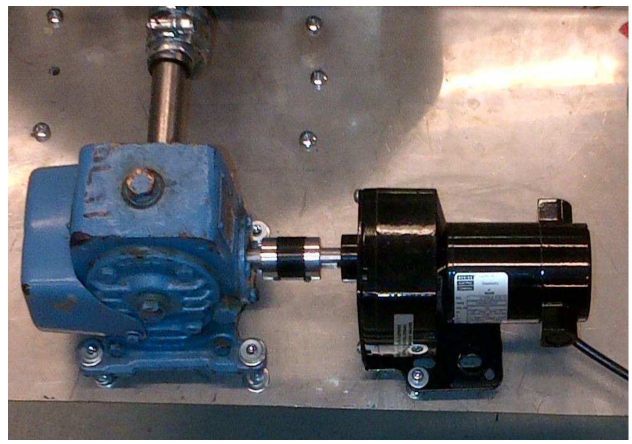


Figure 33: Gear Reducer and Motor

4.5. Control System Design

4.5.1 Electric Hardware Setup

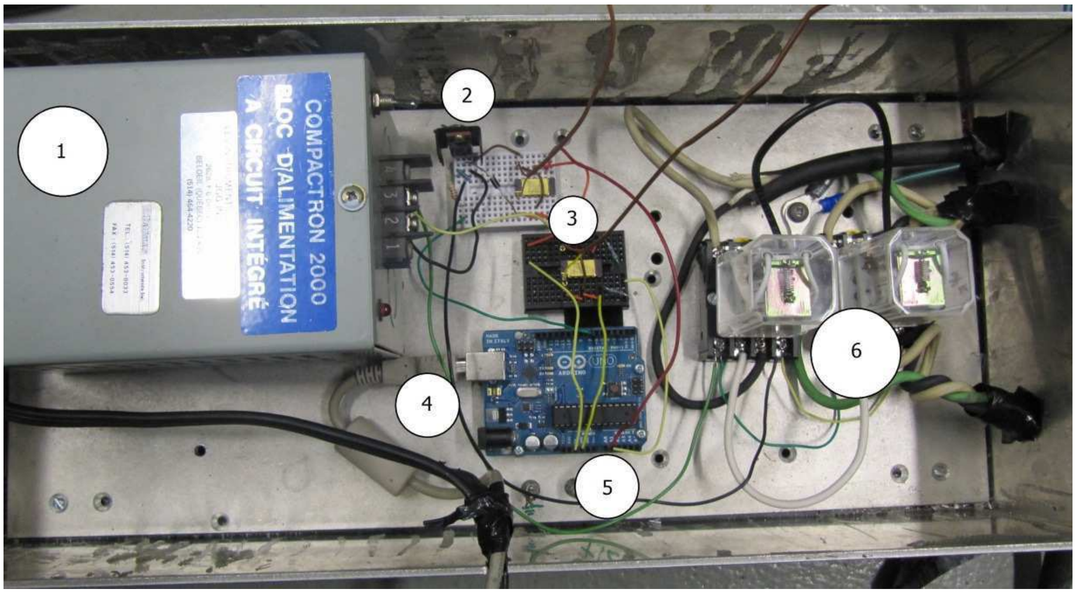


Figure 35: The Circuit Box

Table 8: Circuit item descriptions

Item #	Description
1	24 Volts DC Power Supply
2	Transistor N-Channel MOSFET IRF-530
3	2X Thermocouple Amplifier AD545
4	USB 2.0 A/B Cable
5	Arduino Uno Microcontroller
6	2X Relay KIR2P8QX24

The above Figure 35 is the complete setup of the circuit box. The Arduino Uno receives analog inputs from the two thermocouples. One of the thermocouples takes the temperature readings within the pyrolysis chamber, the second surface readings of the heating element. The Arduino interprets the analogue signals and produces a five volt signal from the digital pin to the transistor, allowing the 24volts DC power supply to power the coil of both electro mechanic relays. It completes the heater circuit and thus provides heat to the pyrolysis chamber. For the complete wiring diagram, refer to Appendix A.

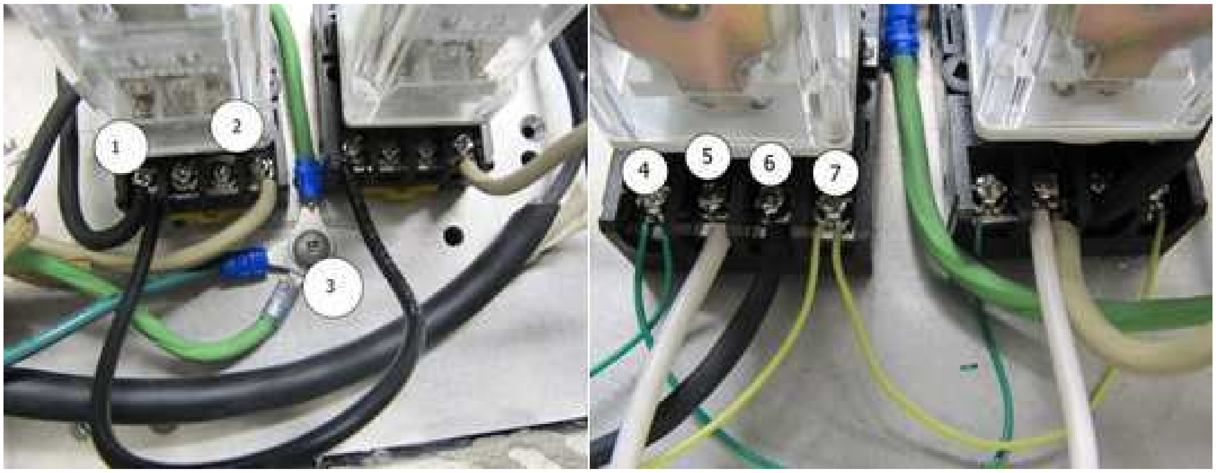


Figure 36: Relay KIR2P8QX24 (Front & Back)

Table 9: Relay item descriptions

Item #	Description
1	Pin 1 of Relay
2	Pin 8 of Relay
3	Common Ground
4	Pin 7 of Relay
5	Pin 6 of Relay
6	Pin 3 of Relay
7	Pin 2 of Relay

Figure 37: Relay Schematic

The relay KIR2P8QX24 is of type double pole double throw, where the coil will connect two pairs of terminals, with the option of having the switch normally open or normally closed. The Figure 37 shows the layout of each pin on the relay. The pin 2 and pin 7 are the control pins, where 24volts DC is needed to energize the coil. The pin 1 is used with pin 4 being normally closed and pin 3 being normally opened. As for the pin 8, it is used with pin 5 being normally closed and pin 6 being normally opened. On the Figure 36 above, the control pins and the heaters are connected in parallel, with the switch being normally open. This allows both heaters to operate independently. The common ground is attached to the circuit box and to the pyrolysis unit as a safety measure.

The wattage of the heaters was initially estimated using fundamental heat transfer principles. A core temperature of the chamber was assumed and a thermal resistance network was generated. This calculation yielded wattage of 100W that was completely nonsensical.

Speaking to technical representatives from several companies it was determined that a wattage of 25W/in^2 would meet our pyrolysis needs. The cost of ceramic and mica heaters would land the project over budget and were thus deemed unacceptable. A Montreal based company, Tempora, offered to provide a heating system capable of producing 15W/in^2 for \$600. After holding on to the system for two weeks and not responding to phone calls, they did not do the work they had promised and the design team was force to improvise a last minute solution. Two spare heating elements of unknown specification were obtained and the following was done to determine how best to use them.

To calculate the wattage of the heaters the following equation is used:

Eq. 26 $$\boldsymbol{Power = \frac{V^2}{R}}$$

Where:

V= Voltage, V

R= Resistance, Ohm

The spare heaters had an internal resistance of 32ohms and when connected to 240Vac power supply the wattage was found using Eq. 26 to be 1800W. In order to approach the 15W/in^2 target both heaters were necessary, producing 3600W. The current passing through the wire was then be calculated by using the following equation:

Eq. 27 $\boldsymbol{I = \frac{V}{R}}$

Where:

I = Current

V = Voltage

R = Resistance

With both heaters in parallel, the current drawn from the power supply is 15 Amps. In order to meet the electrical power requirement, a #12 American wire gauge (AWG) size wire was needed. Since the Relay KIR2P8QX24 has a wire size rated for only 10amps current, it is required to connect the two relays in parallel so each one will have lower amperage passing through it.

4.5.2 Thermocouples

Figure 38 : Thermocouple Type K

The selected temperature sensor was a type K thermocouple, since it allowsa sensing temperature up to 1300°C. The thermocouple probe shown above in Figure 38 was used to measure the temperatureinside the pyrolysis chamber.The compression fitting connector allows the probe to be threaded onto the pipe with a ¼" NPT which acts as a seal. A bare wire thermocouple of type K was used to measure the temperature at the surface of the heater.

Since the thermocouple produces only a voltage in the range of millivolts, the signal needs to be amplified in order to have a better resolution for the Arduino to acquire the data. In addition, all thermocouples need cold junction compensation (CJC), as a reference point for the voltage signal. The amplifier AD595 was found to be the ideal candidate able to perform both amplification and CJC. The chip also has a pre-trimmed setting to 0 volts at 0℃, and an output of 10 millivolts/℃, this serves as the calibration factor for the Arduino A/D converter [16].

The sensing range is limited with the selected amplifier, since the microcontroller can receive a maximum of five volts as an analog signal input. The Arduino has a limitation of receiving 500℃ as a reading. To overcome this limit, the voltage divider technique was used to increase the range of the sensor. This consists of putting two resistors of the same resistance in series and record at the midpoint of the two resistors. Through this technique the Arduino was able to read temperatures up to 1000℃ with half of the original accuracy and resolution.

The Arduino has a memory of 1024 bytes for analog inputs, and the following is a calculation for the resolution of the thermocouple signal without a voltage divider.

$$\frac{500\ ℃}{1024 bytes} = \frac{0.488\ ℃}{byte}$$

Another benefit obtained by using the AD595 amplifier is that the output has a maximum error of ±3℃. For the pyrolysis unit, the design team found an error of 3℃ acceptable.

4.5.3 Pressure Gauge

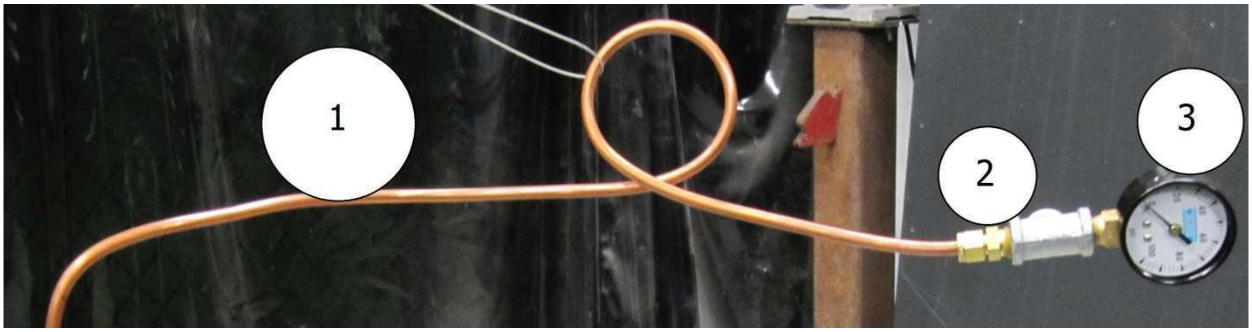


Figure 39:Pressure Gauge

Table 10: Pressure gauge item description

Item #	Description
1	Copper Tubing Pigtail
2	Tee connector
3	Pressure Gauge

As most pressure sensing devices are sensitive to heat, it is common to uses a pigtail connection or syphon, in steam boilers. The concept is to dissipate the heat from the vessel gas, condensing it into liquid form before the pressure gauge as shown in Figure 39 above. The pressure within the vessel is then directly transferred to the gauge by compressing the liquid, incompressible, in the syphon. The selected pressure gauge had a limiting value of 100 psi. For the scope of the project, only 37 psi is required which falls well within the reading range of the pressure gauge.

4.5.4 Back Pressure Regulating Valve

Figure 40: Back Pressure Regulating Valve

To regulate the pressure inside the pyrolysis chamber, a pressure regulator is used. The selected model is of type 98H with ½ NPS which is standardized, with a maximum working temperature and pressure of 207℃ and 75psi. The internal core of the regulator is a spring mechanism, and the spring constant can be modified by means of adjusting the push rod length at the top bolt. The regulator has a diaphragm that is sealed with a gasket and is separated once the preset pressure has been reached.

To adjust the pressure setting, a compressed air pressure regulator was used in conjunction with the pressure gauge. Another key aspect of pressure regulator is the maximum mass flow rate, which is determined by dividing the wattage of the heater by the enthalpy of evaporation, which gave the value of approximately 15lbs per hour. The calculation was needed in order to confirm that the pressure regulator will work for our specifications otherwise the pressure would build up inside the pyrolysis chamber.

Note that the design temperature was reduced to a maximum value of 207℃ during the selection of the back pressure regulating valve. This was because the next class up of valves capable of operating at 400℃ where in the price range of $1600-2300. One valve would use the entirety of the project budget.

4.5.5 Software Setup

The system flow chart of Figure 41 below is the program logic for the Arduino Uno. The overall C++ program is attached to the Appendix B. At startup, the microcontroller performs a reset to all variable and put the heater on hold, for 5 seconds. The control loop starts by recording the temperature inside the pyrolysis chamber and on the surface of the heater. Then, it turns on the heaters only when both temperatures are below their target values respectively. When one or both temperatures are above the target temperatures, the Arduino will turn off the heaters by cutting off the voltage supplied to the transistor. A delay timer has been added to the system in order to protect the life span of the electro mechanic relays. Also, when one of the temperatures exceeds the limit, the system will turn off the heaters and terminate the program. This acts as a safety feature to protect the integrity of the unit and safety of the operator. By writing the source code in C++ programming language, the control system can easily vary the sampling rate. It is set to be the control loop overall the run time. Further explanation of the program is within the program given by the comments after the "//" signs.

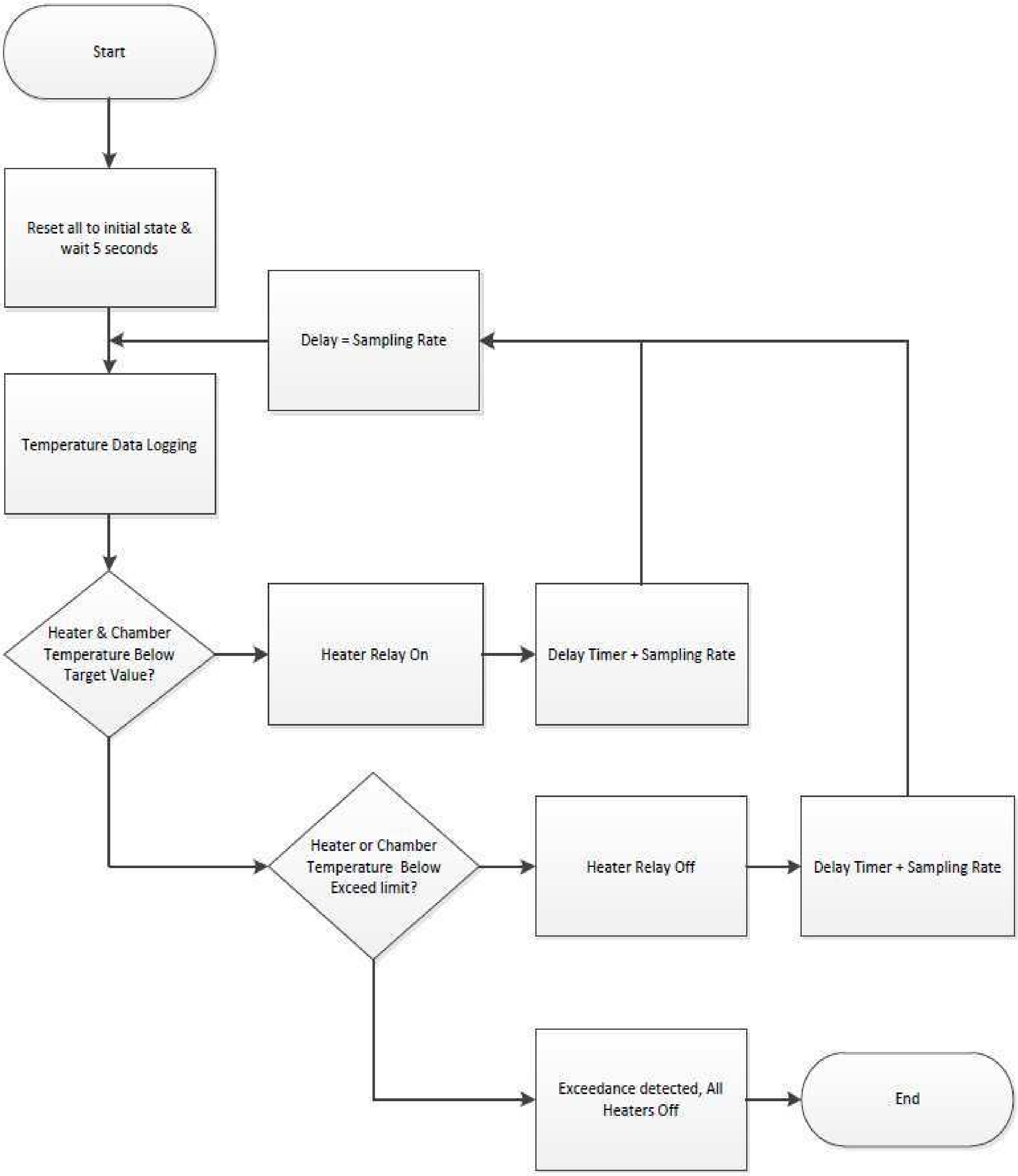


Figure 41: System Flow Chart

4.5.6 Energy requirement and heating time

This section describes the heat required to reach the re-evaluated reduced system temperature (150°C) under the given pressure along with the required heat-up time.

screw diameter	*3.5*	*in*
Length of track	*15*	*in*
Volume occupied by screw	*144.32*	*in^3*

A water to sand ratio of 60:40 was used to create the feedstock mixture. This ratio was based on some tests that were done regarding the tendency of the mixture to flow. The mixture was assumed to occupy 40% of the screw volume:

$$\mathbf{V_w = (V_s)(0.4)(0.6) = (144.32.5in^3)(0.4)(0.6) = 86.6in^3}$$

Given the density of water to be 1,000kg/m^3 (0.0161kg/in^3) it is possible to calculate the mass of water present in the vessel to be:

$$\mathbf{M_w = (V_w)(\rho_{water}) = (86.6in^3)(0.0161kg/in^3) = 1.40kg}$$

Where:

Vw = Volume of water, in^3

Vs = Volume occupied by screw, in^3

Mw = Mass of water

ρ_{water} = Density of water, kg/in^3

The design parameters are thus the following:

- Initial temperature of the rig : 294 K (21°C)
- Target temperature : 423K (150°C)
- Desired pressure: 37 psi

The enthalpy of superheated steam at 423K (150°C) was found using steam tables to be:

h = 2,765 KJ/kg [17]

Therefore the energy needed to bring the water in the chamber to the required temperature is expressed using:

$$\text{Eq. 28} \qquad \boldsymbol{Q = mh} \ \textbf{[17]}$$

Where:

Q= energy
m= mass
h= enthalpy

$$\boldsymbol{Q} = \mathbf{1.40kg} \times \mathbf{2,765KJ/kg} = \mathbf{3,871\ KJ}$$

The heater installed on the chamber will provide 3,600 W of energy, and so without considering any losses, the time it would take to heat the water to the desired temperature is

$$\mathbf{T} = \frac{\textbf{energy required}}{\textbf{heater wattage}} = \frac{\mathbf{3{,}871{,}000\ J}}{\mathbf{3{,}600\ W}} = \mathbf{1075.28s = 17.9min}$$

4.6. Chamber Stress

Although difficult to verify experimentally, it is crucial to analyze this part in order to validate that the chamber will not fail under the stress of the pressure.

The parameters relevant to this section are tabulated below in Table 11.

Table 11: Parameters

ID	0.1531566m	6.065in
OD	0.167298m	6.625in
Thickness	0.0070707m	0.28in
Pressure	255106Pa	37psig

To determine whether the chamber is considered to be a thin-walled cylinder or not, the following criteria must be satisfied: "*When the wall thickness is less than about 1/10 of the radius, the cylinder can be considered thin-walled*" (Norton, 2011) [5].

Radius = $\frac{ID+OD}{4} = \frac{(0.1532m+0.1673m)}{4}$ = 0.08011m

Radius' = $\frac{Radius}{10} = \frac{0.08011m}{10}$ = 0.008011m

Since 0.007071m is less than 0.008011m, the chamber is assumed to be thin-walled.

From Norton [5], the tangential, axial and radial stresses on a thin- walled element are described using the following equations:

Eq. 29 $\sigma_t = \frac{\boldsymbol{p*r}}{\boldsymbol{t}}$

Eq. 30 $\sigma_a = \frac{\boldsymbol{p*r}}{\boldsymbol{2*t}}$

Eq. 31 $\sigma_r = 0$

Where :

σ_t = tangential stress

σ_a=axial stress

σ_r= radial stress

p = the pressure

t = thickness

$\sigma_t = \frac{255\ 106*0.08011}{0.007071} = 2{,}890{,}442.1$ Pa

$\sigma_a = \frac{p*r}{2*t} = \frac{255\ 106*0.07835}{2*0.007071}$ =1, 445,221.0 Pa

σ_r = 0 Pa

Eq. 32 $\sigma_{von} = \sqrt{\boldsymbol{\sigma_t}^2 - \boldsymbol{\sigma_t \sigma_r} + \boldsymbol{\sigma_a}^2}$

$\sigma_{\text{von}} = \sqrt{2{,}890{,}442.1^2 - (2{,}890{,}442.1)(1{,}445{,}221.0) + 1{,}445{,}221.0^2}$ =2,503,196.3 Pa

Given that the yield strength of the material is 250,000,000 Pa, we can state from the calculations above that the chamber is safe. The safety factor is

Eq. 33 $\text{SF} = \frac{\boldsymbol{S_y}}{\boldsymbol{\sigma_{von}}}$

Where :

SF = Safety Factor

Sy= Yield strength

σ_{von}= Von Mise's stress

$$\text{SF} = \frac{S_y}{\sigma_{von}} = \frac{250{,}000{,}000}{2{,}503{,}196.3} = 99.9$$

But these results do not take into account the stress concentration factors caused by the holes in the cylinder or the elevated operating temperature. It is therefore necessary to analyze the chamber further. The ANSYS Workbench and CATIA Generative Structural Analysis Workbench were used in order to revalidate the previously determined safety factor.

Using CATIA, the chamber was modeled as a cylinder including design features and geometric lengths. The end-caps were also generated as 1-inch thick circular bodies to account for axial stress in the cylinder. The CATIA model is shown in Figure 40.

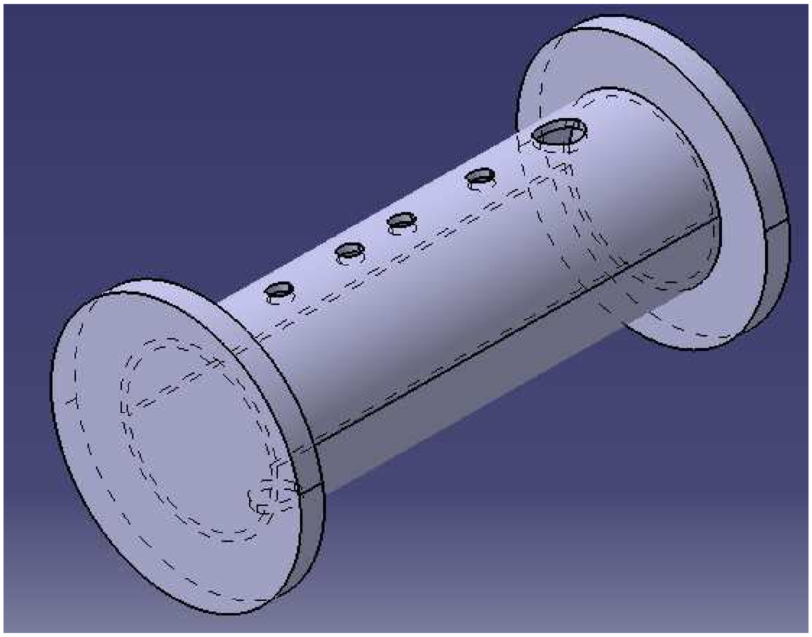


Figure 42: CATIA Model

After applying the proper supports and loads, the model was meshed and the analysis started.

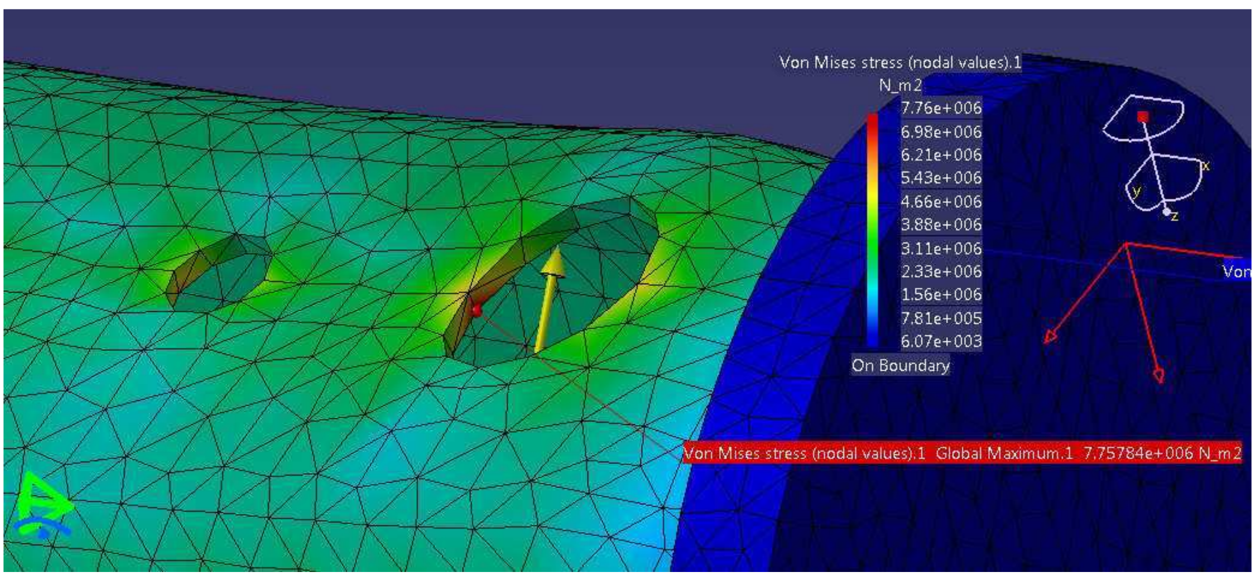


Figure 43: CATIA Analysis of holes

As seen in Figure 43, the maximum stress occurred at the inner surface of a drilled hole. The holes act as stress raisers and increase the expected stress values by a considerable amount. It should be noted that the region around the holes might show signs of fatigue or failure before any other region over an extended period of time or cycles.

The resulting maximum Von Mise's stress was 7.76MPa which resulted in a safety factor of:

$$SF = \frac{250{,}000{,}000}{7{,}760{,}000} = 32.2$$

ANSYS Workbench was then used to load the CATIA geometry and appropriate constraints and loads were subsequently added. After meshing the model, the analysis was run to obtain the location of maximum Von Mises' stress shown below in Figure 44:

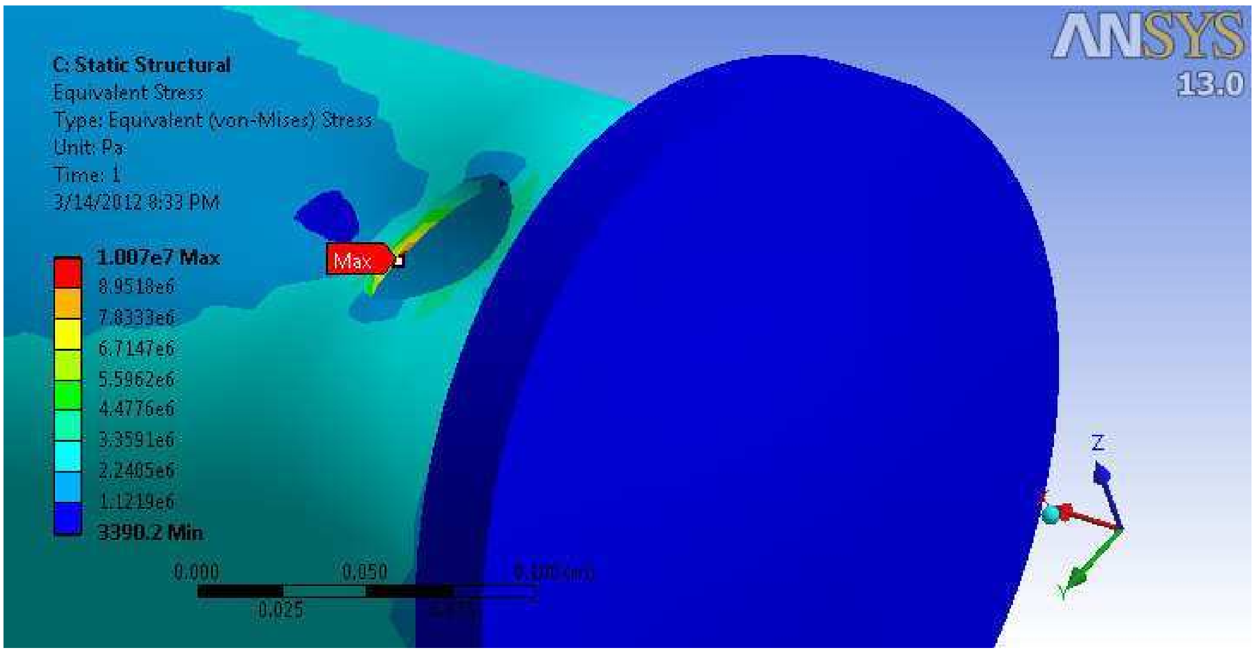


Figure 44: ANSYS Analysis of holes

The resultswere consistent with those obtained with CATIA. The resulting maximum Von Mise's stress was 10.07MPa which yields a safety factor of

$$SF = \frac{S_y}{\sigma_{von}} = \frac{250{,}000{,}000}{10{,}070{,}000} = 24.8$$

Note that the ANSYS analysis was performed to complement and validate the CATIA analysis. ANSYS is more elaborate stress analysis software and therefore yields more accurate results than the CATIA.

Summary: The pressure vessel was found to be more than able to withstand the design operating conditions.

4.7 End Cap Stress Analysis

Another main part of the pyrolysis chamber structure is the end cap. The modes by which this component could fail are fairly alarming and therefore need to be considered and analyzed. Much like the chamber, the end cap can be approximated to a circular plate with a 1" thickness and the analysis ran subsequently. Unfortunately because of the various holes that are present in it, the results would be inaccurate. A CATIA and ANSYS structural analysis were then performed to observe stresses in this component.

4.7.1. End Cap Stress Analysis – CATIA

After applying 37psi on the inside surface of the end cap and setting user defined restraints on the bolt holes, the part is meshed and then solved.

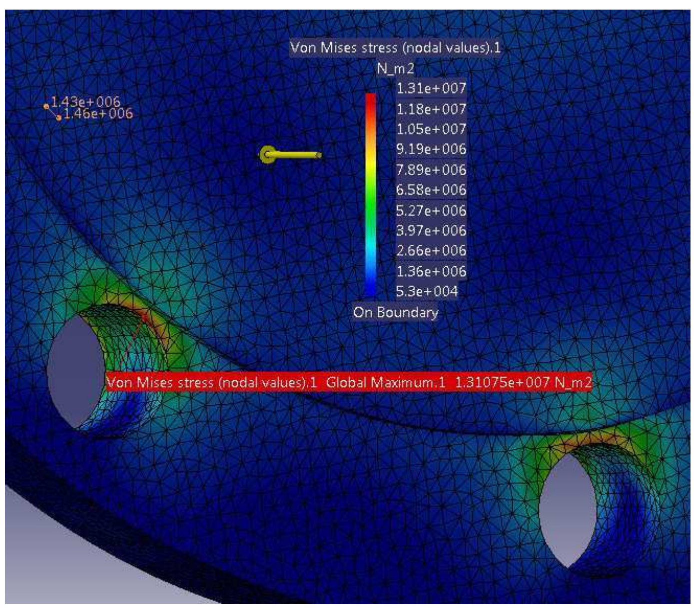


Figure 45: CATIA End Cap analysis

What is shownin Figure 45 is that the maximum Von Mises' stress occurs at the inside edge the bolt holes. This is due to the fact that the sharp edge present at that location. Knowing that the yield strength of steel is 200GPa, we can calculate the safety factor of the end cap

$$SF = \frac{S_y}{\sigma_{von}} = \frac{200{,}000{,}000}{13{,}100{,}000} = 15.27$$

This is a considerably large safety factor, and based on this analysis the end cap is deemed safe for operation under specified conditions.

4.7.2. End Cap Stress Analysis – ANSYS

Again 37psi is applied on the interior surface of the end cap and the bolt holes are used as restraints.

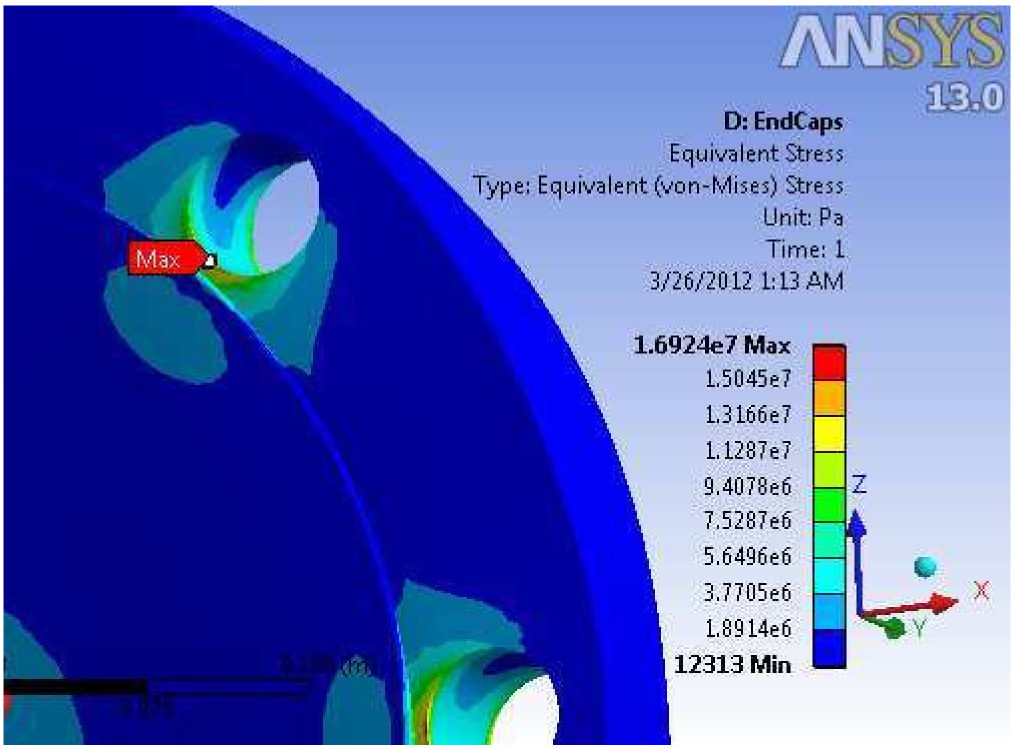


Figure 46: ANSYS End cap Analysis

Figure 46 shows that the site of maximum stress is at a bolt hole; the reason being the edge at that location. Taking the yield strength of the material as 200GPa, the safety factor was found to be:

$$SF = \frac{S_y}{\sigma_{von}} = \frac{200{,}000{,}000}{16{,}924{,}000} = 11.82$$

This number is more conservative than the one yielded in the CATIA analysis, but it is still very large and therefore the end caps are deemed safe for operation under specified conditions.

4.8. Thermal analysis

The grounds for carrying this analysis out here lie in the thermal limitations of the chosen ball valves. These valves are rated at 185°C and it is therefore important to choose pipe lengths that will not allow them to heat over their prescribed temperatures. The two critical pipe lengths that connect to ball valves were loaded in a steady-state thermal analysis in ANSYS.

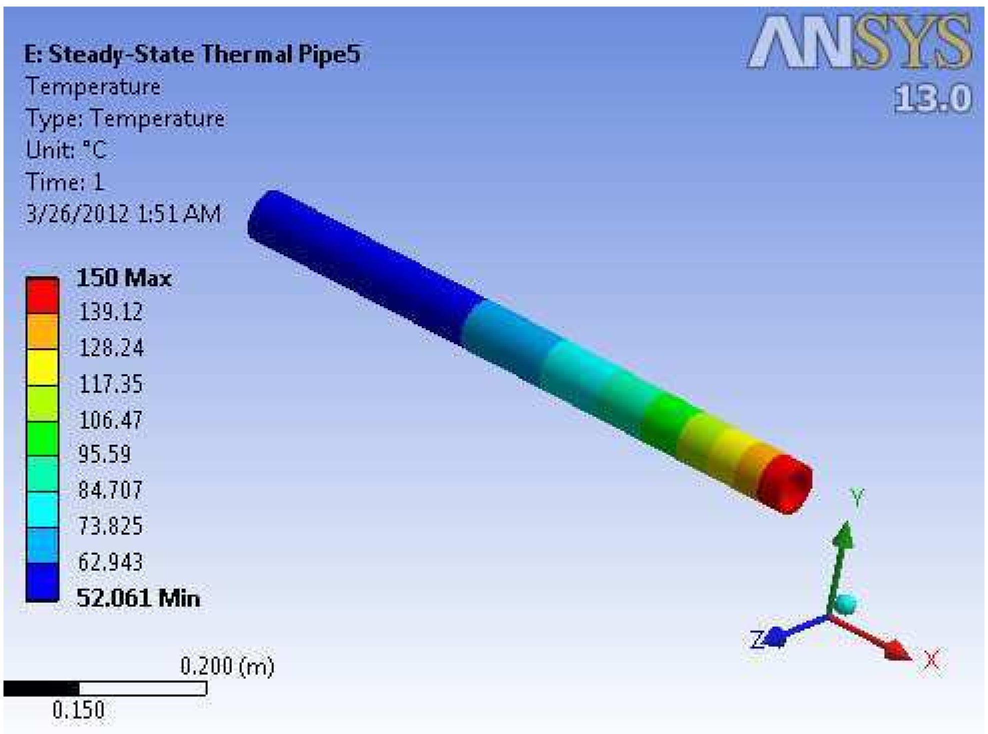


Figure 47: ANSYS Heat Simulation for ½" Pipe

Figure 47 shows the temperature distribution in the gas release pipe section of the intake. The temperature at the base is the desired 150°C and diminishes with radiation and free convection to a minimum temperature of 52°C at the ball valve end. This confirms that for this length of this pipe, the ball valve will be under its prescribed temperature and therefore safe.

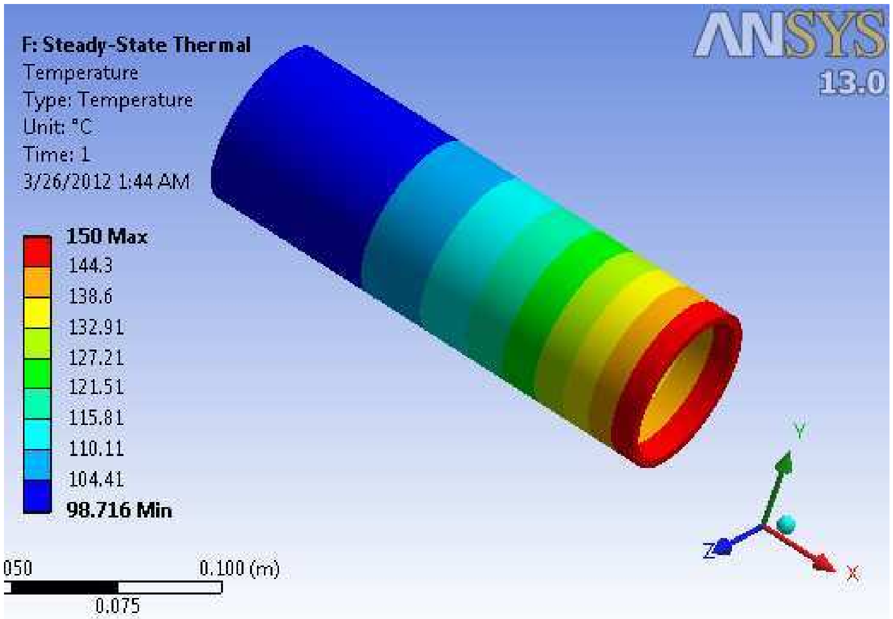


Figure 48: ANSYS Heat Simulation for 1 1/4" pipe

Figure 48 shows the pipe segment that is used in the solid intake and extraction. The temperature at the base is set to the desired 150°C and the gradient can be observed through this pipe as heat is lost through radiation and convection. The temperature at the ball valve end is 99°C which is close to the restricting temperature of 185°C but still below it. It is concluded that if the temperature in the chamber remains at no more than 150°C, then the ball valve will be operating under its prescribed temperature and therefore safe.

5. MANUFACTURING AND ASSEMBLY

The pyrolysis proof of concept unit comprises of many connecting and interlocking parts that need to be manufactured to close tolerances. These parts also need to be assembled with an equal amount of precision in order to insure the integrity of the system. The manufacturing stages and assembly of the critical components will be covered in this section.

Once the pipe that would be used for the pressure vessel was cut to the desired length and appropriately dimensioned openings were drilled. The intake, extraction, thermocouple bung, pressure gauge bung and pressure regulator piping were then welded by William Chicoine, the in house welder. The two slip on flanges were also welded to the chamber. Figure 49 shows the main chamber after welding.

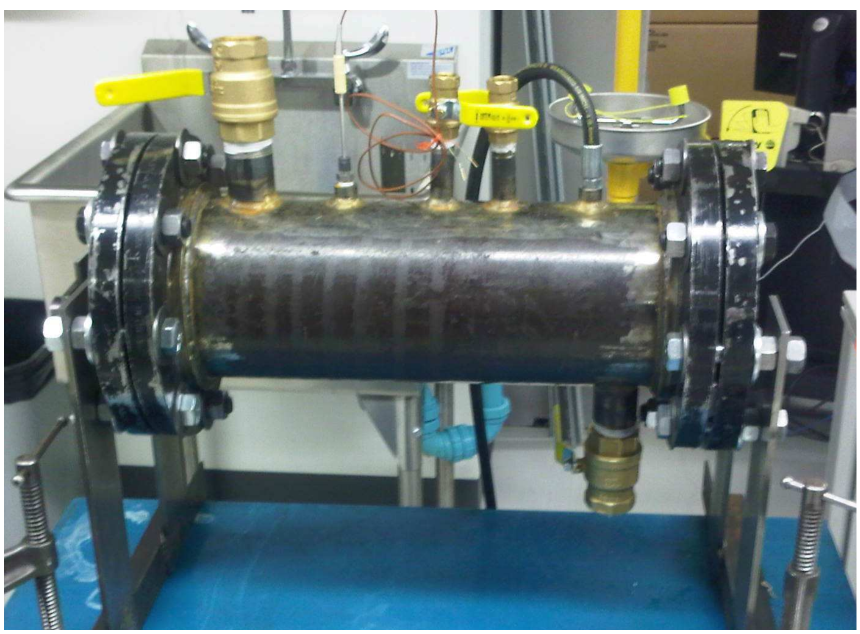


Figure 49: First Stage of Assembly

Next the gasket is centered on the slip on the flange and the end caps are bolted on. In order to minimize uneven strain on the end caps and to ensure that all of the bolts are tightened evenly, a systematic bolting technique is used. Figure 50 shows the bolting pattern that yields the best result.

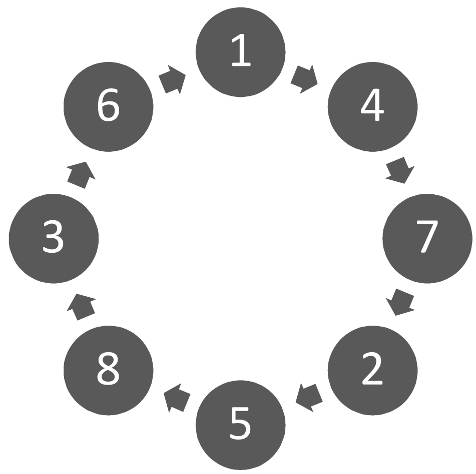


Figure 50: Bolt Tightening Sequence

The number indicates the bolt tightening sequence. This pattern was followed and the bolts tightened at an interval of around 20 ft-lbs until reaching the final torque of 125 ft-lbs. Note that the calculated required torque was approximately 100ft-lb. The reason for torqueing to 125 ft-lb was due to bolt relaxation of approximately 20% over the first 24hr period. Leak tests using both water and air were performed and the results are discussed in Section 6. The intake and extraction piping was then installed. The end caps were removed and the auger was placed inside the chamber. The end caps and gaskets were installed once again using the same procedure described above.

Next, the heaters, insulation and protective aluminum are installed onto the chamber. First, the heating coils being very flexible and were very easy to wrap around the chamber. Once the heaters were wound by hand they were tied in place by steel cables to ensure contact with the chamber at all times. A total of two heating elements were used and are connected in parallel with each other. Figure 51 shows what the chamber looked like after the installation of the heating elements.

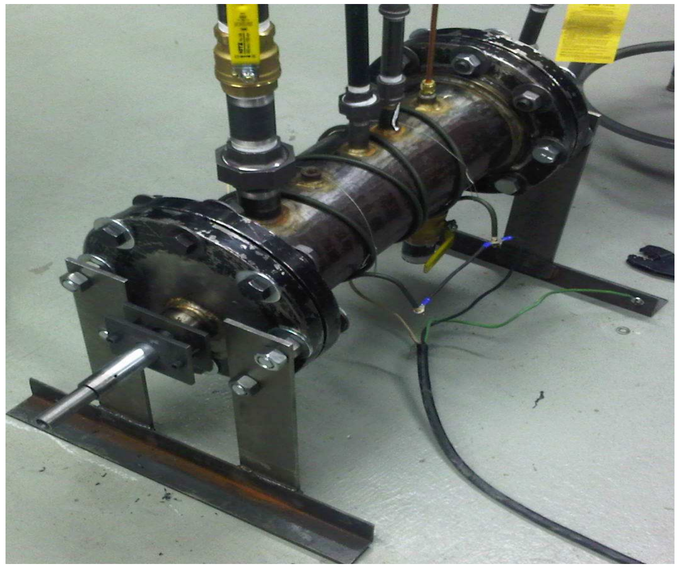


Figure 51: Second Step of Assembly

The next step was to wrap the chamber at the end cap level with a wire meshing, similar to chicken wire, creating a spacing of approximately 1.5in between the heating elements and the meshing. A layer of insulation was then placed on top of the chicken wire and was screwed in place. The air gap between the insulation and heating elements ensured that it did not burn and added an extra layer of insulation. An aluminum sheet is placed around the insulation to protect it from moisture and wear and tear. The aluminum sheet also limits the exposure of the insulation fibers with the operators of the unit. The final unit is shown in Figure 52.

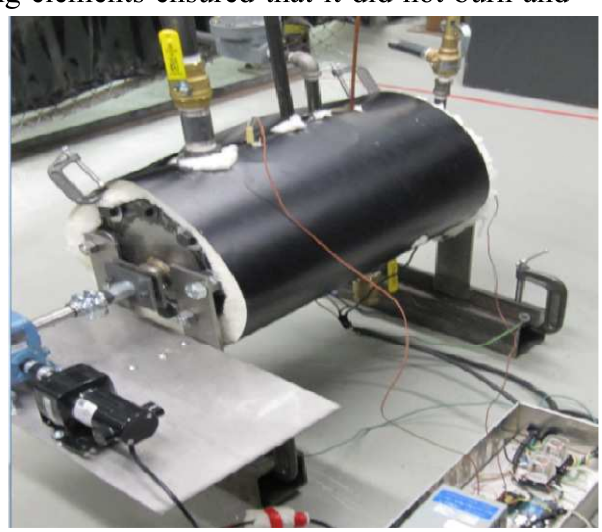


Figure 52: Third Step of Assembly

The packing seal was then installed to keep the pressure seal of the vessel. The first step when installing the packing was to cut at a 45° angle the required amount of rings that would fit around the shaft. The first ring was placed around the shaft and pushed in using the compressing plate system described in Section 4.4.3. The same procedure was repeated for each ring placing the joint at a distance of 90° one from another each time as shown in Figure 53. This procedure was recommended by John Crane, and was described in the Packing Installation Instructions [18].

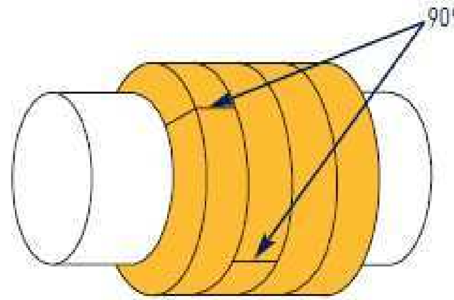


Figure 53: Packing Rings installation [18]

The last step is to tighten the packing system to compress the packing seal to its functional length. To get the correct compression length, an iteration method is used by filling the vessel with water and slightly increasing the pressure and tightening the bolt until the packing seal is fully effective and there is no leaks observed. Compressing the packing seal using bolts can be seen in Figure 54.

Figure 54: Packing Seal System

The last step was to build a stand for the motor and the reducer. First, an aluminum sheet was cut to the desired length and holes were drilled in the proper position to hold both components in place. In order to support the metal sheet, 2 L-shaped brackets were bolted to the stand. The final result is seen in Figure 55.

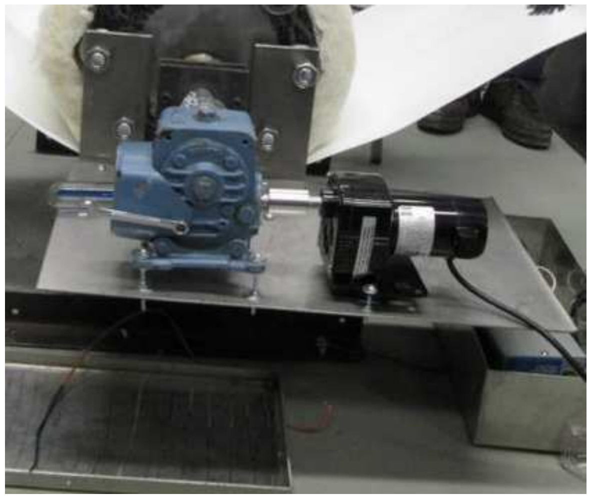


Figure 55: Motor and Reducer Stand

6. TEST PROCEDURES

The assembled rig comprises of a number of mechanical and electrical components. Furthermore, when all these sub-assemblies are working together, there is a substantial amount of energy stored in the form of heat and pressure making the rig potentially harmful to the operators, or bystanders. It is therefore imperative that effective test procedures are developed and carried out in order to identify and resolve any malfunctioning components before the unit is operated at its designed temperature and pressure. In order to target the possibly problematic components, test procedures needed to be devised in a fashion where every sub-assembly was tested individually. The test procedures designed for this purpose can be found in Appendix C. Below is a discussion about the results of these test procedures.

6.1. Liquid Leak Test

The energy density of air is much greater than that of water, meaning, if a vessel is filled with air at 37 psi, it has much more stored energy than if it was filled with water at the same pressure. This is due to the compressibility of air and the fact that water can be considered incompressible. The vessel in question is hence more "dangerous" when filled with air than water. The approach here is to test the strength of the material as well as the permeability of the system. Figure 56 shows a threaded bung that was welded onto the main chamber. This piece was used to connect the hose of the water pump during the liquid leak test. Once everything was set up the chamber was filled with water and pressure was applied as per the test procedures outlined in Appendix C.

Figure 56: Threaded Bung

The first time the chamber was tested in this fashion, many of the welds leaked, as well as the utilized gaskets. The welds were then redone by Mr. Chicoine, this time passing over his previous welds using a Tungsten Inert Gas (TIG) welding. In the second leak test, the welds were no longer problematic. The gaskets required more effort to fix. The bolted flanges were tightened with the gaskets in place using the cross-tightening method and a torque wrench. Although effective, this technique very hard to duplicate, and for this reason it was deemed more consistent to build shims that would allow the gaskets to be squeezed in a controlled and repeatable manner. Figure 57 shows the liquid leak test set up. Over the span of one week, under the supervision of the engineering in residence, nine liquid leak tests were performed before achieving the desired results.

Figure 57: Liquid Leak Test

6.2. Air Leak Test

Once the chamber passed the liquid leak test, it was then deemed important to subject it to air leak tests. This was because air molecules are smaller than water molecules, leaks that did not arise with the water tests could show up in the subsequent air tests. Using the same threaded bung as for the water pump, the pressurized air supply valve was set up. As the chamber was pressurized with air, it was also sprayed with soapy water. The aim of this procedure is to see where air leaks are located by the bubbling of the soapy water. Figure 58 shows team members Nicholas Matsushita-Fournier, Ho-Wai Leung and Mathieu Parent spraying the pressurized vessel with soapy water and inspecting it for leaks.

Figure 58: Soapy Water Inspection

Figure 59 shows team member HoWai Leung measuring chamber expansion with a large micrometer and end cap deflection with a strain gauge. These deflection values were to be compared to software modeled values in validation tests, but the deflections of the chamber and the flanges were so small that the instruments could not detect them.

Figure 59 : Vessel Strain Monitoring

6.3. Combined Test

After the tubular heaters were wrapped around the chamber, the drive system was assembled and the circuits connected. Figure 60 and 61 show the vessel with the heaters bare and after insulation was installed

Figure 60: Pre-test Setup

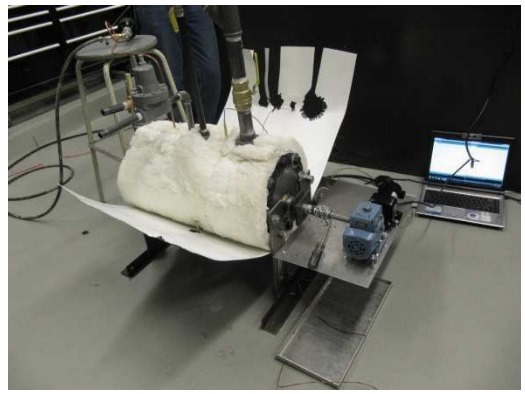


Figure 61: Bare Heater Setup

The aim of the following tests was to see how the sub-assemblies would interact together. This phase of the testing was more complex in nature and had substantially larger risks, and thus it was important to have proper safety procedures prior to testing. These safety measures are listed below

1. Safety glasses for everybody in the vicinity of the test zone.
2. Blast doors set up to shield operators and observers.
3. CO_2 powder extinguisher on hand for possible electrical fires.
4. Team member ready to shut off breaker switch for 240V wall socket if signalled by short range radio.
5. Fenced off areas where danger potential is the greatest (see Appendix E)
6. Downdraft table snorkel venting the unit's exhaust.

The pyrolysis chamber was pressurized with air, and the back pressure regulating valve adjusted to the desired 30psi. This component was then tested by increasing the pressure inside the chamber above 30psi and confirming its venting capacity. With the pressure still acting in the chamber, the intake mechanism was tested to ensure its proper functioning and the resulting pressure drop was recorded.

It was noted that as the chamber was pressurized, there was a considerable leak at the pressure gauge connection. This was due to the air feed hose being slightly deformed at the mating end. The purpose of this pressurization was to verify that once the motor was engaged, no air would leak from the packing seal. Since the leak due to the air feed hose could not be stopped, the amount of time needed for a drop of 20psi due to the leak was determined. The chamber was then pressurized to 37psi, the motor was engaged, and the time for the pressure to drop to 17psi was recorded.

Because this was not accounted for before testing began, it was not included in the test procedures. The results are tabulated below in Table 12.

Table 12: Combined Test Results

Condition	Time taken to go from 37 to 17 psi
Motor not running	2min 41sec
Motor running	2min 06sec

As expected, there was a leakage increase through the packing seal when the motor was running. The seal was then tightened, and the test repeated until the time difference between when motor was on/off was within 8s.

6.4. Heat Test

The next step in testing was to heat the chamber. Two thermocouples were installed on the rig; one inside the chamber to measure the interior temperature, the other one was placed directly in contact with the tubular heaters to measure the temperature at the sheath. The first series of tests that were performed were aimed at confirming that the heaters were functioning properly. The elements were turned on until low temperature changes from the sheath were read and then turned off by terminating the Arduino program run. Temperatures from 50°C to 100°C were achieved here. Details can be found in the test procedures of Appendix C.

Next the control loops were tested to see if they could turn the heaters on and off through the relays that were commanded by the Arduino chip microcontroller. The trigger temperature was set to a relatively low value (150°C) and data was acquired. Figure 62 shows the results of this test.

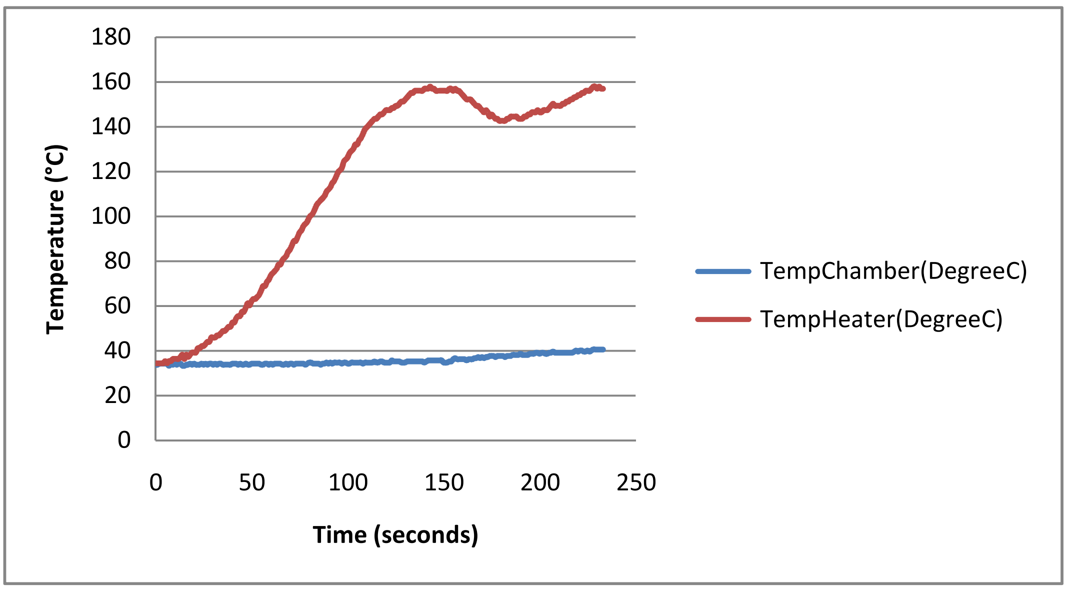


Figure 62: Relay controlled heaters

Figure 62 shows that the heaters peaked at the desired 150°C then shut off and turned on again after their sheath temperatures decreased below the target temperature.

After the control system proved to be effective, incremental heat tests were performed as all other component temperatures were monitored with an infrared temperature reader, details of these tests can be found in the test procedures of Appendix C.

The maximum sheath temperature of the heaters was to be determined for engineering validation test purposes. The heaters were turned on, and data was acquired until the elements' sheath temperature leveled off. The results are shown in Figure 63.

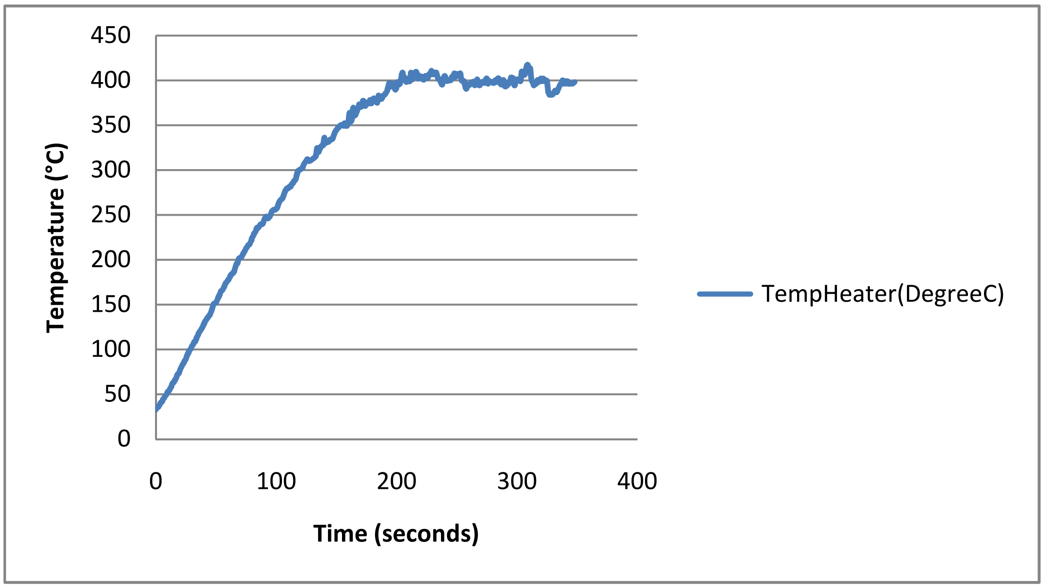


Figure 63: Maximum Sheath Temperature

Figure 63, shows the sheath temperature readings with respect to time. The results seem to level off at 400°C.

After collecting data from heat tests, results showed that for the amount of volume contained inside the chamber and the energy delivered to it by the tubular heaters, the maximum pressure we could build inside was roughly 23psi. If it was necessary to have more pressure than this, additional heaters would be required. Although this is lower than what was anticipated, it is still enough to carry on with the test procedures.

After the test procedures were completed for the heat section alone, the operational tests were performed and results acquired via the pressure gauge and the microcontroller. The unit proved to function as was expected in the design phase.

Figure64 depicts the temperature of the heater surface and inside the chamber. There are two control loops here; one that regulates the surface temperature of the heaters to 350°C, and the other that regulates the temperature inside the chamber to 100°C. If any of these two values are exceeded the heaters automatically shuts off. It clearly shows that after the heater is turned on, the temperature of the chamber rises. Furthermore, as the chamber's temperature reaches its boundary value, the heaters are automatically turned off and the chamber's temperature subsequently starts to diminish.

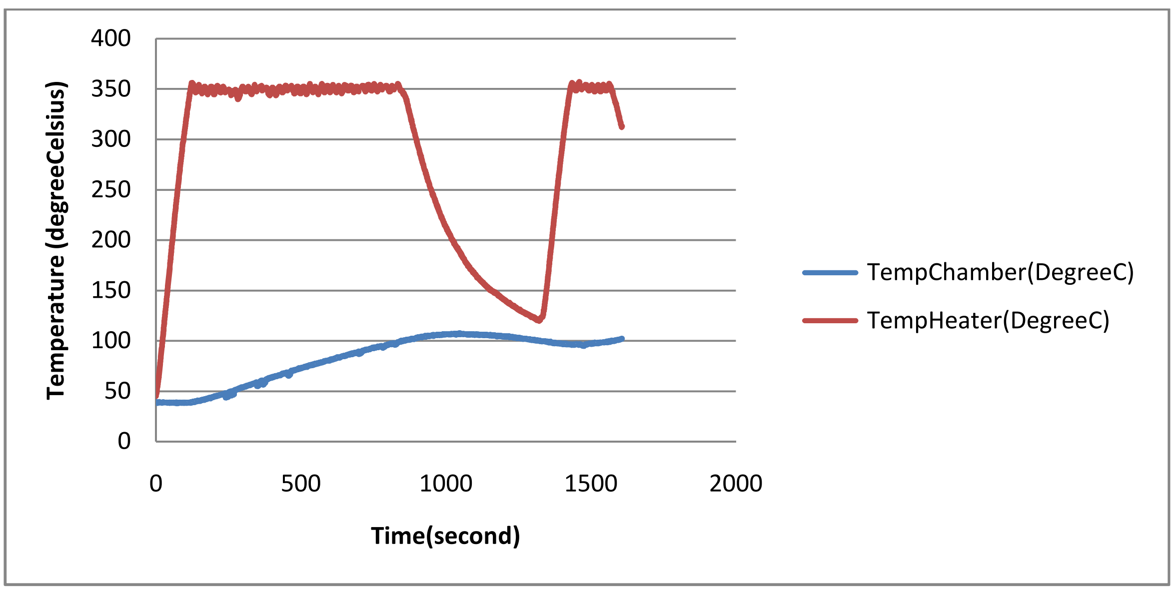


Figure 64 : Temperature Cycling

All the heat control loops were programmed in C-language and the source code utilized can be found in Appendix B.

The heat loss when the temperature inside the pyrolysis unit has reached steady state at 150ºC is required to determine how many watts are actually transferred to the unit. The natural convection method is used to calculate the heat transfer from the end caps surfaces and insulation shell surface to the surrounding.

The heat loss through thealuminum shell is 56.49Watts, which is fairly low due to the insulation. The temperature at the surface of the shell and the surrounding temperature were measured to be 50ºC and 24ºC, respectively. These values were used to perform the analysis, and the complete calculationsare attached in Appendix F.

The data was tabulated using excel to calculate the heat lost on both end caps. Using the vertical plate geometry equations, the left end capcalculations were done and are available in Appendix F:

Table 13 : Results of Heat Loss Calculations

Surfaces	Film Temperature	k	Pr	v	Ra_D
Left End Cap	65	0.0284	0.719	1.95E-05	2.776E+12
Right End Cap	73	0.0290	0.717	2.03E-05	2.864E+12
Surfaces	**D(meter)**	**Nu**	**h**	**As**	**Qdot**
Left End Cap	0.2286	1546.13	192.082	0.0821	1292.93
Right End Cap	0.2286	1561.29	198.242	0.0821	1594.75

Result:

When computing the summation of losses due to both end caps and the aluminum shell, the value obtained from analysis comes to 2944Watts. The analysis was simplified, by disregarding the heat loss through piping. Overall, the calculations prove that the pyrolysis unit is in an operating steady state. This means that the heat entering the system (3600Watts from the heaters), nearly equal to the heat out of the system plus the heat provided to the feedstock.

7. IMPACT OF ENGINEERING ON SOCIETY AND THE ENVIRONMENT

Coming up with innovative and sustainable energy and waste management systems has become a great priority to researchers and policy makers as global concerns for the environment and pollution management increase. Pyrolysis is an application of a technology that provides a possible solution to both of these problems. This process can have major positive impacts on the environment, economy and agriculture sector.

Biochar has properties that are beneficial to agriculture and city waste management on a micro and macro scale. For example, the process can be carried out in a house basement where it would have the dual purpose of heating the home while producing Biochar for gardening. On a city wide scale, organic waste can be collected weekly similarly to garbage and recycling, reducing the volume of waste in municipal landfills. When used as a soil amendment Biochar can increase crop yields, and act as a carbon sink as was outlined in Section 1.5.

The sequestered carbon can be sold to polluting companies in order to reduce the overall carbon footprint. The idea behind locking away carbon through pyrolysis is as follows: Consider the hypothetical Company X. This company releases carbon by-products into the atmosphere at a rate of several tons every year. Its emissions over the span of ten years are as listed below, accounting for economic growth.

Table 14: Yearly carbon emissions accounting for economic expansion

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Carbon emissions (tons)	2000	3000	4500	6000	8000	10000	13000	16000	18000	21000	25000

Now consider that this company has an agreement with a bioenergy pyrolysis plant that "locks-away" a certain amount of carbon every year in the name of Company X. Now consider the following three scenarios. If the pyrolysis plant rids the atmosphere of an amount of carbon that is lower than what was produced by Company X, then we have a carbon reduction scenario

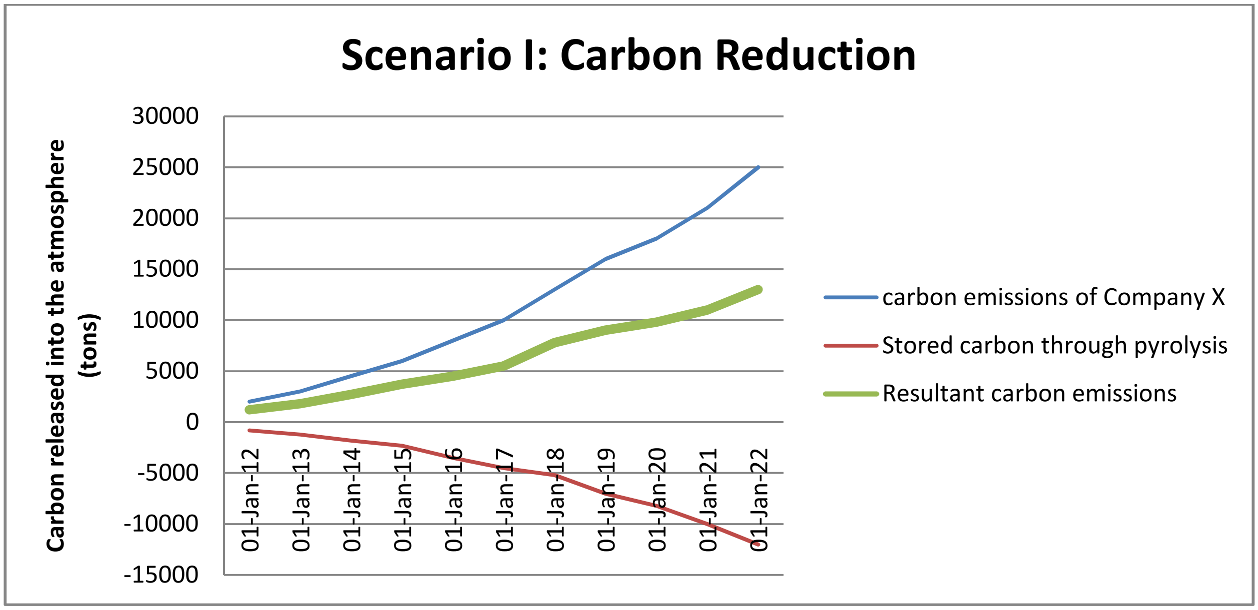


Figure 65: Scenario I net-carbon reduction

Figure 65 shows the carbon emissions graph that would result under scenario I. We note here that the resultant carbon emissions line (in green) is lower than the Company X carbon emission line (in blue). This means that there would be less carbon emitted into the atmosphere as a result of the pyrolysis plant reversing slightly the impact of Company X on the environment.

The second scenario occurs when the pyrolysis plant "locks-away" as much carbon as Company X emits into the atmosphere. In this case we have a break-even scenario.Figure 66 shows that the curves corresponding to the carbon emissions of Company X and the stored carbon through pyrolysis (respectively blue and red) are equal. This means that Company X has no net-environmental footprint in terms of carbon emissions.

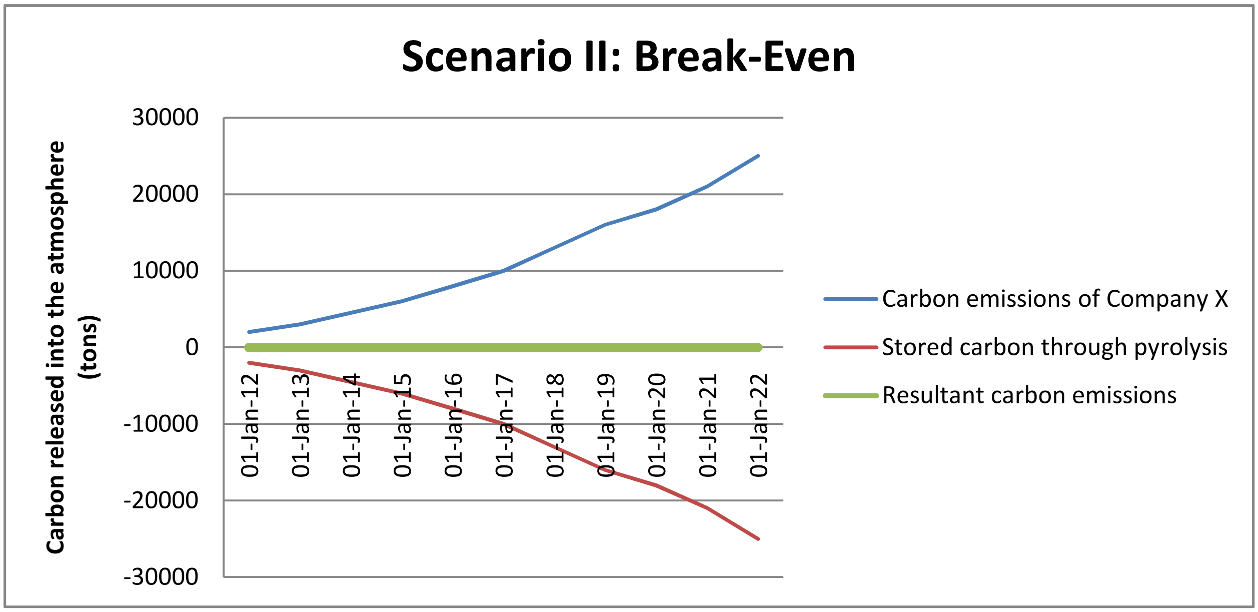


Figure 66: Scenario II break even

The third and last scenario considered is when the pyrolysis plant “locks-away” more carbon emissions than what was produced by Company X.

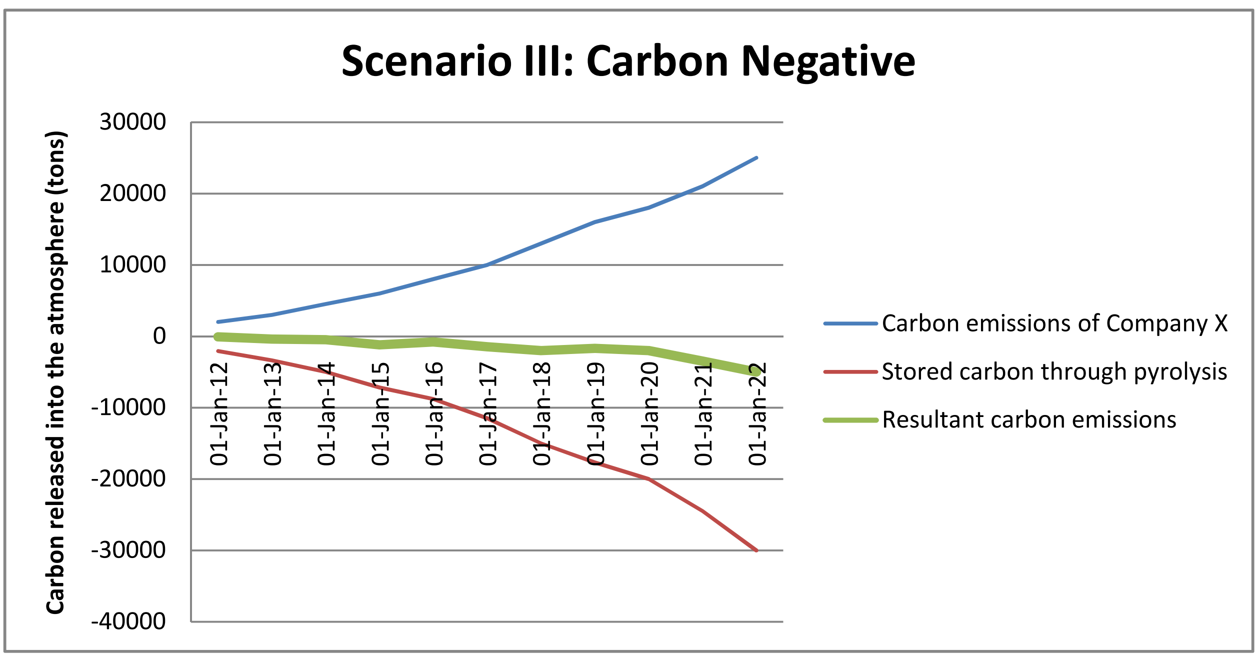


Figure 67: Scenario III carbon negative

Figure 67 shows that the amount of carbon stored by the pyrolysis plant is greater than that emitted by Company X. The resultant line droops below zero meaning the overall amount of carbon emissions in the atmosphere is actually reduced. The coupled effect of Company X and the pyrolysis plant was actually beneficial to the environment. Scenario III would thus revolutionize both the waste management and energy production in Canada. If this scenario were to occur a significant step would have been taken toward solving the current global warming and environmental crisis that society faces today.

8. ECONOMICS AND PROJECT MANAGEMENT

8.1. Economics

In order for such a large project to be possible, funds needed to be raised. After an application process that required a project presentation to a board of directors, Concordia's Sustainable Action Fund (SAF) agreed to sponsor the pyrolysis unit waste management proof of concept. SAF is a community within the University of Concordia that aims to sponsor projects that benefit undergraduate students with environmental concerns as the quintessential element of their every decision. Having fulfilled these requirements, SAF agreed to sponsor the pyrolysis waste management unit for $1975 CAD. Along with the funding from SAF, several key items were donated from the EDML.

8.2. Team Organization

The first step taken to organize the project was the democratic election of a team leader with the responsibility of delegating tasks, ensuring deadlines were met, and essentially worked as the project manager. Next a list was generated of the different tasks that were necessary for the project's completion. The list was comprised of the following:

- ***Information Gathering and Research***: Researching the pyrolysis process in sufficient detail to direct other team members in the design and specification stages.
- ***Scheduling and purchasing:*** Organize the project into a Gantt chart. Determine what the budget should be for each component of the unit and find quotes from different companies.

- ***Fundraising:*** Secure funding from outside organizations to purchase material for the project
- ***Material and Component Selection***: Selecting the appropriate material and hardware while considering the operating temperatures and pressure. The budget is also a consideration
- ***Manufacturing***: Organizing the manufacturing order and process sheets. Creating and assembling the actual unit via all the processes offered in the EDML.
- ***Testing***: Applying and following test procedures to plot the progress of the final unit
- ***Computer aided design***: Creating all the working drawings and models via the drawing program.
- ***Stress calculations***: Completing the heat and stress analysis required to ensure a safe design. This includes hand calculations, comparison with pressure vessel standards and ANSYS stress models.
- ***Controls***: Choosing the appropriate electrical equipment and design of the control system

Figure 68 provides a block diagram for the distribution of project responsibilities and also gives the managerial structure used throughout the project. Several online services were used as organizational tools to ensure order and structure were maintained as the project progressed. These online services were Dropbox, Google Calendar and Google Documents.

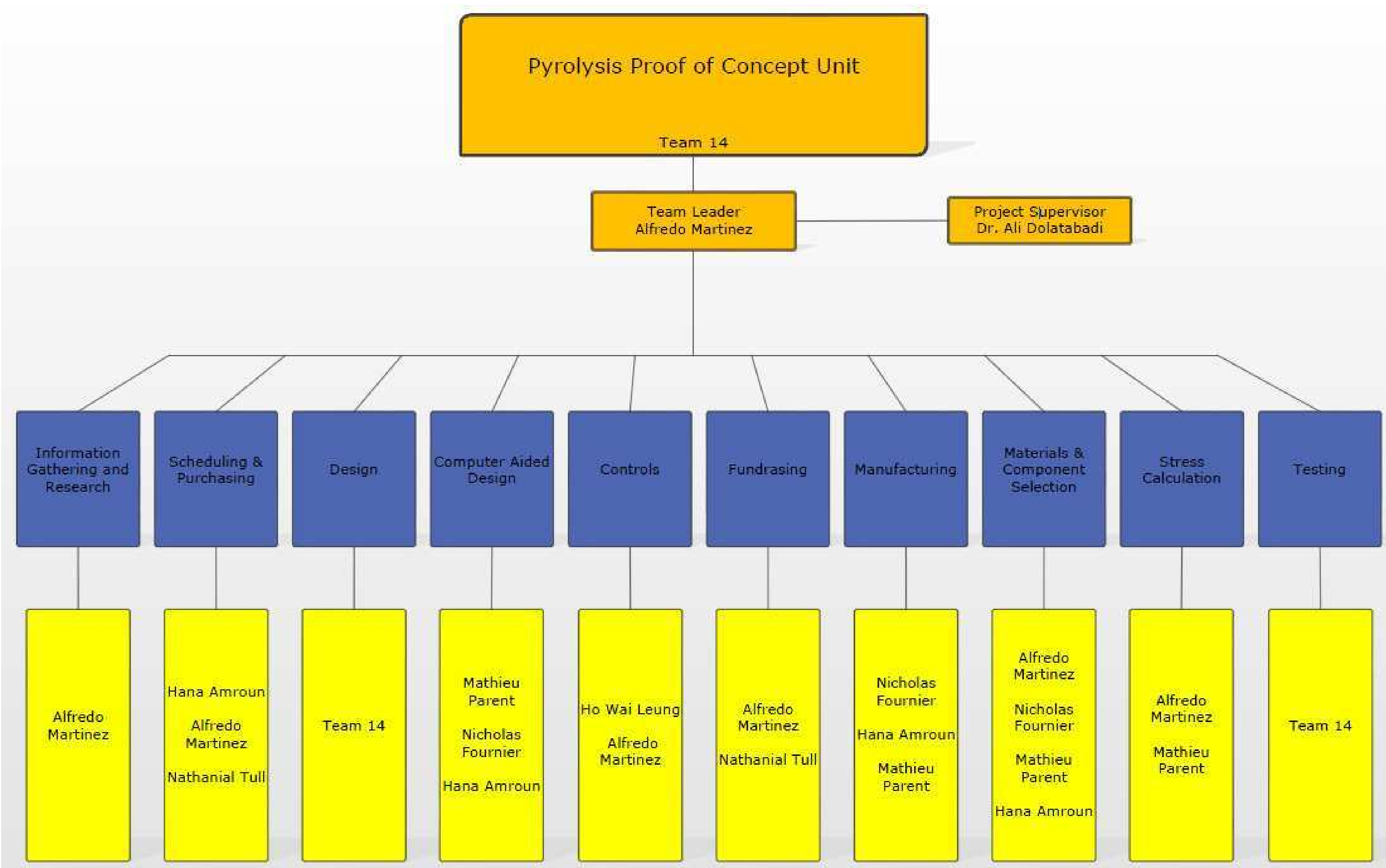


Figure 68: Project breakdown and organizational structure

8.3. Gantt Chart

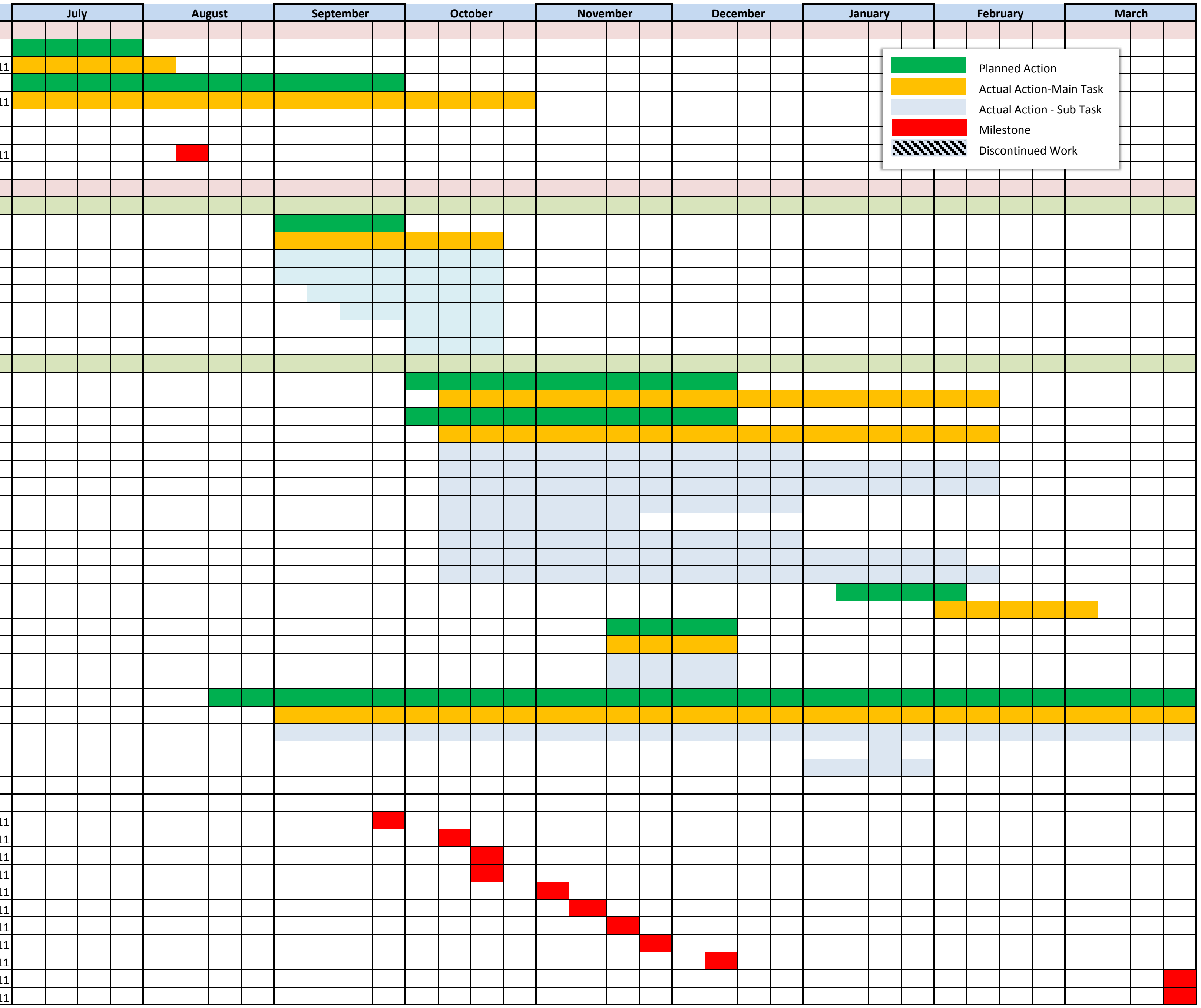
After the tasks in Figure 68 had been identified and that a team structure had been agreed upon, a Gantt chart was subsequently created in order to keep track of deadlines and outline the progress of the pyrolysis waste management unit. The Gantt chart was up-dated on a regular basis throughout the duration of the project and was used a tool to track the progress of individual and of overall work. The Gantt chart can be seen page 112 and it uses the flowing color scheme:

- Green: used to schedule the tasks required in order to complete the
- Orange: used to show the actual time required to complete a main task. The beginning of each main task begins at the earliest beginning of a subtask and ends at the lasted finish of a subtask
- Light blue: used to show the actual time taken to complete a subtask
- Hashed: used to indicate work that was complete on a given subtask which was later deemed unnecessary and terminated
- Red: used to indicate the milestones of the project

8.4. Bill of Materials

A bill of materials was used to keep track of expenses involved in building the pyrolysis unit. It was a critical tool in ensuring that the budget was not exceeded. The final bill of material can be seen in Appendix H and it provides the name of the items that were purchased along with part numbers, the venue of purchase and/or if the part was donated by a sponsor.

	Responsible:	% Complete	Start	Finish
Project Pre-approval			M/D/YR	M/D/YR
Literature Review	AM	100	7/1/2011	8/1/2011
Contacting Resources	AM	100	7/1/2011	11/1/2011
Milestone:				
Submit project pre-approval proposal	AM	100		8/10/2011
POC Design:				
Preliminary Design:				
Literature Review		100		
Pyrolysis	AM	100		
Preliminary System Specifications:	Team 14	100		
Controls Schematic	SL	100		
Technical survey (identification of alternatives)	Team 14	100		
Decision Matrix	MP/NF	100		
Detailed Design:				
Final System Specifications:				
Design Tasks:		100		
Heating System	SL/HA/MP	100		
Feeding System	NF	100		
Extraction System	MP	100		
Pyrolysis Chamber	NF	100		
Condensation System	MP	100		
Archimedes Screw	AM/NT	100		
Sealing	AM	100		
Motor/Reducer	NT, NF	100		
Manufacturing:	HA/NF/MP	100		
Other Tasks:				
Economic Analysis	SL	100		
Environmental Study	SL	100		
Organizational:		90		
Supporting Documentation	Team 14	100		
Maintenance Manual	TBA	N/A		
Standard Operating Procedures	MP/SL	100		
Milestone:				
Letter of intent:	AM	100		9/27/2011
SAF Funding Proposal:	AM	100		10/7/2011
Funding Presentation:	MP/NF/NT	100		10/19/2011
Project Proposal	AM	100		10/18/2011
Concept Approval	NF	100		11/1/2011
Midterm Progress Report & Presentation	Team 14	100		11/14/2011
Form and Functional Model	Team 14	100		11/22/2011
Preliminary Approval of all part drawings	Team 14	100		11/29/2011
Final Approval of all part drawings	Team 14	100		12/13/2011
Final Report:	Team 14	65		3/28/2011
Poster Session:	Team 14	10		3/28/2011



9. CONLCUSION

In a small allotted time frame, it was possible to secure funding for the project, design and manufacture the pyrolysis system and produce a fully functional POC that met the objectives and constraints that framed the project. The pyrolysis chamber, including the flanges and packing seal extension were designed to meet the temperature and pressure constraints of 400°C and 38psi respectively and also met ASME B&PV standards. The objective of manufacturing a hermetic unit was satisfied, along with the size constraint of 128.cm x 58cm x 120cm.

The intake and extraction design were proven to operate effectively, allowing continuous operation. The POC was proven capable of operating at a core temperature of 150°C and produce 23psi of steam. It must be noted that the initial temperature and pressure specifications were not met due to two problems: valves that were unable to operate at an initial design temperature of 400°C and a heating system that did not provide enough heat flux density to build up pressure to 37psi. Valves had been found that could operate at 400°C, though an exponential jump existed in pricing when going from 185°C operating temperature to 400°C. Ceramic heating units had also been found capable of producing more than double the wattage that was obtained with the POC.

With more funding the appropriate valves, heating system, and pressure transducers could have been purchased and all of the initial design objectives could have been met. It would then be possible to pyrolyze organic material, generating all byproducts and most importantly Biochar. It is hoped that this report has demonstrated that the conceived pyrolysis system is sound and further investment would lead to a functional prototype.

10. RECOMMENDATIONS

- Using the current system design high temperature valves, safety release valves, and back pressure regulating valves, should be purchased in order to reach temperatures required for pyrolysis.
- An alternative to purchasing these expensive valves would be to devise a cooling system for the pipe extensions leading to the valves. A list of possible design options to cool the pipe extensions are:
    - Fined pipe extensions
    - Counter flow heat exchangers installed on tube extensions. Comprising of copper tubing wrapped around pipe extension. The copper tubing would have circulating water as a cooling liquid.
- The intake/extraction systems could also be automated by installing high torque servos to operate the ball valves or replace them by solenoid. It must be noted that installing high torque servos would be significantly less expensive than purchasing solenoid valves.
- The extraction system would require a cooling section in order to ensure that the biochar was at a temperature that auto-ignition would not occur when in contact with air.

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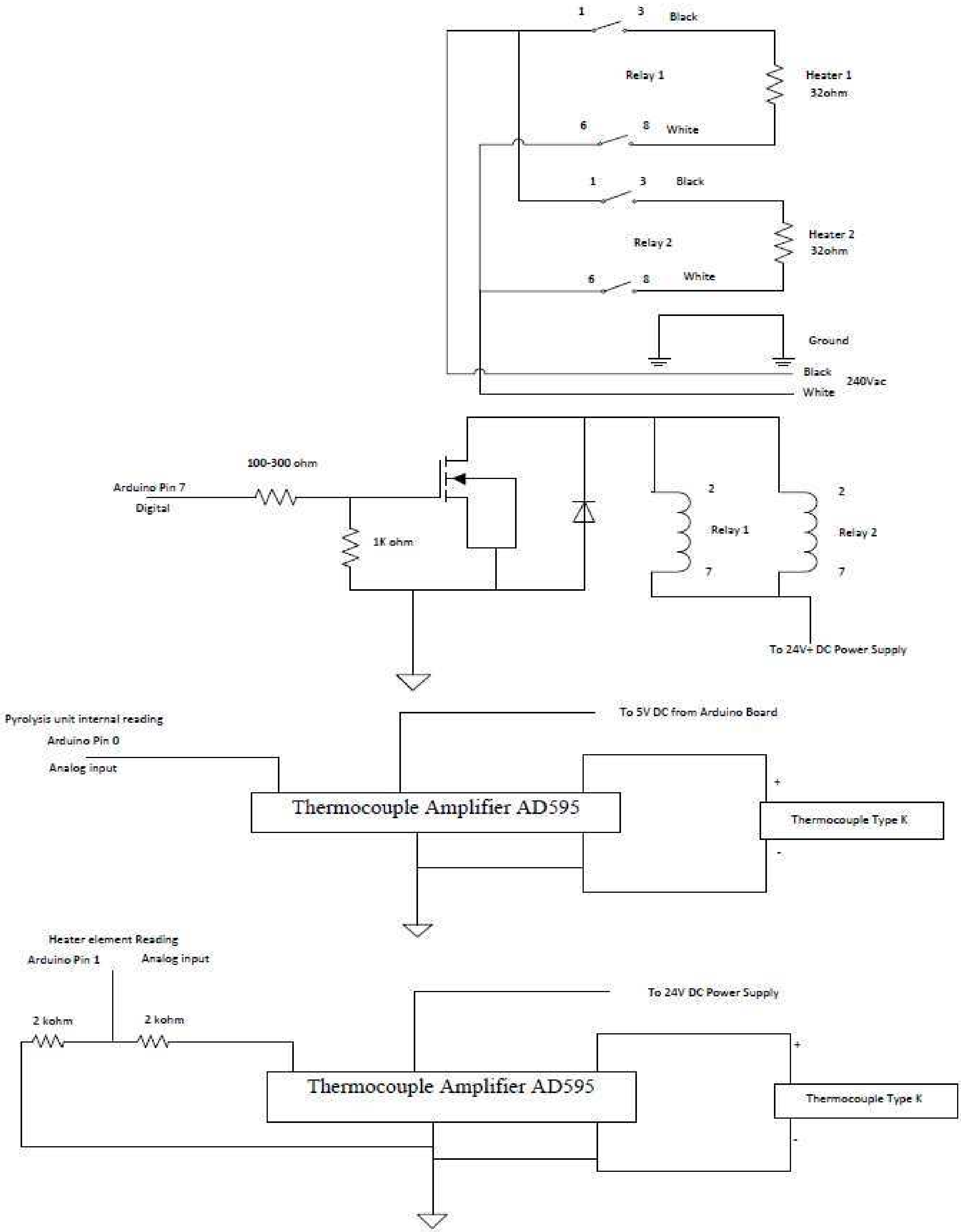
APPENDIX A :Control Schematic



APPENDIX B: Control Programs

Arduino Uno Program

```
//define pin number
constint heater = 7;
constint sensorPin1 = A0;
constint sensorPin2 = A1;
//define independant variable
static double time=0.0;
static double timer=0.0;
//define dependant variable
double temp1;//temperature within chamber
double temp2;//temperature at the heaters
double tempbits1;//temperature in Digital reading(chamber)
double tempbits2;//temperature in Digital reading(heater)
staticint allow=1;//control loop variable
staticbooleanheaterstatus=0;//heater status on display
//operator specifications
const double temperaturetarget1 = 30.0;//degree Celsius
const double temperaturetarget2 = 70.0;//degree Celsius
const double samplingrate=1.0;//second
const double statusdelay=10.0;//second
//setup run once only
void setup() {
analogReference(DEFAULT);
pinMode(heater,OUTPUT);
Serial.begin(9600);
delay(5000);
Serial.println("time(Second)\t bit1 \t TempChamber(DegreeC) \t bit2 \t TempHeater(DegreeC) \t
allow \t heaterstatus");
}
//Loop run continuously in a loop with the sampling rate specified by operator
//and the arduino is performing Hardware-in-a-Loop(HIL)
void loop() {
  // read the value from the sensor and display:
  tempbits1=analogRead(sensorPin1);
  tempbits2=analogRead(sensorPin2);
  //the slop of the equation below is the calibration
  //for thermocouple, the amplifiers have a pretrimmed setting
  //which starts at the origine, and slop is 10mV/degreeC
  temp1=(500.0/1024.0)*tempbits1;
  temp2=(980.0/1024.0)*tempbits2;
  //display time,temperature in bits and calibrated value
Serial.print(time);
Serial.print("\t");
Serial.print(tempbits1);
```

```
Serial.print("\t");
Serial.print(temp1);
Serial.print("\t");
Serial.print(tempbits2);
Serial.print("\t");
Serial.print(temp2);
Serial.print("\t");
  //see void heatercontrol() function
heatercontrol();
  //see void heatercontrolstatus() function
heatercontrolstatus();
  //update time
time=time+samplingrate;
  //perform sampling rate delay
delay(samplingrate*1000.0);
}
voidheatercontrol()
{
  //Heater Control:
if(temp1<temperaturetarget1 && temp2<temperaturetarget2 && allow==1){
    //Turn On heater when both temperature is below targets
digitalWrite(heater,HIGH);
if(heaterstatus==0){
allow=0;
    }
heaterstatus = 1;
  }
if(temp1>=temperaturetarget1 || temp2>=temperaturetarget2 && allow==1){
    //Turn Off heater when any temperature is above targets
digitalWrite(heater,LOW);
if(heaterstatus==1){
allow=0;
    }
heaterstatus = 0;

  }
  //exceedance detection
if(temp1>=temperaturetarget1+50.0 || temp2>=temperaturetarget2+50.0){
allow=2;
digitalWrite(heater,LOW);
heaterstatus = 0;
  }
}
voidheatercontrolstatus(){
  //limit heater to change state only after the number of second staying in state
if(allow == 0){
```

```
timer=timer+samplingrate;
    //delay after a switch On/Off is made to accomodate the max operating speed
    //and avoid temperature fluctuation error to cause relay to become unstable
if(timer>=statusdelay){
allow =1;
timer =0;
    }
  }
if(allow == 2)
  {
    //exceedance temperature detected, turn off all system
digitalWrite(heater,LOW);
Serial.println("TEMPERATURE EXCEEDANCE DETECTED");
  }
  //show control parameter status:
  //show allow status,
  //one means that the EM relay can change state
Serial.print(allow);
Serial.print("\t");
  //show heater status and end line,
  //one means that the heater is On.
Serial.println(heaterstatus);
  }
}
```

Appendix C : Test Procedures

Team	14
Device	Pyrolysis POC
Test Date	2012-03
Location	EDML C, EDML B, SAE Cage
Test Lead	Alfredo Martinez-Iglesias
Test co-lead	Hana WissemAmroun
Test Staff	Ho Wai Leung, Nicholas Matsushita-Fournier, Mathieu Parent, NathanialTull
Observers	None

Approvals for testing	
Test Lead	Alfredo Martinez-Iglesias
Program Manager	Dominic Ng
Professor	Henry Hong

PREOPERATION CHECKS

	Name of task	**Description**	**Signature**	**Date**
SFT1	Guarding	The assembled unit has proper guards against any possible malfunction (blast doors, danger tape, spotters)		2012-02-29
SFT2	Personal protective equipment	Safety goggles, proper footwear, temperature resistant gloves, no jewelry, long hair tied back		2012-02-27
SFT3	Safety release valve	Check that valve is installed properly		2012-03-17
SFT4	Fire	Have a fire extinguisher within the vicinity of the testing area		2012-03-21
SFT5	Wiring	Inspect wiring system for loose connections, shorts and make sure everything is grounded		2012-03-19
SFT6	Stability	Ensure rig is mounted on steady supports		2012-02-15
SFT7	Pressure transducer	Ensure pig-tail is filled with water		2012-03-19
SFT8	Pressure transducer	Ensure pressure can be recorded adequately		2012-03-20
SFT9	Temperature sensor	Ensure Temperature can be recorded through software		2012-03-19
SFT10	Pressure regulator	Set maximum pressure to 30 psi and ensure device regulates pressure above this value		2012-02-27
SFT11	Ball valves	Ensure the valves are well supported and free to operate unobstructed		2012-03-17

SFT12	Rotary Shaft	Ensure the shaft is installed as per assembly drawings and is free to rotate unobstructed		2012-03-18
SFT13	Liquid leak test	Ensure the chamber is free of any major leaks (see table 1)		2012-03-02

Table 15 Liquid Leak Test

Temperature	Pressure (psi)	Time (s)	Recorded pressure	
			Before	After
atm	5	180s (3mins)		
	10			
	30			
	60			
	125	12 hours		

	Name	Description	Signature	Date
DEV1	Post-test Inspection	Check for damaged components and play in mating parts		2012-03-02

	Name of task	Description	Signature	Date
SFT14	Air pressure test	Ensure the assembled unit is capable of sustaining pressure (see table 2, table 3, table 4 and table 5)		2012-03-02

Table 16 Pressurized Air Test

Temperature	Pressure (psi)	Time (s)	Recorded pressure	
			Before	After
atm	10	180s (3mins)		

	25			
	30			

Table 17 Pressurized Air Test With Rotating Auger

Temperature	Pressure (psi)	Time (s)	Recorded pressure	
			Before	After
atm	10	180s (3mins)		
	25			
	30			
	35			

	Name	Description	Signature	Date
DEV2	Post-test Inspection	Check for damaged components and play in mating parts		2012-03-02

Table 18Pressurized air test while operating feed system

Temperature	Pressure (psi)	Time (s)	Recorded pressure	
			Before cycle	After cycle
atm	5	N/A		

	10			
	23			
	25			
	28			

Table 19Pressurized air test while operating extraction system

Temperature	Pressure (psi)	Time (s)	Amount of cycles required	Average pressure lost per cycle (psi/cycle)
atm	From 20 to 15	N/A		
	From 25 to 20			

	Name	Description	Signature	Date
DEV3	Post-test Inspection	Check for damaged components and play in mating parts		2012-03-23

	Name of task	Description	Signature	Date
SFT15	Heater test	Make sure heater is capable of being activated and deactivated via programmed software		2012-03-21
SFT16	Temperature test	Ensure the rig is capable of sustaining elevated temperatures (see table 6)		2012-03-23

Table 20Temperature test

Temperature	Pressure (psi)	Time (s)	Apparent issues?	
			YES	NO
30	atm	180 (3mins)		
50				
80				
100				
	Name	**Description**	**Signature**	**Date**
DEV4	Post-test Inspection	Check for damaged components and play in mating parts		2012-03-23
120	atm	180 (3mins)		
140				
150				
160				
	Name	**Description**	**Signature**	**Date**
DEV5	Post-test Inspection	Check for damaged components and play in mating parts		2012-03-23

	Name of task	Description	Signature	Date
SFT17	Combined pressure-temperature test	Ensure the rig is capable of sustaining elevated temperatures and pressures (see table 7)		2012-03-23

Table 21Combined pressure – temperature test

Temperature	**Pressure (psi)**	**Time (s)**	**Recorded pressure**	
			Before	**After**
110	N/A	180		
		300		
		600		
	Name	**Description**	**Signature**	**Date**
DEV6	Post-test Inspection	Check for damaged components and play in mating parts		2012-03-24
Temperature	**Pressure (psi)**	**Time (s)**	**Recorded pressure**	
			Before	**After**
130	N/A	180		
		300		
		600		
	Name	**Description**	**Signature**	**Date**
DEV7	Post-test Inspection	Check for damaged components and play in mating parts		2012-03-24
Temperature	**Pressure (psi)**	**Time (s)**	**Recorded pressure**	
			Before	**After**
150	N/A	180		

		300		
		600		
	Name	**Description**	**Signature**	**Date**
DEV8	Post-test Inspection	Check for damaged components and play in mating parts		2012-03-24

OPERATIONAL TESTS

	Name of task	Description	Signature	Date
OPS1	Rotary shaft	Test pressure seal when shaft is rotating (see table 8)		2012-03-24

Table 22Rotating shaft under elevated temperature and pressure

Temperature	Pressure (psi)	Time (s)	Recorded pressure	
			Before	**After**
110	N/A	180 (3mins)		
	Name	**Description**	**Signature**	**Date**
DEV9	Post-test Inspection	Check for damaged components and play in mating parts		2012-03-24
Temperature	**Pressure (psi)**	**Time (s)**	**Recorded pressure**	
			Before	**After**
130	N/A	180 (3mins)		
	Name	**Description**	**Signature**	**Date**
DEV10	Post-test Inspection	Check for damaged components and play in mating parts		2012-03-24
Temperature	**Pressure (psi)**	**Time (s)**	**Recorded pressure**	
			Before	**After**
150	N/A	180 (3mins)		

	Name	**Description**	**Signature**	**Date**
DEV11	Post-test Inspection	Check for damaged components and play in mating parts		2012-03-24

	Name of task	Description	Signature	Date
OPS2	operating system	Test rig for its designed purpose (i.e. feed – drive – extraction) (see table 9)		2012-03-25

Table 23Full operation (rotating drive shaft – feed – extraction)

Temperature	Pressure (psi)	Time	Recorded pressure	
			Before	**After**
110	N/A	Intake cycle + 180s + extraction cycle		
	Name	**Description**	**Signature**	**Date**
DEV12	Post-test Inspection	Check for damaged components and play in mating parts		2012-03-25
Temperature	**Pressure (psi)**	**Time (s)**	**Recorded pressure**	
			Before	**After**
130	N/A	Intake cycle + 180s + extraction cycle		
	Name	**Description**	**Signature**	**Date**
DEV13	Post-test Inspection	Check for damaged components and play in mating parts		2012-03-25
Temperature	**Pressure (psi)**	**Time (s)**	**Recorded pressure**	
			Before	**After**
150	N/A	Intake cycle + 180s + extraction cycle		
	Name	**Description**	**Signature**	**Date**
DEV14	Post-test Inspection	Check for damaged components and play in mating parts		2012-03-25

APPENDIX D: Decision Matrix

Definition of Decision Matrix Criteria:

Manufacturability - **Labour Time**: Amount of time required to manufacture and assemble the system.

- **SkillLevel**: Level of skill that is required to manufacture and assemble the system

Cost - **Hardware**: The relative cost of material that cannot be manufactured and must be bought such as sensors, controller, heaters etc.

- **Materials**: The cost of the material that will be used to manufacture components
- **Maintenance**: The approximate cost associated with the upkeep of the system, such as the cost of components that must be replaced and the amount of cleaning that is required to maintain the ability to operate of the system.

Engineering - **Quality of Analysis**: The amount of assumptions that must be made in order to model the system. Complex geometries or unknown values are examples of items that will increase the amount of assumptions that need to be made.

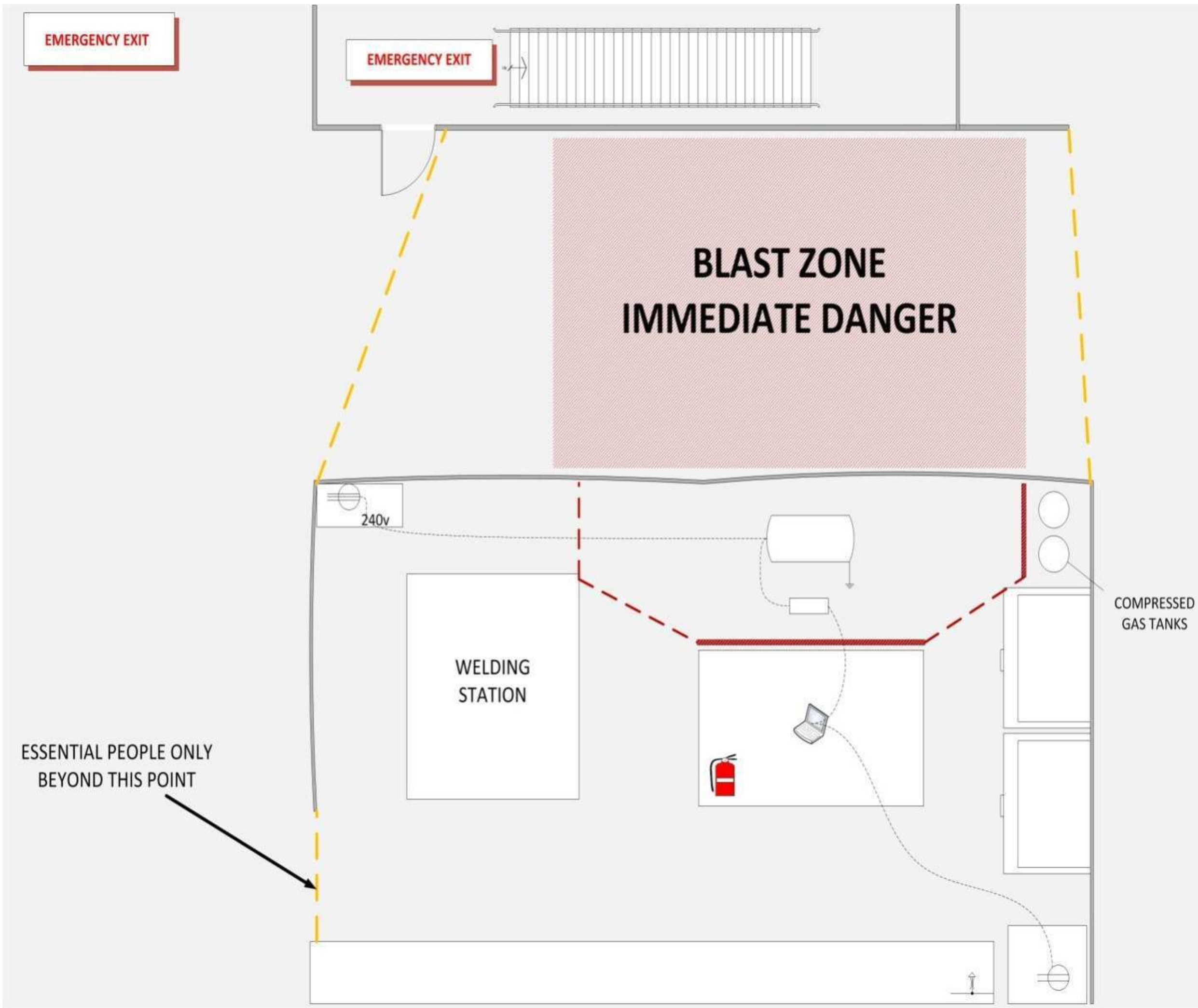
- **Validation**: How easy it is to verify the parameters being calculated. This may be due to the difficulty in placing sensors at exact locations.

Simplicity:

How easy it is to implement a given sub-system in order to achieve the optimal performance

- Pressure System
- Feed System
- Heating System
- Control System

APPENDIX E: Testing Safety Layout



APPENDIX F: Heat Losses Calculations

Heat Lost from Shell:

Assumption:
1- Steady operating conditions exist
2- Air is an ideal gas
3- The atmospheric pressure is 1atm

First, calculate the film temperature:

$$T_f = \frac{(T_S + T_\infty)}{2} = \frac{50 + 24}{2} = 37℃$$

Where:

T_s = surface temperature
T_∞ = surrounding ambient temperature

$$\beta = \frac{1}{T_f} = \frac{1}{310K}$$

Where:

B = Volume expansion coefficient

With the above temperature, the following properties of air at the film temperature were found in Table A-15 (Heat & Mass Transfer Yunus A. Cengel).

$$k = 0.0264 \frac{W}{m * K}$$
$$v = 1.6738 * 10^{-5} \frac{m^2}{s}$$
$$Pr = 0.72628$$

Where:

k = Thermal conductivity
v = Kinematic viscosity
Pr = Prandtl Number

The characteristic length is the diameter from the center of the pyrolysis unit to the unit surface,

Lc = D = 12inch =0.305m

The Rayleigh number can be computed with the following equation:

$$Ra_D = \frac{g\beta(T_s - T_\infty)D^3}{v^2}Pr$$

$$= \frac{9.81\frac{m}{s^2} * \frac{1}{310}\frac{1}{K} * 37\ K * (0.305\ m)^3}{\left(1.6738 * 10^{-5}\frac{m^2}{s}\right)^2} 0.72628 = 86.12 * 10^6$$

The natural convection Nusselt number can be calculated with the following equation:

$$Nu = \left(0.6 + \frac{0.387 * Ra_D^{\frac{1}{6}}}{\left(1 + \left(\frac{0.559}{\mathrm{Pr}}\right)^{\frac{9}{16}}\right)^{\frac{8}{27}}}\right)^2 = 54.22$$

$$h = \frac{k}{D}Nu = \frac{0.0264}{0.305} * 54.22 = 4.693\frac{W}{m℃}$$

$$A_s = \pi Dl = \pi * 0.305 * 0.483 = 0.463m^2$$

$$\dot{Q} = hA_s(T_s - T_\infty) = 4.693\frac{W}{m℃} * 0.463m^2 * (50 - 24)℃ = 56.49W$$

Where:
$\dot{Q} = Heat\ Lost\ to\ surrounding$
$h = natural\ convection\ coefficient$
$A_s = Surface\ Area$

Sample Calculation (left end cap):

First, calculate the film temperature:

$$T_f = \frac{(T_S + T_\infty)}{2} = \frac{106 + 24}{2} = 65℃$$

$$\beta = \frac{1}{T_f} = \frac{1}{338K}$$

With the above temperature, the following properties of air at the film temperature were found in Table A-15 [reference: Heat & Mass Transfer Yunus A. Cengel]

$$k = 0.0284\frac{W}{m * K}$$

$$v = 1.95 * 10^{-5}\frac{m^2}{s}$$
$$Pr = 0.719$$

The characteristic length is the diameter from the center of the pyrolysis unit to the unit surface,

Lc = D = 9inch =0.2286m

The Rayleigh number can be computed with the following equation:

$$Ra_D = \frac{g\beta(T_s - T_\infty)D^3}{v^2}Pr$$

$$= \frac{9.81\frac{m}{s^2} * \frac{1}{338}\frac{1}{K} * 65\ K * (0.2286\ m)^3}{\left(1.95 * 10^{-5}\frac{m^2}{s}\right)^2}0.719 = 2.776 * 10^{12}$$

The natural convection Nusselt number can be calculated with the following equation, for a vertical plate:

$$Nu = \left(0.825 + \frac{0.387 * Ra^{\frac{1}{6}}}{\left[1 + \left(\frac{0.492}{\mathrm{Pr}}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}}\right)^2 = \left(0.825 + \frac{0.387 * (2.776 * 10^{12})^{\frac{1}{6}}}{\left[1 + \left(\frac{0.492}{0.719}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}}\right)^2 = 1546.13$$

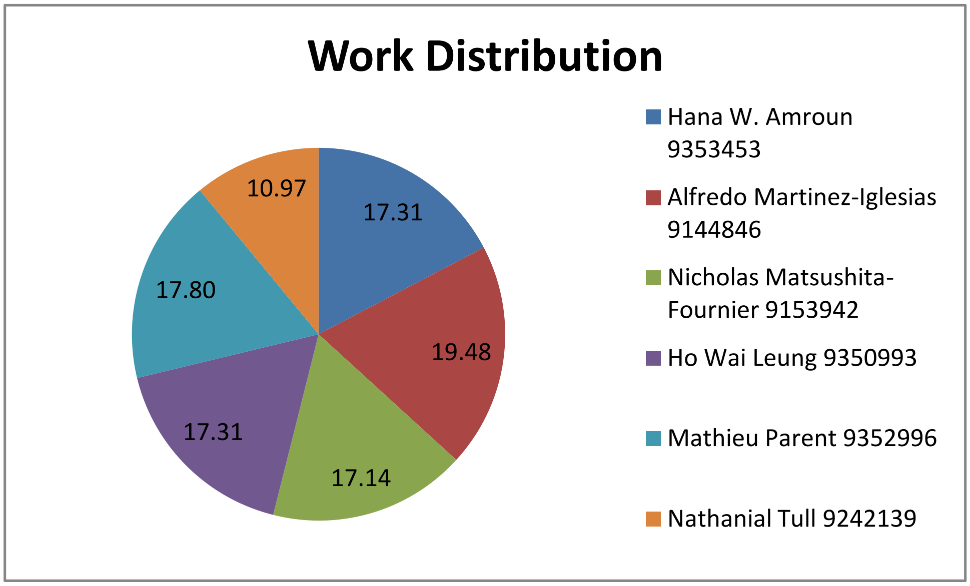
$$h = \frac{k}{D}Nu = \frac{0.0284}{0.2286} * 1546.13 = 192.082\frac{W}{m°\mathrm{C}}$$

$$A_s = 2\pi r^2 = 2 * \pi * \left(\frac{0.2286}{2}\right)^2 = 0.0821m^2$$

$$\dot{Q} = hA_s(T_s - T_\infty) = 192.082\frac{W}{m°\mathrm{C}} * \ 0.0821m^2 * (106 - 24)°\mathrm{C} = 1292.9W$$

APPENDIX G WORK DISTRIBUTION

The following pie chart provides the work distribution of each member throughout the duration of the project.



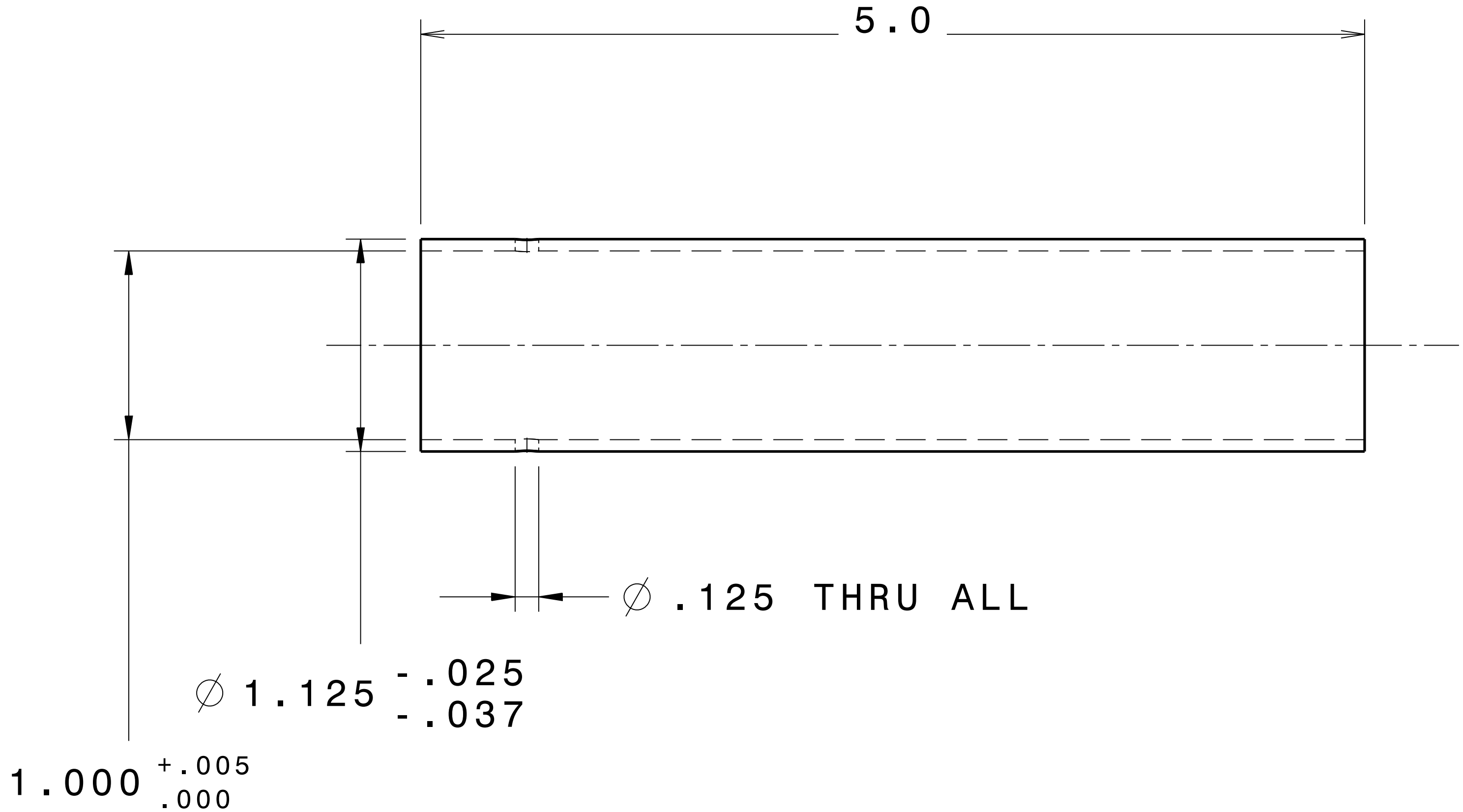
APPENDIX H : Bill of Materials

Year	2011-2012
Team	14
Device	Pyrolysis

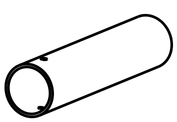
							CASH			TIME					SPONSORS	
Sub Sytem	Item	Description	Drawing#/Part#	MNF/OEM/SPL	Part Number	QTY	Material [$/Unit]	Total [$]	Labour [$]	Student Manufacturing - EDML B [hours]	EDML A [hours]	technician	Work To Be Done	technician time	Sponsor	Sponsored Amount
Intake	1	Wye (NPS 1 1/4)	44605K356	Sutton Plumbing	44605K356	1	24.67	24.67	-	-	-	-	-	-	-	-
	2	Wye (NPS 1/2)	44605K353	Sutton Plumbing	44605K353	1	9.63	9.63	-	-	-	-	-	-	-	-
	3	Ball Valve (NPS 1 1/4)	47865k26	Sutton Plumbing	47865K26	2	28.34	56.68	-	-	-	-	-	-	-	-
	4	Ball Valve (NPS 1/2)	47865K23	Sutton Plumbing	47865K23	2	8.49	16.98	-	-	-	-	-	-	-	-
	5	Union (1 1/4)	-	Sutton Plumbing	-	1	21.12	21.12	-	-	-	-	-	-	-	-
	6	Union (1/2)	-	Sutton Plumbing	-	1	10.05	10.05	-	-	-	-	-	-	-	-
	7	Funnel	-	Canadian Tire	-	1	2.29	2.29	-	-	-	-	-	-	-	-
	8	Pipe Reduced Male Bit (1 1/4 to 1/2 LGTH 4)	7818K217	Sutton Plumbing	7818K217	1	4.96	4.96	-	-	-	-	-	-	-	-
	9	Nipple Both End THD (NPS 1 1/4 LGTH 6'')	44615k547	Sutton Plumbing	44615K547	2	2.97	5.94	-	-	0.5	Bill	Cut then Weld to chamber	0.5	-	-
	10	Nipple Both End THD (NPS 1/2 LGTH 6'')	44615k544	Sutton Plumbing	44615K544	2	1.46	2.92	-	-	0.5	Bill	Cut then Weld to chamber	0.5	-	-
	11	Nipple Both End THD (NPS 1/2 LGTH 2'')	44615K434	Sutton Plumbing	44615K434	2	0.78	1.56	-	-	-	-	-	-	-	-
	12	Nipple Both End THD (NPS 1 1/4 LGTH 2'')	44615K437	Sutton Plumbing	44615K437	1	1.72	1.72	-	-	-	-	-	-	-	-
	13	Nipple Both End THD (NPS 1 1/4 LGTH 4'')	44615K467	Sutton Plumbing	44615K467	1	2.30	2.30	-	-	-	-	-	-	-	-
Extraction	14	Collection Pan	-	Canadian Tire	N/A	1	6.99	6.99	-	-	-	-	-	-	-	-
	15	Ball Valve (NPS 1 1/4)	47865k26	Sutton Plumbing	47865K26	2	28.34	56.68	-	-	-	-	-	-	-	-
	16	Nipple Both End THD (NPS 1 1/4 LGTH 3'')	44615k547	Sutton Plumbing	44615K547	1	2.97	2.97	-	-	0.5	Bill	Cut then Weld to chamber	0.5	-	-
Heater	17	Heaters	OEM SHEET	Omega.com	TRI-1644/120V	2	-	-	-	-	-	-	-	-	Omega	350
	18	Nut ¾"-16 (Pack of 10)	OEM SHEET	Home Depot	93827A267	1	9.00	9.00	-	-	-	-	-	-	-	-
Drive	19	Screw Shaft 1 1/8"x3'	S1	EDML	N/A	1	-	-	-	-	1	Juan	Cut	-	EDML	98
	20	Ice Fishing Auger	S2	Le Baron	2895t57	1	85.00	85.00	-	-	1	Juan	Cut	-	-	-
	21	Steel Cylinder 1.5"x Diameter2" (Auger Shaft Connection)	S16	EDML	N/A	1	-	-	-	-	1	Juan	-	-	-	-
	22	Drive Motor	-	EDML	-	1	-	-	-	-	-	-	-	-	EDML	402
	23	Reducer	-	EDML	-	1	-	-	-	-	-	-	-	-	EDML	67.84
	24	Steel Plate 1/4" (back and front packing plate)	S11, S14	EDML	N/A	1	-	-	-	-	2	Juan	Cut	-	-	-
	25	Pipe NPS 1	S13	EDML	N/A	1	-	-	-	-	1	Juan	Cut then bore	-	-	-
	26	Steel Cylinder aprx 2"xDiameter 2.5" (Housing)	S3	EDML	N/A	1	-	-	-	-	1	Juan, Bill	Lathe, Weld	1	-	-
	27	Solid Steel Shaft (Screw Shaft Extension)	S5	EDML	N/A	1	-	-	-	-	1	Juan, Bill	Cut then Weld	1	-	-
	28	1/4" Bolts	-	EDML	-	2	-	-	-	-	-	-	-	-	-	-
	29	Washer	-	EDML	-	4	-	-	-	-	-	-	-	-	-	-
	30	Packiong Seal	S15	John Crane	N/A	1	-	-	-	-	-	-	-	-	John Crane	50
Pressure Vessel	31	Outer Pipe NPS 6	C1	EDML	7750K202	1	-	-	-	-	2	Juan	Cut then drill	-	EDML	234.11
	32	Insulation 15"x48" Fiber Glass	-	RONA	-	2	6.77	13.54	-	0.5	-	-	-	-	-	-
	33	Internal Track	C13	EDML	N/A	1	-	-	-	-	1	Juan, Bill	Bending then weld to Chamber	-	EDML	20
	34	Gasket (multiple set)	OEM SHEET	Specialty Gaskets	N/A	1			-	-	-	-	-	-	Secialty Gaskets	100
	35	Pressure End Cap 1"	C6, C7	Branco	N/A	2	39.88	79.76	-	-	1	Juan	Boring	-	-	-
	36	Slip on Flange 1"	C4	Branco	N/A	2	47.84	95.68	-	-	-	Bill	Weld to Chamber	1	-	-
	37	Bolts	OEM SHEET	Attache Richard	91571A246	16	1.14	18.27	-	-	-	-	-	-	-	-
	38	Washer	OEM SHEET	Attache Richard	98038A265	32	0.17	5.39	-	-	-	-	-	-	-	-
	39	Nut	OEM SHEET	Attache Richard	90521A235	16	0.23	3.70	-	-	-	-	-	-	-	-
	40	Vessel Stand	-	EDML	-	1	-	-	-	3	-	Bill	Welding	1	EDML	20
Control	41	Thermocouple type K BareWire	-	Omega.com	DH-1-24-K-12	1	18.00	18.00	-	-	-	-	-	-	-	-
	42	Thermocouple Type K Probe	-	Omega.com	KMTSS-125G-6	1	24.00	24.00	-	-	-	-	-	-	-	-
	43	Thermocouple Type K (Ungrounded)	-	Omega.com	KMTSS-125U-6	1	43.03	43.03	-	-	-	-	-	-	-	-
	44	Thermocouple Amplifier	-	Newark.com	66F4167	1	33.92	33.92	-	-	-	-	-	-	-	-
	45	Thermocouple Holder	-	Swagelok.com	SS-6M0-1-4RT	1	7.49	7.49	-	-	-	-	-	-	-	-
	46	Emergency Release Valve (75PSI)(1/8")	-	Controles Laurentide		1	255.00	255.00	-	-	-	-	-	-	-	-
	47	Cast Iron Pressure Regulator (1/4")	-	Controles Laurentide		1	350.00	350.00	-	-	-	-	-	-	-	-
	48	Relay	-	ABRA	KRP-13	2	9.95	19.90	-	-	-	-	-	-	-	-
	49	Relay Base	-	ABRA	R95-H3 27E122	2	6.95	13.90	-	-	-	-	-	-	-	-
	50	Arduino Basic Kit	-	Robotshop.com	RB-Rbo-16	1	37.99	37.99	-	-	-	-	-	-	-	-
	51	365 Resistors Package (73Standard resistors X 5 Each)	-	Robotshop.com	RB-Ibo-94	1	14.85	14.85	-	-	-	-	-	-	-	-
	52	100 Ceramic Capacitor Pack	-	Robotshop.com	RB-Dfr-86	1	2.90	2.90	-	-	-	-	-	-	-	-
	53	Thermocouple Bung	T1	EDML	-	1	-	-	-	-	-	-	-	-	EDML	10

Support & Misc Hardware	54	Aluminum Cover 24"x55"	-	Fidele Arsenault	-	1	23.61	23.61	-	-	-	-	-	-		
	55	Chicken Wire	-	Probex	-	1	19.69	19.69	-	-	-	-	-	-		
	56	Aluminum Tape	-	Probex	-	1	11.99	11.99	-	-	-	-	-	-		
	57	Hardware (Screw, Washer, Bolts, Nuts)	-	RONA	-	1	14.90	14.90	-	-	-	-	-	-		
	58	Hardware (Screw, Washer, Bolts, Nuts)	-	Probex	-	1	34.94	34.94	-	-	-	-	-	-		
	59	Metal Clamp	-	Canadian Tire	-	2	0.69	1.38	-	-	-	-	-	-		
	60	Stand Base	ST2	EDML	-	2	-	-	-	-	-	-	-	-	EDML	20
	61	Billet Leg	ST1	EDML	-	4	-	-	-	-	-	-	-	-		40
Presentation Material/Documentation	62	Folder	-	Dollarama	-	1	3.75	3.75	-	-	-	-	-	-	-	-
	63	Poster	-	Bureau En Gros	-	2	5.56	11.12	-	-	-	-	-	-	-	-
	64	Index Guide	-	Concordia Bookstore	10102725	1	0.96	0.96	-	-	-	-	-	-	-	-
	65	Security Tape	-	Canadian Tire	-	1	5.99	5.99	-	-	-	-	-	-	-	-
	66	Tape	-	Concordia Bookstore	10032398	1	1.76	1.76	-	-	-	-	-	-	-	-
		TOTALS						**1712.21**	**0**	**3.5**	**13.5**	**0**	**0**	**5.5**	**0**	**1411.95**

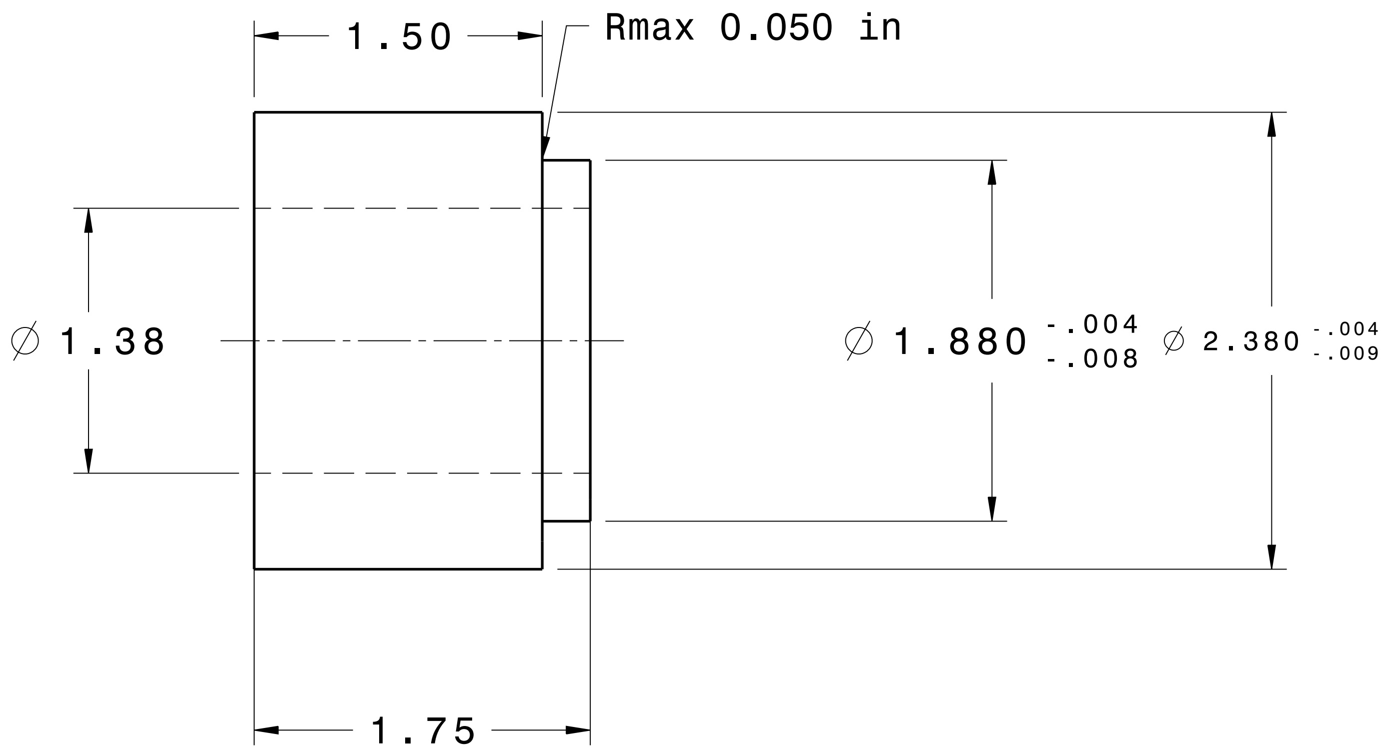
APPENDIX I : CAD DRAWINGS



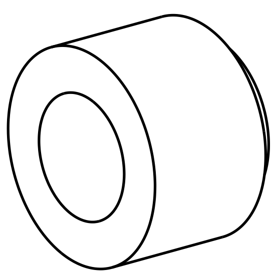
Notes
1- Steel, 4' stock, OD 1.125", ID 1"



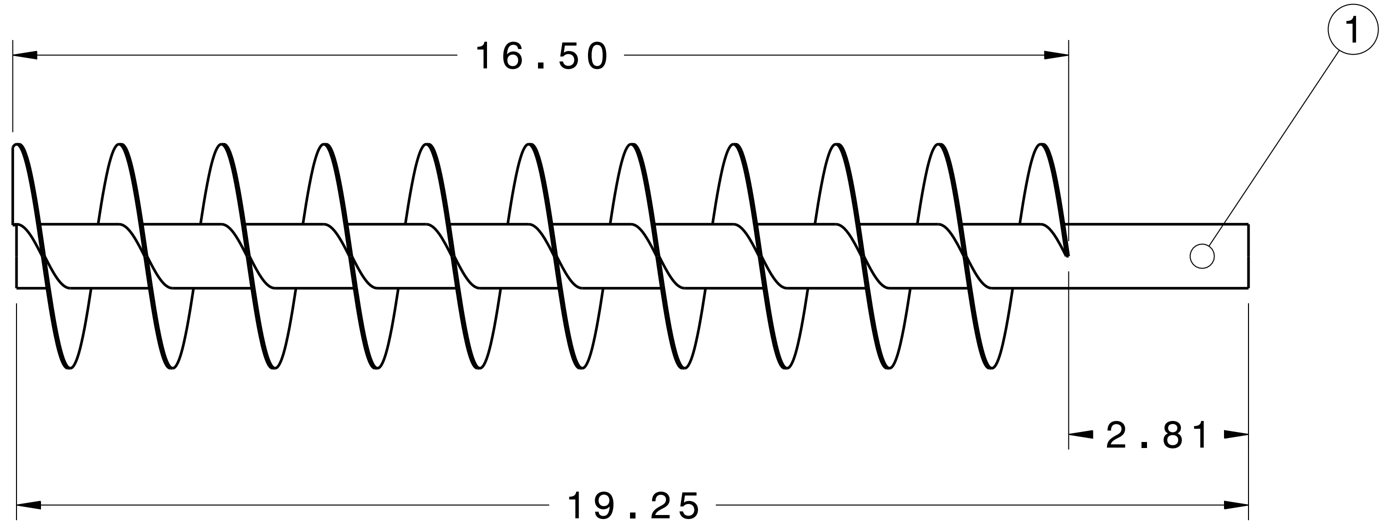
UNIVERSITÉ Concordia UNIVERSITY	MATERIAL Steel	SURFACE ROUGHNESS √250	TITLE Screw Shaft
	FINISH Clean	TOLERANCES UNLESS OTHERWISE SPECIFIED X ± .1, .X ± .05, .XX ± .005, .XXX ± .002, ANGLE ± .5 °	
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	DESIGNER Team 14	ALL DIMENSIONS IN **INCHES** UNLESS OTHERWISE SPECIFIED	A SIZE / DATE 01/12/2012 / USED ON MECH 490
	DRAFTER N.M-Fournier	APPROVED H.Amroun / SCALE 1:1	SHEET 1 / 1 / DWG NO. S1 / REV NO. 00



Note:
Machined from a solid steel block

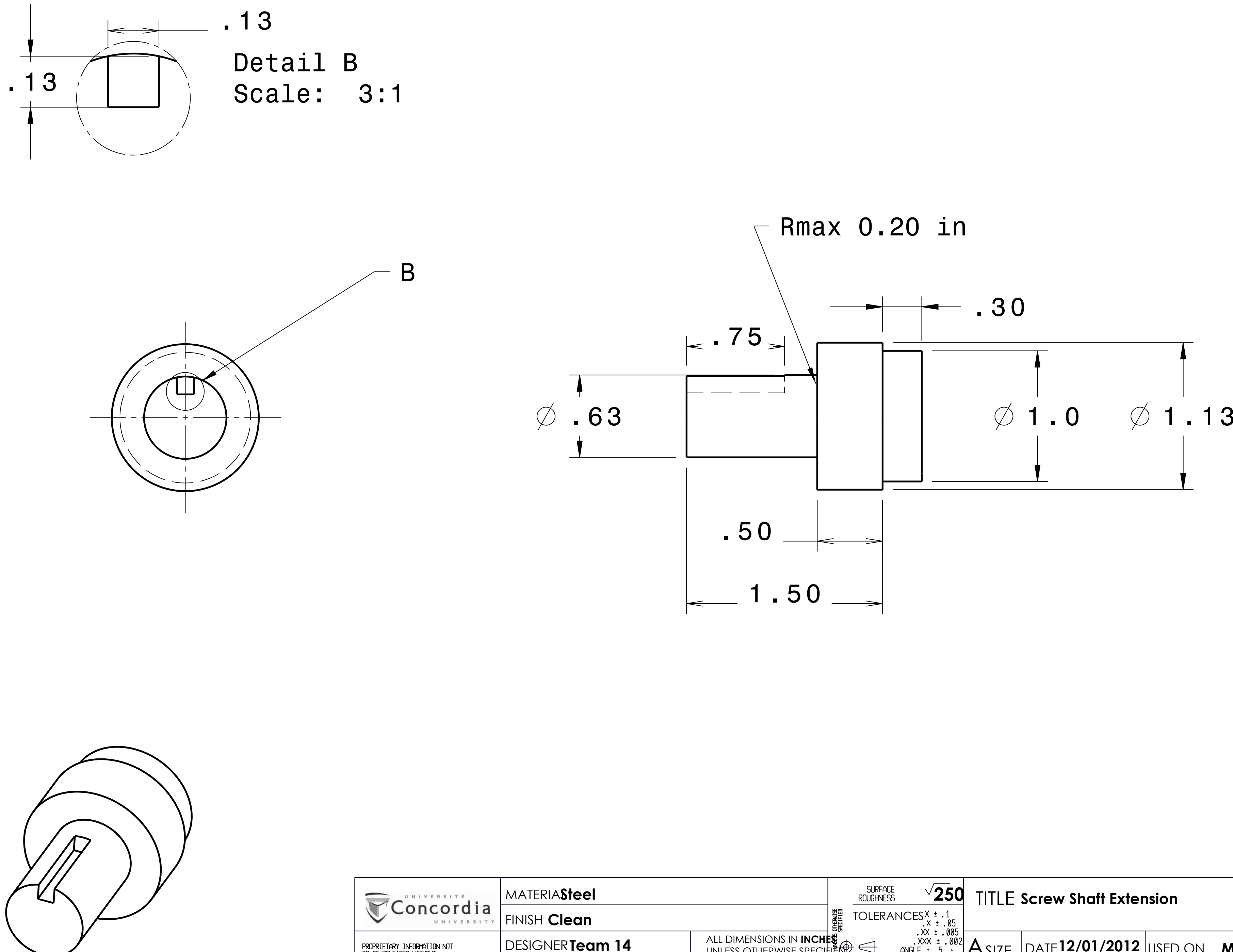


UNIVERSITÉ Concordia UNIVERSITY	MATERIAL Low Carbon Steel	SURFACE ROUGHNESS $\sqrt{250}$	TITLE Housing
	FINISH Clean	TOLERANCES UNLESS OTHERWISE SPECIFIED X ± .1, .X ± .05, .XX ± .005, .XXX ± .002, ANGLE ± .5 °	
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	DESIGNER Team 14	ALL DIMENSIONS IN **INCHES** UNLESS OTHERWISE SPECIFIED	A SIZE · DATE 19/01/2012 · USED ON MECH 490
	DRAFTER N.M-Fournier	APPROVED M.Parent · SCALE 1 : 1	SHEET 1 / 1 · DWG NO. S3.Housing · REV NO. 00

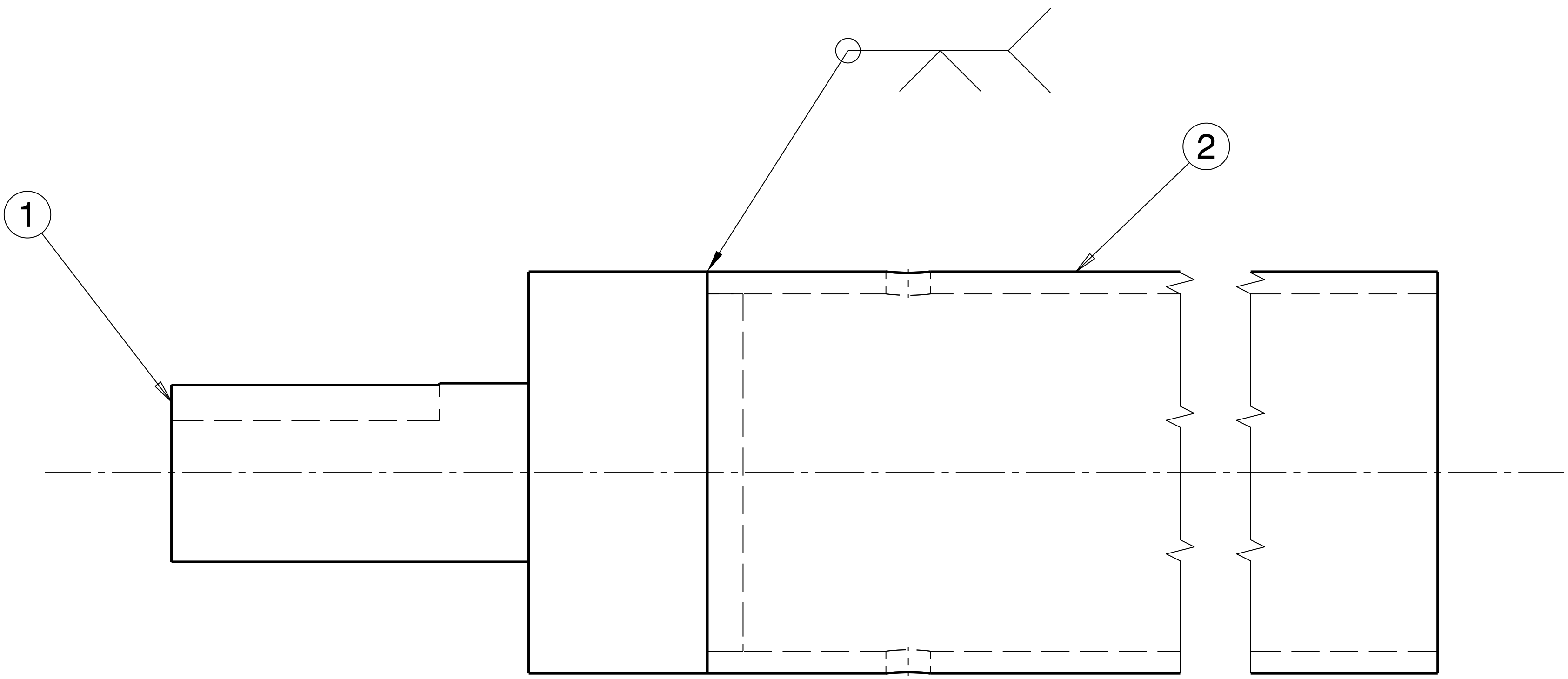


Note:
1. Auger

UNIVERSITÉ Concordia UNIVERSITY	MATERIAL **Various**	SURFACE ROUGHNESS $\sqrt{250}$	TITLE **Auger**
	FINISH **None**	TOLERANCES UNLESS OTHERWISE SPECIFIED X ± .1, .X ± .05, .XX ± .005, .XXX ± .002, ANGLE ± .5 °	
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	DESIGNER **Team 14**	ALL DIMENSIONS IN **INCHES** UNLESS OTHERWISE SPECIFIED	A SIZE — DATE **2012-02-08** — USED ON **MECH 490**
	DRAFTER **H.Amroun**	APPROVED **M.Parent** — SCALE **1 : 3**	SHEET **1 / 3** — DWG NO. **S4** — REV NO. **00**

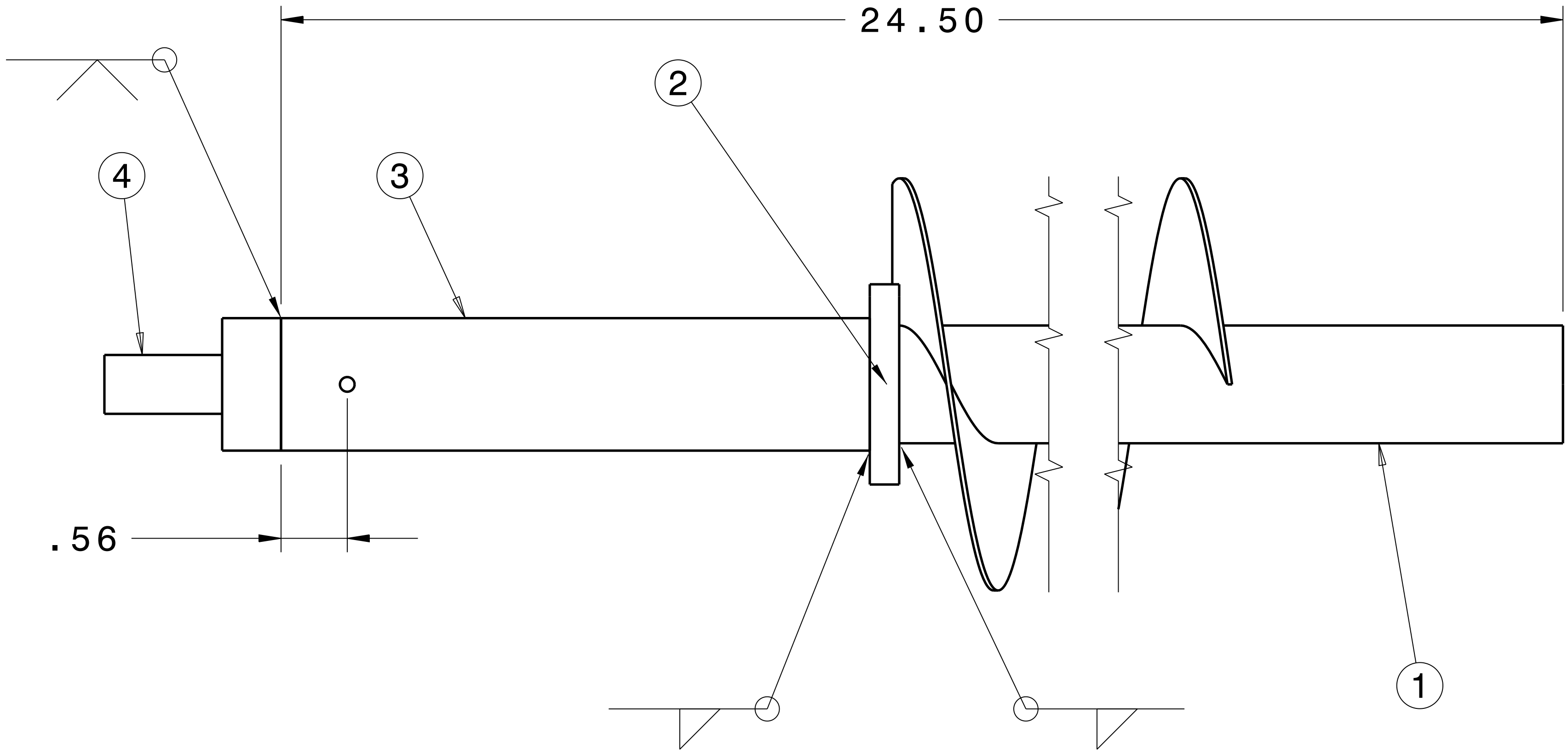


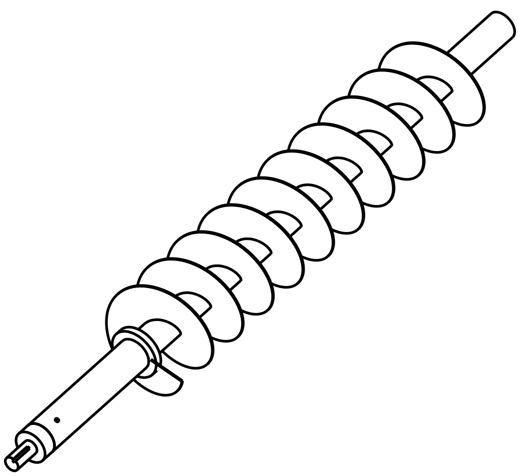
Université Concordia University	MATERIAL Steel	SURFACE ROUGHNESS √250	TITLE Screw Shaft Extension
	FINISH Clean	TOLERANCES UNLESS OTHERWISE SPECIFIED .X ± .1 .X ± .05 .XX ± .005 .XXX ± .002 ANGLE ± .5°	
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	DESIGNER Team 14 / ALL DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED		A SIZE / DATE 12/01/2012 / USED ON MECH 490
	DRAFTER M.Parent / APPROVED M.Parent	SCALE 1 : 1	SHEET 1 / 1 / DWG NO. S5 / REV NO. 00



Note:
1- S5 - Screw Extension
2- S1 - Shaft

UNIVERSITÉ Concordia UNIVERSITY	MATERIA Low Carbon Steel	SURFACE ROUGHNESS $\sqrt{250}$	TITLE **Shaft With Extension**
	FINISH **Clean**	UNLESS OTHERWISE SPECIFIED TOLERANCES X ± .1 .X ± .05 .XX ± .005 .XXX ± .002 ANGLE ± .5 °	
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	DESIGNER **Team 14** / ALL DIMENSIONS IN **INCHES** UNLESS OTHERWISE SPECIFIED		A SIZE / DATE **27/01/2012** / USED ON **MECH 490**
	DRAFTER **N.M-Fournier** / APPROVED **N.M-Fournier**	SCALE **2 : 1**	SHEET **1 / 1** / DWG NO. **S6** / REV NO. **00**

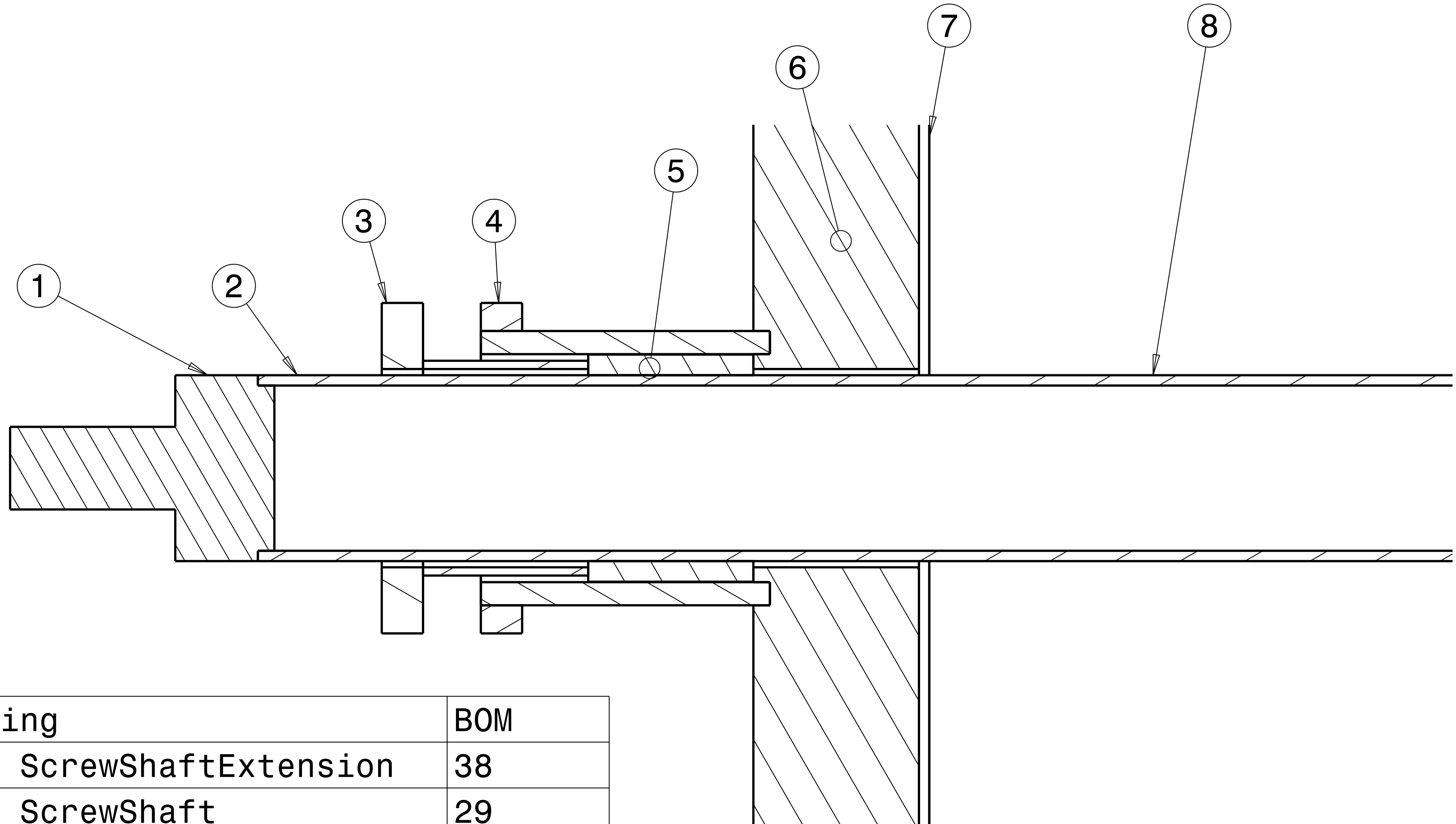




Note:
1. Auger Refer to Drawing S4
2. Shafts Connection Refer to Drawing S16
3. Shaft Refer to Drawing S1
4- Shaft Extension Refer to Drawing S5

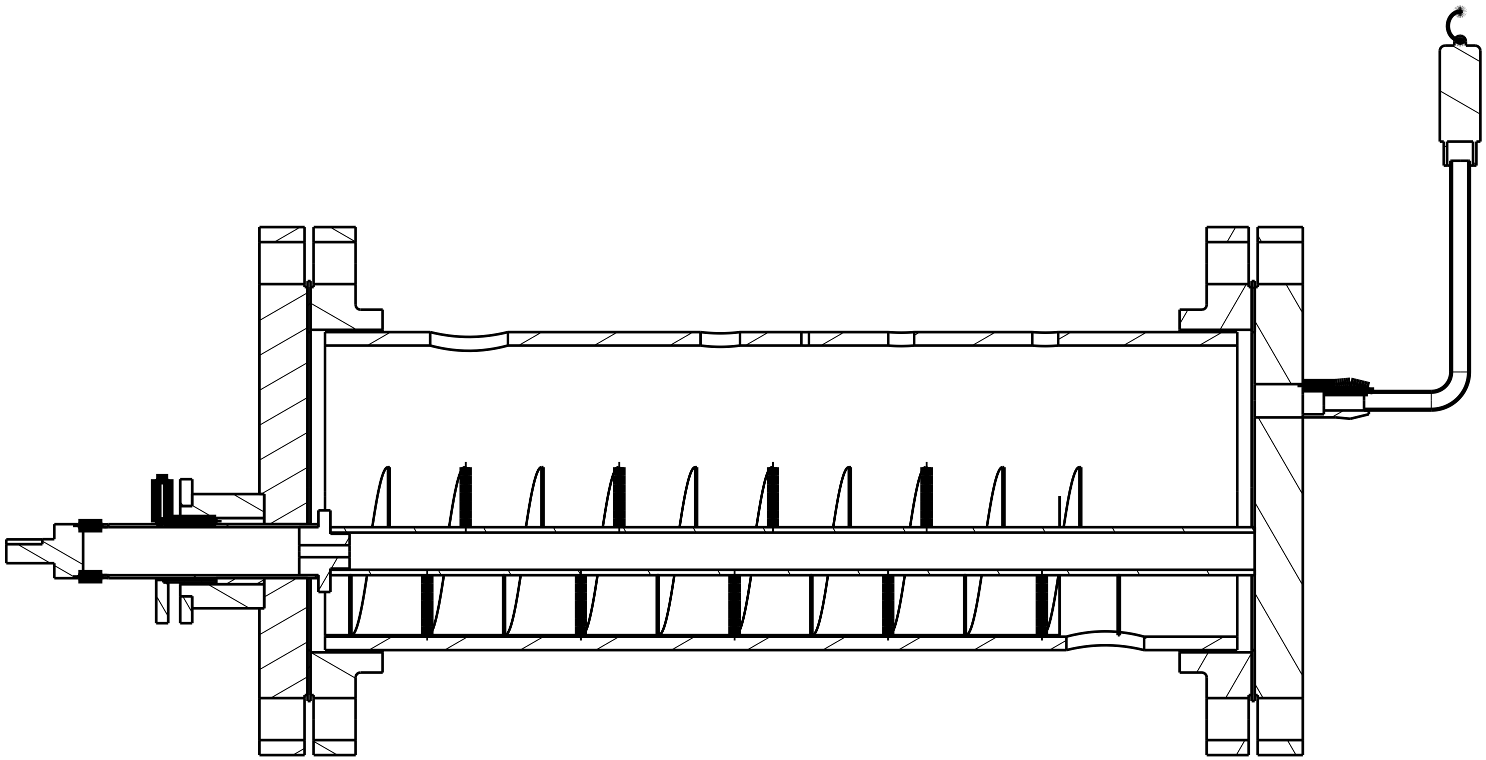
- Rmax of 0.25" on the two "Shaft Connection" welds

UNIVERSITÉ Concordia UNIVERSITY	MATERIAL Various		SURFACE ROUGHNESS √250	TITLE Auger.connection.shaft
	FINISH Various		TOLERANCES .X ± .1, .X ± .05, .XX ± .005, .XXX ± .002, ANGLE ± .5 °	
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	DESIGNER TEAM 14	ALL DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED	A SIZE	DATE 12/34/5678 USED ON MECH 490
	DRAFTER H.Amroun	APPROVED H.Amroun	SCALE 1 : 3	SHEET 1 / 1 DWG NO. S8 REV NO. 00

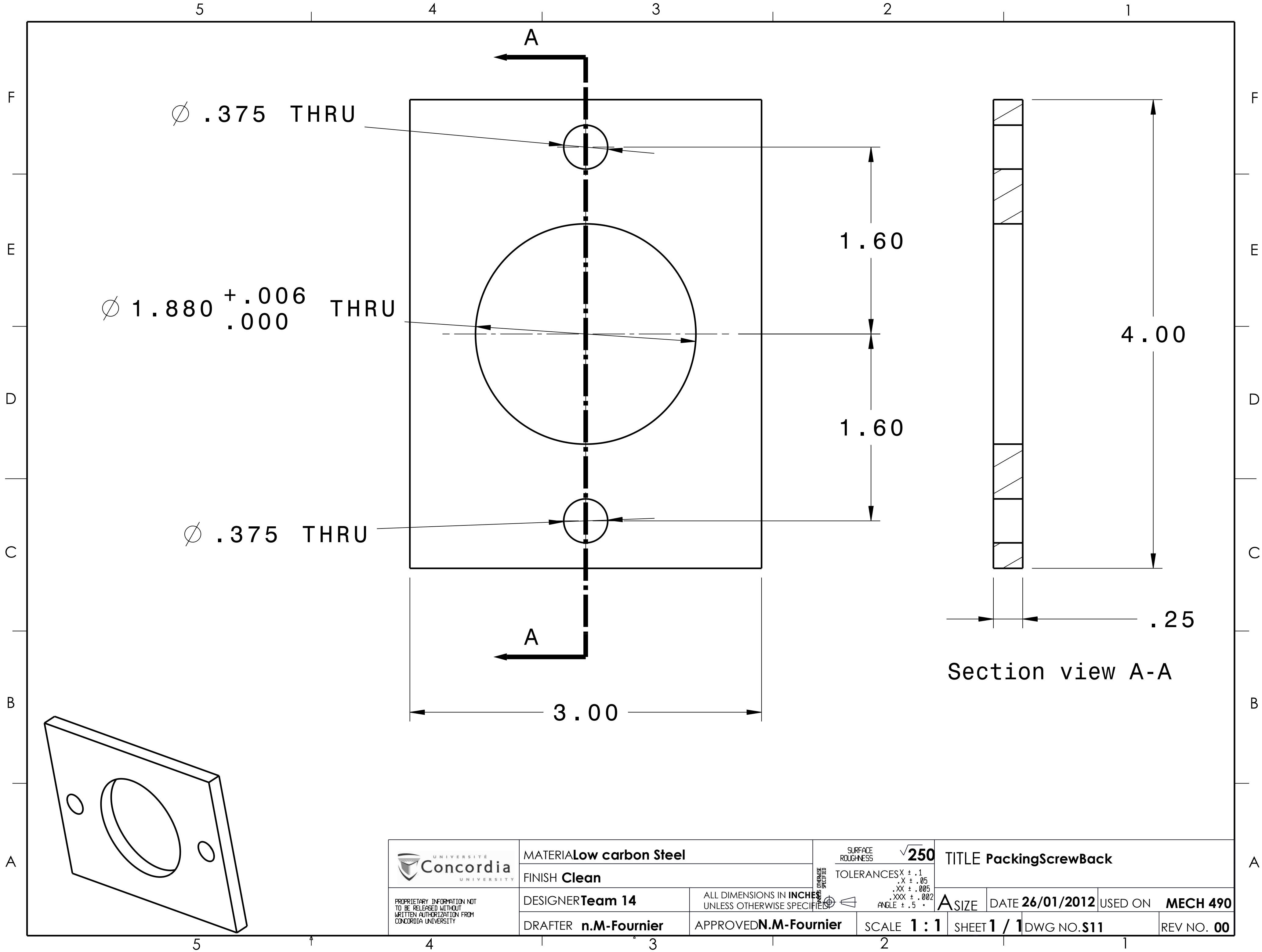


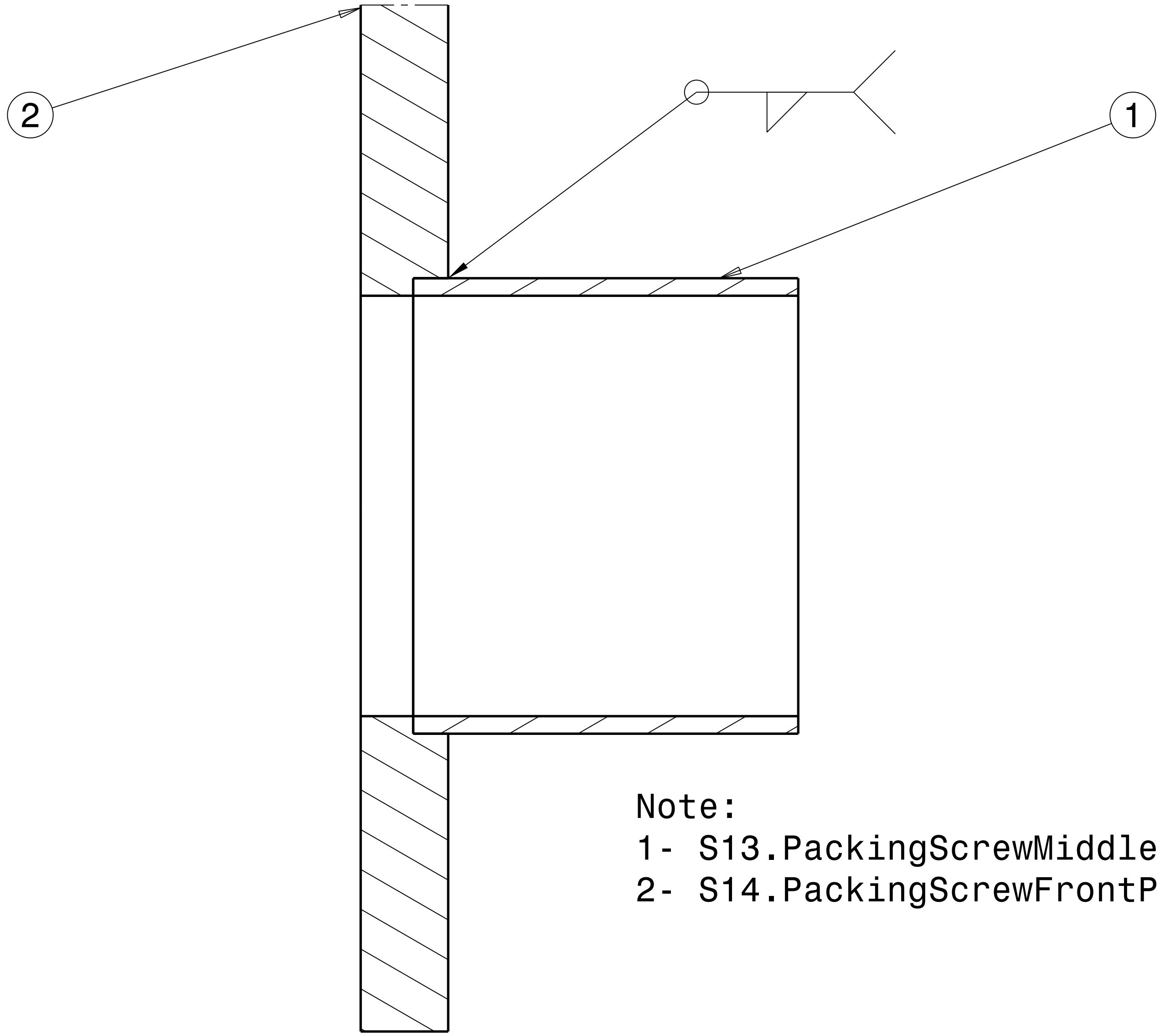
Item	Drawing	BOM
1	S5 - ScrewShaftExtension	38
2	S2 - ScrewShaft	29
3	S12 - PackingScrewFront	
4	S11 - PackingScrewBack	36
5	- Packing	39
6	68095K169 - EndCaps	
7	Gasket	44
8	S1 - ScrewShaft	29

Université Concordia University	MATERIAL Various	SURFACE ROUGHNESS √250	TITLE LeftEndAssy
	FINISH Clean	TOLERANCES UNLESS OTHERWISE SPECIFIED .X ± .1 .XX ± .05 .XXX ± .005 .XXXX ± .002 ANGLE ± .5 °	
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	DESIGNER Team 14 / ALL DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED		A SIZE / DATE 25/01/2012 / USED ON MECH 490
	DRAFTER N.M-Fournier / APPROVED M.Parent	SCALE 1 : 1	SHEET 1 / 1 / DWG NO. S9 / REV NO. 00

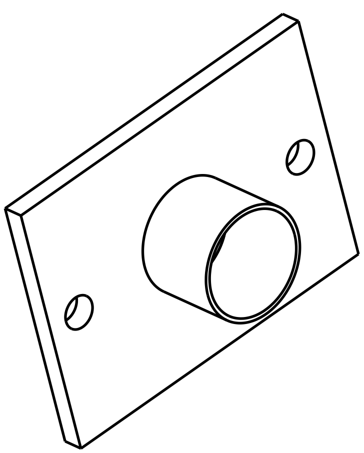


Université Concordia University	MATERIAL Various		SURFACE ROUGHNESS $\sqrt{250}$	TITLE **Cylinder Cross Section**		
	FINISH **none**		TOLERANCES (UNLESS OTHERWISE SPECIFIED) X ± .1, .X ± .05, .XX ± .005, .XXX ± .002, ANGLE ± .5 °			
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	DESIGNER **Team 14**	ALL DIMENSIONS IN **INCHES** UNLESS OTHERWISE SPECIFIED		A SIZE	DATE **2/9/2012**	USED ON **MECH 490**
	DRAFTER **H.Amroun**	APPROVED **M.Parent**	**Scale: 1:4**	**Sheet 1/1**	**DRWG # S10**	**REV 00**

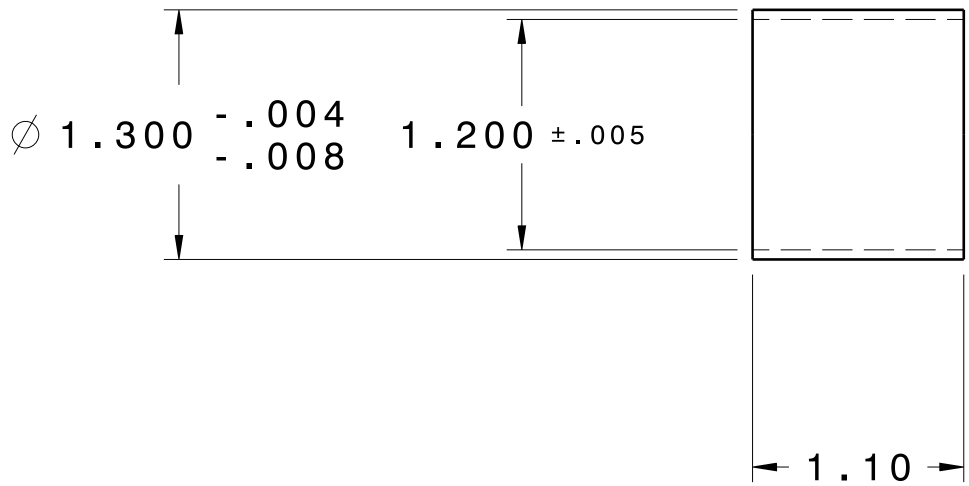

A
∅ .375 THRU
∅ 1.880 +.006 .000 THRU
∅ .375 THRU
1.60
1.60
4.00
.25
A
3.00
Section view A-A
Concordia UNIVERSITY
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY
MATERIAL Low carbon Steel
FINISH Clean
DESIGNER Team 14
DRAFTER n.M-Fournier
ALL DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED
APPROVED N.M-Fournier
SURFACE ROUGHNESS √250
TOLERANCES X ± .1 .X ± .05 .XX ± .005 .XXX ± .002 ANGLE ± .5°
UNLESS OTHERWISE SPECIFIED
SCALE 1 : 1
TITLE PackingScrewBack
A SIZE
DATE 26/01/2012
USED ON MECH 490
SHEET 1 / 1
DWG NO. S11
REV NO. 00

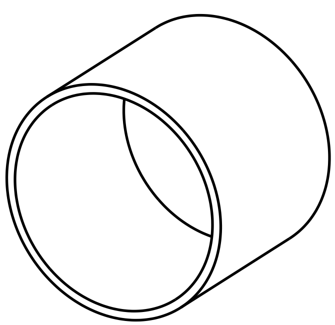


Note:
1- S13.PackingScrewMiddle
2- S14.PackingScrewFrontPlate



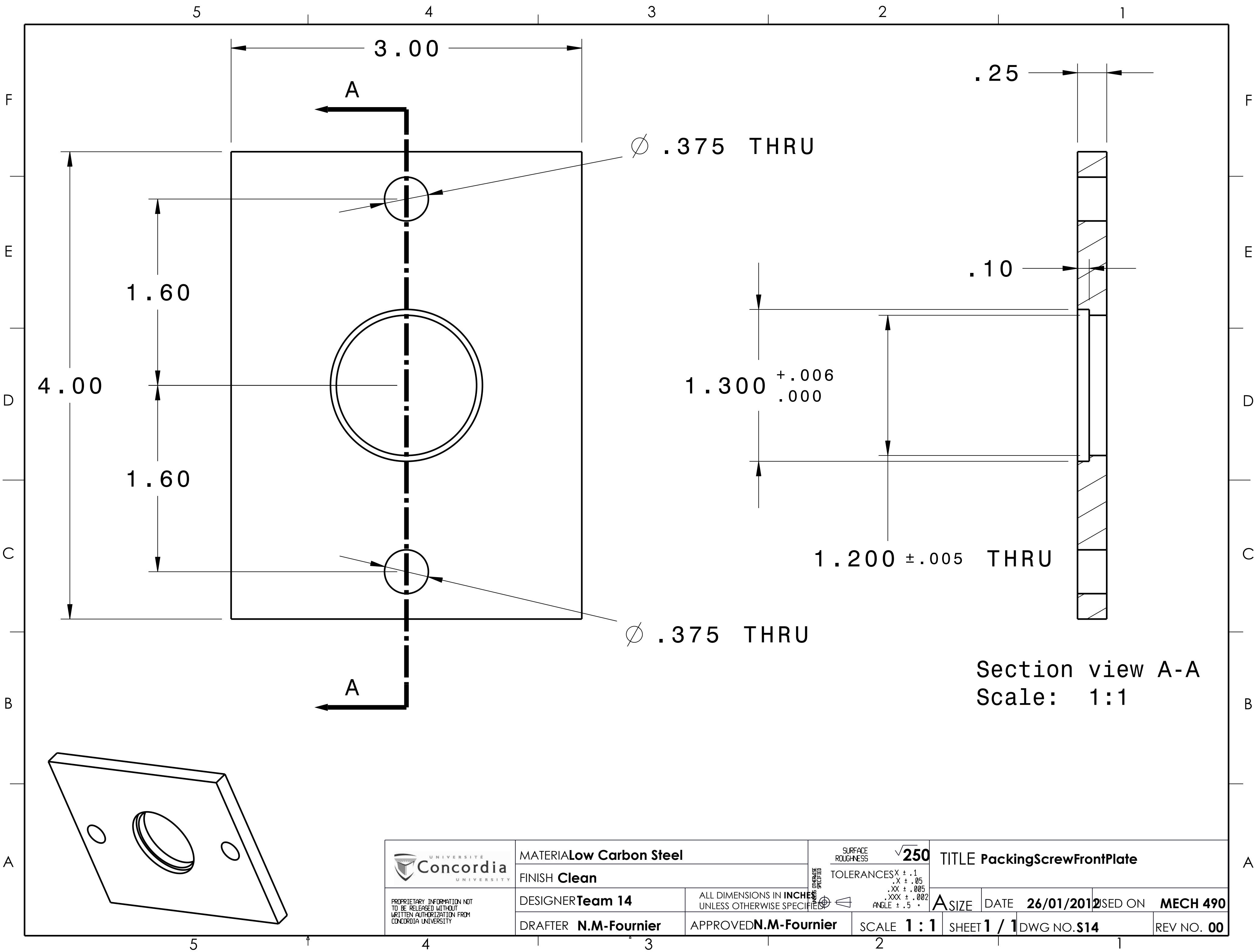
Université Concordia University	MATERIAL Low Carbon Steel	SURFACE ROUGHNESS √250	TITLE PackingScrewFront
	FINISH Clean	TOLERANCES UNLESS OTHERWISE SPECIFIED X ± .1, .X ± .05, .XX ± .005, .XXX ± .002, ANGLE ± .5°	
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	DESIGNER Team 14	ALL DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED	A SIZE — DATE 25/01/2012 — USED ON MECH 490
	DRAFTER N.M-Fournier	APPROVED M.Parent — SCALE 2: 1	SHEET 1 / 1 — DWG NO. S12 — REV NO. 00

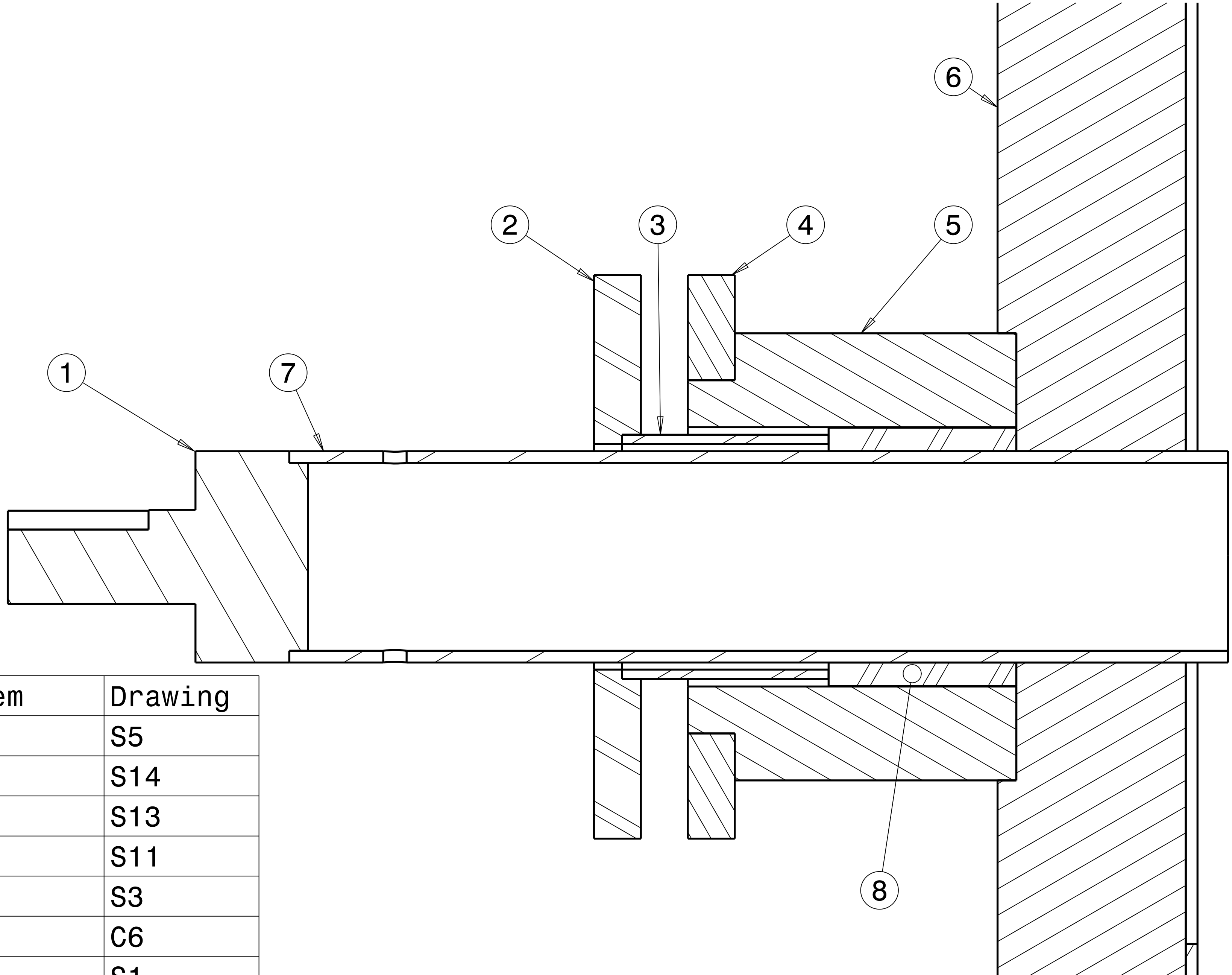




Note: Part is machined from a NPS 1" pipe

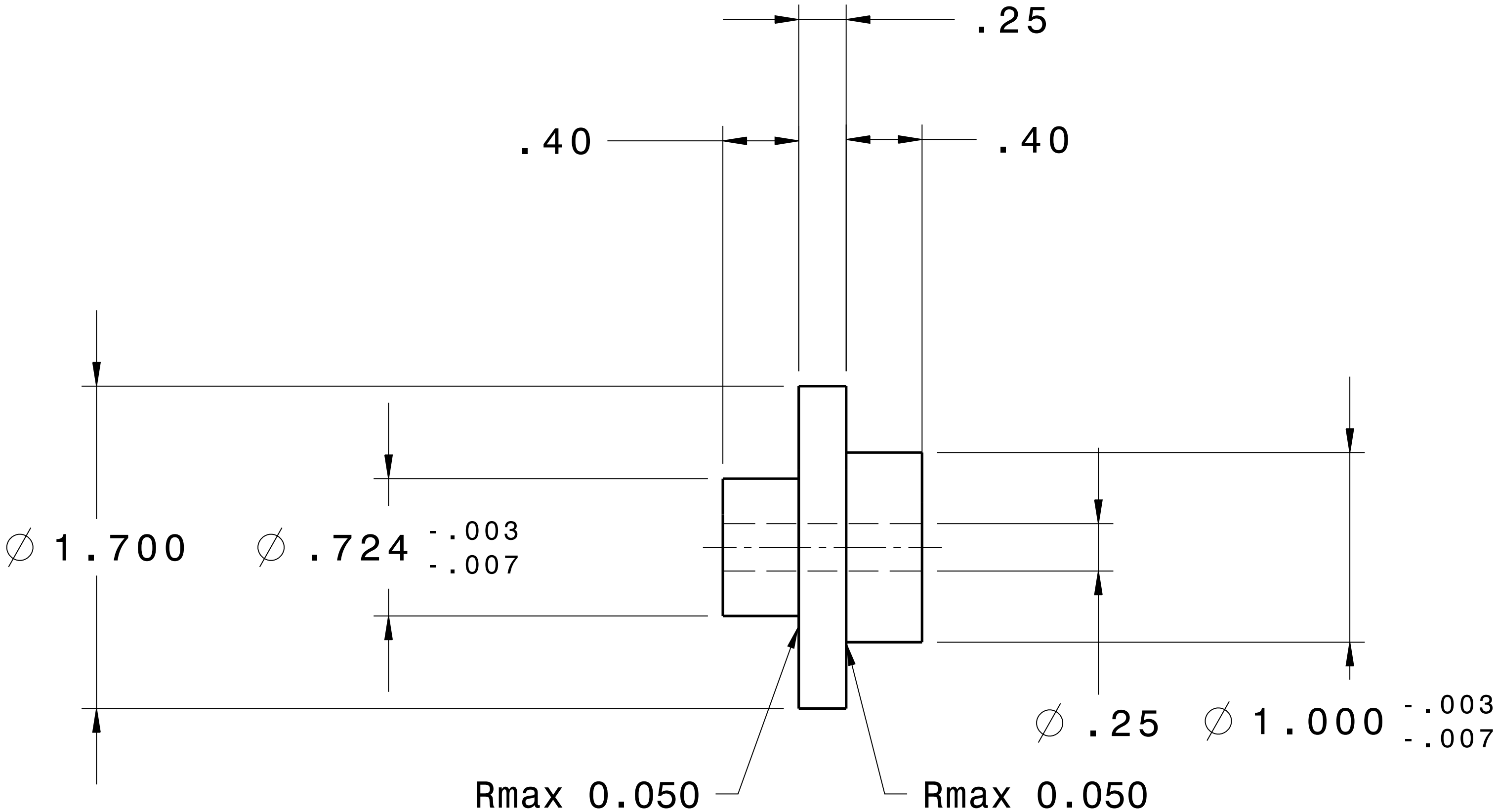
UNIVERSITÉ Concordia UNIVERSITY	MATERIAL Low Carbon Steel		SURFACE ROUGHNESS √250	TITLE PackingScrewMiddle
	FINISH Clean		UNLESS OTHERWISE SPECIFIED TOLERANCES X ± .1, .X ± .05, .XX ± .005, .XXX ± .002, ANGLE ± .5 °	
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	DESIGNER Team 14	ALL DIMENSIONS IN **INCHES** UNLESS OTHERWISE SPECIFIED		A SIZE · DATE 26/01/2012 · USED ON MECH 490
	DRAFTER N.M-Fournier	APPROVED N.M-Fournier	SCALE 1 : 1	SHEET 1 / 1 · DWG NO. S13 · REV NO. 00

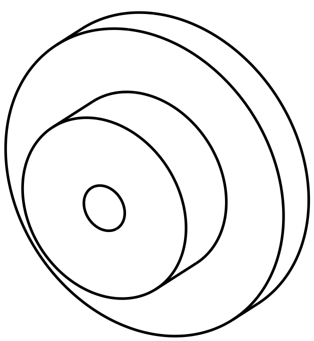

3.00
A
∅ .375 THRU
1.60
4.00
1.60
∅ .375 THRU
A
.25
.10
1.300 +.006 .000
1.200 ±.005 THRU
Section view A-A
Scale: 1:1
UNIVERSITÉ Concordia UNIVERSITY
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY
MATERIAL Low Carbon Steel
FINISH Clean
DESIGNER Team 14
DRAFTER N.M-Fournier
ALL DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED
APPROVED N.M-Fournier
SURFACE ROUGHNESS 250
TOLERANCES X ± .1 .X ± .05 .XX ± .005 .XXX ± .002 ANGLE ± .5°
TITLE PackingScrewFrontPlate
A SIZE
DATE 26/01/2012
USED ON MECH 490
SCALE 1 : 1
SHEET 1 / 1
DWG NO. S14
REV NO. 00



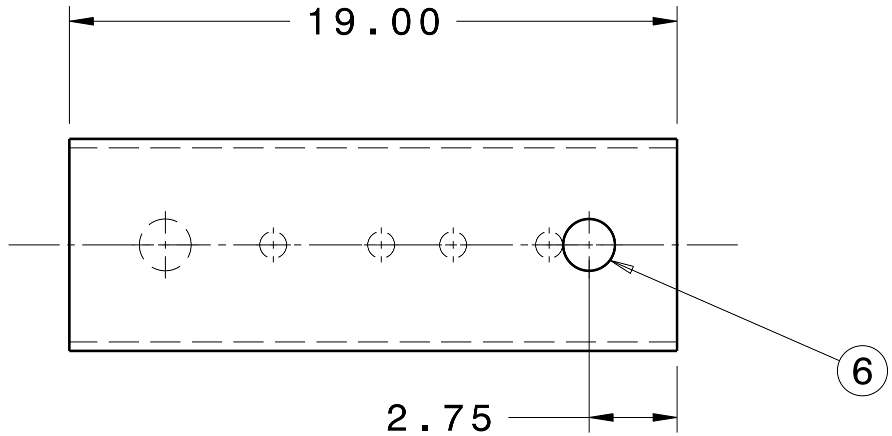
Item	Drawing
1	S5
2	S14
3	S13
4	S11
5	S3
6	C6
7	S1
8	Packing Seal

Université Concordia University	MATERIAL Various	SURFACE ROUGHNESS $\sqrt{250}$ TOLERANCES X ± .1, .X ± .05, .XX ± .005, .XXX ± .002, ANGLE ± .5° UNLESS OTHERWISE SPECIFIED	TITLE **Left End**
	FINISH **Clean**		
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	DESIGNER **Team 14** / ALL DIMENSIONS IN **INCHES** UNLESS OTHERWISE SPECIFIED		A SIZE / DATE **27/01/2012** / USED ON **MECH 490**
	DRAFTER **N.M-Fournier** / APPROVED **M.Parent**	SCALE **13:10**	SHEET **1 / 1** / DWG NO. **S15** / REV NO. **00**



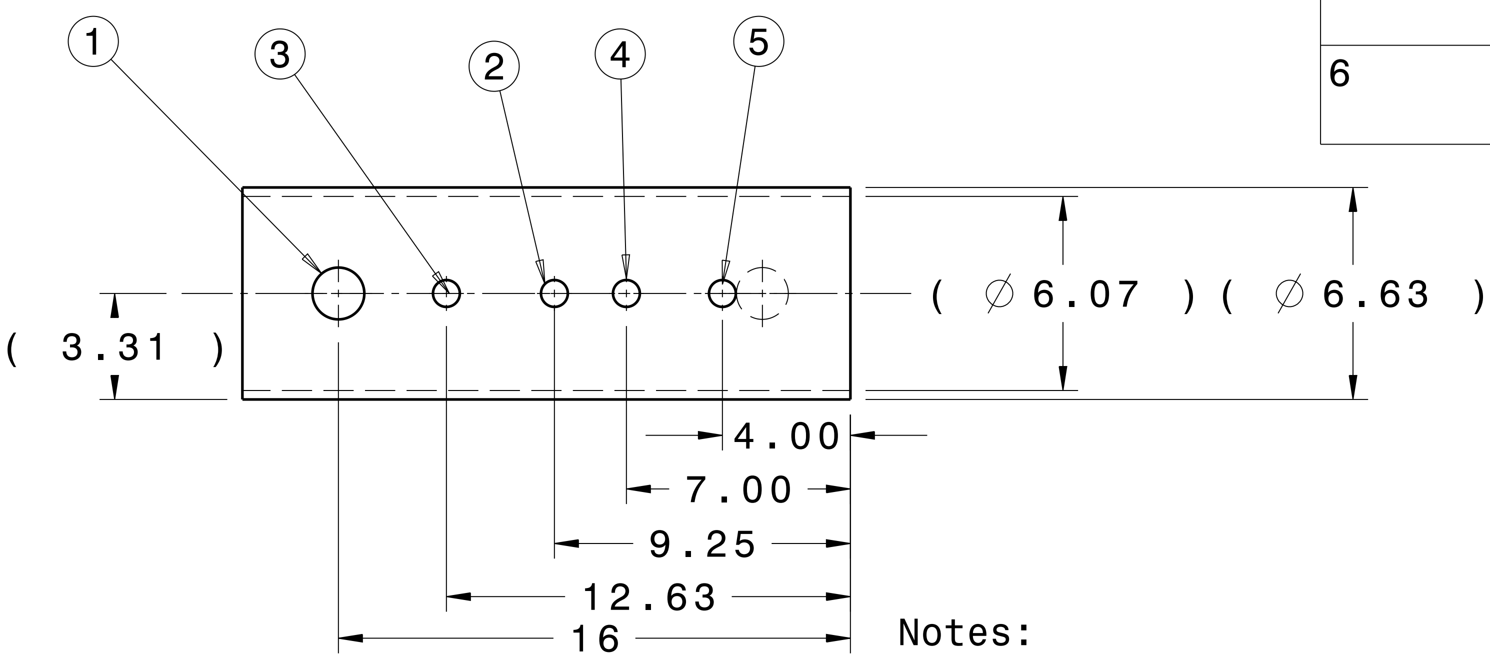


UNIVERSITÉ Concordia UNIVERSITY	MATERIA **Low Carbon Steel**	SURFACE ROUGHNESS √**250**	TITLE **Shaft Link**
	FINISH **Clean**	TOLERANCES UNLESS OTHERWISE SPECIFIED X ± .1, .X ± .05, .XX ± .005, .XXX ± .002, ANGLE ± .5 °	
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	DESIGNER **Team 14**	ALL DIMENSIONS IN **INCHES** UNLESS OTHERWISE SPECIFIED	A SIZE / DATE **31/01/2012** / USED ON **MECH 490**
	DRAFTER **N.M-Fournier**	APPROVED **M.Parent** / SCALE **1 : 1**	SHEET **1 / 1** / DWG NO. **S16** / REV NO. **00**



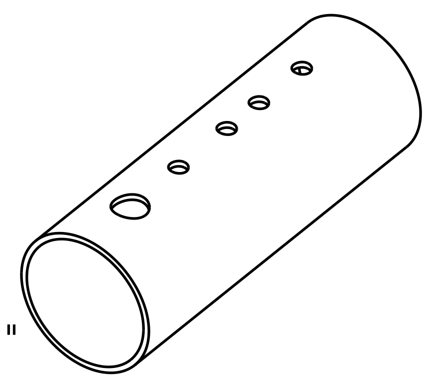
TOP VIEW

Item	Nominal Diameter	Standard Limit
1	∅1.67	+.04 -0
2	∅0.84	+.025 -0
3	∅0.84	+.025 -0
4	∅0.84	+.025 -0
5	∅0.84	+.025 -0
6	∅1.67	+.04 -0



BOTTOM VIEW

Notes:
36" stock, tubular, NPS 6"



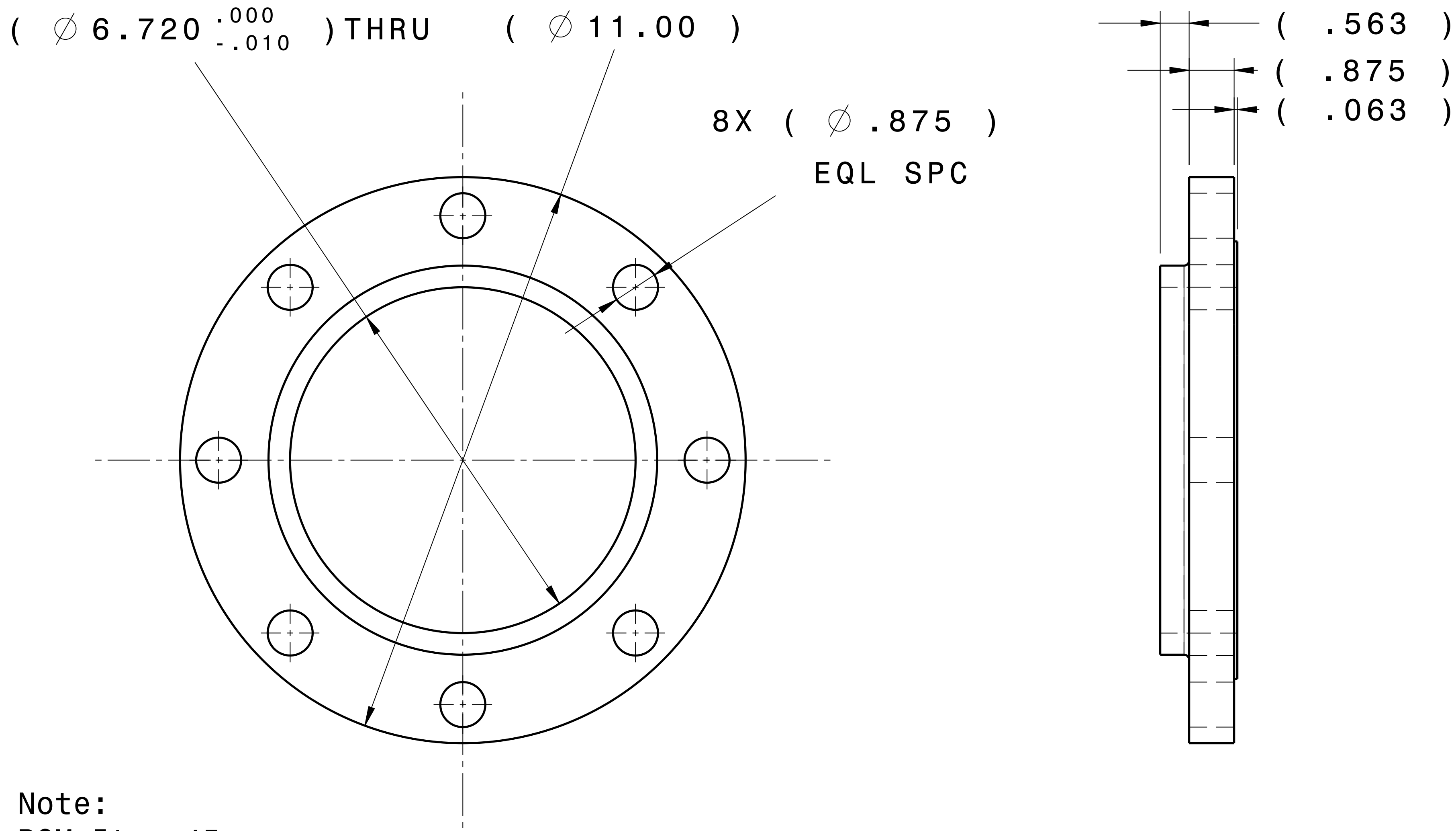
UNIVERSITÉ Concordia UNIVERSITY

PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY

MATERIAL **Low Carbon Steel**
FINISH **Clean**
DESIGNER **Team 14**
DRAFTER **H.Amroun**
ALL DIMENSIONS IN **INCHES** UNLESS OTHERWISE SPECIFIED
APPROVED **M.Parent**

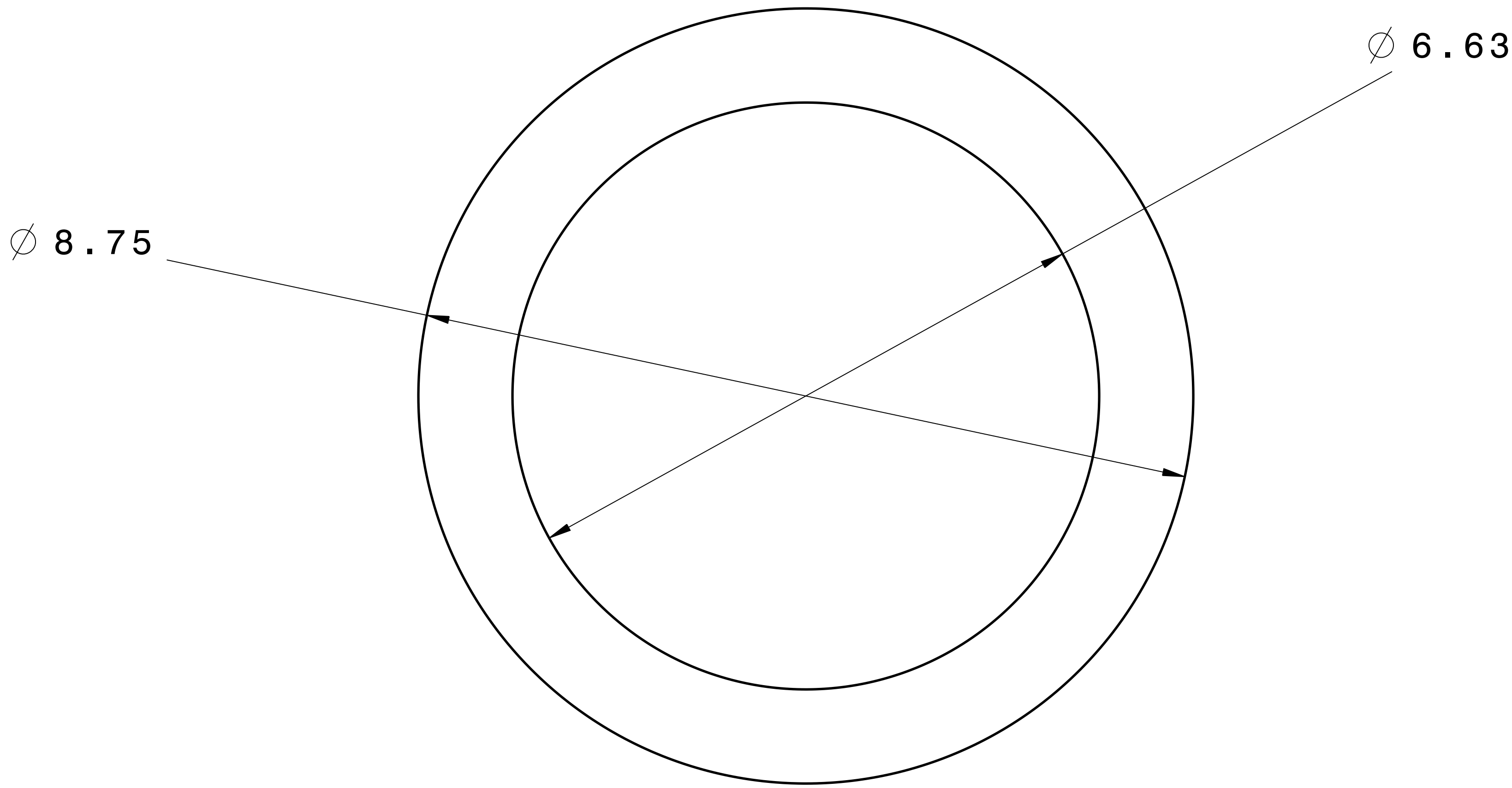
SURFACE ROUGHNESS √250
TOLERANCES UNLESS OTHERWISE SPECIFIED X ± .1, .X ± .05, .XX ± .005, .XXX ± .002, ANGLE ± .5 °

TITLE **Chamber**
A4
DATE **01/12/2012**
USED ON **MECH 490**
SCALE **1 : 6**
SHEET **1 / 1**
DWG NO. **C1**
REV NO. **00**



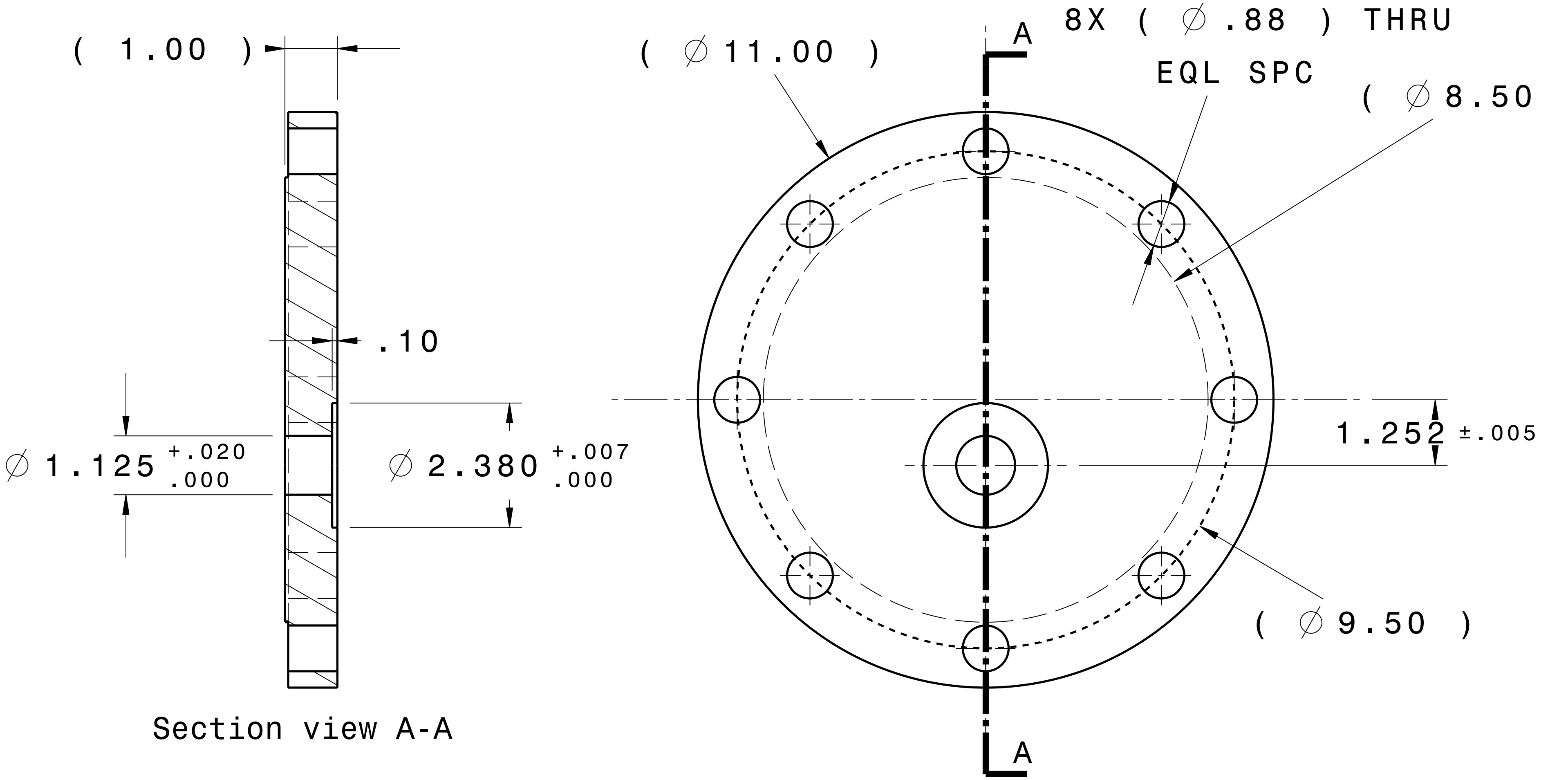
Note:
BOM Item 45

Université Concordia University	MATERIAL Low Carbon Steel Sheet	SURFACE ROUGHNESS √250	TITLE Chamber Flanges	
	FINISH Clean	UNLESS OTHERWISE SPECIFIED TOLERANCES X ± .1, .X ± .05, .XX ± .005, .XXX ± .002, ANGLE ± .5 °		
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	DESIGNER TEAM 14	ALL DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED	A4	DATE 01/12/2012 USED ON MECH 490
	DRAFTER H. AMROUN	APPROVED M. PARENT	SCALE 1 : 2	SHEET 1 / 1 DWG NO. C4 REV NO. 00

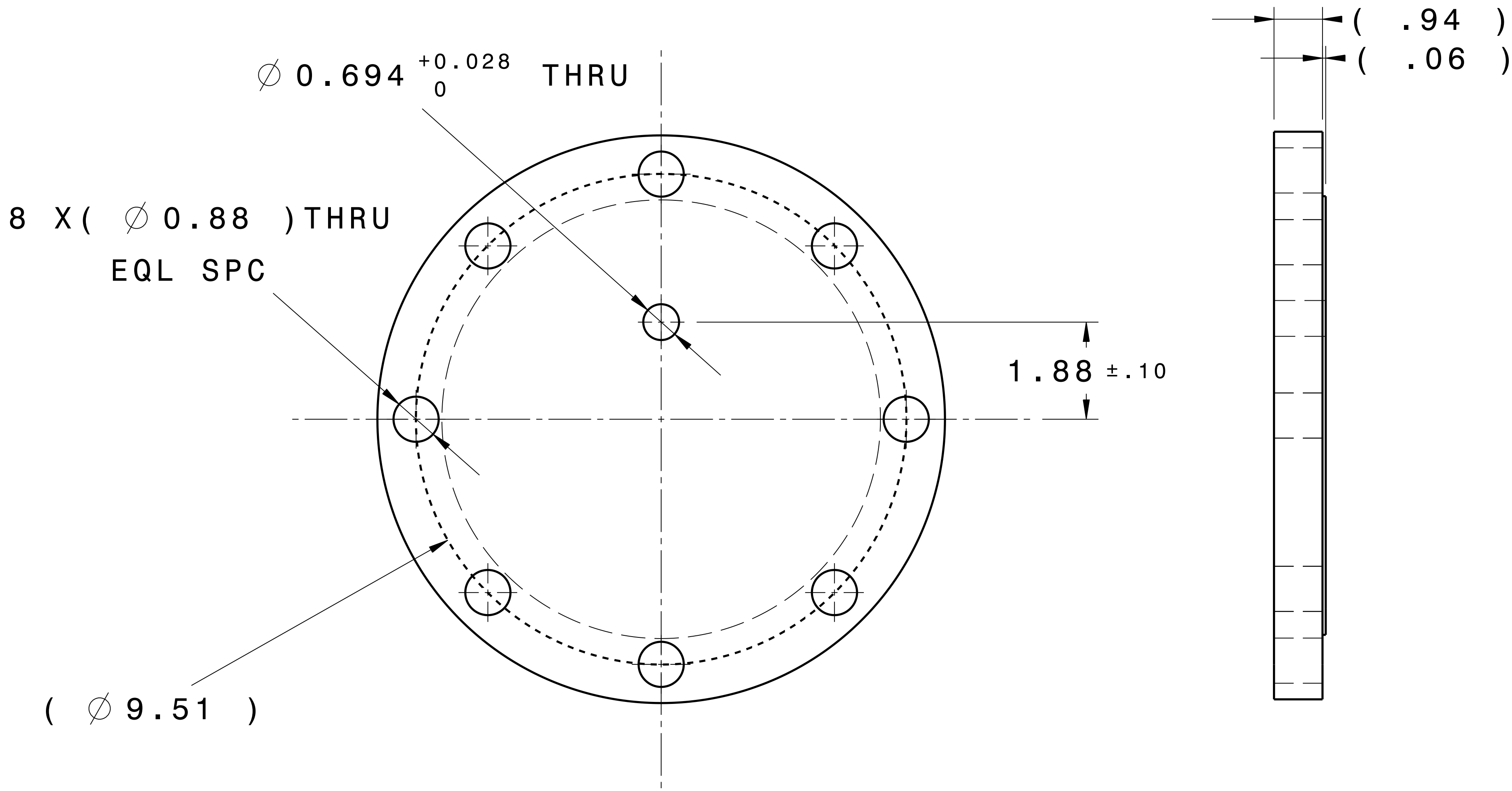


Note:
1/16" thick graphite gasket.

Université Concordia University	MATERIAL **Graphite**	SURFACE ROUGHNESS √**250**	TITLE **Gasket**	
	FINISH **Clean**	TOLERANCES UNLESS OTHERWISE SPECIFIED X ± .1, .X ± .05, .XX ± .005, .XXX ± .002, ANGLE ± .5 °		
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	DESIGNER **TEAM 14**	ALL DIMENSIONS IN **INCHES** UNLESS OTHERWISE SPECIFIED	A SIZE	DATE **1/12/2012** USED ON **MECH 490**
	DRAFTER **H.Amroun**	APPROVED **M.Parent**	SCALE **1 : 2**	SHEET **1 / 1** DWG NO. **C5** REV NO. **00**



Concordia University	MATERIAL Low Carbon Steel Sheet		SURFACE ROUGHNESS √250	Chamber Left End Cap
	FINISH Clean		TOLERANCES (UNLESS OTHERWISE SPECIFIED) .X ± .1, .X ± .05, .XX ± .005, .XXX ± .002, ANGLE ± .5°	
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	DESIGNER Team 14	ALL DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED	A SIZE	DATE 1/12/2012 — USED ON MECH 490
	DRAFTER H.Amroun	APPROVED M. Parent	SCALE: 1/3	SHEET 1/1 — DWG No: C6 — Rev 00

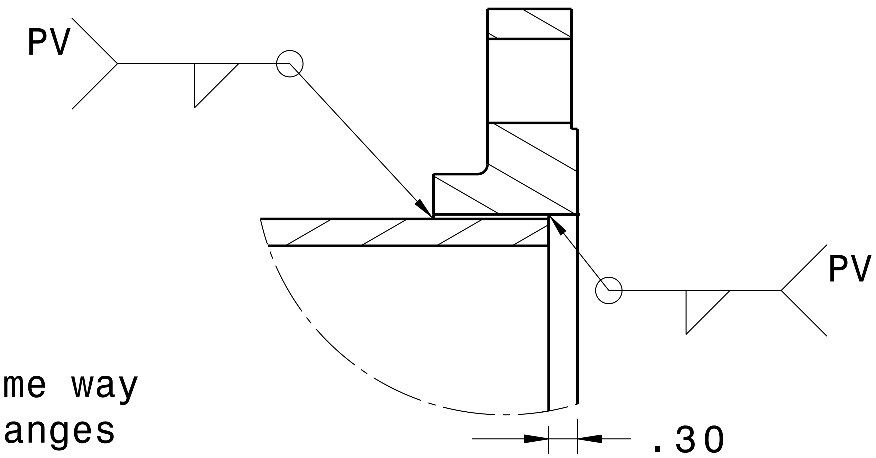


Stock End cap BOM item 44

Université Concordia University	MATERIAL Low Carbon Steel Sheet	SURFACE ROUGHNESS √250
	FINISH Clean	TOLERANCES UNLESS OTHERWISE SPECIFIED: X ± .1, .X ± .05, .XX ± .005, .XXX ± .002, ANGLE ± .5°
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	DESIGNER Team 14	ALL DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED
	DRAFTER N.M-Fournier	APPROVED M.Parent
	SCALE 1 : 2	SHEET 1 / 1

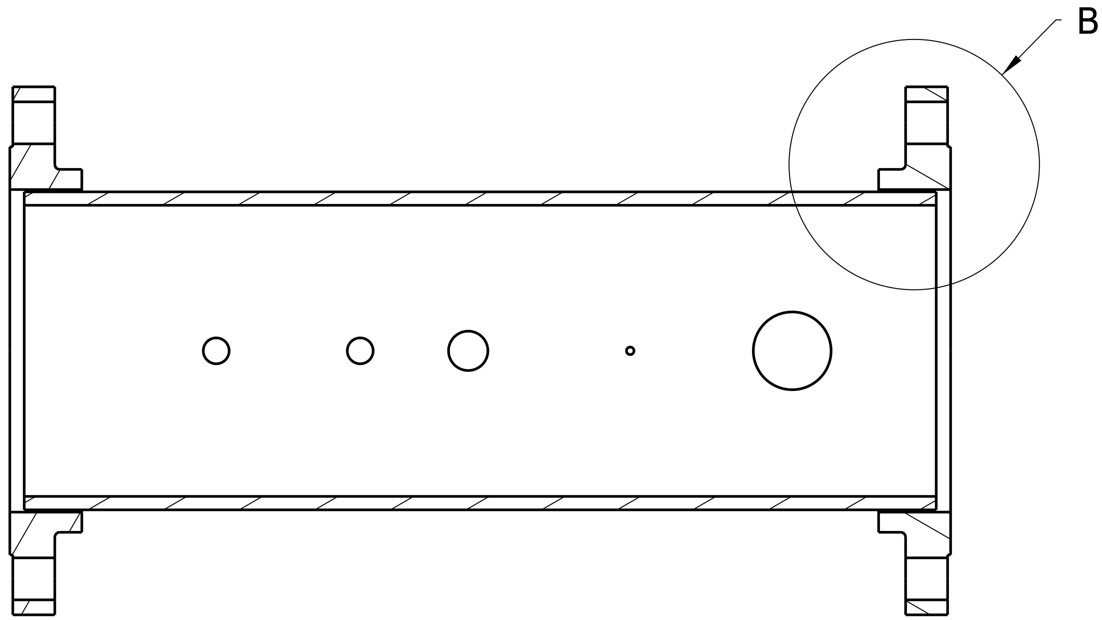
TITLE **Pyrolysis Chamber Right End Cap**

A SIZE | DATE 01/12/2012 | USED ON MECH 490 | DWG NO. C7 | REV NO. 00

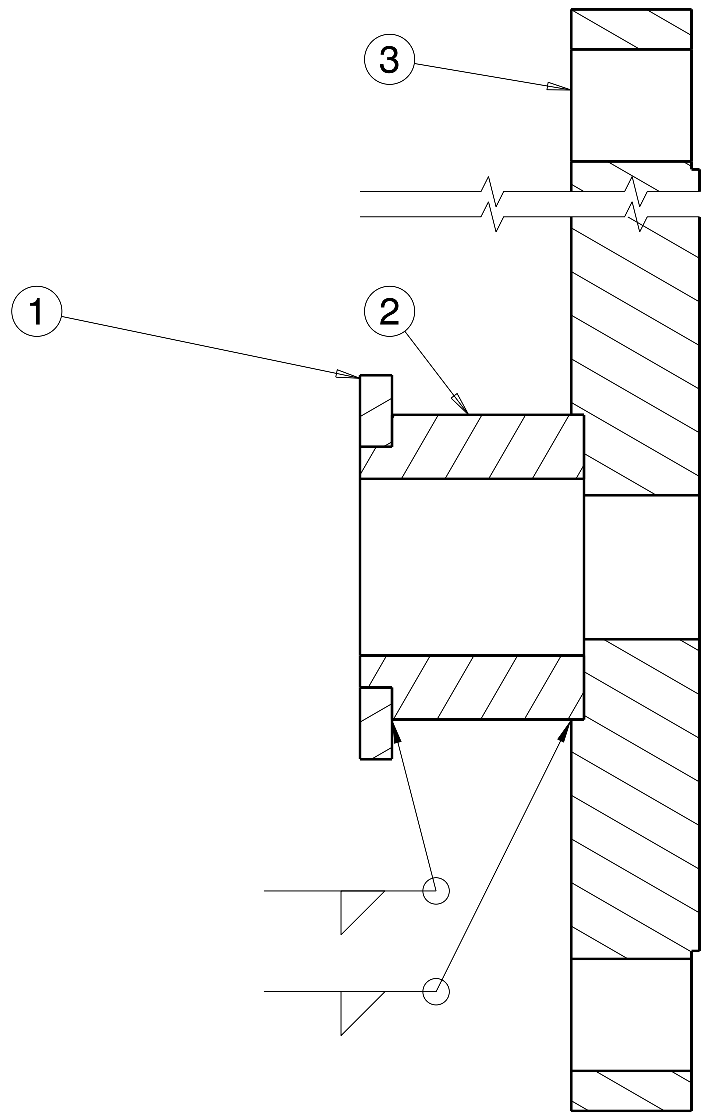


Detail B
Scale: 1:2

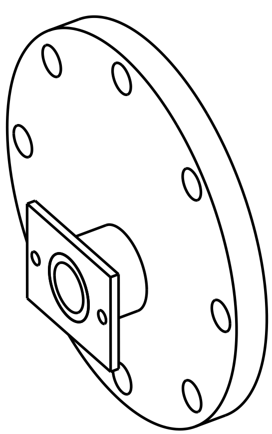
Note:
-Both Slip On Flanges are welded the same way
-Weld should not pass the end of the flanges



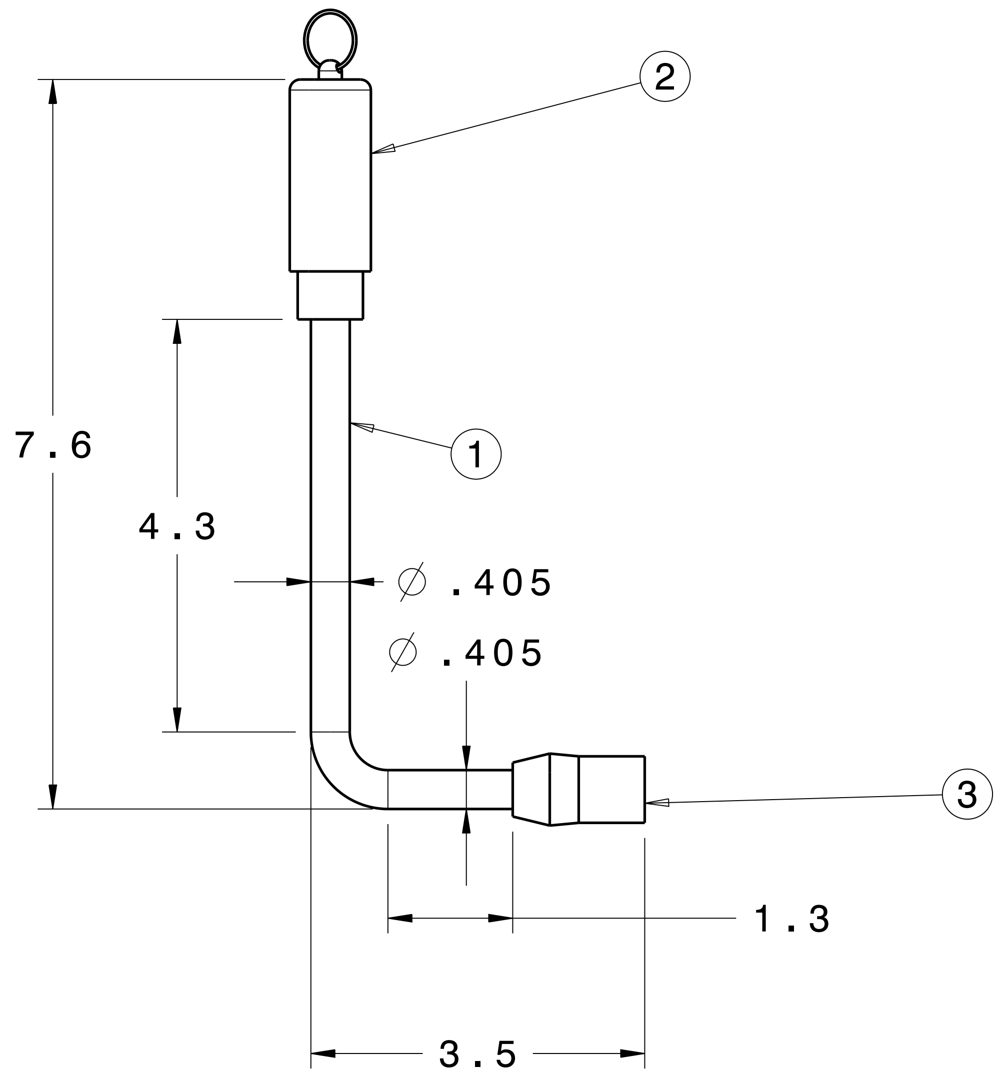
UNIVERSITÉ Concordia UNIVERSITY	MATERIAL Various	SURFACE ROUGHNESS √63	TITLE Cylinder and flange assembly	
	FINISH None	TOLERANCES UNLESS OTHERWISE SPECIFIED X ± .1, .X ± .05, .XX ± .005, .XXX ± .002, ANGLE ± .5°		
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	DESIGNER Team 14	ALL DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED	A SIZE	DATE 12/34/5678	USED ON MECH 490
	DRAFTER H.Amroun	APPROVED N-M.Fournier	SCALE 1 : 4	SHEET 1 / 1	DWG NO. C8	REV NO. 00



Note:
1- S11 - PackingScrewBack
2- S3 - Housing
3- C6 - EndCapLeft

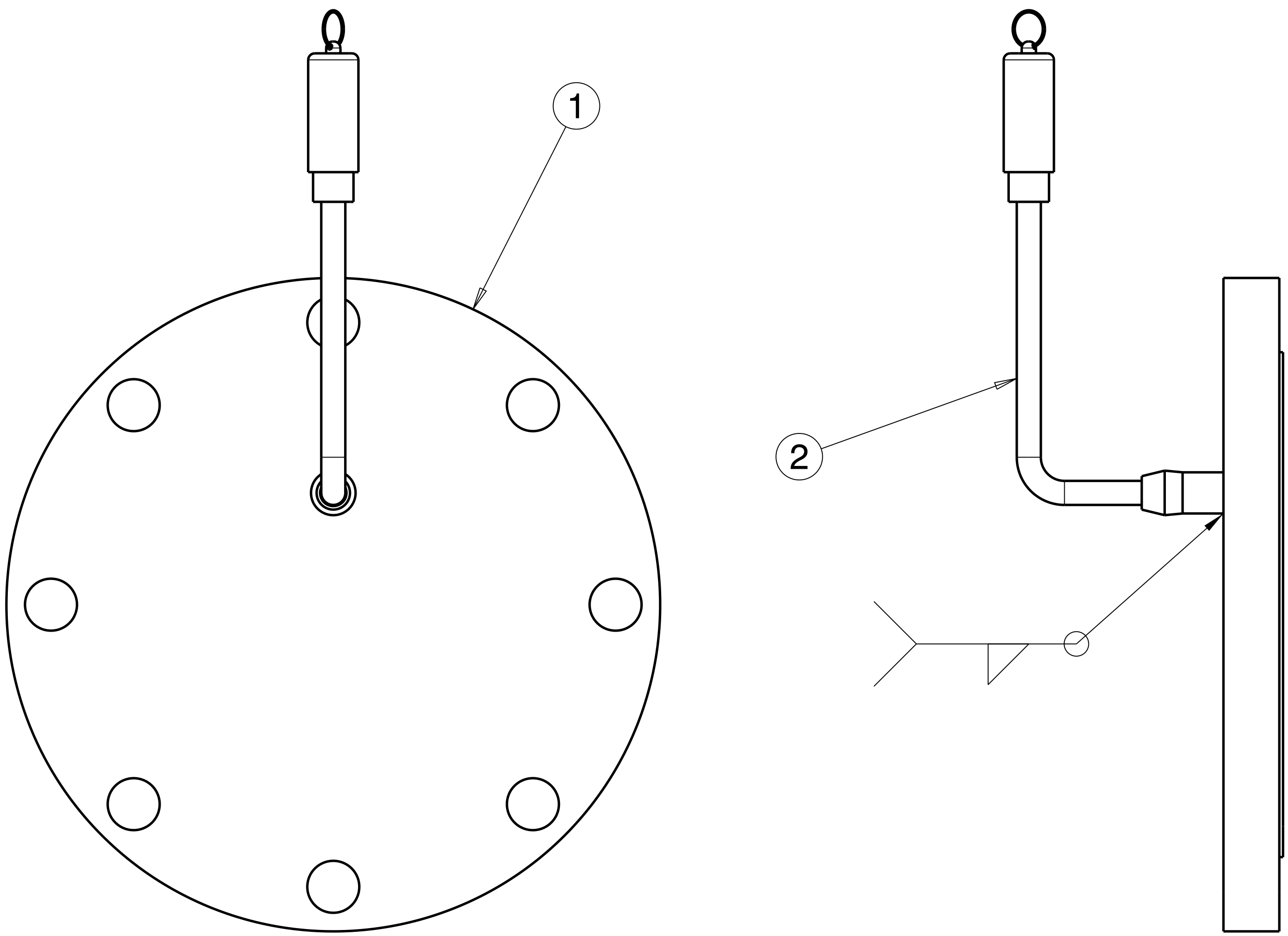


PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	MATERIA **Low Carbon Steel**		SURFACE ROUGHNESS √**250**	TITLE **Cap Packing Assembly**
	FINISH **Clean**		UNLESS OTHERWISE SPECIFIED TOLERANCES X ± .1, .X ± .05, .XX ± .005, .XXX ± .002, ANGLE ± .5 °	
	DESIGNER **Team 14**	ALL DIMENSIONS IN **INCHES** UNLESS OTHERWISE SPECIFIED		A SIZE — DATE **27/01/2012** — USED ON **MECH 490**
	DRAFTER **N.M-Fournier**	APPROVED **M.Parent**	SCALE **2:3**	SHEET **1 / 1** — DWG NO. **C9** — REV NO. **00**



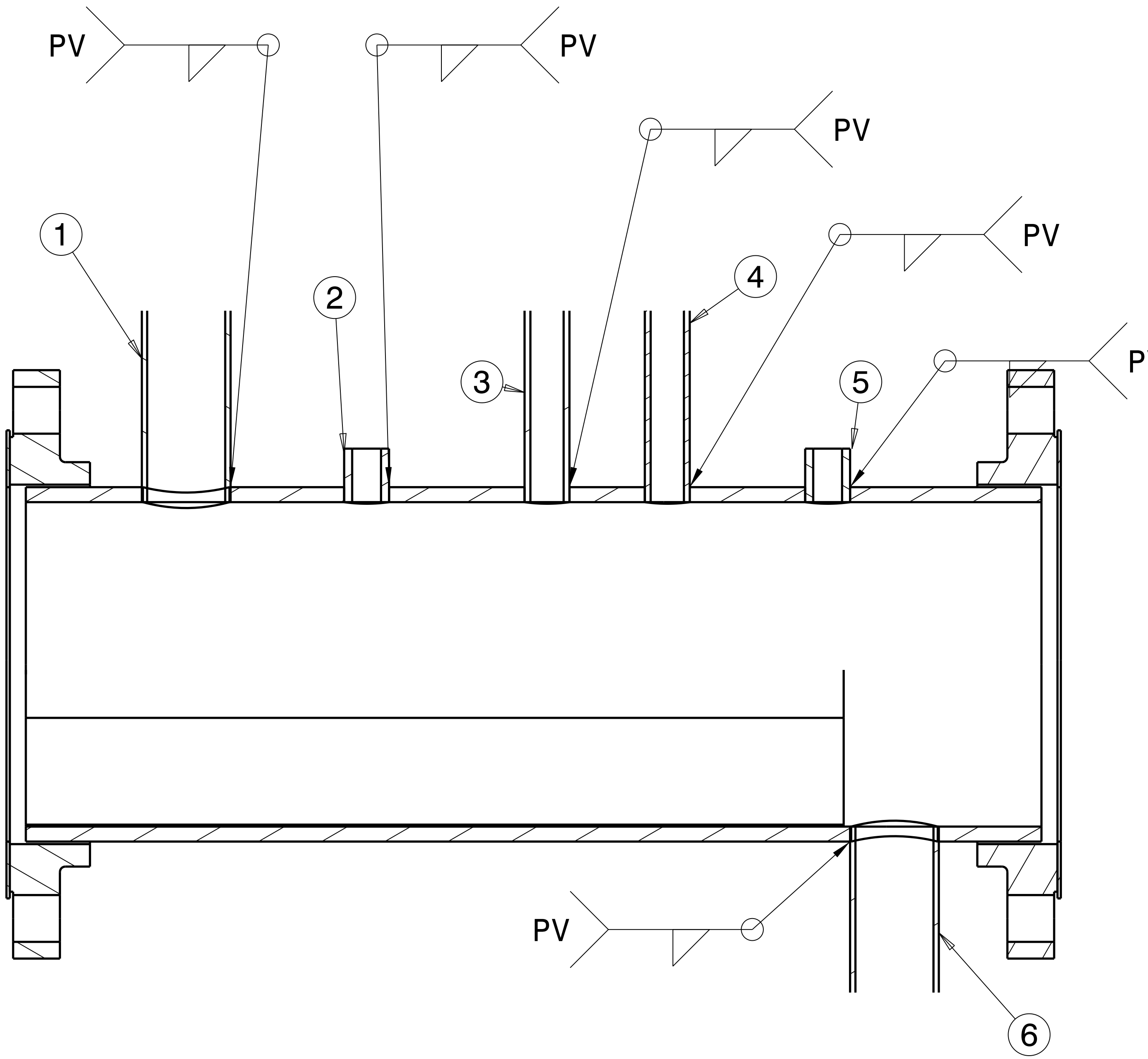
1- NPS 1/8 Steel Pipe
2- Emergency Release Valve
3- Bung

Concordia University	MATERIA **Welded Steel**	SURFACE ROUGHNESS √**250**	TITLE **Emergency Release Valve**
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	FINISH **Clean**	TOLERANCES UNLESS OTHERWISE SPECIFIED X ± .1, .X ± .05, .XX ± .005, .XXX ± .002, ANGLE ± .5 °	A SIZE
	DESIGNER **Team 14**	ALL DIMENSIONS IN **INCHES** UNLESS OTHERWISE SPECIFIED	DATE **16/01/2012** USED ON **MECH 490**
	DRAFTER **N.-Fournier**	APPROVED **M.Parent** SCALE **1 : 2**	SHEET **1 / 1** DWG NO. **C10** REV NO. **00**



Note:
1- Refer to Drawing C7
2- Refer to Drawing C10

Université Concordia University	MATERIAL Welded Steel		SURFACE ROUGHNESS √250	TITLE Right End Cap with Emergency Valve
	FINISH Clean		TOLERANCES UNLESS OTHERWISE SPECIFIED X ± .1, .X ± .05, .XX ± .005, .XXX ± .002, ANGLE ± .5 °	
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	DESIGNER Team 14	ALL DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED	A SIZE	DATE 16/01/2012 USED ON MECH 490
	DRAFTER N.-Fournier	APPROVED M.Parent	SCALE 1 : 3	SHEET 1 / 1 DWG NO. C11 REV NO. 00



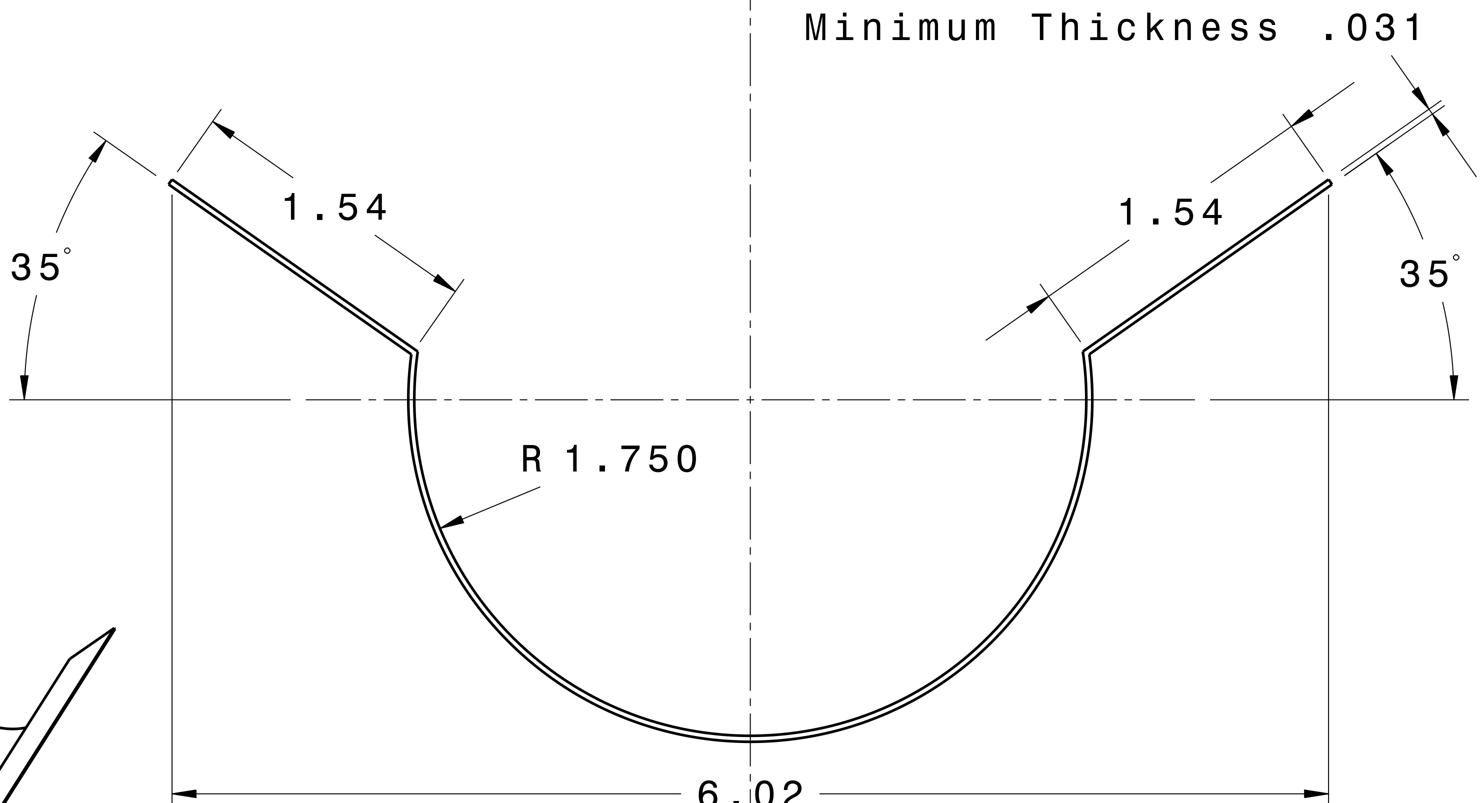
Concordia University	MATERIAL Low Carbon Steel	SURFACE ROUGHNESS √250	TITLE Chamber with Piping
	FINISH BLACK ANODIZE	TOLERANCES X ± .1, .X ± .05, .XX ± .005, .XXX ± .002, ANGLE ± .5 ° (UNLESS OTHERWISE SPECIFIED)	
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	DESIGNER Team 14 — ALL DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED		A SIZE — DATE 23/02/2012 — USED ON Mech 490
	DRAFTER N.M-Fournier — APPROVED W.Amroun	SCALE 1 : 3	SHEET 1 / 1 — DWG NO. C12 — REV NO. 00

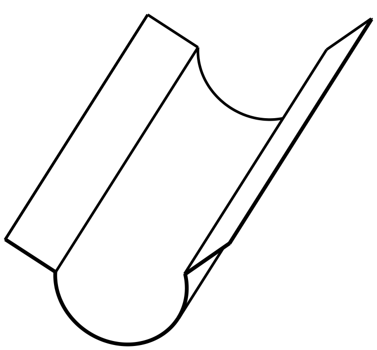
Note:

Stock Sheet cut to 9.13" wide x 15.3" long

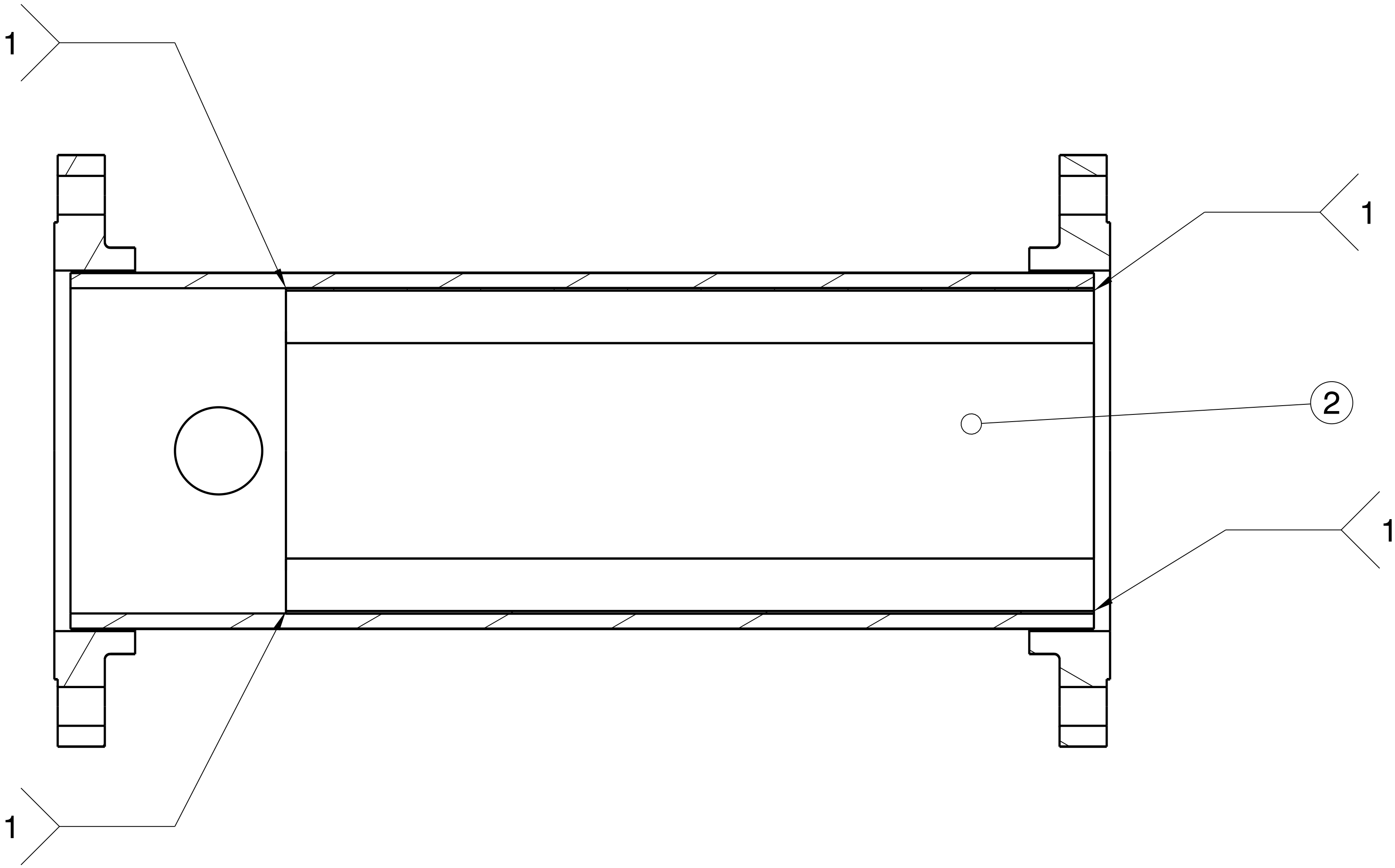
To be bent then rolled along the 9.13" edge

The only critical dimension is the R 1.75 as the auger must be able to rotate freeling inside.
The other dimensions may be approximated as such that the final track assembly fits inside the main chamber (C1) and the auger can rotate freely





Université Concordia University	MATERIA Low carbon steel		SURFACE ROUGHNESS √250	TITLE Rolled Track
	FINISH none		TOLERANCES UNLESS OTHERWISE SPECIFIED X ± .1, .X ± .05, .XX ± .005, .XXX ± .002, ANGLE ± .5 °	
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	DESIGNER Team 14	ALL DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED		A SIZE · DATE 1/27/2012 · USED ON MECH 490
	DRAFTER H.Amroun	APPROVED M.Parent	SCALE 1 : 1	SHEET 1 / 1 · DWG NO. C13 · REV NO. 00



Note:
1- Welds are only to fix the track in place
2- C13 Track Assembly

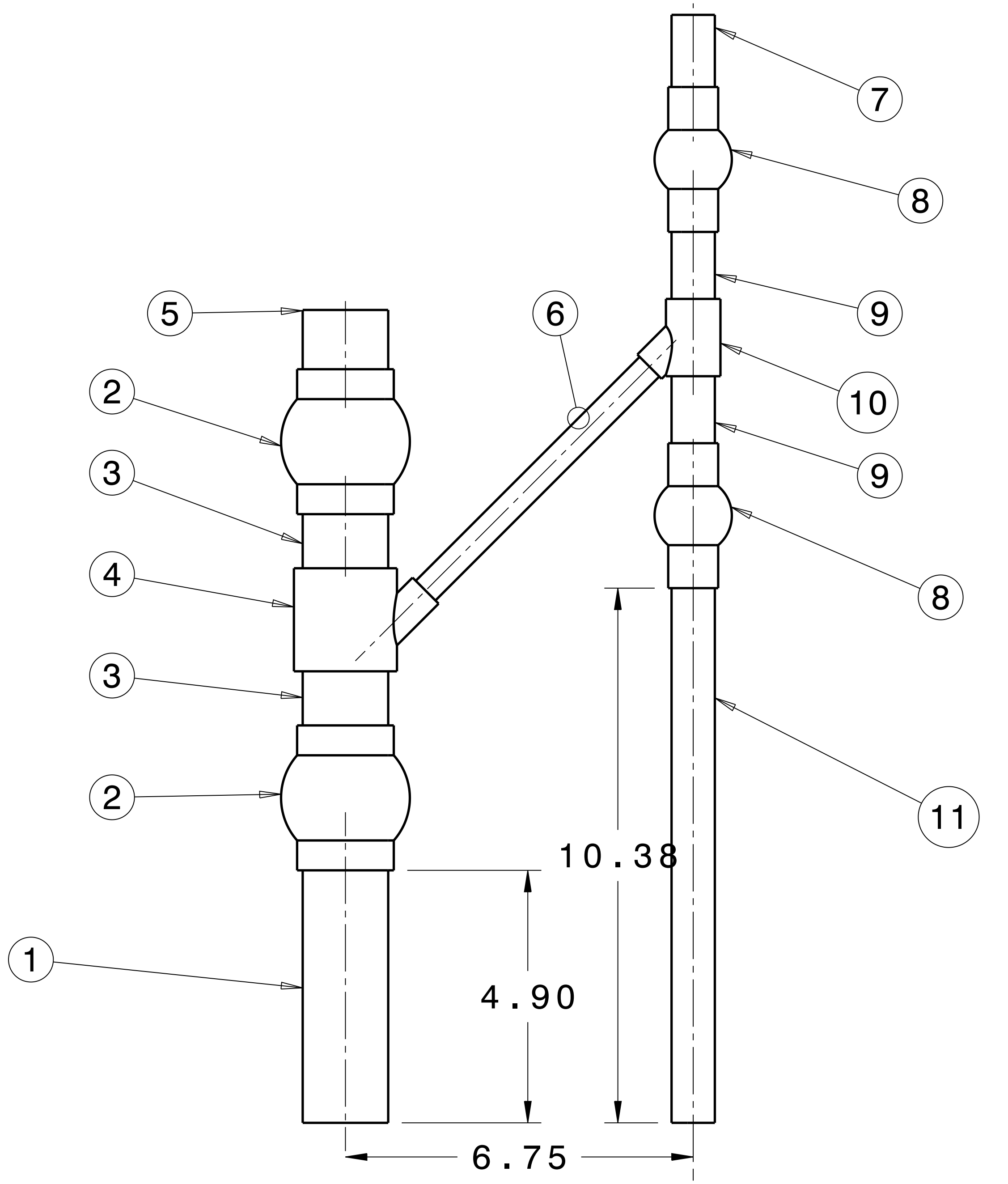
UNIVERSITÉ Concordia UNIVERSITY	MATERIAL Low Carbon Steel	SURFACE ROUGHNESS √250	TITLE Top Section of Chamber Weld
	FINISH Clean	UNLESS OTHERWISE SPECIFIED TOLERANCES .X ± .1 .X ± .05 .XX ± .005 .XXX ± .002 ANGLE ± .5 °	
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	DESIGNER Team 14 / ALL DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED		A SIZE / DATE 27/01/2012 / USED ON MECH 490
	DRAFTER N.M-Fournier / APPROVED H.Amroun	SCALE 1 : 3	SHEET 1 / 1 / DWG NO. C14 / REV NO. 00

Item	BOM #
1	8
2	3
3	12,11
4	1
5	8
6	7
7	9
8	4
9	10
10	2
11	9

Note:
1- All pipe connections are to be threaded.

2- The intake system is to be welded to the chamber as in drawing C12

3- Only the distance between the two vertical columns are critical, the other dimensions are there only as a guildline



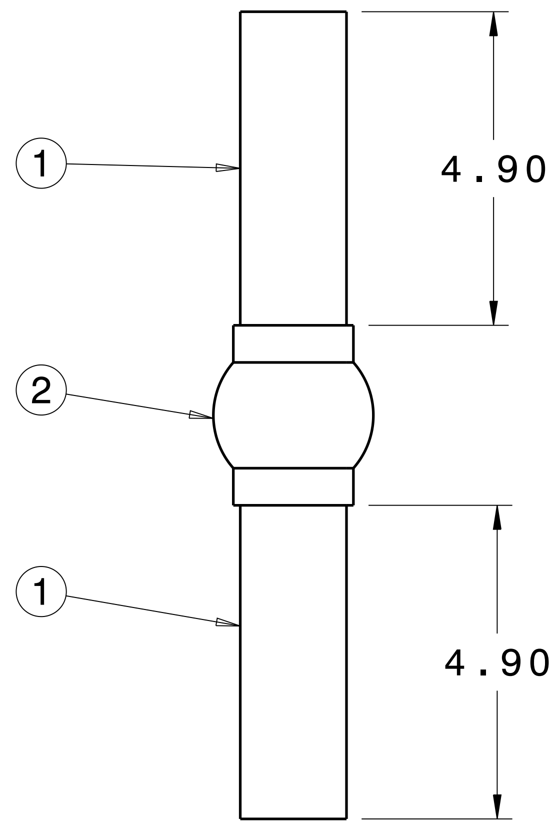
Concordia University	MATERIAL Low Carbon Steel Pipe	SURFACE ROUGHNESS √250	TITLE Intake
	FINISH Clean	TOLERANCES X ± .1, .X ± .05, .XX ± .005, .XXX ± .002, ANGLE ± .5°	
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	DESIGNER Team 14	ALL DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED	A SIZE; DATE 27/01/2012; USED ON MECH 490
	DRAFTER N.M-Fournier	APPROVED M.Parent; SCALE 1 : 3	SHEET 1 / 1; DWG NO. P1; REV NO. 00

Item	BOM
1	15
2	14

Note:

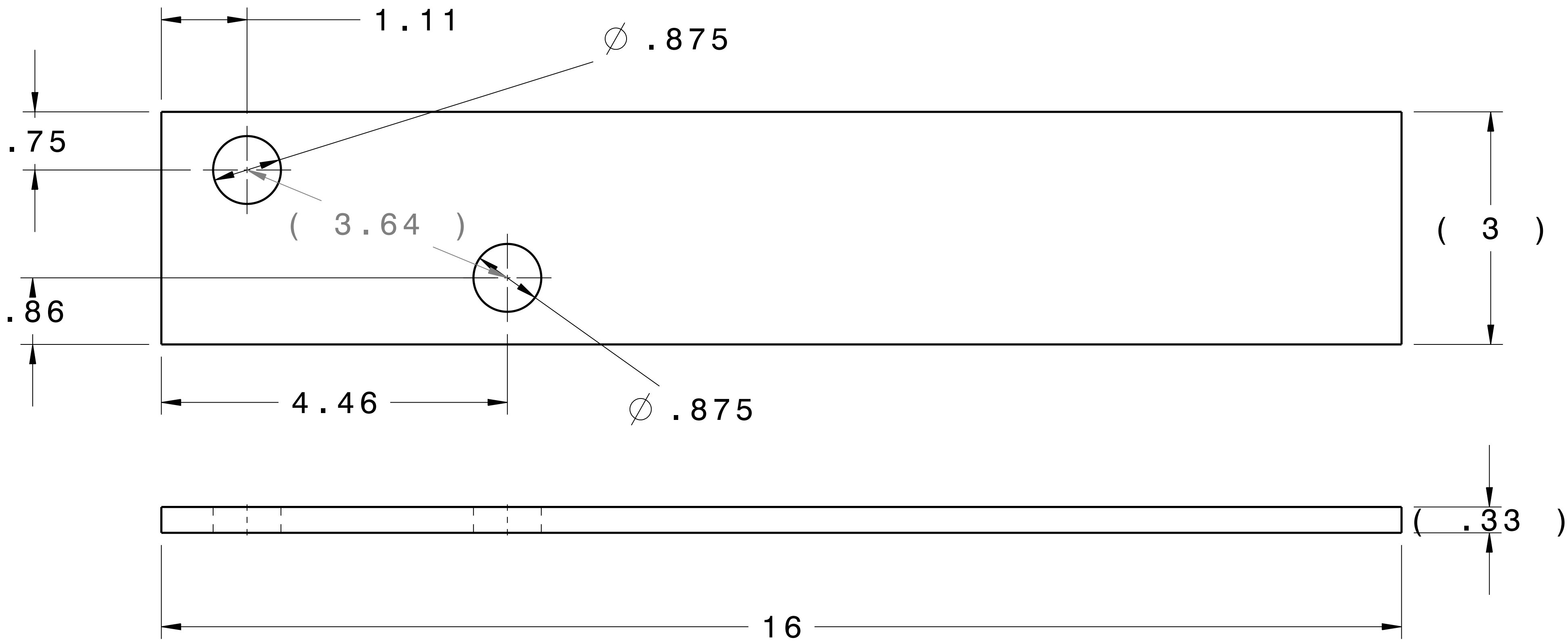
1- Dimension are meant to be a guildline only

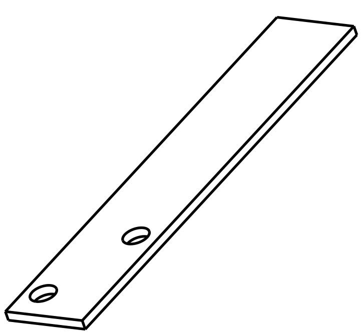
2- The extraction system is be welded to the chamber as in C12



Université Concordia University	MATERIAL Low Carbon Steel Pipe	SURFACE ROUGHNESS √250	TITLE Extraction
	FINISH Clean	TOLERANCES X ± .1, .X ± .05, .XX ± .005, .XXX ± .002, ANGLE ± .5°	
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	DESIGNER Team 14	ALL DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED	A SIZE — DATE 27/01/2012 — USED ON MECH 490
	DRAFTER N.M-Fournier	APPROVED M.Parent — SCALE 1 : 3	SHEET 1 / 1 — DWG NO. P2 — REV NO. 00

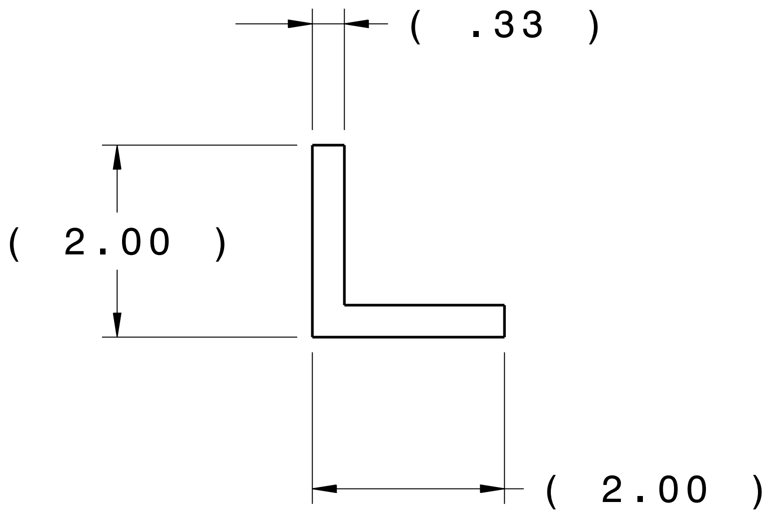
Stock width is as found in EDML B
Part is needed 4 times

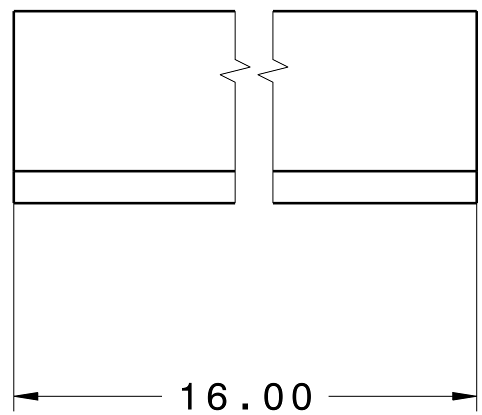


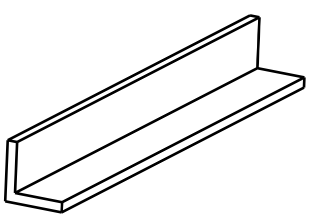


Université Concordia University	MATERIAL 1/4 x 3" Billet	SURFACE ROUGHNESS √250	TITLE Billet Leg	
	FINISH NATURAL	UNLESS OTHERWISE SPECIFIED TOLERANCES X ± .1, .X ± .05, .XX ± .005, .XXX ± .002, ANGLE ± .5 °		
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	DESIGNER TEAM 14	ALL DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED	A4	DATE 20/02/2012	USED ON MECH 490
	DRAFTER M.PARENT	APPROVED N.MATSUSHITA	SCALE 1 : 2	SHEET 1 / 1	DWG NO. ST 1	REV NO. 00

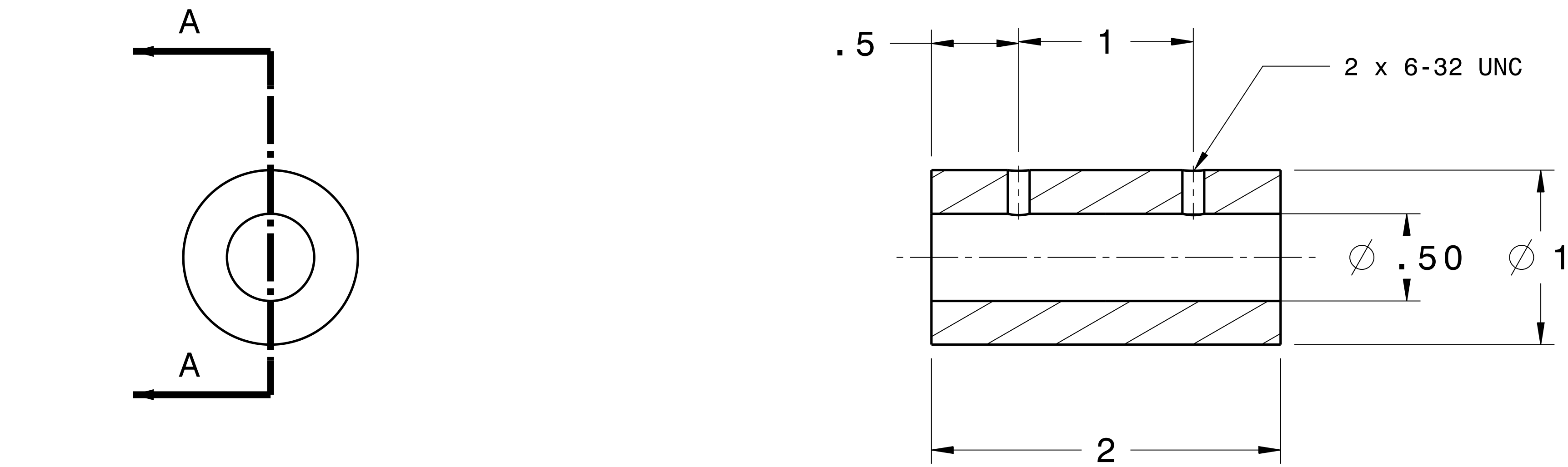
Part is needed 2 times

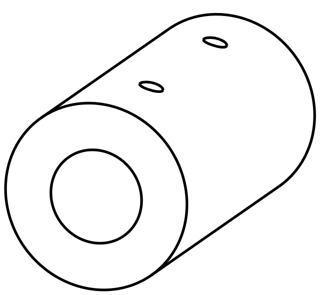




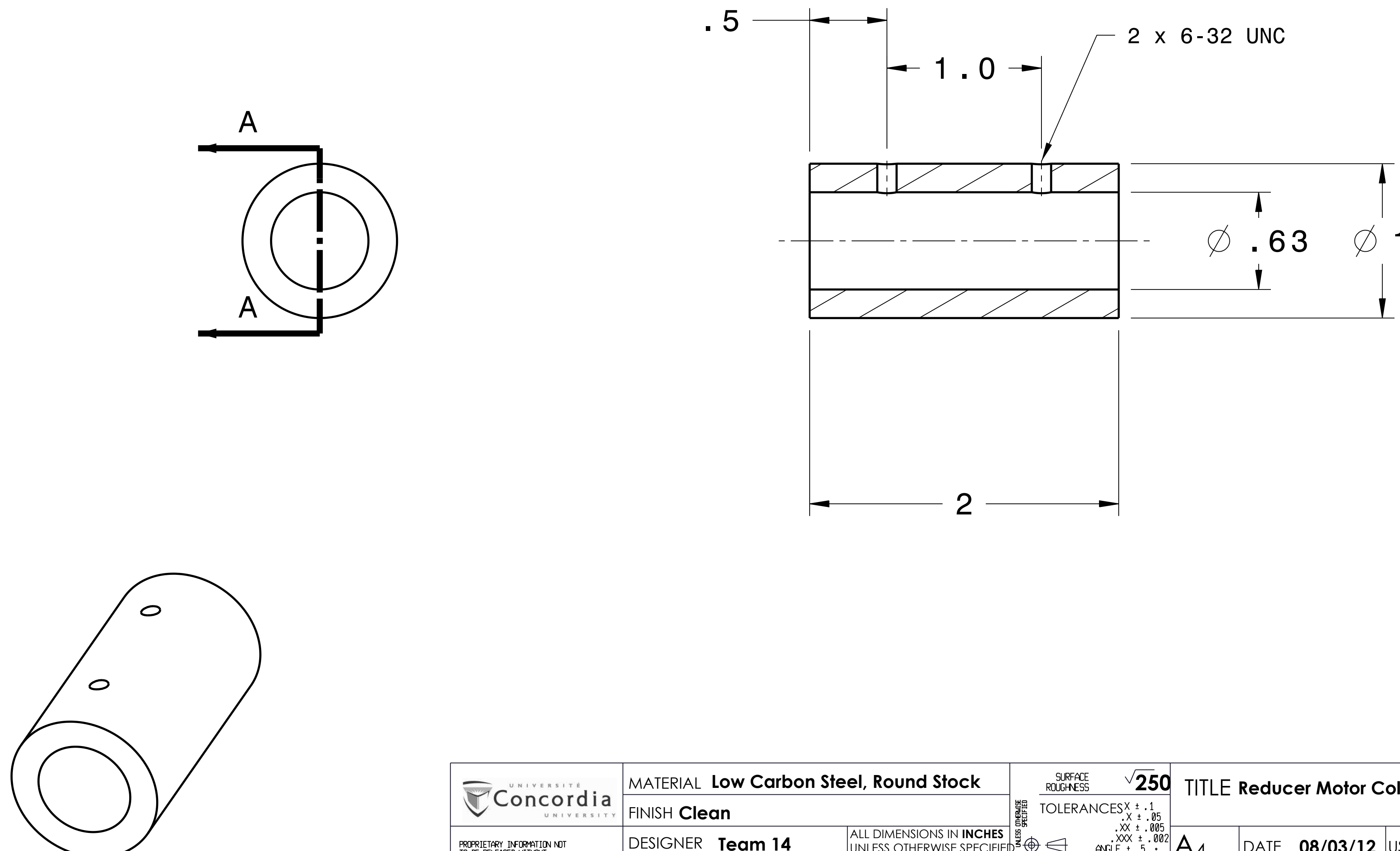


Université Concordia University	MATERIAL 2" x 2" angle	SURFACE ROUGHNESS √250	TITLE **Stand Base**
	FINISH **NATURAL**	UNLESS OTHERWISE SPECIFIED TOLERANCES X ± .1, .X ± .05, .XX ± .005, .XXX ± .002, ANGLE ± .5 °	
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	DESIGNER **TEAM 14** — ALL DIMENSIONS IN **INCHES** UNLESS OTHERWISE SPECIFIED	A4	DATE **20/02/2012** USED ON **MECH 490**
	DRAFTER **M.PARENT** — APPROVED **N.MATSUSHITA**	SCALE **1 : 2**	SHEET **1 / 1** DWG NO. **ST2** REV NO. **00**





UNIVERSITÉ Concordia UNIVERSITY	MATERIAL Low Carbon Steel, Round Stock		SURFACE ROUGHNESS √250	TITLE Motor Reducer Collar
	FINISH Clean		UNLESS OTHERWISE SPECIFIED TOLERANCES .X ± .1 .X ± .05 .XX ± .005 .XXX ± .002 ANGLE ± .5 °	
PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY	DESIGNER Team 14	ALL DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED		A4 DATE 07/03/12 USED ON Mech 490
	DRAFTER N.M-Fournier	APPROVED M.Parent	SCALE 1 : 1	SHEET 1 / 1 DWG NO. T3 REV NO. 00



Université Concordia University

PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY

MATERIAL **Low Carbon Steel, Round Stock**

FINISH **Clean**

DESIGNER **Team 14**

DRAFTER **N.M-Fournier**

ALL DIMENSIONS IN **INCHES** UNLESS OTHERWISE SPECIFIED

APPROVED **M.Parent**

SURFACE ROUGHNESS √**250**

TOLERANCES UNLESS OTHERWISE SPECIFIED X ± .1, .X ± .05, .XX ± .005, .XXX ± .002, ANGLE ± .5 °

SCALE **1 : 1**

TITLE **Reducer Motor Collar**

A4

DATE **08/03/12**

USED ON **Mech 490**

SHEET **1 / 1**

DWG NO. **T4**

REV NO. **00**