Super Critical Carbon Dioxide Metal Working Fluid Delivery System

Steve E. Hecker, Daniel R. Leader,
Daniel S. Merz, and David P. Powers

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Section Instructor: Steve Skerlos
Department of Mechanical Engineering
University of Michigan
Ann Arbor, MI 48109-2125

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EXECUTIVE SUMMARY

Metal working fluids (MWFs) are used to provide cooling and lubrication for metal machining processes. Industry uses aqueous metal working fluids composed of oil, water, surfactants, and additives. This form of cutting fluid is extremely expensive, harmful to the environment, and hazardous to workers.

A system using super critical CO_2 (*$scCO_2$*) and soybean oil was developed and works better than conventional MWFs for many machining processes. Our task was to enhance the current $scCO_2$ system by increasing the flow rate of the cutting fluid, designing a subsystem to deliver continuous oil flow to the pressure vessel, designing an oil refill sensor to alert the user when the pressure vessel is low, and designing a method to vary the concentration of oil being delivered to the workpiece.

We conducted research to determine products that would fulfill our design specifications. We purchased the P-350 pump from Thar Technologies increasing the flow rate by a factor of 7. We recommend using a HPLC pump to deliver continuous oil flow into the pressure vessel. However, this was not incorporated into our final design. Two thermocouples were used to detect the difference in temperature gradients for the oil and $scCO_2$. The differences in heat capacities for the oil and $scCO_2$ will allow the used to detect when the oil level is low. Lastly, we added multiple inlets for CO_2 that increased agitation of the $scCO_2$ and oil mixture thereby increasing the concentration of oil dissolved in $scCO_2$.

A fabrication plan was created for a pressure vessel mount and clamp. A stainless steel mount was machined to support the weight of the pressure vessel and an aluminum clamp was machined to resist the torque required to open the vessel. The assembly of the pump, cooler, vessel, tubing, valves, and fittings can be found on pg. 26.

While our design satisfies our specifications, some aspects of our system could be enhanced. It was determined that a wide and short vessel allows for better mixing of the $scCO_2$ and oil. Also, we could have machined the cart to the exact size necessary to make it easier to maneuver.

All major components of the system have been assembled. However, a few small components must still be ordered as seen in Table 3 on pg 33. Once this is completed, taping and turning tests should be conducted and compared to data from the previous system. Next, complete an analysis of the temperature gradients and create an algorithm for LabView. Then LabView can be used to automatically alert the user to refill the oil. Further testing can then be done to examine if this system could be used as a level sensor. In addition, experimentation should be done to determine the amount of time necessary for the system to equilibrate. If the time required to equilibrate is long, testing with an HPLC pump to provide continuous oil flow should be completed. Finally, conduct tests to compare use of one and two inlets of CO_2 and its effect on the concentration of oil dissolving in $scCO_2$.

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INTRODUCTION

Currently metal working fluids (MWF) are used worldwide to provide lubrication and cooling in metal machining operations. Aqueous metal working fluids are composed of water, oil, surfactants, and additives. These fluids are very expensive and require extensive pumping systems to deliver MWF around a manufacturing plant. Further, these additives and surfactants are harmful to both the environment and workers and disposal of these fluids is very expensive.

Recently a metalworking fluid composed of supercritical Carbon Dioxide ($scCO_2$) and dissolved soybean oil has been created. This system substantially reduces the environmental and worker impact while providing better lubricity and cooling in machining operations. The goals of our project are enhance the current system by:

1) increasing the flow rate to provide adequate lubrication and cooling for high intensity machining operations as well as the ability to use multiple nozzles,
2) designing an oil refill sensor, alerting the user that more oil must be placed into the vessel
3) designing a new subsystem that will continuously deliver oil to the pressure vessel so that the machining process is not interrupted to replenish the lubricant,
4) designing a method to better agitate the scCO2 and oil concentration, allowing for further testing.

PROJECT REQUIREMENTS AND ENGINEERING SPECIFICATIONS

Since our project is set around enhancing a system that already exists, our project requirements are already in the form of technical specifications. The following specifications are described in detail below.

REDESIGN THE CURRENT SYSTEM TO PRODUCE A HIGHER FLOW RATE While the current system is fully functional and has proven extremely useful for experimentation, it is not industry ready. The current pump produces a maximum flow rate of 50 grams per minute and is able to supply enough cooling and lubrication for light-duty machining operations. However, it is inadequate for heavy-duty metal shaping processes. Compacted Graphite Iron (CGI) and Titanium, used in the automobile and aerospace industries for their particularly high strength, are very difficult to shape. The high strength and stiffness of CGI that makes it useful in cylinder bores for engines, also makes it challenging to machine, while the low heat conductivity of Titanium results in very high temperatures at the tool-work piece interface. Current research for small scale machining indicates that the $scCO_2$ system works better than conventional cutting fluids for both CGI and Titanium (Clarens, 2008). However, our task is to scale up the current system and design and construct a new system that is able to deliver a flow rate large enough that it will provide adequate lubrication and cooling for these high intensity machining operations on a larger scale. A higher flow rate also allows for multiple delivery nozzles which have been shown to greatly influence the effectiveness of the cutting fluid as well as tool life. Precision of delivery is important in MQL as its effectiveness depends greatly on minimal fluids providing the necessary cooling and lubrication. In addition, increasing the pressure allows for through-tool delivery, a method for delivery of MWFs directly to the work surface, providing another effective method for fluid delivery.

DESIGN A SUBSYSTEM TO DELIVER CONTINUOUS OIL FLOW TO THE PRESSURE VESSEL The current system uses a batch process for mixing the oil and CO_2, meaning that every so often an employee must disassemble the pressure vessel and pour in a fresh "batch" of oil. During this time, lubrication and cooling cannot be delivered to the cutting area, resulting in downtime for the machine. Our task is to design a new subsystem that will continuously deliver oil to the pressure vessel so that the machining process is not interrupted to replenish the lubricant. This will save both time and money by reducing the downtime of the machine, increasing the lifetime of the pressure vessel, and eliminating the need for training to disassemble the vessel.

DESIGN A REFILL OIL SENSOR IN THE PRESSURE VESSEL In order to provide continuous oil flow, there needs to be an indicator of when to refill the vessel. When the vessel contains no oil there is no way to know without removing the bolted enclosure. As previously discussed this batch process is very time consuming and requires a long lag time to allow the oil to dissolve in the $scCO_2$.

DESIGN A METHOD TO "TUNE" THE OIL-CO_2 MIXTURE In addition to controlling the flow rate of the system, it is also desirable to be able to vary the mixture of the fluid being applied to the cutting area. Some operations require a lot of lubrication but little cooling, while others need more cooling than lubrication. To make the new system flexible so it can be used in all applications, the amount of oil and $scCO_2$ exiting the system must be variable. In the current system, only two different mixtures can be obtained by changing the placement of the tube drawing the fluid out, as illustrated in Figure 1. Our task is to design a method that can be used to vary the mixture to more than just those two compositions so that it can be optimized for many different machining and forming operations.

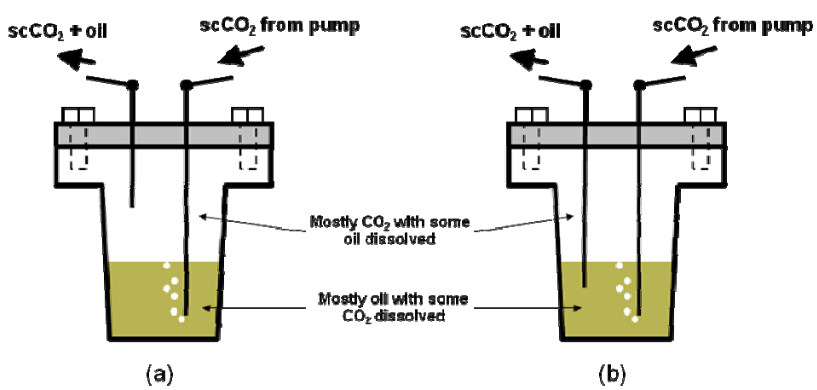


Figure 1 – (a) Tube drawing fluid from top of pressure vessel yields mixture of 90% CO_2 and 10% oil; (b) tube drawing fluid from bottom of vessel yields mixture of 20% CO_2 and 80% oil (Clarens, 2008).

CONCEPT GENERATION

The concepts we generated can be divided into four major categories based on function:

1) Produce a higher flow rate
2) Continuous oil flow to the vessel
3) An oil refill sensor
4) A method for tuning the CO_2-Oil mixture

The concept generation process began by developing a functional decomposition model to insure that the additional features of our delivery system met the design specifications of our sponsor. This can be seen below in Figure 2. The functions highlighted in red are the new or modified functions of our system.

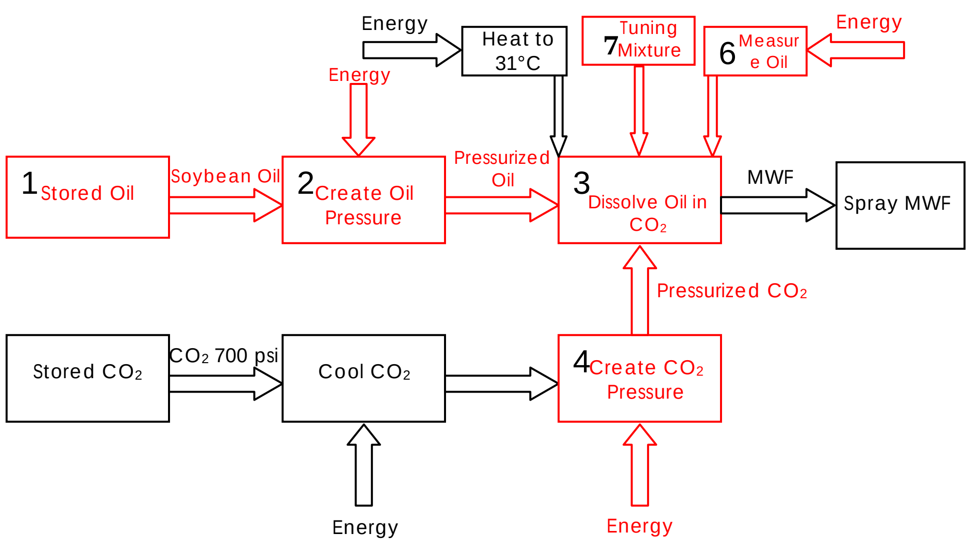


Figure 2 – Functional decomposition of MWF delivery system.

Functions 1 and 2 from Figure 2 above represent an external storage container for the oil and a pump to allow for continuous flow. Function 4 is a new pump that will allow us to increase the pressure and flow rate of the MWF. Our goal is to achieve a discharge pressure ranging from 5,000-10,000 psi and a flow rate between 200-350 grams per minute. Function 3 is the new pressure vessel and we are aiming for a pressing rating between 10,000-12,000 psi to allow for a proper safety factor. Function 7 represents additional inlets of CO_2 used to agitate the mixture in an attempt to dissolve more oil and increase lubricity. Finally, function 6 will be used to measure the oil level in the vessel. This device will indicate when the vessel when need to be replenished by the external source to the vessel.

Once the basic functions were determined for our design, we began brainstorming different design concepts with our sponsor and assistant researchers that would meet these qualifications. Also, a similar delivery system used by Ford was referenced for benchmarking our alpha design.

REDESIGN THE CURRENT SYSTEM TO PRODUCE A HIGHER FLOW RATE In order to obtain a higher flow rate a new pump is needed. We decided to use a reciprocating pump; a positive displacement pump where the volume of the cylinder is changed by the movement of the piston. These pumps are ideal for use in high pressure, low flow situations which accommodates our application (Hydraulic, 2008). The standard pump is the P-50 with a flow rate of 50 grams per minute. We therefore only looked at pumps with much higher flow rates. Our choices were narrowed to the P-200 and P-350, seen in Figure 3, each being able to maintain high enough flow rates and pressures for our design setup.

Figure 3 – P-50, P-200, and P-350 pumps (thartech.com).

DESIGN A SUBSYSTEM TO DELIVER CONTINUOUS OIL FLOW TO THE PRESSURE VESSEL The basic concept for the continuous oil flow subsystem is that in order for the oil to flow into the vessel, the oil must be at a higher pressure than the contents of the vessel. This can be accomplished in one of two ways: (1) depressurizing the vessel, or (2) using a pump to increase the oil pressure above the pressure of the vessel.

The first method is to fully depressurize the vessel, the cover can be removed and the oil can be poured in manually, as is currently done. No additional equipment would be required.

Another option to be considered is for an off-site pump system which could be used to pressurize small portable vessels of oil to a pressure higher than that of the contents of the pressure vessel already in the system. The portable vessel would be capped off to contain the pressure, and then transported to the scCO_2 cart where the oil is needed. The vessel would then be connected to the main pressure vessel and a valve opened between them. The high pressure oil would flow into the pressure vessel until the pressures reach equilibrium between the two vessels. The valve would then be closed, and the small vessel would be reused.

If a secondary pump and smaller vessel were added to the current system, we could also satisfy the desire to deliver continuous oil flow. This smaller vessel would be depressurized and filled with oil. The second pump would then pressurize that vessel to a pressure higher than the pressure of the large vessel. A valve between the vessels would then be opened, and the high pressure oil would flow into the large vessel. The valve would then be closed, and the process would be repeated when necessary.

Instead of another high pressure, high flow rate pump; a hand-crank high pressure generator would pressurize a small amount of oil to a pressure exceeding that of the pressure vessel. When oil needs to be added, the operator would add oil to the manual pump, open a valve connecting the pump to the pressure vessel, then crank the pump. The oil would be injected into the pressure vessel, and the valve would then be closed.

Similar to the hand crank, a High Performance Liquid Chromatography (HPLC) pump, used for pumping liquid mixtures at high pressures through a stationary media to separate the mixture, could be used in the final design. These pumps would be able to deliver oil at pressures well above the supercritical pressure for CO_2. The inlet to the HPLC pump would be placed in a container of oil at ambient pressure, and the outlet of the pump would be connected directly to the pressure vessel. The pump would be turned on to add oil to the vessel, and the flow rate could be varied to create true continuous flow.

PRESSURE VESSEL DESIGNS A new pressure vessel must be selected because the desired pressure for the new system will exceed the pressure rating of the vessel currently being used.

The first kind of pressure vessel that may be implemented is a Tubular Reactor Series vessel. Tubular reactors are long, cylindrical pressure vessels with a small inner diameter. There are two connection ports on the vessel. The covers on each end are threaded for easy removal. This type of reactor is currently implemented in Ford's system. The pressure ratings for this type of reactor are sufficient to provide a factor of safety of at least 2.

Another series of pressure vessels are the OC Series O-ring Reactors. OC Series reactors are very much like the Tubular Series, but the bottom of the vessel is permanently sealed, and the diameter is larger. The cover on the top is threaded for easy removal. Again, the pressure ratings are sufficient to provide a safety factor of 2 or more. The standard model of the reactor has two connection ports, but more can be added.

DESIGN A REFILL OIL SENSOR IN THE PRESSURE VESSEL In order to determine the oil level in the pressure vessel the first design idea considered includes laser beam light sensors. This system is similar to the laser detectors that are used to prevent garage doors from closing on a person or object. As Figure 4 shows, a laser emitter would be mounted inside the pressure vessel opposite a receiver. When the oil level is above the beam (2), it will not pass through the oil and will instead be diffracted and absorbed by the oil. If the oil level is below the laser (1), the beam will pass directly from the emitter to the receiver. The receiver would send a signal to the operator indicating whether or not it is receiving the laser beam, and if so, that the oil level is low.

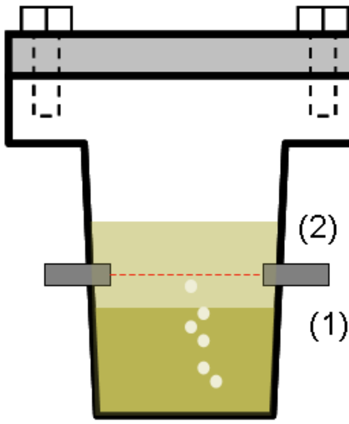


Figure 4 – Laser beam sensors for refill oil sensing.

Another similar design to the laser light sensors would incorporate a series of light emitting diodes (LEDs) and photo-resistors on the inside of the pressure vessel providing a gradual indicator of the oil level in the vessel. This concept is shown in Figure 5. The three LEDs are always turned on, but the oil will prevent the light from reaching the corresponding photo-resistors. If the oil level falls below an LED, the corresponding photo-resistor will be exposed to the light, changing its resistance. This change in resistance is detected using a comparator, whose signal is used to turn off the level indicator lights on a panel that is visible to the user.

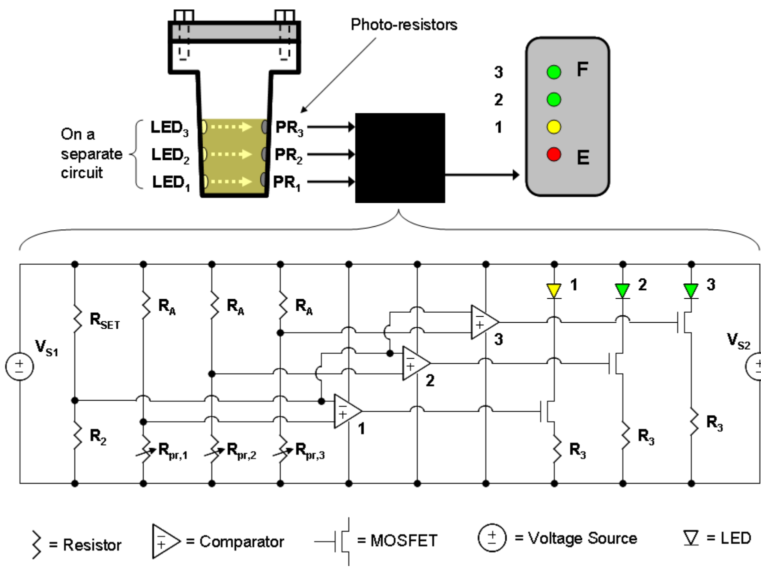


Figure 5– Method using LEDs and photo-resistors to determine oil level.

Instead of using light sensors another refill sensing method is to use sound. When the $scCO_2$-oil MWF is exiting the nozzle, a high-pitched sound can be heard. When no oil is dissolved in the $scCO_2$ (meaning the vessel is empty), the pitch of that sound changes. The change in pitch would be detected and the user would know that more oil should be added. While it may be possible to detect the pitch change with the human ear, it would be more effective to use a microphone and analyze the sound using computer software and provide the user with a clear notification when the vessel is empty. This concept is illustrated in Figure 6.

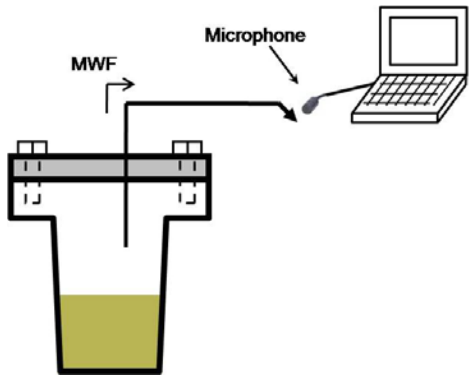


Figure 6 – Sound detection at the nozzle for refill oil sensing.

A different level measurement tool, the dipstick, could be implemented. This simple method is already used to measure the level of oil in most automobiles. A clean dipstick is dropped down into the vessel until it touches the bottom and then removed. The oil residue left on the dipstick is an indicator of the oil level in the vessel. This method is illustrated in Figure 7.

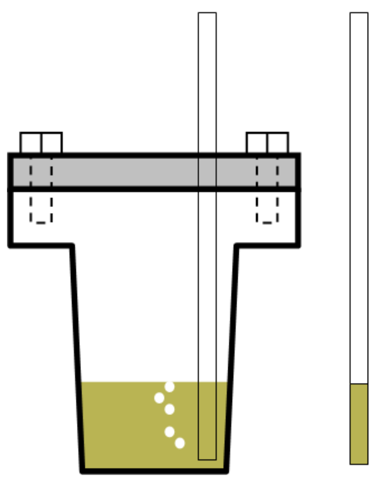
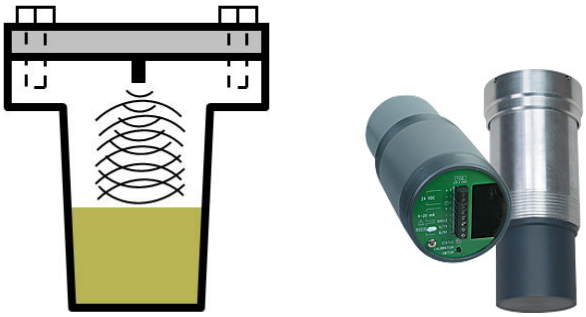


Figure 7 – Dipstick method to measure the oil level in the vessel.

An ultrasonic detector could also be used for the liquid level indicator as seen in Figure 8. The detector is mounted on the underside of the vessel cover, and houses both a signal emitter and receiver. Much like a dolphin uses echo-location, the detector emits sound at an ultrasonic frequency which reflects off of the surface of the oil in the vessel. By measuring the time between the initial emission of the sound and the reception of the reflected sound, the device is able to determine the oil level in the vessel.



(a) (b)

Figure 8 – (a) Ultrasonic oil level detection system, (b) example ultrasonic detection unit (LVU41 from omega.com).

The last design idea was to create a system of thermocouples inside the pressure vessel. The heat capacities of oil and $scCO_2$ are very different, meaning that when constant heat is applied, the change in temperature with respect to time for each of the fluids will be distinguishable. A thermocouple is used to monitor the temperature in the vessel at the location where the band heater is attached, as shown in Figure 9. Every time the band heater turns on to heat the vessel, the time-temperature curve will be recorded then compared to the known curves for oil and $scCO_2$. If the recorded curve matches the known curve for $scCO_2$, then the oil level has fallen below the thermocouple. If several thermocouples are used in this fashion, the oil level can be tracked more accurately.

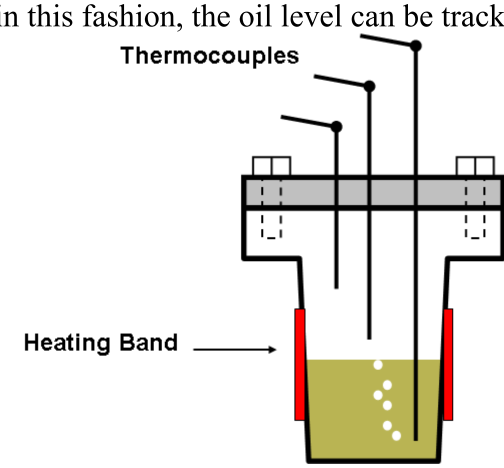


Figure 9 – Thermocouple method for oil level indicator.

DESIGN A METHOD TO "TUNE" THE OIL-CO_2 MIXTURE Our final design goal is to design a method to control the amount of oil sent to the cutting zone. For lubrication intense processes, such as tapping, it is best to draw from the liquid phase (mostly oil) at the bottom of the vessel. For cooling intense applications, such as turning of titanium in the aerospace industry, it is best to draw from the vapor phase in the vessel (mostly CO_2). The amount of oil being delivered can further be controlled by adjusting the amount of oil dissolved in the $scCO_2$. Currently little is known about what factors affect the oil concentration, or how to control them. Further testing will provide us more information on the composition of the MWF inside the pressure vessel. This will allow us to develop concepts for controlling the mixture and thereby the amount of lubrication at the cutting zone.

The first control to tune the oil mixture is to draw cutting fluid from different locations in the pressure vessel. In the current system, in order to draw fluid from the liquid phase in the vessel, it must be depressurized so that the outlet connection can be loosened so that the outlet tube can be dropped down into the liquid. A new pressure vessel with multiple connection holes on the top and bottom of the vessel would allow the user to easily switch between drawing the MWF from the top and the bottom of the vessel. Valves will be used so that there is no need to depressurize the vessel in order to disconnect a tube from one outlet and move it to another.

Research already conducted indicates that the solubility of oil in $scCO_2$ is directly related to the pressure. Therefore, selecting a pump that is able to provide a wide range of pressures will potentially allow the oil concentration to be controlled by varying the pressure.

The last method of tuning the concentration is to have multiple inlets for CO_2. In the current systems, CO_2 is delivered to the vessel through a single inlet, submerged in the oil so that the gas bubbles up through the oil to aid in the dissolution of the oil into the $scCO_2$. If the CO_2 is delivered to the vessel through multiple inlets, all of which are submerged in the oil, more of the oil will be agitated and potentially more of it will dissolve. A valve could be used to control the number of inlets that the gas is flowing through, in turn controlling the amount of oil that is dissolving in the $scCO_2$.

CONCEPT SELECTION

METHODS OF CONCEPT SELECTION We developed multiple concepts for each function of our new delivery system and narrowed them down based on their overall ability to meet the specified qualifications of our sponsor. Using these qualifications and available information on the existing model, we were able to select the best possible components for our design. Our goal was to obtain a $scCO_2$ MWF delivery system which met the new specifications while maintaining both versatility and cost effectiveness.

REDESIGN THE CURRENT SYSTEM TO PRODUCE A HIGHER FLOW RATE Although pumps from companies other than Thar Technologies were considered, they were eventually eliminated due to their inability to meet the desired flow rate. Therefore our choices based on the requirements of pressure and flow rate came down to the P-200 and the P-350. There is a price difference in the pumps as the P-350 costs $18,210 and the P-200 costs $14,677. The P-200 has a flow rate of 200 grams per minute and the P-350 has a flow rate of 350 grams per minute which are both adequate for use in heavy machining processes. Again both pumps are able to support multiple nozzles while maintaining the desired pressure. The higher flow rate of the P-350 will be more versatile and more stable at higher flow conditions. The P-350 reaches an approximate maximum discharge pressure of 5,000 psi while the P-200 can reach pressures of approximately 10,000 psi. Both are able to pressure gaseous CO_2 to the supercritical range, however, pressures above 5,000 psi are not necessary for lab testing. Therefore, the higher flow rate of the P-350 is recommended.

DESIGN A SUBSYSTEM TO DELIVER CONTINUOUS OIL FLOW TO THE PRESSURE VESSEL

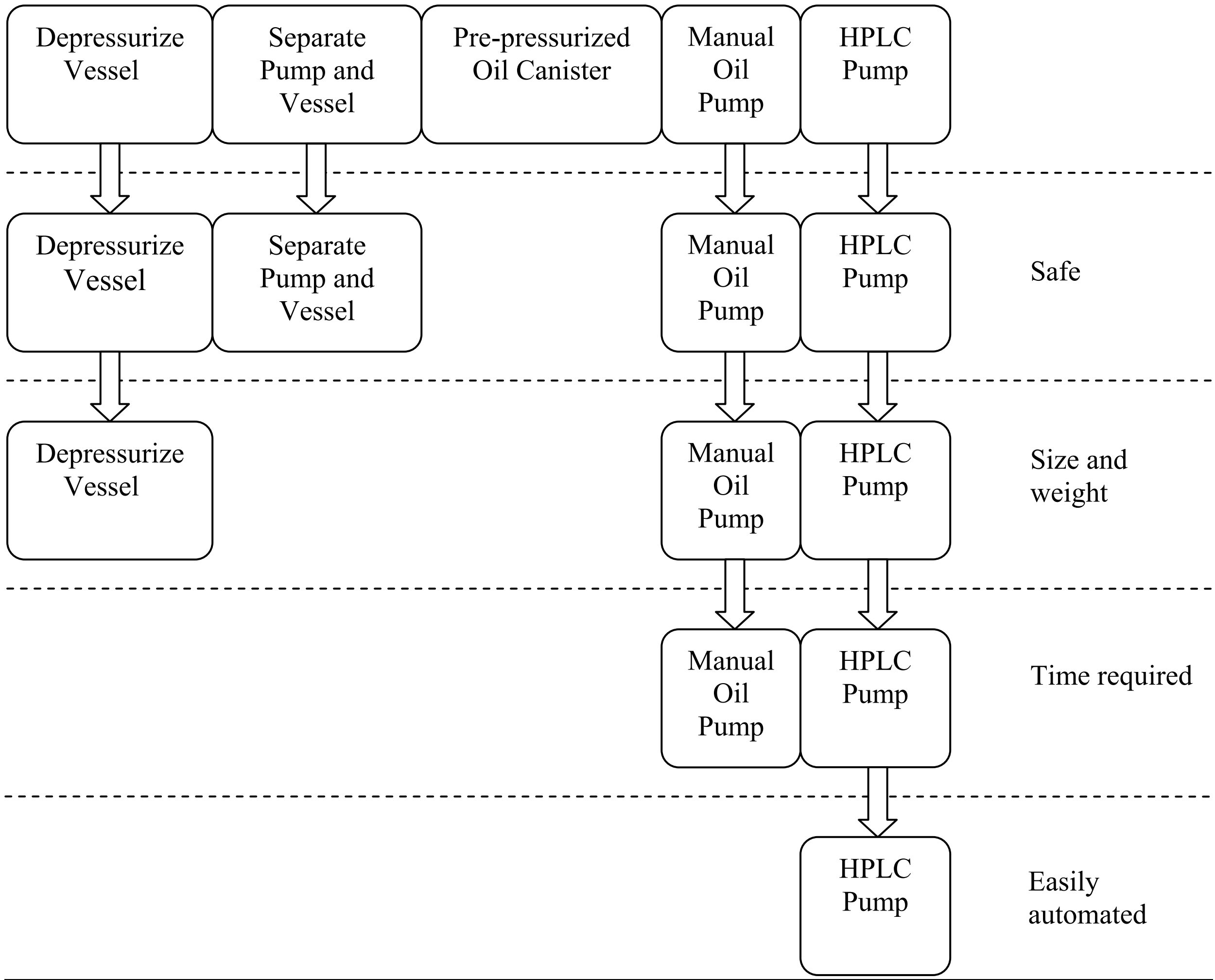


Figure 10 – Selection tree for pressure vessel.

The selection criteria were narrowed down as seen in Figure 10. The depressurized vessel design would require no additional or costly equipment, as the oil is poured in by hand. This eliminates the extra weight and maintenance concerns that would accompany the incorporation of more equipment. However, there are several disadvantages with this design. Time will be consumed as the operator removes the cover of the vessel and pours in the oil. More time will then be consumed as the vessel is re-pressurized. In addition to the time it takes for the pump to pressurize the vessel to the desired level, it will also take some time for the oil to dissolve in the supercritical CO_2 and reach equilibrium. All of this wasted time would cost the user both time and money.

Using the separate pump and pressure vessel design, there is no need to depressurize the main pressure vessel and the machine will experience no downtime. In addition to being expensive, the size and weight of an additional pump, pressure vessel, and controls would likely require a second cart to support the new system. The addition of another pressurized vessel will be accompanied by increased safety concerns, as well as maintenance costs. This method will also require the operator to pour the oil into the secondary vessel, forcing the operator to stop machining for a short time.

If the pre-pressurized oil container is used, there is no need for a separate pump and vessel on the cart itself and the small vessels can be reused many times, minimizing the amount of extra equipment required. The biggest concern with this design is safety. There is an incredible amount of risk associated with transporting small vessels at very high pressures around a manufacturing facility. In addition to the safety issues, this method of delivery would be less efficient than others because there is no way to maintain the pressure of the oil as it flows into the main pressure vessel, causing some oil to remain in the small vessel once the pressures have reached equilibrium.

Instead of pre-pressurizing the oil, a small hand pump could be used to pressurize the oil as needed. The hand pump is small and could be mounted directly on the cart. The cost of the pump, $1154, is able to inject oil at a pressure of 15,000 psi, meaning the pressure vessel would not have to be depressurized, resulting in no downtime for the machine. Through mechanical advantage, the work required to operate the pump is minimal, so any operator should be able to use it. Since this is a hand operated pump, the operator will have to take a short time away from machining whenever the vessel needs to be replenished with oil. There is no way to automate the process, or control the rate of oil flow into the vessel.

In place of a hand pump to pressurize the oil, an HPLC pump could remove the need for physical work by the user. HPLC pumps are small both in size and weight allowing it to fit on the cart. It would require a minimum amount of piping and connections. No extra pressure vessel is required; therefore, the safety risk is reduced. The lowest cost models of these pumps are able to deliver liquid at pressures of 0-6000 psi, meaning that the pressure vessel would not have to be depressurized for the oil to be added. The flow rates of HPLC pumps are adjustable and can be controlled by computer, so a true state of continuous flow could be created where the amount of oil going into the pressure vessel is equal to the amount exiting through the nozzle. The pumps can be expensive ($1500-$2000); however, in the grand scheme of the system this cost is small compared to the other components. Therefore, we recommend using a HPLC pump to maintain truly continuous oil flow.

While we recommend this system, it will not be incorporated into the final design. Since this system is to be operated in a testing environment instead of a manufacturing environment, the lag time for the system to re-saturate is less important. If later testing is desired to incorporate truly continuous flow, the HPLC pump is modular and can be implemented in the system with relative ease.

PRESSURE VESSEL SELECTION The selection tree for the pressure vessel is shown in Figure 11. Of the three possible pressure vessel models, only the Tubular Series and the OC Series have a pressure rating high enough to provide a safety factor of 2 when the fluid is being pressurized to 5000 psi. Both the Tubular and OC Series vessels are easily disassembled, so that is not a deciding factor between the two. Since this new system will be used for research, it is desirable to have a flexible number of inlets and outlets on the vessel. The Tubular Series vessel has only two ports and is not easily customized, while the OC Series vessel can have several ports on the top, bottom, and side walls of the vessel. For this reason, the Tubular Series vessel is considered inadequate, leaving the OC Series vessel as the best option for the new pressure vessel. The OC Series vessel also has a much larger volume than the Tubular Series vessel. While a comprehensive study has not yet been conducted to determine the effects of the vessel volume, it is known that on an existing cart that uses the Tubular Series vessel there have been fluctuations in pressure (and inherently temperature) presumably due to the small volume. Therefore, it stands to reason that a larger volume would create a more stable system.

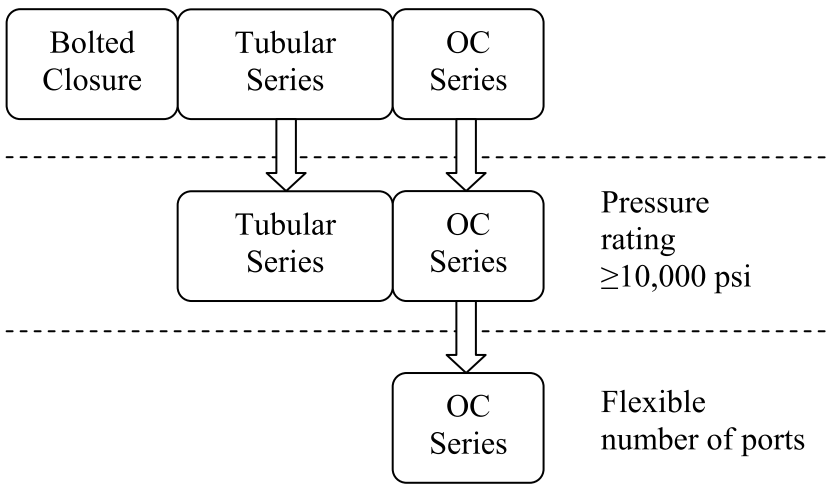


Figure 11 – Selection tree for pressure vessel.

DESIGN A REFILL OIL SENSOR IN THE PRESSURE VESSEL The selection criteria for the oil level refill indicator were based upon the design's ability to: work inside the pressure vessel, maintain pressure in the vessel, and allow for fully continuous automated oil flow into the vessel. After narrowing the designs, the thermocouple design was chosen as seen in Figure 12.

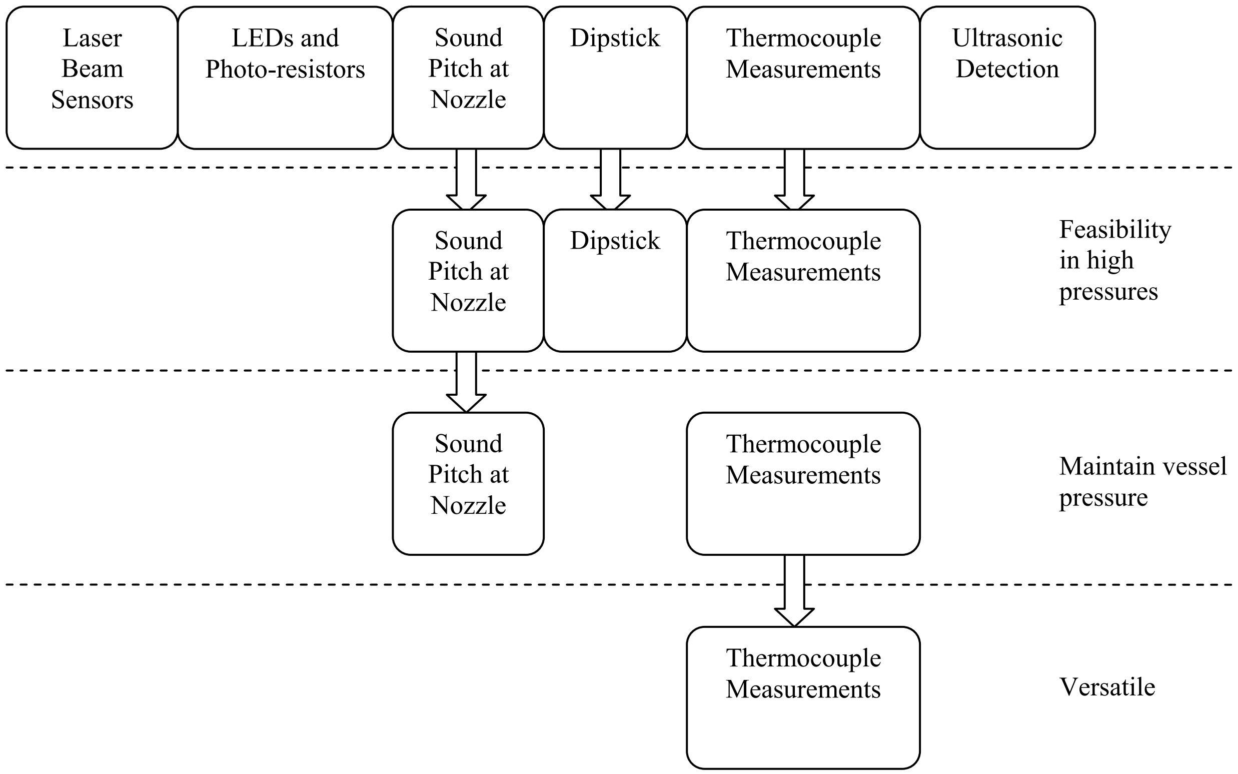


Figure 12 – Oil level refill indicator design selection

The first design criterion was that it would need to be able to withstand the high pressures seen in the pressure vessel. Measuring the sound pitch at the nozzle is able to be employed in the design because this method would be in use at the nozzle. Hearing the pitch at the nozzle is not effected by the high pressures in the vessel. Thermocouples and dipsticks are able to function regardless of the high pressures seen in the vessel; hence they also satisfy this criterion.

However the laser light sensors, the LED sensors, and the ultrasonic detector were eliminated from our final design consideration because of the high pressure conditions. The laser light sensors and LED sensors would both need to be incorporated on the inside of the vessel. Under such high pressures, both the LED's and the laser light sensors would break due to stresses in the vessel, posing both a safety concern and a design concern. The price of the ultrasonic detector is approximately $900. Without testing the device we do not know if it will work at high pressures. Since it would be expensive to test this device and it is unknown whether or not it would work as a level sensor, we have decided not to implement this design.

The oil level refill indicator design should also make sure that the pressure vessel will always remain pressurized. Again, the sound pitch design is reasonable because hearing the pitch at the nozzle is not effected by the high pressures in the vessel. Similarly the thermocouples would not require that the vessel be depressurized and would able to take continuous readings while inside the vessel. Hence both the sound pitch and thermocouple designs satisfy this objective.

The dipstick design works by placing the dipstick into the vessel and then removing it. With such high pressures in the vessel removing the dipstick without breaking the pressure seal is practically impossible. Since it cannot maintain vessel pressure, this design was not considered for the final design.

The last design specification was for the design to be versatile. If the pitch at the nozzle design was used there would be no indication for when the oil in the vessel was getting low, only when there is no oil in the vessel. However, using thermocouples there would be a warning as to when to add oil to the vessel. Also, in a manufacturing environment, there is some concern that measuring the pitch at the nozzle will become difficult due to background and erroneous noise. Therefore the best design for the oil level indicator was determined to be the thermocouple design.

DESIGN A METHOD TO "TUNE" THE OIL-CO_2 The pressure vessel selection will allow us to provide multiple inlets for the system and allow us to test their affect on the mixing process of oil and CO_2. Similarly, the new pump design will allow for a large range of flow rates, allowing for further testing as well. However, this aspect of our design is not yet completed and new ideas must still be considered.

PARAMETER ANALYSIS

MATERIAL SELECTION We used the CES software to determine the most appropriate materials for the pressure vessel mount and clamp. First, we determined the function, objective, and constraints of each individual component. Next, the material indices were found. Table 1 below describes the function, objective, and constraints for the pressure vessel mount and clamp as well as the material indices.

	Pressure Vessel Mount	**Pressure Vessel Clamp**
Function	• Support the vertical load of the pressure vessel	• Resist torsion required to open the pressure vessel
Objective	• Inexpensive • Resists buckling under pressure vessel load	• High strength but small weight
Constraints	• 6 inches in length • Legs and plate must be made of same material to allow for welding • Support 122 lbs in compression	• Easily machined • Must be 1" thick block • Available
Material Indices	• Column, minimum cost, buckling load prescribed • $E^{1/2}/(C_m \rho)$	• Beam, minimum weight, strength prescribed • $\sigma^{2/3}/(\rho)$

Table 1 – Material selection for pressure vessel mount and clamp.

Using the material indices we determined the top five materials for each component before eventually selecting stainless steel 304 for the mount and wrought aluminum alloy 6060-T6 for the clamp. Ultimately, stainless steel 304 was selected due to its availability, its ease for welding, its ability to support the load and resistance to buckling, and its minimal cost. Aluminum alloy 6060-T6 was selected because it is easy to machine, available from a local supplier, as well as strong and lightweight.

DESIGN FOR ASSEMBLY We created a design for assembly chart for the legs and plate of the pressure vessel mount and it can be seen below in Table 2.

1	2	3	4	5	6	7	8	9	Name of Assembly
Part ID Number	Number of times the operation is carried out consecutively	2 digit manual handling code	Manual handling time per part	2 digit manual insertion code	Manual insertion time per part	Operation time, seconds (2) *[(4)+(6)]	Operation cost, cents, 0.4*(7)	Figures for estimation of theoretical minimum parts	Mounting Block
1	4	00	1.13	00,96	1.5, 12	58.52	23.41	0	Legs
2	1	03	1.69	N/A	N/A	1.69	.68	1	Plate
						60.21	24.08	1	3(1/60.21) = 5%
						TM	CM	NM	$3(N_m/T_m)$

Table 2 – Design for assembly of vessel mount and clamp

For our system, the majority of the components were pre-assembled by the manufacturer. The only component that required assembly was the legs and plate of the pressure vessel mount, a fairly easy procedure. Because there are only two parts involved, the most efficient redesign for assembly would be to fabricate them as one piece. We intend on only manufacturing 100 systems so the cost saved in assembly would be outweighed by material costs.

DESIGN FOR ENVIRONMENTAL SUSTAINABILITY In Appendix F, the total mass of air emissions, water emissions, use of raw materials, and solid waste for the pressure vessel mount (stainless steel 304) and the clamp (aluminum 6060) can be seen. As you can see, the aluminum creates significantly more waste within each one of these categories than the stainless steel.

DESIGN FOR SAFETY We performed a risk assessment for the pressure vessel mount. The major risks were the vessel falling over and exploding, high pressure MWF in the user's eye, and placing the vessel into the mount. All three of these are high level risks but very unlikely to actually occur. Some unanticipated risks we encountered were objects falling onto the mount as well as the ergonomics of our system. The procedures that are difficult for the user to perform such as getting in position under the vessel do not occur often so we do not anticipate any long term health risks. There are other risks such as head bumping and cutting oneself that may occur but the severity is minimal.

MANFUACTURING PROCESS SELECTION For our MWF system we anticipate that other professors or companies will want to conduct testing. We estimated that 100 systems would be put into production. With this in mind, we determined the most appropriate manufacturing process for the vessel mount and clamp using the CES Manufacturing process selector. The first thing we had to consider when selecting the manufacturing process for the legs and plate of the pressure mount was that the cart had to be made from stainless steel, thus preventing corrosion from chemicals and other metal working fluids while in a manufacturing environment. This left us with two options for joining the legs to the cart, by either welding or using bolts. Drilling holes in the bottom of the cart and threading the legs would be very tedious and time consuming while providing a less stable mount. Therefore we determined welding was our best option. In order to weld the legs and plate to a stainless steel cart they also needed to be constructed from stainless steel. We determined that manual metal arc welding was the most appropriate for our particular application. This type of welding can easily be used to join stainless steel materials by using a weld rod to provide filler metal to the work surface. This form of welding is very economic for low volume production such as for our system. It is also very effective in compression and torsional loading which this component will be experiencing.

A few constraints were considered before determining how to manufacture the pressure vessel mount clamp. First, the clamp had to be a certain thickness to allow for the two pieces to be bolted around the vessel. As a result, we used aluminum because it was cheap and readily available. Therefore we could no longer weld the clamp to the plate. We considered two methods for shaping our clamp; die casting or machining. Die casting would have been the best alternative for high volume production however, since we only making 100 the costs associated with die casting would be greater than that of machining. Also, aluminum is a soft metal and can be machined fairly quickly. All of the necessary drilling and threading can be completed in a relatively short amount of time for experienced machinists on the mill.

REDESIGN THE CURRENT SYSTEM TO PRODUCE A HIGHER FLOW RATE The P-350 pump is able to provide a maximum discharge pressure of 5000 psi. In order to provide supercritical CO_2, the pump must be able to reach a minimum of 1100 psi. So, the P-350 exceeds this requirement. Since the current pump is unable to keep up with the flow out of the nozzle, the new pump must be able to deliver a higher flow rate than the current 50g/min. The P-350 is able to deliver 7 times that flow rate.

PRESSURE VESSEL The new pressure vessel will need to be mounted to the cart in a way that supports the 102 lb. load vertically, as well as prevents the entire vessel from spinning or tipping over, especially when the operator is removing the lid. The mounting method must not obstruct access to the two connection ports in the bottom of the vessel. Furthermore, the top of the vessel must be elevated above the top shelf of the cart so that the cover is easily accessible. The bottom of the vessel has a fillet to aid in mounting, but does not have any pre-drilled holes for mounting screws.

The vertical load of the vessel will be supported by a plate elevated on four legs. Shown in Figure 13(A), a 3.5 inch diameter hole will be cut into a stainless steel plate for the bottom 0.75 inches of the vessel to slide into (see Appendix B for vessel dimensions). Square tubular legs 6 inches in length, also stainless steel, will be welded to the underside of the plate at the corners. The legs will then be welded to the bottom shelf of the cart. Directly above the plate a hole of diameter 4.38 inches will be cut in the top shelf of the cart. When installed on the cart, the vessel will be slid down through this hole and set into the hole in the plate.

To prevent the vessel from spinning when the operator is removing the cover, a clamp will be placed on the vessel and secured to the mounting plate. The clamp will be in two pieces, shown in Figure 13 (B) and (C), with one piece secured to the mounting plate with either bolts or welds. The clamp will be made of either steel or aluminum depending on material availability, and the material choice will dictate the joining method. The other half of the clamp will not be secured to the plate, but will be joined with 2 bolts to the secured half and tightened around the vessel. The hole in the clamp will be machined to a diameter of 4.5 inches, slightly larger than the outer diameter of the vessel, so that a thin layer of rubber can be inserted between the clamp and the side of the vessel to prevent wear due to metal-to-metal contact as well as increase the coefficient of friction between the clamp and vessel. Full engineering drawings can be seen in Appendix C.

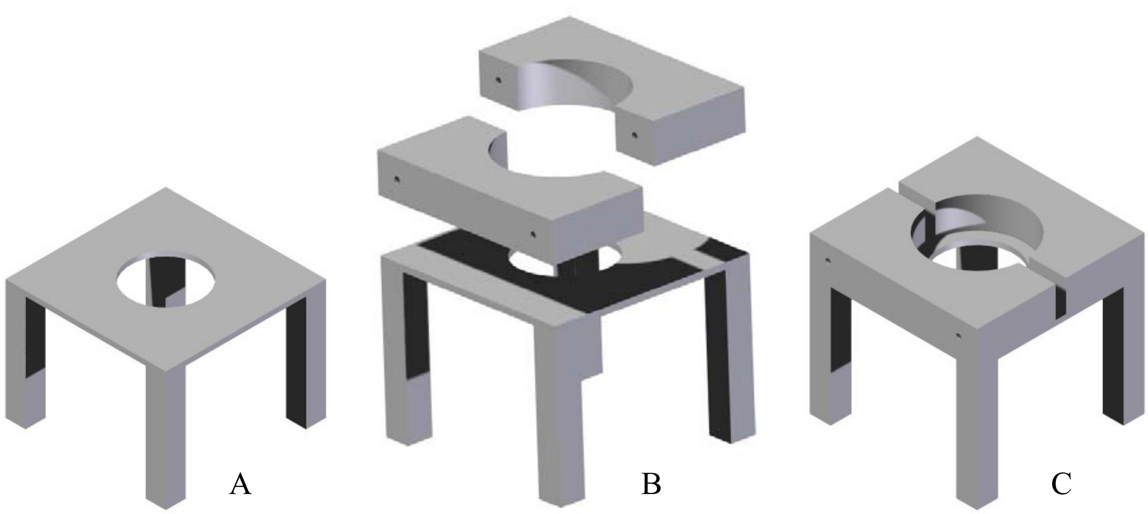


Figure 13 – (A) Mounting base plate model, (B) exploded view of clamp with mounting plate, and (C) model final assembly of clamp onto mounting plate.

A simple force and torque analysis was performed to verify that the clamping force will provide enough friction to prevent the vessel from twisting when the operator removes the cover. The basic equations used in the analysis are shown below in Equations 1-5. $F_{applied}$ is the force applied by the operator to the moment arm of length l_{arm}. $F_{friction}$ is the frictional force generated by the clamp with a static friction coefficient of μ_s, and r_{vessel} is the radius of the vessel where the clamp is acting. F_{bolt} is the total amount of clamping force generated by N_{bolts} bolts, each tightened with a torque of T_{bolt}. K is the torque coefficient for the bolt based on the bolt surface condition, and d_{bolt} is the nominal diameter of the bolt.

$$T_{applied} = F_{applied} \times l_{arm} \quad \text{(Eq. 1)}$$

$$T_{friction} = F_{friction} \times r_{vessel} = F_N \times \mu_s \times r_{vessel} \quad \text{(Eq. 2)}$$

$$F_N = F_{bolt} = \frac{T_{bolt} \times N_{bolts}}{K \times d_{bolt}} \quad \text{(Eq. 3)}$$

$$F_N = F_{bolt} = \frac{T_{bolt}}{K \times d_{bolt}} \quad \text{(Eq.4)}$$

$$T_{friction} = \frac{\mu_s \times T_{bolt} \times N_{bolts} \times r_{vessel}}{K \times d_{bolt}} \quad \text{(Eq. 5)}$$

To prevent vessel from twisting, $T_{friction} > T_{applied}$

For this analysis, two standard ¼"-20 bolts have been used (nominal diameter of 0.25 in.), with a K coefficient of 0.2 (Sommer, 2008). The bolts are tightened with a torque of 50 in-lb. The static coefficient of friction for rubber on steel is 0.7 (Elert, 2008). From the vessel drawing in Appendix B, the vessel radius is 2.19 in. The moment arm is assumed to be 14 inches, and the operator applies a force of 80 lb at the end of the arm. Under these assumptions, the torque induced by the operator is approximately 87 ft-lb, while the torque generated by the friction of the clamp reaches 256 ft-lb. Since the torque from friction is much greater than the torque generated by the operator, the vessel will not twist. In fact, the operator could double the applied force or double the length of the moment arm, and the clamp would still successfully prevent the vessel from twisting.

The materials and tools needed to fabricate the mounting plate and clamp are readily available from local raw materials suppliers. A fabrication instruction plan for the mounting plate and clamp is included in Appendix D.

DESIGN A REFILL OIL SENSOR IN THE PRESSURE VESSEL To measure the oil level in the pressure vessel we have decided to use the thermocouple approach. One thermocouple will be placed exactly seven inches from the bottom of the vessel and the other will be placed exactly seven inches from the top of the vessel. This symmetry will provide equal re-radiation from the top and bottom of the vessel. It is also necessary that the thermocouples be located directly in the center of the heating bands. This will assure that each thermocouple receives the same heat flux allowing for comparison of temperature gradients. Figure 14 shows the heat transfer from the heating band to the thermocouples.

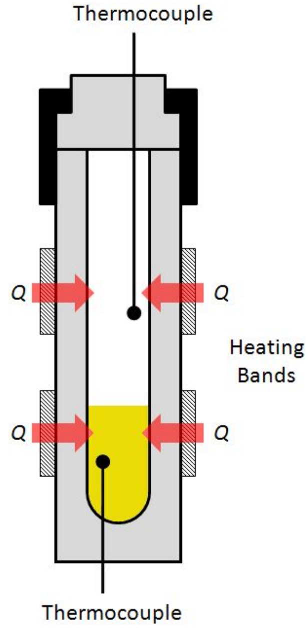


Figure 14 – Equal heat applied to oil and CO_2, differences in specific heat produce differences in temperature gradients of oil and CO_2

The basic engineering principle relies on the difference in heat capacity of oil and scCO_2. The definitions of specific heat of oil, C_{oil}, and scCO_2, C_{co2}, are given in equations 6 and 7 below.

$$C_{oil} = \frac{\Delta Q}{\Delta T_{oil}} \quad \text{(Eq. 6)}$$

$$C_{CO_2} = \frac{\Delta Q}{\Delta T_{CO_2}} \quad \text{(Eq. 7)}$$

As can be seen in the figure, equal heat Q, is transferred to both thermocouples. Therefore we can combine equations 6 and 7, yielding Equation 8.

$$\frac{C_{CO_2}}{C_{oil}} = \frac{\Delta T_{oil}}{\Delta T_{CO_2}} \quad \text{(Eq. 8)}$$

The specific heat of vegetable oil is 1.67 kJ/kg K. In the gaseous state, the specific heat of CO_2 is 0.846 kJ/kg K. However, in the supercritical state the specific heat increases dramatically as seen in Figure 15 (Kemmere, 2005).

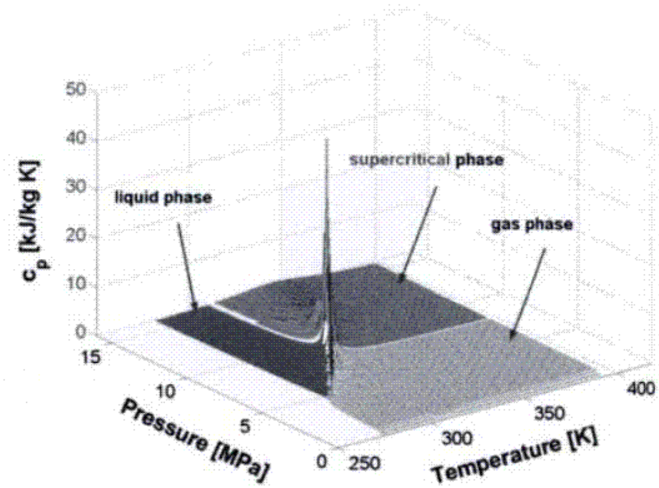


Figure 15 – Large increase in specific heat at the supercritical phase (Kemmere, 2005).

Therefore we can conclude that $C_{CO_2} > C_{oil}$. Consequently, we know that $\Delta T_{oil} > \Delta T_{CO_2}$. The temperature of the oil will increase faster than the temperature of the CO_2. This temperature gradient will be the basis of the thermocouple design.

UTILITY CART Since this system will be used in a test environment in different locations a mobile cart which can store the components and move from one location to another is necessary. The cart selected for the system is a utility cart from Grainger.com. Figure 16 is a picture of the cart.

Figure 16 – Utility Cart for scCO_2 MWF system (1NFD6 Grainger.com)

Our system incorporates many large components and placement of these parts on a mobile cart requires careful consideration of both the size and weight. Of course all parts must be able to fit on the cart. Also, the shelf of the cart must be able to withstand the load applied via the weight of the components. Further, with highly pressurized components it is necessary that the cart not tip over unexpectedly. Using these criteria the parts will be assembled on the cart as seen in the model below, Figure 17.

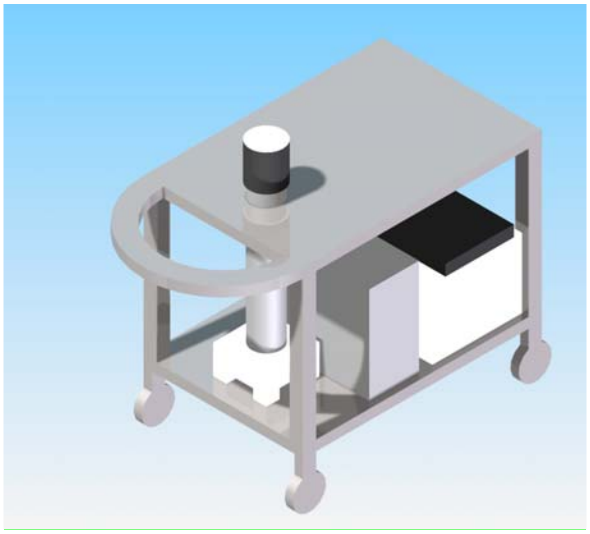


Figure 17 – 3-D model of the MWF cart

From the scaled model it is clear that all parts are able to fit on the cart with enough space. The bottom shelf of the cart has a load capacity of 600 lbs. From the force analysis shown in Figure 18, it can be seen that the total force on the bottom shelf is 232 lbs. This is a safety factor greater than 2.5.

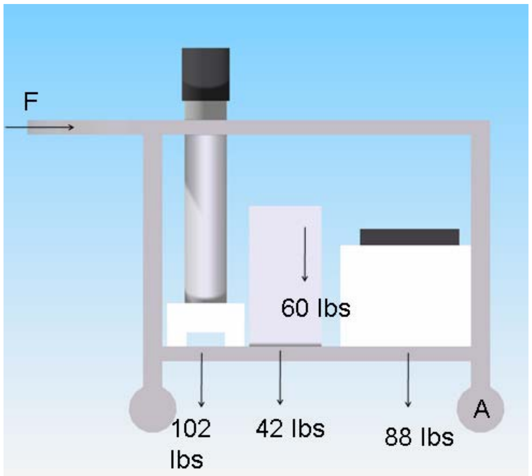


Figure 18 – Force analysis of cart

Summing the moments about point A, we were able to determine the horizontal force, F, applied at the handle which would tip the cart assuming the wheels do not roll. This moment analysis can be seen below in Equations 9 and 10.

$$\sum M_A = 0 \qquad \text{(Eq. 9)}$$

$$F \cdot 30'' = 102\text{lbs} \cdot 28.5'' + 42\text{lbs} \cdot 20.25'' + 60\text{lbs} \cdot 21'' + 88\text{lbs} \cdot 7.75'' \qquad \text{(Eq. 10)}$$

Solving for F, we were able to determine that the force required to tip the cart is 190 lbs. This force is much larger than any anticipated force which would act on the handle of the cart, validating the cart choice and layout design.

FINAL DESIGN

A schematic containing the final design can be seen below in Figure 19.

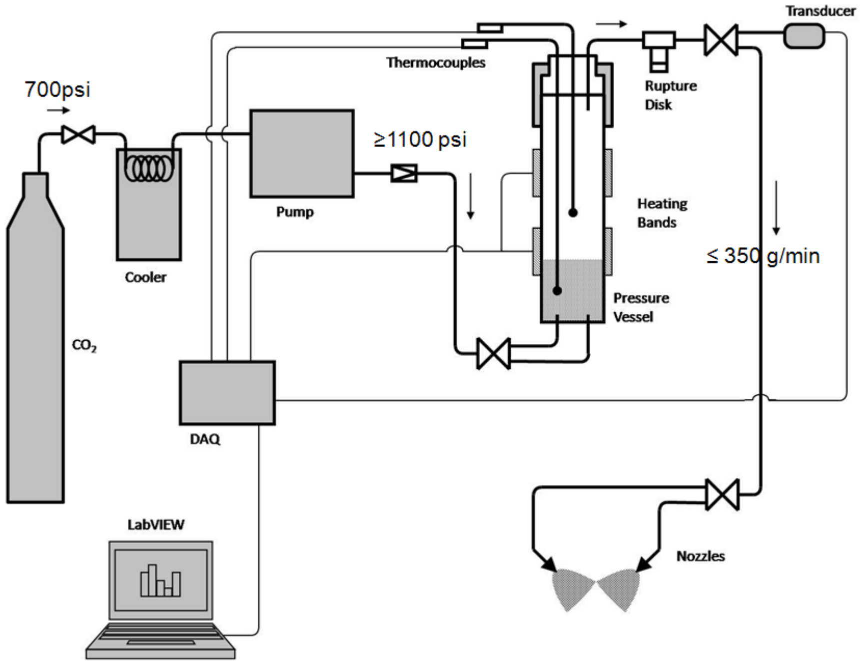


Figure 19 – Schematic of the final design

Food grade CO_2 at 700 psi is delivered to a Julabo F-200 cooler. The temperature of the CO_2 is decreased to allow for easier compression of the CO_2 which occurs in the P-350 pump from Thar Technologies. In order for the CO_2 to reach the supercritical range, the pump must pressurize the CO_2 to at least 1100 psi. From here the pressurized fluid is delivered through two inlets, via a three-way valve, into the pressure vessel. Two Tempco TNB01051 heating bands line the outside of the pressure vessel. These heating bands interact with the National Instruments SC-2345 data acquisition unit to make certain that the temperature inside the vessel remains above 32°C, keeping the fluid in the supercritical range. Two Omega KQSS-116G-12 K-type thermocouples inside the pressure vessel, which also interface with the data acquisition card, are used for the thermocouple level sensing system. A Zook rupture disk rated for 10,000 psi is located at the exit of the pressure vessel. This relief ensures safety and security for users and prevents failure of the pressure vessel. A Sensotec TJE-0743-11TJG pressure transducer is also positioned at the pressure vessel exit. This transducer corresponds with the data acquisition card giving a measure of the vessel pressure as well as verifying that the vessel pressure is in the supercritical range. Finally, the cutting fluid is delivered to the workpiece via nozzles at a maximum flow rate of 350 g/min. A list of all materials used for the test setup can be seen in Appendix A.

REDESIGN THE CURRENT SYSTEM TO PRODUCE A HIGHER FLOW RATE Based on the data and consulting with our sponsor we have chosen use the P-350 pump from Thar Technologies. This pump can maintain a higher flow rate and is therefore more versatile for different machining processes. The increased flow rate will also allow for multiple nozzle and through-tool delivery experiments in the future.

PRESSURE VESSEL We have selected the OC-11 pressure reactor. It has a large volume preventing concentration fluctuations inside the vessel and is rated to 12,500 psi which will allow for high pressure testing. Moreover it has a screw-top which will allow the user to easily add oil to the vessel when needed.

DESIGN A REFILL OIL SENSOR IN THE PRESSURE VESSEL We will use the two thermocouple system to determine when oil needs to be added to the system. It relies on the heat capacities of oil and $scCO_2$ and their temperature gradients. LabView will monitor the temperature gradient of both thermocouples in the system and when the gradients are equal will alert the user to add more oil to the system.

FABRICATION PLAN

The fabrication process for the cart is divided into four phases. These phases are:

1. Vessel mount fabrication
2. Cart modification
3. Cooler lid modification
4. System assembly

Remember to always wear proper safety equipment when handling and machining metal. Be careful of sharp edges after cutting, and always wear safety glasses.

VESSEL MOUNT FABRICATION The vessel mount consists of two separate sub-assemblies: a plate supported by four legs, and a clamp bolted to the plate. Step by step instructions for fabricating and assembling the pieces and attaching them to the cart can be found in Appendix D. Note that there was one engineering change from the initial design. The clamp is still secured to the plate using bolts, but instead of holes in the clamp, the final design uses slots. This allows the clamp to slide so that it can be easily tightened around the vessel.

CART MODIFICATION As shown in the system model in Figure 17, the vessel will protrude through the top shelf of the cart. Use a plasma cutter to cut the hole to a diameter of 4.625”, centered 6.5” from the end of the cart and 12.125” from the sides, as shown in Figure 20 (A). Cut a 14.5” length of rubber tubing (1/4” ID x 1/2” OD) and slit it all the way down one side with a utility knife. Fit the tubing around the edge of the hole in the shelf. This helps to clean up the hole made by the plasma cutter providing a snug fit for the vessel.

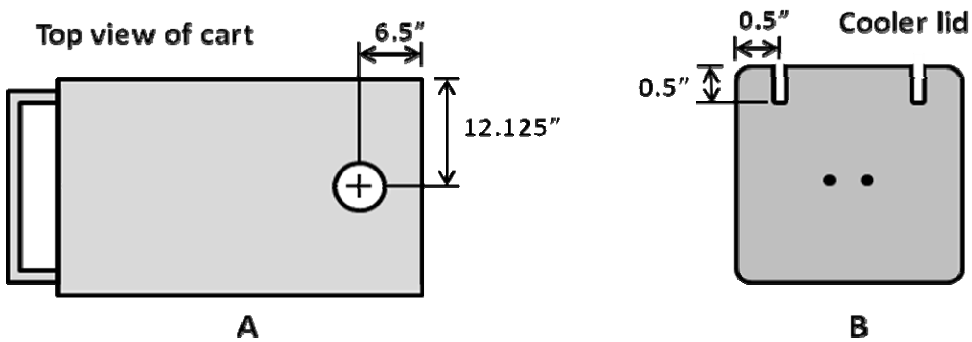


Figure 20: (A) Location of hole in top shelf of cart; (B) Slots to be milled in cooler lid.

COOLER LID MODIFICATION CO_2 is delivered through tubing from the food-grade cylinder to the cooler and then to the pump. In order for the CO_2 in the tubing to be cooled, two small slots were milled in the cooler lid. To do this, remove the handle and the lower piece of the cooler lid via the two screws using a small Phillips screwdriver. On the back edge of the lid (the edge that is farthest back from the front of the cooler), use a 1/8" mill (600 RPM, slow feed) to create two slots each 3/8" in length. The first is 0.5" away from the right side, and the second is 0.5" away from the left, as shown in Figure 20 (B). Remove an additional 0.01" of material from each side of each slot using climb milling to allow clearance for the tubing and give a smooth surface finish. Use a metal file to remove any sharp edges that could damage the tubing.

SYSTEM ASSEMBLY The large components of the system are arranged as shown in Figure 21. Use clear vinyl tubing to connect the cooler to the pump. The connections on the cooler are for 3/8" ID tubing, while the connections on the pump are for 1/4" ID tubing. Therefore plastic 1/8" to 1/4" couplings are used to connect the tubing together. Refer to the pump manual when connecting the cooling tubes for inlet and outlet placement.

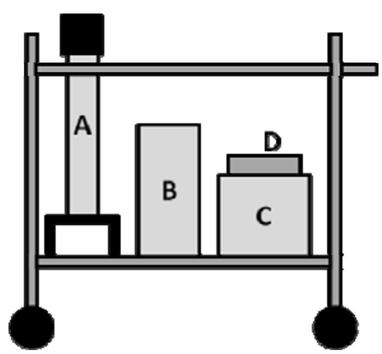


Figure 21: Cart layout, where A is the pressure vessel, B is the cooler, C is the pump, and D is the data acquisition board.

When connecting the tubing that will be carrying CO_2 or the pressurized metal working fluid, every connection must be made using a sleeve and a gland to keep a high pressure seal. To install a sleeve and gland onto a piece of tubing, first slide the gland onto the tubing, followed by the sleeve. Position the gland and sleeve so that there is approximately 1/8" of tubing protruding beyond the sleeve. Insert the sleeve, gland, and tubing into the appropriate female connector. Using a wrench, screw in the gland until snug, then tighten slightly to crimp the sleeve onto the tubing. Pull on the tubing to make sure it does not slide out of the connection. If it does come out, remove the gland and repeat this process. Unless otherwise stated, the High Pressure (HiP) part numbers of the sleeves and glands used are 15-2AM1 and 15-2A1, respectively. These are used with 1/16" tubing.

Using a female-to-male adaptor (HiP:15-21AF1AM2), connect the tubing from the outlet valve on the pump to the inlet side of the one-way valve (HiP:15-41AF1). Connect tubing from the outlet of the one-way valve to the inlet of a three-way valve (HiP:15-15AF1) so that the CO_2 can be split into two lines. Connect one of the outlets from the three-way valve to one of the holes on the top of the pressure vessel using an adaptor (HiP:15-21AF1HM4). Connect the other outlet from the three-way valve to a hole on the bottom of the vessel using the same adaptor. Again using the same adaptor, connect one of the remaining holes on the top of the vessel to one side of the T-type safety head (HiP: 5-63AF1). Be sure to correctly install a rupture disc into the safety head. Connect the other side of the safety head to the inlet of a three-way valve (HiP:15-15AF1) so that the now $scCO_2$ can be split into two lines. Connect one of the outlets from the three-way valve to the pressure transducer using an adaptor (HiP:15-21AF1NMB). Connect the other outlet from the three-way valve to the inlet of another three-way valve (HiP:15-15AF1). Both of the outlets on this valve are then connected to tubing with a sleeve and a glad, acting as a nozzle to spray fluid onto the cutting zone.

Connect two K-type thermocouples (Omega:KQSS-116G-12) into the two remaining holes on the top and bottom of the pressure vessel using adaptors (HiP:15-21AF1HM4-T). Install the sleeves onto the thermocouples such that each thermocouple is 7" into the vessel (note that this requires the sleeves to be located in different places on the thermocouples since the vessel lid is thicker than the bottom of the vessel). Wire the thermocouples to the proper input modules (NI: SCC-TC01) on the National Instruments Data Acquisition (NI DAQ) board. Likewise, wire the pressure transducer to the proper input module (NI:SCC-CI20). Wire the heating bands in parallel to a power source and a relay module (NI: SCC-RLY01) on the DAQ board according to the wiring diagram in Figure 22. Refer to the "SCC Quick Start Guide" included with the DAQ board when installing the input modules and cabling the board to a laptop using a PCMCIA card (NI:PCI 6036E).

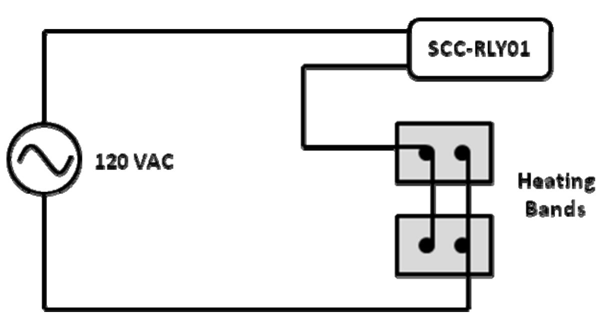


Figure 22: Wiring diagram for heating bands.

VALIDATION

$scCO_2$ - MWF In order to validate the previous system design, tests were conducted using titanium in a turning operation. During each test, the lubricant, coolant, and gas pressure (bar) were recorded. Titanium was chosen because it causes rapid tool wear due to the large amounts of heat generated when it is machined. A wear limit of .15mm was imposed on the cutting tool and the amount of time in seconds was monitored until this level was reached (Claren, 2008). From the results shown in Figures 23-25 below, it is apparent that conventional flood coolants vastly outperformed the combination air and soybean oil. However, $scCO_2$ and soybean oil showed a wear rate that was 2 to 4 times lower than that for conventional flood MWFs after 300s. To further prove this concept, the mean time to failure or .15mm of wear was 100s for Air and soybean oil, 900s for MWF flood, and 1400s for $scCO_2$ and soybean oil. (Claren, 2008).

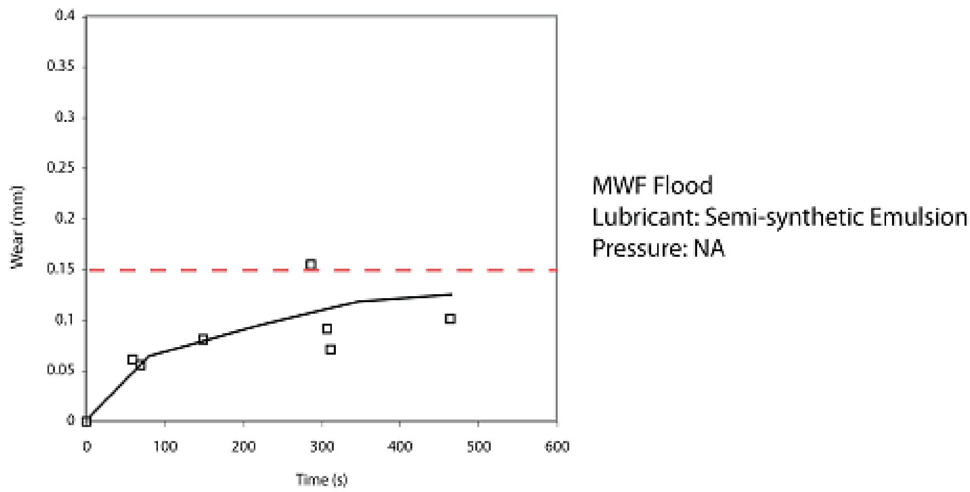


Figure 23. Tool wear in titanium turning operation using MWF flood for lubrication and cooling (Claren, 2008).

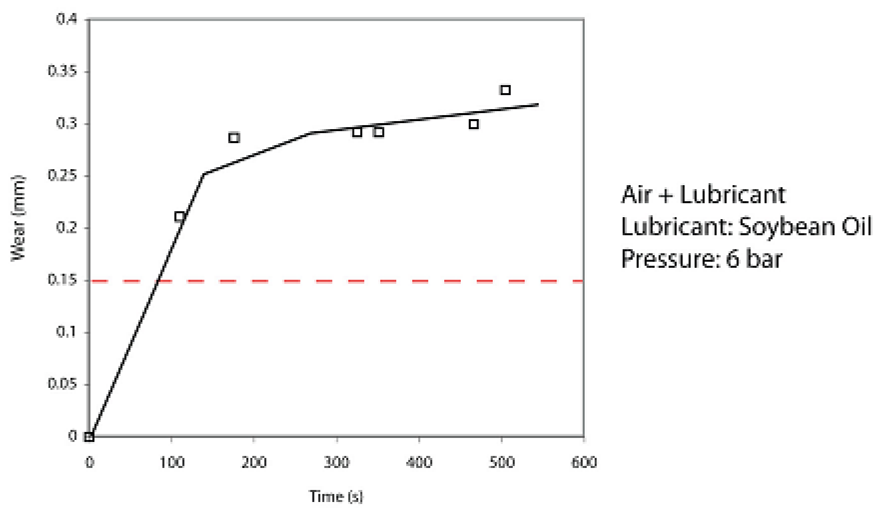


Figure 24. Tool wear in titanium turning operation using air for cooling and soybean oil for lubrication (Claren, 2008).

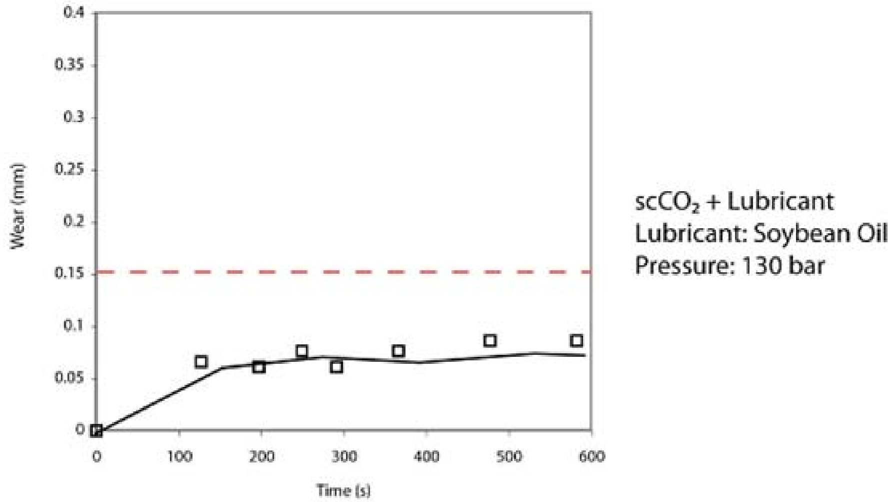


Figure 25. Tool wear in titanium turning operation using $scCO_2$ for cooling and soybean oil for lubrication (Claren, 2008).

DESIGN A REFILL OIL SENSOR IN THE PRESSURE VESSEL In order to validate the oil refill concept we have designed and carried out three tests using two thermocouples. Using a smaller pressure vessel, we mirrored the setup of the full scale system with the appropriate valves, nozzles, heating band, etc. The first test was to run the system with just $scCO_2$ to verify that each thermocouple received the same amount of heat from the heating band. As can be seen in Figure 26 below, the thermocouples responded in the same manner to the heating band.

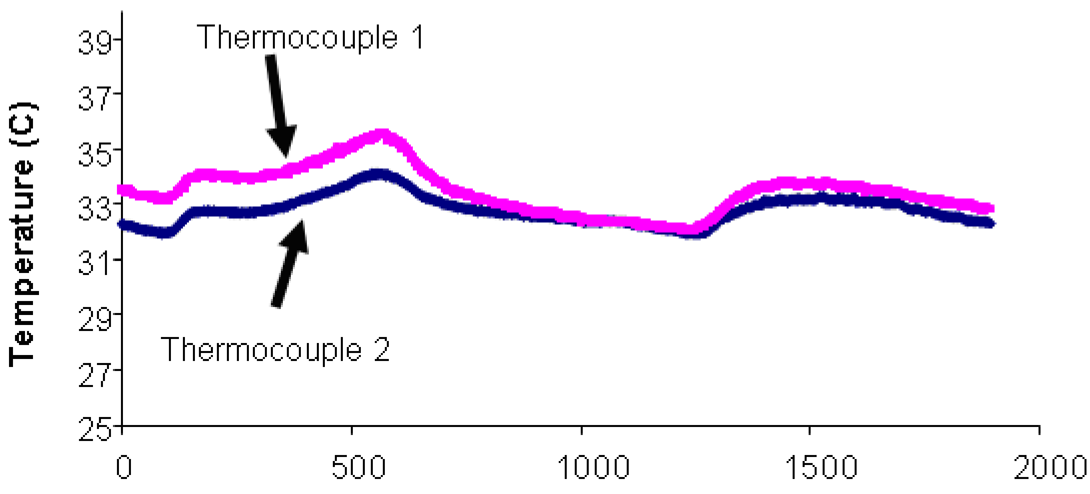


Figure 26 – The temperature gradients of Thermocouple 1 and Thermocouple 2 are equal when only scCO2 is inside the vessel.

The next test simulated the situation in which there was enough oil inside the pressure vessel. Hence, the vessel was pressurized into the supercritical range with one thermocouple immersed in oil and a second thermocouple in $scCO_2$. After the heating band was turned on, the temperature gradients of each thermocouple were recorded. The results of the tests are shown in Figure 27.

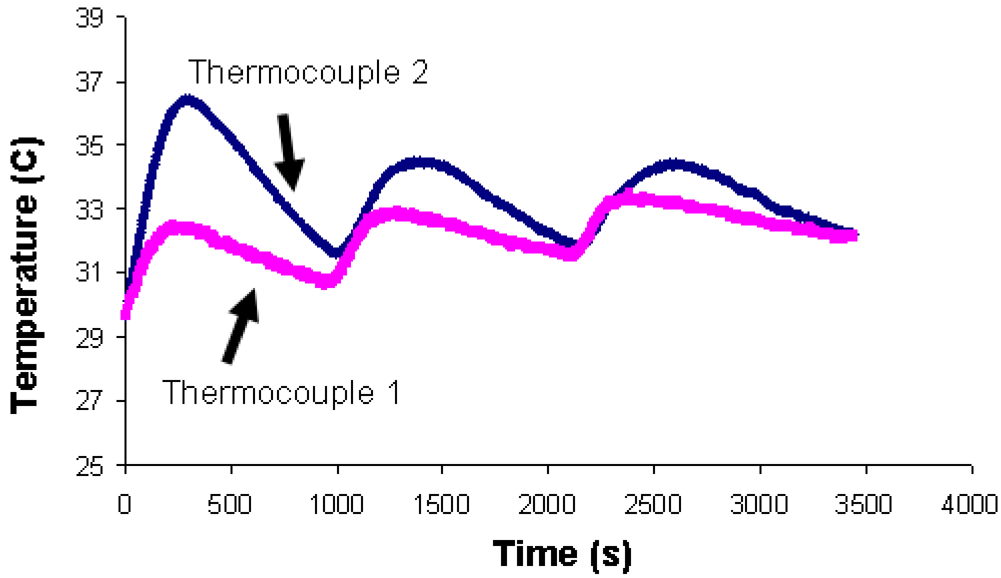


Figure 27 – The temperature gradient of Thermocouple 1 (scCO2) differs from the temperature gradient of Thermocouple 2 when in oil.

The final test was run with oil in the bottom of the vessel but with both thermocouples in the $scCO_2$' simulating the empty condition. This test was run to ensure that the presence of oil in the bottom of the vessel did not affect the temperature gradient of the bottom thermocouple. The results can be seen in Figure 28.

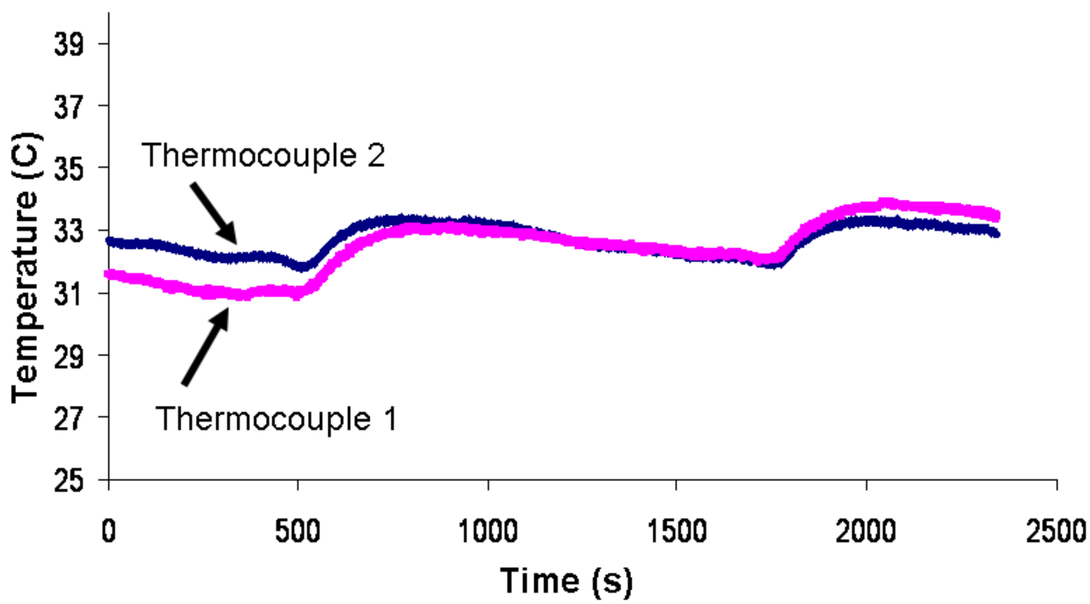


Figure 28 – The temperature gradients of Thermocouple 1 and Thermocouple 2 are equal when the oil level is below Thermocouple 2.

Testing reveals that the temperature of oil changes much faster than that of the $scCO_2$, confirming the theoretical analysis.

DISCUSSION

While the components used in the new system satisfy the original design criteria, some realizations were made throughout the process of assembling the system. This section details the strengths and weaknesses we've identified in the system as it was assembled, and these should be taken into account when replicating the system. We are confident that this system will perform as expected, but further research will ensure that every component is exactly the right choice.

The selected OC-11 reactor more than meets all the criteria specified for the pressure vessel. It is rated at 12,500 psi allowing for experimentation with pressures up to 6250 psi while maintaining a safety factor of 2. The cap screws on and off making it very easy to replace the oil in the vessel, and the customized number of ports allows for many different configurations during testing. Results from testing of the cart currently in use at one of Ford's facilities indicate that a small volume is not desirable because the pressure and temperature are prone to small fluctuations. The large volume of the OC-11 reactor helps stabilize the system by preventing small fluctuations in pressure. However, this large volume also makes the system bulky and increases the time for the system to reach a state of equilibrium. The geometry of the vessel also makes cleaning the interior difficult. The customized nature of the vessel resulted in an increased cost and a longer lead time. While the vessel satisfies the requirements that were set for it, the requirements did not completely encompass all possible design considerations; therefore, a different vessel may be desirable in future systems. Ideally, an analysis would be conducted to determine the smallest possible volume that is not prone to pressure and temperature fluctuations. An investigation into the effects of the geometry of the vessel would also be helpful, but could also be very expensive as several different vessels would be required.

The mobile cart from Grainger satisfied the design criteria. It is able to withstand the weight of the system components with a suitable safety factor. The large surface area of the shelves accommodates the sizes of the system components, and also allows plenty of extra space for a computer and tools. The bulkiness of the cart and the fact that only the front wheels are able to steer make it difficult to maneuver in tight spaces. Some advantage would be gained by constructing a customized cart that is tailored to the size of the system so that the cart is no larger than necessary. Four wheel steering would drastically help with maneuvering, and pins could be used to lock the back wheels into the forward direction for pushing the cart down a hallway or across a plant. The Grainger cart also lacks wheel brakes, which could be problematic on steep inclines. While the system is designed and expected to be used exclusively on level ground, the addition of brakes would make it more versatile and safer.

The use of thermocouples to determine when the vessel needs to be refilled is very effective. It gives a clear indication of when the oil level has fallen below a set point in the vessel, and the concept is very straightforward. The temperature gradients when the fluid inside the vessel is heating and cooling can be monitored by LabVIEW and an automated alarm can be implanted so that the operator doesn't have to monitor or analyze any data. The design also allows for future testing which could eventually lead to an oil level indicator. Since the specific heat of a substance is dependent on the mass of the substance present, it is certainly possible that small changes in the temperature gradient of the oil could be used to determine the mass (and therefore the volume) of oil remaining in the vessel. However, having two thermocouples in the vessel occupies two inlets on the pressure vessel, preventing additional CO_2 inputs or fluid outputs. If another inlet or outlet is needed for a specific experiment, one of the thermocouples can be temporarily removed for the experiment, but this will obviously disable the oil refill alarm.

RECOMMENDATIONS

When completing this project we relied on two bill of materials provided for us from prior systems. However the bill of materials failed to incorporate everything that was needed to assemble the entire system. While all large components were ordered and assembled a couple small components need to be purchased to complete the system assembly. Table 3 shows a table with all the parts that must still be ordered. We recommend ordering these parts as soon as possible because we learned that lead times are often much longer that what the suppliers claim.

Company	Description	Part Number	Quantity
High Pressure	Female Taper Seal to Male High Pressure	15-21AF1HM4	3
	Female Taper Seal to Male Taper Seal	15-21AF1AM2	1
	1/8" Tube Gland	15-2AM2	2
	1/8" Tube Sleeve	15-2A2	2
	Female to Female Coupling Adaptor	15-21AF2	1
	10 ft High Pressure Tubing 1/8" OD	15-9A2	1
National Instruments	NI SCC-CI20 Pressure Transducer Input Module	777459-05	1

Table 3 – Components that must still be purchased.

Once these parts are ordered and assembled we recommend extensive testing. Testing on the overall system should be completed through turning and tapping tests as are currently performed using the old system. If the results of the tests using the new system are as good as or better than the results obtained using the old system, that will validate the new system.

In order to test the thermocouple refill sensor, the system should be used in machining operations, starting with a vessel full of oil and running until there is little to no oil remaining in the vessel. Completing this test multiple times will provide an experimental temperature gradient for both oil and $scCO_2$ in the system. An algorithm for automatically examining and analyzing the gradients should then be coded into LabVIEW. In addition, we recommend gathering extensive data on the behavior of the temperature gradients at many different oil levels to explore the feasibility of using the temperature gradients to determine the actual level of the oil. As the oil level drops the fluid composition will change. The temperature gradient will be affected by this and, with further research, it may be possible to determine how the gradient is affected by the level of oil in the vessel.

We also recommend additional testing resources be spent on determining the amount of time the system takes to reach equilibrium when first started up. If a long ramp-up time is required for the system to reach equilibrium after the vessel has been disassembled for refilling, a continuous flow of oil into the vessel may be valuable as it would allow the system to run for extensive amounts of time without interruption. Experimentation could be completed using an existing HPLC pump in the EAST Lab to determine if the system ramp-up time could be reduced or even eliminated using this technique.

Finally, testing with multiple inlets for CO_2 should is highly recommended. Tool wear and torque data from turning and tapping tests, respectively, should be collected using one inlet and then using two inlets of CO_2. The data from the two should then be compared to determine the effect of the additional inlet. The thermocouple on the bottom of the vessel could be temporarily removed so that two CO_2 inputs could be placed on the bottom to determine if two streams of CO_2 bubbling up through the oil affect the composition of the fluid or the ramp-up time of the system. If results show that it is desirable to have multiple CO_2 inlets on the bottom of the vessel, future vessel design criteria should take into account the need for at least three ports on the bottom (one for the thermocouple, at least two for CO_2 inputs). Depending on the geometry of the vessel, it may be possible to add a port through the side of it for the thermocouple, freeing up one of the ports on the bottom of the vessel.

CONCLUSION

Nearly two billion liters of water-based and straight oil metalworking fluids are consumed each year. These forms of MWF utilize a non-renewable source of mineral oil and can create serious health risks for workers. As a result, Professor Steve Skerlos and his colleagues at the University of Michigan have successfully developed an alternate MWF that uses soybean oil dissolved in supercritical carbon dioxide. This system is actually more effective than traditional flood MWFs in both turning and tapping operations tested thus far. The design goal of this project is to further enhance the current system by producing a higher flow rate, developing an oil refill indicator, and developing a method for tuning the $scCO_2$-oil mixture.

Multiple concepts were generated for each design requirement and the concepts were narrowed down based on their ability to fulfill the criteria. The method for ultimately choosing our final design was driven by engineering analysis. The P-350 from Thar Technologies pump was selected because it satisfied the required flow rate and pressure, delivering a maximum flow rate of 350 grams/minute at a maximum discharge pressure of 5,000 psi. The OC-11 Reactor pressure vessel from High Pressure Equipment satisfied the required volume and pressure rating, 1 liter and 12,500 psi, respectively. Using heat transfer analysis and heat capacity values we projected that two thermocouples placed at different locations in the vessel could be used as an oil refill indicator. Experimentation using an existing system confirmed that the concept will work, though tests still need to be run using the new cart to completely validate the design. Finally, the cart was selected based on its load capacity and size so that it can safely hold all of the system components without any danger of tipping.

While all of the large components of the system are assembled, a few small but necessary components have yet to be ordered. Once these small components are ordered and assembled into the system, it will be ready for use. Tests will be conducted to validate the system as a whole, determine temperature gradients of the different compositions in the vessel, study the effect of multiple inlets of CO_2, and quantify the amount of time required to reach equilibrium. The new system is more versatile so that new experiments can be conducted with higher pressures and flow rates, which was not possible with the previous system.

ACKNOWLEDGEMENTS

Team 26 would like to personally thank: Steve Skerlos, Doug Maclean, Angela Park, Andres Claren, Bob Coury, Amanda Gaytan, Kelly Talcott, and Kathy McCrumb for their help, guidance, time and most importantly their patience.

INFORMATION SOURCES

METAL WORKING FLUIDS BACKGROUND Metal Working Fluids (MWF) are used in many manufacturing processes including forming, cutting, tapping, etc. MWFs provide a critical need for manufacturing because they provide lubrication and cooling of the metal and tool as well as increase the tool life, part quality, and help to accelerate manufacturing time (S.J. Skerlos et al., 2008). As can be seen below in Figure 29, metal working fluids account for a significant amount of total manufacturing costs.

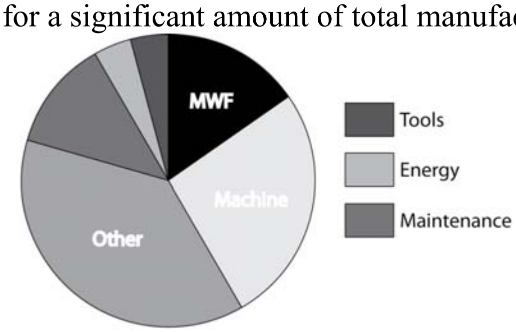


Figure 29. Total metal manufacturing costs (Claren, 2008).

WATER-OIL BASED MWF DELIVERY SYSTEM The most common MWFs are aqueous combinations of oil and water. However, the two do not mix. Therefore it is necessary to provide surfactants which chemically bind oil and water. Additives are then needed for antifoaming, rust preventatives, extreme pressure, stunting bacteria growth, etc (S.J. Skerlos et al., 2008). While the combination of these additives and surfactants has suited manufacturing needs of lubricity and cooling, they are very expensive, harmful to the environment, and harmful to workers.

The largest costs associated with MWF, as seen in Figure 30, are disposal and equipment. Much of the equipment cost is associated with pumping large amounts of fluid around a manufacturing plant with piping, bins etc. (Clarens, 2008). Eventually after repeated use the MWF has a high level of biological growth and deteriorated performance causing for the fluid to be disposed of (S.J. Skerlos et al., 2008). This disposal is very costly, even larger than the initial purchase cost.

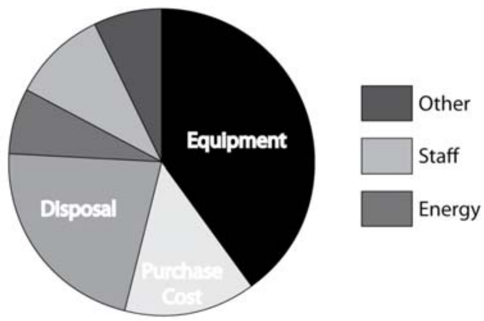


Figure 30. Breakdown of MWF costs (Claren, 2008).

Annually, 2 billion liters of MWF are used worldwide, however, it is estimated that the waste is close to ten times greater due to the need for dilution of chemical additives (Bartz, 1998). Currently combinations of aerobic, anaerobic, membrane, activated sludge, and oxidization processes are used to treat MWFs. This disposal cost the United Kingdom $32 million dollars yearly (Cheng et al., 2005).

Further while the MWF is treated, it still poses environmental concerns. Specifically, Nitrogen Oxides, Sulfur Dioxide, Hydrogen Chloride and heavy metals are all found in treated MWF wastewater (Cheng et al. 2005). When these contaminants are returned to the water supply they can cause oxygen depletion, wildlife contagion, and nutrient loading. (Clarens, 2008).

These aqueous fluids are also very harmful to workers. Continuous reports of Hypersensitivity Pneumonitis (HP), an inflammation of the lung caused by foreign particles, have been shown in MWF plants. (Hodgson et al., 2001) Initial exposure by misting, MWF and bacteria particles being carried through the air, causes acute lung disease but prolonged exposure can cause chronic lung disease. Chronic lung disease often results in pulmonary fibrosis, an irreversible scarring of lung tissue. (WebMD, 2008) In the United States alone 1.2 million people are exposed daily to MWFs with risk of developing such diseases. (Hodgson et al., 2001) Even more serious diseases have been found in these aqueous fluids including bacteria such as *Legionella sp.* and *Mycobacteria sp.* (S.J. Skerlos et al., 2008).

MQL-MWF DELIVERY SYSTEM Due to all of these issues, some manufacturers are attempting to move to away from water and oil MWF and instead toward gas-based Minimum Quantity Lubrication (MQL) systems. (Li, 2007) MQL in machining is the use of 100 ml/hr of MWF or less. A typical method for MQL is to deliver a very small amount of oil mixed with a copious amount of high pressure air to the work piece. (Liao, 2007) Oil and gas can be delivered without the need for surfactants and additives, removing bacteria growth in MWFs and in turn providing a safer environment for workers. There is much less equipment associated with air-based fluids because the fluid will no longer be pumped around a manufacturing plant, and since only the minimum required quantity of oil is used there is no need for collection and recycling of MWFs. Disposal costs and environmental impact are greatly reduced as both air and renewable oils are used.

However, there are still some problems with MQL delivery systems. First, mixing oil and air is a tedious process and current methods have issues with response, stability, and control of fluid delivery. Chip removal is another issue to consider when using MQL. The work piece is not flooded with MWF and therefore excess material is not carried away and alternative methods must be used. Lastly, using larger tool speeds around 125 m/min the effectiveness of MQL systems is greatly reduced. (Liao, 2007)

scCO_2 MWF DELIVERY SYSTEM Since the air and oil MQL systems are less effective, a different kind of MQL system utilizing scCO_2 has been developed and has shown better results than both aqueous and current air based solutions. The benefit of scCO_2, like other gas-based MWFs, is that the oil and fluid mix without the need for additives. As seen in the phase diagram in Figure 31, the super critical point is reached at a temperature of 304 K and a pressure of 72.8 bar. In this region, scCO_2 is neither a liquid nor a gas. In this super critical state it is denser than a gas, but less dense than the liquid.

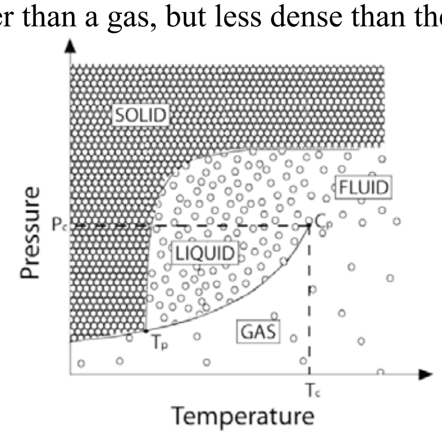


Figure 31. Phase diagram, illustrating the critical point of CO_2

Currently a scCO_2 system is being tested for cooling capacity, tool life, and lubricity. A schematic of the current design is shown in Figure 32.

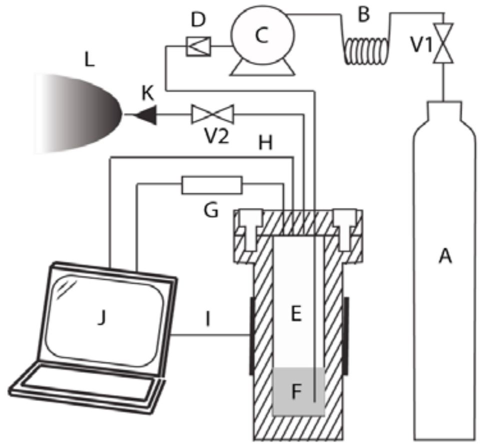


Figure 32. Schematic of current $scCO_2$ system. (A. cylinder of food-grade CO2, B. cooling unit C. pump, D. one-way valve, E. high pressure vessel, F. heating element, G. soybean oil, H. pressure transducer, I. thermocouple, J. computer, K. data acquisition device, L. nozzle, M. lathe, V1 and V2 are valves) (Claren, 2008).

The MWF delivery system uses food-grade CO_2 at 700 psi and compresses it to 1100 psi. The CO_2 is then bubbled into a pressure vessel containing soybean oil. The oil then dissolves in the CO_2 and the mixture is delivered to the metal via a nozzle (S.J. Skerlos et al., 2008).

Testing of this experimental setup has provided astounding results. Not only is $scCO_2$ with soybean oil better for the environment and for factory workers than other MWF systems, but it has shown a higher cooling potential and lubricity than other typical MWFs including a water and petroleum oil mist. Extensive research into the tool life has also been done. Using this $scCO_2$ system, less flank wear was observed on the face of the tool. Another surprising result is that increasing the pressure of the CO_2 raises the cooling potential and allows for an increase in oil concentration, which in turn increases lubricity. In water based MWF systems, there has been a tradeoff between lubricity and cooling. Therefore being able to provide both more cooling and lubricity is a major advantage to this $scCO_2$ system (S.J. Skerlos et al., 2008).

BIOS

Daniel Leader is a mechanical engineering student at the University of Michigan. He is from Sterling Heights, Michigan which is about an hour east of Ann Arbor. He has been interested in engineering from the time he was pretty young. Both of his parents work for General Motors Powertrain in Warren and his dad has always been interested in cars and motorcycles which was passed down to Dan. He also has a sister who is a freshman at the University. His future plans as of now are to get a job in an engineering field and work for a few years before going back to school to receive a higher degree. He is an active member in the fraternity of Phi Gamma Delta here on campus and lives on the corner of Hoover and State Street. College football is one of his favorite pastimes and football season here at the University is the best time of year.

David Powers is a mechanical engineering undergraduate student at the University of Michigan. He was born in Philadelphia, Pennsylvania and lived there until he was 7 years old. After moving to Shaker Heights, Ohio he attended Shaker Heights High School. Right after high school, David moved back to Pennsylvania to Newtown, less than an hour outside of Philadelphia. He still considers Philadelphia to be his home town, and religiously roots for all of the local teams. David became interested in engineering in high school once he realized that reading and taking a foreign language were not part of the curriculum. He has always enjoyed math and science far more than any English classes. Upon entering the University of Michigan he considered becoming an aerospace engineer. The summer before his freshmen year he was able to travel to Cape Canaveral, Florida to witness the launch of a commercial cable television satellite. However when deciding to declare his major he determined that although he enjoyed aerospace, the industry is narrow and provides some limitations specifically in terms of job location and smaller job market than mechanical engineering. Therefore, he decided to declare as a mechanical engineer and now as a senior to get a job any day now. After getting a job, David hopes to save enough money to return to the classroom to get his masters in mechanical engineering.

Steve Hecker will be graduating the University of Michigan in December 2008. He has lived his entire life in Kalamazoo, MI with his father Kent, mother Teresa, older sister Amanda, and younger brother Mathew. His father played in the University of Michigan marching band from 1970 to 1974. He graduated with a degree in Pharmacy and has worked for Pfizer for thirty years. His sister teaches third grade and his brother is currently a freshman at Michigan. Steve received three varsity letters and will work for The Dow Chemical Company this summer.

Daniel Merz is an undergraduate student in the mechanical engineering program at the University of Michigan in Ann Arbor. He will graduate in April of 2008 with a BSE in Mechanical Engineering and plans to immediately enter the workforce, though it is likely that in the future he will return to school for graduate studies. Dan owes much of his inspiration to become an engineer to his grandfather, who worked as an engineer at Ford for many years, as well as his parents who have been very supportive. He has lived his entire life in Dexter, MI, graduating from Dexter High School in 2004. Dan has played the trumpet in the Michigan Marching Band the last four years, and attained Rank Leader status in 2007. Music has been a large part of his life since childhood, starting piano lessons when he was 7 years old and then picking up the trumpet in middle school. Although he turned down a scholarship to enter the music education program at Western Michigan University, he still enjoys playing in multiple ensembles at the University of Michigan. Outside of the classroom and the band, Dan enjoys spending time with friends and family, as well as downhill and water skiing. He has spent the last four summers interning in the engineering department at NSK Corporation in Ann Arbor. Though his career may take him elsewhere in the near future, he ultimately hopes to return to the Ann Arbor area to settle down and start a family.

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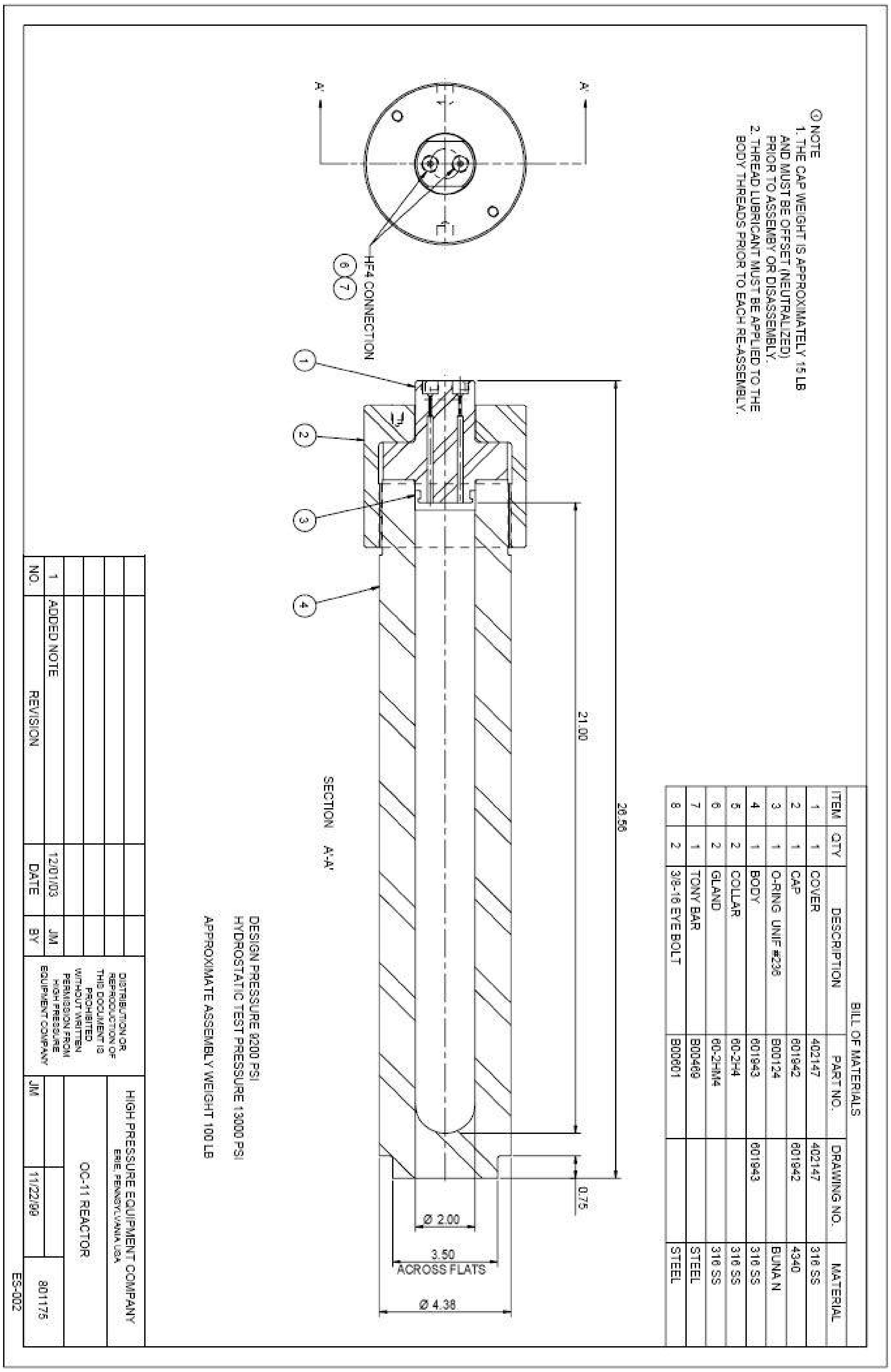
APPENDICES

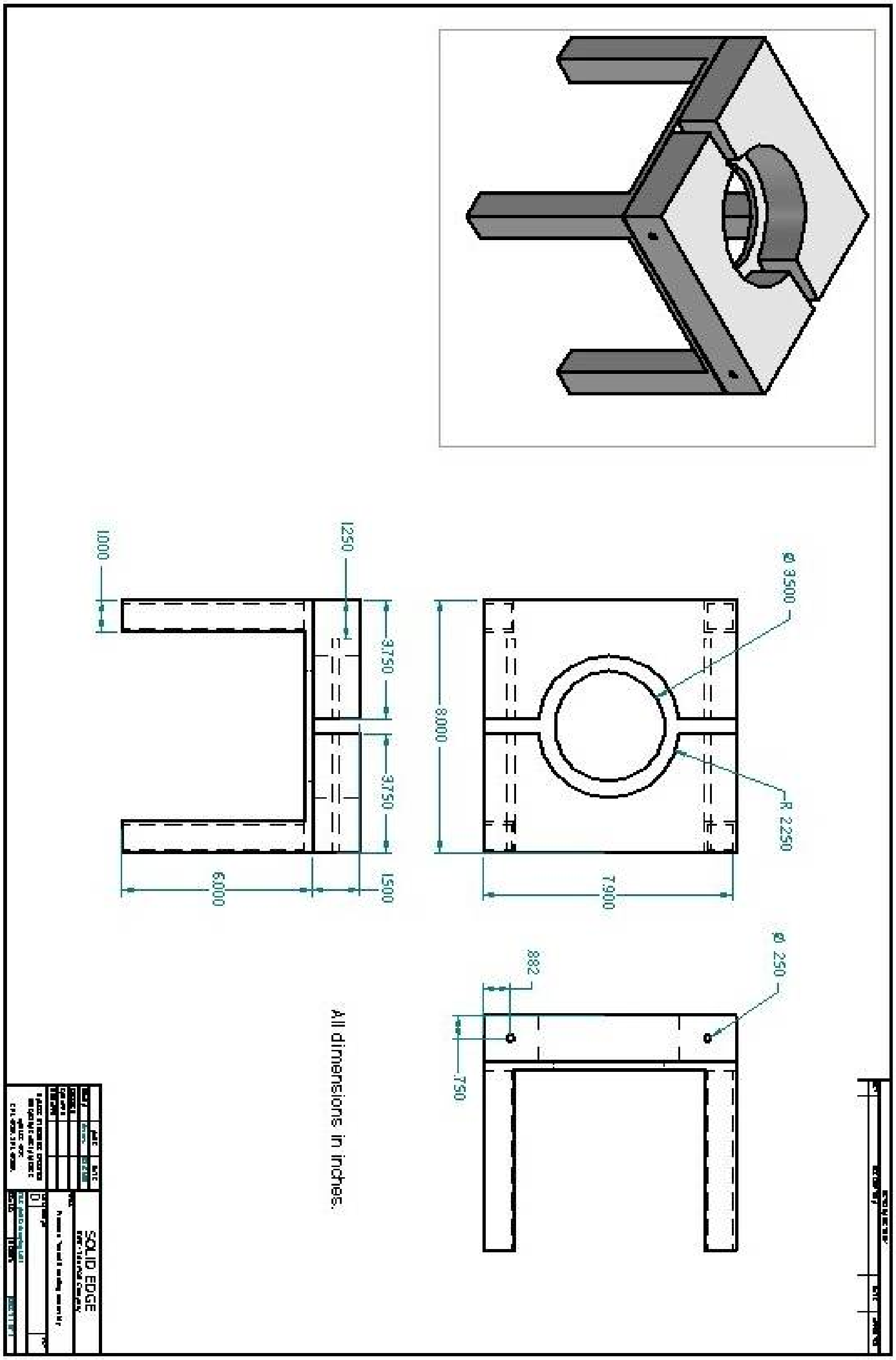
Appendix A: Bill of Materials

Bill Of Materials for ME 450 W08 Team 26 Cart					
Company	Description	Part Number	Quantity	Unit Price ($)	Price ($)
Jack's Hardware	Teflon Tape		1	1.29	1.29
	Electrical Tape		1	1.59	1.59
	Crescent Wrench		1	4.29	4.29
	3/8" Washers		12	0.11	1.32
	3/8" Vinyl Tubing (feet)		6	1.00	6.00
	1/2" Vinyl Tubing (feet)		6	1.00	6.00
	3/8" Bolts 5" Long		2	1.20	2.40
	3/8" Bolts 2" Long		4	0.80	3.20
	3/8" Nuts		4	0.30	1.20
Julabo	Recirculating Cooler	F200	1	2490.00	2490.00
High Pressure	Taper Seal Gland	15-2AM1	30	4.30	129.00
	Pressure Vessel	OC-11	1	4395.00	4395.00
	Taper Seal Sleeve	15-2A1	40	2.50	100.00
	High Pressure Tubing - 1/16", .030" ID	15-9A1-030	50	3.95	197.50
	Adaptor	15-21AF1NMB	3	31.00	93.00
	Thermocouple Adaptor	15-21AF1HM4-T	2	49.50	99.00
	3-Way Valve	15-15AF1	3	170.00	510.00
	1-Way Valve	15-41AF1	1	91.00	91.00
	Tee Type Safety Head	15-63AF1	1	120.00	120.00
Tempco	Band heater	TNB01051	2	95.35	190.70
TharTech	Pump	P-350	1	16380.90	16380.90
Sensotec	Pressure Transducer	TJE-0743-11TJG	1	560.00	560.00
	Assembly Cable	060-0603-17	1	75.00	75.00
	Transducer Amplifier	UV BE 124	1	329.00	329.00
National Instrument	Signal reader	SC-2345	1	349.00	349.00
	1-Channel Relay Module	SCC-RLY01	1	79.00	79.00
	1-Channel Thermocouple Input Module	SCC-TC01	2	169.00	338.00
	PCMCIA Card for laptop	778561-01	1	1099.00	1099.00
	K-type thermocouple wire-30m	745787-k030	1	99.00	99.00
Grainger	Service Cart 24 x 36 in.	1NFD6	1	512.00	512.00
Omega	K Type Thermocouple	KQSS-116G-12	2	22.00	44.00
	K thermocouple male connector	SMPW-K-M	2	1.75	3.50
Zook	Rupture Disks type PB	060628-3034	6	16.83	101.00
RadioShack	13.5/30 VDC Converter	273-1668	1	26.99	26.99
Carpenter Brother's Hardware	Power Strip		1	17.99	17.99
Total					**28456.87**

Appendix B: Engineering drawing of standard OC-11 pressure vessel from HIP



Appendix C: Engineering drawing for vessel mounting plate and clamp assembly



Appendix D: Fabrication instructions for pressure vessel mount

RAW MATERIALS

12”×12” ×1” aluminum (6061) plate
12”×12” 16 gauge stainless steel (304) plate
36” 16 gauge stainless steel (304) 1” square tube

All raw materials can be purchased locally from ASAP Source in Ann Arbor (www.asapsource.com). The total raw material cost is approximately $150.00.

STAINLESS STEEL PLATE

Begin with the 12”×12” stainless steel plate. Using a band saw (100 ft/min), trim the plate to approximately 8.25”×8.25”. The exact size is not important as long as all sides are slightly longer than the final length of 8”. Use a face mill (600 RPM, slow feed) to square up the sides of the plate and finally trim the dimensions down to exactly 8”×8”.

With the mill, use an edge finder (600 RPM) to locate the exact center of the plate. Use a center drill (900 RPM, slow feed) to make a small hole in the center of the plate, and drill the hole thru with a 7/32” drill bit (500 RPM). Use a 1/4” reamer (100 RPM) to widen the hole and ensure that it is perfectly round. Use the mill to locate and center drill the four bolt holes (900 RPM). Use a 13/32” drill bit to drill the holes thru (500 RPM).

Center a rotary table under the spindle of a mill using a dial indicator, then center the plate beneath the spindle by putting a 1/4” drill bit into the spindle and lowering it down so that the bit goes perfectly into the hole drilled in the center of the plate. Secure the plate to the rotary table. Using a 1/4” end/face mill (600 RPM), move the spindle along the x-axis 1.6925”, then plunge the bit through the plate. Slowly turn the rotary table 360°, cutting a hole of exactly 3.635” in diameter.

STAINLESS STEEL LEGS

Cut the 36” length of square stainless steel tube into four lengths of approximately 6.25” using a band saw (100 ft/min). The exact size is not important as long as the pieces are slightly longer than the final length of 6”. There will be some extra tube left over in case a leg needs to be remade. Use a face mill (600 RPM, slow feed) to square up the ends of each leg and finally trim the lengths down to exactly 6”.

ALUMINUM CLAMP

Begin with the 12”×12” aluminum plate. Using a band saw (300 ft/min), trim the plate to approximately 8.25”×8.25”. The exact size is not important as long as all sides are slightly longer than the final length of 8”. Use a face mill (1500 RPM/moderate feed) to square up the sides of the plate and finally trim the dimensions down to exactly 8”×8”.

With the mill, use an edge finder (600 RPM) to locate the exact center of the plate. Use a center drill (900 RPM) to make a small hole in the center of the plate, and fully drill the hole with a 7/32” drill bit (1200 RPM). Use a 1/4” reamer (100 RPM) to widen the hole and ensure that it is perfectly round.

Use the mill to locate to locate and mill the four slots for the bolts with a 3/8” mill (1100 RPM, moderate feed). After milling each slot, remove another 0.015” of material from the sides of the slot using climb milling to allow some clearance for the bolt and give a smooth surface finish. Re-mount the plate on its side and use the mill to locate and center drill the two bolt holes (900 RPM). Use a 5/16” bit drill the holes over half way thru the block, at least 4.25” deep (1100 RPM).

Center a rotary table under the spindle of a mill using a dial indicator, then center the plate beneath the spindle by putting a 1/4” drill bit into the spindle and lowering it down so that the bit goes perfectly into the hole drilled in the center of the plate. Secure the plate to the rotary table. Using a 3/8” mill (1100 RPM), move the spindle along the x-axis 2.125”, then plunge the bit 0.1” into the plate. Slowly turn the rotary table 360°. Lower the bit another 0.1”, then again slowly turn the rotary table 360°. Repeat this procedure until the slot is completely through the 1” plate, producing a hole of 4.625” in diameter.

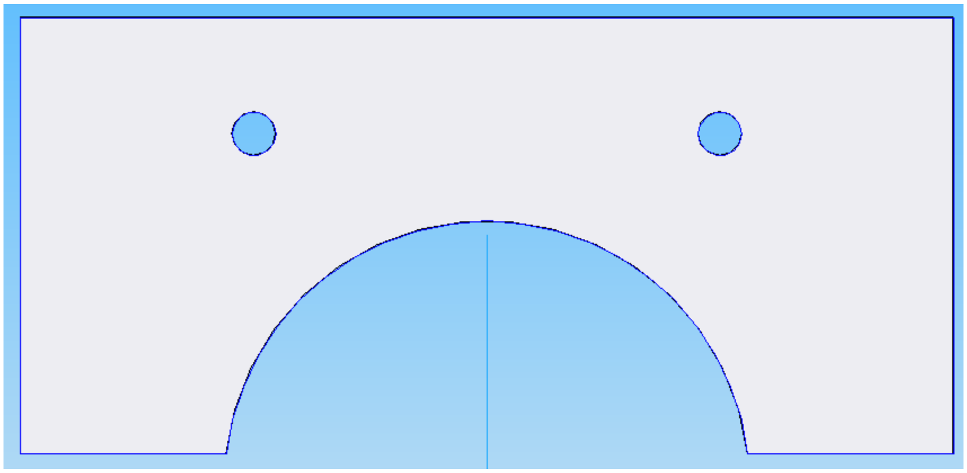
Use a band saw (300 ft/min) to cut the plate exactly in half along the axis perpendicular to the axis of the two 5/16” bolt holes. Fixture the two halves side by side in a vice with the freshly cut faces facing up, and place on a mill. Using a 5/8” mill (1000 RPM, moderate feed), mill 1/4” off of each freshly cut face. Use a 5/16” drill bit to finish drilling the two bolt holes, then use a chamfer tool to chamfer the two holes on one half (300 RPM). Use a 3/8”-16 tap to thread the holes, starting at the chamfer and going as deep as possible. On the other half, widen the two bolt holes using a 13/32” drill bit (1100 RPM).

ASSEMBLY

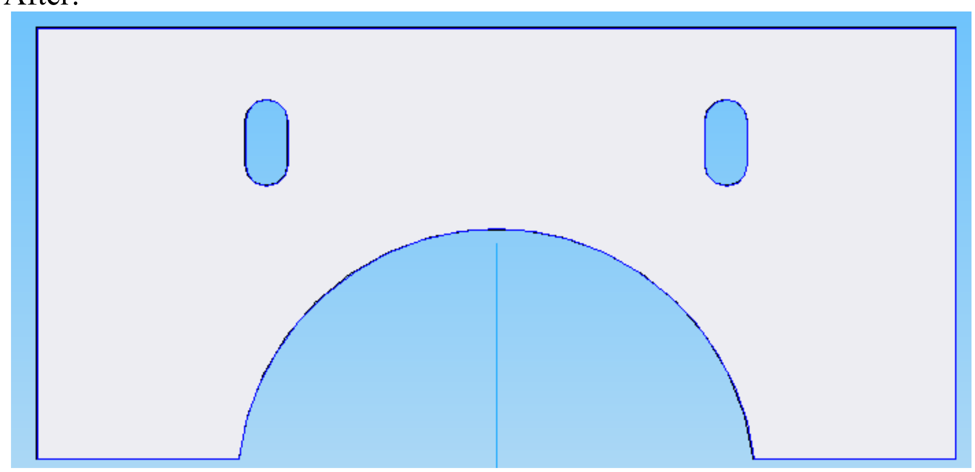
Fillet weld the four legs onto the corners of the stainless steel plate, then fillet weld the legs to the bottom shelf of the cart, centering the plate directly under the location where the 4.625” hole will be cut in the top shelf of the cart. Loosely bolt the two halves of the aluminum clamp onto the stainless steel plate using four 2” long 3/8” bolts and nuts, with washers on both sides. Loosely bolt the two halves together using two 5” long 3/8”-16 bolts, with at least one washer per bolt. Once the vessel has been inserted, then these two bolts should be tightened, followed by tightening of the four short bolts.

Appendix E: Engineering Change Notice

Before:



After:



Notes: Slots allow clamp to slide so that it can be easily tightened around the vessel.

Team 26
Project: $scCO_2$ delivery system
Ref Drawing: Vessel Clamp
Engineer: Dan Merz 4/3/08
Authorized Change: Bob Coury 4/3/08

Appendix F: Group Assignments

Material Selection Assignment

1. Legs and plate for pressure vessel mount
    a. Function
        i. Support the vertical load of the pressure vessel
    b. Objective
        i. Inexpensive and resist buckling under pressure vessel load
    c. Constraints
        i. Legs must be 6 inches in length
        ii. Legs and plate must be made of the same material to allow for welding
        iii. Legs must be able to weld to stainless steel cart
        iv. Must support 122 lbs vertically
        v. Support torsional load applied when opening pressure vessel
        vi. Corrosion resistant
2. Material Indices
    a. Column, minimum cost, buckling load prescribed
        i. $E^{1/2}/(C_m \rho)$
    b. Freshwater
    c. Non-Flammable
    d. Weak acids and alkalides
3. Top Five Material Choices
    a. Wrought austenitic stainless steel 304
    b. Alumina (85) (410)
    c. Brick (Common, Hard) (2.25)
    d. Glass Ceramic (N11)
    e. Ni-Cr White Cast Iron (BS grade 3G)
4. Final Choice
    a. Stainless Steel 304
        i. Availability
        ii. Allows for easy welding to the stainless steel cart
        iii. Able to support load
        iv. Corrosive Resistant
        v. Minimizes cost and is able to resist buckling
1. Pressure vessel Clamp
    b. Function
        i. Resist torsion required to open the pressure vessel
    c. Objective
        i. High strength but small weight
    d. Constraints

i. Easily machined
ii. Must be 1” thick block
iii. Available

5. Material Indices
   a. Beam, minimum weight, strength prescribed
      i. $\sigma^{2/3}/(\rho)$
   b. Non-Flammable
   c. Freshwater
   d. Less than 10 pounds (density must be less than .156lbs/in^3)
   e. Yield Strength greater than 10 ksi
   f. $ 7.5/lb
6. Top Five Material Choices
   a. Glass Ceramic (N11)
   b. Wrought aluminum alloy 6060 – T6
   c. Graphite (pure)
   d. Alumina(88)
   e. Silicon
7. Final Choice
   a. Wrought aluminum alloy 6060 – T6
      i. Easy to machine
      ii. Available from local supplier
      iii. Strong and lightweight
      iv. Able to resist torsional load

Design for Assembly

1. Assemble legs and plate for pressure vessel mount

1	2	3	4	5	6	7	8	9	Name of Assembly
Part ID Number	Number of times the operation is carried out	2 digit manual handling code	Manual handling time per part	2 digit manual insertion code	Manual insertion time per part	Operation time, seconds (2)	Operation cost, cents, 0.4*(7)	Figures for estimation of theoretical	Mounting Block
1	4	00	1.13	00,96	1.5, 12	58.52	23.41	0	Legs
2	1	03	1.69	N/A	N/A	1.69	.68	1	Plate

						60.21	24.08	1	3(1/60.21) = 5%
						TM	CM	NM	$3(N_m/T_m)$

2. Test for minimum number of parts
    a. Do parts move relative to each other?
        i. NO
    b. Must these parts be made of different materials?
        i. NO
    c. Would combination of these parts prevent assembly or disassembly of other parts?
        i. NO
    d. Has servicing of the assembly been adversely affected
        i. NO
3. The most efficient redesign for assembly would be to fabricate the legs and plate as one piece. This would require no assembly whatsoever. However, this would waste large amounts of material, and would not be worth the assembly cost savings. Since our design will not be replicated many times, the total assembly cost is much lower than the material cost.

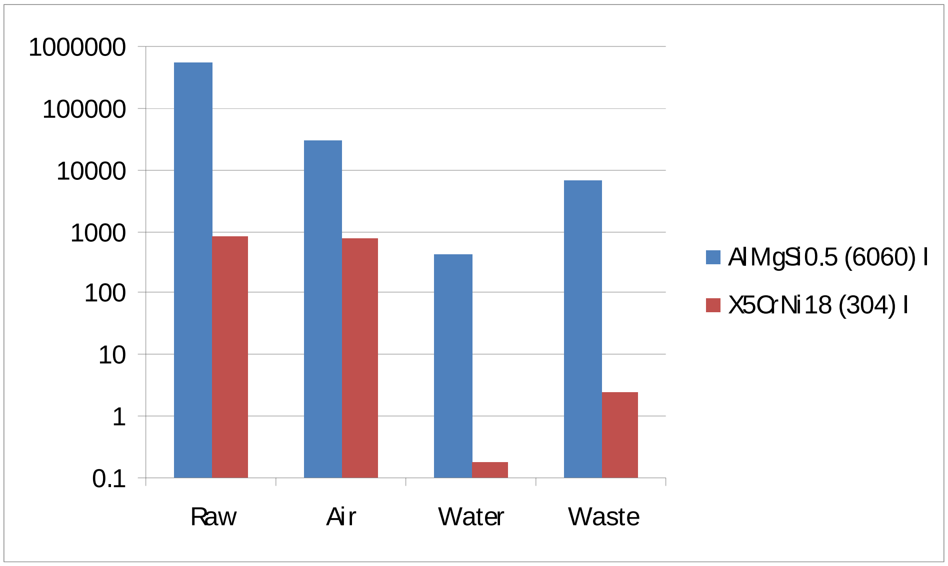
Design for Environmental Sustainability

1, 2, 3.)

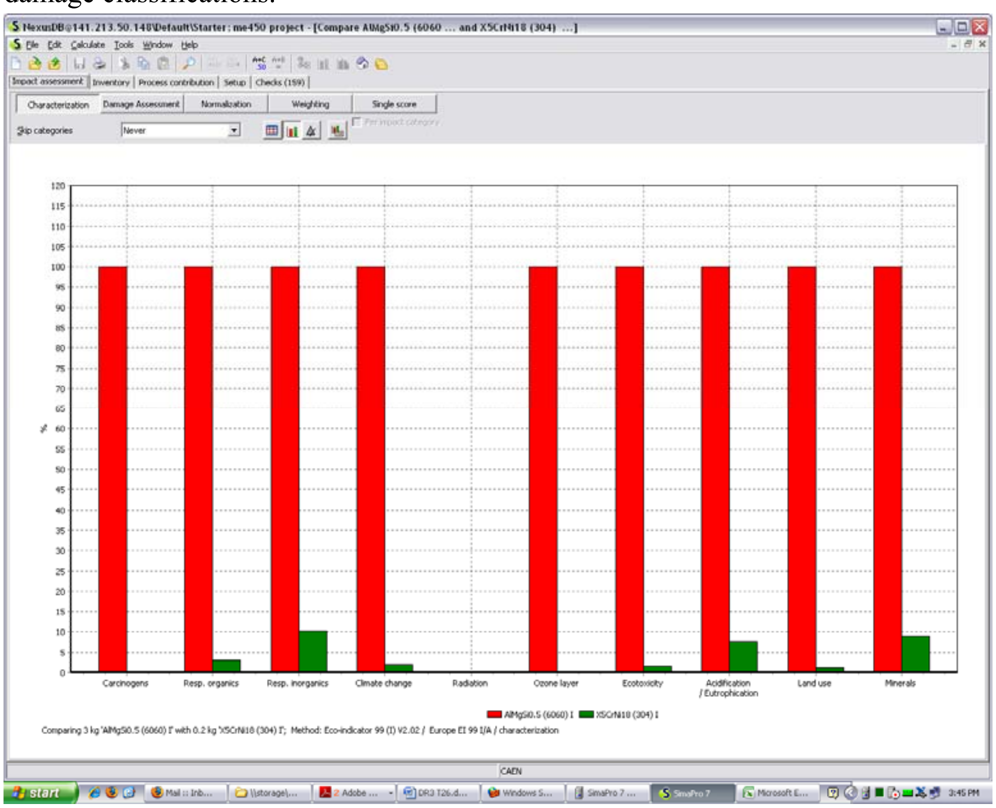
a. Stainless Steel – X5CrNi18 (304) 0.2 kg

b. Aluminum – AlMgSi0.5 (6060) 3 kg

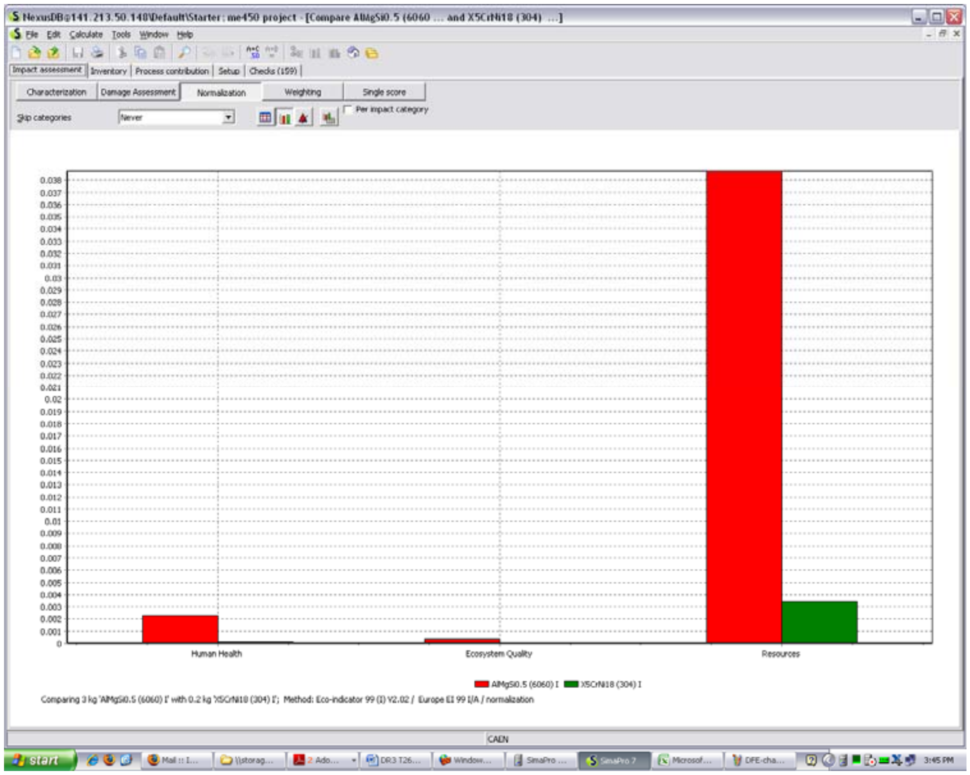
4.)



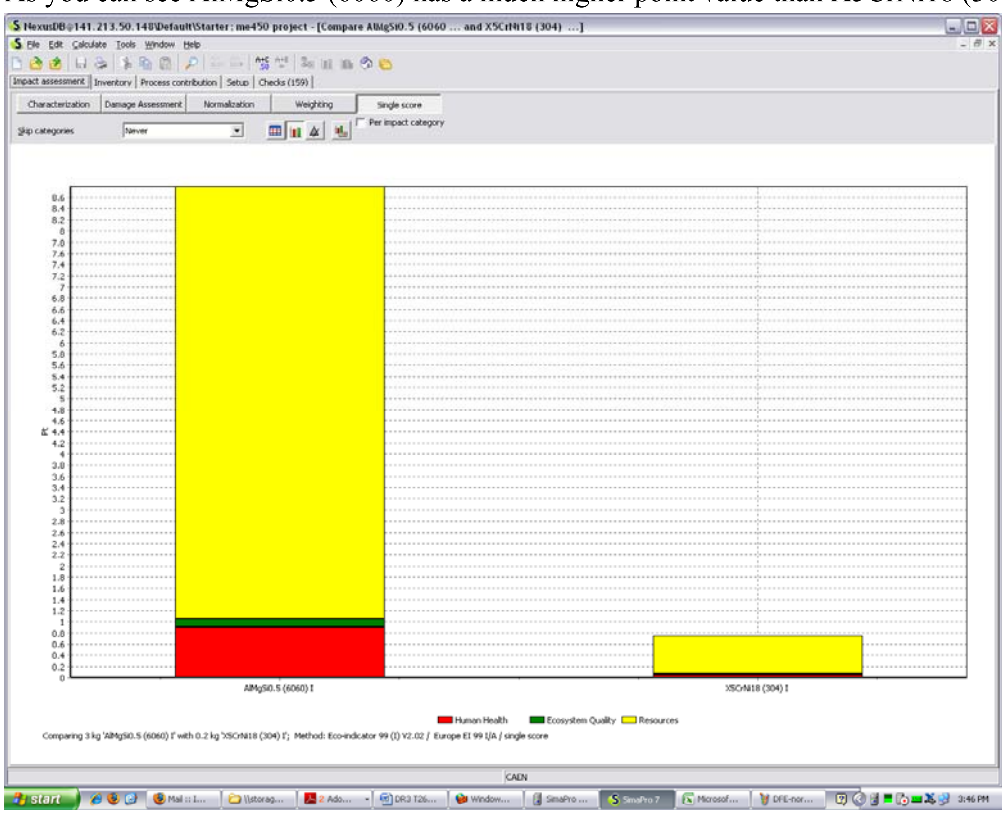
5.) As you can see AlMgSi0.5 (6060) has a bigger impact within each of the EcoIndicator 99 damage classifications.



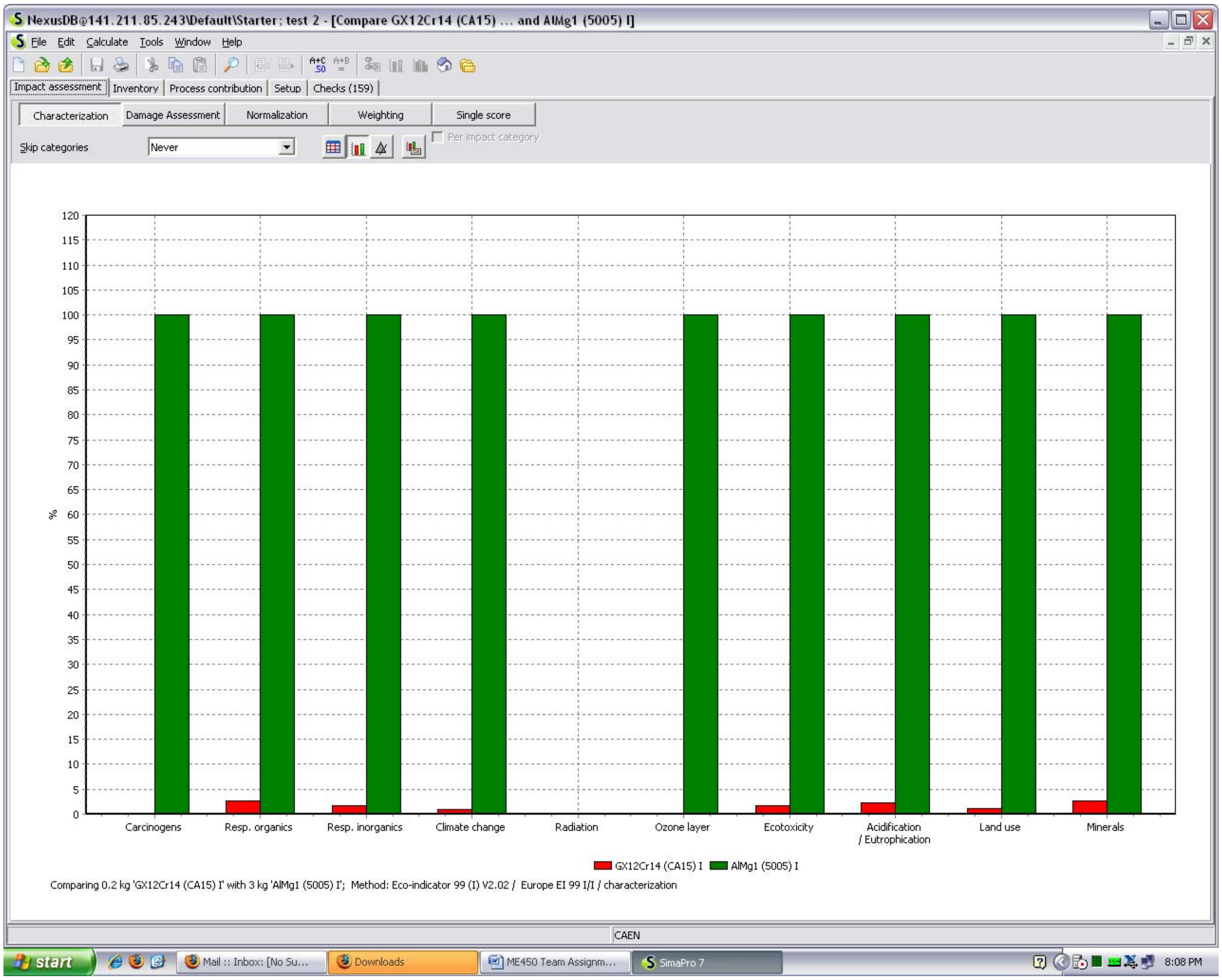
6.) As you can see Resources is much more likely to be important than ecotoxicity and human health.



7.) As you can see AlMgSi0.5 (6060) has a much higher point value than X5CrNi18 (304).



We conducted the same analysis for another choice of stainless steel and aluminum as seen in Figure 4. These results show that the environment mental impact of GX12Cr14 (CA15) stainless steel and AlMg (5005) aluminum are very similar to the materials previously selected. With this in mind, it would not be necessary to change the two types of materials we selected that best suited our needs.



Design for Safety

1.) The major risks can be seen in Figure 5. The major risks are the vessel falling over and exploding, high pressure air in your eye, and placing the vessel into the mount. All three of these are high level risks but very unlikely to actually occur.

	Item Id	User	Task	Hazard Category	Hazard	Cause/Failure Mode
8	1-1-8	All Users	All Tasks	fluid / pressure	high pressure air	When working on the mounting block, a high pressu

	Item Id	User	Task	Hazard Category	Hazard	Cause/Failure Mode	Severity	Exposure	Probability	Risk Level
1	1-1-1	All Users	All Tasks	mechanical	crushing	Body parts between the 122 lb vessel and the mount when inserting the vessel into the mount.	Serious	Remote	Unlikely	Moderate
2	1-1-2	All Users	All Tasks	mechanical	cutting / severing	Possible sharp edges on plate could cut skin.	Slight	Remote	Negligible	Low
3	1-1-3	All Users	All Tasks	mechanical	stabbing / puncture	Possible sharp corners on plate could puncture skin.	Slight	Remote	Negligible	Low
4	1-1-4	All Users	All Tasks	mechanical	head bump on overhead objects	When working on the mount, user could raise head and contact the top shelf of the cart.	Minimal	Occasional	Possible	Moderate
5	1-1-5	All Users	All Tasks	slips / trips / falls	object falling onto	If an object hit the vessel or mounting block, the vessel could fall over and explode.	Catastrophic	Remote	Unlikely	Moderate
6	1-1-6	All Users	All Tasks	ergonomics / human factors	posture	Since mount is on lower shelf of cart, the user must get down on hands and knees to access it.	Minimal	Occasional	Probable	Moderate
7	1-1-7	All Users	All Tasks	material handling	excessive weight	Removeable sides of aluminum clamp could inflict harm/damage if not handled carefully.	Slight	None	Negligible	Low
8	1-1-8	All Users	All Tasks	fluid / pressure	high pressure air	When working on the mounting block, a high pressure air source may be right next to your head. If there were a computer error that caused the pressure within the vessel to go extremely high, the rupture disk on the vessel would explode.	Serious	Frequent	Negligible	Moderate

2.) Some unexpected risks were seen, including objects falling onto the mount and ergonomic risk. Something that is not ergonomically correct will have long term health risks that are not immediately obvious to the operator. The other hazards such as head bumping and cutting yourself are possible but the severity is minimal.
3.) FMEA is the Failure Mode and Effect Analysis. It is focused on component failures while risk assessment is focused on people failures. It focuses on what people do and the associated hazards and risks.
4.) Acceptable risk is risk that remains after protective measures have been taken and is accepted in a given context. Zero risk doesn't actual exist because everything has a certain risk associated with it.

Manufacturing Process Selection

For our metal working fluid system we anticipate that other professors or companies will want to conduct testing so we estimated that 100 systems would be put into production. With this in mind, we determined the most appropriate manufacturing process for the vessel mount and clamp using the CES Manufacturing process selector. The first thing we had to consider when selecting the manufacturing process for the legs and plate of the pressure meant was the fact the cart had to be made from stainless steel. The cart had to be made from stainless steel to prevent corrosion from chemicals such as other metal working fluids while in a manufacturing environment. This left us with two options for joining the legs to the cart, by either welding or using bolts. Drilling holes in the bottom of the cart and threading the legs would be very tedious and time consuming so we determined welding was our best option. The legs and plate now had to be made of stainless steel to allow them to be welded. We determined that manual metal arc welding was the most appropriate for our particular application. The type of welding can easily be used to join stainless steel materials by using a weld rod to provide filler metal to the weld. This form of welding is very economic for low volume production such as for our system. It is also very effective in compression and tensional loading which this component will be experiencing.

The pressure vessel mount clamp had a few constraints that we first had to consider before determining how it was going to be manufactured. First, the clamp had to be a certain thickness to allow for the two pieces to be bolted around the vessel. As a result, we used aluminum because it was cheap and readily available. Therefore we could no longer weld the clamp to the plate. We considered two methods for shaping our clamp; die casting or machining. Die casting would have been the best alternative for high volume production however, since we only making 100 the costs associated with die casting would be greater than that of machining. Also, aluminum is a soft metal and can be machined fairly quickly. All of the necessary drilling and threading can be completed in a relatively short amount of time for experienced machinists on the mill.