Final Report

MichiganEngineering

Project title: **Supercritical Carbon Dioxide Delivery Through-the-Tool to Metalworking Operations**

Prepared for: **ME 450**
Fall Semester 2006
University of Michigan
Ann Arbor, Michigan

Submitted to: **Steven J. Skerlos, Ph.D.**
Department of Mechanical Engineering
University of Michigan
Ann Arbor, Michigan

Distribution: **Andres F. Clarens**
EAST Laboratory
Department of Environmental Engineering
University of Michigan
Ann Arbor, Michigan

Prepared by: **Team 18**
Chris Frayne
Mohammad Fahim Islam
Diana Platt
Brendan Sherry

Submitted on: **December 14, 2006**

Table of Contents

Executive Summary

The use of supercritical Carbon Dioxide ($scCO_2$) in metalworking lubrication applications has thus far been proven to be very beneficial in such operations as the drilling of hard steels and the turning of hard iron composite steels [1]. Current methods of $scCO_2$ delivery to machining processes such as turning involve the use of an external high pressure spray applied directly to the machining surface. While these methods have shown improved machining properties, the high pressure spray does not associate well with softer metals in drilling applications because of the chips' inability to work its way out of the drill flutes [1]. To address this issue our team will consider the method of through-tool lubrication delivery.

We began our project by benchmarking current through-tool lubrication delivery systems on the internet and found two different styles that are currently being used in the manufacturing industry. The first is a coolant fed inducer which couples a stationary collar to a rotating spindle and delivers the metalworking fluid (MWF) through the center of the tool. The second is a coolant fed bushing which surrounds the drill bit where the drill enters the chuck and delivers the MWF at high pressures along the outside of the drill bit. After discussing our benchmarks with our sponsors, we set up a meeting with Ford to get an up close look at the delivery systems they are currently using. When visiting Ford in Dearborn we learned about another benchmark, Minimal Quantity Lubrication (MQL), which is considered a dry, high pressure system that creates oil-in-air emulsions which are delivered through the tool to the working surface.

Once we completed our benchmarking we evaluated the resources available to us at the university to determine which type of MWF through-tool system would be most practical to work with. After discussing our project with Steve Erskine in the Engineering Resource Center (ERC) at the University of Michigan and receiving several professional opinions, we decided to purchase a tool holder with a coolant induced collar which can adapt to V-flange CAT-40 compatible CNC machines at the University of Michigan. Other systems such as those seen at Ford were deemed impractical due to budget restrictions and while the coolant-fed bushing system would fail to deliver MWFs directly through the tool.

The initial obstacle that we encountered when purchasing a spindle with a coolant inducer was finding one which could withstand the high pressures of $scCO_2$ (greater than 1200 psi). We determined that the optimal approach to solving the pressure issue would be to design our own coolant induced collar which could replace the one currently on the tool holder. After extensive research through different suppliers, we ended up purchasing a through-tool spindle with a removable coolant-induced collar from Collis. They provided us with multiple CAD drawings which aided us in designing a new collar of the tool holder which could withstand higher pressures.

We received the tool holder and developed an alpha design which involved manufacturing a new coolant-induced collar. Our plan was to change the material from brass to stainless steel for material compatibility, incorporate rotary seals, and increase the overall size of the collar to handle high pressures. While the alpha design was a solid overall concept design, it overlooked many of the intricacies that surfaced later on in the design phase. Shortly after developing the alpha design we spent a considerable amount of time on design parameter analysis and design adjustments which we feel addressed all of our design problems. Changes to the alpha design involved the addition of an E/R style collet holder and interchangeable collets to allow for various drill bit sizes. While the collet was rated to seal at pressures as high as 1500 psi, in order to obtain a seal between the tool holder and the collet holder, we welded the shank of the collet holder into the bore of the tool holder. Along with the collet holder and collet we purchased a ¾" drill bit with through holes that were slightly less than 1/8" in diameter. These relatively large through holes allowed us to run a high-pressure tube, with the optimal diameter to length ratio, through the drill bit in order to obtain a relatively large metalworking fluid flow rate (to allow for chip removal) without the CO_2 leaving its supercritical phase prematurely due to pressure losses within the tool holder.

For the manufacturing process of our prototype, since the tolerances of the collar are very strict when dealing with high pressures, we chose to outsource the manufacturing of the collar to Superior Machine. While the collar was being manufactured, we sent the tool holder and collet holder to the welding department at Washtenaw Community College to be permanently welded together to achieve a high pressure seal. At this time we also discovered that the threading on the back of the drill bit would allow us to use a high pressure fitting to seal and secure the metal tubing through the drill bit.

Once we received the manufactured parts from Superior Machine and Washtenaw Community College, we assembled the tool holder and ran $scCO_2$ through the stationary tool holder to determine whether all of the components sealed properly. We found two leaks in the system that we had to address in our final design.

Our final design accounted for the sealing issues that were prevalent in our prototype. First we designed a bushing that would resist movement of the collar in the positive vertical direction, which in turn would prevent the rotary seals from tearing within the collar. Secondly, we designed a conical seal that would seal the interface between the collet holder and the drill bit. Our final modification to the prototype was a new design for the tool holder that eliminated the ridges around the body and incorporated a tapered ramp that would allow for easier assembly and would eliminate the chance of seal damage during assembly. Lastly, the newly designed tool holder had the collet adapter machined into it, in order to eliminate the need for welding the interface.

Since we were unable to test the environmental benefits of our system with our prototype, because of sealing issues, we had to validate our project by means of mathematical calculations. We acquired information regarding the amount of energy consumed and carbon dioxide released when manufacturing one drill bit and compared that to the calculated amount of energy the pump uses and the calculated amount of CO_2 emissions that the metalworking fluids produces. With these calculations we were able to determine how long our system must increase tool life in order to be deemed more environmentally friendly than traditional aqueous systems.

Introduction

The purpose of this project is to incorporate supercritical carbon dioxide ($scCO_2$) into a through-tool/spindle lubrication delivery system for metalworking processes. Companies such as Ford and Boeing have forever had a costly concern with machine tool life in several of their machining processes. The outcome of our project could potentially remedy these problems if the coupling of the independently successful innovations of $scCO_2$ MWFs and through-tool delivery is able to yield enhanced machining properties such as longer tool life, higher lubricity with lower oil concentrations, cryogenic cooling, and very clean parts while simultaneously reducing the overall environmental impact of machining processes [1].

As the world of metalworking and machining processes have evolved, so too have the MWFs that are used to optimize tool life and the efficiency of machining processes. The University of Michigan Environmental and Sustainable Technologies (EAST) Laboratory has found that by replacing the water of existing oil-in-water emulsions with $scCO_2$, a number of MWF problems can be either partially or completely eliminated while significantly improving upon the overall efficiency of metalworking operations [2].
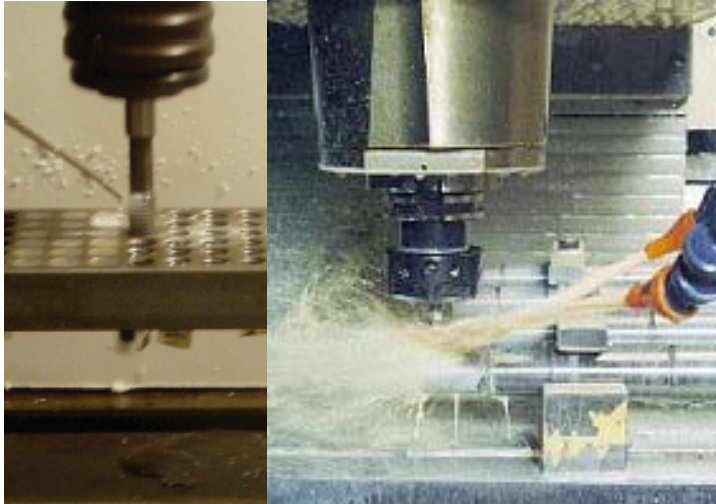
Figure 1. The current process of applying a $scCO_2$-based MWF externally is shown to the left. This process compares favorably to that of applying a water-based MWF, which is shown to the right.

Historical problems associated with maintaining traditional MWFs consisting of oil-in-water emulsions have raised much concern with respect to the environment, user health, and cost. The primary problem arising from the use of water-based MWFs is the growth of microorganisms within the fluids [2]. There are also health risks associated with the biocide additives used to control such microorganisms [2]. Also, the costly efforts to upkeep and run inefficient MWF maintenance systems are often times not enough to prevent the need to replace mass quantities of the MWFs. By replacing the water within the emulsions with $scCO_2$, and using minimal amounts of oil (as little as 1/10 traditional concentrations) in a controlled application environment, the MWFs no longer harbor microorganisms and the need for biocides is altogether eliminated [3]. Not only does the addition of $scCO_2$ eliminate health and environmental hazards, but it also results in improved lubrication, improved surface finish, heightened thermo conductivity (ability to remove heat from the work piece) and leads to a decrease in surface contact between the tool and work piece, resulting in more favorable tool life [2]. Another positive aspect of using $scCO_2$ in MWFs is the fact that CO_2 is a byproduct of Ammonia Synthesis and if it were not being used in the application of MWFs it would be released into the atmosphere. This is otherwise known as a "waste-to-food" application.

It should be noted that within the last five years, many of these problems surrounding the use of traditional water-based MWFs have been addressed by the implementation of minimum quantity lubrication (MQL). MQL is a process by which the water of traditional MWFs is replaced by pressurized air (75-100 psi). The oil is then injected into the air as particles with diameters no more than a few microns and the oil-in-air MWF is then applied to the working surface through the tool. This process has

allowed for many of the health risks associated with traditional MWFs to be eliminated while exhibiting improved machining efficiency and lower overall costs [5].

The success of MQL in through tool applications with oil-in-air emulsions has inspired the EAST laboratory to research how feasible it would be to incorporate their idea of scCO$_2$-based MWFs into a through tool system. Such a system that incorporates scCO$_2$ will be advantageous not only because the system will eliminate the need for large vats of health hazardous liquid MWFs, but also because scCO$_2$ has been proven to dissolve oil within itself much easier than air or water is able to, thus leading to a much more cost effective, safe, and operationally efficient MWF delivery system [1].

Current scCO$_2$ processes involve the application of the MWF through a high pressure, external spray. While this may be adequate in such surface machining operations as turning, its integration into drilling and sub-surface milling operations with softer materials tends to create a hindrance in the area of chip clearance and material removal [16, 17]. Thus, we have accepted the EAST laboratory's project of designing a through-spindle/tool application of scCO$_2$-based MWFs for drilling operations.

Information Sources

There are no technical benchmarks that currently exist specifically for the through-tool application of scCO$_2$-based MWFs. However, the concept of through-tool application of conventional MWFs consisting of oil-in-water as well as oil-in-air emulsions does have several benchmarks which may very well serve as initial engineering platforms for our project. Initially, through the tool application of MWFs consisted of injecting traditional oil-in-water emulsions to the working surface of the tool. Later on, the interest surrounding through tool delivery of MWFs increased heavily in the wake of the discovery of MQL. MQL is the process of emulsifying the desired metalworking oil in air rather than in water. The droplets of oil, which are mixed within the air, are usually in the range of 1-10 microns so as to limit the effects of centrifugal forces within the rotating spindle [5]. These oils can then be directed through the tool, directly to the working surface at rates of 10-100 mm^3/hour [5]. The advantages of MQL will be covered further in the subsection labeled 'Minimum Quantity Lubrication Benchmarks'.

Non-Minimum Quantity Lubrication Benchmarks. Through-tool application of traditional metalworking fluids was initially administered through the direct center of the drill as can be seen in Figure 2, but posed several problems, the most serious of which were increased brittleness and a weakened structural stability of the drill bit [8]. Later designs tended to administer MWFs through the flutes of the drill rather than directly through the center of the bit. This technique can be seen in Figure 3 and is done by way of a coolant inducer (shown in Figure 4). A coolant inducer is a device that consists of a coolant inlet that remains stationary while the MWF is injected into the rotating spindle. A series of high-pressure fittings and o-rings allow for a secure seal between the coolant inlet and spindle [9]. Another way that MWFs have been fed more directly to the working surface of a tool is by way of a coolant-fed bushing system which is shown in Figure 5. A coolant-fed bushing system consists of a standard drill bit that is surrounded by a bushing at the point that the bit enters the chuck. The bushing is fed with the desired high pressure MWF through the spindle of the machine and disperses the MWF along the outer edges of a standard drill bit [10]. This system may pose similar
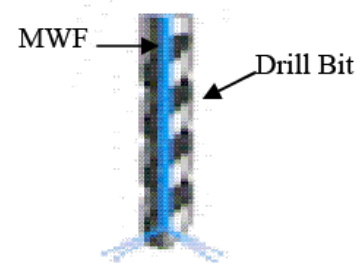
Figure 2. Original Through-Tool MWF Design [8]
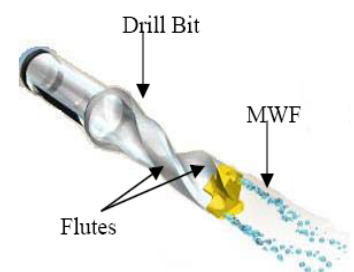
Figure 3. MWFs being delivered through-tool by way of the drill flutes [8]

7

problems to those witnessed in external $scCO_2$ applications but it is a technical benchmark nonetheless.
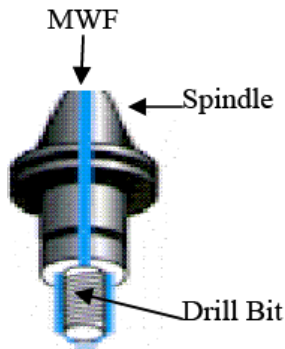
Figure 5. MWFs delivered by way of coolant-fed bushing [10]
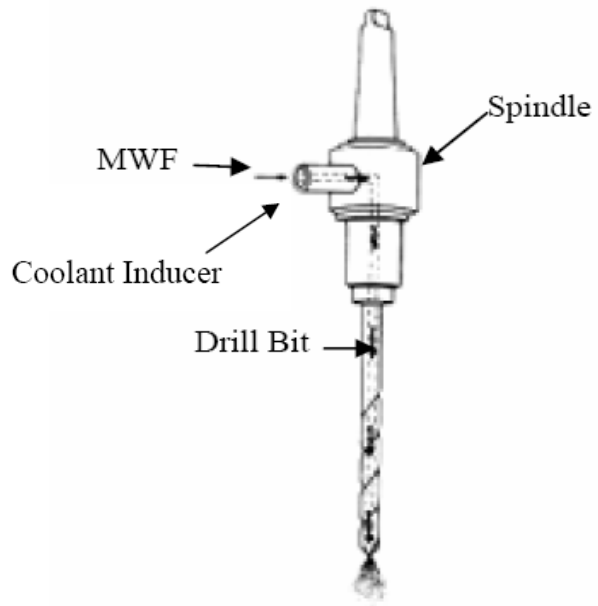
Figure 4. MWFs delivered through-tool by way of a coolant inducer [10]

Each of the above processes for the application of water-based MWFs can be adapted to administer the fluids either through the spindle or through the holder/chuck of the desired machine.

Much of our research relative to current through-tool MWF delivery systems was garnered through contacts at the U of M Engineering Research Center and various suppliers of these through-tool MWF application systems such as Collis American Manufacturer and the George Whalley Company. Such suppliers have successfully designed multiple variations of through-tool MWF delivery systems. The coolant inducers are the most common and practical of these systems and are commonly pressure rated to between 250 psi and 1000 psi. Coolant inducers of such capacities can cost anywhere from $250 to well over $1000.
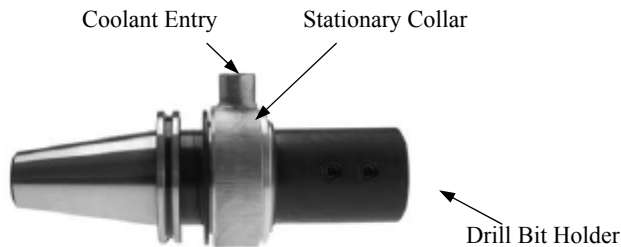
Figure 6. Actual side view of a standard coolant inducer produced by Collis for standard non-MQL applications through the tool [9].
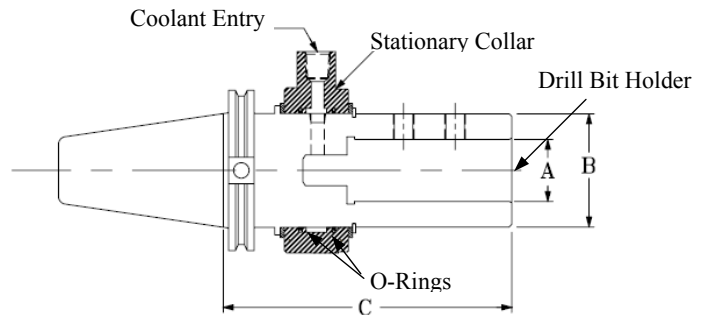
Figure 7. Engineering drawing of a standard coolant inducer produced by Collis for standard non-MQL applications through the tool [9].

Figure 6 and 7 show an actual side view and the corresponding engineering drawing for one of Collis' coolant inducers for non-MQL applications. The stationary couple is sealed around the tool holder by way of two O-rings. The O-rings provide an adequate seal for the system while allowing the tool holder to rotate within the stationary couple.

Minimum Quantity Lubrication Benchmarks. Our trip to the Dearborn Ford Facilities on September 28, 2006 gave us some insight into how Ford is currently delivering MWFs in minimum quantities through the tool of the machine. Their systems are extremely complicated and just as expensive, but the opportunity to see the technology that they employ in the area of MQL brought with it an understanding of how the systems work, what problems are often incurred, and how those problems can be overcome.

Ford currently utilizes two systems from a company called Bielomatik. The two systems differ in the manner through which the oil is introduced into the pressurized air. The first through-tool system that we learned about was the one-channel system. In the one-channel system the oil and air are mixed prior to their entering the spindle. This brings centripetal forces into the picture. Centripetal forces have been known to drive the efficiency of the MWF down as the oil droplets are drawn out of the air and stick to the inside wall of the spindle. To limit these effects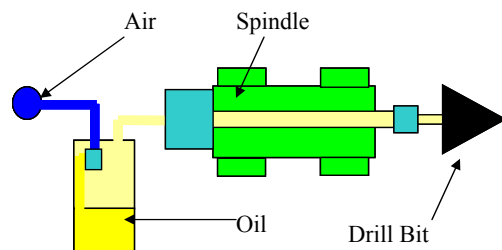, the one channel system deals with extremely small oil droplets which are roughly 1 micron in diameter. These diameters are nearly inert to the effects of centripetal forces and are achieved through a complex

Figure 10. Bielomatik's one-channel oil/air MWF system for MQL applications [5].

valve and nozzle setup that can disperse the oil droplets with the desired size and flow rate. A simple diagram of the one-channel system can be seen in Figure 10 [5].
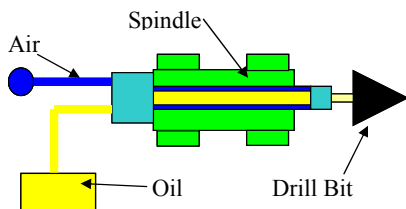
Figure 8. Bielomatik's two-channel oil/air MWF system for MQL applications [5].

The second system that we learned about at Ford was the two-channel system. The idea of the two channel system is to keep the oil and air separate throughout the system and mix the two directly prior to the MWF being injected through the bit. This delay of mixing allows for the effects of centripetal forces within the rotating spindle upon the oil droplets to be minimized. With the effects of centripetal forces limited, the oil droplets are able to exhibit larger diameters of 2-5 microns. Particles of this diameter are much easier to produce than the 1 micron diameter particles utilized in the one-channel system. A basic diagram of the two-channel system can be seen in Figure 8 [5].

To give a more complex view of the Bielomatik two-channel delivery system, Figure 9 has been provided. The oil droplets are injected into the system by way of a quick or solenoid valve and travel inside the lance, which is held stationary. The air is then injected into the rotating spindle which is powered by a rotary transmission and travels along the outside of the lance. The barbs on the outside of the lance trip the air into turbulence and allows for a more uniform mixture between the air and oil at the pipe nozzle.
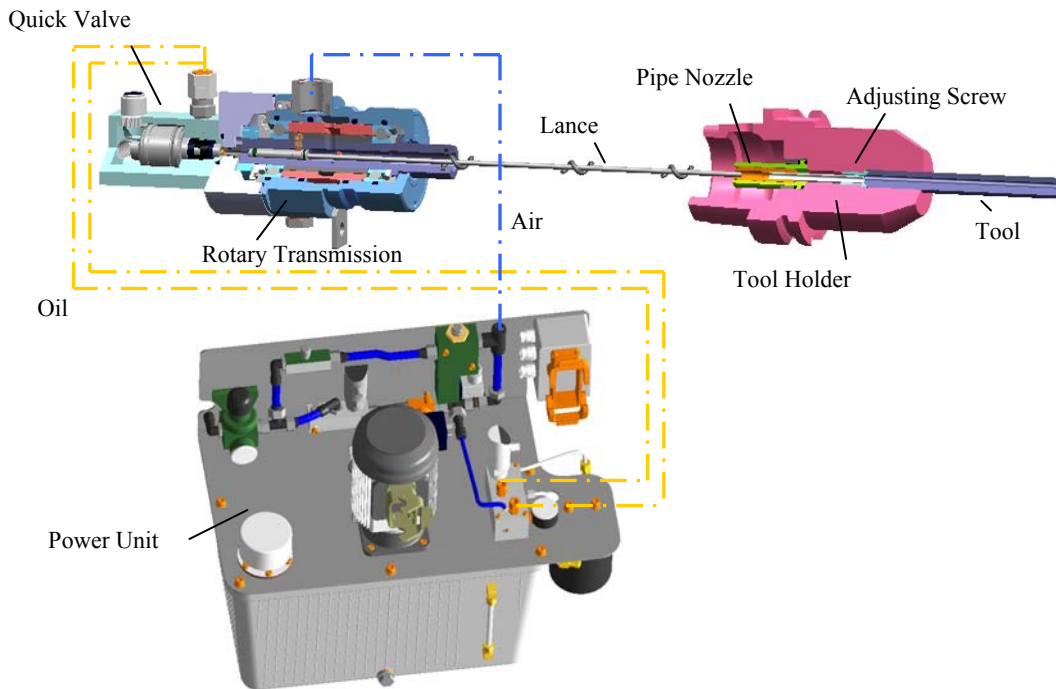
Figure 9. The above diagram lays out in more detail, the Bielomatik two-channel oil/air MWF system for MQL applications. Note how the oil and air travel to the pipe nozzle separately, where they are mixed prior to entering the tool [5].

Both of the Bielomatik systems operate under air pressures of 75 psi to 100 psi and have oil mass flow rates between 10 mm³/hour and 100 mm³/hour [21]. With such low flow rates of oil, the MQL processes are considered to be dry. The output of oil is so small that it is often times not visible to the human eye. Tim Hull and Alexander Stoll of Ford's Powertrain Manufacturing Technology Department informed us that these systems could withstand pressures that are much higher than the aforementioned range, but for the sake of cost reduction, Ford chooses to operate at pressures that are just high enough to obtain reasonable efficiency.

When placed side-by-side, there are a few logistical differences between Bielomatik's two MQL systems. The two-channel system compares to the one-channel favorably as it has a longer service life, lower maintenance costs, fewer losses during tool changes, less restrictions from the EPA due to larger oil particles (oil doesn't remain in the ambient air as easy), and can control the output of oil more accurately [5]. Despite the various advantages of the two-channel system, overall capital costs for the two systems are more or less equal. It is for this reason that the two-channel system has become the primary MQL system at Ford.

What scCO$_2$ Can Bring to Current Through-Tool Systems

Through-tool machining systems currently being used in the manufacturing world involve working fluids other than supercritical carbon dioxide (scCO$_2$); most commonly oil-in-water and oil-in-air emulsions. Research and previous lab tests conducted by the Environmental and Sustainable Technologies (EAST) Laboratory at The University of Michigan have determined that scCO$_2$ external spray applications, which provide fluid to the machining surface topically, increase the tool life and efficiency of the machining process in comparison to other working fluids while reducing overall environmental impact when compared to aqueous MWF delivery systems [2]. The presence of scCO$_2$ allows for a reduction in oil concentrations by as much as 90% while leading to improved surface finish, reduced contact between the tool and work piece, longer tool life, higher lubricity, higher cryogenic cooling and an overall higher

efficiency [2]. It has also been seen that through-tool applications of oil-in-water MWFs and through-tool MQL applications of oil-in-air MWFs has correlated to higher machining efficiencies. Therefore, the implementation of $scCO_2$ into through-tool processes is believed to be able to improve upon the overall efficiencies witnessed in both the topical application of $scCO_2$ and current through-tool processes involving oil-in-water and oil-in-air MWFs.

The external sprays of current $scCO_2$ MWF systems tend to hinder chip clearance in the drilling of softer metals, such as aluminum and magnesium, because there is nothing forcing the soft chips up the flutes of the drill and out of the work piece [16, 17]. Delivering the working fluid through the tool will eliminate this problem by forcing the chip up and out of the piece through the flutes of the drill bit, and in turn will expand the capabilities of $scCO_2$ processing.

Customer Requirements and Engineering Specifications

The use of $scCO_2$ in through-tool applications does not currently exist and thus warrants the research and investment required to obtain through-tool $scCO_2$ technology. When investing in a new technology, a customer needs to be assured that the capabilities of the new system surpass those of current systems, and maintain acceptable levels of consistency and reliability.

A customers' foremost concern, especially when dealing with high pressure applications, is safety. Safety standards for the $scCO_2$ system are comparable to those of other high pressure through-tool systems and may include: drill bit stability within the chuck, material strength if a hollow bit is utilized, avoiding brittleness as low temperatures within the system are experienced, and guaranteeing that bushings/connections within the system can withstand elevated pressures of 1000-5000 psi.

Another objective of investing in a new manufacturing process is cost reduction by way of efficiency. To optimize efficiency, certain engineering targets are determined such as flow rate and pressure, which maintain the carbon dioxide at a supercritical state and eliminate the threat of clogging within the system due to rapid expansion of the CO_2. Limiting pressure losses due to internal rapid expansion within the system was a matter of fitting the tubing from the existing EAST system to our setup and allowing the MWF to flow throughout the system without introducing significant geometrical amplifications. Maintaining adequate pressure and temperature throughout the system keeps the CO_2 in its supercritical state and in turn reduces the amount of oil that prematurely falls out of the MWF while preventing the formation of ice within the tubing. This will result in a more efficient system.

Keeping in line with the concern of lowering costs, it was our objective to limit the overall cost of our through-tool delivery system while limiting the cost of upgrade for the customer. Limiting the cost of upgrade was accomplished by designing our system to fit onto existing machines in the form of a coolant-induced spindle. This in turn made the product much more marketable as we will not be asking the customer to buy a whole new machine.

The last major concern of the customer lies within the subject of making sure that the system operates with ease. This means that certain desirable system characteristics must exist such as the ability of the system to be maintained and cleaned easily, and the user being able to quickly and easily interchange drill bits. Other customer requirements include the ability of the system to handle variable speeds and an overall decrease in the impact that machining has on the environment.

All of the above customer requirements have been correlated with engineering specifications. These engineering specifications include:

1. Delivery pressure of the MWF at the work piece

2. Number of system components
3. Pressure at which the bit is ejected from the tool holder (failure criteria)
4. Volume flow rate of $scCO_2$ and oil
5. Machining efficiency
6. Hours of operation before failure
7. Surface roughness of the work piece
8. Amount of excess fluid
9. Pressure at which coolant inducer fails
10. Coefficient of friction between the coolant inducer and spindle
11. Maximum spindle speed at which the system seals
12. Symmetry about the neutral axis (safety)

The process of correlating customer requirements and engineering specifications numerically along with the comparison of the customer requirements to benchmarked systems can be seen in Appendix A.

General Concept Generation

During and after the initial research phase of the project, numerous ideas were generated and sketched by hand. A total of eight different general concepts were put onto paper and weighed against one another. The following section will highlight these designs.

Stationary Spindle. One of our earliest designs revolved around the problem of coupling a stationary $scCO_2$ inlet with a rotating spindle. Common sense tells one that by eliminating the stationary to rotary couple, this problem could be avoided. This would entail having the work piece rotate while the oil-in-$scCO_2$ MWF was delivered through a stationary drill bit. However, this concept basically took a drill press and turned it into a lathe, and would be highly impractical and dangerous for larger and non-symmetrical parts. The drawbacks of this concept were heavy enough to eliminate the idea before a sketch was ever drawn up.

Drill Bit Coolant Inducer. Another early design involved a drill bit coolant inducer. This design was seen as being impractical, simply because the drill bit is so small and each bit would require its own coolant inducer. A sketch of this concept can be seen in Appendix C.3.

Coolant-Fed Bushing System. The idea of designing a coolant-fed bushing system similar to the system shown in the information sources section of the report (Figure 5 on Page 8) was brought up early on in the research process. However, it would not significantly simplify the coupling of a rotating spindle with a stationary coolant inlet, and furthermore, it did not meet the criteria of through-tool application. Therefore the coolant-fed bushing system was ruled out fairly quickly.

Top-Mounted Coolant Inducer. The mounting of a coolant inducer on the top of the drill press was first seen as a way to gain valuable work space for our design. If we were able to mount the coolant inducer to the top of the machine, there would be little to no space constraints (such as those encountered when working inside the tool holder). However, this system would ultimately require extreme changes to the entire machine in order to incorporate our design. A concept sketch of this design idea can be seen in Appendix C.5.

Internally Driven Spindle. Our trip to the Ford facilities in Dearborn, Michigan on September 28th offered some insight as to how we may want to design our prototype. All of their MQL systems revolve around a hollow spindle through which the MWFs are injected while the spindle is driven internally, rather than from the top of the machine. This concept is similar to the sketch shown in Appendix C.7, where the actual spindle of the machine is hollow. The idea seemed to ease our design constraints as far

as coupling a spindle with a stationary coolant inlet was concerned; however, all of the machine tools at the University are equipped with solid spindles. This would be a huge problem as far as gaining access to an existing machine for testing is concerned.

Modifying an Existing Coolant Inducer. The most promising of our initial ideas seemed to be the concept of modifying an existing coolant inducer. The existing coolant inducers consist of a collar that is slipped over the tool holder, similar the design shown in Figures 6 and 7 on Page 8. The collar remains stationary while the tool holder rotates inside the collar while the MWF enters the collar from the side and is sealed by o-rings riding between the collar and the tool holder. Once the MWF exits the collar it is channeled to the center of the tool holder and out the tip of the tool by way of small passages machined into the tool holder and a drill bit with internal through-holes. The basic idea of modifying an existing system looked promising and gave way to a number of quality ideas. Nearly all of our modification ideas included the manufacturing of a completely new collar assembly that could be applied to the existing tool holder. The following sections will highlight a few of the changes that we brought to the drawing table for consideration.

> *All-encompassing coolant inducer.* The idea of an all-encompassing coolant inducer arose as we research companies such as Collis American Manufacturers and The George Whalley Company who produce coolant inducers for the delivery of oil-in-water MWFs in non-MQL applications. They produce coolant inducers that are rated for 250, 750, and 1000 psi. The concept of an all-encompassing coolant inducer basically revolved around the idea that a bulkier coolant inducer apparatus would significantly raise the pressure rating of our system. This is believed to be a somewhat valid revelation, however, bigger does not always mean better and being able to successfully seal the system at upwards of 1200 psi would most likely require further work.

> *Externally pressed-in seals.* Our next modification idea for the existing coolant-induced tool holder was to replace the O-rings within the collar with externally pressed-in seals. A sketch of this concept can be found in Appendix C.4. This idea would be fairly easy to produce and assemble, which was a plus, but we had a hard time finding a press-in seal that could withstand extremely high pressure. It seemed likely that the seals would be ejected from the system and present a serious safety hazard.

> *Addition of snap rings.* In an attempt to address the problem associated with externally pressed-in seals described above, we came up with a design that held the seals in place with the addition of snap rings. A concept sketch can be seen in Appendix C.5. These snap rings would better prevent the seals from ejecting when the system was pressurized. Further research led us to our next design problem which was the inverse relationship between the sealing capability and the maximum rotational speed that a seal can handle.

> *Addition of rotary seals and bushings.* In contacting suppliers of seals and relying on a group member's past experience with the rotation of high-pressure seals, we were able to find a seal that could handle our prescribed system pressure of 1200 psi while being able to run up to 7,000 rpm. These rotary seals would still be held in by heavy-duty snap rings and the whole collar assemble would remained centered about the tool holder through the application of low friction bushings. A concept sketch including the addition of rotary seals and bushings can be seen in Appendix C.1.

> *Bolt-on collar assembly.* We were fairly comfortable with the design that is shown in Appendix C.1 after the addition of the high-pressure rotary seals and bushings because it seemed to address all of the immediate concerns of the project while remaining somewhat

elegant in appearance. However, we decided that if that design were to fail under high pressure, then its good looks wouldn't be of much help. Therefore we decided to design the bolt-on addition to the collar which would fit over the seals and hold them in place, ensuring that no parts would be ejected from the collar assembly. This design option can be seen in Appendix C.8 and will be implemented to ensure a comfortable factor of safety within the collar.

General Concept Selection Process

Before we could come to a conclusion on our general design we reviewed the sketches of each concept and discussed the feasibility of each design. We were quick to notice the many limitations that would be encountered in coming up with a solid platform for our project. Any design ideas that encountered enormous limitations early on in the design phase were thrown out. Designs that were initially eliminated included the stationary spindle, the drill bit coolant inducer, the coolant-fed bushing system, and the internally driven spindle.

It was quite obvious after some conversing amongst team members that the modification of an existing coolant inducer would provide us with a fairly sound design platform from which we could perfect our system.

Alpha Concept Description

Our alpha design concept involved redesigning the collar assembly of a coolant induced tool holder currently produced by Collis. There were a couple of reasons for our selection of the Collis product. Above all else, the people at Collis were extremely helpful and willing to help us out. They were the only supplier that was willing to supply us with engineering drawings of their products. We also wanted to make sure that the collar of the coolant inducer could be removed, as the majority of our project was going to revolve around applying our own collar to the existing tool holder. Collis concurred that the collar could be removed with ease. This insured that we could adapt our own collar design to the existing tool holder. We purchased the Collis tool holder that was V-flange CAT-40 compatible. This ensured that the tool holder would fit in the CNC machining in the Engineering Research Center at the University of Michigan for prototype testing. It is important to note that this connection into the machine will not need to withstand high pressures as all of the pressure will be introduced into the system after the point of connection.

We removed the coolant inducing collar that the unit came with and plan on replacing it with our own design. Our alpha design can be seen in Figures 12 and 13 on Page 15. The design looked to utilize high pressure rotary seals instead of the previously used o-rings. We first had to make sure that the material of the seals would be completely compatible with the scCO$_2$ MWF. The supplier of these seals, American High-Performance Seal (AHPS) informed us that the seals would be made out of Ekonal filled PTFE with a Nitrile o-ring and that both materials are compatible with scCO$_2$. This design will also utilize low friction, molybdenum-disulfide lubricated nylon bushings (not included in the drawings) to stabilize and center the coolant inducer. The stabilization garnered from the bushings ensured that the seals would not lose their sealing integrity. This alpha design can be compared with the coolant-induced tool holder that was purchased from Collis (shown in figure 11 on Page 15). The current tool holder utilizes a collar that is made of brass. Our design will replace the existing collar with a larger one made of stainless steel so as to increase the material yield strength and eliminate any chance of chemical incompatibility between the coolant inducer and the MWF. The coolant inlet of our design will also differ from the original. It will be smaller so that the geometry of the coolant supply hose and the tool holder will be more homogeneous.

Figures 15 and 16 give a better look into how the internal structure of the collar was to be changed in our design as compared to the original which is shown in Figure 14. One should note that the o-rings of the original collar were to be replaced by high-pressure rotary seals, similar to those seen most commonly in the automotive world. These high-pressure rotary seals are held in place by heavy duty snap rings. In preparation for the chance that snap rings that will prevent the rotary seal from being ejected from the collar at such high pressures did not exist, we planned to implement a bolt-on structure around the collar as can be seen in Appendix C.8. A cross-sectional engineering drawing of our alpha design, without the bolt-on structure can be seen in Appendix D.
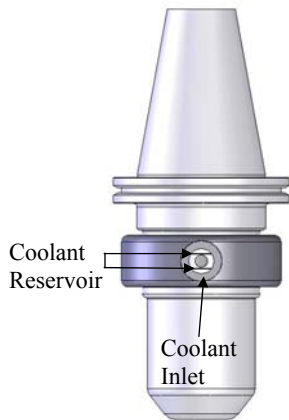
Figure 11. Original coolant-induced tool holder.
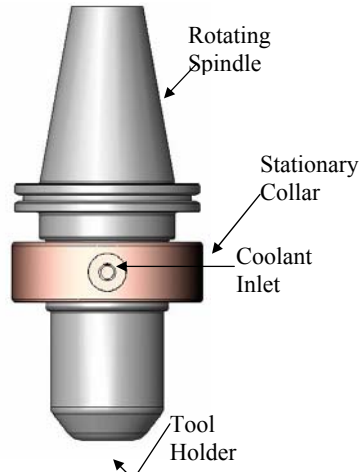
Figure 12. Re-designed coolant-induced tool holder.
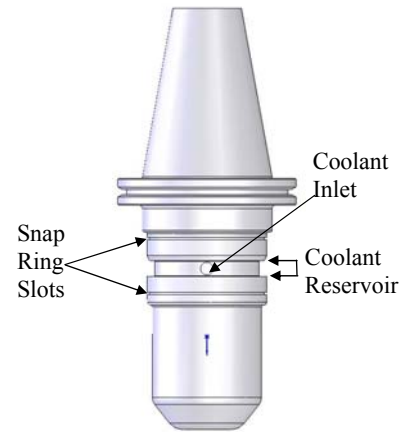
Figure 13. Coolant-induced tool holder with collar slipped off.
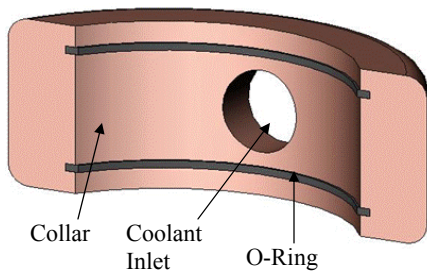
Figure 14. Original collar for Collis coolant-induced tool holder.
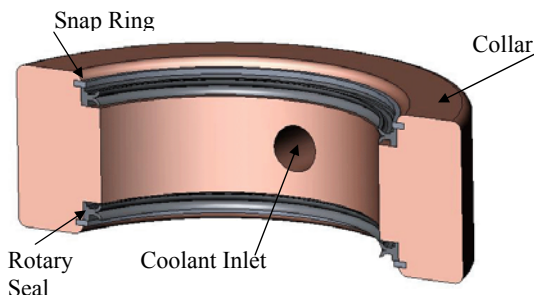
Figure 15. Re-designed collar for Collis coolant-induced tool holder.

Figure 16. Re-designed collar for Collis coolant-induced tool holder in an exploded view.

15

Engineering Design Parameter Analysis and Design Modifications

After we had a solid re-design for the collar of the tool holder planned out, our attention was directed toward the lower half of the tool holder assembly. While our initial concept seemed to be reliable from afar, a more detailed look into the engineering parameters and specifications brought with it countless problems, all of which needed to be designed around 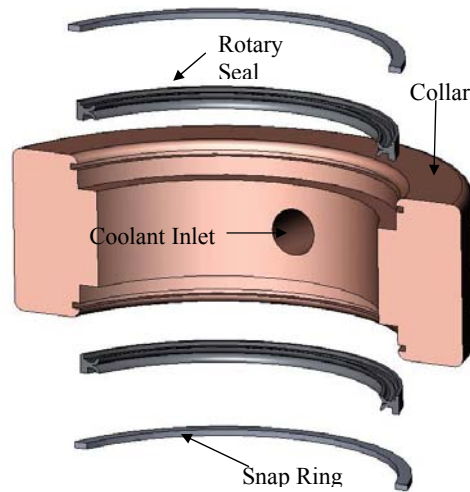while making sure that one problem was not remedied by creating another. Most all of these problems that surfaced after the design of the alpha concept had to do with the internal pressure rating aspects of the system. The process of planning out the internals of the system revolved heavily around limiting the effects of extremely high pressures upon the system after the MWF enters the tool holder. All of the design concepts that were considered and thrown out, along with the ideas that are to be applied to the prototype are explained in detail throughout the following section.

Varying Orifice Sizes within the System. One of our earliest concerns regarding the adaptation of an existing coolant-induced tool holder was one with respect to the varying internal dimensions of the tool holder. We were concerned that if the coolant was entering the tool holder through a tube with an internal diameter of 0.03" and expanded rapidly upon entry into the much larger inner geometry of the tool holder, there would undoubtedly be formation of snow, in turn completely clogging the system. Even if the system did not become clogged with snow, the rapid expansion would force the CO_2 out of its supercritical phase and therefore the oils being held within the CO_2 would become insoluble and machining efficiency would greatly depreciate.

In order to address the problem of running $scCO_2$ through varying internal dimensions, we created a setup with varying internal dimensions through which we could run the high-pressure MWFs. This setup can be seen in Figure 17.
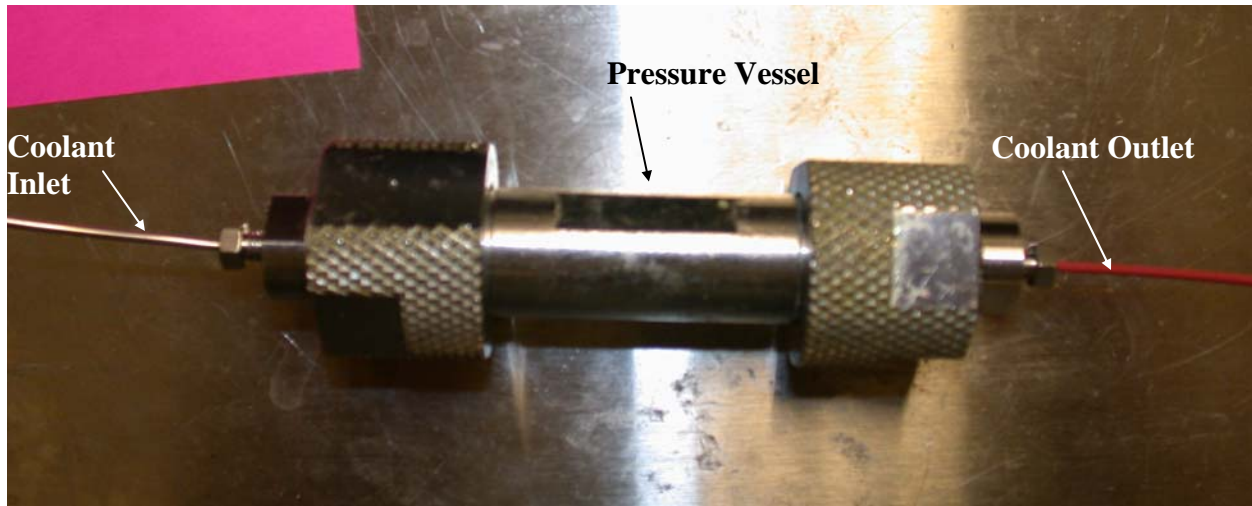
Figure 17. Test setup for the validation of using varying internal dimensions.

The inner diameter of the coolant inlet was 0.03" while the diameter of the coolant outlet was varied between 0.005" and 0.03". The outlet diameter was varied in order to see how large the outlet hole could be without seeing a significant amount of snow and oil inside the pressure tube after several minutes of testing. The coolant outlet was cut to a length of 12", which simulates the overall length of our prototype drill bit. The length of the coolant outlet comes into play as the restriction of a tube in fluid dynamics is dependant upon the ratio of inner diameter to length. The pressure vessel had internal dimensions that were on the same order of magnitude as those of our purchased tool holder to ensure the practicality of our tests.

Each test of varying outlet diameter was run for 3 minutes at MWF pressures of 1500 psi. The results were very similar to what one could expect. For the larger outlet diameters the pressure vessel became extremely cold, verifying that there was not enough resistance in the coolant outlet to provide sufficient backpressure in the vessel. This led to the pump struggling to keep up with the MWF flow rate and rapid expansion of the CO_2 upon its entrance into the vessel. This also resulted in a small amount of oil coming out of the MWF emulsion which remained within the vessel.

Some oil was witnessed falling out of the MWF with all of the tested outlet diameters. However, the amount decreased steadily as the outlet diameter was decreased. The oil falling out of the CO_2 becomes a secondary concern to snow formation due to the fact that excess oil will eventually be forced out of the vessel whether it is dissolved in CO_2 or not. The formation of snow, unlike the formation of excess oil, disappeared as the outlet diameter was decreased to the order of 1/1000 of an inch. These tests were enough to initially prove that we would be able to use our tool holder without having to alter the relatively large internal dimensions, so long as our outlet diameter was on the order of 1/1000 of an inch to insure enough back pressure to keep the CO_2 in or near its supercritical state until it exits the system at the end of the drill bit.

Drill Bit Through-Hole Diameter. It was our intention to keep the MWF in its supercritical state until it reaches the working surface of the drill bit. This required a path through the drill bit with small enough holes to ensure adequate backpressure in the system. However, too small of a hole through the drill bit would limit the flow rate of MWF significantly, leading to poor chip removal from the hole being drilled. Therefore, tests similar to those run on the setup from Figure 17 on Page 16 will need to be run in order to find the optimal drill bit through-hole diameter. However, these

Figure 18. Top view of the drill bit.

tests will need to be run on a working prototype rather than in the previously mentioned lab setup in order to ensure accuracy and to incorporate actual chip removal. The setup shown in Figure 17 sufficed in validating our overall concept, but lacks enough accuracy to optimize the system and cannot simulate the process of drilling. In order to allow for the through-hole diameter of our prototype drill bit to be variable and thus able to be optimized, we purchased a series 805, ¾", through tool drill bit from the George Whalley Company. This drill bit has through holes that are about 0.125" in diameter and also has a helix path that is fairly

Figure 19. Side view of the drill bit.

mild so that we can feed high pressure tubes through the drill bit. This will allow our outlet diameter (and thus the ratio of outlet diameter to drill length) to be varied so that the optimal tradeoff between backpressure and flow rate within the system can be achieved. Once the optimal diameter of outlet tubing of 0.006" was decided upon through prototype testing, a stainless steel tube with the optimal diameter was inserted into the through-holes of the drill bit to solidify the outlet geometry. Figures 18 and 19 both show the drill bit that was purchased. The manner in which the tubing was fastened within the through-holes of the drill bit and tube interchangeability is explained in the following section labeled "Preventing Drill Bit Ejection".

Preventing Drill Bit Ejection. A major design aspect of our system revolved around designing the insides of the tool holder so as to limit pressure loss while limiting the chance of the drill bit ejecting from the system when in use. In an attempt to satisfy these design parameters, we first came up the idea of running high pressure tubing all the way through the tool holder and drill bit, thus eliminating the need to seal the system below the coolant-inducing collar. These tubes would also relieve the back of the drill bit of all high pressures. The only problem was finding a way to secure the high pressure tubing within the tool holder. The following ideas are those which we came up with in an attempt to remedy this problem. The first two of the following ideas were thrown out and we would eventually have to design around a drill bit that saw significant pressure from the back.

> *Epoxy high pressure tubes within the tool holder.* Our initial plan in securing the high-pressure tubes within the tool holder was to epoxy them. Besides being extremely crude, we had concerns about the epoxy's ability to seal around the 8620 steel of the tool holder while in shear. This idea may have gotten the prototype to work, but the number of cycles to failure would inevitably be dangerously low. It was for this reason that this option was not pursued beyond the brainstorming phase.

> *Manufacture a press-fit insert.* A second and more in-depth attempt to secure the high-pressure tubes within the tool holder and remove pressure form the back of the drill involved the manufacturing of a press-fit insert that would be pressed up into the bore of the tool holder. A sketch of this concept can be seen in Figure 20. Once the insert is pressed into the bore, the tubes with threaded ends and high-pressure ferrules can be screwed into the insert thus removing the effects of pressure from the components of the system that come after the insert, so long as the insert is adequately sealed. Several concerns arose early on that eventually led to the dismissal of the design idea. The first problem was the overall lack of space. The design would have to incorporate fittings and adjustable nuts for the tubes at a depth of about 2.5" all within and inch diameter. Another problem was getting a press-fit to seal at 1200-1500 psi and being able to remove the insert if it didn't seal. The final problem that arose was the fact that at the deepest point of the tool holder bore the diameter of the bore actually increases. A bore that increases in diameter makes a press fit nearly impossible to seal.
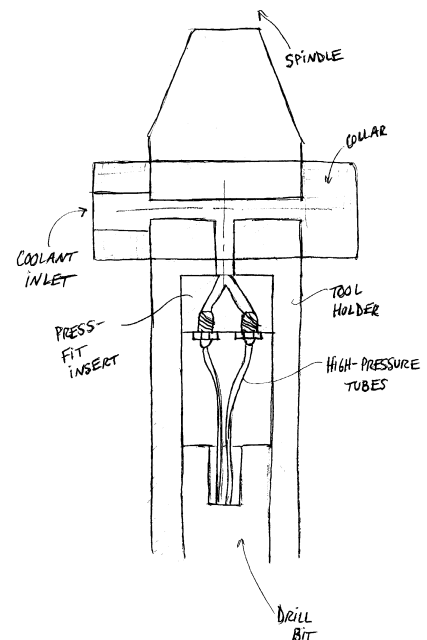
Figure 20. A sketch of the press-fit insert design.

With both of our ideas for removing the pressure from the back of the drill bit altogether by running high pressure tubes throughout the whole system (as opposed to the inside of the tool holder acting as a pressure vessel) being eliminated, we had to return to the drawing board.   Our team eventually moved away from the idea of running tubing throughout the whole system and chose to limit the use of high-pressure tubing to only within the drill bit through-holes. By incorporating high-pressure tubing which runs from the back of the bit to the end of the drill bit through-holes, the optimal inner diameter to length ratio of the outlet tube could be utilized. The tubing was secured within the drill bit by way of high-pressure fittings from Swagelok which screwed into the back of the drill bit and were sealed with Teflon tape. This setup can be seen in Figures 21 and 22 on Page 19. After the outlet tubing was secured within the drill bit, there remained the problem of pressure on the back of the drill bit. Rather than removing the

pressure from the back of the drill bit, we eventually decided to adapt to the high-pressure conditions with interchangeable sealing collets, set screws and permanent welds, all of which are laid out in detail in the next several sections. Not only did these new concepts utilize the optimal outlet diameter of 0.006" with an outlet length of roughly 12"while removing the risk of drill bit ejection, but they also inadvertently allowed for interchangeability of different size drill bits. This will become very valuable as each size drill bit no longer will need its own unique tool holder.
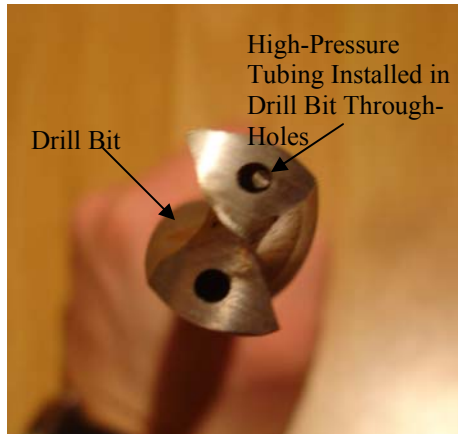
Figure 21. A bottom view of the high-pressure tubing within the drill bit.
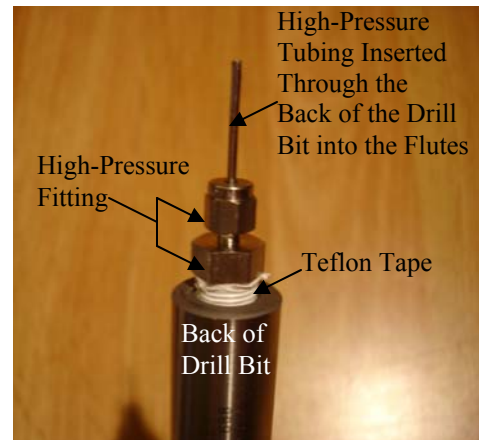
Figure 22. A view of the high-pressure tubing inserted through the drill bit from the back.

Interchangeability of Drill Bits. Shortly after obtaining our coolant-induced tool holder from Collis, we realized that the current bore into which the drill bit is inserted measures 1" in diameter. This means that only a drill bit with a 1" diameter shank could be inserted directly into our tool holder and any other size drill bit would require its own coolant-induced tool holder. This would be extremely costly as the coolant inducer would fail to adapt to different size drill bits. To remedy this problem, we decided to purchase an adapter with a 1" diameter shank (which would fit into our existing tool holder) that has the ability to house any size collet ranging from 2 mm up to ¾". These collets would in turn be able to secure a drill bit of an equivalent size. Thus the inclusion of the collet holder allows any size drill bit to be utilized in our tool holder, so long as the bit has the correct size collet.

When choosing the exact collet holder that we wanted to use as well as what line of collets we wanted to place in the collet holder, there were several iterations to choose from. There are more or less two types of collet holders to chose from; the T/G series which has a flat on the shank so that it can be held within the bore of the tool holder by the existing set screw, or the E/R series which does not have a flat machined into the shank. However, the collets that are utilized within the E/R series collet holder are able to seal at aqueous pressures as high as 1500 psi, thus eliminating the risk of drill bit ejection that was mentioned earlier. The only problem that remained with the choice of the E/R collet and collet holder assembly was securing the collet holder within the tool holder without the existence of a flat for set screws to rest in. In this case the gains from the pressure rated E/R series collet and collet holder outweighed the need of a flat in order to secure the shank of the collet holder into the bore of the tool holder as we would later be able to machine our own flat.

The collet and collet holder that we purchased can be seen in Figure 23a on Page 20. The collet holder is a standard E/R series and the collet being used is an E/R 32, which holds a ¾" drill bit. This collet can be changed to whatever size is desired, but for our prototype we chose a ¾" drill bit to give us more space to work in the drill bit through-holes. The entire tool holder assembly can be seen in Figure 23b on Page 20.
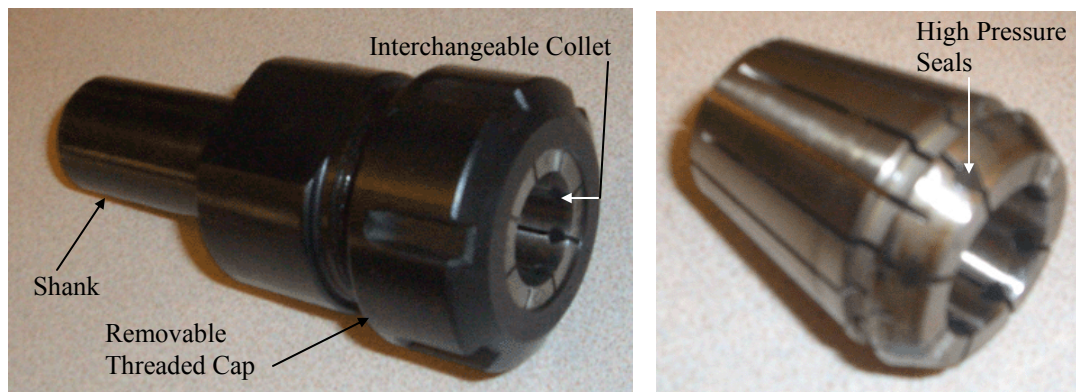
Figure 23 a. The assembly of the E/R collet holder and E/R 32 collet are shown at left. To the right is the E/R 32 collet with high-pressure seals when removed from the collet holder.
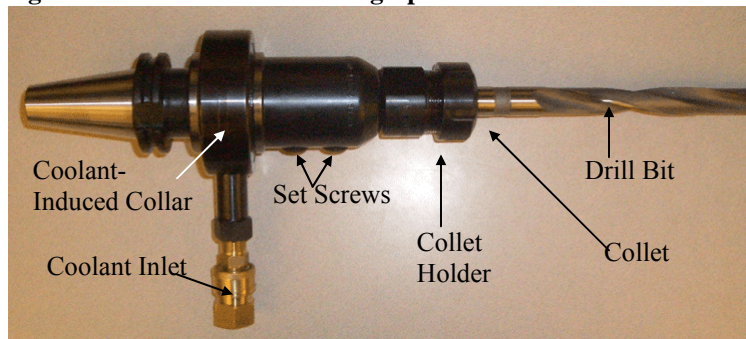
Figure 23 b. The assembly of the tool holder, collar, collet holder, collet and drill bit.

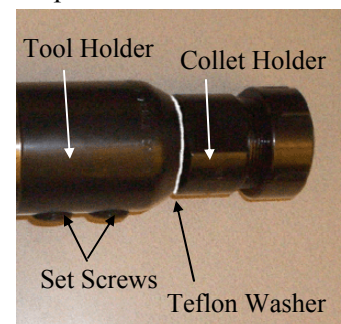**Seal between the Collet Holder and Tool Holder.** Obtaining a seal between the shank of the collet holder and the bore of the tool holder is a design problem that is solely related to obtaining a working prototype. In other words, this problem would be non-existent in our final design as our final design would eliminate the collet holder by having a tool holder with an E/R collet holder built directly into it. We were unable to do this for our prototype due to the fact that tool holders with E/R collet capabilities built in are not currently produced for through-tool applications. Therefore, we had to devise a way to obtain a high pressure seal between our collet holder and tool holder.

Current processes that incorporate the marriage of a coolant-induced tool holder and collet holder rely on the extremely close tolerance that exists between the two to provide an adequate seal. However, these applications usually involve pressures of less than 250 psi with aqueous MWFs and exit diameters in the drill bit (on the order of 0.0625-0.125") that are large enough to provide a definite path of least resistance. In the case of scCO$_2$, such a tolerance fit will surely fail as pressure exceed 1200 psi, the diameter of the drill bit through-holes are so much smaller (0.005"), and the mobility of a supercritical fluid is so much higher than that of a liquid. This mobility can be attributed to the negligible surface tension of scCO$_2$ [17]. In order to obtain an adequate seal between the collet holder and tool holder, the following ideas were brought up with the last being the optimal choice in the end.

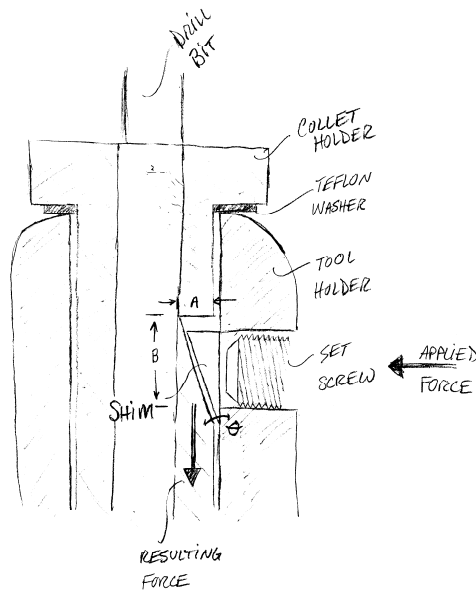**Figure 24. Proposed Teflon seal between the tool holder and collet holder.**

Teflon washer. The first idea for an adequate seal between the tool holder and collet holder that was brought about and not immediately thrown out was the concept of placing a Teflon washer at the interface of the two parts (at the bottom of the tool holder) as can be seen in Figure 24. Teflon is often times used in

20

conjunction with CO_2 when a seal is desired due to the fact that it expands when exposed to CO_2, thus generating a stronger seal whenever a leak starts [18]. The only problem with this idea is generating enough compression force upon the seal to avoid leaking at pressures greater than 1200 psi.

Figure 25, along with the corresponding mathematical computations validate the premonition that a force great enough to adequately compress the Teflon seal would be extremely hard to achieve. According to our calculations, due to space limitations, we would only be able to achieve a compressive force that is roughly ¼ the magnitude of the input force.

$$A_{\max} = 0.25"$$
$$B = 0.875"$$
$$\theta = \tan^{-1}\left(0.25 \middle/ 0.875\right) = 15.95°$$

$$F_{out} = F_{in}\sin(15.95°)$$
$$F_{out} = 0.27 F_{in}$$
$$F_{in} = \frac{T}{kD}$$
$$F_{in} = \frac{25(ft-lb)}{0.2*0.5(in)*1(ft)\middle/12(in)} = 3000lb$$

$$F_{out} = 0.27 F_{in} = 810lb$$

Figure 25. A sketch of the design that seals with a Teflon washer.

Using the equation for the force applied by a bolt, where k is the stiffness constant of the bolt (roughly 0.2 for steel), D is the diameter of the bolt and T is the applied torque (25 ft-lb) we were able to come up with a reasonable value for the force that could be applied to the shim. Through geometric relations and constraints, a reasonable output force used to compress the Teflon washer comes out to be 810 lbs. While 810 lbs seems to be a fairly large force, we must remember that the force exhibited in the opposite direction by the MWF pressure will most likely equal or exceed 810 lbs, thus rendering this design idea uncertain.

Threaded adapter. The next idea that we had was to manufacture an adapter that had a male end that would fit into the tool holder and a female end that would accept the shank of the collet holder. The threads could be sealed with either liquid Teflon of Teflon tape prior to being connected to ensure an adequate seal. This idea would also require threads to be machined into the bore of the tool holder and the shank of the collet holder. This would generally not be a problem; however Collis informed us that the material of the two pieces exhibited a hardness of 52-55 Rockwell C, a hardness that is next to impossible to machine. It was for this reason that a threaded adapter was eliminated as an option to obtain a seal between the tool holder and the collet holder.

Permanent weld. The last idea that we came up with to seal the collet holder within the tool holder was to apply a permanent weld between the two. Welding the two pieces together would undoubtedly insure that no CO_2 would leak from the interface. This idea brought with it some uncertainty at first due to the fact that the material properties of each material were different and the tool holder had already been heat treated. With the interface of the two parts already beveled, the welding together of the two parts would only require a brief pre-treatment. The black oxide coating must first be removed from both surfaces by way of sanding or grinding. Both parts must then be heat treated to 400°F so that both surfaces can accept the weld [23].

Figure 26. The interface between the tool holder and collet holder that was welded.

Once we were absolutely certain that the internals of our tool holder would not need to be accessed, we decided on the concept of a permanent weld to obtain a sufficient, permanent seal between the tool holder and the collet holder. This weld is aided in securing the collet holder shank within the tool holder by way of an existing set screw. This set screw rests within a flat that has been machined into the shank of the collet holder.

Sealing around Set Screws. The set screws that secure the collet holder within the tool holder would not seal scCO$_2$ by being screwed in alone. However, by welding the screws permanently into place this problem was eliminated. These welds can also be seen in Figure 26.

Keeping the Collar Assembly Stationary during Drilling. Once the final design is manufactured and hooked up to the actual drill press, we will want a way to keep the collar assembly stationary as the tool holder spins within it. Since the coolant inlet is not entirely rigid, we will implement a support. This support can be as simple as piece of angle iron that can be bolted onto the safety plate of the collar assembly and extends upward. It will then come in contact with the drill press housing (more specifically a pre-existing piece of aluminum that protrudes out from the housing) and will prevent the collar from spinning. A sketch of this concept is shown in Figure 27.
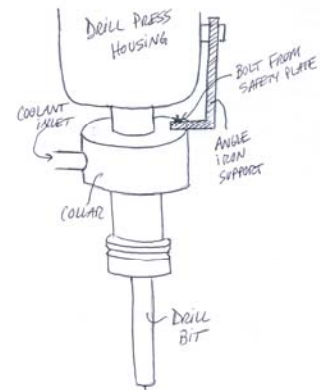
Figure 27. A sketch of the support design which prevents the collar from spinning.

Prototype Description

The compilation of our alpha design modifications that were decided upon after the completion of our engineering design parameter analysis translate quite smoothly into the description of our prototype. The bulk of our prototype exists in the redesign of the Collis coolant inducer. Figure 28 on Page 23 highlights our prototype collar design with isometric, exploded, and cross-sectional views.
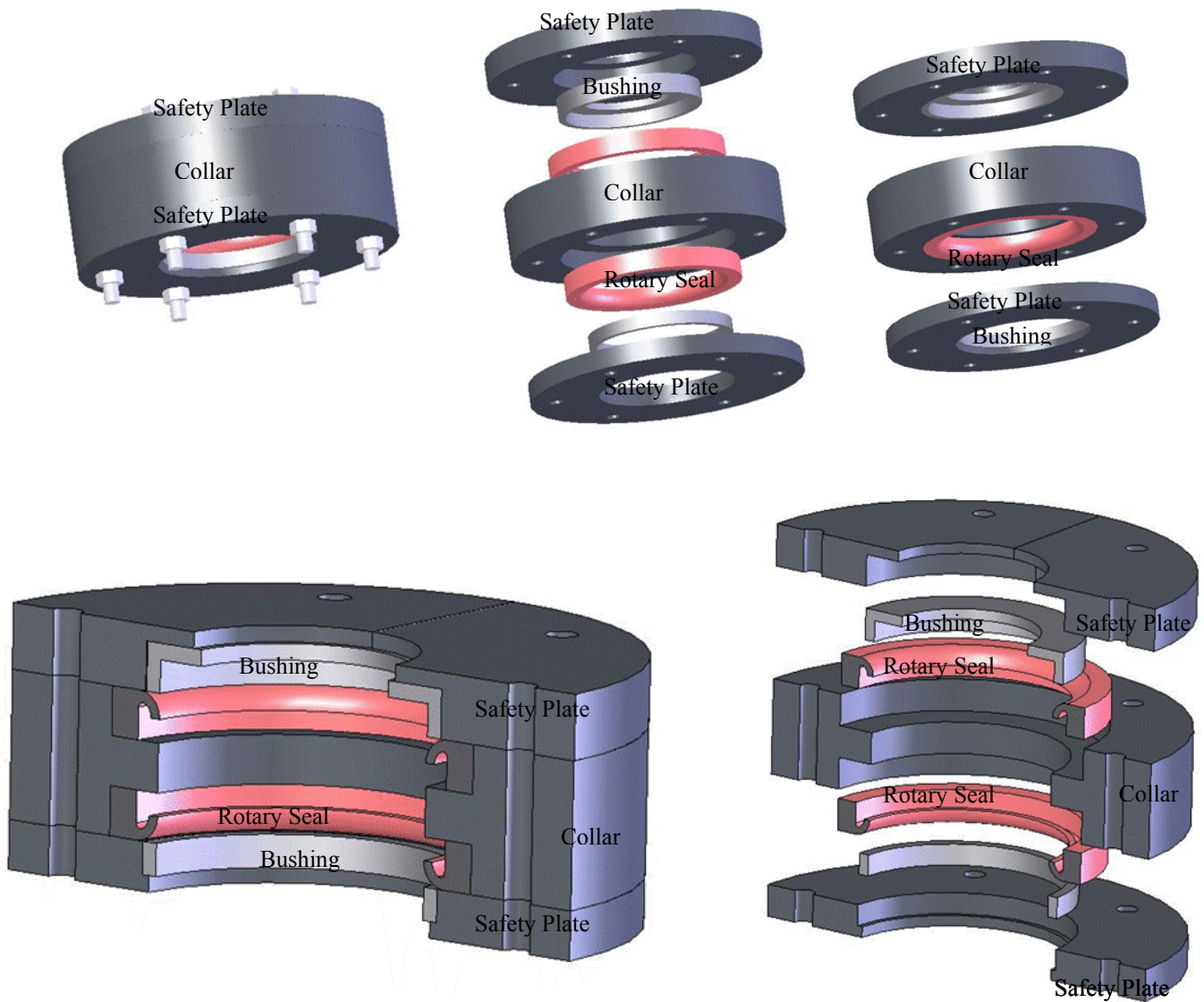
Figure 28. Five different views of the prototype collar design.

The collar design accepts the MWF and later directs it into the tool holder. Our confidence in the collar design concept exists for several different reasons. The rotary seals are rated for rotational velocities as high as 5000 rpm while still being able to seal at pressures as high as 1500 psi. Since the rotary seals are not completely rigid, we incorporated two bushings which will keep the collar assembly concentric with the tool holder to prevent the seals from deforming and loosing their integrity. We are also confident that the collar will be safe to operate even if it were to fail, due to the safety plates which are bolted in compression on the top and bottom of the collar. These plates will prevent the rotary seals and bushings from ejecting in case of failure.
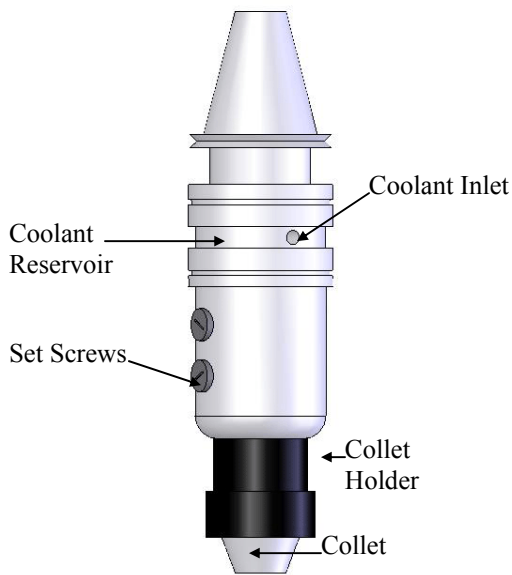
Figure 29. Assembly of the tool holder, collet holder, and collet.

The prototype collar will be slipped over our assembly of the tool holder, collet holder, and collet which can be seen in Figure 29. The total prototype including the collar assembly with the illustrated fluid path can be seen in figure 30. We were quite confident that the most dependable area of the system existed after the collar assembly. With our collet holder secured into the tool holder with welded set screws along with a weld at the interface, the collet holder will not spin within the tool holder and prevents leakage between the tool-holder and collet-holder. After the fluid passes into the collet holder, it will enter the E/R high-pressure collet which can seal around the drill bit and is rated for aqueous pressures of 1500 psi while ensuring that the drill bit will not be ejected. Once the MWF is in the drill bit, it will be directed into the high-pressure tubes which are threaded into and sealed within the existing through-holes of the drill bit. A bill of materials for the prototype is shown in Table 1.
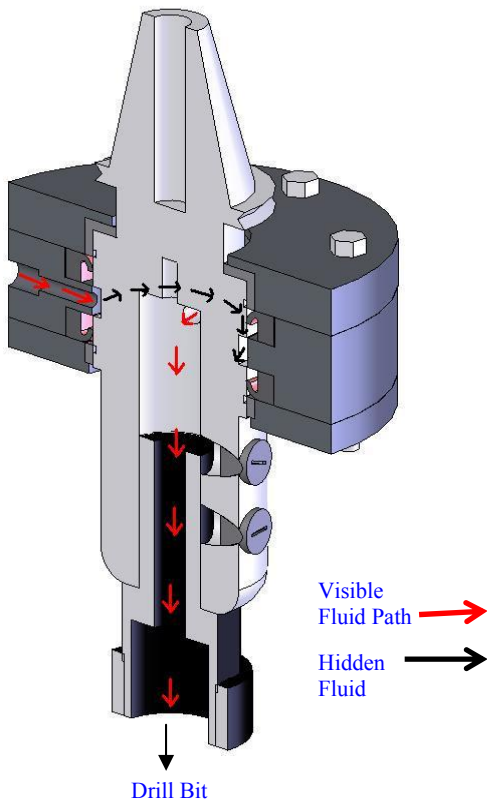
Figure 30. A cross-sectional view of the entire prototype without the drill bit inserted into the collet.

Table 1. Prototype Bill of Materials

Manufacturer	Part Number	Description	Price
Collis	76832	ER32 1x423 straight shank collet chuck	$137.96
Collis	73834	40 V-flange mount x 1" bore coolant induced toolholder	$264.88
George Whalley Company	805-041	Series 805 3/4" diameter coolant fed drill bit	$155.99
E.T.M.	4500282	3/4" coolit jet ER32C ETM collet # 707189	$57.51
American High Performance Seal	Custom Ordered SB40 Seal	SB40 profile rotaryseal 2.490"IDx3.375"ODx 0.375"HT ekonal filled PTFE with nitrile O-ring	$85.60/seal x 4 seals
Bolt Depot	590	1/4"-20 x 2-1/2" long grade 8 bolt	$0.27/bolt x 6 bolts
Bolt Depot	2675	1/4"-20 grade 8 hex lock nuts nylon insert	$0.29/nut x 6 nuts
Bolt Depot	3060	1/4" grade 8 USS flat washer	$0.10/washer x 10 washers
Swagelok		1/8" nut and ferrule	$5.00
Superior Machine		Collar Assembly	$912.00
		TOTAL	$1,880.04

Prototype Manufacturing Plan

The bulk of our prototype manufacturing was outsourced due to part complexities and safety concerns when dealing with extremely high pressures. All processes that required machining have detailed corresponding engineering drawings, all of which can be found in Appendix D.

The rotary seals that we used in our prototype were custom made to comply with our pressure standards. This task was outsourced to American High Performance Seals who manufactured the seals out of Ekonal-Filled PTFE.

Our coolant inducing collar was also custom made for the same reason as the rotary seals. The creation of this part was done by Superior Machine who machined this product out of stainless steel for strength and its chemical compatability with $scCO_2$. Engineering drawings of the collar assembly that were sent to Superior Machine can be seen in Appendix D along with the necessary machining tolerances. Another process that we outsourced is the welding of the collet holder to the tool holder and the welding of the set screws into the tool holder. This step ensured an excellent seal between the two parts and was completed by the welding department at Washtenaw Community College.

Tolerances played a very important role when it came to the rotary seals fitting correctly into the collar. If the fit was anything less than perfect, our entire setup would fail. For this reason the grooves in the coolant inducer which hold the rotary seals have tight tolerances in order to ensure a close fit. Washtenaw Community College was also contracted to add a smooth surface finish (8 micro-inches) to the tool holder where it comes into contact with the rotary seals of the collar assembly. American High Performance Seal has informed us that the rotary seals perform best with surface finishes equal to or better than 4-8 micro-inches.

Another area where close tolerances played a major role was in the threading of the $scCO_2$ inlet hole. If the tolerances are not close enough there will be major leakage. Areas where tolerances were less important include the end caps of the coolant inducer which are bolted on. This is because their purpose is to house the bushings and prevent the rotary seals from flying out in the case that failure does occur, rather than to seal against pressure leaks.

There are several machining operations that were carried out by our team. The grinding of a 1/2" flat into our collet holder was performed to prevent it from rotating within the tool holder prior to the welding of the set screws. The set screw that will sit in the flat will be aided by the permanent weld at the tool holder/collet holder interface in preventing any rotation. The flat can be seen in Figure 33. Due to the hardness of the collet holder (52-55 Rockwell C), this process was carried out using a surface grinder in the University of Michigan Auto Lab rather than with a standard mill. Our team was also in charge of manufacturing the bushings that are housed within the collar assembly to keep the

Figure 33. The collet holder with a flat machined into the shank.

collar centered on the tool holder. These bushings were be made in the University of Michigan Auto Lab on a lathe.

Our group also assembled a coolant inlet that fits into the collar assembly. This inlet is composed of stainless steal parts ordered from Swagelok which are listed in the bill of materials on Page 24. It is composed of 0.03" inner diameter tubing which will be sealed into the collar by way of a male adapter and high-pressure ferrule.

The last component of our prototype that our group planned on manufacturing is an angle iron support that will be secured to the collar assembly by way of the bolts on the safety plates. The support has not yet been made due to the fact that our prototype has not been tested in a CNC machine. This support will be bent so that it interfaces with the housing of the drill press when the tool holder begins to spin. What this will do is keep the coolant inlet along with the collar stationary during drilling operations. This support will be cut to length on a band saw and bent into shape with the aide of applied heat if needed.

The manufacturing of our final design will differ from our prototype model in several ways. The first difference will be that the collet holder will not have to be welded into our tool holder because ideally a tool holder with a built in collet holder would be used. The final design of the tapered tool holder will most likely need to be cast or forged along with machining operations to achieve a uniform tool holder. The second main difference deals with the metal tubing in the flutes of the drill bit. These would be non-existent because they are inserted merely to emulate smaller diameter flutes within the drill bit. Our final design will incorporate a drill bit with the correct diameter through-holes. The final design will also require the machining of an additional bushing that will sit on top of the collar assembly. The last part of the final design that will require manufacturing is the conical collet seal. This seal will most likely need to be outsourced due to the extremely high tolerances that are needed to seal in $scCO_2$ applications.

Prototype Testing

The testing of our system left much to be desired as far as chip removal, tool wear, and machining efficiencies are concerned. Before our prototype could be tested in a CNC machine with $scCO_2$ at 1200 psi while rotating, we had to first test to see if all aspects of the prototype could seal while in static equilibrium. This involved connecting the prototype to the pump and slowly raising the pressure. At 150 psi, the prototype started to leak from around the drill bit and also from around the top rotary seal. We are still quite confident in the sealing capabilities of the rotary seals; however, they are extremely delicate. The actual assembly of our prototype took nearly three hours in an attempt to install the seals unharmed. Despite our best efforts, upon disassembly of the prototype, we found that the seals had caught on a pre-existing groove within the tool holder and torn during installation.

While we remain confident that our rotary seals will work if they have easier installation, the seal around the drill bit seems as though it was flawed from the start. While the manufacturers of the sealing collet informed us that it was designed for pressures as high as 1500 psi, we completely overlooked the fact that this pressure rating was for use with aqueous MWFs. Between our exit diameter of 0.006"and the absence of surface tension along with the extreme molecular mobility of $scCO_2$, the metal-on-metal seal between the drill bit and collet never stood a chance.

Both problems that limited our prototype testing are covered more in depth in the next section of the paper as we will explain the changes that need to be made between the prototype and the final design.

Final Design Description

Many aspects of our final design will be very similar to those of our prototype with a few modifications. Our final design looks to limit the overall complexity of the system by creating a tool holder much the same as the one purchased from Collis, except for the fact that it will eliminate the need for a collet holder-tool holder interface, by having a collet holder built into the end of the tool holder. This will not only make the tool holder roughly four inches shorter, but it will also eliminate the need to weld a collet holder into the bore of the tool holder. This will in turn eliminate the weld at the collet holder-tool holder interface, as well as at the set screws, both of which could lead to an unsymmetrical tool holder that is spinning on the order of 1000 rpm. The process of making the tool holder and collet holder one piece is a way simplifying the design while increasing the safety of the overall system.

The final design of the tool holder will also look to eliminate the pre-existing slots that were machined into the original Collis tool holder for its snap rings to rest within while adding a gradual taper from the bottom of the tool holder to the top. The surface that has been machine into the Collis tool holder for the MWF to flow within has been transferred to the collar assembly to make the final design of the tool holder surface completely void of sharp corners. The objective of doing so is for ease of rotary seal installation and to protect against tearing of the delicate seals. These changes have been illustrated in Figure 31.
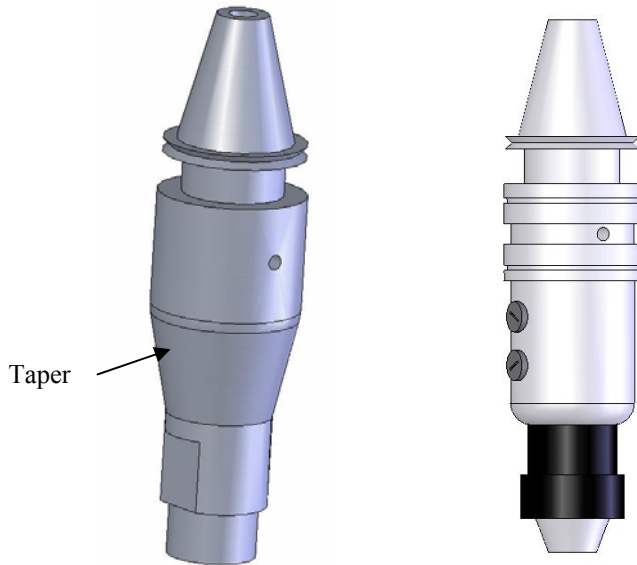

Figure 31. The final tool holder design at left is one piece with a smooth tapered surface while the prototype on the right is neither.

With the drill through-hole diameter that supplies the flow restriction which optimizes the tradeoff between MWF flow rate and maintaining a constant pressure within the tool holder known (5/10,000); our final design will also incorporate the production of a new line of drill bits. All of the drill bits in the line will exhibit this through-hole diameter-to-length-ratio that results in optimal flow restriction. This optimal flow restriction will keep the system pressurized and the MWF in its supercritical form until it exits the drill bit. This will in turn lead to the oils remaining dissolved within the $scCO_2$, a flow rate that will allow for heightened chip removal rates, cryogenic cooling of the working surface, and improved lubricity at the cutting surface of the drill bit.

While the top bushing within our prototype collar assembly prevents the collar from falling downward, we overlooked the fact that the prototype collar is free to slide upward. This can be easily remedied by the implementation of an additional bushing above the collar assembly. This additional bushing will ensure stability of the collar and can be seen in the left part of Figure 32 on Page 26.

The last change that we would recommend for a final design would be an improvement of the collet assembly which is meant to seal around the drill bit. While the seals within our prototype collet were rated for 1500 psi, we overlooked the fact that that rating was for aqueous MWFs which exhibit high surface tension. With $scCO_2$, the MWF has a surface tension that is almost immeasurable; resulting in higher molecular mobility and a collet that leaks around the drill bit. To address this problem, we design a conical insert with an o-ring that rests on the collet and an additional o-ring that seals around the drill bit. The conical design allows for the seal to increase significantly as the cap of the collet is tightened down. This conical seal design can be seen in Figure 32 on Page 27.
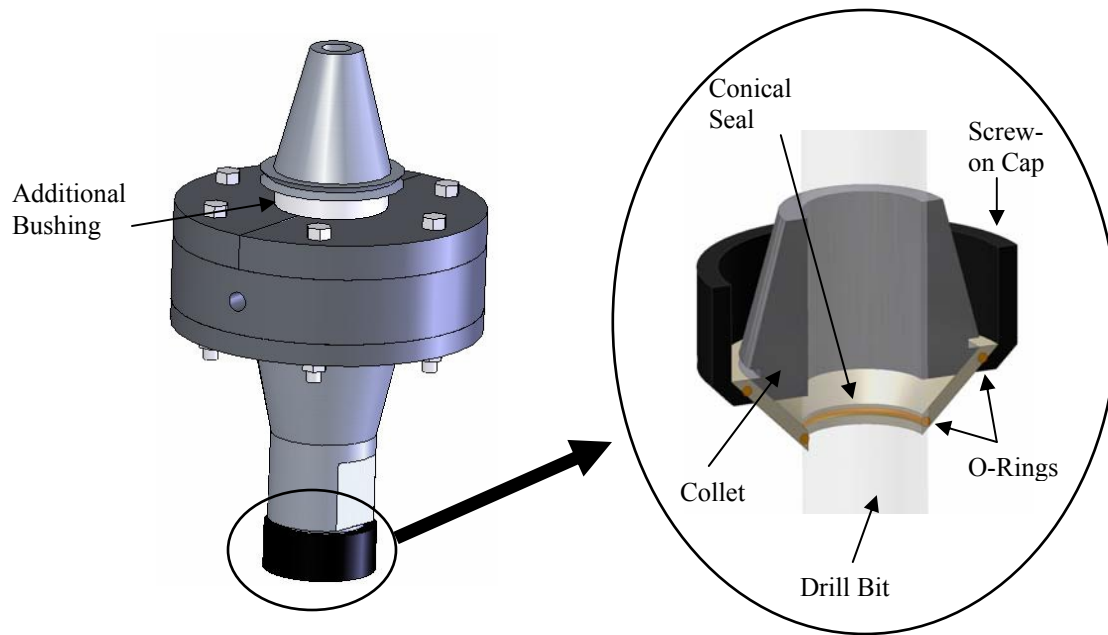
Figure 32. Drawing of final design proposals including an additional busing to prevent the collar assembly from moving upward and a conical seal to improve sealing capabilities around the drill bit.

Problem Analysis

To ensure that our project meets our goals, we incorporated fundamentals of fluid dynamics and heat transfer to ensure that our system operates at the optimal flow rate and pressure to facilitate sufficient cooling, lubrication and chip removal. The system has also been engineered such that it can handle the stresses induced by the extremely high operating pressures required to maintain CO_2 in its supercritical phase. As our team worked towards meeting the goals that we laid out, we continued to run into and address problems that were both expected and unexpected. The purpose of this section is to overview the design problems that were addressed throughout the design phase.

Each of the design problems that are overviewed below have been laid out in greater detail in the sections of the paper titled 'Engineering Design Parameter Analysis and Design Modifications' and 'Final Design Description.

Maintaining adequate, uniform pressure. The first major design problem that we came across was coming up with a design that could couple a stationary coolant inlet with a rotating tool and transporting a supercritical CO_2 solution successfully throughout the entire system without losing substantial pressure. The dissection and understanding of similar, inexpensive, rotating fluid delivery systems such as rotating sprinklers aided in our efforts to understand how to successfully couple the coolant inlet with the tool holder. Our research efforts lead us to the concept of coolant-induced tool holders and in turn sparked the generation of the majority of our initial design ideas.

Addressing drill bit through-hole size. It was agreed upon within the group that the optimal through-hole size within the drill bit was 0.006" but could be changed to different diameters through the implementation of the threaded high-pressure fitting which screws the tubing into the back of the drill bit. Too big of a hole will lead to frost within the tool holder and the oil becoming insoluble within the CO_2. Too small of a hole will lead to extremely low flow rates and poor chip removal.

Preventing drill bit ejection. The next major problem that we encountered was how we were going to go about sealing the drill bit safely within the system and insuring that it would not be ejected during use. We came up with several design idea to address this problem. These ideas included running high-pressure tubes from the collar all the way through the drill bit and securing them with epoxy as well as the idea of manufacturing a press-fit insert into which high-pressure tubes could be inserted. Both of these ideas however were thrown out due either to the crudeness of the idea or a complete lack of space within the tool holder. This problem would eventually be addressed by utilizing a collet holder along with an E/R style collet that will secure our drill bit and seal at pressures as high as 1500 psi. However, after pressurizing the prototype, it was found that a new conical seal design between the drill bit and collet would have to be manufactured due to the fact that the existing seal was design for aqueous systems and leaking when used in conjunction with $scCO_2$.

Allowing for the interchangeability of drill bits. We also wanted our design to applicable to machining processes involving any size drill bit. This problem was also addressed by the use of a collet holder that has the ability to house any size collet ranging from 2 mm to ¾" in diameter. However, this brought about the problem of not being able to seal the shank of the collet holder within the bore of the tool holder at extremely high pressures.

Sealing the collet holder within the tool holder. The E/R style collet holder relies on a close tolerance fit within the tool holder to seal at pressures of 250 psi and below. Once pressures of 1200-1500 psi are introduced, this tolerance seal becomes completely inadequate. We had several ideas that addressed this problem. A threaded adapter with a male end for the bore of the tool holder and a female end for the shank of the collet holder would seal well. However, the 8620 steel that both of the parts are made out of exhibit a hardness over 50 Rockwell C which is nearly impossible to thread. We also contemplated a Teflon washer at the interface of the collet holder and tool holder, but could not find a sure fire way to compress the washer. Therefore we decided to seal the two parts together by way of a permanent weld that is aided by a set screw; the only idea that guaranteed a seal at pressures of 1200-1500 psi while ensuring that the two parts would not rotate with respect to one another.

Obtaining a seal around the set screw. The set screw that works alongside the weld in holding the collet holder stationary within the tool holder cannot seal by itself at extremely high pressures. In order for the screw to seal, either liquid Teflon or Teflon tape is to be added to the threads of the set screw.

Material compatibility. Although we have taken material compatibility into consideration already, it is an ever-present problem when working with $scCO_2$. If there is a chemical compatibility issue that is overlooked, we may have trouble keeping the oil dissolved in the CO_2 and may experience material breakdown within the system. The problem of materially compatibility has already been partially addressed by the selection of stainless steel for the collar redesign and Ekonal PTFE for the rotary seals. However, we may encounter other material issues further down the line as lubricants for the collar assembly must be chosen wisely.

Running a non-aqueous MWF. It became obvious early on that the Collis coolant-induced tool holder that we purchased failed to meet our specifications for plumbing layout, dimensions, pressure capabilities (>1200 psi) and chemical compatibility. One problem that was less obvious was that of maintaining proper lubrication, which is often times provided by

traditional aqueous MWFs. Without a liquid MWF running through the coolant inducer, we may find that an increase in heat inducing friction will negatively affect the performance of the system. We were able to maintain proper lubrication by applying traditional bearing grease to the contact surface of each bushing.

System optimization. After successfully transporting the supercritical CO_2 through the tool we will need to optimize the final design for performance. Experiments designed to measure our system's performance compared to current through-tool coolant systems will need to be formulated. It will then be necessary to tweak our design to obtain maximum efficiency.

Ease of assembly. After finding that the assembly of our prototype caused our rotary seals to tear, we decided to design a tool holder that has no sharp edges that could possibly interface with and destroy the seals. This tool holder will also have a gradual taper so that the seals can be gradually worked into place.

Validation and Environmental Impact Analysis

The introduction to this paper highlighted numerous advantages that oils dissolved in $scCO_2$ hold over the same oils dissolved in aqueous solutions. Aside from the cryogenic cooling and improved lubricity that lead to an increase in machining efficiencies, $scCO_2$ metalworking fluids also bring about a reduction in environmental and occupational health hazards; some of which have been validated and others that have yet to be. The following reductions in environmental and occupational health hazards have been validated thus far; an elimination of the need to dispose of large quantities of liquid MWFs into the environment ($scCO_2$ MWFs have oil flow rates that are considered to be dry), an elimination of surfactants that are used to dissolve oil in water ($scCO_2$ readily dissolves metalworking oils), and an elimination of bacteria growth within the MWFs and thus an elimination of the need to use bacteria fighting biocide additives which are extremely harmful to one's health ($scCO_2$ does not harbor bacteria growth).

While the aforementioned environmental and occupational health improvements have already been proven, we must still address how the CO_2 emissions and energy consumption associated with our final design will compare to those associated with the old standard of aqueous MWF systems.

Comparison of CO_2 Emissions. First we will look to compare the CO_2 emissions that are associated with the production of one of our drill bits. We can assume that the production emissions for an aqueous MWF drill bit and the drill bit used in our system are more or less identical. We can then factor in the additional amount of CO_2 that our system uses (since it is being used to carry the oil) by using the CO_2 mass flow rate along with a given time. We will then compare the total emissions of the aqueous system to that of our final design and find how long our system must increase tool life by to justify the use of CO_2 as a MWF.

Baseline drill bit production CO_2 emissions. To find the CO_2 emissions associated with the production of one drill bit, we compiled the emissions data that is shown in Table 2 on Page 30 for the production and machining of basic steel drill bits along with the geometry of our drill bit which can be seen in Figure 34 on Page 30. We started by finding the density of steel (ρ_{steel}) along with the volume of stock steel needed to produce one ¾" diameter drill bit (V_o). A slightly larger initial diameter of 0.80" is assumed to allow for a surface finish to be added.

$$\rho_{steel} = 0.294 \frac{lb}{in^3}$$

$$V_o = \frac{\pi(0.80in)^2}{4}(9.75in) = 4.9009in^3$$

We can multiply the two together to get the stock mass of steel, M_o, needed to produce one drill bit.

$$M_o = \rho V_o = (0.294\frac{lb}{in^3})(4.9009in^3) = 1.44086lb = .65356kg$$

The next step involves finding the diameter of steel that must be removed from the back of the drill bit, V_{back}, so that the threads can be added. We also found the volume that needs to be removed around the outside diameter of the stock piece of steel to reach a ¾" final diameter, V_{OD}, along with V_{flutes}, the volume that needs to be removed from the flutes. Note that this volume is assumed to be 40% of the material that exists below the threaded cavity of the drill bit.

Figure 33. Basic dimensions associated with the production of our ¾" drill bit.

$$V_{back} = \frac{\pi(0.5in)^2}{4}(3.375in) = 0.663in^3$$

$$V_{OD} = \frac{\pi(0.8^2 - 0.75^2)in^2}{4}(9.75in) = 0.5935in^3$$

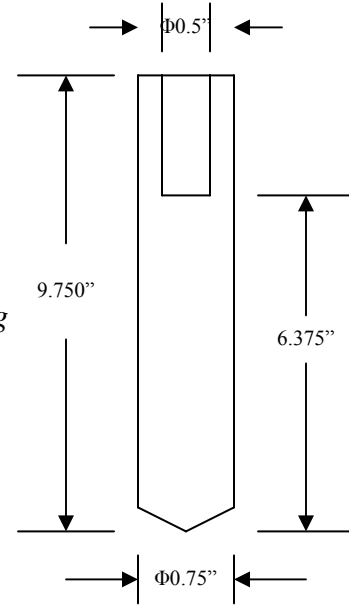$$V_{flutes} = \frac{\pi(0.75in)^2}{4}(6.375in)(0.4) = 1.1266in^3$$

The three volumes that were calculated above can then be added together to get the total volume of steel that is to be removed from the drill bit, $V_{removed}$, and the mass of that amount of material ($M_{removed}$) can easily be found by multiplying the volume by the density of steel.

$$V_{removed} = V_{OD} + V_{back} + V_{flutes} = 5.5225in^3$$

$$M_{removed} = \rho V_{removed} = (0.294\frac{lb}{in^3})(5.5225in^3) = 0.74162lb = 0.33639kg$$

We can now incorporate the data for CO_2 emissions from Table 2 and apply them to the process of producing one drill bit. We first want to find ε_{steel}, the amount of CO_2 that is emitted from producing our piece of stock steel. This can be found by multiplying the specific mass of producing steel by the initial mass of the steel.

$$\varepsilon_{steel} = M_o(2667\frac{g}{kg}) = 1743.0g$$

Table 2. Specific energy requirements and CO_2 emissions for basic steel drill bit production operations [8].

Process	Energy(MJ/kg)	CO_2 Emissions (g/kg)
Material production		
Basic steel production	25.05	3,679
Pre-processing		
Ladle refining	1.27	141
Remelting	6.25	1,012
Ingot casting	3.31	
Reheat furnace	1.87	
Hot rolling	1.45	282
Cold rolling	1.15	129
	15.30	1,564
Processing		
CNC milling: roughing cuts	24	6,072
CNC milling: finishing cuts	600	151,800
	624	157,872
Post-processing		
Annealing	1.19	
Atomization	1.00	145
	2.19	145

Next we can find $\varepsilon_{pre\text{-}treat}$, the amount of CO_2 that is emitted is pre-treating the stock piece of steel. Again, the specific mass of emissions can be found in Table 2.

$$\varepsilon_{pre-treat} = M_o(2576\tfrac{g}{kg}) = 1683.6g$$

The next step of emissions treatment is that associated with machining. We can get the specific mass emissions of CO_2 from Table 2 and multiply it by the mass removed during machining. Note that we are assuming 95% of the machining to be rough machining and the remaining 5% to be finish machining.

$$\varepsilon_{rough} = M_{removed}(6072\tfrac{g}{kg})(95\%) = 1940.4g$$

$$\varepsilon_{finish} = M_{removed}(151800\tfrac{g}{kg}) = 2553.2g$$

There are also emissions associated with post-treating the finished product which can be calculated by multiplying the specific emissions for the post-treatment of steel by the final mass of the piece.

$$\varepsilon_{post-treat} = (M_o - M_{removed})(145\tfrac{g}{kg}) = 47.4g$$

Now we can sum up all of the aforementioned emissions and find the amount of CO_2 that is emitted into the atmosphere through the manufacturing of one of our drill bits.

$$\varepsilon_{baseline} = \varepsilon_{steel} + \varepsilon_{pre-treat} + \varepsilon_{rough} + \varepsilon_{finish} + \varepsilon_{post-treat} = 7967.6g \; CO_2 \text{ per drill bit}$$

Comparison of baseline to final design CO_2 emissions. With the emissions associated with the production of one drill bit known, we will now look to compare that value with the amount of CO_2 attributed to the use of our scCO$_2$ MWF and see just how long our system would have to

prolong the life of a drill bit for these emissions to be justified. First, we know that our system possesses a $scCO_2$ flow rate of roughly 10 g/min.

$$\overset{\circ}{\varepsilon}_{prototype} = 10\tfrac{g}{\min}$$

So we know that the total emissions associated with the use of $scCO_2$ will be equal to the flow rate multiplied by t_{new}, the time of use.

$$\varepsilon_{prototype} = \overset{\circ}{\varepsilon}_{prototype}\, t_{new} = 10\tfrac{g}{\min} \cdot t_{new}$$

However, since some of the CO_2 that we are using is a waste product of such processes as ammonia synthesis, we are only attributing half of the emissions to our process.

$$\varepsilon_{attributed} = \overset{\circ}{\varepsilon}_{prototype}(50\%)t_{new} = 5\tfrac{g}{\min} \cdot t_{new}$$

Now we equate the emissions of our system with the emissions that it takes to make an additional drill bit to see how long it takes our system to use the amount of CO_2 that is associated with the production of this additional drill bit.

$$\varepsilon_{attributed} = \varepsilon_{baseline}$$
$$5\tfrac{g}{\min} \cdot t_{new} = 7967.6 g$$
$$t_{new} = 1593.52 \min = 26.55 hr$$

So we see that after roughly 26 hours, our system will go through the amount of CO_2 with one drill bit while pumping $scCO_2$ that it would take an aqueous system to go through two drill bits. Prior to 26.55 hours, our system uses less CO_2, assuming that it is using the original drill bit and the aqueous system replaces their drill bit at least once. However, if the aqueous system is able to go 26.55 hours without a drill bit change, then it will have lower emissions.

The above information can be rather hard to analyze without a baseline aqueous system tool life to work from and some testing of our final design. The debate over whether or not the emissions of our system are less than that of an aqueous MWF system will not be fully ironed out until side by side testing of both systems has been run.

Comparison of Energy Requirements. The second aspect of environmental impact comparison between our final design and an aqueous system has to do with system energy requirements. We will compare the two systems in much the same manner as we did for emissions in that we will find the energy associated with the production of a drill bit as well as the additional energy that our system needs to run the CO_2 pump. One should note that this area of comparison may not even need to be looked at because of the fact that aqueous systems need a pump that has similar power requirements to our pump to run. However, we have run our calculations under the assumption that the pump for aqueous systems requires an amount of energy that is negligible in comparison to our $scCO_2$ pump in order to stay conservative in our comparison.

Baseline drill bit production energy requirements. Table 2 allows us to calculate the energy that goes into making a drill bit in the same way that we were able to calculate the corresponding CO_2 emissions. All of the calculations are the same except for the fact that each value for emissions (ε) has been replaced with a value for energy (E).

$$E_{steel} = M_o(18.80\tfrac{MJ}{kg}) = 122869MJ$$

$$E_{pre-treat} = M_o(21.55\tfrac{MJ}{kg}) = 14.0842MJ$$

$$E_{rough} = M_{removed}(24\tfrac{MJ}{kg})(95\%) = 7.6697MJ$$

$$E_{finish} = M_{removed}(600\tfrac{MJ}{kg})(5\%) = 10.0917MJ$$

$$E_{post-treat} = (M_o - M_{removed})(2.19\tfrac{MJ}{kg}) = 0.6946MJ$$

$$E_{total} = E_{steel} + E_{pre-treat} + E_{rough} + E_{finish} + E_{post-treat} = 44.8271MJ \text{ (per drill bit)}$$

In the end we are able to find that each of our ¾" steel drill bits requires roughly 45 MJ of production energy.

Prototype energy requirements. Under the conservative assumption that the pump that feeds an aqueous MWF system requires far less power than the pump that feeds our final design, we looked to find the time that it takes the two system to be equivalent in energy consumption assuming that our final design is able to run with a single drill bit while an aqueous system will require one tool change. At a mass flow rate of 10 g/min for the $scCO_2$ within our system, the pump draws 969 W of power (P_{pump}) [8]. By multiplying this power requirement by the time of use, we are able to come up with the energy that is used by our pump (E_{pump}).

$$E_{pump} = P_{pump}t = (969\tfrac{J}{s})t$$

We can then set the energy requirement for our pump equal to that of making an additional drill bit so that we can solve for the time it takes for our pump to use the energy that it takes to make an additional drill bit.

$$E_{pump} = E_{total}$$

$$969\tfrac{J}{s}\cdot t = 44.827MJ$$

$$t = 46261s = 12.85hr$$

So we see that after roughly 13 hours, our system will go through the amount of energy with one drill bit while pumping $scCO_2$ that it would take an aqueous system with no power requirements to go through two drill bits. Prior to 12.85 hours, our system uses less energy, assuming that it is using the original drill bit and the aqueous system replaces their drill bit at least once. However, if the aqueous system is able to go 12.85 hours without a drill bit change, then it will have a lower power requirement.

It seems that in our conservative estimate that the power requirement for the aqueous pump is negligible, the energy used by our prototype (break even time of 13 hours) has become more of a limiting factor that the CO_2 emissions (break even time of 26 hours). However, one would most likely find in reality that our conservative assumption is not very realistic and that our system may in fact improve tool life while using less energy to pump the MWFs. This of course can and will not be known until our final design is tested.

Conclusions

Research conducted by the Environmental and Sustainable Technologies (EAST) Laboratory at The University of Michigan have determined that external spray applications of scCO$_2$ in machining processes increase tool life and efficiency in comparison to other metalworking fluids in external applications. There are currently several benchmarks for delivering oil-in-water as well as oil-in-air MWFs through the tool and have been found to increase machining efficiency while lowering costs and overall environmental impact. It is for this reason that our team has designed a system to incorporate scCO$_2$ into a through-tool lubrication delivery system.

Our specific design focuses on drilling applications involving softer materials where chip removal can become an issue. Since our system will need to operate at extremely high pressures, our customer's as well as our own principal concern is safety. Other customer requirements include reduced cost, which we have addressed by providing them with a system design that when compared to their current systems will provide superior lubricity and cooling capacity to the working surface, thus making the process more efficient and less costly.

Through research of current through-tool MWF delivery systems, we garnered a strong base knowledge that led to our alpha design; the retrofitting of an existing coolant-induced tool holder. The existing tool holder is designed to handle aqueous MWFs at pressures of 250 psi or less whereas are running non-aqueous, supercritical carbon dioxide based MWFs as pressures of more than 1200 psi. The biggest design problem was coming up with a way to successfully transport the MWF through the machine tool while maintaining its supercritical state as well as allowing for its rapid expansion at the working surface of the tool.

Our alpha design was solid from afar, but nearly all of the internal complexities of the project had yet to be captured. Therefore, our team spent a significant amount of time coming up with design modifications that would eliminate certain design problems without bringing about new problems. Our team also spent time verifying that each of our chosen design modifications is plausible. We currently have a prototype that leaked during static equilibrium at 150 psi, but have come up with a final design that we feel meets or exceeds all of our design parameters. Once our final design is manufactured and is in full working condition, procedures, variables, and standards for testing the design can be formulated and carried out so as to increase the efficiencies and decrease the environmental and occupational health hazards of sub-surface machining operations.

The completion of this project will lead to a MWF application system that not only increases overall machining efficiency, but also eliminates nearly all of the environmental impact that is traditionally seen with traditional aqueous MWF systems.

Biographical Sketches

Chris Frayne. Chris Frayne is from Farmington Hills, Michigan and attended Farmington High School. He is a senior in the College of Engineering at The University of Michigan where he is majoring in Mechanical Engineering. His interest in mathematics, which led him to choose engineering as major, has paved the way to an interest in the world of finance. This past summer he interned at Sigma Investment Counselors, Inc. in Southfield, Michigan where he concentrated primarily on equity market research and portfolio management. After graduating this May, he plans on pursuing a career in portfolio management while concurrently enrolling in a three year program to obtain his Chartered Financial Analyst (CFA) designation.

Fahim Islam. Mohammad Fahim Islam is from Allen Park, Michigan and attended Allen Park High School. He is currently attaining a BSE in mechanical engineering here at the University of Michigan. He is currently a senior and plans to work fulltime in an engineering career after the year is over. Fahim has worked the past two summers at Ypsilanti Community Utilities Authority and at Dow Corning in engineering internships to gain valuable experience.

Diana Platt. Diana Platt is from Farmington Hills, Michigan and attended Farmington Harrison High School. She is currently enrolled as a senior in the College of Engineering at The University of Michigan and is majoring in Mechanical Engineering. Diana enjoys Mechanical Engineering because it allows her to apply engineering and mathematical concepts in order to problem solve. Also, she has an interest in business subjects such as economics and accounting. For the past two summers she interned at Hitachi America Limited in Farmington Hills where she learned Computer Aided Design (CAD) software and worked with a new welding technology called Friction Stir Welding. In the future, she plans on spending time in the workforce before returning to college to obtain her Master of Business Administration.

Brendan Sherry. Brendan Sherry is from Farmington Hills, Michigan and attended Harrison High School. He is interested in being a mechanical engineer because he likes the challenges of designing and the reward of successfully finishing a project. After he obtains his bachelor's degree he plans on staying at the University of Michigan to acquire his masters degree. After his masters he plans on finding a position in the automotive industry where hopefully some of his work will be hands on. Brendan worked as an intern the past summer at the Robert Bosch Corporation in Farmington Hills, MI.
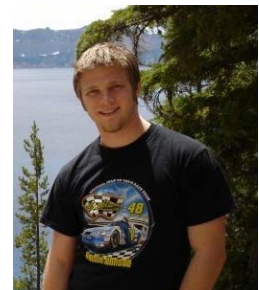
References

Scientific Literature

1. Supercritical CO_2 Metalworking Fluids: Concept and Results to Date, Steve Skerlos (Department of Mechanical Engineering, University of Michigan), Microsoft PowerPoint Presentation, August 2006
2. Feasibility of Metalworking Fluids Delivered in Supercritical Carbon Dioxide, Clarens, Hayes, Skerlos (Department of Civil and Environmental Engineering, Department of Mechanical Engineering, University of Michigan), 2006
3. Optimal Design of Metalworking Fluids for Microfiltration Recycling, Clarens, et al., (Environmental and Sustainable Technologies (EAST Laboratory), Department of Mechanical Engineering, University of Michigan), Microsoft PowerPoint Presentation, June 13, 2005
4. Minimum quantity lubrication (MQL) applications in automotive power-train machining, Filipovic, A. (General Motors Powertrain, Pontiac, MI, USA), *Machining Science and Technology,* v 10, n 1, Jan.-March 2006, p 3-22
5. MQL Project Ford: Bielomatik Division Lubrication Systems, Microsoft PowerPoint Presentation, © Bielomatik, February 2005
6. Dry machining and minimum quantity lubrication, Weinert, K. (Dept. of Machining Technology, University of Dortmund), CIRP *Annals – Manufacturing Technology,* v 53, n 2, 2004, p 511-537
7. Minimum lubrication milling of titanium alloys, Hassan, A. (Sch. Of Mech. Eng., Shanghai Jiao Tong Univ., China), *Materials Science Forum,* v 471-472, 2004, p 87-91
8. Comparison of Life Cycle Emissions and Energy Consumption for Selected Metalworking Fluid Systems, Clarens, et al., (Dept. of Civil, Environmental, and Mechanical Engineering, University of Michigan), 2006

Internet Websites

9. http://www.iscar.com/ProductLines/ProductLineDetail.asp?CountryID=1&ProductLineDetailID=327
10. www.collistool.com
11. http://www.unist.com/umi-max%20thru%20the%20tool%20lubrication.htm
12. http://www.fuji-bc.com/english/ndm/index.html
13. http://www.unist.com/umi-max%20thru%20the%20tool%20lubrication.htm
14. http://itwfpg.com/acculube/eco_booster.html
15. http://www.thomasnet.com/products/drills-coolant-fed-24111635-1.html
16. http://www.americanheller.com/soliddrilling-main.html
17. http://www.coolantfedtooling.com
18. http://dom.semi.org/web/wsemi.nsf/url/0112wuii

Human Sources

19. Andres F. Clarens, Environmental Engineering, University of Michigan
20. Professor Steven J. Skerlos, Mechanical Engineering, University of Michigan
21. Kenneth Stamper, Transmission Plant Operations, Ford Motor Company
22. Timothy Hull, Powertrain Manufacturing Technology Department, Ford Motor Company
23. Alexander Stoll, Powertrain Manufacturing Technology Department, Ford Motor Company
24. Steve Erskine, Engineering Resource Center, University of Michigan
25. Washtenaw Community College, Welding Department

Supplier PDF Files

26. Unist, Thru-the-Tool Systems brochure
27. Tapmatic, Minimum Quantity Delivery Systems brochure
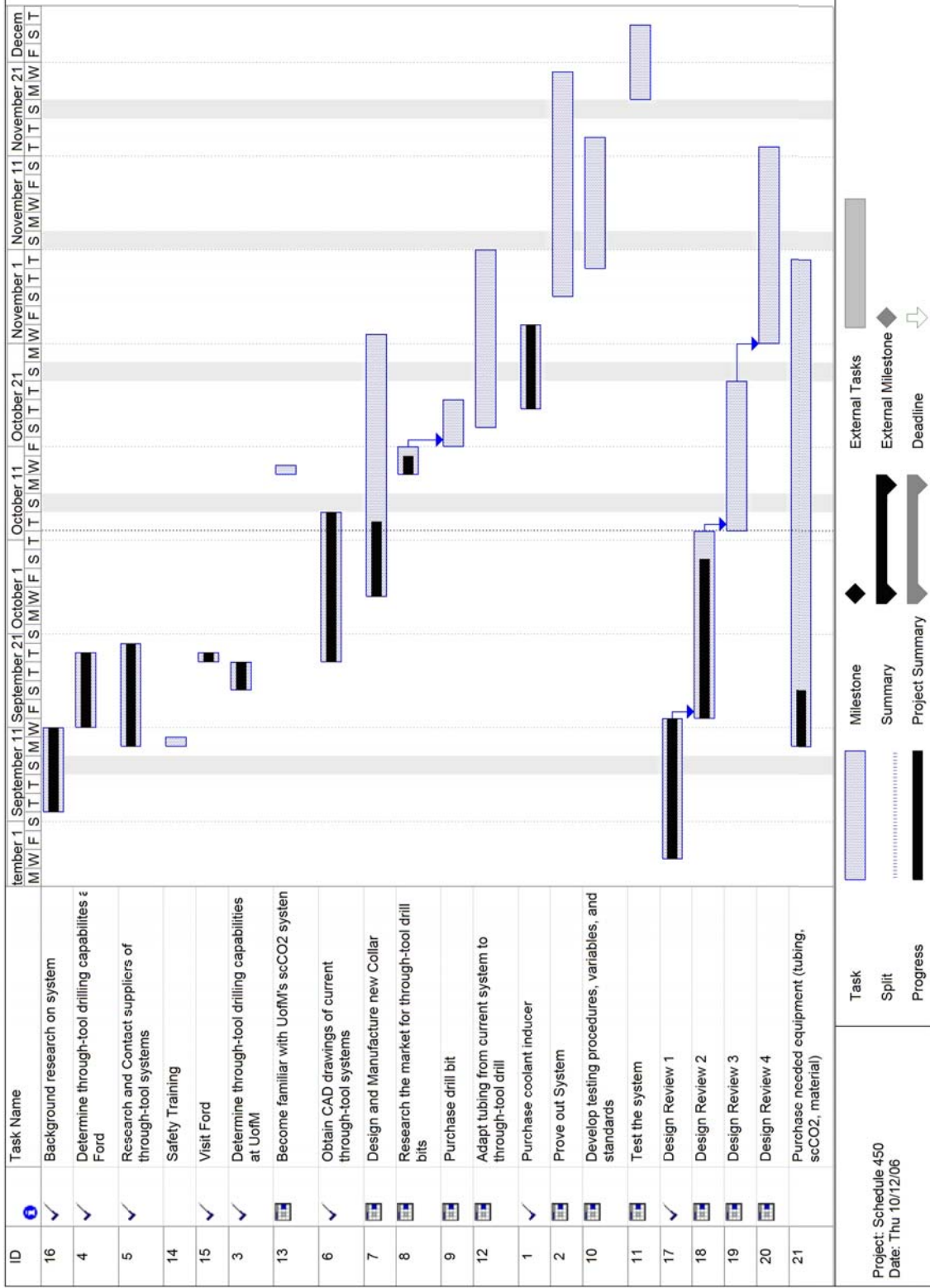28. Acculube, EcoBooster Minimum Quantity Delivery System brochure

Patents

29. Threaded tool with coolant supply, Josef Giessler, 7,073,988, October 2, 2003
30. Arbor for mounting a tool to a spindle of a machine tool and a machining method of employing the same, Tani, et al., 4,921,376, April 26, 1989
31. Pump design for circulating supercritical Carbon Dioxide, Jur, et al., 6,558,475, November 21, 2003
32. Cryogenic Machining, Shane Y. Hong, 5,901,623, May 11, 1999
33. Mixing systems for processes using supercritical Carbon Dioxide, Jur, et al., 6,558,475, May 6, 2003

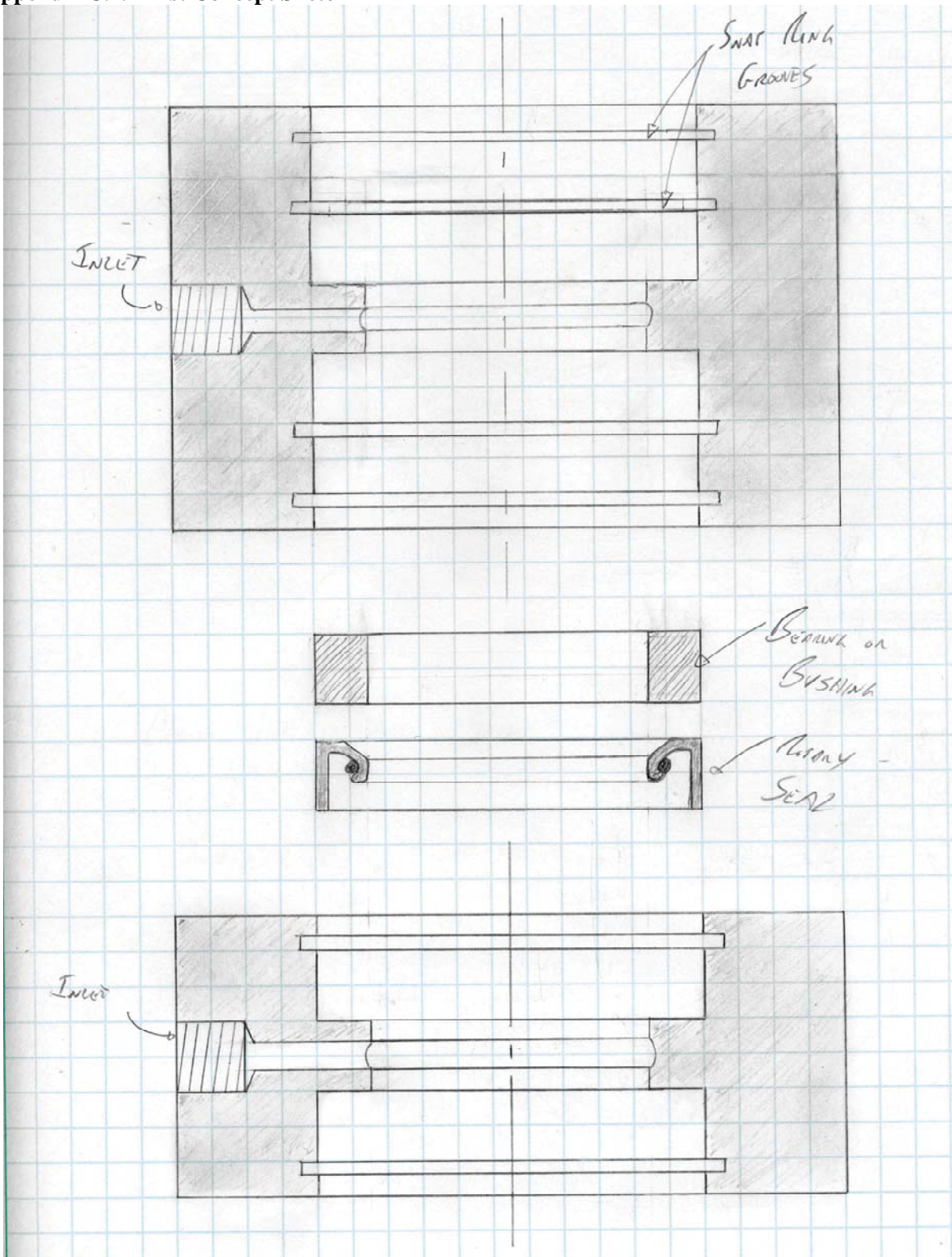**Appendix A. Correlation of Customer Requirements and Engineering Specifications**

1	Very weakly related
3	Weakly related
5	Moderately related
9	Strongly Related

Customer Requirements	Normalized Importance to Customer (Relative Weight)	Delivery Pressure	Mass of Removed Chip	Amount of Excess Fluid	Hours of Operation before Failure	Machine Efficiency	Volume Flow Rate	Pressure at Which Tool is Ejected From Spindle	Number of Components	TOTAL - CUSTOMER REQUIREMENTS	RANK	Importance	Rotary Seal	Snap Washers	Press-Fit Bearings	Coolant Tubing	Coolant Inlet	Inner-System Lubrication	Design Alternatives	Coolant-Fed Bushing	Liquid MWF Coolant Inducer	Bielamatik Two-Channel Oil/Air System	Bielamatik One-Channel Oil/Air System
Compatible with Soft Metals	1.0	9	1	9	1	7	9	1	9	46	1	0.13	1	1	1	1	1	0		3	5	9	9
Good Chip Clearance	1.0	1	9	8	3	6	5	1	9	42	2	0.12	0	0	0	0	0	0		1	5	9	9
Dosen't Clog	0.8	9	9	9	3	1	1	1	1	27.2	5	0.08	0	0	0	9	5	5		5	5	5	5
Safe to Use	0.7	1	1	1	9	8	5	9	5	27.3	4	0.08	9	9	9	9	9	3		5	5	5	5
Easy to use/install	1.0	0	1	5	1	5	0	5	9	26	6	0.07	5	3	3	3	9	1		5	9	1	1
Low Maintenace	0.7	0	5	9	9	1	0	5	5	23.8	8	0.07	5	5	5	5	5	9		5	9	1	3
Easy Refill	0.7	0	0	3	1	3	9	1	5	15.4	12	0.04	1	1	1	1	5	0		3	5	3	3
Low Cost	0.7	0	0	3	5	5	3	3	5	16.8	10	0.05	5	1	3	1	3	1		5	5	1	1
Improved Tool Life	0.5	5	5	5	8	9	4	3	4	21.5	9	0.06	5	5	3	3	3	3		3	3	5	5
Handles High Pressures	1.0	9	1	1	5	5	3	9	0	33	5	0.09	9	5	5	5	9	3		1	1	5	5
Handles Variable Spindle Speeds	0.5	0	0	0	5	5	0	3	1	7	13	0.02	9	3	9	1	1	9		5	3	9	9
Doesn't Leak	1.0	5	0	9	3	3	1	3	1	25	7	0.07	9	5	5	1	5	3		1	3	9	9
Improved Machine Performance	0.5	1	1	5	9	9	1	5	0	15.5	11	0.04	9	5	5	3	3	3		3	5	9	9
Reduced Envrionmental Impact	1.0	1	3	9	3	9	5	1	1	32	3	0.09	1	1	1	1	1	3		3	1	9	9
Units		kPa	g	M^3	Hrs.	Na	Vol.	kPa	#														
Total		41	36	76	65	76	46	50	55														
Engineering Specs Ranked		7	8	1	3	1	6	5	4														

User-Perceived Quality — Part Characteristics

Appendix B. Projected Project Timeline

ID	Task Name
16	Background research on system
4	Determine through-tool drilling capabilites at Ford
5	Research and Contact suppliers of through-tool systems
14	Safety Training
15	Visit Ford
3	Determine through-tool drilling capabilities at UofM
13	Become familiar with UofM's scCO2 system
6	Obtain CAD drawings of current through-tool systems
7	Design and Manufacture new Collar
8	Research the market for through-tool drill bits
9	Purchase drill bit
12	Adapt tubing from current system to through-tool drill
1	Purchase coolant inducer
2	Prove out System
10	Develop testing procedures, variables, and standards
11	Test the system
17	Design Review 1
18	Design Review 2
19	Design Review 3
20	Design Review 4
21	Purchase needed equipment (tubing, scCO2, material)

Project: Schedule 450
Date: Thu 10/12/06

Legend:
Task
Split
Progress
Milestone
Summary
Project Summary
External Tasks
External Milestone
Deadline

Appendix C.1. First Concept Sketch

Appendix C.2. Second Concept Sketch
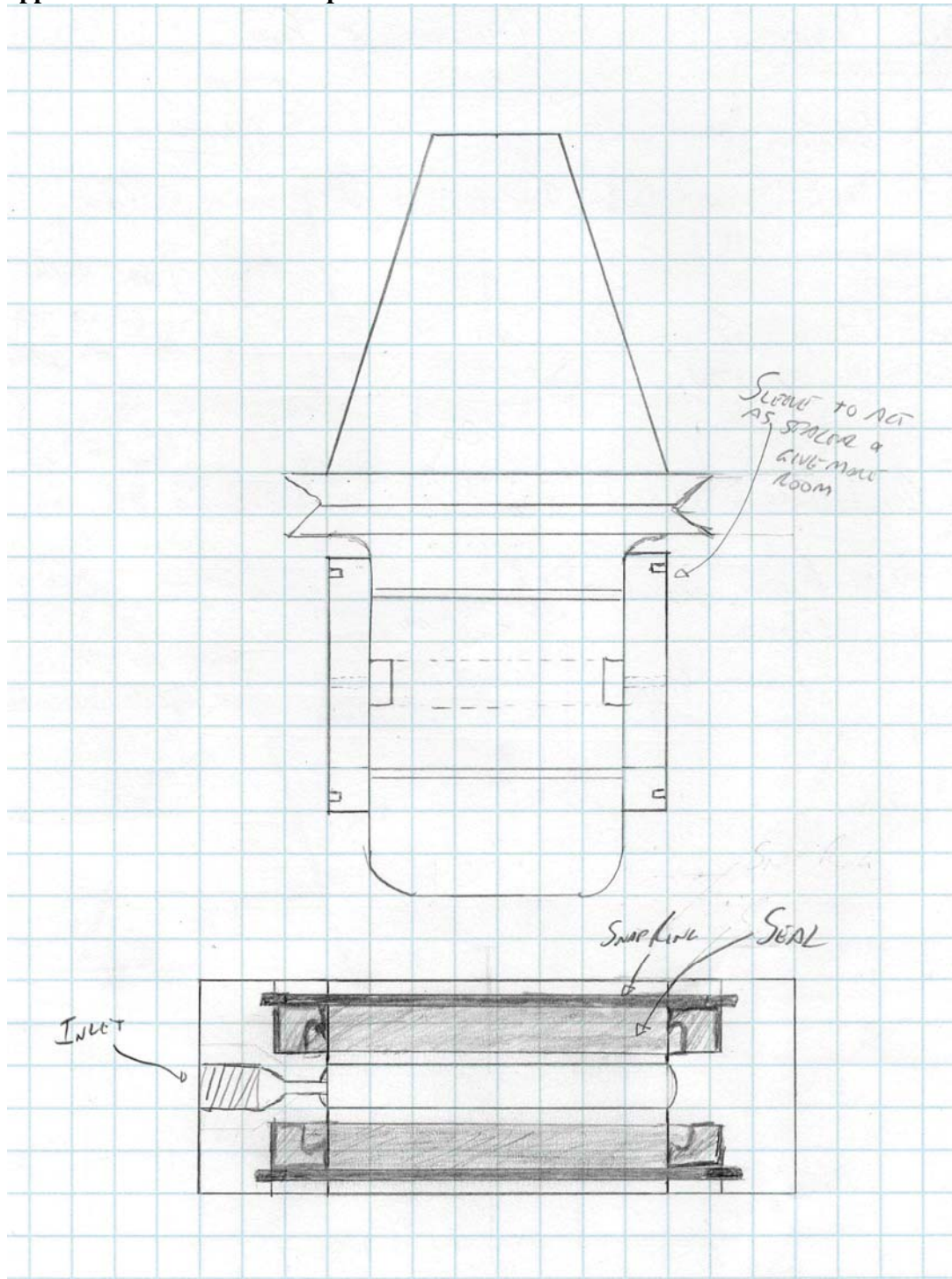
Appendix C.3. Third Concept Sketch

Inlet
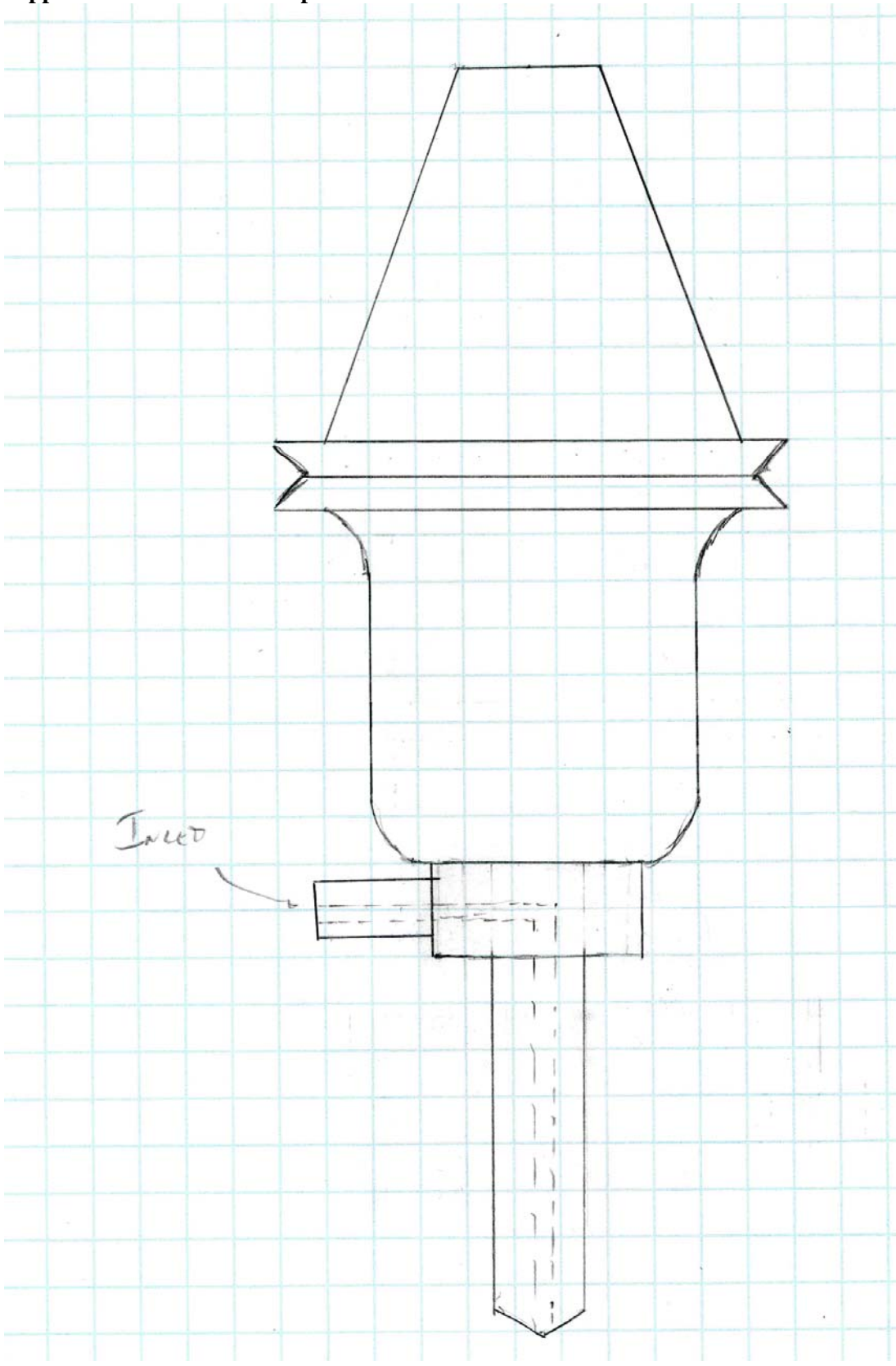
Appendix C.4. Fourth Concept Sketch
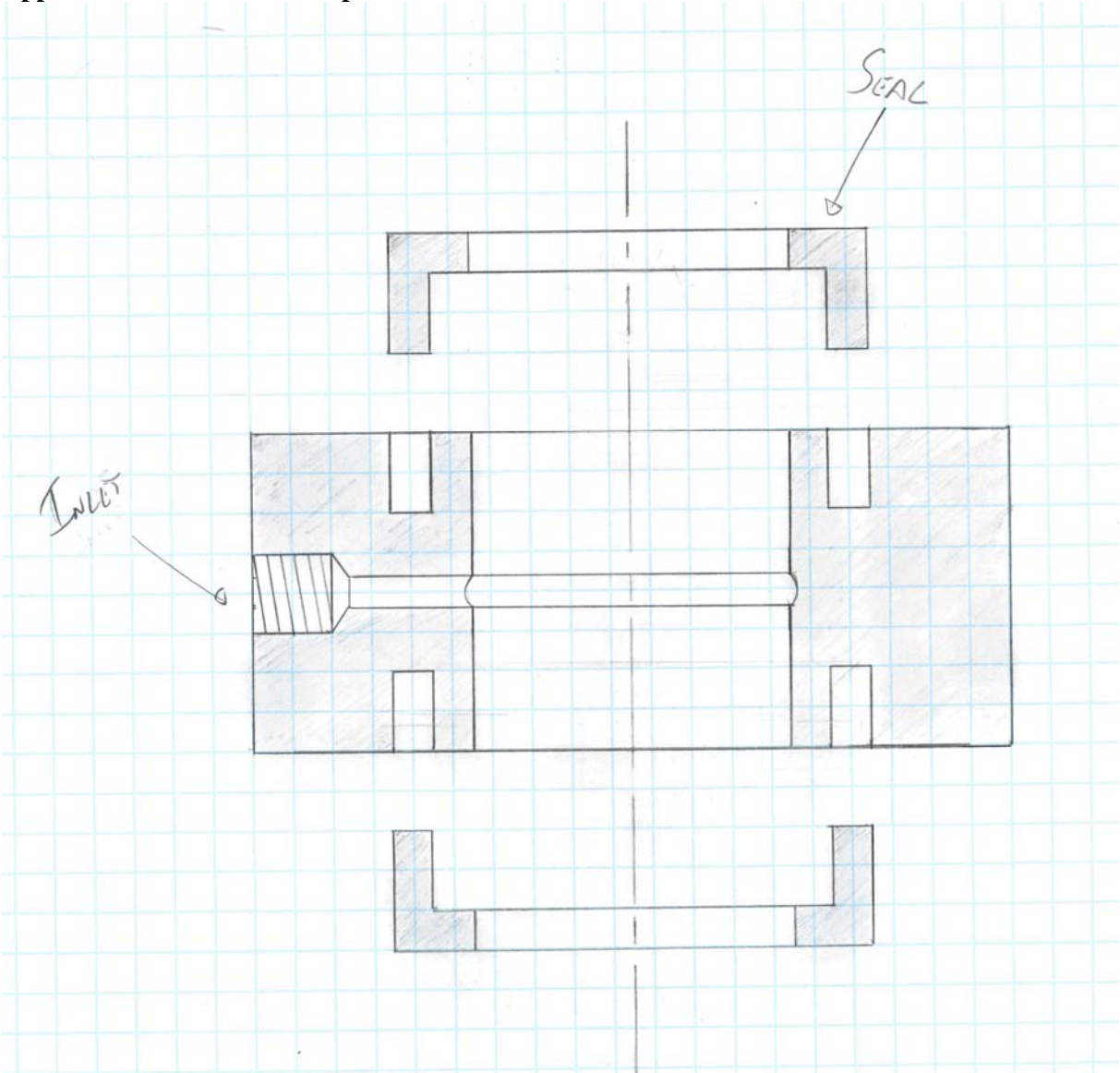
Appendix C.5. Fifth Concept Sketch
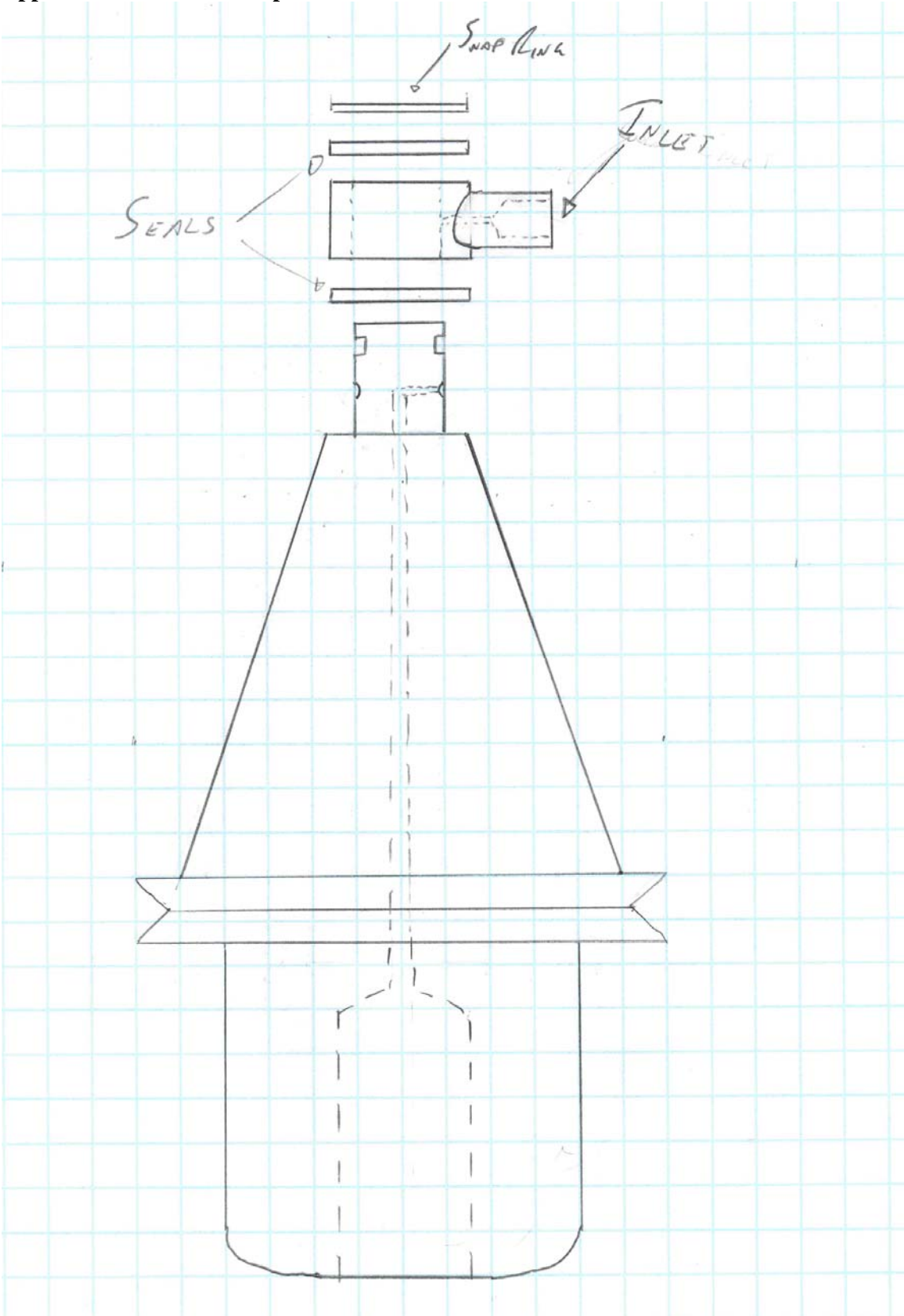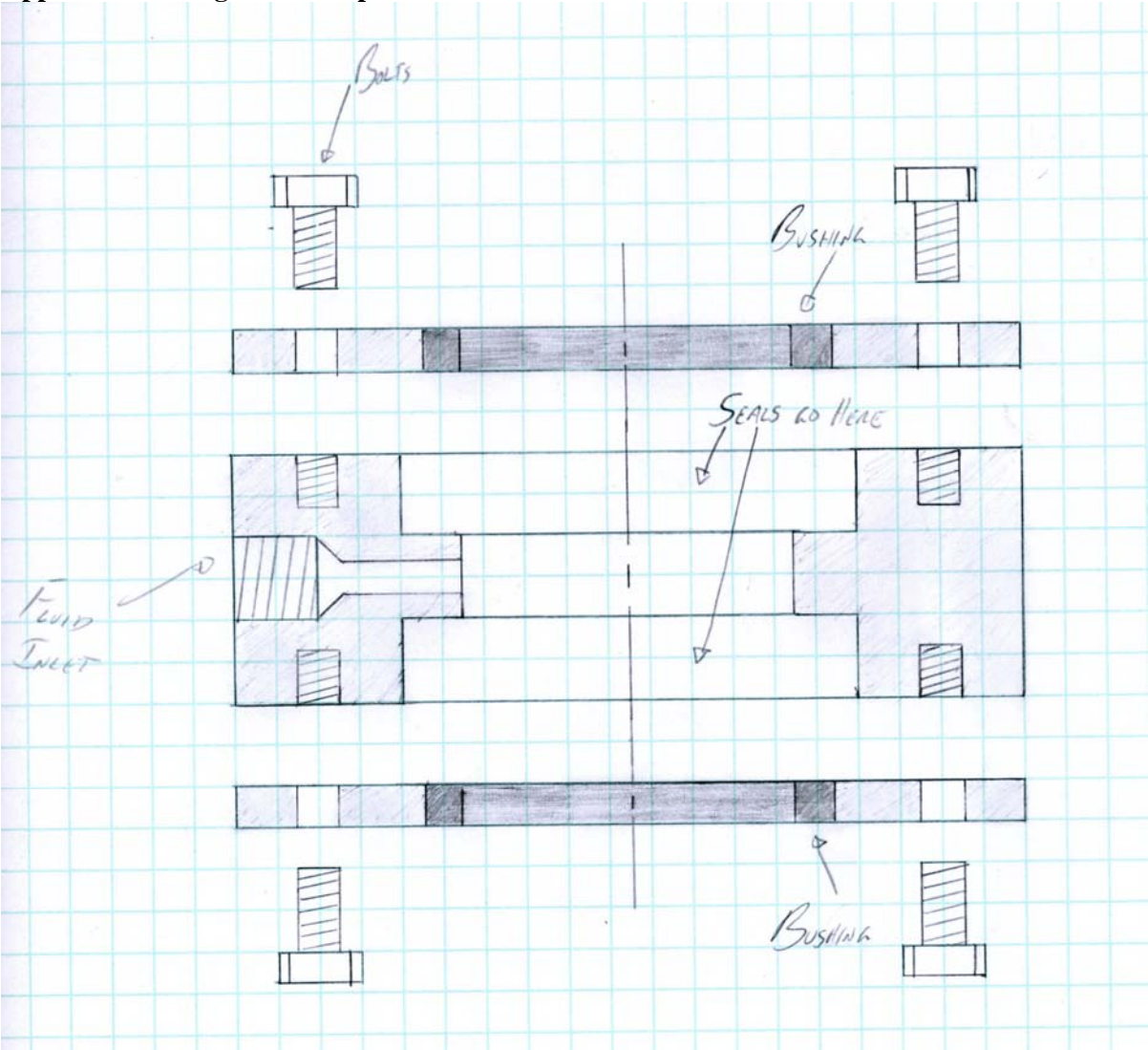
Appendix C.6. Sixth Concept Sketch
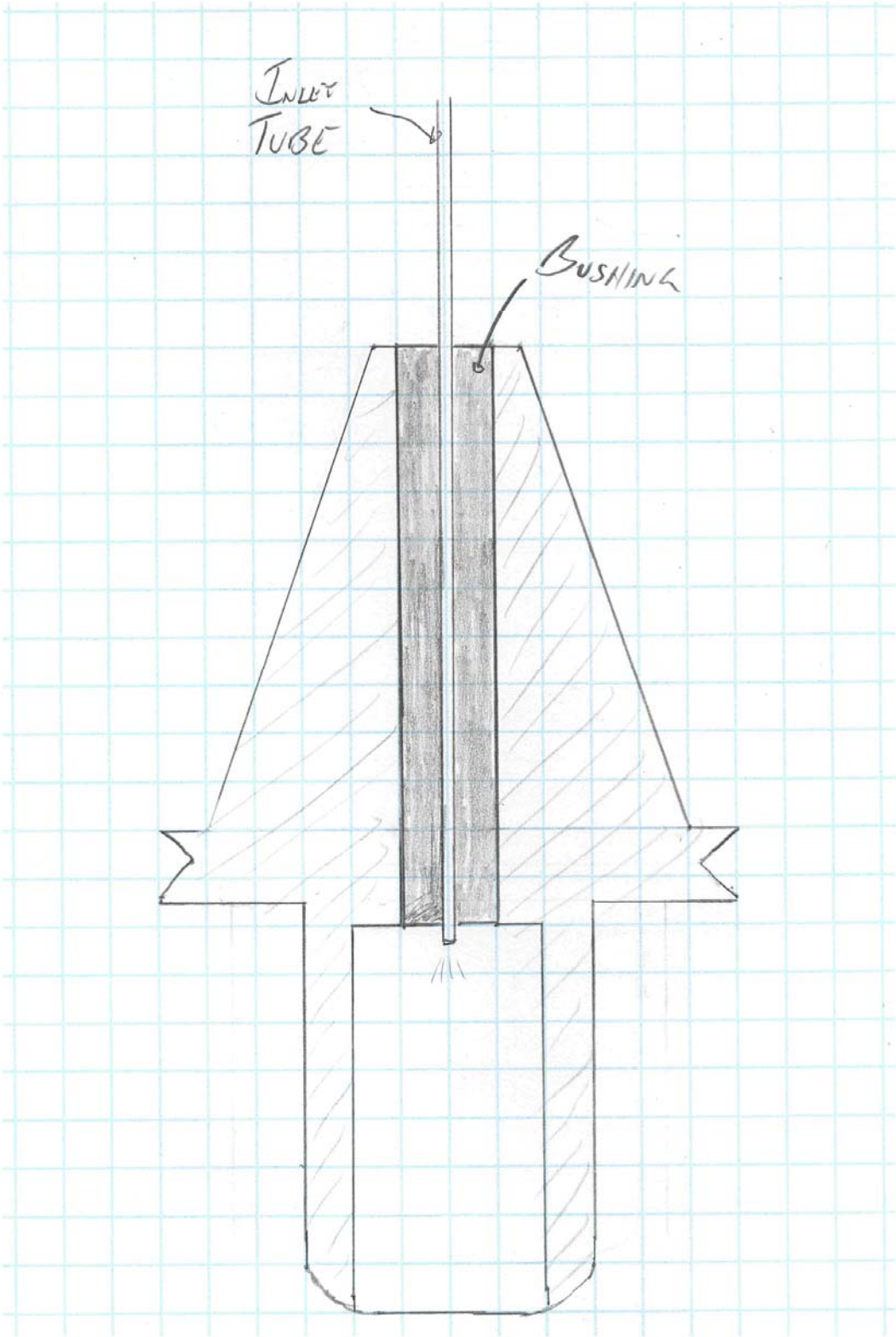
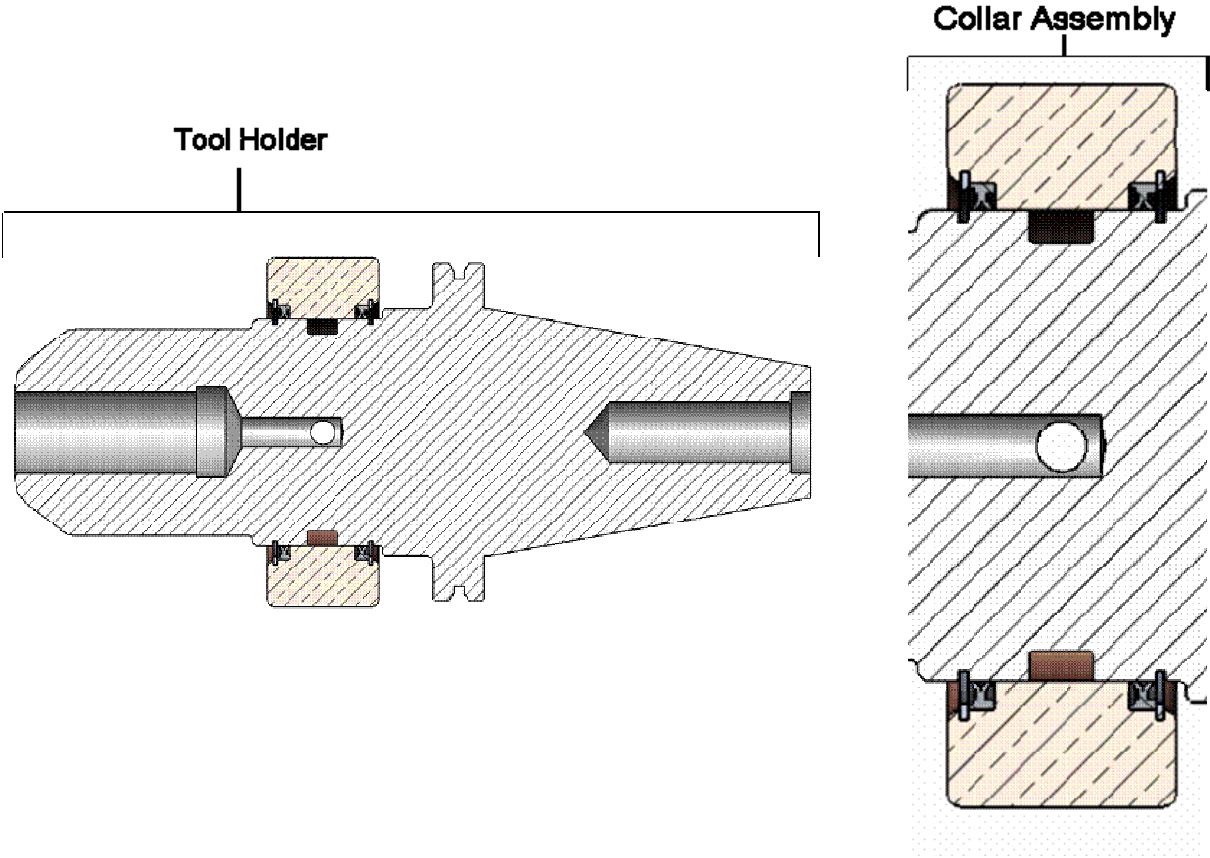**Appendix C.7. Seventh Concept Sketch**
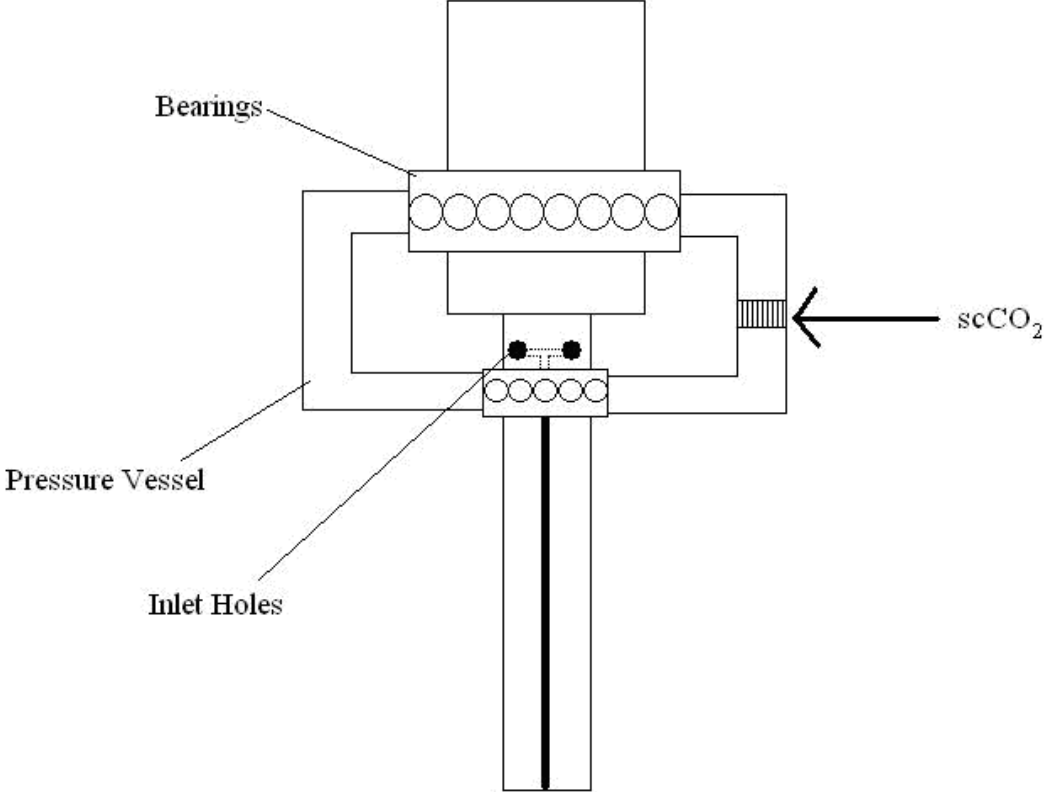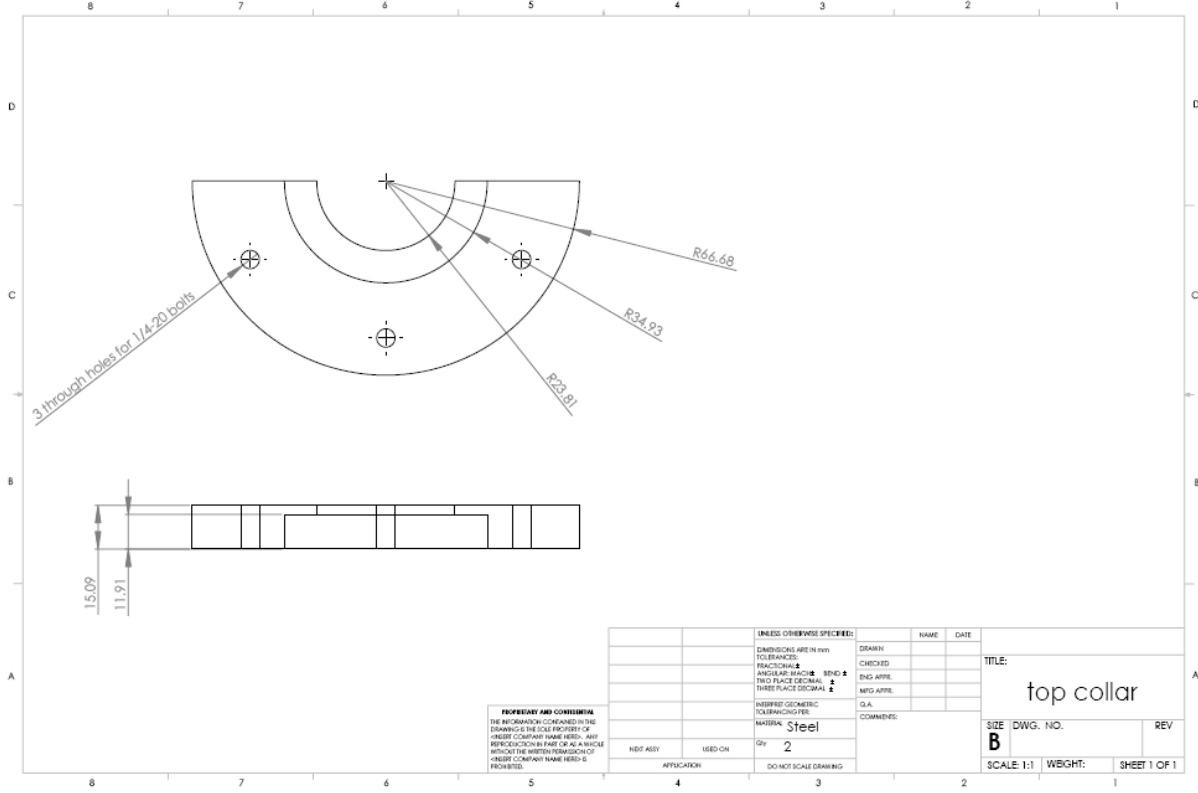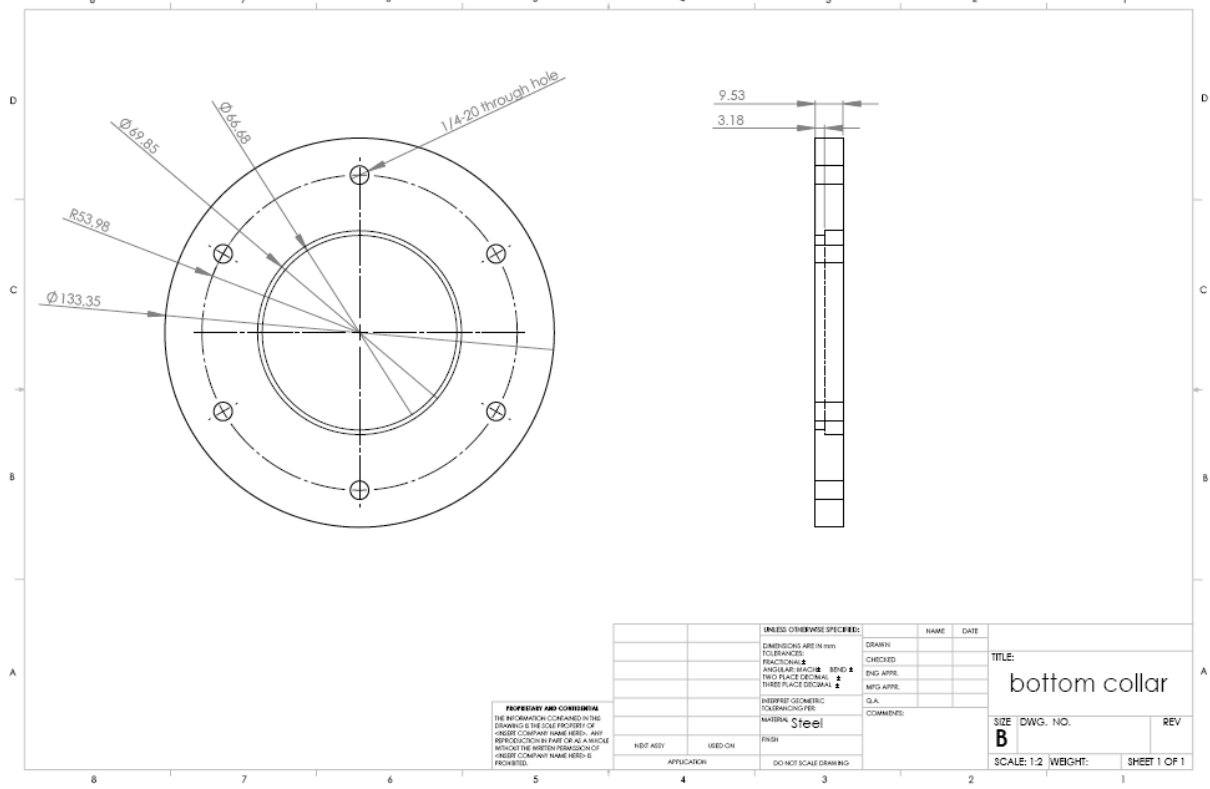
Appendix C.8. Eighth Concept Sketch

Appendix D. Cross-Sectional Engineering Drawing of Alpha Design

Tool Holder

Collar Assembly

Appendix D. 1. Engineering Drawing for Top Safety Plate

Appendix D. 2. Engineering Drawing for Bottom Safety Plate

TITLE:

bottom collar

MATERIAL: Steel

SIZE **B**   DWG. NO.   REV

SCALE: 1:2   WEIGHT: SHEET 1 OF 1

Appendix D. 3. Engineering Drawing for Top Bushing

Ø 69.85
Ø 44.19
Ø 63.50

11.91
8.73

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN mm
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH±   BEND ±
TWO PLACE DECIMAL   ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC
TOLERANCING PER:

MATERIAL

FINISH

NAME | DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:

TITLE:

bushing
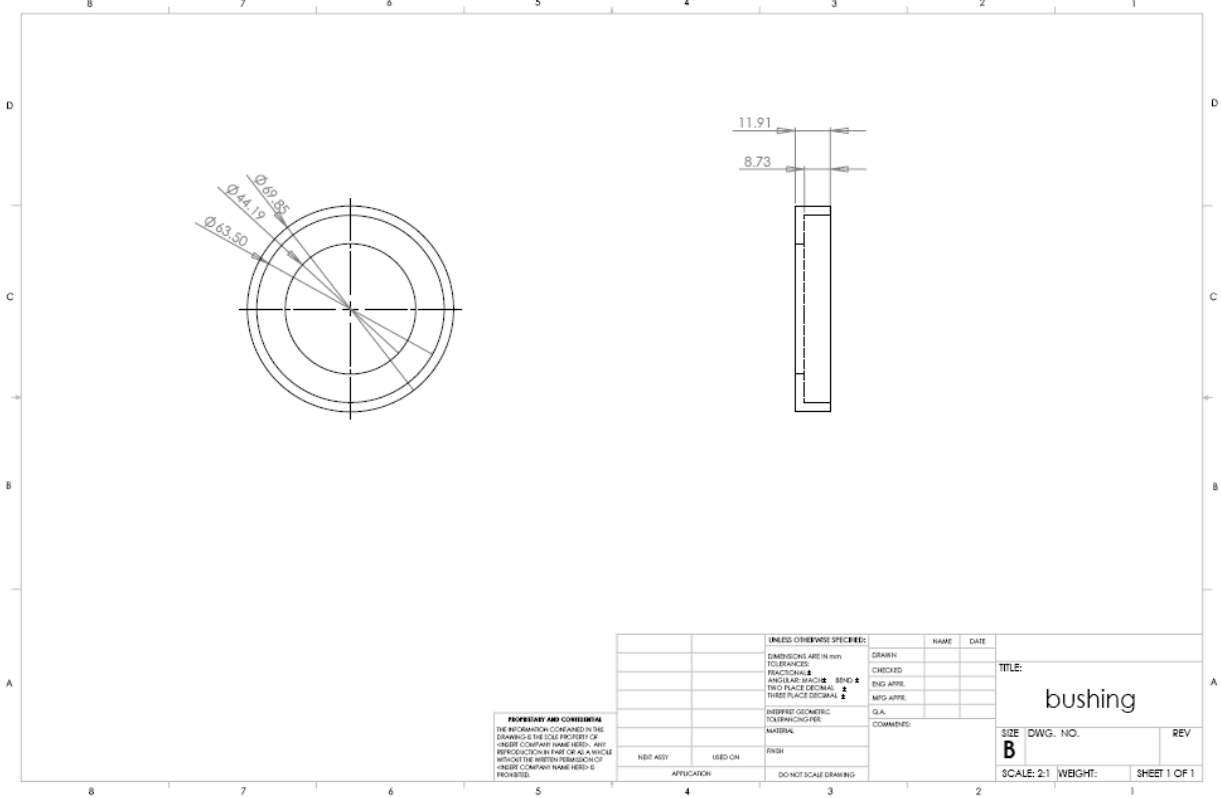
PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS
DRAWING IS THE SOLE PROPERTY OF
<INSERT COMPANY NAME HERE>. ANY
REPRODUCTION IN PART OR AS A WHOLE
WITHOUT THE WRITTEN PERMISSION OF
<INSERT COMPANY NAME HERE> IS
PROHIBITED.

NEXT ASSY | USED ON

APPLICATION | DO NOT SCALE DRAWING

SIZE DWG. NO.   REV
B

SCALE: 2:1 WEIGHT: SHEET 1 OF 1

Appendix D. 4. Engineering Drawing for Bottom Bushing

Appendix D. 5.   Engineering Drawing for Collar Body
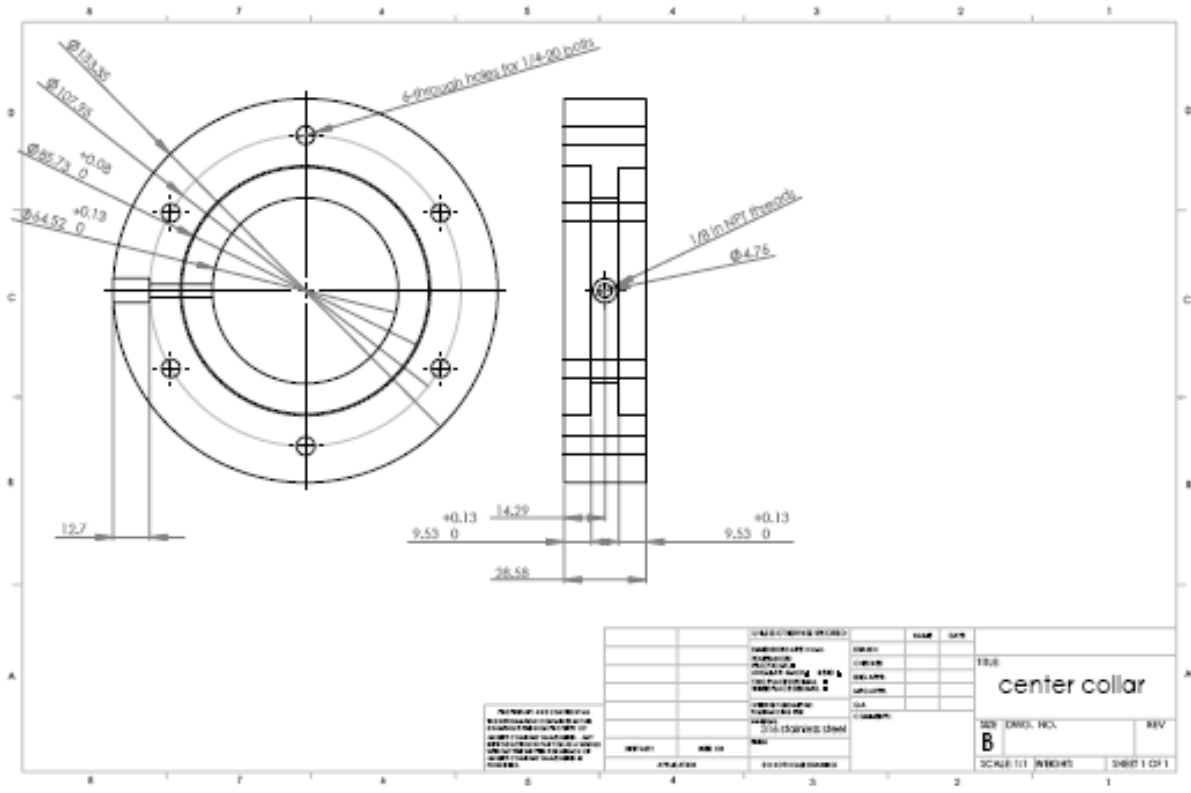
Appendix E. Pictorial of Prototype Assembly