Design of a High Pressure System to Aid Horizontal Directional Drill Bit Steering

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Project Introduction

Horizontal Directional Drilling (HDD) is a technique that provides a means of installing underground utilities without cutting a trench in the soil (i.e. trenchless). Several equipment manufacturers have been successful in designing, manufacturing, and marketing units for this task. HDD equipment typically performs well unless the soil is very hard. A senior design team, The West Central Pump Works, Inc., under the direction of Dr. Paul Weckler, was challenged with this problem by one of the equipment manufacturers and was asked to develop a creative solution.

Statement of Work

The Charles Machine Works, Inc. (of Perry, OK) is the manufacturer of the high quality Ditch Witch™ product line, which includes: compact utility products, trenchless products, trenchers and plows, vacuum excavation systems, pipe bursting systems, electronic products, and trailers. In the fall of 2006, The Charles Machine Works, Inc. (Ditch Witch) came to the Biosystems and Agricultural Engineering (BAE) department with a need to enhance the performance capabilities of one of their trenchless products. Past agreements between the company and the BAE department have resulted in positive outcomes. The West Central Pump Works set out to continue building that relationship.

The West Central Pump Works, Inc. is composed of four Biosystems and Agricultural Engineering Senior students interested in the field of mechanical design. Ditch Witch came to the team, looking for creative solutions to their design problem.

Figure 1: JT520 (CMW, 2001)

Ditch Witch JT520 units (Figure 1) are used for compact horizontal directional drilling (HDD) tasks. They are ideal for shallow product installations and are commonly used in residential areas. Relative to larger Jet Trac units, the JT520 is a comparatively low powered unit. The problem presented to the team involved complications the unit encounters when steering the drill head through compacted soils.

Typical operation of the unit involves a rotating bit (beacon) that is continually lubricated with drilling fluid. When steering of the beacon (Figure 2) is required, rotational motion is stopped and the bit is forced (pushed or thrust) through the soil. When it reaches the desired position, rotational motion is resumed. A problem arises when the soil is too solid for the beacon to push through during the steering process.

Figure 2: JT520 Beacon

Ditch Witch requested a design that solved the challenges of injecting a high pressure fluid through the drill string for a short period of time to aid in steering the beacon in hard, dry soil conditions. Ultimately, the team was concerned with producing high pressure down the drill pipe to achieve a high velocity stream of fluid to erode material in the drill path. Consultation with the sponsor after the fall semester led the team to the development of a dual hydraulic cylinder system solution to the design problem. The system was designed so Ditch Witch would be able to implement it into future unit models with appropriate modifications, if they choose to do so.

While the ultimate design factor controlling the problem solution was a high pressure, high velocity jet of water, other factors played a key role in the design process. The following list describes many of these factors.

- Operating Conditions
  - Typically 150 ft (30 sticks) of pipe on a machine.
  - Two to five feet typical boring depth.
  - Steering in characteristic soil conditions generally requires about 15 seconds.

    - An operator steers approximately 15 times per bore.
    - The expected unit usage: approximately 2-5 minutes per bore and 200 bores per year.
    - The original mud pump can pump a maximum of 5 GPM and 500 PSI.
    - The hydraulic pump on the unit can pump 10 GPM to auxiliary functions at 2500 PSI.

- Fluid
    - Drilling fluid will be the high pressure fluid utilized in any possible future applications of the design.
    - Water was acceptable for use in the concept

- Model Application: The team's design should be specifically applicable to the JT520 model.

- Considerations
    - Any high pressure hoses within three feet of the operator must be shielded.
    - If high pressure hose is used, its strength should be adequate to handle the design pressures.
    - Space limitations on the unit.
    - An electronic control system was desired for the implemented design solution.
    - High pressure fluid may be applied through the drill stem in multiple short (approximately 5 second) repeated intervals.
    - Minor modifications to the unit and hydraulic fitting changes were acceptable.
    - Concept was not required to fit on the JT520 for testing.

The team spent most of the fall semester concentrating on concept generation and performing theoretical design calculations. The design variable of concern was the exit velocity of the jet of fluid out of the drill string nozzle. However, there was no data available. It was known that when the pressure at the nozzle exceeds 1500 PSI, there tends to be cutting action in the soil. This exit pressure was the goal of the design process for the team. It was also known that faster and more penetrating soil erosion occurs with higher pressures. Ditch Witch engineers stated that the smallest nozzle that would be used with a high pressure system is a 0.070 in nozzle (Figure 3).

Figure 3: 0.070 in Nozzle

At the end of the fall semester, the team presented two design solutions to sponsor representatives (Appendix A). A dual hydraulic cylinder system was chosen from the two by the representatives. A detailed task list of spring semester activities, including individual team members' responsibilities, is located in Appendix B.

Research and Investigation

The West Central Pump Works, Inc. spent considerable time during the fall semester conducting background research as part of the investigation of the assigned project. This research included a literature review, an extensive US and European patent search, an investigation of competitive companies and products, and an analysis of current solutions to the problem. The team concentrated on subsurface drilling with the use of high pressure fluid to assist in below ground horizontal boring.

Background Literature Review

Extensive searching through multiple indexes and databases provided no relative information about the use of high pressure fluid to assist in the steering of horizontal directional drilling machines. However, the fifth edition of Fluid Mechanics by Frank M. White became an important resource for the pressure and fluid flow analysis of the pipe and beacon head. Useful information from this text included the Bernoulli and Reynolds Number equations, coefficients of friction for pipe flow, head loses in pipes and fittings, and the kinetic energy correction factor.

Patent Research

The US Patent and Trademark Office (USPTO, 2006) and the European Patent Office (EPO, 2006) were used for patent research for this design project. A search of the recent US patent *applications* was conducted and nothing of relevance to the project was found. The search of the European Patent Office produced no results of interest to the project.

Five patents were chosen from the current *approved* US Patent and Trademark Office patent database for further consideration: US4957173, US5054565, US4674579, US4714118, and US4306627. These patents were chosen after the team felt that their relevancy to the project produced the greatest concern. Patent US4674579 was found to be relevant to the sponsor's goal, but not necessarily relevant to the team's design.

After recommending that the sponsor look further into the details of this patent last fall, the team was informed that the sponsor already owned that specific patent and all patents developed by that particular company. Further investigation provided that no other patents proved to be of relevance to the team's project. Summaries of each patent are located in Appendix A (pg 7) and the full patents are located in Appendix A (pg 27).

Current Relevant Products

The team also spent considerable time in the fall semester compiling a list of current products, produced by Ditch Witch and their competitors, which would be relevant to the project. The products and their descriptions are located in Appendix A (pg 11). After this research was performed and discussed with the sponsor, the team determined that there were no current products comparable to the design the team would develop.

Current Solutions

In select areas of the United States the problem of drilling diversion has become more prevalent. Ditch Witch dealers in these areas have attempted solutions in the absence of one provided by the company. These solutions are presented in Appendix A (pg 13). While operators have found these solutions to produce satisfactory results, the team felt that it could develop a much more predictable solution to the problem based on engineering analysis, validation, and design testing.

Development of Engineering Specifications

Analysis of High Pressure System Requirements

During the fall semester, the team performed a thorough analysis of the JT520 and its requirements of a high pressure pumping attachment (Appendix A, pg 37). The team utilized the fifth edition of Fluid Mechanics by Frank M. White (2003) extensively to perform this analysis. Equations from this resource can be found in Appendix A (pg 32).

For the analysis, the team was provided a table that showed the correlation between pressure and flow allowable for the nozzle specified for the high pressure system application. The data for a 0.070 in nozzle can be found in Appendix A (pg 34). These data were plotted against each other in two charts and a trend line was fit (Appendix A, pg 34). The equations of the trend lines were later used to verify loss calculations and check correlations in pressure and flow at the nozzle.

Ditch Witch established a requirement that the system must produce at least 1500 PSI at the nozzle. Setting this as a minimum requirement, the team determined the pressure requirement of the high pressure pumping system. Using the equations of Appendix A (pg 32) and coefficients from the Fluid Mechanics textbook, the team was able to theoretically characterize the drill pipe and estimate that system production of 2500 PSI and 7 GPM would produce satisfactory results at the end of the drill stem. Later testing confirmed if this analysis held true.

Concept Generation and Evaluation

Pumping System

HM5x20z

The first design solution was developed and analyzed by the team during the fall semester. This design involved using two hydraulic cylinders, one filled with water and one filled with hydraulic fluid, to pump high pressure water through the drill string. An additional power source would be required and water would be supplied directly from the water tank on the trailer to be used as the high pressure fluid through the drill string. It also involved use of a wireless control system.

Knowing the system requirements, the team determined components that would operate synergistically to achieve the high pressure pumping goal. Table 1 lists the components of the system.

HM5x20z Component List	
Engine	Honda 2.5 HP, 7800 RPM, CCW Rotation (Honda, 2006)
Pump	Sherwood Rubber Impellor Pump, 8 GPM, +3500 RPM (Surplus Center, 2006)
Hose	5/8" X 100' Soft Garden Hose (Lowes, 2006)
Cylinder	2- 5" X 20" w/ 1.5" Rod
Control Valve	4 Way, 3 Position, Tandem Centered
Electrical	TeleChief TM2000 (Control Chief, 2003)
Tank	Ditch Witch 50 gal

Table 1: HM5x20z Component List

The two hydraulic cylinders would be mounted on the machine and would require fluid power input from the ground drive of the JT520. One cylinder would be supplied water from an impellor pump, supply tank, and engine on the trailer (Figure 4).

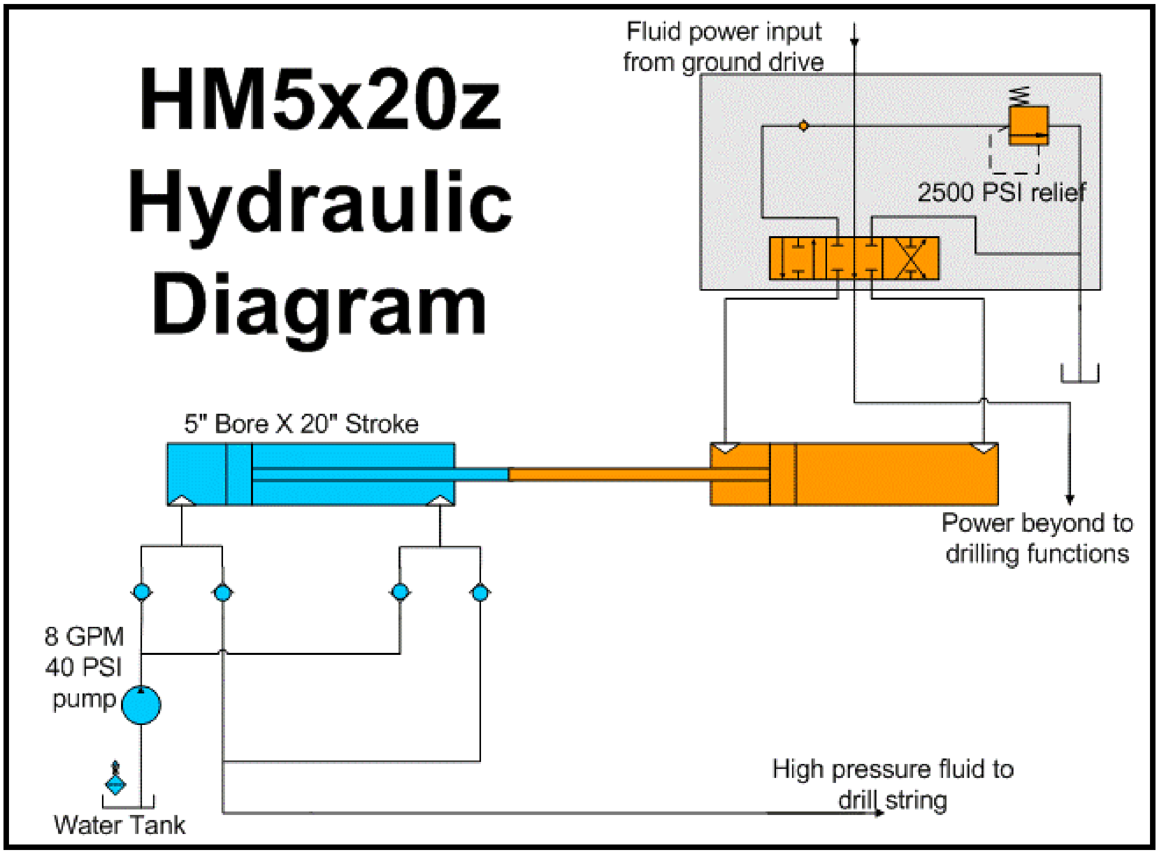

Figure 4: HM5x20z Hydraulic Diagram

The team viewed this solution as innovative and saw the benefit of removing the rotational power supply requirement for the high pressure portion of the system. However, the design had its significant downfalls. The implementation of an additional power source was not preferred by the sponsor. After being presented with this design idea, the sponsor requested that the power source be only the unit itself, eliminating another power source and more complexity to the system. The team was also informed at the beginning of the spring semester that drilling fluid taken directly from the mud pump on the unit would be acceptable as the high pressure fluid, eliminating the need for a hose from the water tank to the high pressure system. Size of this system was the final disadvantage. As designed, this system was too large (approximately 74 in long and 7 in wide) to fit onto the current unit and remain functional.

HM3x20z

The second design solution developed by the team was an extensive redevelopment of the HM5x20z. Like the HM5x20z, the HM3x20z solution was intended to involve two hydraulic cylinders, one filled with water and one filled with hydraulic fluid, placed on the unit to pump high pressure water through the system. The two cylinders were designed to share the same plunger rod, significantly reducing the amount of space needed to contain the cylinder system. Unlike the HM5x20z, this system was preferred by the sponsor over the original system. Its size, lack of additional power source requirement, and method of operation were its most significant attributes over the HM5x20z.

The HM3x20z pulled its hydraulic power directly from the JT520 unit through a complex hydraulic valve system that was controlled with an electrical switch. Hydraulic fluid returned to the unit upon exiting the cylinder, again through the valve system. Water (and eventually drilling fluid) to be used for drilling was supplied from a water source, such as a water hose or an FT5 unit (Appendix A, pg 12), through the mud pump on the JT520 to the water cylinder through a set of check valves. Upon exiting the cylinder, the water was directed to the drill stem (Figure 5).

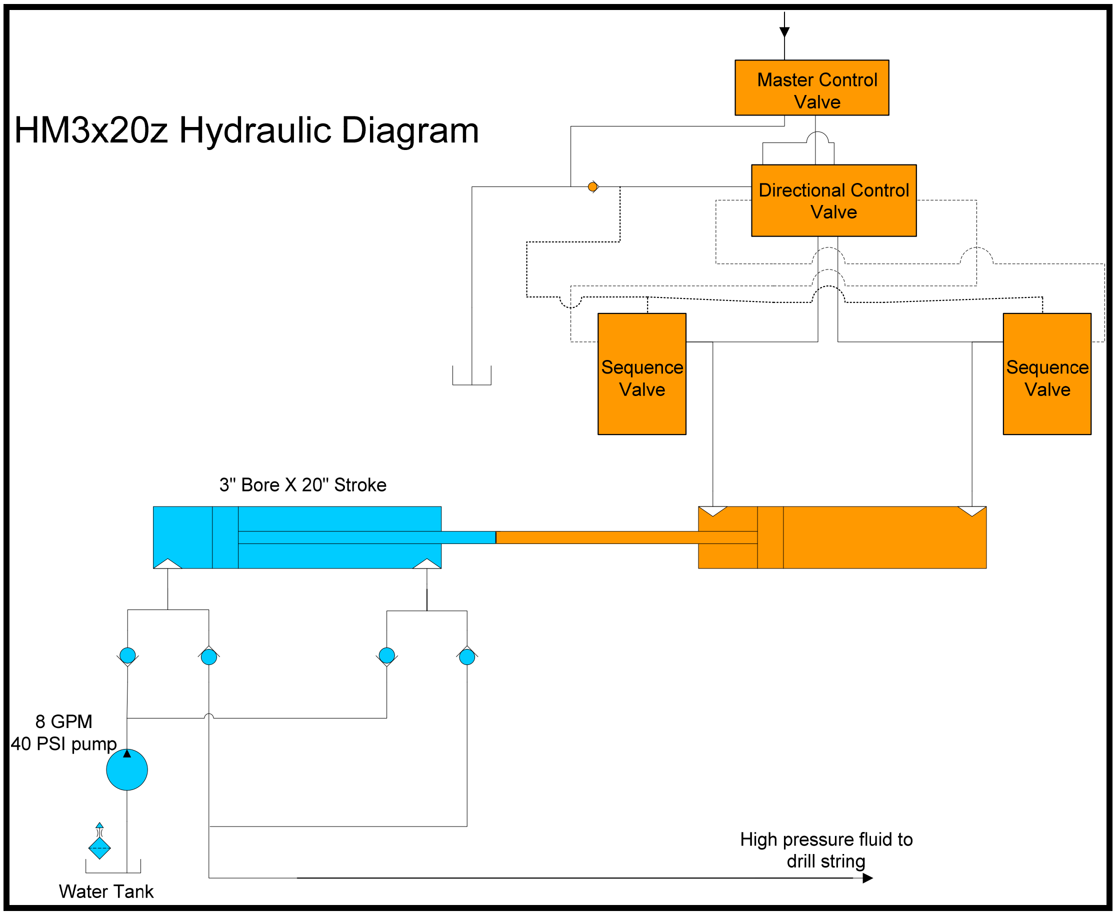

Figure 5: HM3x20z Hydraulic Diagram

Table 2 lists the components of the system.

HM3x20z Component List	
Cylinder	2- 3" X 20" from Ditch Witch
Piston Rod	1.5" from Ditch Witch
Check Valve	4- Spring-Loaded Ball Check Valve (from Ditch Witch)
Directional Valve	Directional Control Valve (from Sun Hydraulics)
Sequence Valve	2- Sequence Valve (from Sun Hydraulics)
Control Valve	Spool, 3-Way, NO Master Control Valve (from HydraForce)
Electrical	Momentary Switch

Table 2: HM3x20z Component List

In the initial design stage, the team determined a location on the unit to place the high pressure system. By adding pipe box extensions, the team could place the cylinders and a supporting structure in the bottom of the pipe box, while allowing enough room to store a full drill string of pipe. The team also located room under the unit to mount the valve assembly out of sight and out of the way of normal operation.

The other significant advantage of the HM3x20z over the HM5x20z involved the drilling fluid source. With further analysis, the team determined that an additional power source to supply drilling fluid to the system was not necessary and that fluid could be drawn in through the current pump on the unit and directed to the cylinder. This finding reduced complexity of the system, significantly improved ease of use, and lowered the cost of the overall system. All of which were very appealing to the team and sponsor.

Frame

The team determined it would be necessary to design and construct a supporting structure for the system. This structure, or frame, contained the cylinders and absorbed the forces created during cylinder operation. Three different designs were developed and analyzed based on manufacturability, safety, strength, and serviceability.

Design #1 – Four-Tube Frame

The first design involved constructing a frame of four 1 ¼ x 2 ½ in rectangular steel tubes and four 1 in steel plates (Figure 6). Two of each were welded on each side of the frame. The sides were connected by two pins, which also ran through the cylinders, mounting them to the frame. Of the three frame design alternatives, this was the most complex. While serviceability was a strength of this design, as access to the system was provided through the top or bottom, safety was a concern for the same reason.

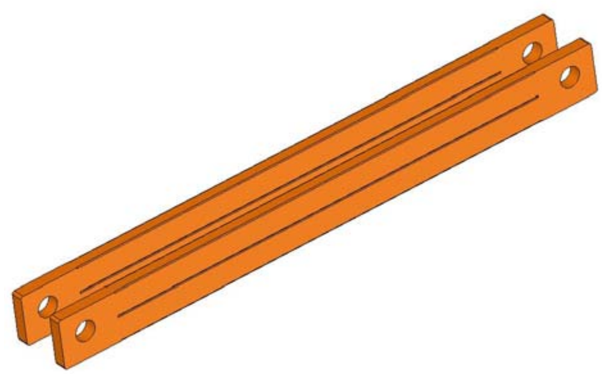

Figure 6: Four-Tube Frame Solid Model

Design #2 – Single-Tube Frame

The second frame design was a 4 x 6 in rectangular steel tube that completely enclosed the cylinder system (Figure 7). Four 2 in holes were drilled in the frame for the pins that mounted the cylinders inside the frame. All valves and fittings corresponding with the cylinders were fit into the frame beside the cylinders. Being completely enclosed, the cylinder system would have no way of harming an operator if failure occurred. However, serviceability was limited for this design. In order to service the cylinder system, the frame had to be taken off of the JT520 and tipped on one end for the cylinders, fittings, and valves to slide out.

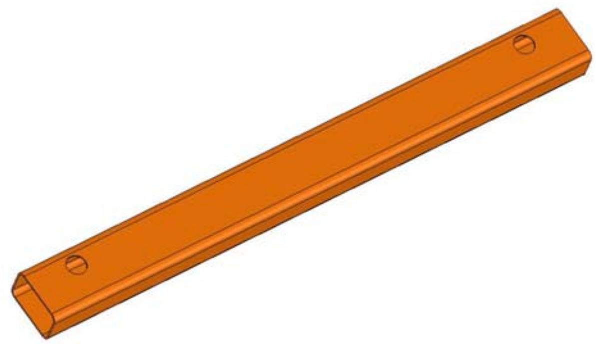

Figure 7: Single-Tube Frame Solid Model

Design #3 – C-Channel Frame

The final frame design incorporated a 6 ¼ x 4 ½ in steel c-channel (Figure 8). Manufacturing included bending a steel plate to form the c-channel shape and drilling four 2 in holes in the frame for the pins that mounted the cylinders inside the frame. All valves, fittings, and hoses were placed beside the cylinders in the frame, fully accessible from the bottom. In order to service the cylinder system, access was provided through the bottom of the frame to service it in place or drop the cylinder system out of the bottom of the frame. The unit

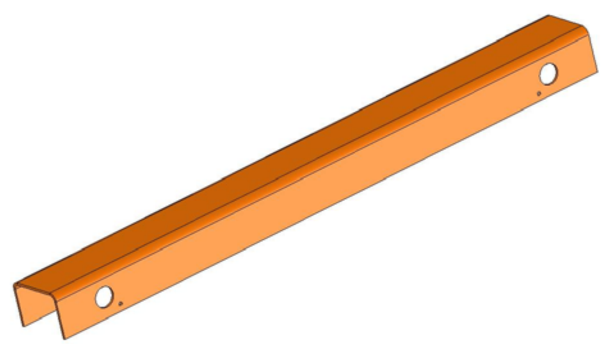

Figure 8: C-Channel Frame Solid Model

operator was completely protected from any system failures, as the cylinder system was completely enclosed on all sides facing the operator.

Qualitative analysis of the frame alternatives by the team led to the following comparison chart (Table 3):

Frame Type	Manufacturability	Safety	Strength	Serviceability
Four-Tube			xx	xxxx
Single-Tube	xxxx	xxxx	xxxx	
C-Channel	xxxx	xxxx	xxxx	xxxx
Legend:	Good = xxxx	Acceptable = xx		Not Good = none

Table 3: Frame Alternatives Analysis

Determination of a Suitable Design

Based on the above feasibility analysis, the team chose the HM3x20z and c-channel frame as the suitable design for further development. This decision was presented to the sponsor. The sponsor gave approval for continuing the design process and provided input on available components for the HM3x20z and methods of manufacturing the c-channel frame.

Before the team continued the design process, it verified that the hydraulic power source from the JT520 would be adequate for operating the HM3x20z, with a supply of 2500 PSI and 7 GPM. Table 4 shows the horsepower requirements of the HM3x20z and the JT520 available power.

Horsepower Requirements HM3x20z	
Available from JT520 (fluid hp)	14.6
Power required by system (fluid hp)	10.2
Power remaining for operations (fluid hp)	4.4

Table 4: HM3x20z Power Requirements

Fluid power required by the system was calculated using the equation:

$$FluidHorsepower = \frac{\Pr essure * Flow}{1714}$$ (White, 2003)

An efficiency of 100% was used in the analysis due to lack of other data at the time of the analysis. However, the team reasoned from the table that the remaining 4.4 fluid hp would support an expected lower efficiency.

Selection and Implementation of the Design Concept

Figure 9: JT520 for Team's Concept

Upon the team's request, Ditch Witch provided a JT520 (Figure 9) during the spring semester. This gave the team more freedom to work on the project and continually modify and improve the design throughout the semester. Much time and consideration was given to selecting and implementing the most appropriate components for the HM3x20z pumping system, frame, electronic control, and implementation of the design. A complete parts list and parts catalog is located in Appendix C.

HM3x20z

Cylinder Performance

One of the problems with the HM5x20z design was its size. Last fall the team designed the system based on the 15 sec steering time that was mentioned to the team by a JT520 operator. The team intended for one stroke of the cylinder to be equal to the typical steering time. In order to do this, the cylinder stroke and diameter had to be large, making the entire system too big (approximately 75 in long and 7 in wide) to fit on the JT520.

Meeting with the sponsor in January, the team was informed that 3 to 5 sec cylinder strokes with sharp hesitations in between would be appropriate and would solve much of the size issue found with the HM5x20z. Using this information and the 2500 PSI and 7

GPM pressure and flow criteria mentioned earlier, the team developed a table that showed stroke length and forces produced during operation of the cylinders (Appendix D). The data showed that for a 5 sec fore stroke, 134 in^3 of water would be displaced. Under this situation, a 3 in diameter cylinder would have a piston area of 7.07 in^2, would require a 19 in stroke, and would produce 17671 lbs of force. Analyzing this data led the team to conclude that a 3 in cylinder would be an appropriate selection for the design.

Available Cylinders Comparison and Selection

Ditch Witch also provided a list of standard cylinders available through the company. The list was composed of hydraulic cylinders with bore sizes ranging from 2 to 4 in and various rod diameters, stroke lengths, and pressure ratings. Using the above theoretical cylinder selection, the team selected a 3 in bore, 1.5 in rod diameter, 20 in stroke, 3000 PSI rated cylinder (part no. 151-117) from the list Ditch Witch provided. Two identical cylinders were ordered, one to be used for hydraulic fluid and one for drilling fluid. The team was informed that later utilization of this system by the sponsor would require an analysis of appropriate cylinder material and seals for the drilling fluid cylinder, but to not be concerned about that for the current project.

In order to save space on the unit, the two cylinders shared the same piston rod. A 1.5 in diameter, 30 in steel rod was ordered from the sponsor. The original pistons were pulled from the cylinders and the rods were disconnected from the piston heads. To appropriately fit in the unit, the rod was cut down to 27 in and both ends were machined to be connected to the piston heads. The single piston with two piston heads was reinserted into the cylinders (Figure 10).

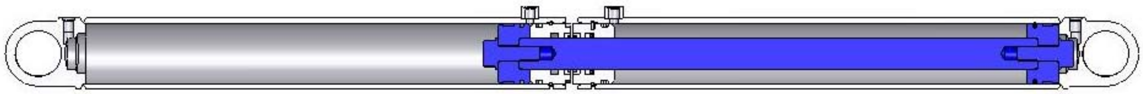

Figure 10: Cylinder Cutaway

With this selection of cylinders and modifications, the overall length of the system was 54 in and small enough to easily fit into its allotted place in the pipe box.

Hydraulic System

The team developed a hydraulic diagram (Appendix E) that depicted the function of the designed system. Both the mud (water) and hydraulic flow were included in the diagram. The team developed this diagram after much time was spent determining the proper path of flow for the mud and hydraulic oil portions of the design. Included in the schematic were the two cylinders, multiple check valves, sequence valves, a directional control valve, and a master control valve. The team recommends referring to this diagram when reading the following description.

In the mud portion of the design, flow was supplied to each side of the piston from the FT5 fluid management system, through the inactive mud pump on the unit, and through check valves to the dual acting cylinder. Flow was supplied to the drill string from each side of the cylinder through check valves. During operation, the mud was displaced by the action of the hydraulic oil cylinder piston.

In the hydraulic oil portion of the design, oil was supplied to the system by the hydraulic pump on the JT520. The flow was directed to the master control valve which, when not operating, directed flow to the hydraulic reservoir on the unit. When actuated by an electrical switch, described later, the master control valve directed flow to the directional control valve. The directional control valve's purpose was to direct flow coming into the system to the correct side of the hydraulic cylinder piston at appropriate times during operation.

Two flow combinations were possible with this valve and were controlled by the sequence valves, which directed pilot pressure to change the directional control valve's position. In the first position, oil flowed from the master control valve, through the directional control valve, and into the left side of the cylinder, actuating the piston to the right and returning oil to the hydraulic reservoir on the unit from the right side of the cylinder. When the piston reached full stroke, pressure built in the system and triggered the sequence valve on the left. This provided pilot pressure to the right side of the directional control valve, actuating it to the second position.

While in the second position, flow was directed to the right side of the cylinder from the master control valve via the directional control valve, actuating the piston to the left and returning oil to the hydraulic reservoir on the unit from the left side of the cylinder. When the piston again reached full stroke, pressure built in the system and triggered the sequence valve on the right. This provided pilot pressure to the left side of the directional control valve, actuating it back to the first position.

These processes, both the mud and hydraulic oil flows, continually repeated while the operator depressed the electrical switch.

Valve Selections

In order for the system to operate as designed, proper valves were selected for the operations described in the previous section. Valves were selected from Sun Hydraulics, HydraForce, and Ditch Witch applications to meet the design requirements. Specification sheets for the valves are located in Appendix C.

In the mud portion of the system, four flow check valves (part no. 149-324, Figure 11) were selected from Ditch Witch's stock of valves. These valves, rated at 64 PSI, were utilized to control flow into and out of the mud pumping cylinder. During preliminary testing of the unit, the team found that the cylinders were not properly filling from the 40 PSI supply of the FT5. To remedy this problem, the team removed the compression springs (part no. 159-326) from the two check valves that prevented backflow out of the cylinder to the FT5. This allowed the 40 PSI supply to reach the cylinder for proper filling, while continuing to prevent backflow.

Figure 11: Check Valve

The hydraulic oil portion of the system was more complicated with the requirement of the hydraulic control and sequence valves. A master control valve (HydraForce SV12-34, Figure 12) was selected to control the flow of oil into the system from the JT520 with the use of an electronic switch. The directional control valve selected was a Sun Hydraulics 4-way, 2-position, pilot-to-shift, detented, directional valve (Figure 13). This directed flow coming into the system to the appropriate sides of the hydraulic oil cylinder piston. A direct-acting sequence valve with reverse flow check (Figure 14) was also selected from Sun Hydraulics' supply and two were ordered for the team's system. These valves' primary function in the system were to control the position of the directional control valve based on the position of the cylinder piston.

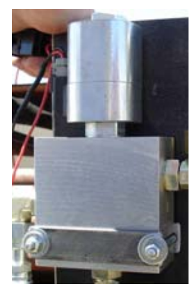

Figure 12: Master Control Valve

Figure 13: Directional Control Valve

Figure 14: Sequence Valve

More detailed descriptions of the functions of the valves selected by the team are located in Appendix C. The above descriptions describe the functions most appropriate for the team's application.

System Plumbing

Hydraulic hoses were implemented into the design, keeping in mind appropriate pressure ratings. Throughout the design process -4, -6, and -8 hydraulic hoses were most commonly utilized. Hydraulic fittings were used in both the mud and hydraulic oil systems where appropriate (Figure 15). During preliminary testing, the team discovered problems associated with the hydraulic hose routing on the valve plate, including parasitic losses and system sensitivities to hose movement. In order to reduce both, the team asked the sponsor to hard line the valve system on the valve plate (Figure 16). However, the team found that hard lining the system locked in the sensitivities of the system with hoses. Further complications with valve operation were experienced with the hard lined system. In the rare event that the system functioned properly, higher pressures were experienced, indicating that many of the parasitic losses of the previous system had been eliminated.

Figure 15: Valve Plate

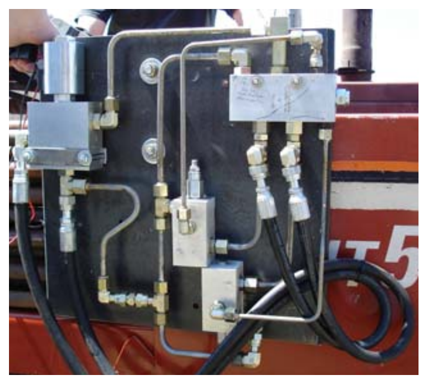

Figure 16: Hard Lined Valve Plate

Frame

The c-channel frame was selected to be the supporting structure for the cylinder system. It was designed to slide into the pipe box and completely enclose the cylinder system on 3 sides, with the bottom side being open to the tracks of the unit. The frame was designed to rest on the angle iron currently attached to the pipe box (Figure 17).

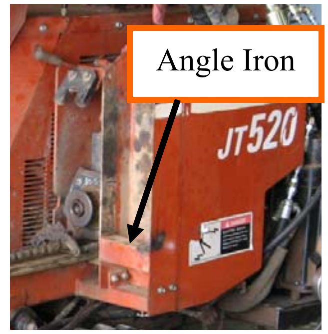

Figure 17: Frame Support

Dimensions

In order to enclose the cylinder system on three sides, the box needed to be wide, long, and tall enough to contain the cylinders, hoses, fittings, and check valves (Figure 18). The team determined that a width of 6 ¼ in, a leg height of 4 ½ in, and a length of 62 in would contain the system.


Figure 18: Frame with Pump

Manufacturing

The team discovered that c-channel of these dimensions was not readily available and would need to be manufactured. Consultation with the sponsor representative led the team to conclude that the frame would need to be laser cut out of a sheet of metal, and bent twice to form the c-channel shape of appropriate dimensions. Due to the sponsor having adequate equipment to do this, it did not present any manufacturability problems.

Material Considerations

The team knew that type and thickness of material would play a key role in the strength of the frame in containing the estimated 17671 lb forces produced by the cylinder system. A mild steel (1018, E = 29 MPSI, S_y = 32 KPSI) was chosen for the frame design.

Knowing this material was readily available, the team was not concerned with added cost or time of acquisition.

Supporting Pins

Equally important to the c-channel portion of the frame were the supporting pins that attached the cylinder system to the c-channel. Not being familiar with the pins readily available for the sponsor, the team relied on the suggestions of the sponsor representative in selecting these components. It was determined that a 2 in pin would be appropriate for the team's application. From their supplies, the sponsor representative selected a hollow SAE 1040/1045 (E = 30 MPSI, S_y = 75 KPSI) material pin with an outer diameter of 2 in. The pin was cold formed, ground, polished, and chrome plated to fit other design applications of the company (Figure 19). To secure the pin to the c-channel frame, a tab was welded onto one end of the pin. This tab allowed the pin to be securely fastened to the frame with a bolt (Figure 20).

Figure 19: Pin

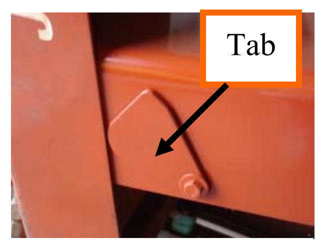

Figure 20: Pin Tab

Bushings

In order to properly fit the cylinders to the supporting pins, 1/8 in thick bushings (one for each pin) were machined and placed through the cylinder eye, fitting between the inside walls of the c-channel frame. The pins then fit into the bushings and the cylinder eye.

Shims

In order to properly fit the cylinders to the c-channel frame and prevent them from sliding laterally, shims were designed and machined to fit on each side of the cylinders. They were designed to fit around the pin bushings so that both the pin and bushing would slide through them. The pins, bushings, and shims prevented any movement of the cylinders during operation to obtain maximum cylinder performance.

Switch

A simple electrical switch was required to allow the unit operator to turn the valve system on and off for the high pressure application. A momentary rocker switch (Figure 21) was selected for simplicity and operator control. The team believed that a momentary switch would eliminate the possibility of the switch being left in the on position and high pressure fluid inadvertently exiting the drill string. Power to the switch was provided by the battery and continued through the circuit to the hydraulic control valve. A ground wire was connected from the hydraulic control valve to the battery's ground terminal.

Figure 21: Momentary Switch

Pipe Box Extensions

In order to implement the design and maintain proper use of the unit, a minor modification had to be made to the existing pipe box. The pipe box was designed by the sponsor to contain 30 sticks of drill pipe at any one time. With the installation of the team's system in the frame of the pipe box, this was no longer possible. Pipe box extensions were designed to mount on top of the existing pipe box structure, thus extending the walls (Figure 22). They were designed to function identically to the original structures.

Figure 22: Pipe Box Extension

Plate mounting

To minimize complexity and maintain serviceability, the team mounted all of the hydraulic valves for the pumping system on an 18 x 18 in steel plate. The original intention was to mount the valve plate under the unit in the space mentioned previously. However, during the testing stage, the team mounted the valve plate onto the side of the pipe box to provide accessibility (Figure 23). When the unit was shown to the sponsor in this configuration, the team was informed that leaving it in that position would be ideal for the sponsor's future use of the unit.

Figure 23: Mounted Valve Plate

Validation of the Design

Before the design process was completed, the team theoretically validated the design. This analysis included an extensive strength investigation on the frame, an appropriate characterization of the pressure drop through the drill string, safety concerns with the designed system, and consideration of weight limitations on the unit's trailer.

Frame

The team took an in-depth look into the strength of the frame. Two primary concerns arose during the design process: buckling of the frame and failure of the connecting pins, both from cylinder actuation. Theoretical calculations and Finite Element Analysis were used to determine the likelihood of the frame buckling and the response to loading. Pin shear and bending were also analyzed using theoretical calculations. The complete analysis for each is located in Appendices F and G.

The likelihood of the frame buckling in any plane was found to be minimal. Safety factors for side-to-side (toward and away from the operator) and up-and-down (arching and bowing of the frame top) buckling for the team's design were found to be 5.3 and 3.4, respectively. Figure 24 depicts the expected response of the frame to loading using ANSYS Workbench 8.1. A tensile loading (forces directed outward) was placed on the frame and the expected higher stress areas were seen. Stress concentration levels were indicated by the colors red, yellow, green, and blue, with red being the highest and blue being the lowest.

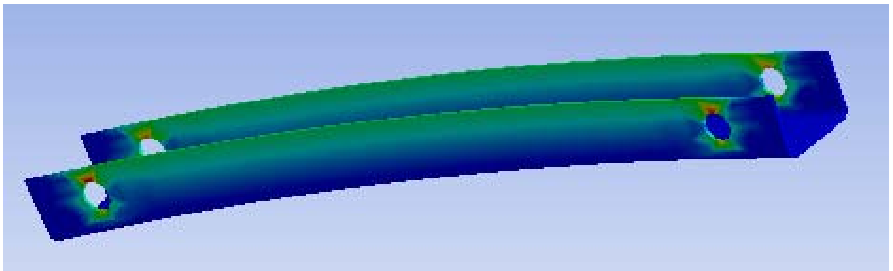

Figure 24: Frame Response to Loading

The combined loading on the pins due to cylinder operation was found to be 16258 lbs (from later testing results). Pin failure analysis, specifically bending and shear, was performed using this force. It was found that, like the frame, it was unlikely that the designed pin would fail due to these forces. The safety factors on shear and bending were found to be 4.0 and 2.6, respectively.

Pressure Drop through Drill String

In the fall design report, the team theoretically characterized the drill pipe to be used under normal operation for the JT520 (Appendix A, pg 37). The system would experience an estimated 4.53 PSI pressure drop per stick of drill pipe under the assumed operating conditions. With this estimation and a full drill string of pipe, the system would experience approximately a 136 PSI pressure drop from input to output of the drill string.

Safety

The team felt it important to ensure their design did not increase the safety hazards of the JT520. To eliminate major hazards, such as the operator being hit by hot oil from a hydraulic hose bursting, precautions were integrated in the design. The c-channel frame and location of the valve plate were designed to shield the operator from any hydraulic failures that may occur. Proper use of hydraulic hose was ensured throughout the assembly process. A complete safety and hazards analysis of the team's design, developed by Brandon Wilkerson and Jonathan Lund, is located in Appendix H.

Trailer Weight Limitations

The team was also concerned about weight constraints of the T9B trailer (Appendix A, pg 42), which has a weight rating of 8650 lbs. Table 5 shows this analysis. With the current JT520 unit and filled FT5 there is approximately 5051 lbs of weight on the trailer. Weight estimates (all based on the assumption of using plain carbon steel for component materials) of the HM3x20z totaled 175 lbs. As shown in the table, implementation of the design will not cause the trailer's weight capacity to be exceeded.

Trailer Weight Capacity	
Trailer Weight Capacity (lb)	8650
JT520 Weight (lb)	2980
FT5 Web Weight (lb)	2071
Total Weight Available (lb)	3599
HM3x20z Weight (lb)	175
Final Left-Over Weight Capacity (lb)	3424

Table 5: T9B Trailer Weight Capacity

Testing Results

Initially, the team wished to perform testing during the fall semester to determine characteristics of the drill pipe and a length of hydraulic hose. These tests would provide data that could be used to perform theoretical calculations to determine specifications for the team's design solution. However, after working with the sponsor, it was determined that assuming certain values would provide sufficient results to support the design process. The team remained committed to conducting tests on the finished concept at the end of the spring semester. Availability of a JT520 during the spring semester for the team's utilization was very beneficial.

HM3x20z

Performance of the HM3x20z high pressure pumping system was the primary focus of all testing. All formal testing was performed using one stick of drill pipe and the hydraulic system before hard lines were installed. One pressure gauge (Figure 25) was placed at the hydraulic directional control valve and another was placed in the drill pipe directly before the beacon housing. A flow meter (Figure 26) was connected to the hydraulic system directly before the master control valve. The system was run with the JT520 operating at full throttle. Pressures in lines returning from the hydraulic fluid cylinder were recorded as back pressure; pressure at the end of the drill string was recorded as exit pressure; flow rate was recorded from the flow meter; and stroke time was measured using a stopwatch and recorded. Fore stroke was the name given to the cylinder stroke when the largest amount of drilling fluid was displaced. Following this system layout, this was the stroke toward the end of the drill string. Back stroke was regarded as the opposite of fore stroke.

Figure 25: Pressure Gauge

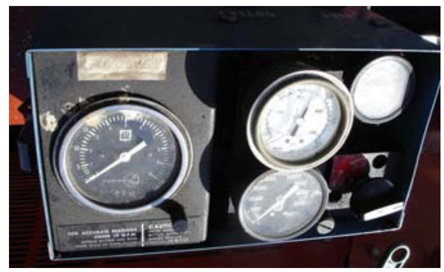

Figure 26: Flow Meter

Figure 27 depicts the pressure readings for the fore stroke of the system. From the graph it can be seen that the pressure out the end of the drill string was 1975 PSI, the hydraulic pressure was 2200 PSI, and there was no back pressure in the system.

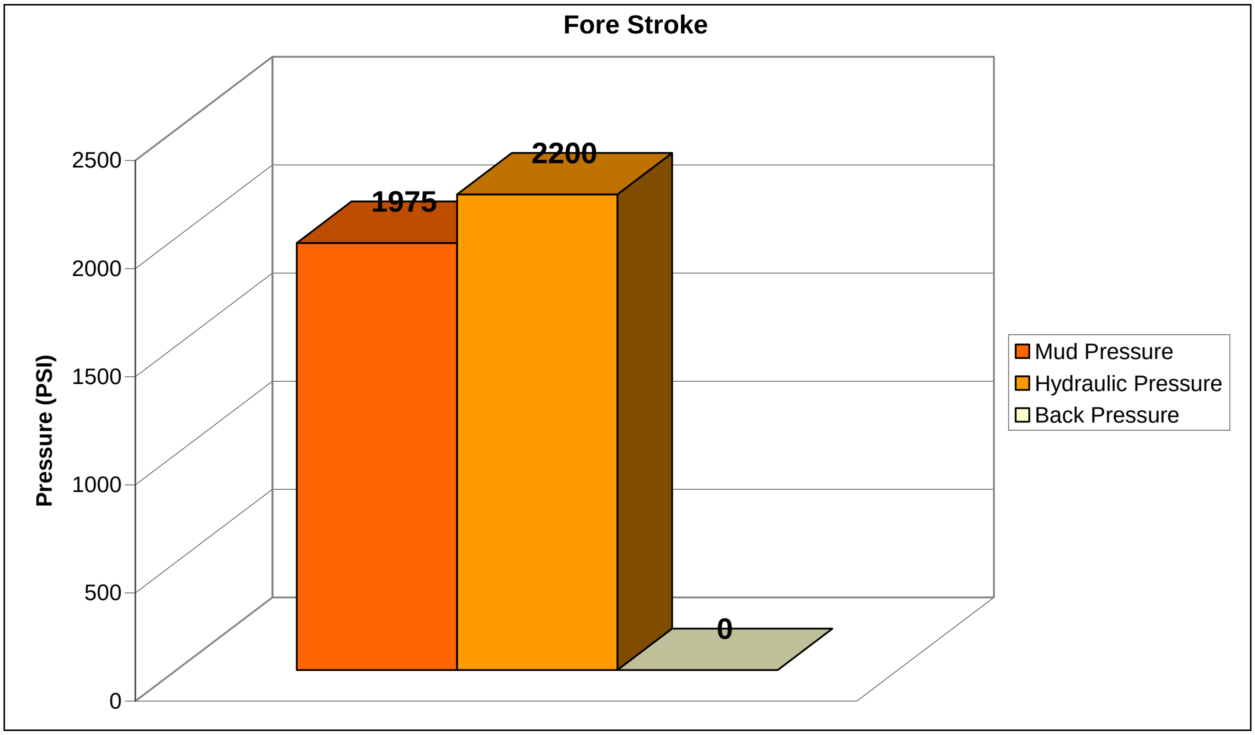

Figure 27: Fore Stroke Pressure Results

Figure 28 depicts the pressure readings for the back stroke of the system. The graph shows that the pressure at the end of the drill string was 1750 PSI, the hydraulic pressure was 2300 PSI, and there was 100 PSI of back pressure in the hydraulic system.

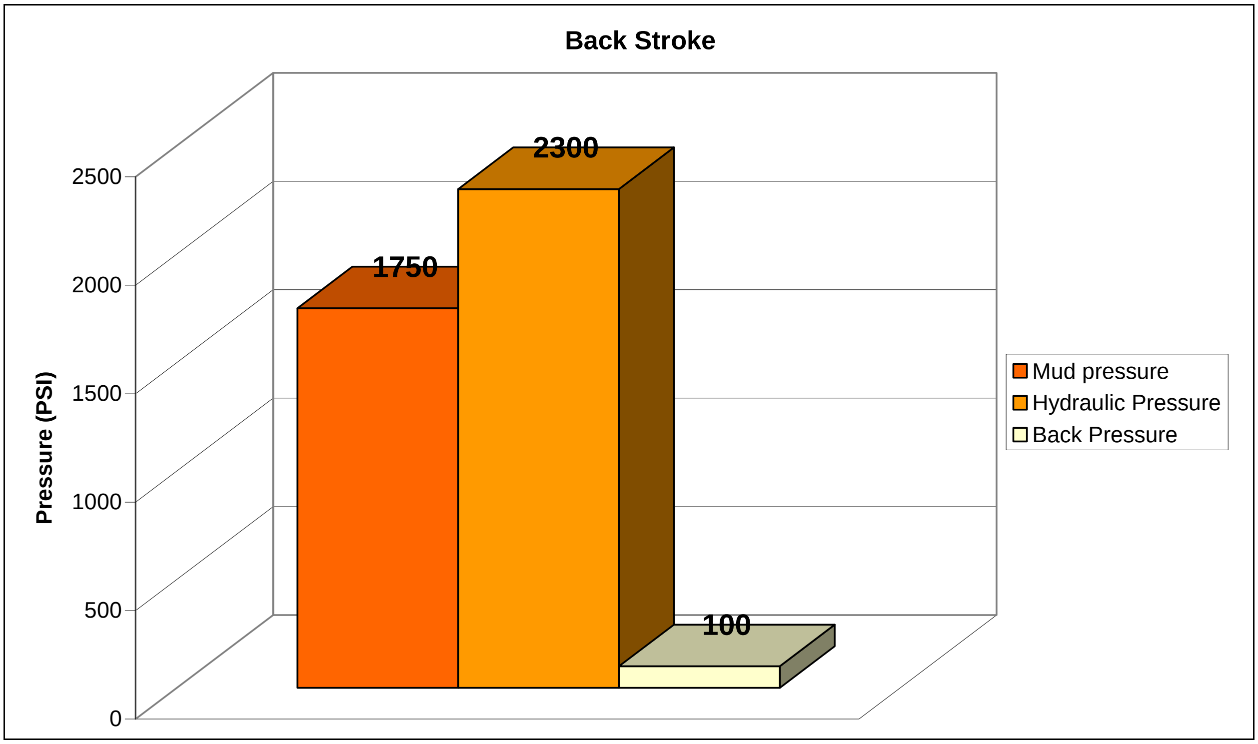

Figure 28: Back Stroke Pressure Results

From this maximum pressure of 2300 PSI, the team found that the maximum force produced by the cylinders during operation that could be imposed on the frame and supporting pins was 16258 lbs using the following equation:

$$Force = \frac{\Pr essure}{Area} \quad \text{(White, 2003)}$$

Figure 27 is a representation of drilling fluid pressure, hydraulic pressure, and flow rate as they occurred during operation of the system. Data for this figure were recorded using the pressure gauges and flow meter described above. Odd numbers on the independent axis depict the fore stroke and even numbers depict the back stroke.

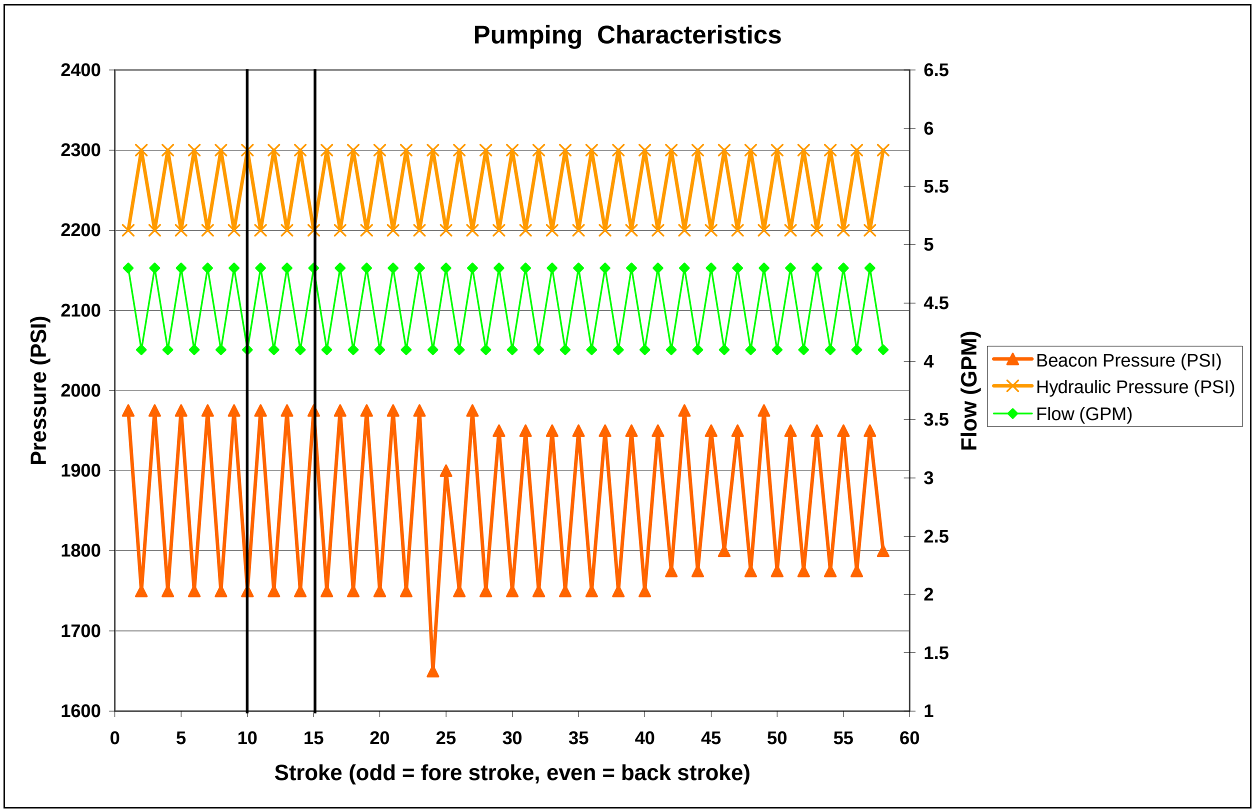

Figure 29: Pump System Operating Characteristics

Time length of stroke is shown in Table 6. The stroke time goal was originally 5 sec. Table 6 shows that actual stroke times were between 5.21 and 5.71 sec, with the fore stroke time being shorter than the back stroke.

Stroke Times	
Fore Stroke (sec)	Back Stroke (sec)
5.30	5.43
5.30	5.71
5.27	5.47
5.21	5.51

Table 6: Stroke Times

As mentioned earlier, with a 7 GPM flow at 2500 PSI supplied from the hydraulic system on the JT520, the designed system is expected to require 10.2 hp for operation. However, the results show that the system is being supplied a maximum of 4.8 GPM at 2500 PSI (from flow meter). With 4.8 GPM flow at 2200 PSI on the fore stroke, the cylinder system requires 6.16 hp. The complete system, being supplied 4.8 GPM at 2500 PSI on the fore stroke, requires 7 hp. Under these conditions, there would be a remaining 7.6 hp for other operations, such as thrusting if the operator felt that it was needed.

The team had the hydraulic valve system hard lined late in the spring semester to decrease parasitic losses and system sensitivities. When the unit was returned to the team and tested, greater problems had developed from the modification. The team was unable to retune the system to make it function properly. The sensitivities that were seen before seemed to be permanently established in the system after the hard lines had been installed.

One of the goals of having the system hard lined was met. On the occasion that the system did function, higher pressures were experienced at the point directly preceding the beacon. Instead of the 1975 PSI maximum pressure that the team observed before, pressures of 2300-2400 PSI were reached. From these results, the team was encouraged that hard lining the system had eliminated many of the parasitic losses in the system.

Drill String Characterization

The team observed during a test with the full drill string connected to the JT520 that pressures at the end of the drill string (out the nozzle) were approximately equal to the pressures at the entrance to the drill string (2300 PSI, Figure 30). With the pressure gauges used in formal testing, pressure drops through the drills string of less than 500 PSI occurred.

Figure 30: Full Drill String Pressure Reading

Frame

The system frame experienced no failure during the testing. If buckling were to occur, arching of the horizontal portion of the c-channel would be observed. No material failure occurred that could be seen by the eye, as the team expected. The team also observed that no bending or shear of the pins occurred from the forces imposed by the cylinders' operation.

Discussion and Conclusions

HM3x20z Performance

The performance of the original HM3x20z during formal testing was satisfactory to the team and sponsor. Pressures ranging from 1750 to 1975 PSI were well above the required 1500 PSI. Although the sensitivities of the system were not of great concern to the sponsor, the team had the system hard lined to increase its reliability during operation. The team had found during formal testing that the system would occasionally lock and not pump properly. Manipulating the flexible hydraulic hoses (Figure 31) would often return the system to proper operation. It was hypothesized that the sensitivity to change of these hoses and the pressures in them were the primary cause of the operating complications and some of the parasitic losses observed during testing.


Figure 31: Flexible Hose Hydraulic System

The flow meter, also equipped with a pressure gauge, indicated that the expected pressure of 2500 PSI was being supplied to the team's hydraulic circuit. However, pressure gauges placed in the circuit indicated that 200-300 PSI was being lost due to parasitic losses in the fittings and hoses. The team found this undesirable, knowing that if 200 PSI was not lost in the hydraulic system, pressures at the drill string outlet would be more effective (1950-2175 PSI). Hard lining the system was intended to reduce or eliminate these problems.

During testing of the hard lined system (Figure 32), the team found that it was possible that those sensitivities to change in the system were necessary for proper functioning of the valves selected by the team. The team was unable to tune the sequencing valves properly for the system to function at all times. Complications with the directional control valve also occurred. The team found that after a couple of pumping cycles, the spool in the directional valve would lock in position, not allowing properly pressurized flow to reach the hydraulic cylinder.

Figure 32: Hard Lined System Test

The team concluded that a fully hydraulic system was not the most appropriate means of controlling cylinder operation. Other methods of controlling operation were investigated and the team determined that electrical control would provide the most reliable results. Another benefit included decreasing complexity of the hydraulic system, as the sequence valves would be removed from the circuit.

A Walvoil SD5, 4-way, 3-position, open center, solenoid valve (Appendix I) replaced the directional control valve in the team's circuit. The sequence valves were removed from the circuit and the solenoid valve was inserted to direct flow from the master control valve to the hydraulic cylinder (Figure 33).

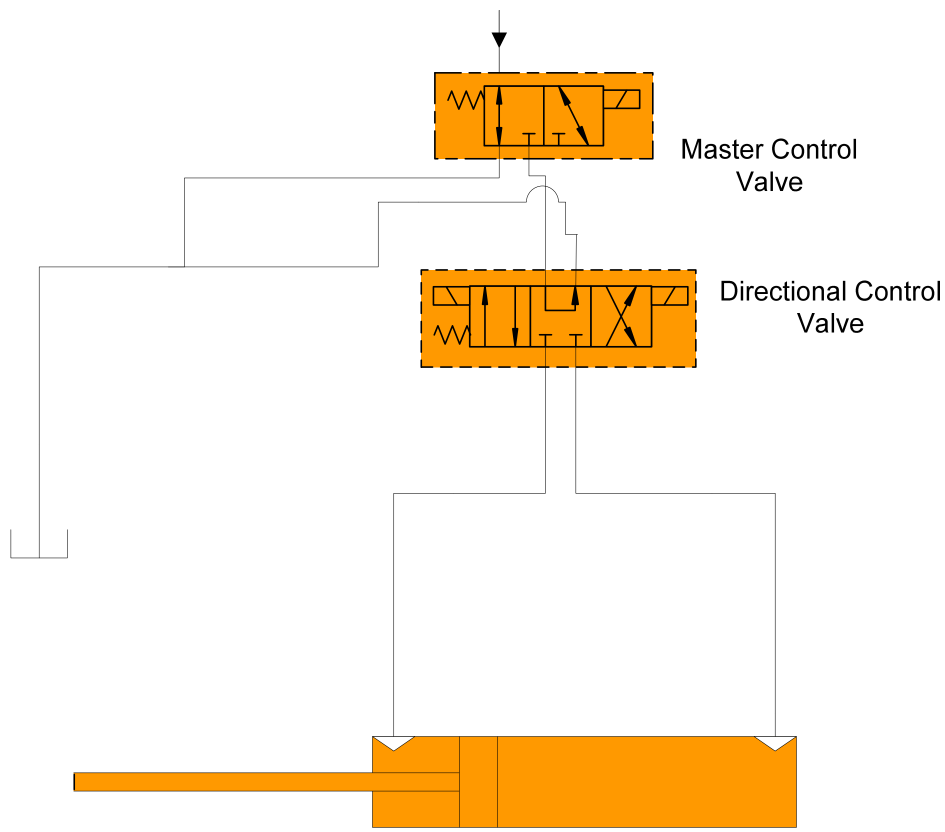

Figure 33: Hydraulic Schematic with Solenoid Valve

A double-pole double-throw, spring centered, momentary rocker switch replaced the original switch to control the master control and solenoid valves. Under normal operation with the drill string in the ground, the operator would hold down the switch in one position and watch a pressure dial on the JT520 dash, while the system cycled through one stroke. When the gauge on the dash drops to zero pressure, the operator would move the electrical switch to the other position and hold it through the next stroke. The operator could continue this cycle until steering was complete.

This system was much more reliable than the fully hydraulic system. Expected operation occurred 100% of the time. Higher pressures than those in formal testing were experienced. The system reliably achieved pressures of 2200 ± 1000 PSI during testing of this modification.

During formal testing, expected flow rates were not being supplied to the hydraulic circuit. Instead of 7 GPM, 4.1 to 4.8 GPM were being supplied to the circuit by the hydraulic pump on the JT520. While this did not negatively affect the performance of the fluid exiting the drill string, it was responsible for the slower stroke times, as stroke time is directly related to flow rate supplied to the cylinder. The team concluded that the hydraulic pump on the JT520 was either not the appropriate one for the unit, or it was not functioning properly.

Flow and pressure results from the formal testing led the team to another conclusion. From the test data, it can be seen that different pressures and flow rates occur for the fore and back stroke. Pressure is dependent on area of the piston head and flow is dependent on volume of the cylinder. In the team's design, one cylinder is dedicated to water and the other to hydraulic fluid. During operation, inflow to one cylinder is on the rod side of the piston head, while inflow to the other cylinder is not, and vice versa. This produces different areas and volumes, resulting in different pressures and flow rates.

If the cylinder system were to be designed as shown in Figure 34, this problem would not be apparent. However, this is not a feasible solution, as leakage can occur around the piston head and contamination of the fluids would be possible. The team concluded that the effects of this situation were not significant enough to find an alternative solution to the problem.

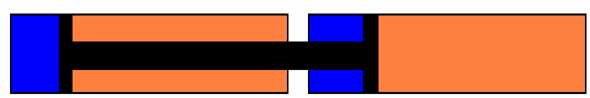

Figure 34: Pump Design for Ideal Performance

Drill String Characterization

From the testing results, the team concluded that the theoretical characterization of the drill string conducted during the fall semester (Appendix A, pg 37) was a good approximation of the system. The team is providing this analysis to the sponsor for future use.

Recommendations

The West Central Pump Works recommends that Ditch Witch consider the HM3x20z system as a solution to their design problem. Several recommendations for improvement of the designed solution have also been formulated by the team.

The most significant recommendation is incorporating the hydraulic valve system into a single valve block. This valve block would perform all the functions of the current system, would be much less complex, would be space saving, and could be easily implemented into the design of the JT520. It is also recommended that the valve block be electronically controlled, as in the final modification to the team's design. Future uses may include implementing a programmable controller to manipulate the system.

The electrical switch in the current design was directly connected to the battery on the JT520. It is recommended that, for safety purposes, the controlling mechanism for the system be connected to the operator presence circuit. This should be done to ensure that inadvertent operation of the system, with the potential to cause injury to a bystander, does not occur.

It is also recommended that the sponsor implement purge ports on the cylinders. This would guarantee that no air is in the circuit, eliminating the need for the system to be tuned for every operation. Also regarding the cylinders, the team recommends the sponsor investigate proper cylinder materials and seals for the drilling fluid portion of the system. All components used by the team were designed for hydraulic oil use only. Full-time operation with drilling fluid would quickly damage the cylinders and seals. The same consideration needs to be given to the check valves for this portion of the system.

Early in the project, the sponsor informed the team that a 0.070 in nozzle would be used in high pressure applications, and this information was used in the design process. The team recommends that all JT520 operators be instructed that this nozzle is the only one to be used if appropriate results are desired. Other nozzles may not achieve successful pressures.

Operating instructions for the designed HM3x20z are located in Appendix J and can be followed, with the described modification, to operate the current JT520 with the high pressure pumping attachment. It is recommended that only those who are experienced operators with the original JT520 system operate the current JT520 with the high pressure pumping attachment. Although a thorough hazards analysis (Appendix H) was performed, the team recommends that the sponsor conduct another safety and hazards analysis using their own formal procedures.

The team believes they have satisfied the sponsor's design needs and has produced a concept that is reliable and can easily be implemented into future JT520 designs. It is also believed that the new capabilities of the JT520, provided by the team's system, will give the sponsor a large competitive advantage over companies who produce units comparable to the Jet Trac (Appendix A, pg 12). The West Central Pump Works, Inc. would like to present the HM3x20z to The Charles Machine Works, Inc. for future consideration of implementation into the JT520 to increase performance and marketability.

Project Schedule

Project scheduling was divided into two sections representing each semester of the design project. The fall semester (Appendix A, pg 44) included project definition, concept development, concept analysis, documentation, and design presentation, with tasks listed under each of these categories. The spring semester included project redefinition, final design analysis, ordering components, manufacture and assembly, testing, documentation, and presentation, again with tasks listed under each. A detailed Gantt chart of the team's progress throughout the year is located in Appendix K. After the final presentation in April, that provided the team's recommended design to the sponsor, the project was complete. All components and materials used by the team, including the new system and JT520 unit, were given to the sponsor.

Budgeting

In the beginning of the project, Ditch Witch did not specify that cost would be a significant item of consideration in the design process. A proposed budget (Table 7) was developed based on the expected components for the system evaluated in the alternatives analysis. The team proposed that $1500 would be an ample budget to cover the costs of the system.

HM3x20z Proposed Budget		
Cylinder	2- 3" X 20" ($200 each)	$400
Piston Rod	1.5"	$50
Check Valve	4- Spring-Loaded Ball Check Valve ($50 each)	$200
Directional Valve	Directional Control Valve (Sun Hydraulics, 2007)	$100
Sequence Valve	2- Sequence Valve (Sun Hydraulics, 2007)	$120
Control Valve	Spool, 3-Way, NO Master Control Valve (HydraForce, 2007)	$100
Electrical	Momentary Switch	$5
Frame		$150
Miscellaneous	Fittings, Hoses, Etc.	$150
Total		$1,275

Table 7: Proposed Budget

After the team's proposed design was finalized, a complete parts list was sent to the sponsor to obtain pricing information based on charges that the sponsor would experience upon ordering those components. The closest estimate the team could develop for an actual budget is shown in Table 8. Richard Sharp (personal communication, 16 April 2007) provided pricing information for the cylinders, piston rod, check valves, directional valve, sequence valves, control valve, and hydraulic fittings. Wayne Kiner (personal communication, 17 April 2007) provided information for the frame and all corresponding components, materials, and labor. The final cost of the unit remained below that of the estimated $1500.

HM3x20z Actual Budget		
Cylinder	2- 3" X 20" ($162 each)	$324
Piston Rod	1.5"	$26
Check Valve	4- Spring-Loaded Ball Check Valve ($81 each)	$324
Directional Valve	Directional Control Valve	$157
Sequence Valve	2- Sequence Valve ($92 each)	$184
Control Valve	Spool, 3-Way, NO Master Control Valve	$98
Electrical	Momentary Switch	$5
Frame		$158
Miscellaneous	Fittings, Hoses, Etc. ($5 per fitting)	$150
Total		$1,426

Table 8: Actual Budget

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Appendix A

Fall Design Report

Appendix B

Team Task List

Activity	Member(s) Active
Team Organization - Weekly Meetings	All
Project Updates with Sponsor	All
Meetings with Safety Group	All
Final Design Analysis	
Receive and Evaluate Current Unit	All
Run Calculations on Cylinder Operation	Curtis
Compare with Cylinders Available	Curtis
Construct Hydraulics Schematic	Curtis, Dustin, Brandon
Construct Mud Flow Schematic	Curtis, Dustin, Brandon
Select Cylinders	All
Research Valves	Curtis
Determine Appropriate Valves	Curtis, Dustin
Order Components	Curtis, Kristin
Receive Components	All
Manufacturing	
Rod Threads	BAE Lab
Supporting Structure	Ditch Witch
Pipe Box Extensions	Ditch Witch
Valve Plate	Curtis, Kristin
Valve Plate Hard Lines	Curtis, Ditch Witch
Assembly	All
Solid Modeling	
Cylinder (2)	Dustin
Rod	Dustin
C-Channel Frame	Dustin
Pipe Box Extension (2)	Dustin
Pin (2)	Dustin
Shims (4)	Dustin
Bushings (2)	Dustin
Frame Alternatives	Dustin
4-Tube Frame	Dustin
Single-Tube Frame	Dustin
Overall System Assembly	Dustin
Manufactured Design Testing and Analysis	
Pressure Tap Beacon Attachment	BAE Lab, Dustin
Set Up Preliminary Test	All
Preliminary Test	All
Formal Test and Video	All
Full Drill String Test	Curtis, Dustin, Kristin
Test Results Analysis	Kristin, Curtis
Supporting Structure Failure Analysis	Kristin, Curtis, Brandon
Drill String Characterization	Curtis
Power Analysis	Curtis

Documentation	
Weekly Activity Plans (Due Mondays)	Kristin
Weekly Activity Summaries (Due Fridays)	Kristin
Spring Accomplishments (Weeks 1, 2, 3)	Kristin
Updated Definition of Customer Requirements	Kristin
Updated Statement of Work	Kristin
Updated Task List	Kristin
Updated Gantt Chart (Weekly)	Kristin
Compilation of Testing and Analysis Results	Curtis, Kristin
Compilation of Components Literature	Dustin, Curtis
Safety and Hazards Analysis	Safety Team
Hydraulic Schematic	Curtis
Operating Instructions	Dustin
Parts List	Dustin
Budget	Dustin, Kristin
Report Draft	Kristin
Report Draft Proofreading	Curtis, Dustin, Brandon
Report Draft Printing	Kristin
Report Revisions	Kristin
Report Proofreading	Curtis, Dustin, Brandon
Report Printing and Binding	Kristin
Web Page	
Update Team and Project Details	Kristin
Add New Documents	Kristin
Presentation	
Presentation Development	All
Presentation Practice	All
Presentation Printing and Binding	Kristin
Final Concept Design Proposal	All

Table B1: Task List

Appendix C

Parts List and Catalog

Part Number	*Quantity*	*Description*	*Supplier*
149-324	4	Spring Loaded Ball Check Valve	CMW
151-117	2	Hydraulic Cylinder	CMW
1-1-1	1	Double End Rod	WCPW
3-1-1	1	Pump Frame	WCPW
3-2-1	2	Cylinder Bushing	WCPW
3-3-1	2	Inside Shim	WCPW
3-3-2	2	Outside Shim	WCPW
3-4-A	2	Tab Pin	WCPW
DCCD-XXN	1	Hydraulic Directional Control Valve	Sun Hydr.
SCCA-LWN	2	Hydraulic Sequence Valve	Sun Hydr.
SV12-34	1	Hydraulic Master Control Valve	HydraForce

Table C1: Parts List

Appendix D

Cylinder Performance

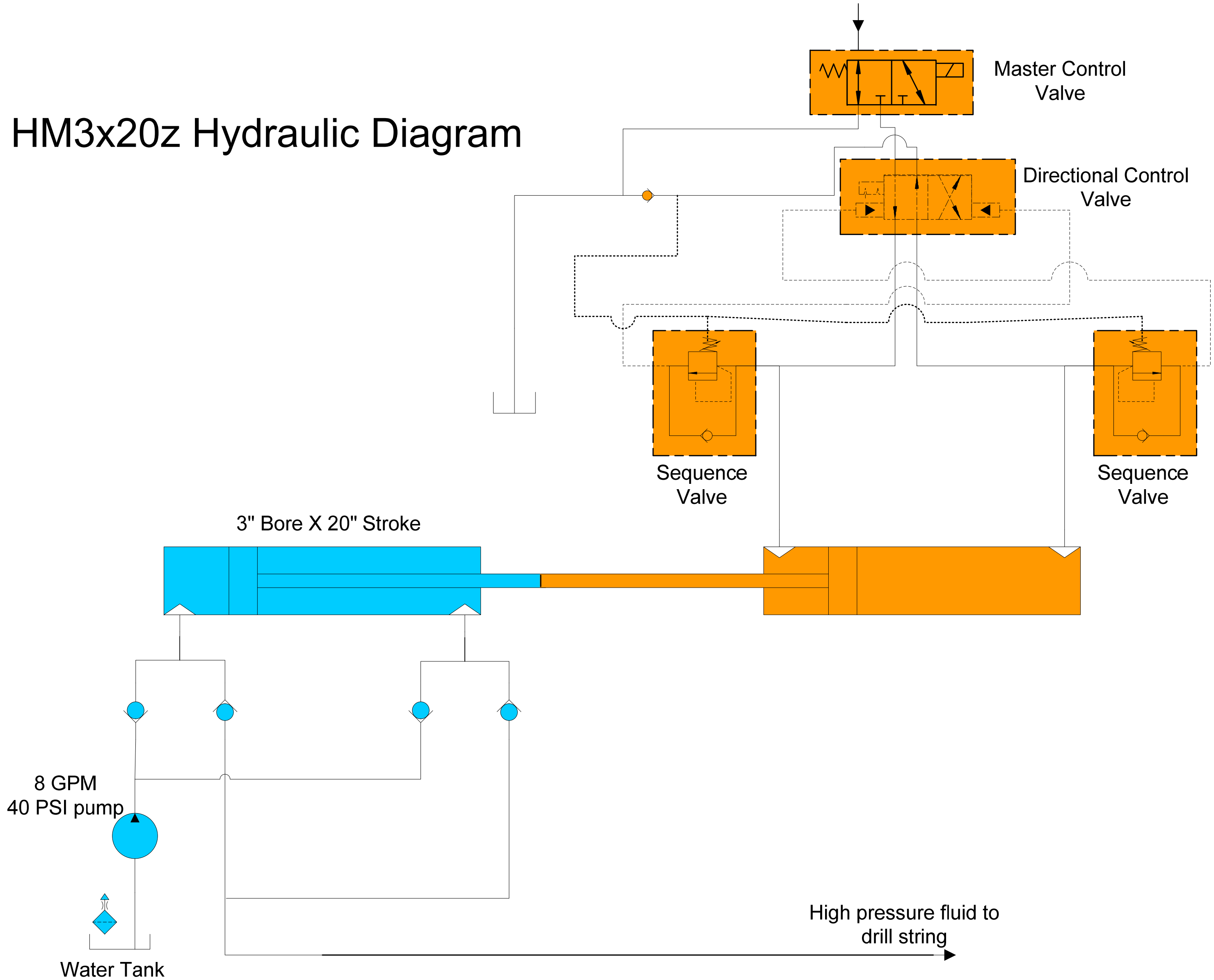
Fore Stroke					
Given:					
Pressure (psi)	**Flow (gpm)**	**Run Time (sec)**			
2500	7	5			
Required Volume (in^3)					
134.75					
bore (in)	**area (in^2)**	**stroke (in)**	**force (lbs)**		
5	19.63	6.86	49087.39		
4.5	15.90	8.47	39760.78		
4	12.57	10.72	31415.93		
3.5	9.62	14.01	24052.82		
3	7.07	19.06	17671.46		
2.5	4.91	27.45	12271.85		
2	3.14	42.89	7853.98		
Back Stroke					
Given:					
Pressure (psi)	**Flow (gpm)**	**Run Time (sec)**			
2500	7	3			
Required Volume (in^3)					
80.85					
bore (in)	**area (in^2)**	**rod area (in^2)**	**rod (in)**	**stroke (in)**	**force (lbs)**
5	19.63	7.85	3.16	6.86	29452.43
4.5	15.90	6.36	2.85	8.47	23856.47
4	12.57	5.03	2.53	10.72	18849.56
3.5	9.62	3.85	2.21	14.01	14431.69
3	7.07	2.83	1.90	19.06	10602.88
2.5	4.91	1.96	1.58	27.45	7363.11
2	3.14	1.26	1.26	42.89	4712.39

Table D1: Hydraulic Cylinder Performance

Appendix E

HM3x20z Hydraulic Diagram

HM3x20z Hydraulic Diagram



Appendix F

Frame Strength Analysis

Variables:

y_{bar} , x_{bar} = Centroid
A = Area
I = Moment of inertia
d = Distance from the neutral axis to the area's centroid
σ = Compressive stress
r = Radius of gyration
P = Load
e = Eccentricity of load P
c = Distance from the neutral axis to the outer fiber of the frame
L = Unsupported length of the frame
E = Modulus of elasticity
n = Safety factor

Equations:

Centroid: $x_{bar} = \dfrac{\sum x_{bar} A}{\sum A}$

Parallel Axis Theorem: $I_x = I_{barx'} + Ad_y^{\ 2}$

Radius of Gyration: $r = \sqrt{\dfrac{I}{A}}$

Secant Formula: $\sigma = \dfrac{P}{A}\left[1 + \dfrac{ec}{r^2}\sec\left(\dfrac{L}{2r}\sqrt{\dfrac{P}{EA}}\right)\right]$

(Hibbeler, 2005, pp. 690-693)

E (psi)	29000000	Buckling about y axis		Buckling about x axis	
Yield stress (psi)	32000	P	16257.7	P	16257.7
Width (in)	6.25	I_y	10.7520	I_x	24.2223
Height (in)	4.5	A_m	3.6875	A_m	3.6875
Thickness (in)	0.25	r	1.7076	r	2.5630
Inside width (in)	5.75	e	1.08	e	0.75
Inside height (in)	4.25	K	1	K	0.5
x_{bar} (in)	0	L	49.72	L	49.72
y_{bar} (in)	3.08	KL	49.72	KL	24.86
I_x (in^4)	24.2223	KL/r	29.1174	KL/r	9.6997
I_y (in^4)	10.7520	c	3.08	c	3.125
		ec/r^2	1.1408	ec/r^2	0.3568
		Stress (psi)	9520.74	Stress (psi)	5993.28
		n	**3.36**	**n**	**5.34**

Table F1: Frame Strength Calculations

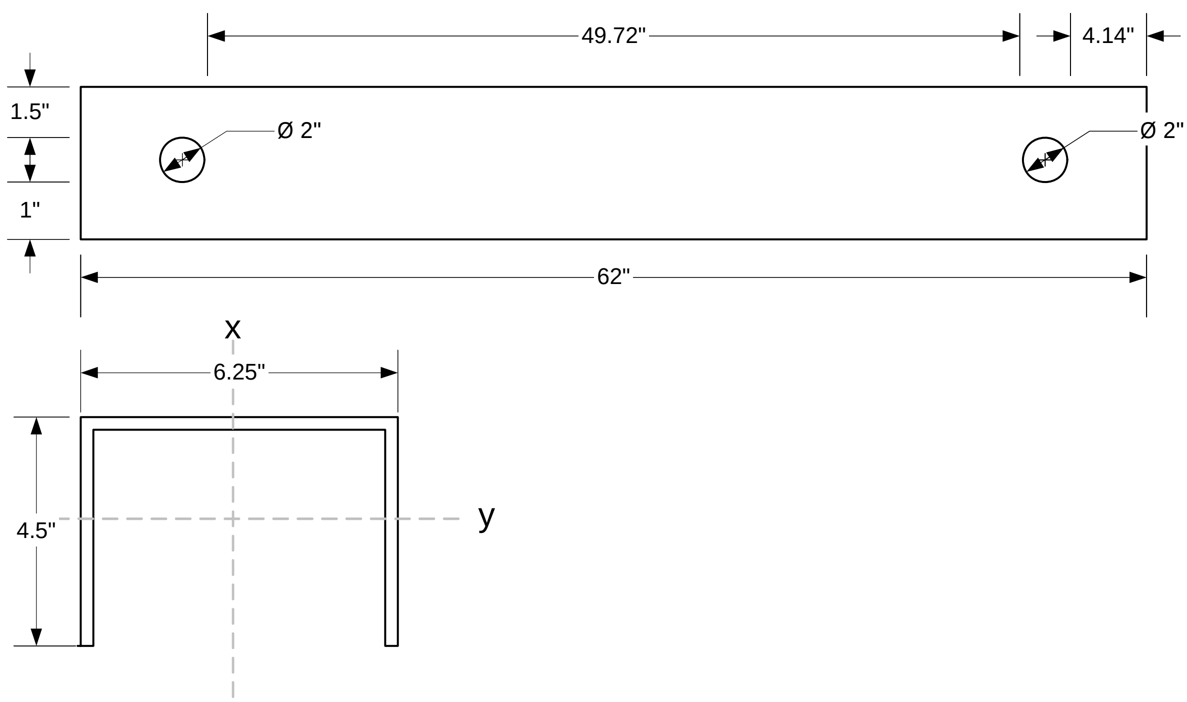


Figure F1: Frame Strength Schematic

Appendix G

Pin Strength Analysis

Variables:

P = Pressure
F = Force
A = Area
D = Outer diameter
d = Inner diameter
I = Moment of inertia
y = Maximum distance from center to outside pin edge
σ = Bending stress
τ = Shear stress
M = Moment
V = Shear
S_y = Yield strength
n = Safety factor

Equations:

$$P = \frac{F}{A} \qquad A_{pin} = \frac{\pi(D^2 - d^2)}{4} \qquad I_{pin} = \frac{\pi(D^4 - d^4)}{64}$$

$$y = \frac{D}{2} \qquad \sigma_{actual} = \frac{My}{I} \qquad \tau_{actual} = \frac{2V}{A}$$

$$\tau_{\max} = \frac{S_y}{2} \qquad \sigma_{\max} \geq \sigma_{actual} \qquad n = \frac{\max imum\_value\_allowed}{actual\_value}$$

(Shigley, 2004, pp. 259-262)

OD (in)	2
ID (in)	1.125
E (psi)	30000000
S_y (psi)	75000
Cylinder width (in)	2
Total pin length (in)	6.25
Distance from left (in)	1.375
Distance from right (in)	2.875
A_{pin} (in^2)	2.147573
I_{pin} (in^4)	0.70677
y_{pin} (in)	1

Cylinder Force	
Diameter (in)	3
Area (in^2)	7.068583
Max pressure (psi)	2300
Force (lb)	16257.74
Dist. load (lb/in)	8128.871

Right rxn. C (lb)	6177.942
Left rxn. A (lb)	10079.8

V_{max} (lb)	10079.8
M_{max} (lb-in)	20109.2

Max shear (lb/in^2)	9387.154
Max stress (lb/in^2)	28452.27

Max allowable shear (lb/in^2)	37500
Safety factor (n)	**3.99**

Max allowable stress (lb/in^2)	75000
Safety factor (n)	**2.64**

Table G1: Pin Strength Calculations

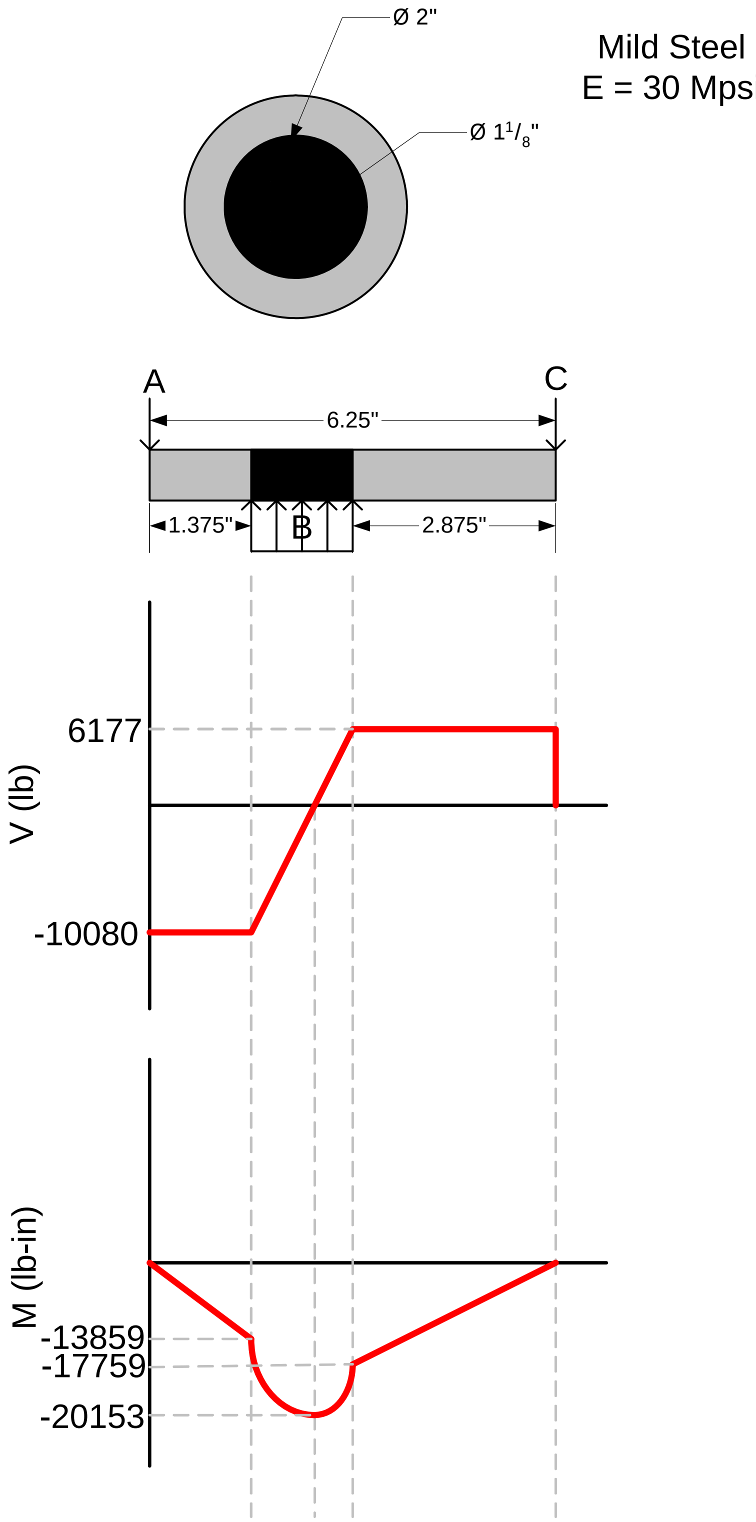


Figure G1: Pin Strength Schematic and Shear-Moment Diagrams

Appendix H

Safety and Hazards Analysis

FPST 4333 / BAE 4022
High Pressure Drilling Aid
System Safety Analysis

FPST Team	BAE Team
Jonathan Lund Brandon Wilkerson	Dustin Holden Curtis Johnson Brandon Kimbrell Kristin Stephens

System Safety Analysis Summary

Safety Analysis Team: Jonathan Lund, Brandon Wilkerson

BAE Team: Dustin Holden, Curtis Johnson, Brandon Kimbrell, Kristin Stephens

For initial analysis, a Preliminary Hazard List Analysis (PHLA) technique was utilized. As a system safety analysis team we were required to analyze the high pressure system that was developed to work as a functioning part of the entire directional drilling machine. Only the high pressure system components were analyzed. Initially we discovered 20 hazardous elements; those elements were broken down into three categories: System Hardware, System Functions, and System Energy Sources. In the PHLA hazards were not prioritized nor were corrective actions recommended. It is purely a mechanism for identifying hazardous elements and where they fit into the system overall. It also outlines possible effects of the hazardous elements.

For the detailed analysis portion of the project a Functional Hazard Analysis (FuHA) technique was performed. The process involves the evaluation of system components in order to identify and mitigate hazards. The FuHA technique identifies the hazardous elements in the same way as the PHLA. It also identifies casual factors that lead to the functional failure of the system and assigns an initial mishap risk index value to the hazardous element. These values are derived from MIL-STD-882 and are shown below:

Probability	**Severity**
A. Frequent	1. Catastrophic
B. Probable	2. Critical
C. Occasional	3. Marginal
D. Remote	4. Negligible
E. Improbable	

The FuHA also calls for recommended actions that will become preventative measures to eliminate or reduce the hazard. When developing the recommended actions the following precedence was taken into consideration:

1. Eliminate hazard through design.
2. Control hazard through safety devices.
3. Control hazard through warning signs.
4. Control hazard through training and personal protective equipment.
5. Tolerate the hazard and risk associated.

After all recommended actions were taken into consideration a final mishap risk index value was established. This value is determined assuming recommended actions have been implemented to mitigate the hazard. Lastly, a status column indicates the current status of the hazard. For the hazard to be classified as “closed” it must have undergone analysis and testing. It also must have been approved for the desired level of effectiveness in mitigating the targeted hazard. An “open” hazard is one that is still in need of analysis and testing. Due to the constraints of this project all hazards will be listed as "open."

While the safety analysis team has classified hazards using both the initial mishap risk index and the final mishap risk index values, it is left to management to determine what amount of risk is tolerable. Therefore, the system safety analysis team has not made any decisions regarding which hazards must be eliminated or significantly reduced.

Preliminary Hazard Analysis				
System Element Type: System Hardware				
No.	**System Item**	**Hazard**	**Hazard Effects**	**Comments**
PHL - 1	Nozzle Structure	Structural failure at nozzle	Personnel injury due to inability to aim high pressure stream	Significant risk only during above ground operation
PHL - 2	Nozzle Structure	Nozzle blockage	Personnel injury due to system rupture because of unsafe operating pressure	
PHL - 3	Hose	Structural failure in hose components	Personnel injury due to inadvertent discharge of high pressure liquids	
PHL - 4	Hose	Hose blockage	Failure of system operation	
PHL - 5	Hose	Hose blockage	Personnel injury due to system rupture because of unsafe operating pressure	
PHL - 6	Fluid control system	Valve failure	Improper flow of fluid in system resulting in system operation failure	
PHL - 7	Fluid control system	Electronic control failure	Improper flow of fluid in system resulting in system operation failure	
PHL - 8	Hydraulic valve assembly	Structural failure	Personnel injury due to high pressure release	
PHL - 9	Hydraulic valve assembly	Structural failure	Personnel injury due to projectile impact	
PHL - 10	Hydraulic valve assembly	Mechanical failure	System failure	
PHL - 11	Fluid discharge	Inadvertent fluid discharge	Improper system operation	Hazard to personnel health when system is operating above ground
PHL - 12	Fluid discharge	Absence of fluid discharge	Failure of system operation	
PHL - 13	Electronic fluid control	Electronic failure	Failure of system operation	Possibly due to inadvertent admission of liquid into electronic system
PHL - 14	Electronic fluid control	Switch malfunction	Inadvertent system operation	May result in personnel injury above ground or system operation failure below ground

PHL - 15	Hydraulic	Over pressurized system components	Personnel injury, system failure
PHL - 16	Hydraulic	Operational failure of system components	System failure
PHL - 17	Electronic	Electronic control switch malfunction	Personnel injury, system failure
PHL - 18	Potential	Inadvertent release of hydraulic energy	Personnel injury, system failure
PHL - 19	Heat	Over heating of hoses	Personnel injury, system failure
PHL - 20	Sound	Fluid discharge	Personnel injury, system failure

System: High Pressure Drilling Aid Subsystem: System Hardware			Functional Hazard Analysis				Analysts: Wilkerson, Lund Date: 4/18/2007		
Function	Hazard No.	Hazard	Effect	Causal Factors	IMRI	Recommended Action	FMRI	Comments	Status
High pressure fluid flow control	FuHA - 1	Structural failure at nozzle	Personnel injury due to inability to aim high pressure stream	Normal wear, improper installation, improper maintenance		Perform routine personnel training to eliminate causal factors, which are mostly operator oriented.			
	FuHA - 2	Nozzle blockage	Personnel injury due to system rupture because of unsafe operating pressure	Improper maintenance		Perform routine inspections of nozzle to ensure open path for fluid to flow through.			
	FuHA - 3	Structural failure in hose components	Personnel injury due to inadvertent discharge of high pressure liquids	Normal wear, improper installation, improper maintenance		Perform routine personnel training and inspections of system hardware.			
	FuHA - 4	Hose blockage	Failure of system operation	Normal wear, improper installation, improper maintenance		Perform routine personnel training and inspections of system hardware.			
	FuHA - 5	Hose blockage	Personnel injury due to system rupture because of unsafe operating pressure	Normal wear, improper installation, improper maintenance		Perform routine personnel training and inspections of system hardware.			
	FuHA - 6	Valve failure	Improper flow of fluid in system resulting in system operation failure	Normal wear, improper installation, improper maintenance		Perform routine personnel training and inspections of system hardware.			

	FuHA - 7	Electronic control failure	Improper flow of fluid in system resulting in system operation failure	Inadvertent initialization, improper installation, normal wear		Perform routine personnel training and inspections of system hardware.			
	FuHA - 8	Hydraulic valve assembly structural failure	Personnel injury due to high pressure release						
	FuHA - 9								

Brandon Wilkerson
Jonathan Lund

BAE Lab Meeting Minutes

February 12th, 2007:

Initial meeting for teams involved in project. Introduced ourselves, received a brief overview of project plans. Attended a lecture from Professor J.D. Brown with our BAE team. Exchanged contact information to allow for e-mail correspondence.

March 1st, 2007:

Groups met at BAE lab to observe functional demonstration of directional driller. Also observed the high pressure drilling aid design in person. Discussed initial system safety concerns. BAE team clarified questions we had about the system.

April 5th, 2007:

BAE team had safety concerns regarding pinch points and ergonomics. These issues were addressed.

Note: The majority of communication and information sharing was conducted via e-mail throughout the course of the semester.

Appendix I

Walvoil SD5

Appendix J

Operating Instructions

If drilling unit is equipped with the optional HM3x20z high pressure steering assist attachment (HPSAA) the following steps should be taken to ensure proper use:

To position the drill head (see JT520 Operator's Manual, pg 85):

1. Read beacon roll.
2. Slowly rotate pipe until locator displays appropriate beacon roll.

To change direction:

1. Rotate pipe to clock position you intend to travel.
2. Ready the HPSAA.

   To ready the HPSAA:

   1. Ensure engine is at full throttle.
   2. Adjust fluid pressure.
      - Move fluid control to no flow position.
3. Depress and hold the HPSAA activation switch for 5-10 seconds.
4. Release HPSAA activation switch.
5. Push pipe into ground.
6. Repeat steps 3 through 5 until desired direction correction is achieved.

To continue drilling:

1. Adjust fluid pressure to desired flow position.

To move forward with out changing direction:

1. Rotate pipe.
2. Push pipe into ground.

Appendix K

Gantt Chart