AN EXPERIMENTAL SETUP TO STUDY THE SETTLING BEHAVIOR OF EPOXY BASED FLUIDS

A Thesis

by

IBRAHIM ISMAIL EL-MALLAWANY

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2011

Major Subject: Petroleum Engineering

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Approved by:

Co-Chairs of Committee,	Jerome Schubert
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Committee Member,	Mahmoud El-Halwagi
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ABSTRACT

An Experimental Setup to Study the Settling Behavior of Epoxy Based Fluids.
(May 2011)
Ibrahim Ismail El-Mallawany, B.S., The American University in Cairo
Co-Chairs of Advisory Committee: Dr. Jerome Schubert
Dr. Hisham Nasr-El-Din

This thesis is part of a project funded by the Minerals Management Service (MMS) (now Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE)) to study the use of epoxy to plug hurricane damaged wells. Some of the wells destroyed by hurricanes are damaged to an extent that vertical intervention from the original wellhead is not possible. These wells have to be plugged to prevent future flows through the well to protect the environment. Cement is usually the preferred plugging material because it is very cheap compared to other materials like epoxy. However, cement can easily get contaminated by sea water or brines present in wells as completion fluids. Therefore, to be able to use cement it has to be placed at the bottom of the well by drilling an offset well all the way to the bottom of the original well. Epoxy, on the other hand, being much more chemically stable can be placed at the very top of the well and let to settle by gravity without fearing contamination. Therefore, in wells described above, epoxy can be much more economical than cement. Placing epoxy at the top of a well and letting it settle by gravity can also be more economical than using cement in other situations such as in a leaking annulus of a well where circulation in that annulus is not possible, or if a well that has been previously plugged starts leaking again after the rig has been removed. Placing epoxy in the manner described can be achieved without using a rig and therefore, would be much more economical than cement.

One of the most important factors in this process is to be able to predict the settling velocity of the epoxy to be able to determine the required setting time of the epoxy so that the epoxy does not set prematurely. In addition, it is important to evaluate whether the epoxy can successfully settle to the bottom and how much of it will adhere to the pipe walls while freefalling. This thesis aims to design, build and run an experimental setup that would help study the settling velocity of epoxy. Some experiments were conducted to assess the effect of different parameters that might affect the settling velocity of the epoxy such as the epoxy's density, the annulus size and the inclination angle. The results show that the settling velocity was proportional to the epoxy's density. Also the settling speed was almost double in experiments done at an angle compared to experiments done at vertical position. The annulus size did not have any clear effect on the settling speed. The adhesion to the pipe walls was found to be proportional to the epoxy's viscosity and angle of inclination and was inversely proportional to the annulus size.

DEDICATION

To my wife and my parents

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Jerome Schubert, my committee co-chair Dr. Hisham Nasr El-Din and my committee member, Dr. Mahmoud El-Halwagi for their guidance and support throughout the course of this research. Thanks to John Maldonado for his help to build and run the experiments. Thanks also to my colleagues, Arash Haghshenas, Tinlee Tilton and Salvador Lopez, for helping me with the experimental setup and running the experiments.

I also want to extend my gratitude for the following:

MMS: for funding me and the entire project.

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Dr. Mikael Olsen and the University's physical plant: for their help and guidance with the experimental setup.

David from Industrial Machines: for building the experimental setup.

NOMENCLATURE

BOEMRE	Bureau of Ocean Energy Management, Regulation and Enforcement
CIBP	cast iron bridge plug
deg	degrees
DIA	diameter
dp	differential pressure
ft	foot/feet
g	gram
gal	gallons
ID	inner diameter
in	inch
lb/lbs	pound/pounds
min	minutes
MMS	Minerals Management Service
OD	outer diameter
PFS	Professional Fluid Systems
ppg	pounds per gallon
psi	pound per square inch
PVC	poly vinyl chloride
sec/secs	second/seconds
TETA	tri-ethylene-tetra-amine
vs.	versus

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1. INTRODUCTION

In the past years many oil platforms have been either completely destroyed or extremely damaged by hurricanes. **Table 1** shows the number of destroyed or extremely damaged platforms according to the MMS released documents. (Energo Engineering 2006, Energo Engineering 2007, BOEMRE 2006 & BOEMRE 2008)

TABLE 1-NUMBER OF WELLS DAMAGED OR DESTROYED BY HURRICANES

Hurricane	No. Destroyed	No. Extremely Damaged
Rita & Katrina	113	144
Ike & Gustav	60	31
Ivan, Andrew & Lily	18	

Table 1 shows that the total number of destroyed or damaged platforms exceeds 350. All these wells need to be plugged and abandoned. Some of these wells will enable plugging by conventional means using cement. However, others will have been destroyed to a point that reentering the well is impossible for example the casing may be buckled at or below mudline or the wellhead might be buried with seafloor mud. This will prevent wire line operations via tubing to set plugs near the packer or punch the tubing to circulate cement into the casing. Cement is mixed with water and therefore is miscible with seawater and brines which are the main packer fluids found in the Gulf of Mexico. Long interaction with these fluids can be devastating causing dilution or contamination of the cement mix which in turn cause it not to cure or lose its compressive or bonding strength. Therefore, for these latter wells the use of cement is not suitable because cement needs to be delivered to the point of application with minimum or no interaction with water and the only way this would be possible for these

This thesis follows the style of *Society of Petroleum Engineers.*

wells is that an intersection well be drilled and intersects at or near the packer meaning that it has to be drilled to full depth. This of course would be very costly and time consuming offsetting the competitive price advantage of cement over other plugging materials. An alternative means to plug these wells is have an intersection well that intersects the original wellbore at the very top through perforations between the wells. Then epoxy would be spotted inside the original wellbore. The epoxy would then settle by gravity all the way down to the packer. Of course, for this to work the well must not be flowing at the time. Epoxy in this situation is an excellent choice because generally they do not mix with water or brines and could reach the packer without being diluted or contaminated.

This thesis is part of a project funded by MMS (now BOEMRE) which aims to investigate the applicability of epoxy or another non cement plugging material to plug hurricane damaged wells described in the previous paragraph. The current limitations of the use of epoxy based materials as a permanent plug is that these materials have very rarely been used for plugging and abandonment applications and the applicability of using such materials has not been adequately studied. The MMS project will include the following research points.

1) Comparing epoxy-based materials against cement abandonments and other potential plugging materials
2) Determining whether epoxy material can effectively drop 7000 feet through a casing annuli and accumulate on top of the packer
3) Determining how long material takes to travel to the bottom of a casing annuli and cure
4) Determining how material performs over time
5) Determining how weighting of this material with $BaSO_4$ affects the compressive and bond strength of the material
6) Determining whether there are other weighting materials which may perform better than $BaSO_4$

7) Ranking various resin and hardener chemical systems for best performance in the field
8) Evaluating the effects of various liquids such as calcium chloride, sea water, and formation hydrocarbons on the resin chemical systems

The work discussed in this thesis is aimed to help study points 2 & 3. It is about designing, building and running an experimental setup that will provide experimental data to help develop a model that could predict the time it takes for epoxy to drop a certain distance from the injection point to the packer. The thesis will also try to investigate how much epoxy will adhere to the walls of the pipe before it reaches the packer so excess epoxy can be injected to overcome this. Another point that will be discussed is whether weighting materials such as barite will be able to hold inside the epoxy without separating during or after it falls through the wellbore.

2. LITERATURE REVIEW

Historically in the oil industry epoxy has been used for sand consolidation, resin coated proppants, remedial casing procedures, formation plugging and many other applications. For example Ng, R. C., McPherson, T.W. and Hwang, M.K. (1994) discusses using epoxy to repair corroded casing in the wellbore. The idea of this patent is that when a part of the casing is corroded, that part gets milled off. Then an under reamer would further open the bore to increase the epoxy's thickness. A retrievable packer is then placed and set right under the corroded section then epoxy is placed above the packer to fill the place of the milled casing and any thief zones in the formation. The patent suggests that epoxy is either placed using a dump bailer or using coiled tubing. Both these placing methods are of course not suitable for the intended application of this thesis. The patent also suggested some epoxy based materials namely Shell's EPON-828 and Shell's EPON DPL-862 as the resin, a Sherling Berlin's diluent 7 as a reactive diluent, fine powder calcium carbonate or silica flour as a filler and lastly Sherling Berlin's Euredur^{200} 3123 as a curing agent. The diluent's function is to increase pot life and gel time of the resin and decrease the epoxy's viscosity. The filler's function is to increase the specific gravity of the resin so the resin does not float and stay lying on the packer. The curing agent obviously causes the resin to cross-link and therefore harden. **Fig. 1** from the patent describes the process where epoxy is placed instead of the corroded casing and thief zones and then drilled off.

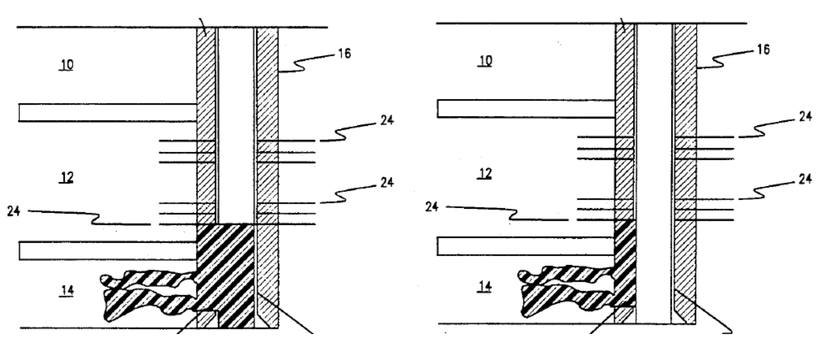

Fig. 1-Epoxy used for remedial casing procedure

An example of an epoxy used for formation plugging is discussed by Knapp and Welbourn (1978). It discusses the use of a resin in an emulsion where droplets are less than 1 micron in diameter to be able to seep through the pore spaces of the formation. The method they suggested is first pumping the resin in the formation and then pump the curing agent after it. This causes regions of high permeability in the formation to be preferentially sealed. The application of this process is for water or gas shut off. It is also used for controlling water in injection wells so it is not lost in useless parts of the formation. The resin would plug areas of high permeability and direct water injected to flow in the desired lower permeability zones of the reservoir.

The only resin product that has been applied for an application similar to the one we are focusing on is a product called Ultra-Seal from a company called Professional Fluid Systems. The company has applied this resin on a few similar applications. For example, High Island Block A330 platform was plugged and abandoned. Several years later gas seepage from the pressure cap of the well was detected by coincidence when a recreational driver was swimming by. The pressure cap was removed by a diamond saw. The gas seepage was found to be coming from micro-annuli between the cement and the casing/conductor walls. The tubing was then sealed with a cast iron bridge plug (CIBP) and the pressure cap was reinstalled. Then the Liquid Bridge Plug (another name for the Ultra Seal resin) was pumped inside the micro-annuli and was waited on for 20 hours. The plug was successful and the gas seepage was stopped. Another application for the Ultra-seal was on Chevron’s Vermillion 31 platform. The platform had a leaking packer and wanted a way to seal the packer without using rig equipment. The annular fluid was seawater and was 8.6 ppg The Ultra-Seal resin was weighted up with a filler material to increase its terminal velocity during its fall and therefore reducing the time of its travel. 168 gallons of the resin was loaded into the annulus and was allowed to fall for 14 hours and then set on the packer for an additional 24 hours. The plug then was pressure tested at 1000 psi and no pressure loss was detected indicating the success of the seal. The Ultra-Seal resin was also applied in another five different wells for different plugging purposes especially hurricane damaged wells. (PFS Aug 2010)

CSI technologies did some fall tests on the Ultra-Seal but on a very small scale. A 2 inch diameter 5 feet in length clear glass pipe was used. A copper pipe was inserted in the first two feet of the pipe to act as a stringer. The pipe was filled with brine weighted with calcium bromide and had a density of 10.4 ppg Epoxy is then loaded into the copper pipe and time is measured when the epoxy exits the copper pipe until it reaches the capped bottom of the pipe. **Fig. 2** shows an illustration of the experiment.

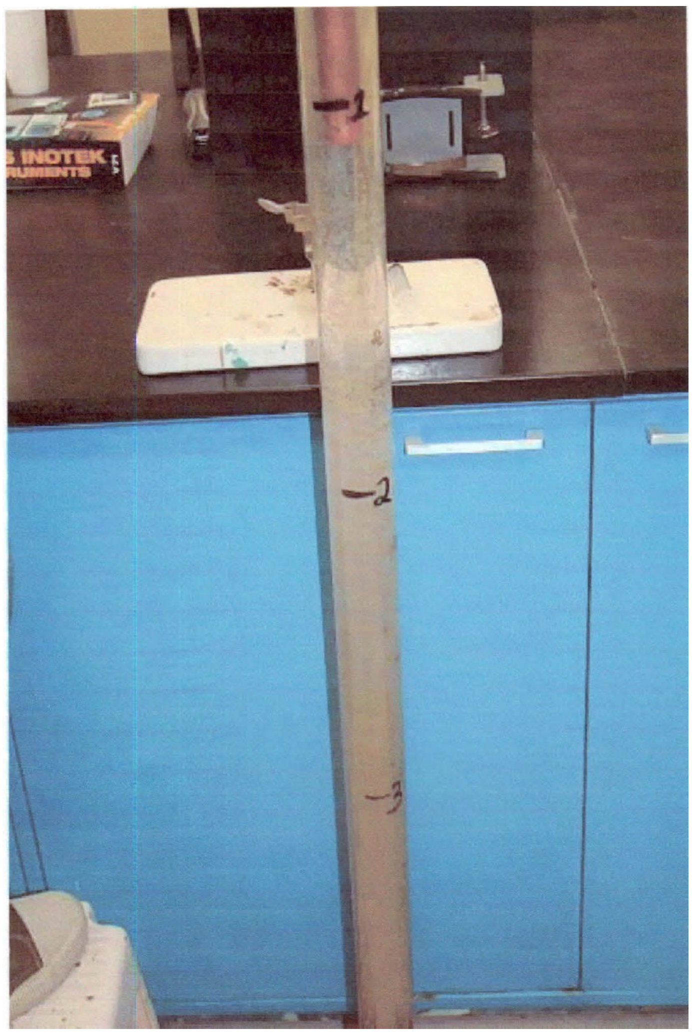

Fig. 2-Test apparatus to measure epoxy's settling velocity. (PFS Aug 2010)

Time is measured at every 1 foot interval over the 3 foot interval. The Ultra-seal was weighted with barite to a density of 16 ppg. The time it took for the resin to fall over the 3 foot interval was 5 seconds, measured visually. The experiment was repeated 3 times yielding the same 5 seconds and therefore it was concluded that the fall rate of the resin would be 36 ft. /min. This experiment has many possible flaws. It did not study the effect of different parameters on the fall rate such as the pipe diameter, density and viscosity of resin and density and viscosity of annular fluid. Also the 3 foot interval is very short. Therefore, not only resin might not reach its terminal velocity during this interval, any small change in time would yield big changes in settling velocity. The 2" pipe diameter is also too small compared to real life application. (PFS Aug 2010)

3. THEORETICAL BACKGROUND

The concept of settling has been studied in many applications such as settling tank, catalytic converters, pneumatic conveying of solids, and gas migration in the oil field. There are a few fundamental concepts behind the theory of settling objects. The most known theory is Stokes' law. Stokes' law provides an equation to predict the settling of solids or liquid droplets in a fluid, either gas or liquid. It assumes that the settling object is a small sphere and that the difference in densities is not large. This is because Stokes' law takes into account only the viscous forces that cause drag and does not account for drag due to impact forces. Therefore, Stokes' law only applies where Reynolds number is very low. Stokes' law is given by the following equation (Batchelor 1967)

$$F_d = 6\,\pi\,\mu\,R\,V \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where F_d is the drag force, μ is the fluid's viscosity, R is the sphere's radius and V is the particle's velocity. When the settling particle reaches terminal velocity then in that case the sum of forces must equal zero. Therefore the drag force must equal the difference between the force due to gravity and the buoyancy force. So F_d can be written as the following equation

$$F_d = \frac{4}{3}\,\pi\,R^3(\rho_{s-}\,\rho_f)g \quad \ldots\ldots\ldots\ldots (2)$$

where g is the acceleration due to gravity, ρ_s is the particle's density and ρ_f is the fluid's density. Now by equating equations (1) and (2) we can solve for the terminal velocity which will lead to the following equation

$$V = \frac{2R^2(\rho_{s-}\,\rho_f)g}{9\mu} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Experimentally, it was found that at Reynolds number less than 0.1 the error is within 1%. From Reynolds number between 0.1 and 0.5 the error is within 3% and between 0.5 and 1 the error is within 9%. When Reynolds number is greater than 1, drag due to impact becomes significant and Stokes' law would lead to large errors. Reynolds number could be computed from the following equation. (Coulson, J.M., Richardson, J.F., Harker, J. H., Backhurst, J. R. 2002)

$$R_e = \frac{4R^3 g\rho_f(\rho_s-\rho_f)}{9\mu^2} \ldots\ldots\ldots\ldots (4)$$

When Reynolds number is large then impact forces become much more dominant and viscous forces can be ignored. In that case Newtonian drag applies. Newtonian drag identifies a parameter called the drag coefficient (C_D) that represents the ratio of the force exerted on the particle by the fluid divided by its impact pressure. The drag coefficient is given by (Batchelor 1967)

$$C_D = \frac{2F_d}{\rho_f V^2 A} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

where A is the projected area of the object that is perpendicular to the direction of flow. For example in case of a sphere the projected area in the direction of flow (or any other direction) is a circle and therefore $A = \pi r^2$. For a spherical particle settling in a fluid the terminal velocity using Newtonian drag could be obtained by equating equation (5) with equation (2) to obtain (Batchelor 1967)

$$V = \sqrt{\frac{4(\rho_s-\rho_f)gr}{3C_D\rho_f}} \ldots\ldots\ldots\ldots\ldots (6)$$

Table 2 below gives rough estimates of drag coefficients for different applications. It must be noted that the drag coefficient varies with Reynolds number.

TABLE 2-DRAG COEFFICIENTS OF DIFFERENT OBJECTS
(Engineeringtoolbox Nov 2010)

C_D	Object
0.48	rough sphere (Re = 10e6)
0.005	turbulent flat plate parallel to the flow (Re = 10e6)
0.24	lowest of production cars (Mercedes-Benz E-Class Coupé)
0.295	bullet
1.0–1.3	man (upright position)
1.28	flat plate perpendicular to flow
1.0–1.1	skier
1.0–1.3	wires and cables
0.1	smooth sphere (Re = 10e6)
0.001	laminar flat plate parallel to the flow (Re = 10e6)
1.98–2.05	flat plate perpendicular to flow (2D)

Newtonian drag should be applied for Reynolds number above 1000. For intermediate values of Reynolds number where both viscous and impact forces are significant, a transitional drag regime occurs. An empirical equation was developed by Schiller and Naumann and is given by the following equation (Coulson et al 2002)

$$C_D = \frac{24}{R_e}\left(1 + 0.15\, R_e^{0.687}\right) \ldots\ldots\ldots.. (7)$$

By using equations (4), (6) and (7) we can solve for the terminal velocity.

The equations discussed all require that the particle has a known shape and they also are used for a particle that is in an infinite fluid. In our application however the shape may not be known and the epoxy is falling in an annulus so the pipe walls will definitely have an impact. This impact must be studied and its significance should be examined.

4. PROPOSED WORK

The experimental setup consists of a 25 ft long pipe fixed on a pipe rack. The pipe rack is designed in such a way to be able to orient the pipe from horizontal to vertical or at any angle in between. The pipe can be full of any desired liquid that could be expected in the wellbore such as seawater, drilling fluid or oil. The setup should allow ease of adjustments, and services such as replacing pipe, replacing fluid in the pipe, installing pressure transducers on pipe, cleaning pipe, retrieving epoxy after it falls etc. Different pipe sizes and pipe materials could be used. Also two different pipe sizes can be inserted into one another to provide an annulus of desired size. The maximum size of pipe was chosen to be 7” diameter. Epoxy would then be dropped from the top of the pipe and the time taken for epoxy to reach different positions of the pipe will be measured. The epoxy is expected to be accelerating at first and then should reach a final terminal velocity. Since the distance between the injection point of the epoxy in the wellbore and the packer will be huge (around 7000 ft), the time it takes to accelerate would be negligible compared to the rest of the journey. Therefore, the terminal velocity of the epoxy used is what will be sought. However, all data will be recorded in case it is needed at a later stage of the project. At start clear PVC pipe and fresh or synthetic sea water will be used to make measurements easier. During these starting experiments an ideal way of measuring the fall rate in an opaque pipe or opaque liquid will be investigated like for example a steel pipe or oil. For example, a pressure transducer could be installed to determine if the difference in hydrostatic pressure when epoxy passes the transducer is detectable or not. If pressure transducers fail other methods to predict fall rate in opaque steel pipe or opaque fluid will be sought.

To study whether weighting materials such barite will not separate from the epoxy, an epoxy that has a density less than water will be used .This epoxy will be weighted up with desired weighting material. This epoxy will then be dropped in the pipe until it either drops or fails to drop.

Lastly, it is important to determine how much epoxy would adhere to the walls of the pipe. This can be done by measuring the difference in volume between the epoxy injected and the epoxy collected at the bottom.

5. DESIGN AND IMPLEMENTATION

5.1 Preliminary Design

The pipe support was to be installed at the University Services Building. This building is the University's warehouse and each department has a plot about 75 ft by 50 ft. This building was chosen because its ceiling is 30 ft high and therefore is the only building on campus that can hold the pipe support in vertical position. Before discussing the final design other alternative designs that were candidates will be introduced to show why the final design was thought to be the best and to give it more appreciation. It was decided that the maximum load that the pipe support would bear would be that of a 7 inch diameter steel pipe full of seawater since it is the most common packer fluid in the Gulf of Mexico. Taking the minimum casing weight which is a 6.54 inch ID the load would be.

7" diameter x 6.54" ID = 17.0 lbs/ft

17.0 lbs/ft x 30 ft length = 510 lbs

Seawater Volume = $\frac{\pi}{4}(\frac{6.54}{12})^2 \times 30 = 7\ ft^3$

Seawater Weight = 7 ft^3 x 64.3 lbs/ft^3 = 450 lbs

Total Weight = (510 + 450) x 10% safety factor = 1056 lbs

The 10% safety factor is to account for any extra fittings and/or accessories. Now as explained in the previous section the pipe support has a few main functions. These functions are to bear the pipe's weight, keep it from moving during experiment and to orient the pipe at any desired angle. Cost was also an important issue to consider since the project has a fixed budget. The first conceptual design was as represented in **Fig. 3** below.

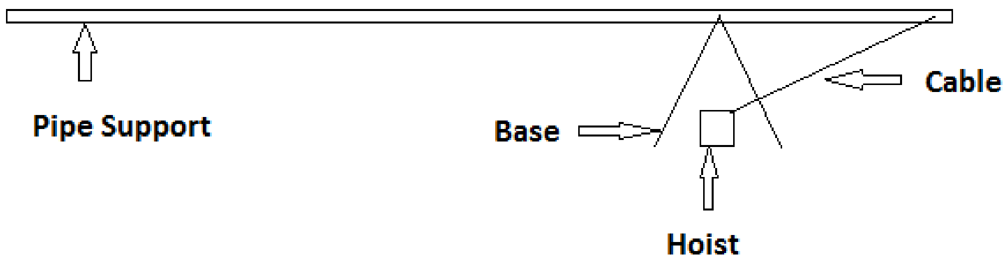

Fig. 3-First conceptual design.

As shown in the figure there would be a base that provides a pivot point for the pipe support the hoist would pull the pipe support from the right end as shown in the diagram to adjust the pipe support's position from horizontal to vertical or any angle in between. Now let us study the forces and moments on the pipe support. There are four forces acting on the pipe support.

1) Base
2) Hoist
3) Pipe
4) Pipe support's own weight

Now assuming a value of 350 lbs for the pipe support's weight, the load of the pipe and pipe support's weight can be represented as a distributed load of 46.87 lbs/ft [(1056+350)/30] of the pipe support. **Fig. 4** shows a schematic of the force distribution on the pipe support.

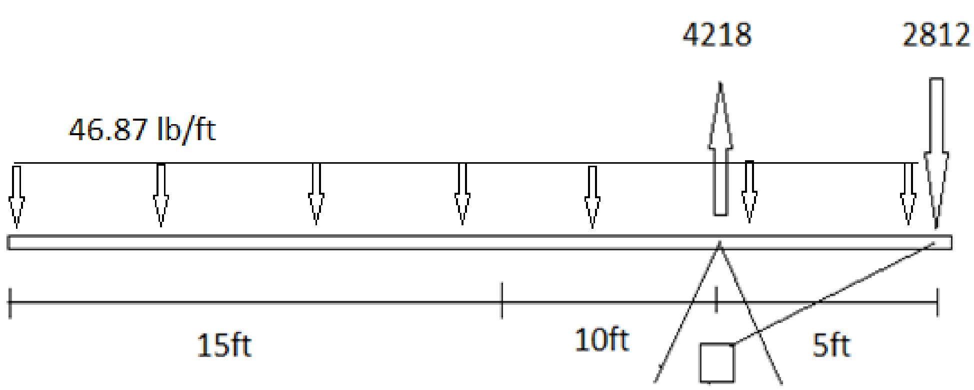

Fig. 4-Force distribution on first conceptual design.

The forces are represented in lbs **Figs. 5** and **6** below show the shear force and the moment distribution along the pipe support.

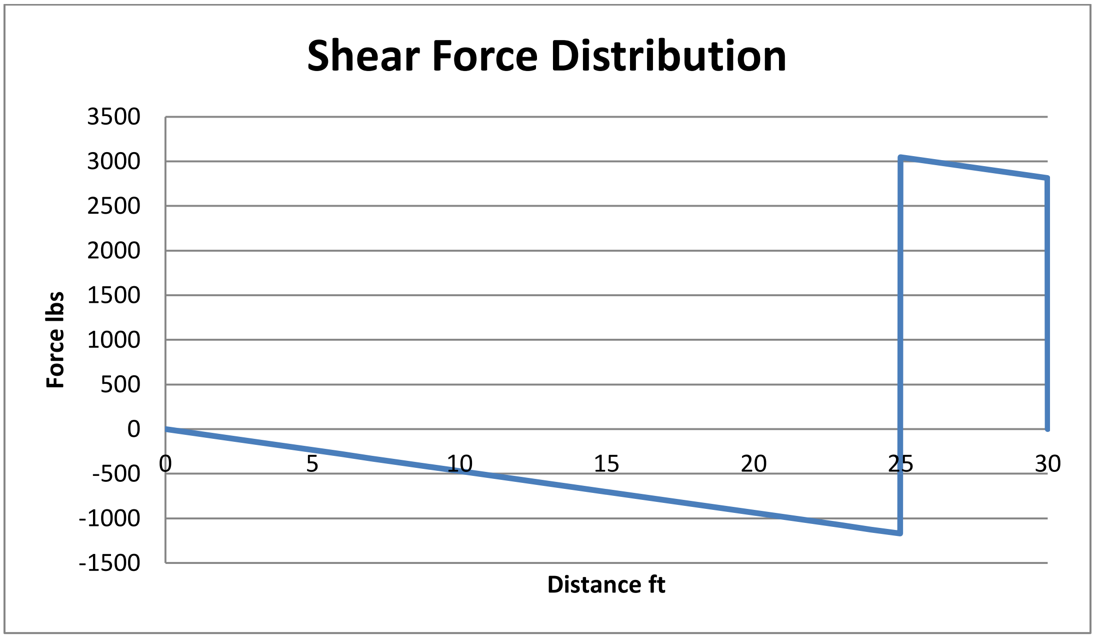

Fig. 5-Shear force distribution of first conceptual design.

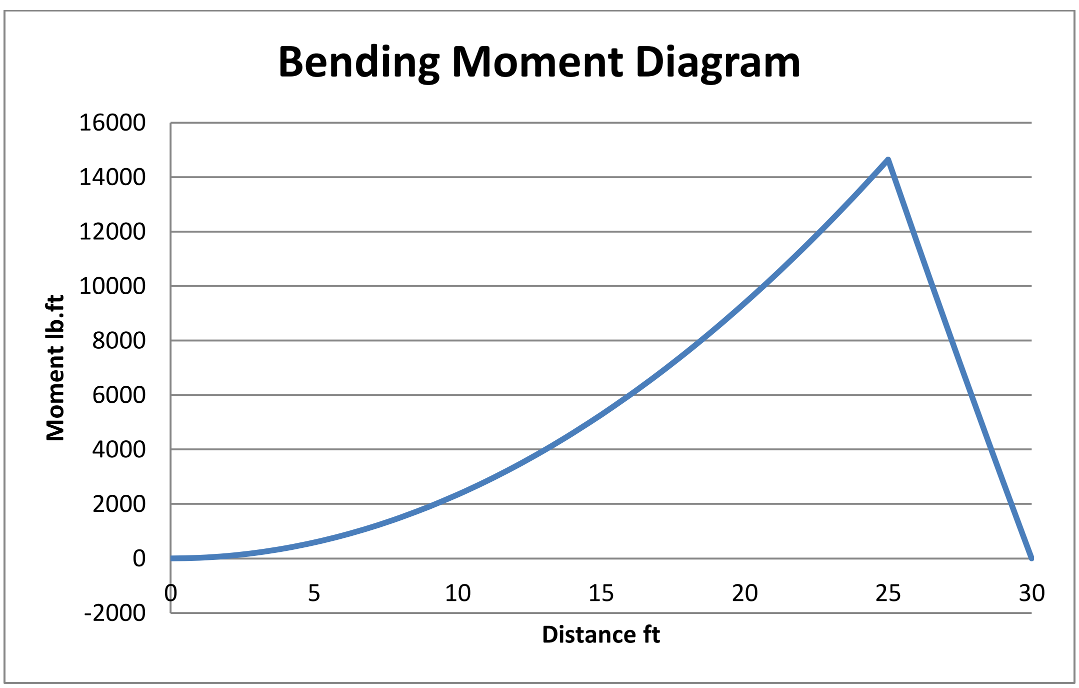

Fig. 6-Bending moment diagram of first conceptual design.

From the above charts it can be seen that the point of maximum stress is at distance 25 ft. The shear force and the bending moment at this point are 4,218 lbs and 14,645 lbs.ft respectively. The yield strength of steel is approximately 36,000 psi. Now we can calculate the moment of inertia (I) of the section.

$$I = M \cdot y / Stress \ldots\ldots\ldots.. (8)$$

Where M is the moment and y is the perpendicular distance between the force and the neutral axis. If we design at 50% of yield and that there would be 2 square steel tubes each carrying half the load then I = 9.76 in^4 per section. Therefore, the smallest standard square steel tube that can carry the load is a 4x4x3/8" steel tube. This section would make the pipe support weight more than a ton and we only assumed 350 lbs so iteration is necessary which will cause the pipe support to be even bigger, more expensive and heavier than it already is. In addition to being too heavy and expensive, another major disadvantage is that the hoist will need to have a capacity of more than 4000 lbs assuming that the angle of the cable with the pipe support is 45 deg and that it weighs only 350 lbs. What we currently have in the university is a 650 lbs hoist this means we will have to buy a new hoist which will also cost a lot of money.

Another alternative that was considered is to have the base in the middle of the structure as shown in **Fig. 7** below.

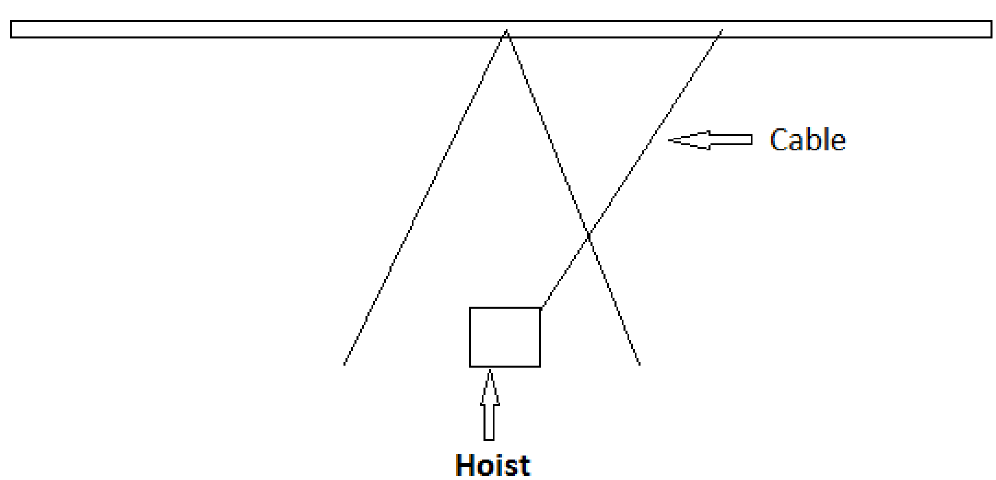

Fig. 7-Second conceptual design.

Fig. 8 shows the force distribution on the pipe support assuming everything is the same.

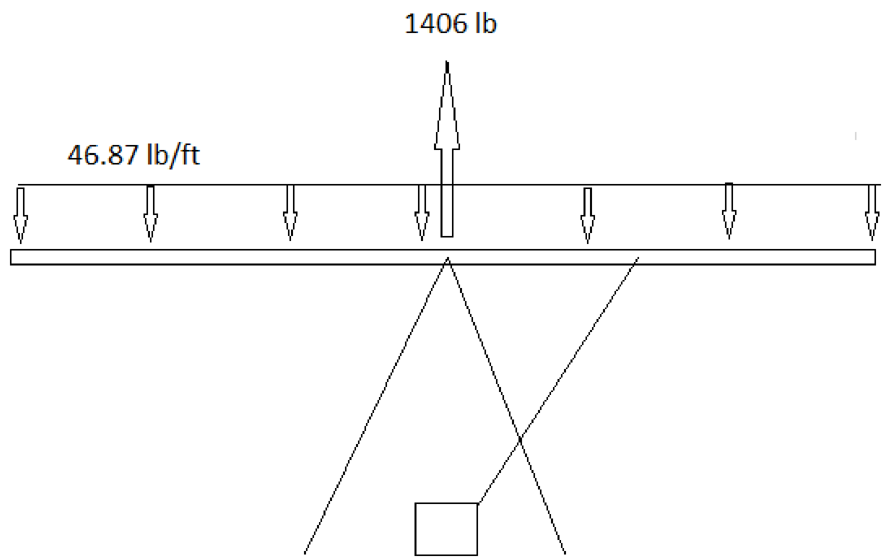

Fig. 8-Force distribution on second conceptual design.

The shear and moment diagram would be as shown in **Figs. 9** and **10**.

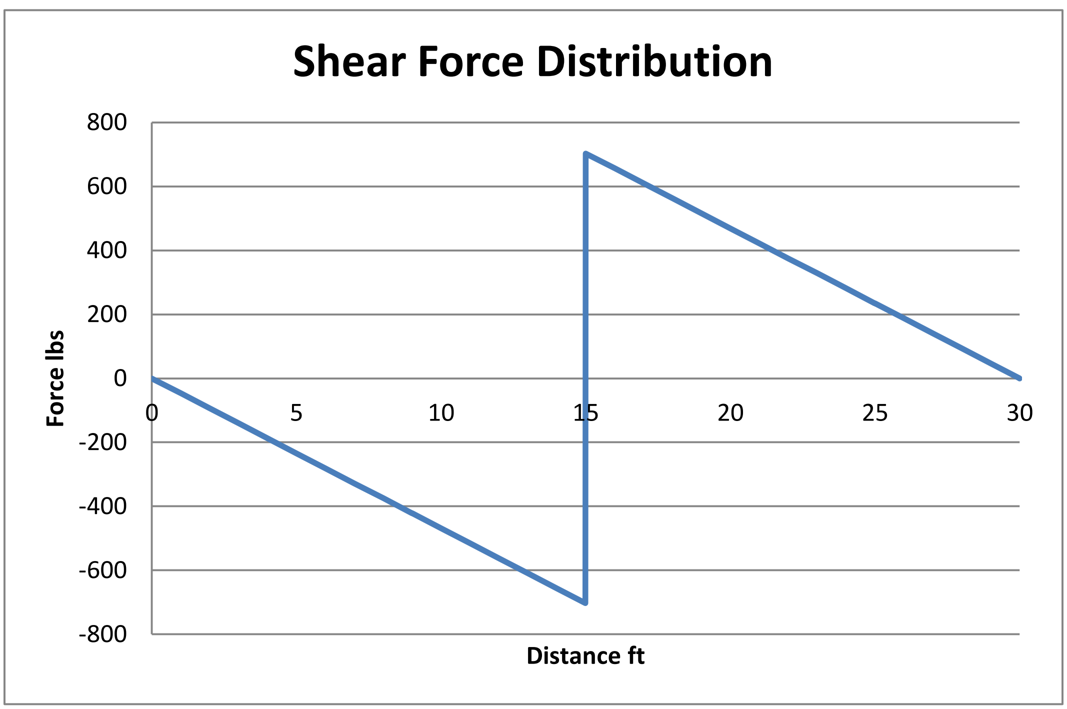

Fig. 9-Shear force distribution on second conceptual design.

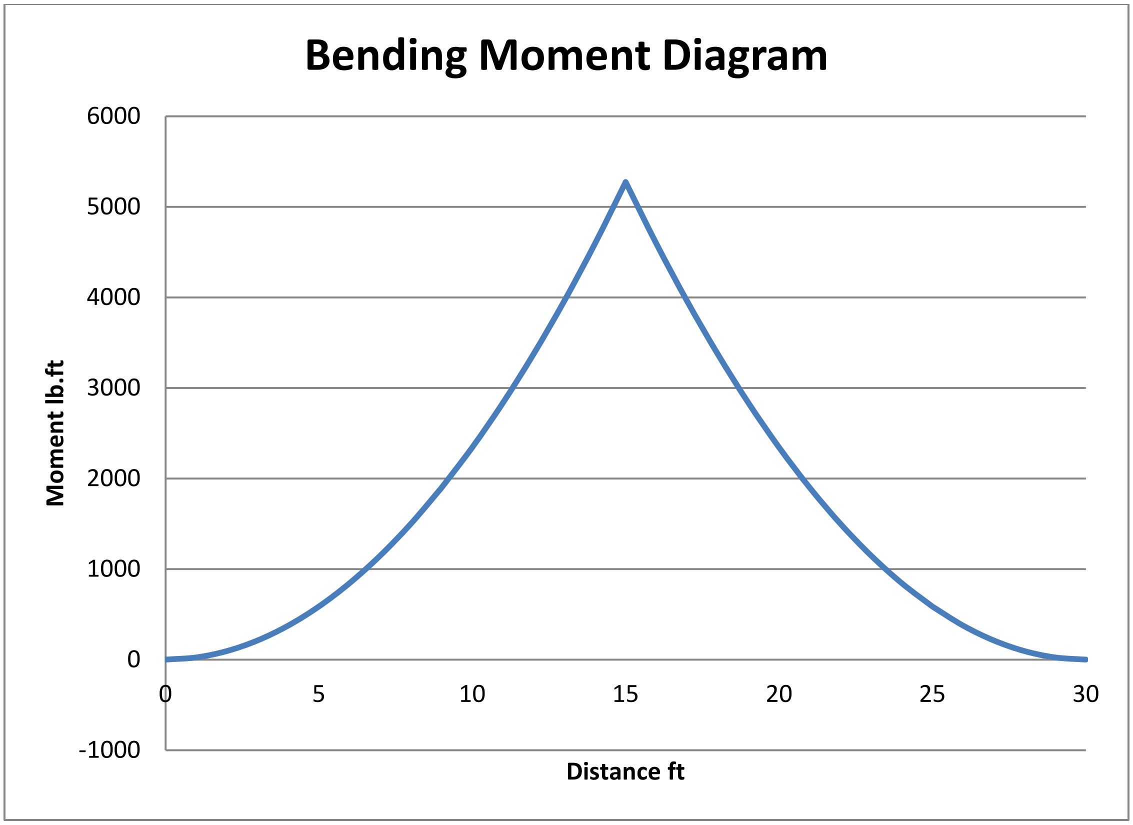

Fig. 10-Bending moment diagram of second conceptual design.

The maximum shear force and bending moment are 1406 lbs and 5272.5 lbs.ft respectively. Using equation 8 and same criteria as before, we get I = 2.64 in^4. The smallest square steel tube that can carry this load is a 3x3x1/4". This section would make the pipe support weight more than 700 lbs and we only assumed 350 lbs so iteration is necessary which will cause the pipe support to be even bigger, more expensive and heavier. An advantage of that setup is that the hoist force is almost zero; it only needs to overcome the friction in the pivot and therefore, we could use the hoist we already have. On the other hand, the major disadvantage of this setup is that the base will be much bigger and the pipe will be at 15 ft height when it is horizontal. This would make it very difficult to change the pipe, add or remove fittings, add epoxy and so on. Also the installation of such setup would be very difficult.

This brings us to the design that has been chosen. The only way that we would have a lower stress than the one in the previous example is by having two supports instead of one. To achieve this then the hoist must act as a support along with the base. This is shown in the **Fig. 11** below.

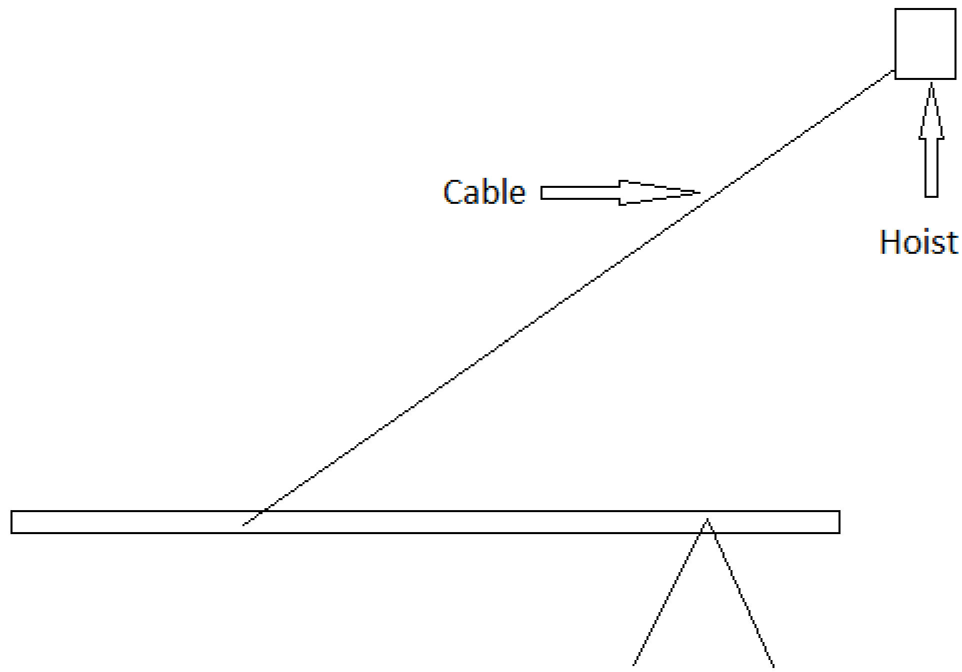

Fig. 11-Conceptual design of current setup.

The hoist would be attached at the ceiling of the building as shown in the picture. This would provide two support points instead of one. This should reduce the stress dramatically as compared to the first design. **Fig. 12** shows the force distribution on the pipe support for this set up.

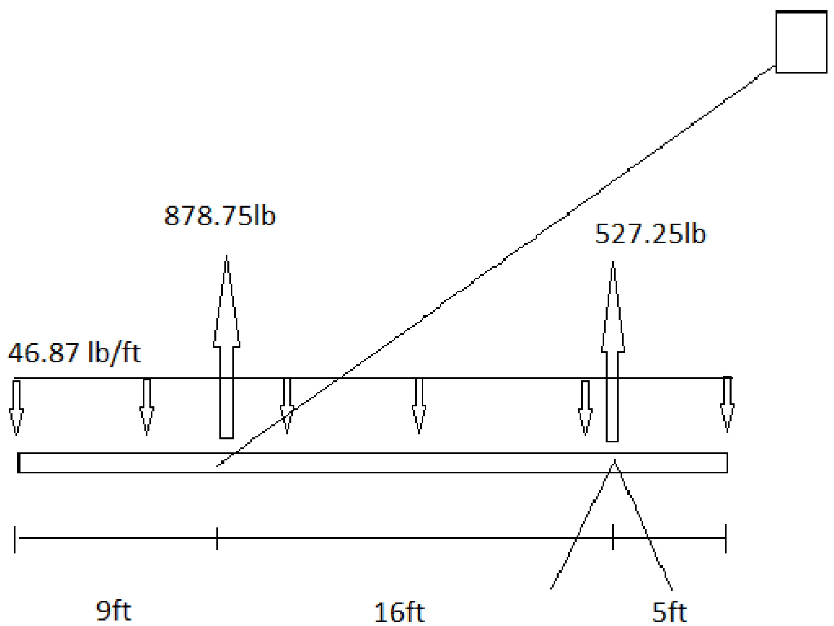

Fig. 12-Force distribution on current setup.

Now let us examine the shear force and bending moment diagrams as shown in **Figs. 13** and **14**.

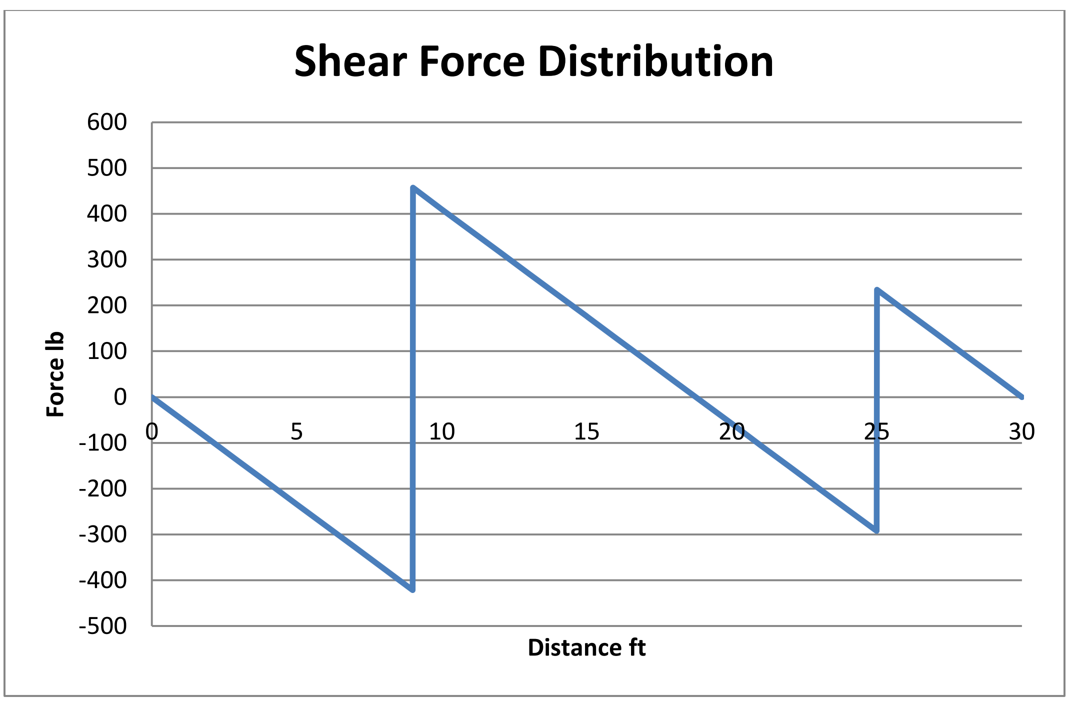

Fig. 13-Shear force distribution on current setup.

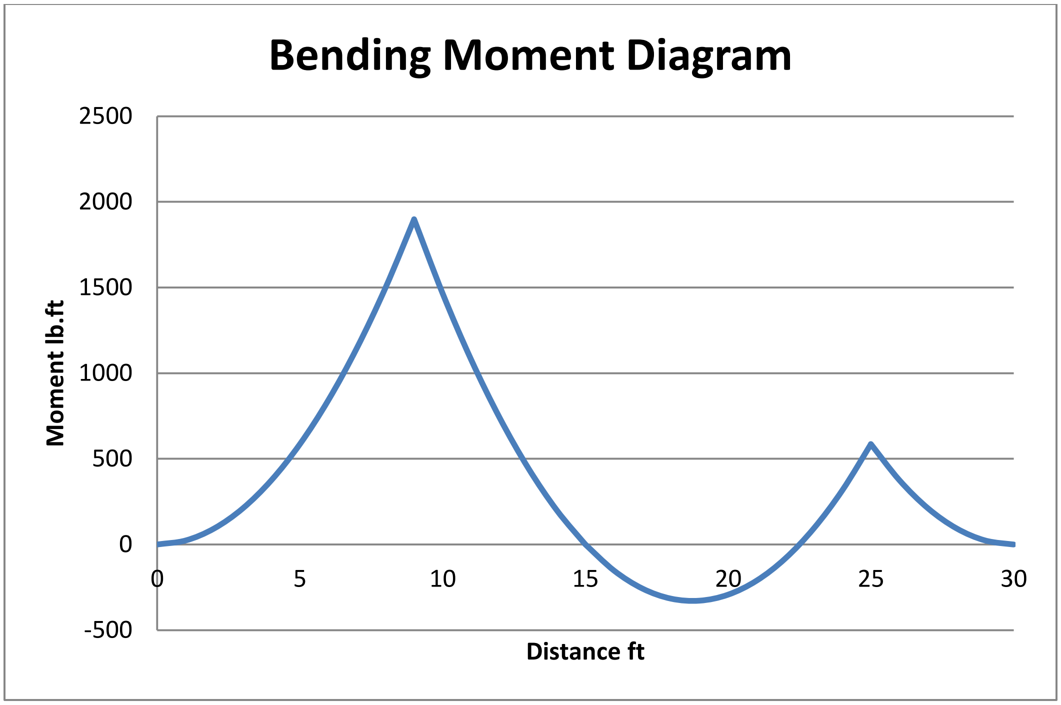

Fig. 14-Bending moment diagram of current setup.

From the diagrams we can see that the maximum shear force and bending moment are 878.75 lbs and 1898 lbs.ft respectively. Using equation 8 and same criteria as before, we get I = 0.633 in^4 per steel tube. The smallest square steel tube that can carry this load is a 2x2x3/16". In this case the weight is almost equal to 350 lbs as assumed and no more iteration is necessary. This is much lighter/smaller and therefore much cheaper and easier to install than previous setups. Another advantage of this setup is that the base is small. The capacity of the hoist in this setup is 1240 lbs assuming that the cable has a 45 degree angle with the pipe support. Though the hoist we had was only 650 lbs capacity we were still able to utilize it for this setup. This was done by using a double line setup which will be explained in or more detail later on in this report. The initial hand calculations concluded that using two 2x2x3/16" square steel tubes would be sufficient for our application. However, further analysis needs to be conducted to more accurately determine whether it is really sufficient or not. So the next step was to create a three dimensional model of the proposed setup and then perform a finite element analysis to determine whether the pipe support would yield or not.

5.2 Detailed Design

The three dimensional model was implemented using the famous software Solidworks. The model consists of two main parts the pipe support and the base.

5.2.1 Pipe Support

Figs. 15 and **16** show the model for the pipe support.

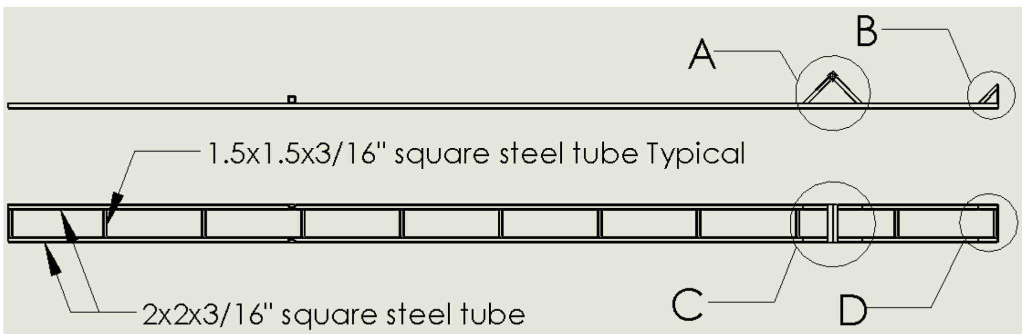

Fig. 15-2-d representation of the 3-d model of the pipe support.

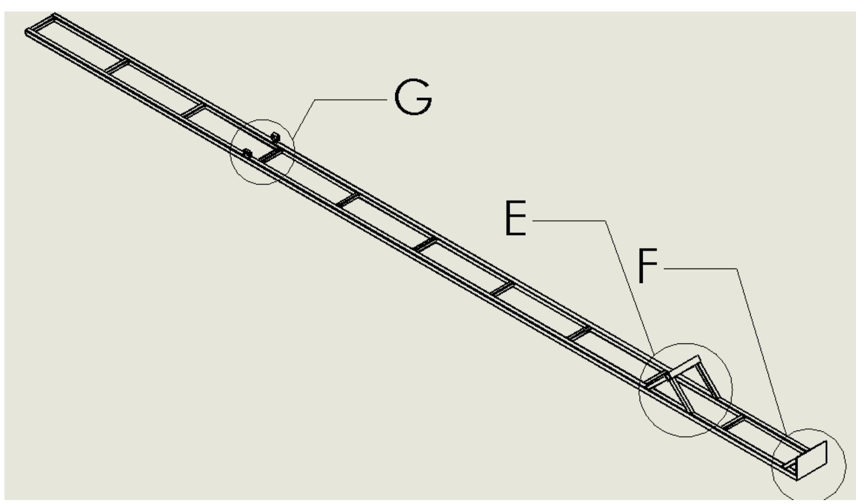

Fig. 16-Isometric view of the 3-d model of the pipe support.

The pipe support consists of two 30 ft long square steel tubes with a 2x2x3/16" section. The two 30ft steel tubes are connected with 10" long square steel tubes that have a 1.5x1.5x3/16” section as shown in the figure above. Circles A, C and E show the pivot link where the pipe support connects to the base through a cylindrical pin. **Fig. 17** shows a blow out of these circles.

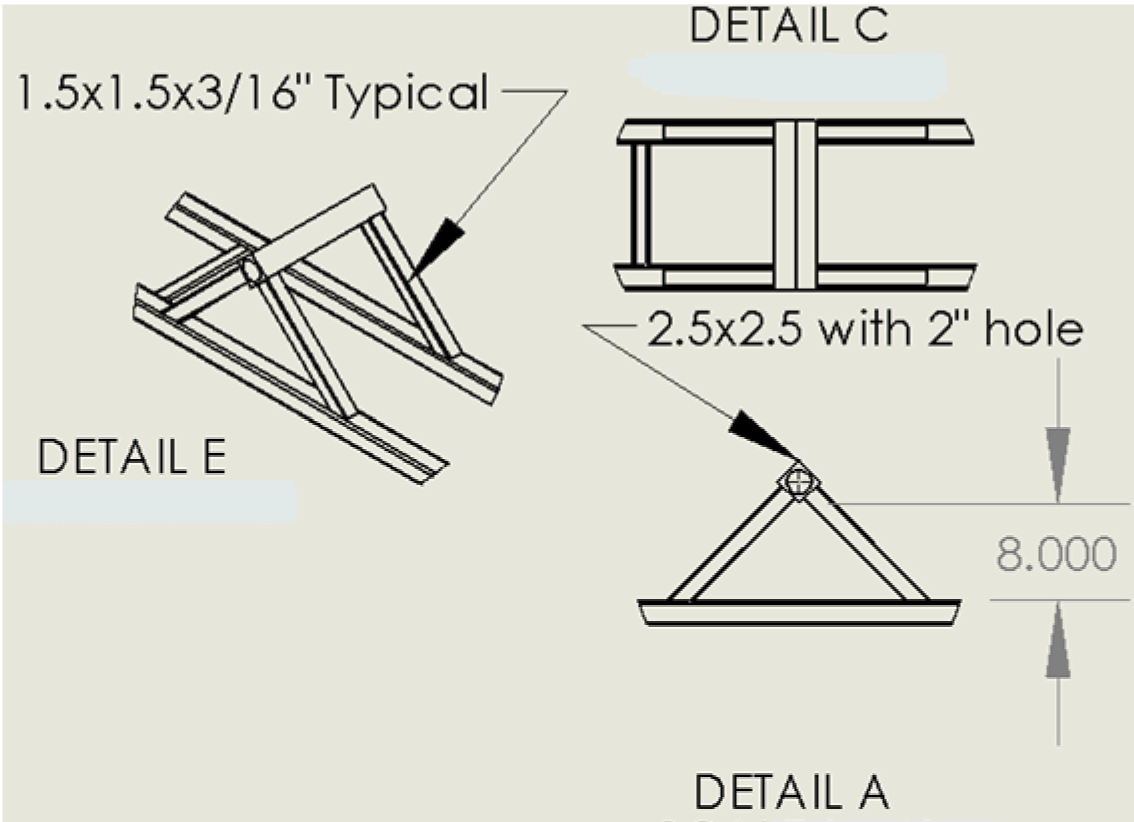

Fig. 17-Detail of the pivot on the pipe support.

The pivot consists of a 2.5x2.5” square steel tube with a 2” hole. It is positioned at 8 inches above the pipe support so the maximum pipe size of 7 inches can be inserted easily. This steel tube is connected to the pipe support through four 1.5x1.5x3/16” square steel tubes at an angle of 45 deg. A 2” cylindrical pin would be inserted into the 2” hole shown in the figure, to connect it to the base while allowing the pipe support to rotate around it. The 2” hole is above the pipe support to help prevent the pipe support from tumbling over. This will become clearer when we discuss the assembly. Circles B, D and F highlight a steel plate at the end of the pipe support to prevent it from falling when it is in vertical position. The steel plate is 14x9x0.25”. The steel plate is welded to the bottom of the two 2x2x3/16” square steel tubes. It is further supported by two 1.5x1.5x3/16” square steel tubes that connect the far end of the plate to the pipe support. **Fig. 18** shows a blow out of these circles.

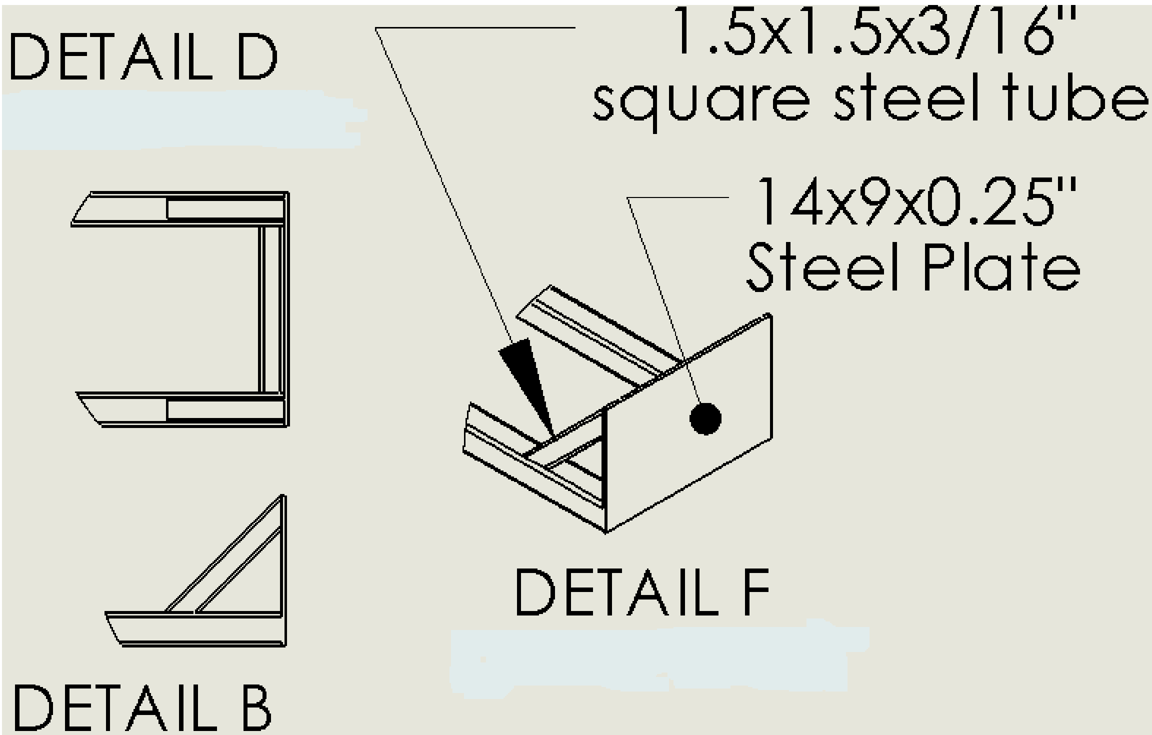

Fig. 18-Detail of the bottom steel plate.

The last detail in the pipe support is shown by circle G which is blown up by **Fig. 19**.

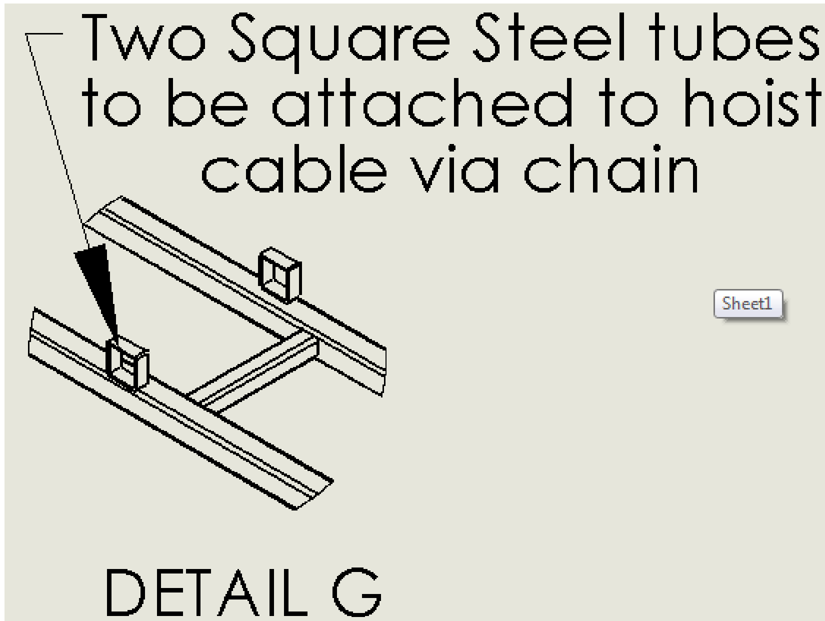

Fig. 19-Detail of the hoist cable attachment to the pipe support.

The two square steel tubes are to be attached to a chain that is attached in turn to the cable of the hoist to lift and lower the pipe support.

Total Volume of Pipe support = 1221 in^3 Total Weight = 353 lbs

5.2.2 Base

The base's function is two provide support to the pipe support and provide a pivot point for the pipe support to be able to rotate about. **Fig. 20** shows the model for the base.

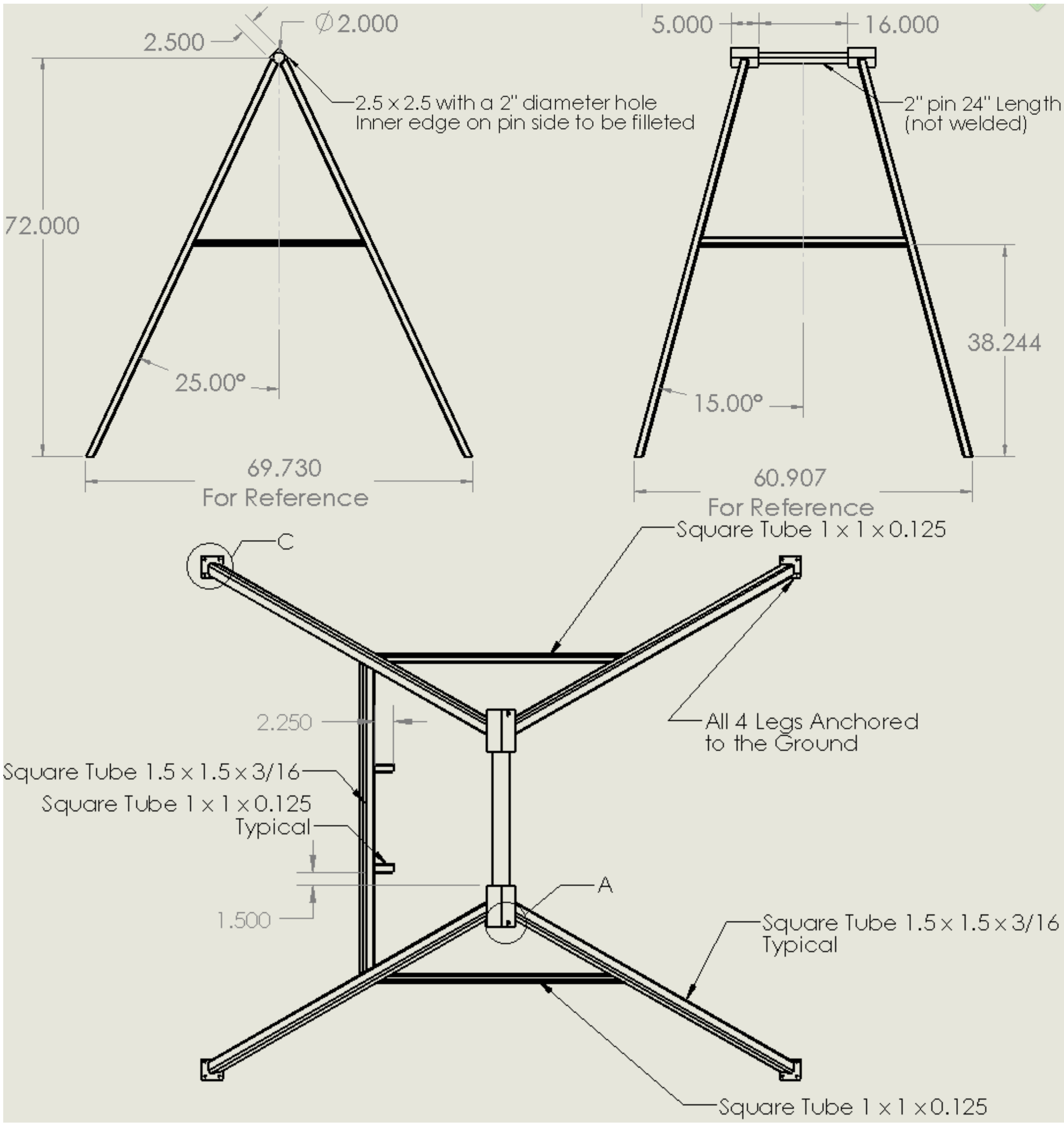

Fig. 20-2d representation of the 3-d model of the base.

The base consists of four legs anchored to the ground. Each leg consists of a 1.5x1.5x3/16" square steel tube. The legs diverge at an angle outward to increase the base area. This increases stability and helps prevent the structure from tumbling over. Each two legs connect to a 2.5x2.5" square steel tube with a 2" hole. The 2" hole holds the 2" cylindrical pin that connects it to the pipe support. The 2" hole goes all the way through to help assembly, so the cylindrical pin can be pushed from one end and pulled from the other. To prevent the cylindrical pin from moving out during operation two small bolts fit into two holes at the end of the 2.5x2.5" square steel tube. This is shown in circle A in **Fig. 20** and blown up in **Fig. 21** below.

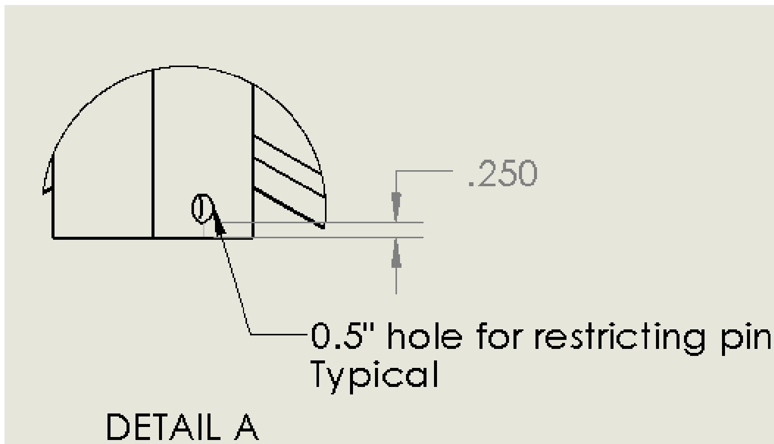

Fig. 21-Detail of the hole for the restricting pin.

The four legs are strengthened by three square steel tubes at the middle, two from the side with a section of 1x1x0.125" and one from the back with a section of 1.5x1.5x3/16". The one at the back has an additional function other than strengthening the base, which is to prevent the pipe support from tumbling after it reaches vertical position. It is equipped with two stops that bump into the 2 main 2x2x3/16" steel tubes of the pipe support, if it travels beyond the vertical position. The two stops are a 1x1x0.125" square steel tube. Each of the four legs of the base have a small steel plate with three holes as shown by circle C in **Fig. 20** and blown up in **Fig. 22**. This is to help anchor the base to the ground via steel bolts.

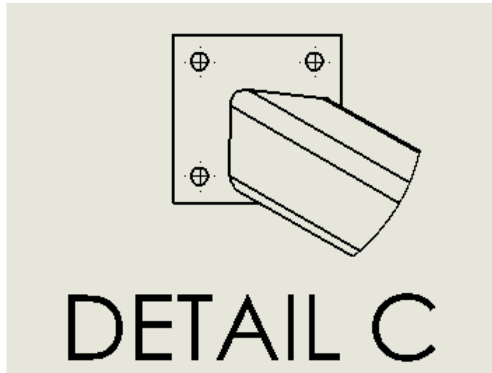

Fig. 22-Detail of how the base is anchored to the ground.

Total Volume of Base = 464 in^3 Total Weight = 132.5 lbs

5.2.3 Assembly

Figs. 23 and **24** below show the pipe support and the base assembled together.

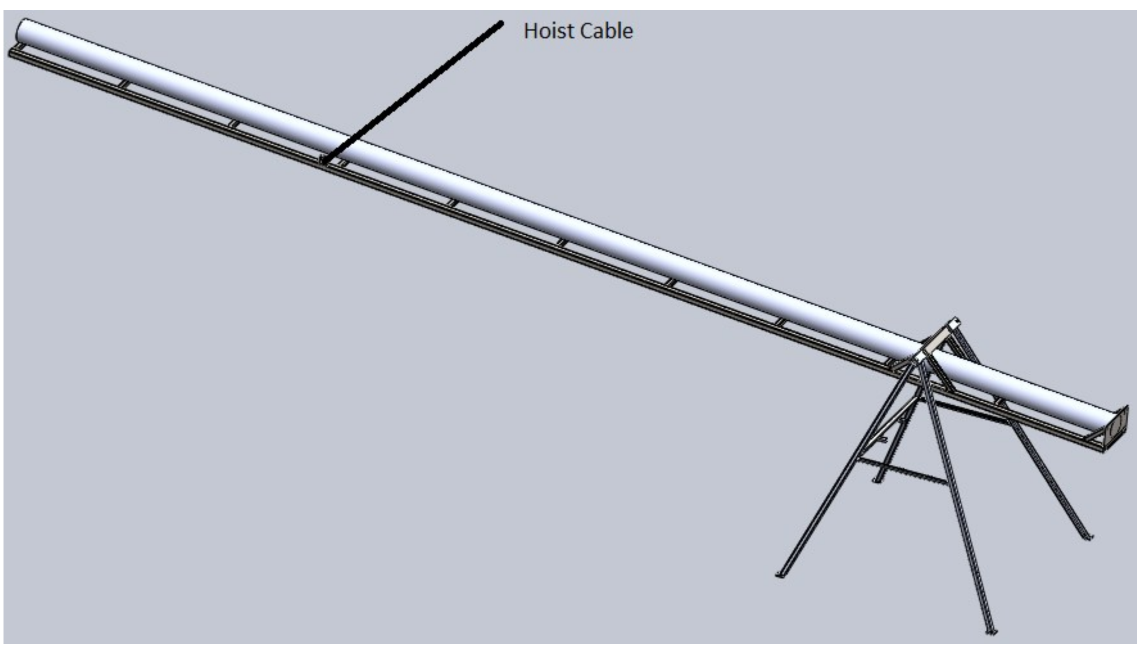

Fig. 23-3d model of the assembly.

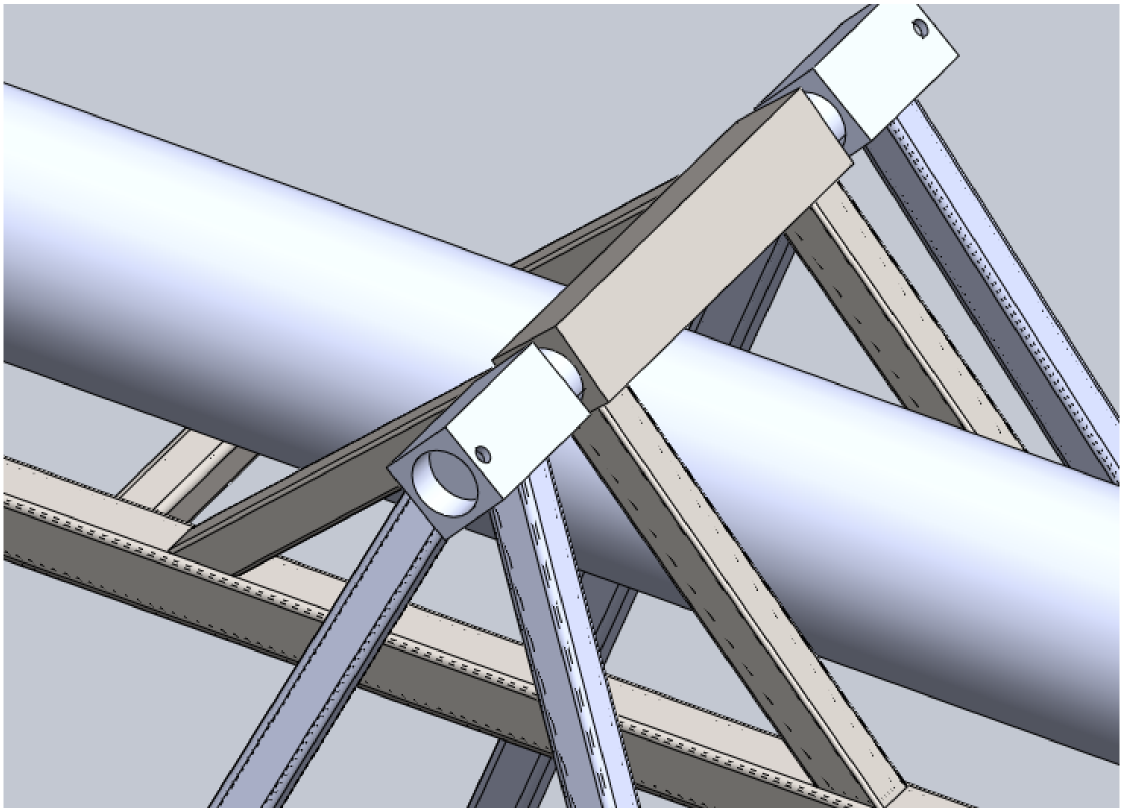

Fig. 24-The connection between the pipe support and the base.

The figure shows the base anchored to the ground, and a 2" pin connecting the pipe support to the base and a hoist cable pulling the pipe support and causing it to rotate around the pin connecting it to the base. **Fig. 24** shows a zoom in on the pin connecting the pipe support to the base.

Assembly is simply done by placing the pipe support's 2" hole concentrically with the base's 2" hole and pushing the pin inside. Then finally adding the two restricting bolts to restrict the pin from coming out. Disassembly is done by pushing the pin from one side and pulling it out from the other.

Since the hoist's cable can only pull the pipe support but cannot push it down, it must be made sure that the pipe support's weight always provides a torque in a direction opposite to that of the cable so it can lower itself in the right direction when the cable is slack. This is illustrated in **Fig. 25** below.

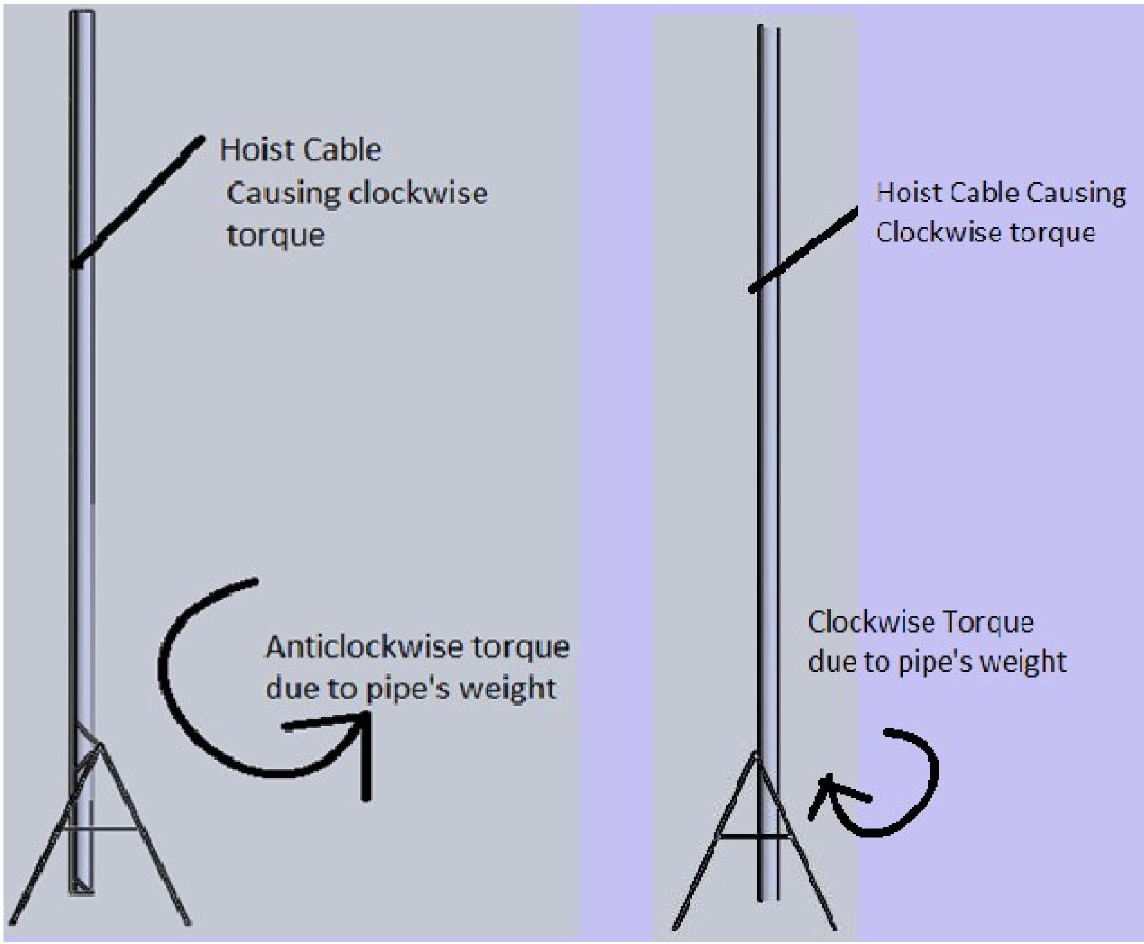

Fig. 25-Assembly is designed to prevent the pipe support from tumbling over.

The figure above shows two cases. The one on the left shows the pivot point above the pipe support similar to the actual design. The one on the right shows the pivot point below the pipe support. For the case on the left the weights of the pipe support and the pipe are causing a torque in an anticlockwise direction which prevents the pipe from tumbling over and also causes the pipe support to return to its original position when the cable is slacked. For the case on the right, the weight is causing a clockwise torque which will cause the pipe to tumble over. Even if there are stops to prevent this, the pipe support will not be lowered if the cable is slacked. The second feature that is clearer in assembly is the stops. The base has two stops to prevent the pipe from tumbling after reaching vertical position. **Fig. 26** shows the stops in action.

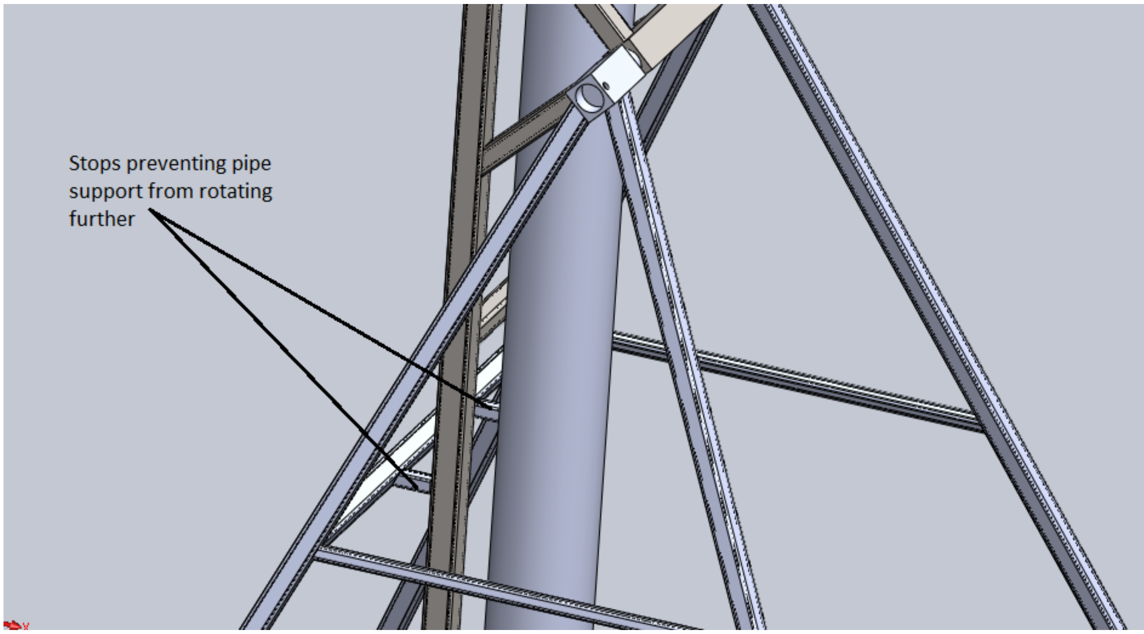

Fig. 26-The stops of the base in action.

In addition to the stops a limit switch should be added to stop the hoist from pulling further once vertical position has been reached. If hoist is still pulling while the pipe support is resting on the stop, the resulting bending moment will be too great for the pipe support members causing it to break. The limit switch should be designed in a way to prevent the hoist from pulling further at this position but still allow it to slack the cable and lower the pipe support.

5.2.4 Finite Element Analysis (FEA)

Although rough hand calculations were implemented a finite element analysis was necessary to make sure that the pipe support and the base are not over designed and more importantly not under designed. The finite element analysis was performed using Ansys. The three dimensional model was imported from Solidworks as an assembly into Ansys. The pipe support was tested in two different static positions, horizontal and vertical. These two positions represent two extremes. When in horizontal position the bending moment is maximized on the pipe support. When in vertical position the force is maximized on the steel plate at the end of the pipe support. In vertical position the force is also maximum on the pin and on the base since at this position the hoist is almost carrying no load and all the weight is on the pin and the base. Any angle between these two extremes would have a stress either less on the pipe support members or less on the steel plate and pin.

The first step in the analysis is to import the geometry of the assembly from Solidworks either in horizontal position or in vertical position. Next, contact between parts of the assembly must be specified like for example between the pin and the base and the pin and the pipe support. Then the next step is to define the mesh which is the process of dividing the parts into small elements. Ansys has a very powerful meshing tool. A tetrahedral element is used to divide the parts into the elements for the analysis. Generally, the smaller the mesh size (element size) the more accurate the results are. The drawback to that is that it would require more computation time and more computer RAM. Time was not an issue so elements were made as small as the computer RAM could handle. For the computer used the smallest element size that could be handled was 0.5 in. **Fig. 27** shows part of the pipe support with the meshed elements. **Fig. 28** shows a closer look on one of the members of the pipe support.

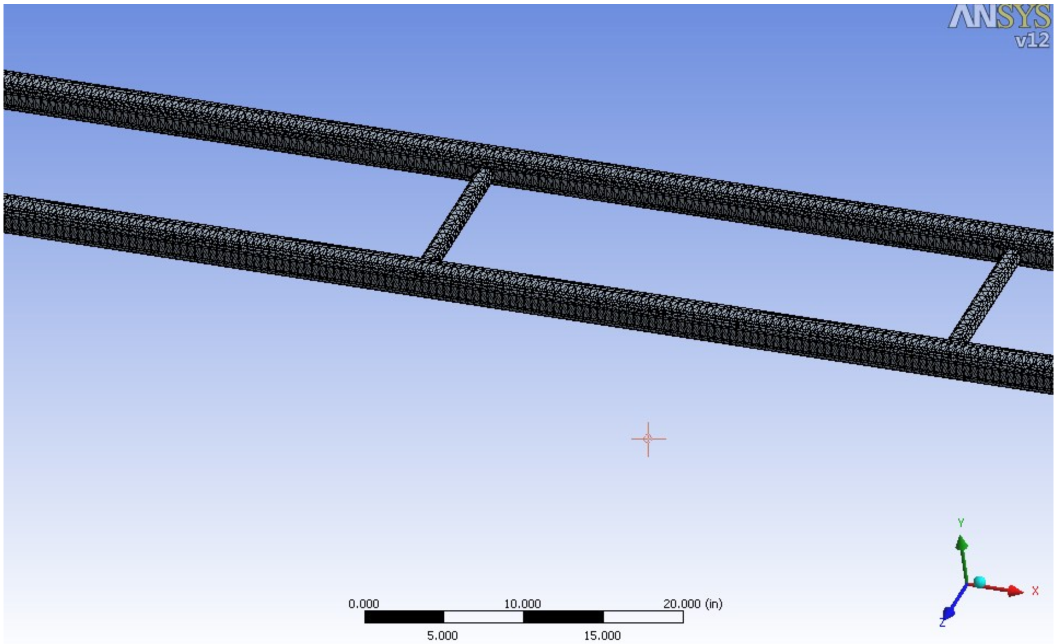

Fig. 27-The mesh for the FEA analysis.

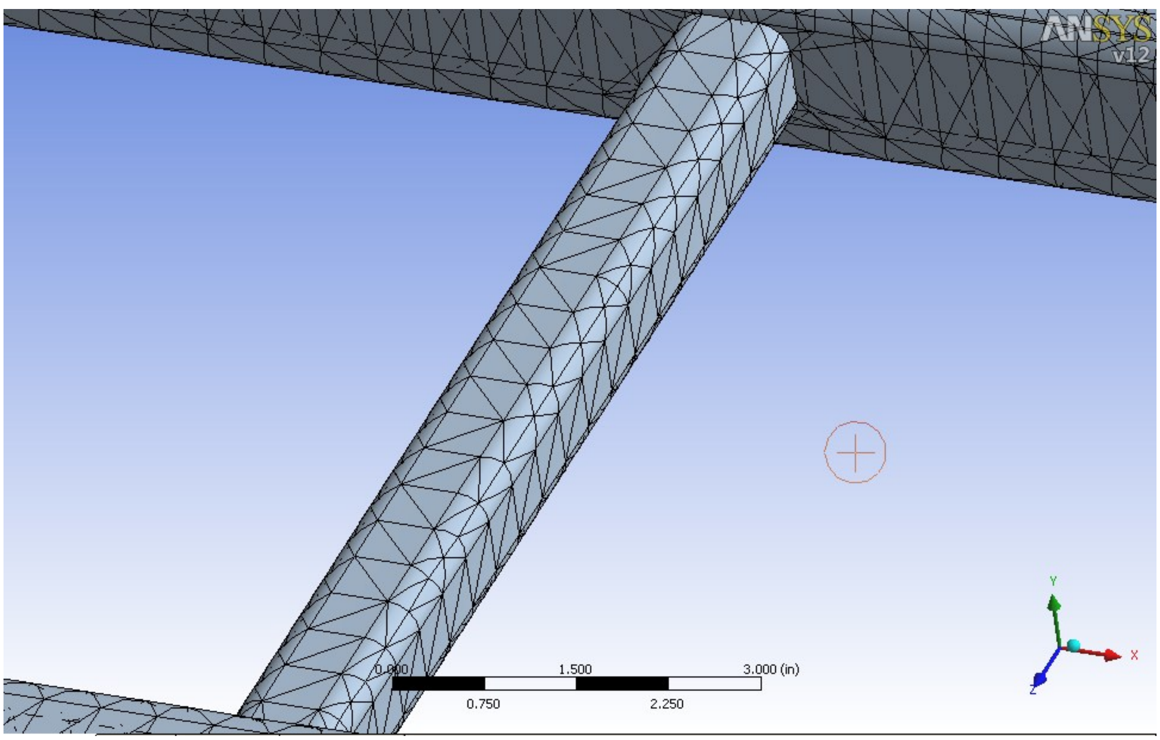

Fig. 28-Closer look on the mesh.

The element size was thought to be sufficient for this application. The next step was to define the forces and the boundary conditions. The forces that are exerted on the structure come from two sources. One is the weight of the pipe and the fluid inside of the pipe on the pipe support and the second source is the weight of the pipe support and the base on themselves. The latter is easily defined on Ansys by specifying a density for the pipe support, the base and the pin then specifying earth gravity in the desired direction. The weight of the pipe and the fluid were defined differently in the horizontal and vertical positions. For the horizontal position the pipe weight was distributed on a small area in the middle of 10” square steel tubes connecting the two 30 ft square steel tubes of the pipe support. A small area was chosen rather than a point load because there will be small rubber pads between the pipe and the pipe support. These pads will distribute the force exerted on them over a small area on the pipe support rather than a point load or a line. The small area was chosen to be 0.5 in^2 in the middle of each of the 10” square steel tubes. There are eleven 10” square steel tubes as shown in **Fig. 29** below.

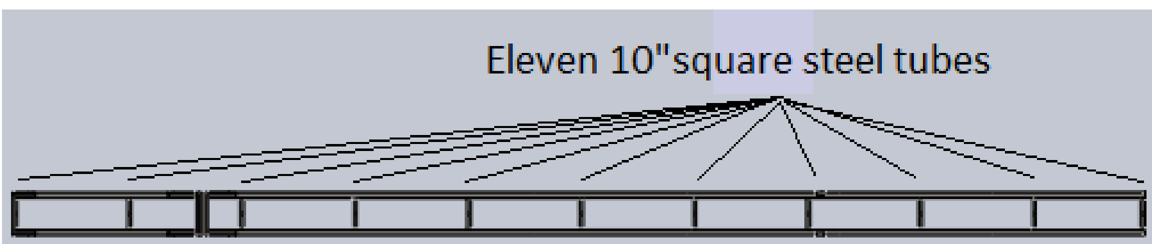

Fig. 29-Pipe support has 11, 10” long square tubes.

Fig. 30 shows a close up to illustrate the small area on the 10” square steel tubes that the force was distributed on.

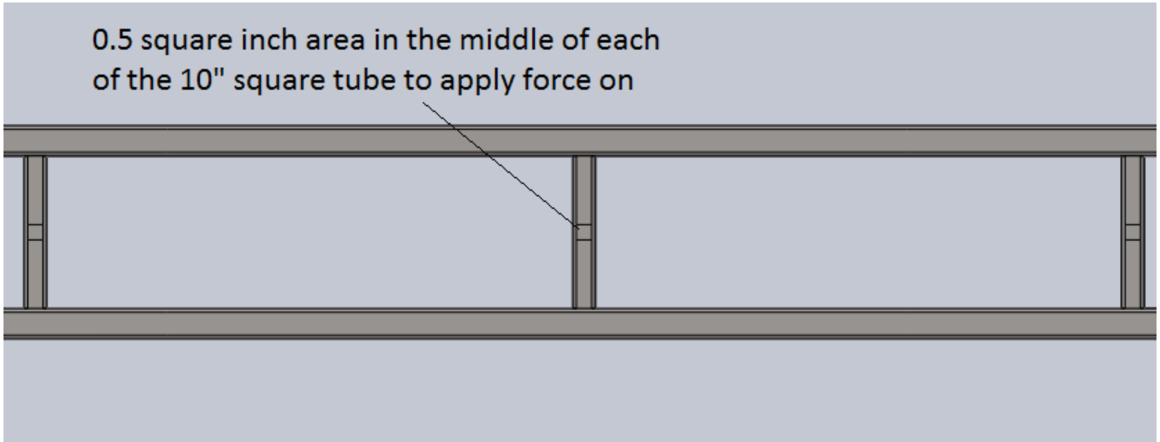

Fig. 30-The area where the pipe is resting on the pipe support.

The force of the pipe with the fluid in it was calculated in the detailed design section of this thesis and was concluded to be 1056 lbs. Now the first and last 10” square steel tube will logically be carrying half the load of the remaining 10” square steel tubes. So then effectively each of the 10” square steel tubes will be carrying 10% of the total weight except the first and the last ones will be carrying 5% of the total load each. Since the force will be distributed on an area then it should be defined as a pressure where the pressure equals the force divided by the area. Since the area is 0.5 in^2 then each 10” square steel tube will have a pressure of

Pressure = 1056 x 10% / 0.5 = 211.2 psi

For the first and the last square steel tubes pressure is = 105.6 psi

The force in the vertical position was applied on the bottom steel plate. An area on the plate that is equal to the pipe base area was defined and the total force of 1056 lbs described earlier was distributed on that area. The pipe has a 7” diameter giving an area of 38.48 in^2. Then the pressure that needs to be applied on that area would be the total force of 1056 lbs divided by the area, giving a pressure of 27.44 psi. This model is actually more extreme than the actual case since the pipe will be tied to the pipe support with tow straps at horizontal. When the pipe is raised into vertical position some of the vertical force will be carried by the tow straps through friction so not all of the vertical force will be on the plate. However, modeling it that way would give us a safer estimate in case the straps were not tightened hard enough.

The next step after the forces are defined is to define restraints on the structure. In both the vertical and horizontal cases a full restraint was applied on the bottom of each leg of the base as they are anchored to the ground. The second restraint was added on the knob where the hoist cable would pull the pipe support.

After defining everything previously mentioned the model will be complete and ready to solve. **Fig. 31** shows the stress distribution on the structure when the pipe support is in the horizontal position. As per the analysis the maximum stress is 20,652 psi depicted by the red color. This occurs at the position where the hoist pulls the pipe support. This agrees with **Figs. 12** through **14** where it was calculated that this point has the maximum shear force and the highest bending moment. **Fig. 32** shows the safety factor distribution on the structure in the same position.

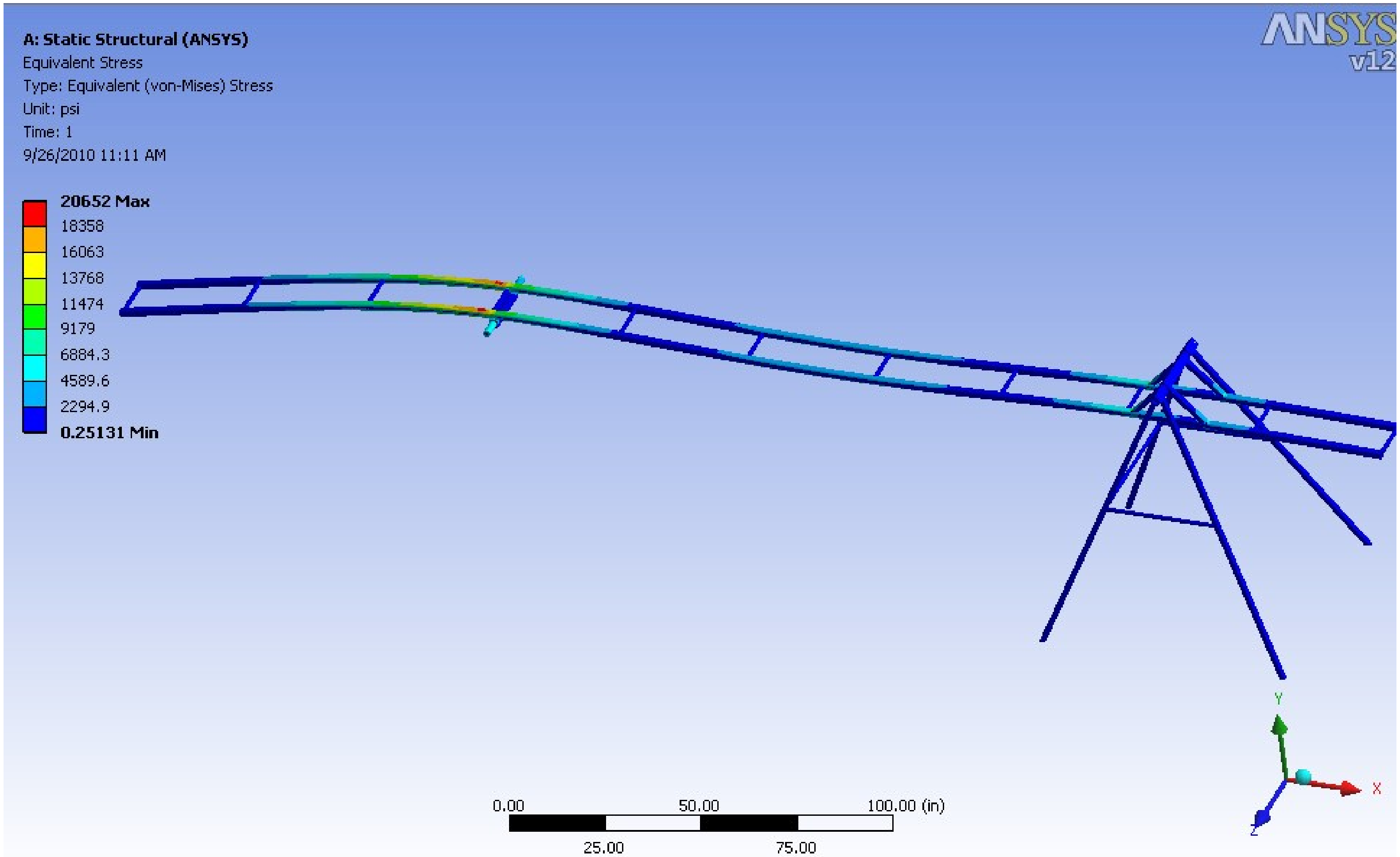

Fig. 31-Equivalent Von-Mises stress on the assembly in horizontal position.

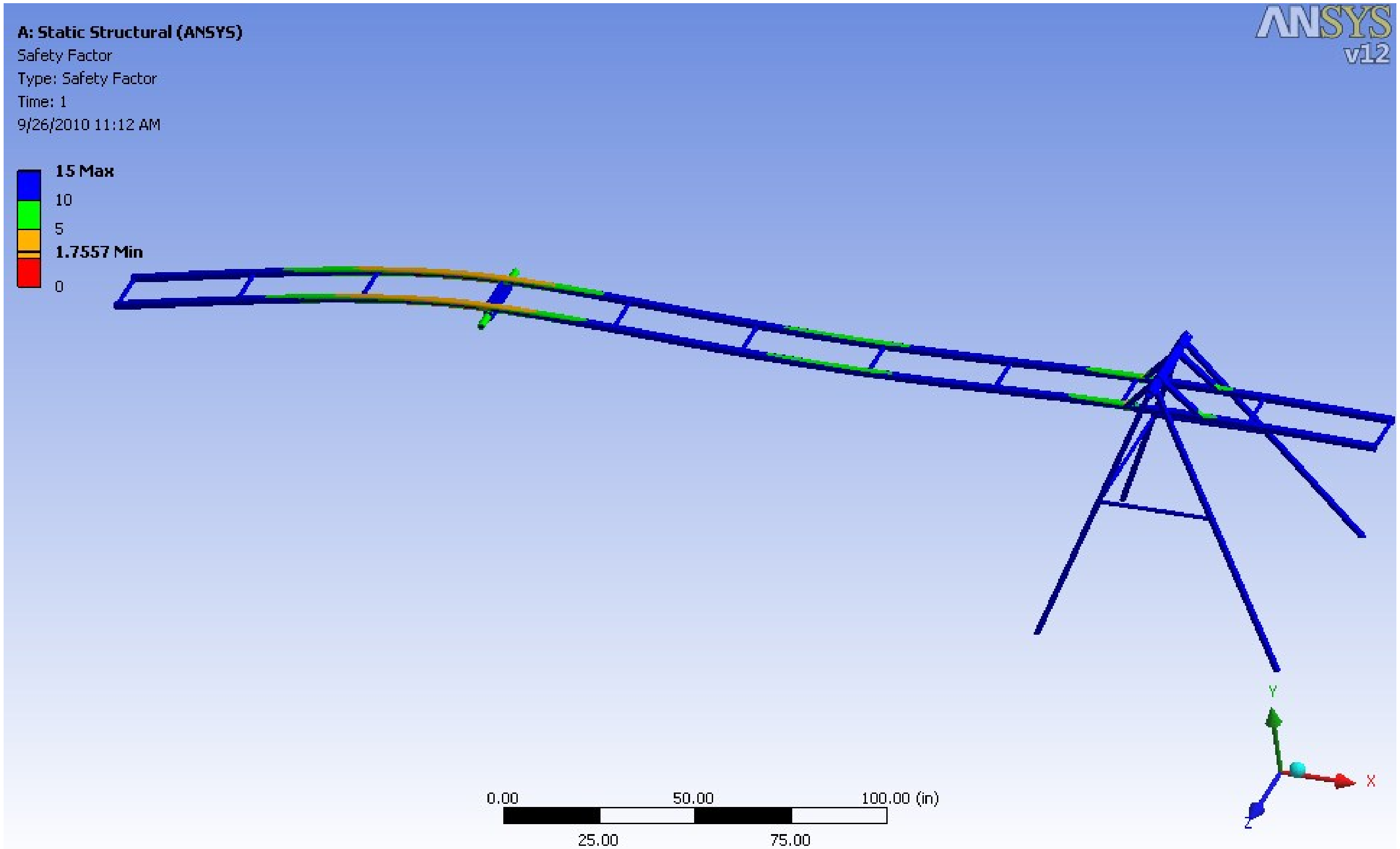

Fig. 32-Safety factor distribution on the assembly in horizontal position.

The minimum safety factor as per **Fig. 32** is 1.756 assuming that the steel's yield strength is 36,000 psi which is the strength of the weakest steel grade. This means that the maximum stress would be about 57% of the yield strength which gives evidence that the design is safe and sound in that position. **Fig. 33** shows the stress distribution in the vertical position.

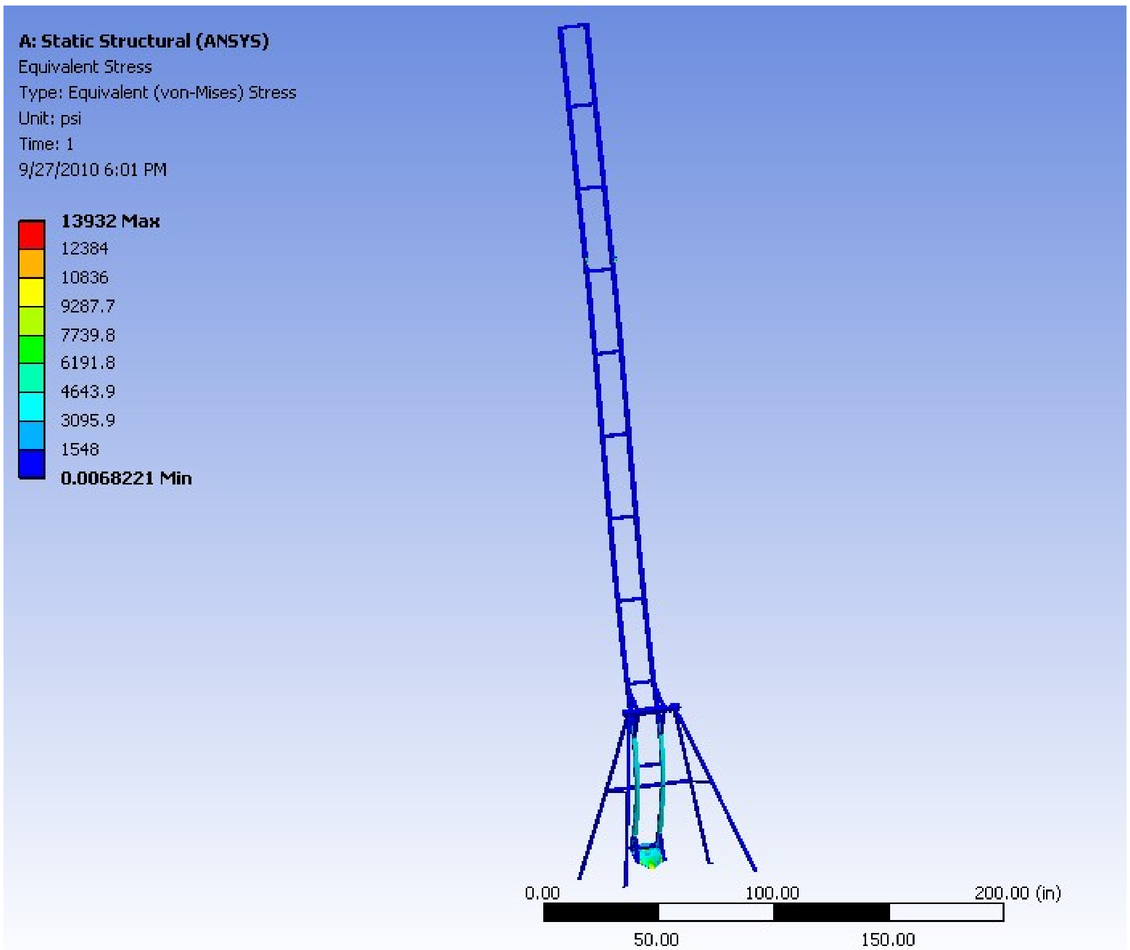

Fig. 33-Equivalent Von-Mises stress on the assembly in vertical position 1.

In the figure it can be seen that the maximum stress is 13,932 psi. It can also be seen from the figure that the most stressed area is the plate and the pipe support between the plate and the pivot. This is because this area sees a large bending moment. The area on top of the pivot only sees a small compressive stress due to the weight of the pipe support on itself. As expected the stress is much smaller than in horizontal position because the bending moment is smaller because the distance between the force and the support is much smaller. However, it was important to run the analysis at vertical position to correctly size the bottom steel plate and check if the 2" pin is strong enough. If the plate was of lesser thickness than 0.25 in the plate would have yielded. **Fig. 34** shows a zoom in on the steel plate from the front and **Fig. 35** shows the steel plate from the back to show where the maximum stress occurs. **Figs. 36** through **38** show the safety factor distribution for **Figs. 33** through **35** respectively.

As can be seen from all the previous figures the entire structure is safe and the minimum safety factor is 1.756. This occurs at the maximum design load when the pipe support is in the horizontal position. Static analysis was considered to be sufficient because the travel speed of the pipe support is very low and therefore excess stresses resulting from the movement of the pipe support could be ignored. At this step the design was deemed safe and implementation was carried out without need for further modifications.

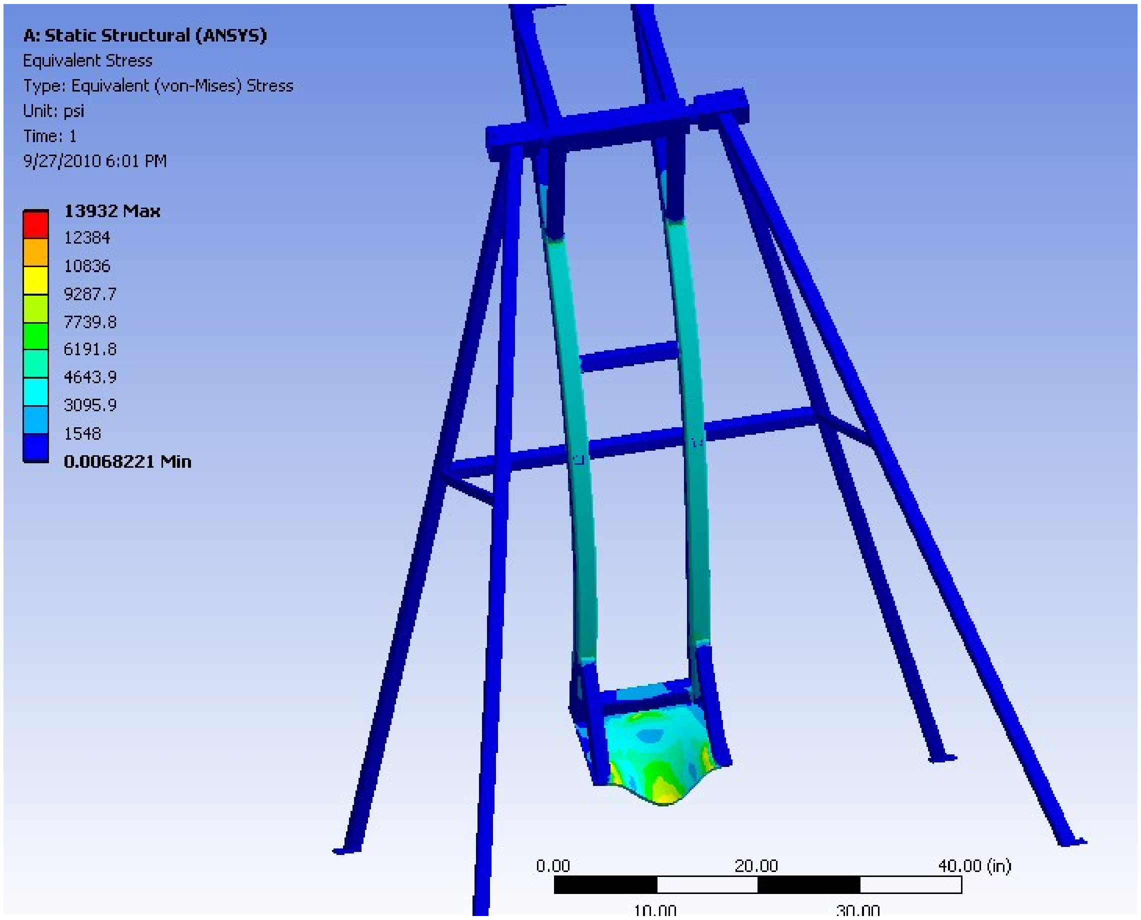

Fig. 34-Equivalent Von-Mises stress on the assembly in vertical position 2.

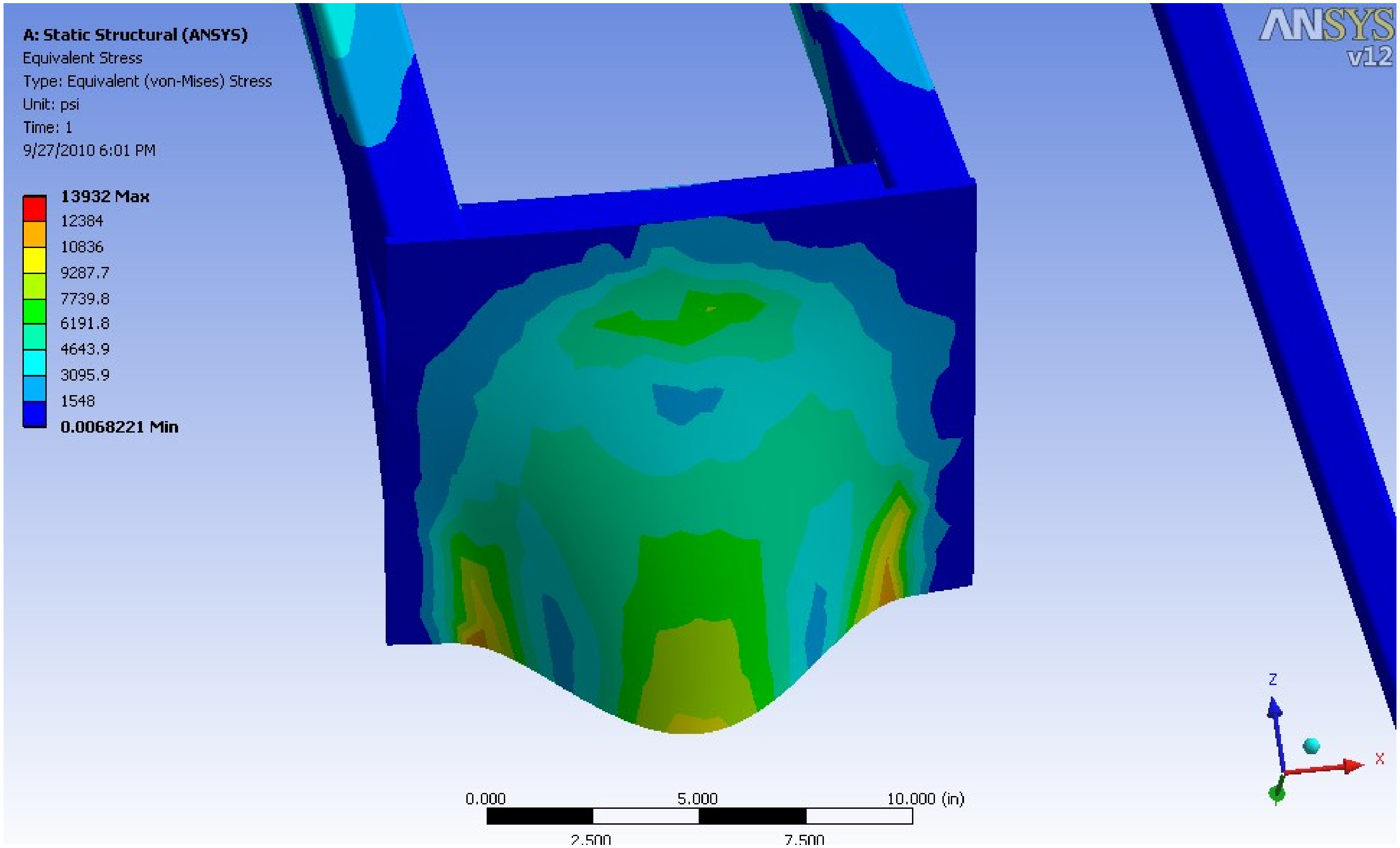

Fig. 35-Equivalent Von-Mises stress on the assembly in vertical position 3.

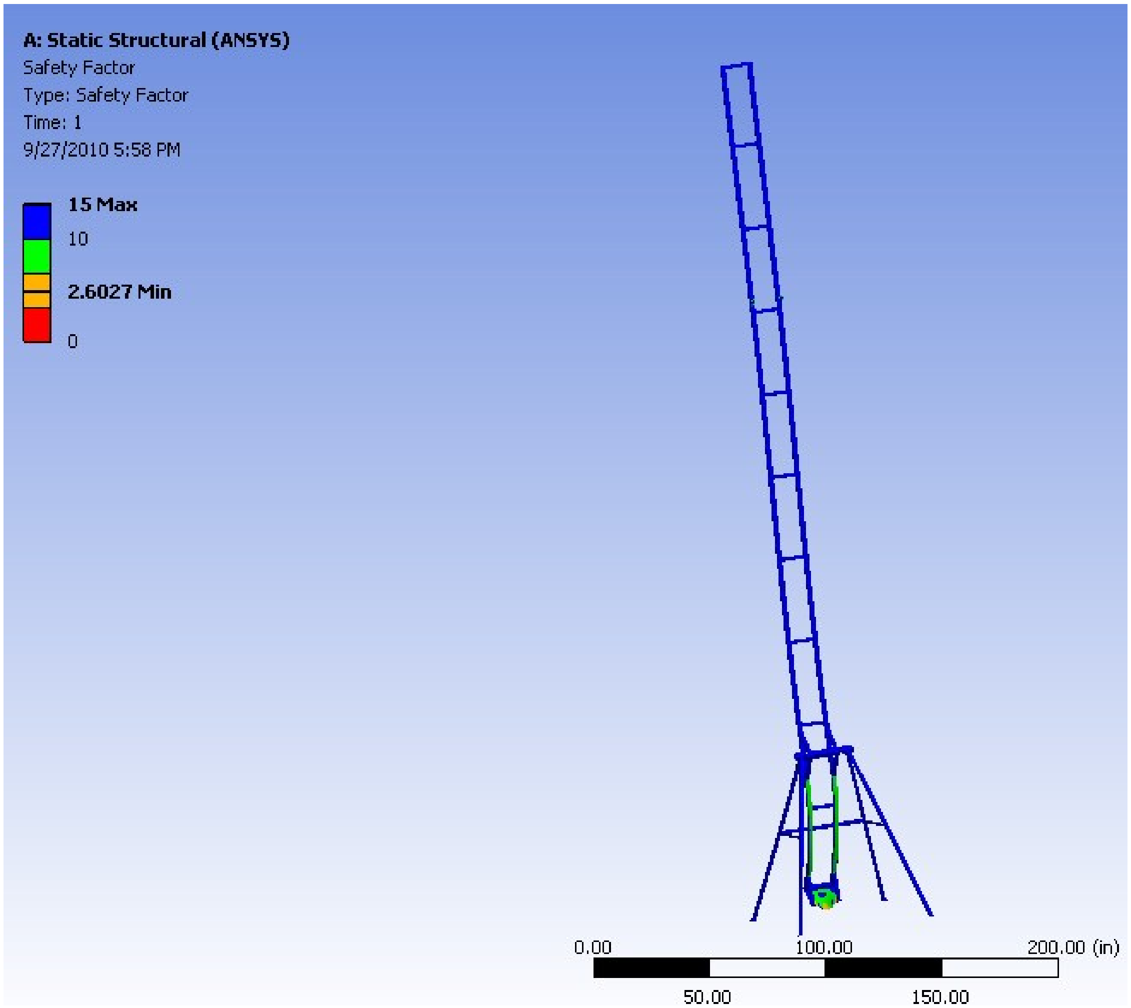

Fig. 36-Safety factor distribution on the assembly in vertical position 1.

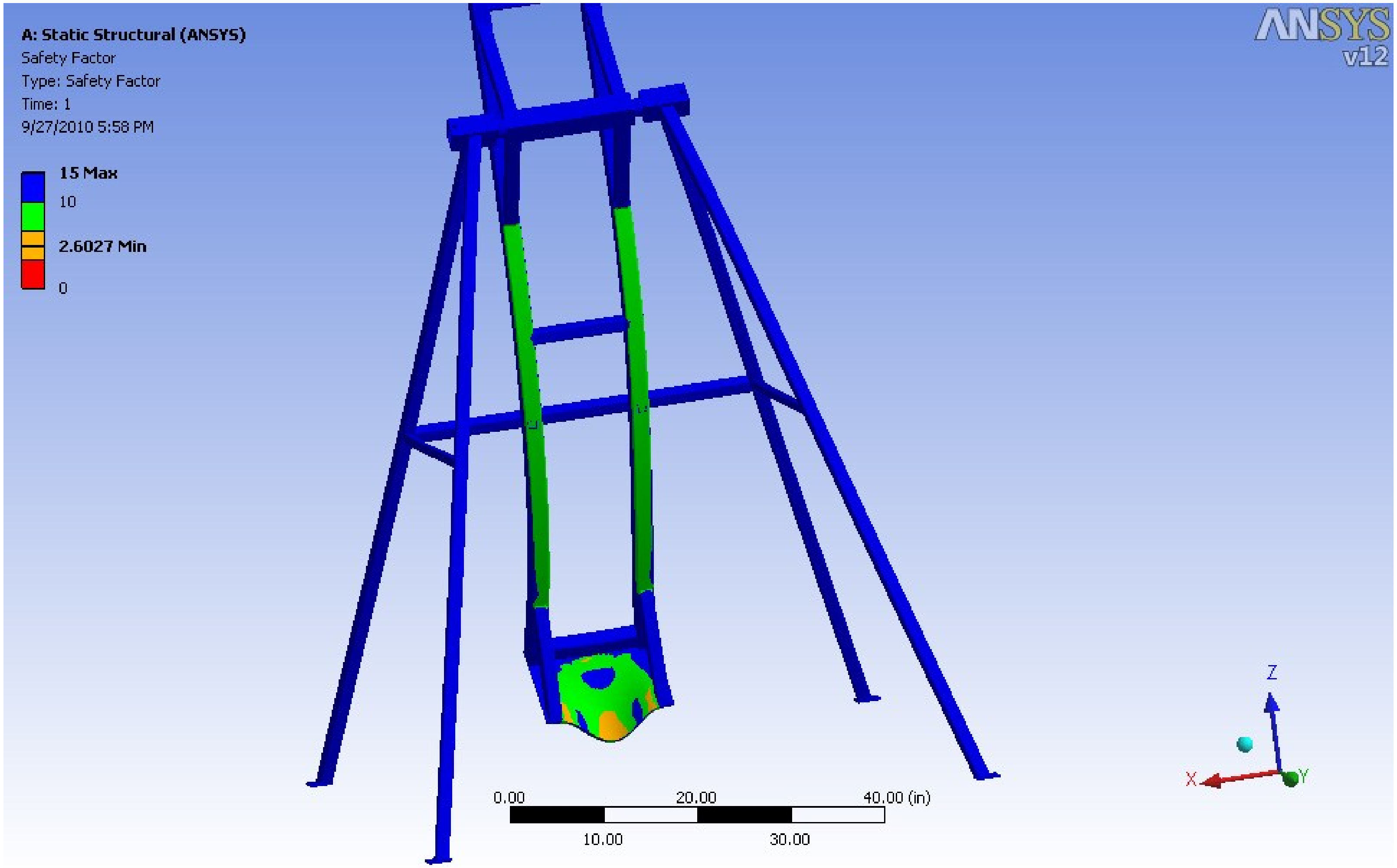

Fig. 37- Safety factor distribution on the assembly in vertical position 2.

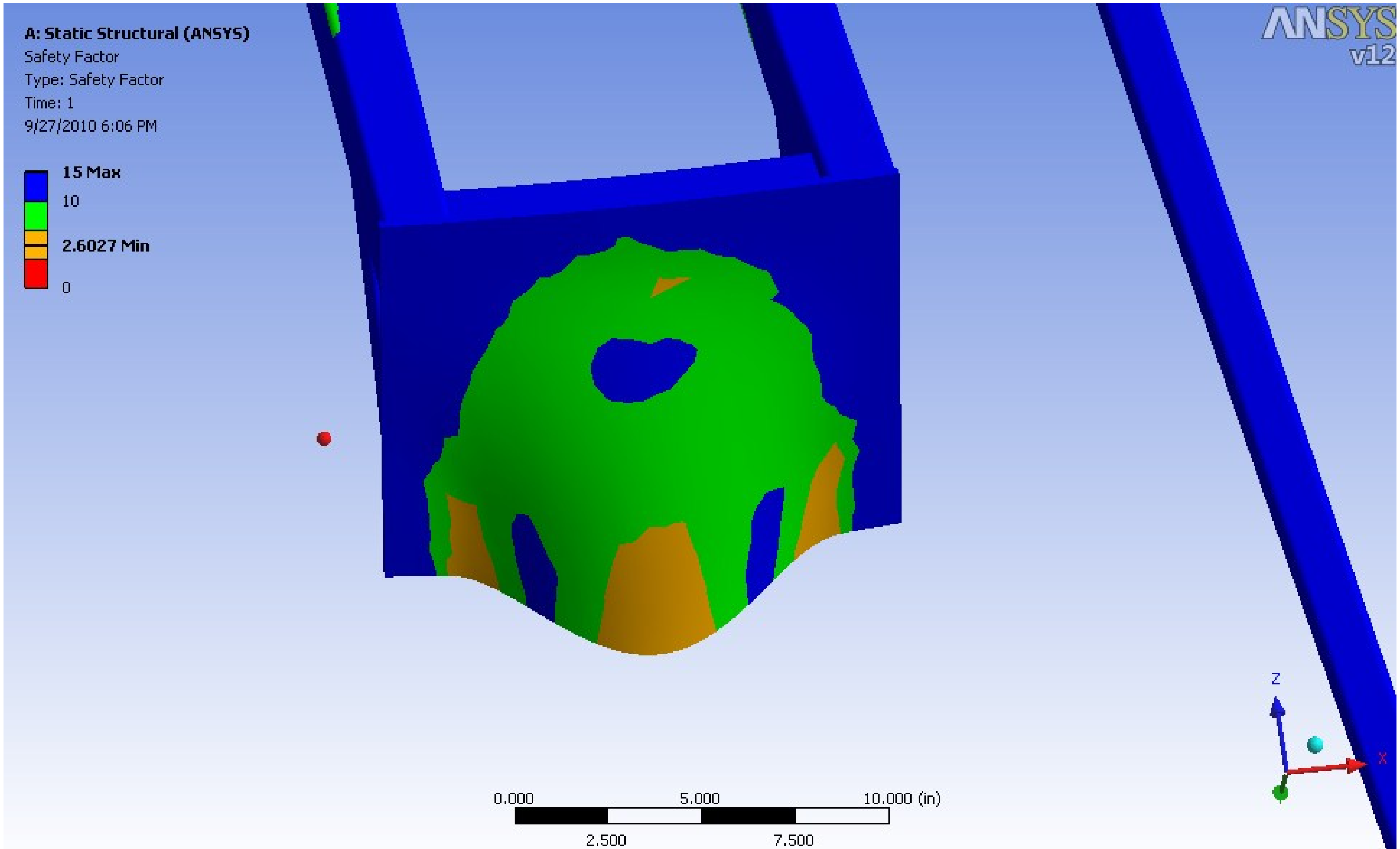

Fig. 38- Safety factor distribution on the assembly in vertical position 3.

5.3 Implementation

5.3.1 Pipe Support Assembly

As discussed before the experimental setup was to be installed in the University Services Building (aka TI Building). The building is a huge warehouse with each department owning a plot inside. The petroleum department owns a plot about 75 ft x 50 ft. This building was chosen because its ceiling just above 30 ft high. The building also has an exposed steel structure that is ideal to mount our hoist and pulleys. The building has vertical I-beams 50 ft apart in a square distribution. Resting on top of these I-beams are horizontal I-beams connecting the vertical I-beams in one direction. In the other direction the horizontal I-beams are connected to one another through small joists as Shown in **Fig. 39**.

Fig. 39-The steel structure of the University Services Building.

A certified structural engineer from the university's physical plant, conducted an analysis on the building's structure to make sure the building can withstand the load from the experimental setup. He was provided with the expected loads from the experimental setup. His conclusion and instruction was that the only safe place to mount the hoist and pulleys are very close to the vertical I-beam and that the small joists should not bear any load. This turned to be convenient because the hoist's remote controller is attached to the hoist through a cable that is only 5 ft long and therefore the hoist needs to be at low level so that the remote controller can be reached. The final setup that was decided to be implemented is schematically shown in **Fig. 41**. As previously discussed the hoist that was available to us had a capacity of only 650 lbs and the maximum expected tension in the cable was approximately 1250 lbs. So for the hoist to work we needed to have a double line setup. This is shown in **Fig. 41**. The cable goes from the hoist to a pulley (snatch block) attached to the horizontal beam at the ceiling then to another pulley attached to the pipe support then attached back to the horizontal beam. This means that even though the tension in the cable cannot exceed 650 lbs the setup can carry loads up to 1300 lbs. There are two other advantages with this double line setup. The first is that the speed of the pipe support will be half of the speed of the cable. This is very important advantage because it reduces dynamic loading and enhances control of the positioning of the pipe support. The second advantage is that this setup will decrease the load on the building. **Fig. 40** illustrates this.

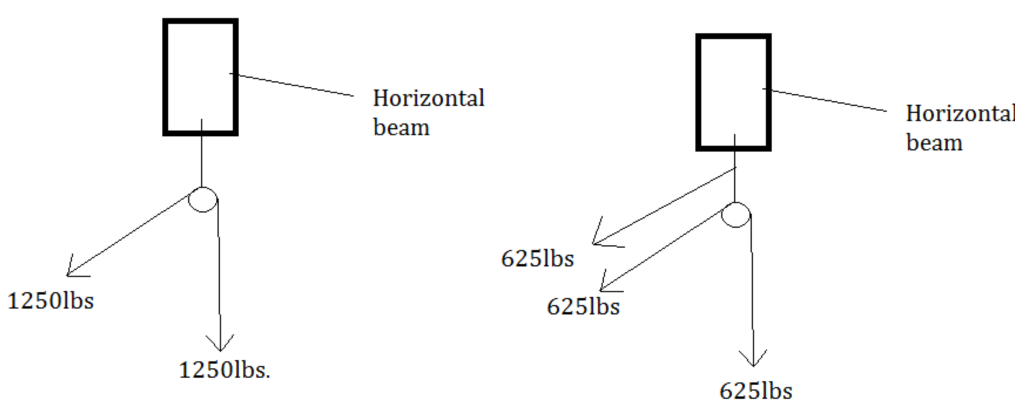

Fig. 40-Forces acting on the beam for single and double line setup.

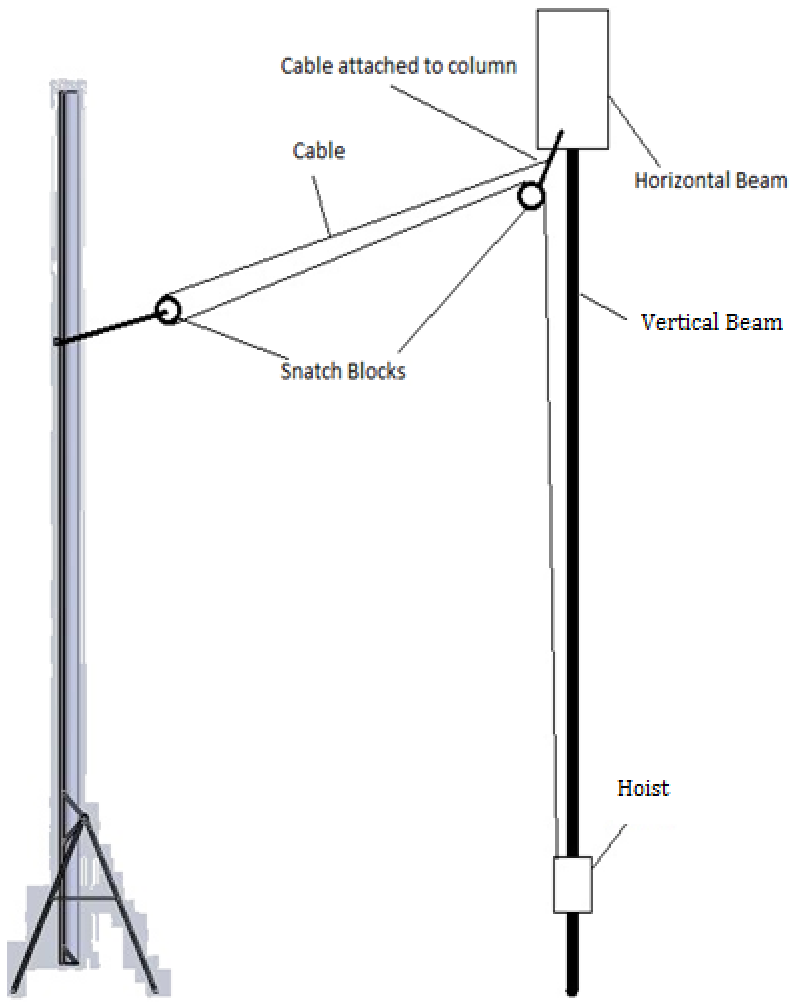

Fig. 41-Schematic of the double line setup.

After the analysis of the building was finished, 2d working drawings of the pipe support and the base were sent to a steel fabrication shop to begin the construction.

The hoist had a 50 ft cable which was not long enough for the setup shown in the previous figure. In addition the cable had a kink in it and needed replacement anyway. A new 100ft cable was bought with the same dimensions as the original cable which is a 3/16" 7x19. (3/16" is the diameter of the cable and 7x19 means that there are 7 strands and each strand has 19 wires.) This cable had a strength of 840 lbs which gives almost a 30% safety factor of the maximum expected load of 650 lbs. A very important factor affecting the cable strength is the pulley. If the pulley is too small the cable carrying capacity and life will decrease. **Table 3** shows the effect of the pulley diameter on the cable strength.

TABLE 3-THE EFFECT OF THE PULLEY'S DIAMETER ON THE CABLE'S STRENGTH (Sava Industries Nov 2010)	
Ratio "A" = Pulley DIA./Cable DIA.	**Strength Efficiency Compared to Original Strength In %**
40	95
30	93
20	91
15	89
10	86
8	83
6	79
4	75
2	65
1	50

The absolute minimum ratio of the pulley diameter over the cable diameter for a 7x19 cable is 18:1 which means the minimum pulley diameter is 3.4". (The Down Engineering Nov 2010) Therefore, the pulley selected was 4". To attach the pulley and the cable end to the top horizontal beam, a beam clamp has been used of suitable capacity. This is illustrated in **Fig. 42**.

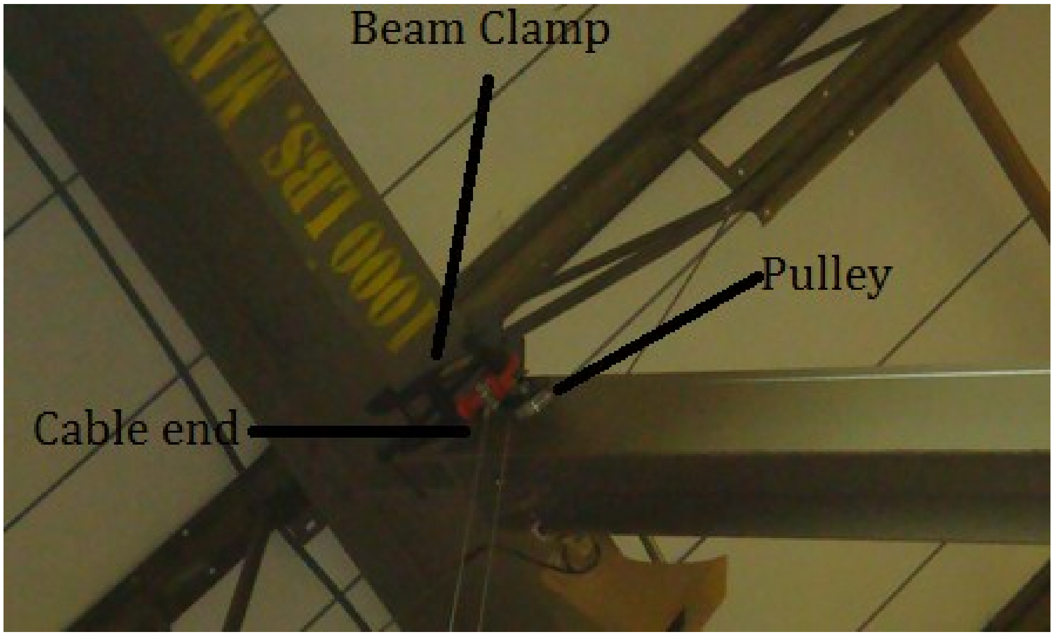

Fig. 42-The beam clamp and the first pulley.

To attach the hoist to the column a steel plate was welded to the column as per the instruction of the physical plant. They preferred to weld the plate rather than bolt it in the column. The plate has a seat for the hoist to be bolted on. **Fig. 43** illustrates this.

Fig. 43-The hoist.

Fig. 44 shows the pipe support with a pipe mounted on top. In the figure it can be seen that the design was closely implemented. The figure shows the base, pipe support, the bottom pulley attached to the pipe support via chain and at the far end there is another base. The second base is to carry the pipe support after the experiment is complete to relieve any load on the building. All steel parts were painted to minimize rusting. Tow straps were used to hold the pipe on the pipe support. Tow straps were compared with steel U-bolts to hold down the pipe but tow straps were preferred for several reasons. First they follow the shape of the pipe so the load would be distributed over an area for steel U bolts if the diameter of the pipe and the U bolt are not exactly equal the load will be applied on a single line rather than an area. Furthermore, the tow straps can accommodate any pipe size. Lastly, the straps will be softer on the plastic pipe where steel U bolts if they are tightened too much, might crack the plastic pipe. Tow straps have a 10,000 lbs strength capacity which is much more than what is needed

Fig. 44-The pipe support assembly.

Rubber pads were placed between the pipe support and the pipe for the same reasons described, to distribute the force over an area rather than a line and to be softer on the pipe. An additional function of the rubber pads is to prevent sliding of the pipe due to its high friction coefficient.

Fig. 45 shows the pipe support in vertical position.

Fig. 45-The pipe support assembly in vertical position.

As described before precautions were taken to prevent the pipe support from tumbling over. **Fig. 46** shows the stops and part of the limit switch system.

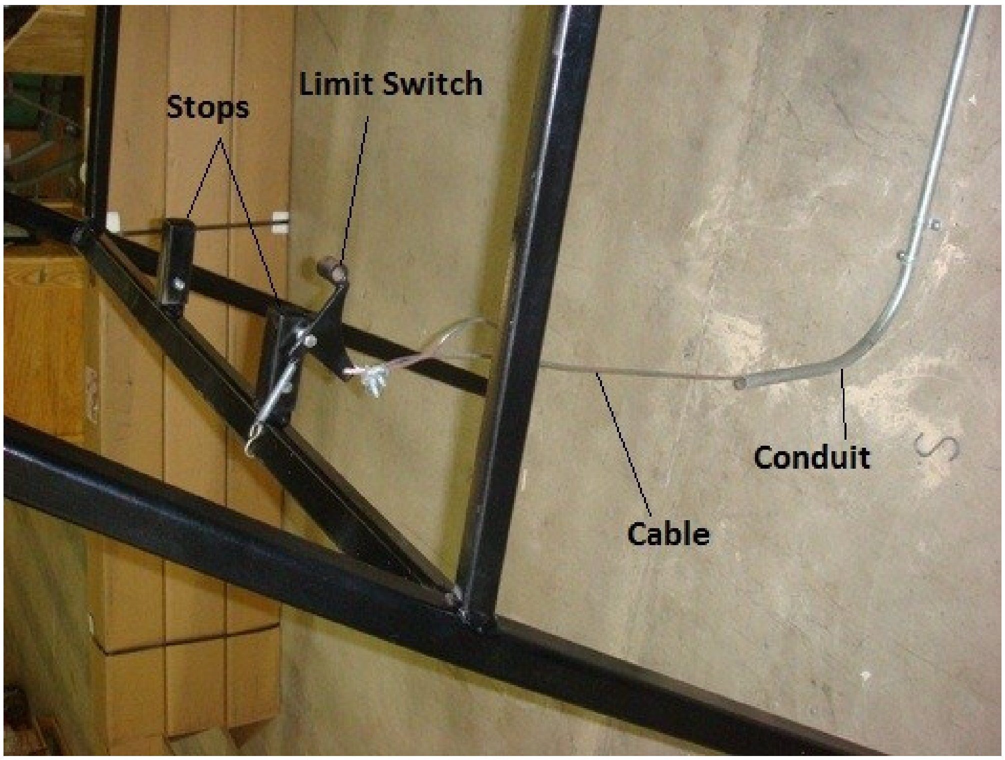

Fig. 46-The limit switch mechanism at base.

The stops prevent the pipe support from travelling too much and tumbling over. The limit switch, as seen in the figure, consists of a lever held forward with a spring and a cable attached to the lever at one end and the built-in limit switch in the hoist. **Figs. 47** and **48** show the built-in limit switch of the hoist and the cable attached to it. The conduit shown in the figures is to provide a guide for the cable and to anchor it to the ground to minimize trip hazards.

Fig. 47-Limit switch handle on hoist.

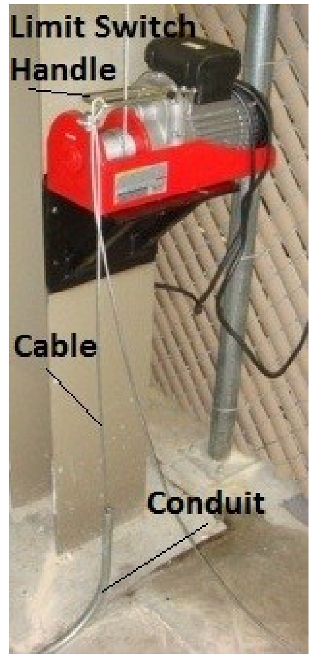

Fig. 48-Limit switch mechanism at hoist.

Basically, when the pipe support reaches vertical position it bumps into the lever and pushes it back. The lever in turn pulls the cable up and the cable in turn pulls the built-in limit switch handle of the hoist down preventing further pulling of the pipe support. **Fig. 49** shows the pipe support pushing the limit switch lever back. **Fig. 50** shows the limit switch lever and the hoist relative positions to give an overview and a better understanding of the system.

Fig. 49-Limit switch mechanism in action.

Fig. 50-Overview of the limit switch mechanism.

The picture above also shows a boom that was laid on the ground to contain liquids in case of a spill and prevents it from reaching the neighboring plot as was required by the safety department.

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5.3.2 Pipe

Starting at the bottom the pipe has a cap at the end that has a hole in its center which has a valve connected to it. A hole was drilled in the bottom steel plate so the valve could be connected to the bottom cap as seen in **Fig. 51**. The function of the valve 1 is to collect the epoxy that has settled at the bottom and then a hose can be connected (hose 1) as shown in the figure to guide the remaining water to the drain.

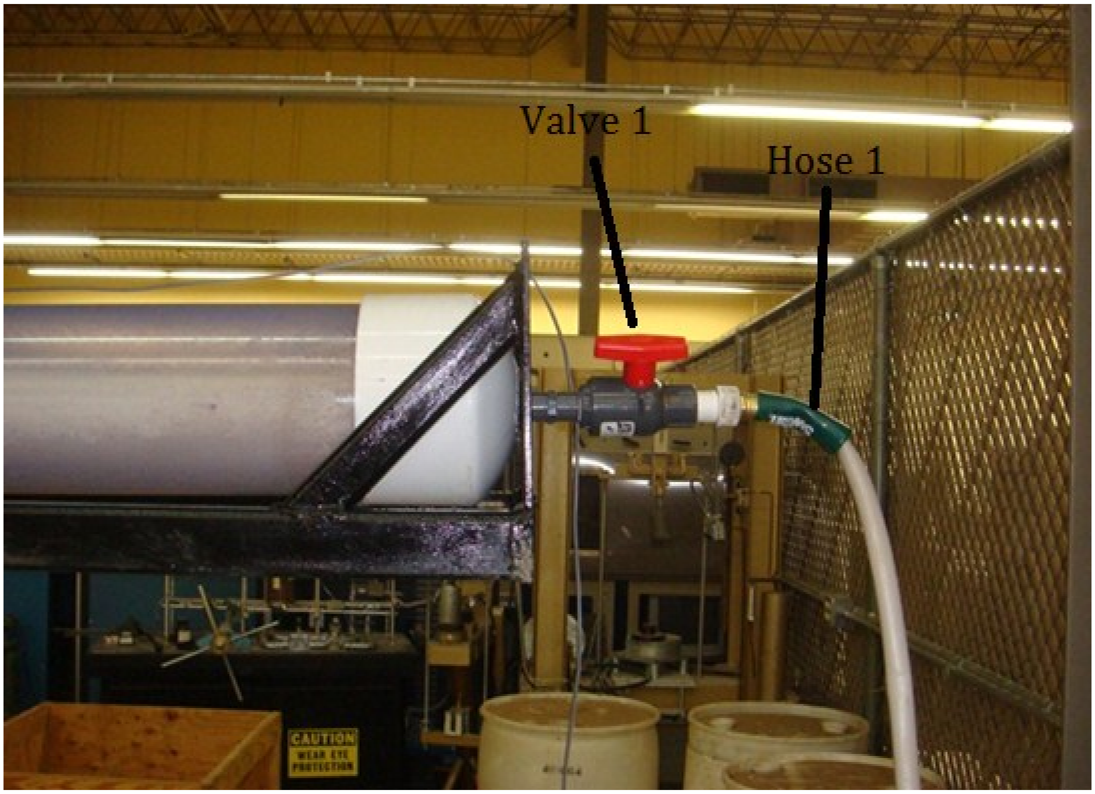

Fig. 51-Pipe fittings 1.

Next comes a 3.5ft long 6” in diameter clear PVC pipe which acts as a collection chamber for the epoxy. On top of that is a PVC tee (first tee) which 6x6x4” that connects the 6” pipe with a 4” tee (second tee) as seen in **Fig. 52**. One side of the 4in tee is connected to a 1” valve (valve 2) that closes and opens communication between the pipe and hose 2. The other side of the tee is connected to a 1” elbow that connects it to a third tee. The third tee connects to valve 3 on one side and a pressure transducer at the other as seen in **Fig. 53**. Valve three controls communication between the pipe and hose 3. Hose 3 is to fill the pipe with water. Hose 2 is connected to the drain and has two functions. One is to allow air to escape while hose 3 is filling the pipe with water. The second function is to drain the water above it when the pipe is vertical.

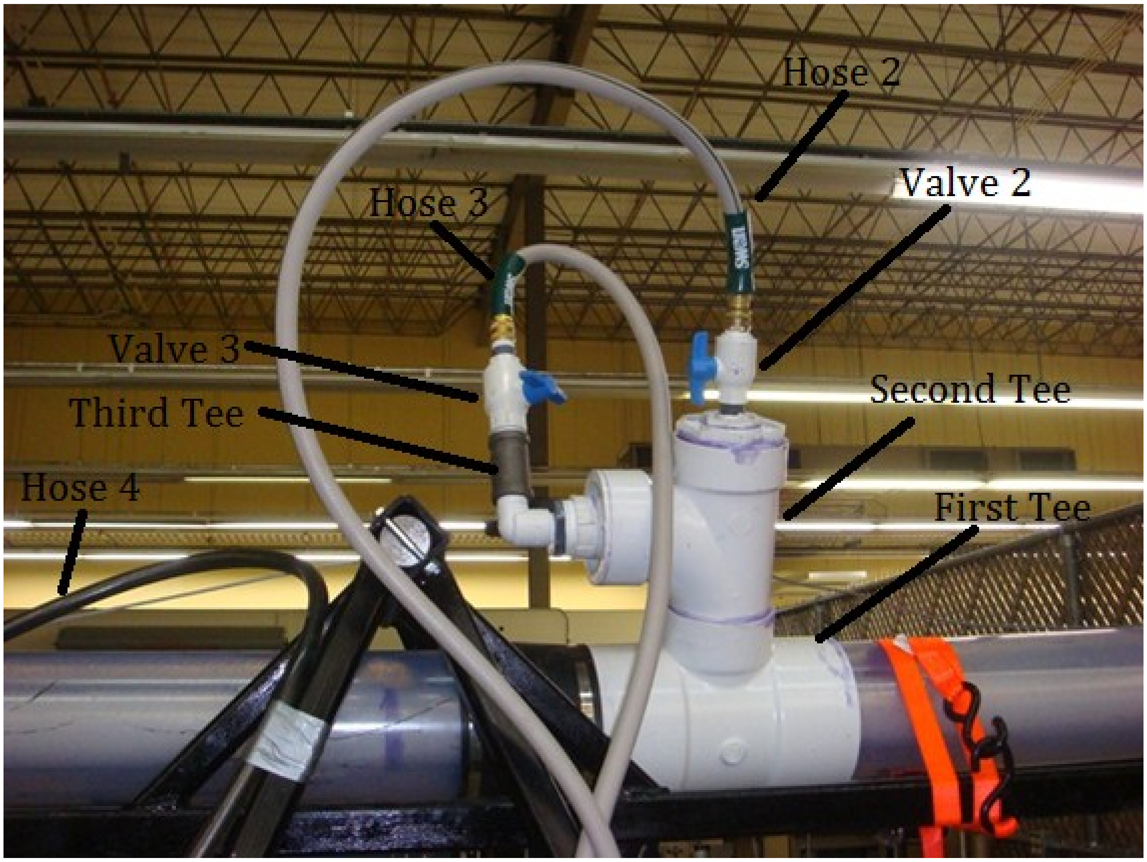

Fig. 52-Pipe fittings 2.

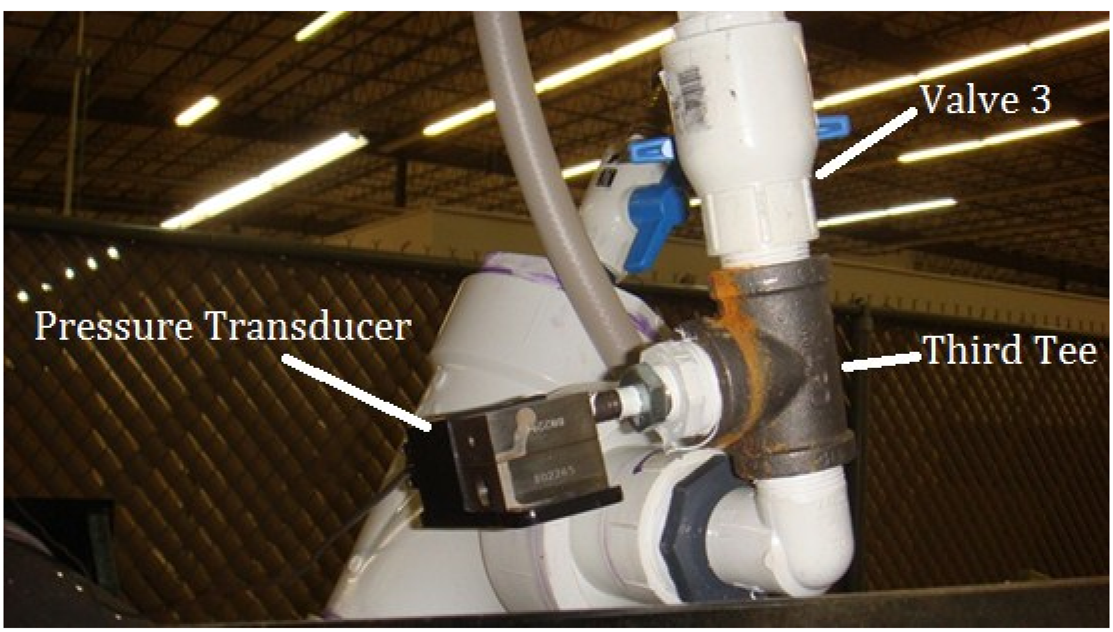

Fig. 53-Pipe fittings 3.

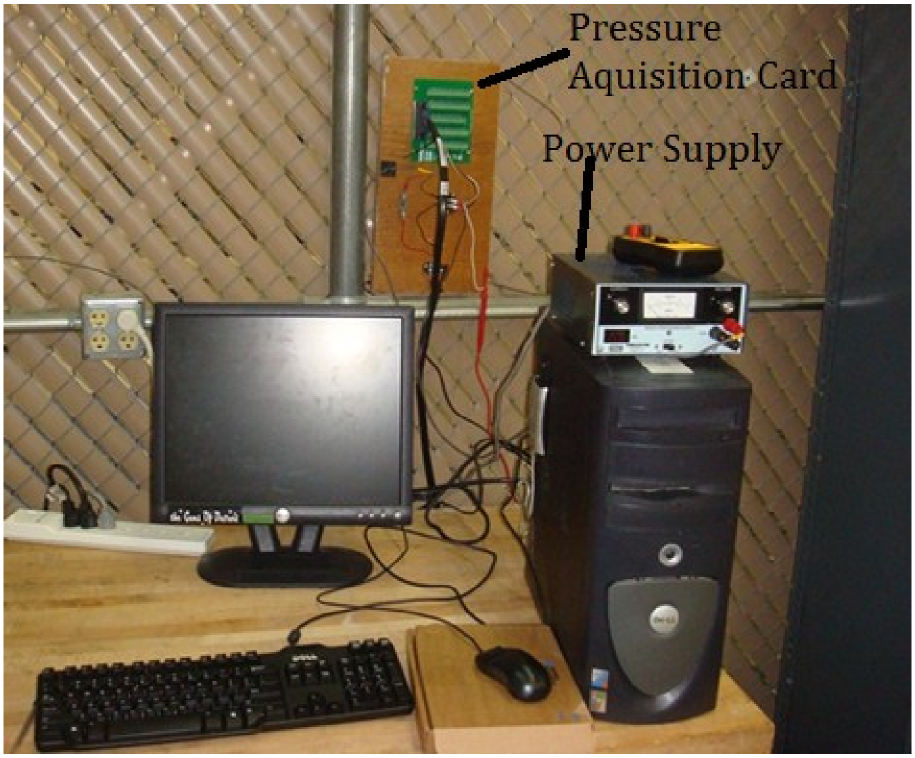

Fig. 54-Pressure acquisition card and power supply of the transducer.

The pressure transducer connects to a data acquisition card to record the pressure to investigate whether this can be a useful way to measure the settling velocity in an opaque steel pipe. **Fig. 54** shows the data acquisition card and the power source to supply correct DC voltage to pressure transducer. DC voltage should be in the range of 10 V to 50 V. 25 V was chosen to be in a safe range.

On top of the first tee is a 6” diameter rubber coupling as seen in **Fig. 52** and clearer in **Fig. 55**. The rubber coupling provides an easy way to access inside the pipe. This is needed either for cleaning purposes or to install and remove smaller pipes inside the 6” pipe to make epoxy flow in an annulus if desired.

Fig. 55-Pipe fittings 4.

Next comes two 10 ft long clear PVC pipes with a rigid coupling between them as can be seen in **Figs. 44** and **45**. On top of those is a 6” PVC valve (valve 4). This valve is what separates the epoxy from the water before the experiment. Attached to the handle of the valve is a cable that allows opening the valve from the ground when the pipe is vertical. When the valve opens epoxy is released in the water and the settling begins. **Fig. 56** shows a picture of the valve with the cable attached to its handle.

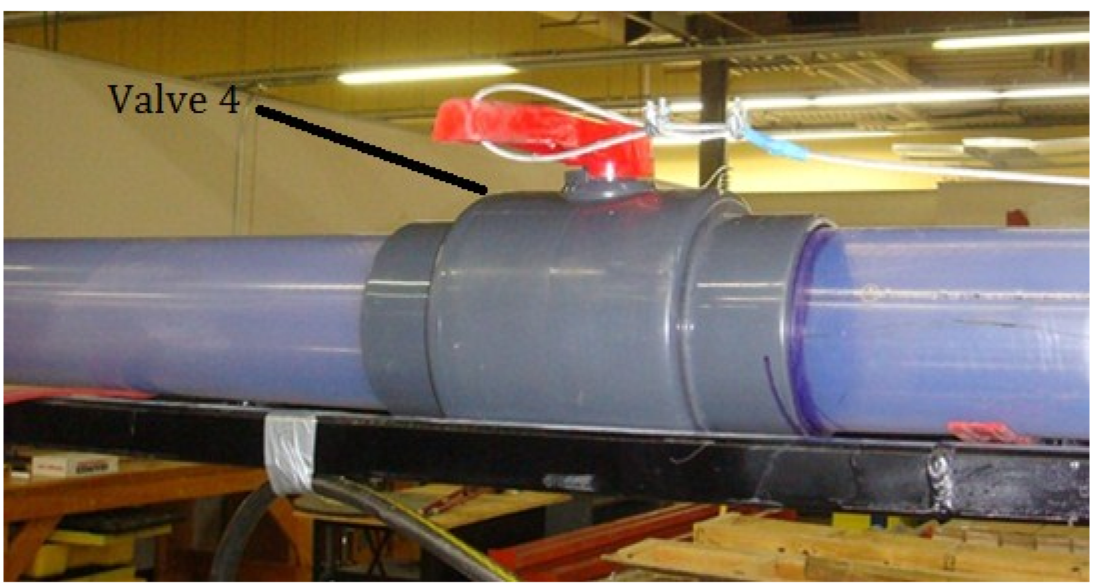

Fig. 56-Pipe fittings 5.

Next is a 3 ft clear PVC pipe to hold the epoxy before it is released in the water at the end is a 90 deg elbow to enter the epoxy in the pipe. **Fig. 57** shows this.

Fig. 57-Pipe fittings 6.

Hose 4 is used to clean the entire interior of the pipe by bringing the pipe to vertical and letting water flow through it. There is a nozzle at the end of the hose to distribute the water around the pipes circumference. During the experiment hose 4 is removed from the elbow.

It is desired to test the settling velocity of the epoxy in an open pipe and in an annulus. Two different pipe sizes have been used to create a small and large annulus. The diameters of those are 1.9” and 3.5”. The smaller pipes are inserted by disassembling the rubber coupling then inserting the smaller pipe into the 6” pipe. The smaller pipes are capped at the top and bottom to prevent epoxy from entering them. Holes have been drilled through their walls on the side to allow the smaller pipes to fill with water while filling the 6” pipe otherwise the pipes would float when the pipe is brought to vertical and would exit from the top valve when opened. The holes are made at an angle that is in opposite direction of the falling epoxy to make sure epoxy would not enter inside the pipes. Centralizers specially designed and fabricated for our application has been used. Four of them are distributed throughout the pipe’s length. The centralizers have three arms to ensure stabilization and are made to be easily assembled and disassembled. They are made of steel and fitted with a piece of teflon board at their tips so when they are slid into the 6” pipe they do not scratch it and to minimize friction to ease the sliding. The centralizers were also painted to minimize rusting. **Figs. 58** and **59** show a picture of the centralizer.

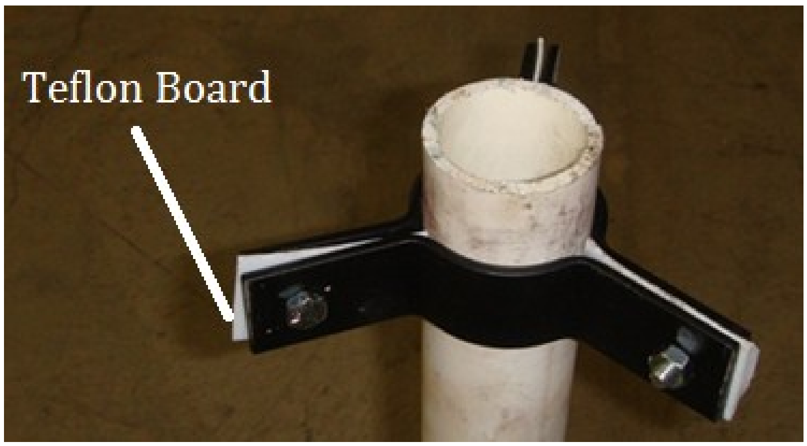

Fig. 58-Centralizer.

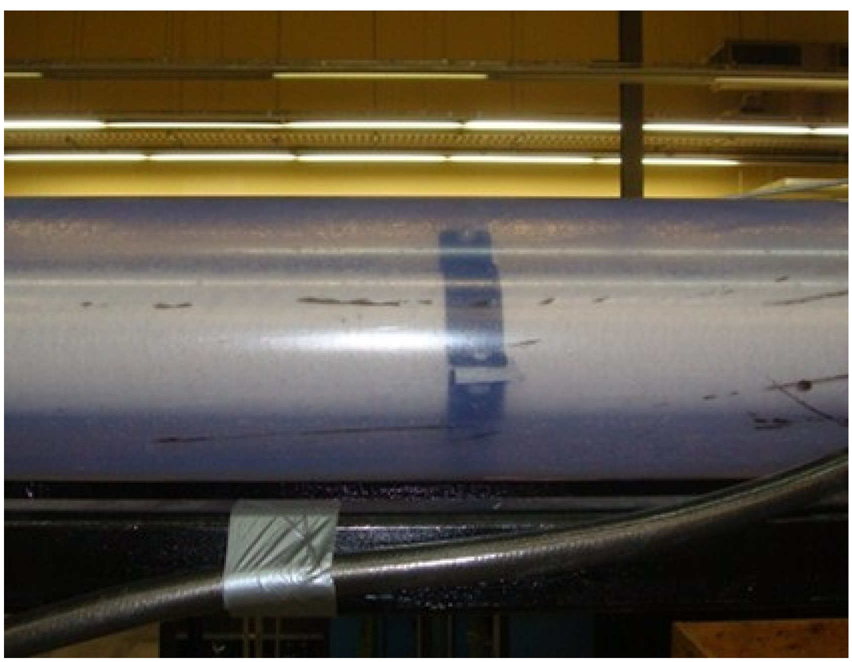

Fig. 59-Centralizer in pipe.

6. THE EXPERIMENT

6.1 The Epoxy

It was desired to test an epoxy that is representative to what would be used in real application. Professional Fluid Systems (PFS Aug 2010) is one of the well-known epoxy manufacturers in the industry. They have a product called Ultraseal that has been successfully used in similar applications to the one we are studying for, as discussed in the introduction. So Ultraseal was the main epoxy used. Ultraseal as with most other epoxies is a mixture of four main components, an epoxy (resin), a diluent, a hardener and a filler material. The epoxy or the resin consists of monomers or short chain polymers that have an epoxide group at their end. The epoxide group is a cyclic ether that consists of three atoms that form a shape that resembles an equilateral triangle. This shape makes the epoxide highly strained and therefore reactive. The hardener mainly consists of polyamine monomers such as triethylenetetraamine (TETA) that readily form stable covalent bonds with more than 1 epoxide (crosslinking) like for example TETA can form up to four bonds. The product therefore becomes heavily crosslinked and becomes hard and strong. The diluent is used to reduce viscosity of the epoxy to make it easier to pump. The diluent is also used to increase pot life and gel time. (Ng 1994) The filler is used to increase the density of the mixture. In the oil industry barite is the most common filler material even with epoxy.

To be able to try different densities and viscosities of epoxy mixtures each constituent was obtained separately from PFS. The constituents are then mixed at different ratios to obtain the different densities and viscosities desired. The hardener was not used because it was thought that it would damage the equipment by hardening on pipe walls and may cause the valves to get stuck etc. The hardener was not used also to be able to use the mixture more than once. So only the epoxy, the diluent and the filler were used in the mixtures.

6.2 Experiment Variables

The following are the variables that were used in the experiment:

1- Epoxy Formulations

Table 4 shows the properties and constituents of the three main epoxy formulations that were used. They are classified as light, medium and heavy representing their relative densities.

TABLE 4-EPOXY FORMULATIONS										
Formulation	Density	Viscosity						Part A (epoxy)	Diluent	Barite
	ppg	R3	R6	R100	R200	R300	R600	g	g	g
light	11.5	4	7	96	192	272	>300	2819	904	1729
medium	13.2	5.5	11	148	294	>300	>300	2584	829	2950
Heavy	14.7	12	22	>300	>300	>300	>300	2352	755	4150

2- Annulus

Three different annuli were used to study the effect of annulus size. The outer pipe is a 6” ID for all three. The three inner pipes are 3.5” OD 1.9”OD and no inside pipe.

3- Angle

The angle is the angle of inclination of the pipe support measured from vertical.

6.3 Experimental and Cleaning Procedures

6.3.1 Experimental Procedure

The experimental procedure is described by the following steps:

1) Get pipe support to horizontal position.
2) Make sure pipe is clean. If not see cleaning procedure.
3) Make sure all hoses are not kinked.
4) Close Valve 1 (**see Fig. 51**) and make sure the 6” PVC valve (Valve 4, **Fig. 56**) is not stuck by opening and closing a couple of times then close it.
5) Open Valve 2 (**see Fig. 52**). (It is very important to open valve 2 before entering water into the pipe otherwise pressure will build up in the pipe and separate the pipe from the rubber coupling as it is not designed to hold against pressure)
6) Start filling pipe with water by opening Valve 3. (**see Fig. 52**).
7) Close Valve 3 when pipe is full. (Pipe will be full when Hose 2 (**see Fig. 52**) starts draining water). (If there is a smaller pipe to make an annulus, make sure it is full of water by inspecting if there are any air bubbles escaping the holes drilled at its side.
8) Close Valve 2.
9) Make sure epoxy is well mixed. Record its density, viscosity and weight. (this can be done before or during previous steps.
10) Remove hose 4 (**see Fig. 57**) from the elbow then pour the epoxy into the elbow.
11) Get the pipe to vertical or to desired angle.
12) Start recording data from the pressure transducer.
13) Two persons are needed starting from this step. One should be ready with a video camera to record the experiment and the other to pull the valve handle via the cable attached to it when the video camera starts recording.
14) Stop video recording and pressure data acquisition when all the epoxy falls to the bottom.

15) Start draining the water in the pipe by opening valve 2.
16) Remove hose 1 (See **Fig. 51**) and start collecting the epoxy at the bottom by opening valve 1.
17) Close valve 1 as soon as water starts to flow through the valve. (you will notice a great change in fluid velocity due to the two orders of magnitude difference in viscosity.)
18) Record the weight of the regained epoxy.
19) Connect hose 1 and start draining the remaining water by opening valve 1.
20) Clean. (see cleaning procedure)

6.3.2 Cleaning Procedure

The following are the steps required to thoroughly clean the pipe:

1) Get pipe support at a very small angle from horizontal where the elbow is the high point and reachable.
2) Make sure valve 4 and valve 1 are open.
3) Use hose 4 to flush the mud inside the elbow then insert hose 4 into the elbow.
4) Repeatedly close valve 4 for a while to build water behind it then open.
5) Close valve 4 and fill some water behind it with hose 4. Then close hose 4.
6) Get pipe support to vertical position.
7) Open valve 4.
8) Open hose 4 and allow enough time for water to flush entire pipe clean.

7. RESULTS AND DISCUSSION

Tables 5 and **6** summarize the results. **Table 5** lists the experiment numbers and their corresponding variables that were controlled before the experiment. Experiment 2 was done before the pressure transducer was setup and therefore was repeated after it was setup. The number between brackets in the experiment numbers represents the original experiment numbers which were ordered by the date they were performed. They were re-numbered here by angle, annulus then epoxy formulation in order to make results more presentable. The angle represents the angle from vertical as previously discussed.

As can be seen in the experiment videos the epoxy does not fall as one part instead it spreads throughout the water column and then recollects at the bottom. This is shown in **Fig. 60**. **Fig. 60** also shows the lead of the epoxy column. Therefore, the "Time Lead" in **Table 6** refers to the time in seconds from releasing the epoxy in the water by opening valve 4 (**Fig. 56**) to the time the lead reaches the bottom. "Time at Coupling" and "Time at Pressure Transducer" are the times from opening the valve till the lead reaches the coupling and the pressure transducer respectively. "Time Tail" is the time from opening the valve until almost all the epoxy recollects at the bottom. This latter entry is very difficult to measure and is somewhat subjective. This is because as the epoxy falls some of the adhered epoxy to the pipe begins to break out and fall. As a result, it will be seen that some epoxy continues to fall even several minutes after the start of the experiment. Moreover, as the epoxy falls in the water, the water becomes muddy from the barite and it is not clear enough to see when the epoxy fall rate actually stops or substantially decreases. The word "visual" in the table indicates that the time was measured visually from the experiment videos by actually seeing the epoxy through the clear pipe reaching its target.

TABLE 5-EXPERIMENT VARIABLES			
Experiment Number	Epoxy Formulation	Annulus	Angle °
1 (13)	Light	6" - 0"	0
2 (3)	Medium	6" - 0"	0
2' (4)	Medium	6" - 0"	0
3 (14)	Heavy	6" - 0"	0
4 (12)	Light	6"-1.9"	0
5 (11)	Medium	6"-1.9"	0
6 (10)	Heavy	6"-1.9"	0
7 (8)	Light	6" - 3.5"	0
8 (6)	Medium	6" - 3.5"	0
9 (9)	Heavy	6" - 3.5"	0
10 (15)	Medium	6" - 0"	30
11 (16)	Medium	6" - 0"	45

TABLE 6-EPOXY SETTLING TIMES							
Experiment Number	Time at Coupling (Visual) sec	Time at Pressure Transducer (Visual) sec	Time Lead (Visual) sec	Time Tail (Visual) sec	Time at Pressure Transducer from pressure readings sec	Time Tail at Pressure Transducer from pressure readings sec	dp after 100 secs psi
1 (13)	15	31	37	89	32	68	0.08
2 (3)	12	29	35	73	-	-	-
2' (4)	12	29	35	76	30	68	0.12
3 (14)	10	24	29	67	24	55	0.15
4 (12)	15	33	40	84	32.5	67	0.08
5 (11)	12	29	34	75	29	59	0.115
6 (10)	8	20	24	65	20.5	56	0.17
7 (8)	14	33	40	100	33.5	82	0.09
8 (6)	11	28	33	75	28	68	0.175
9 (9)	9	22	26	66	24	52	0.18
10 (15)	7	14	16	31	14	20	0.075
11 (16)	7	14	17	30	13.5	15.5	0.05

Fig. 60-The epoxy spreads in the water column.

The times measured by the pressure transducer were obtained from plotting the pressure readings versus time. **Fig. 61** shows the plot for experiment 5 (11) as a typical representation of the other experiments. The remaining plots can be found in the appendix attached at the end of this report.

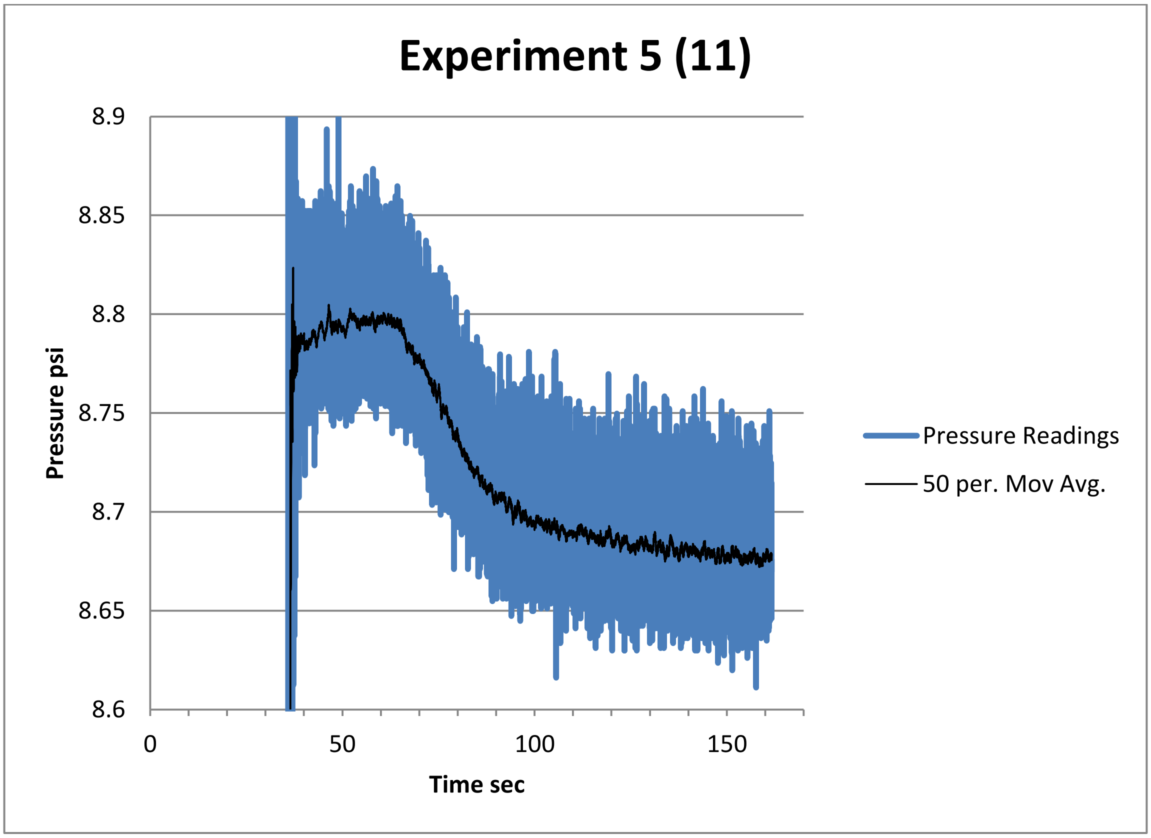

Fig. 61-Pressure readings from experiment 5 (11).

The readings were fitted with a moving average trend line that averages the nearest 50 readings (±25) to smoothen the oscillatory readings and make them easier to interpret. The data acquisition card takes 100 readings per second therefore the trend line averages data over ±0.25 seconds. The sharp increase at 36 seconds marks the start of the experiment. "Time at Pressure Transducer from pressure readings" entry in **Table 6** is the time from the experiment's start till the pressure starts declining which is approximately at 64 seconds in **Fig. 61**. This decline occurs when the epoxy passes the perpendicular opening of the “second tee” in **Fig. 52**. As can be seen from **Table 6** the visual values are very close to the time measured by the pressure transducer which indicates that the pressure transducer can be reliably used for this entry in case an opaque pipe is used. “Time Tail at Pressure Transducer from pressure readings” is the time from the experiment’s start until the sharp decline of the pressure ends which occurs approximately at 95 seconds in the figure above. This latter entry of the table does not give an accurate reading of the tail and therefore was omitted from further consideration. However, the reason why it gives a false reading will be discussed later. Finally, “dp after 100 secs” is the difference in pressure before the pressure decline and the pressure after 100 seconds after the start of the experiment. In **Fig. 61** this would be the pressure at 64 seconds minus the pressure at 136 seconds which is 0.115psi. It can be seen from **Table 6** that this value generally increases with density and decreases by increasing the angle.

There are several reasons for the sharp pressure increase at the experiment’s start. First is that when the epoxy is released it increases the total hydrostatic pressure by about 0.1 to 0.3 psi. The second is that at the point when the pipe is being completely filled with water, the water flows in from hose 3 and out from hose 2. (see **Fig. 52**) As discussed before, valve 3 must be closed first then valve 2 to avoid pressure build up in the pipe that might separate the pipes at the rubber coupling. As soon as valve 3 is closed some water continues to exit through hose 2 due to a siphon effect which causes the pressure at the top side of the pipe to drop below atmospheric pressure. Since the pressure transducer reads differential pressure between the pipe and atmosphere the pressure transducer reads a negative pressure when the pipe is still horizontal. The longer the time lag between closing valve 3 and valve 2 the more the pressure would decrease below atmospheric pressure. When valve 4 is opened and epoxy is released atmospheric pressure is re-established at the top of the water column causing an increase in pressure. A third reason is when the pipe is filled and valves are closed and then brought from horizontal to vertical, the water column increases the pressure at the rubber coupling. This cause the rubber coupling to bulge outwards as seen in **Fig. 62** causing the very small volume of trapped air to expand causing a further decrease to the pressure. This sharp increase in pressure is desirable because it shows the experiment's start clearly on the pressure plots.

Fig. 62-The rubber coupling bulges due to hydrostatic pressure.

It is important to discuss what the pressure transducer is actually sensing. A great misconception would be to think that the pressure transducer is able to sense the entire hydrostatic of the epoxy when it is inserted into the water. Consider **Fig. 63** below.

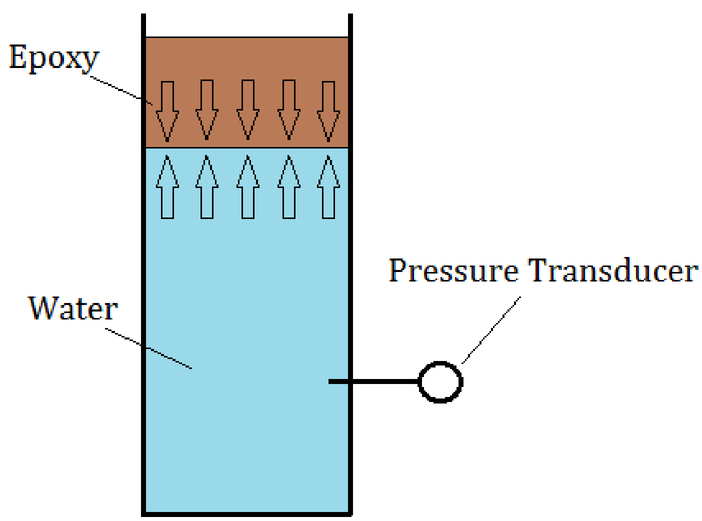

Fig. 63-Schematic of epoxy falling in a vertical pipe.

The only way that the pressure transducer would read the pressure of the water column above plus the pressure of the epoxy column is if the pressure at the water/epoxy interface equalizes. If the pressure at the interface equalizes then the epoxy will not settle because there would be no resultant force pushing it down so clearly this is not the case. Consider another example shown in **Fig. 64**.

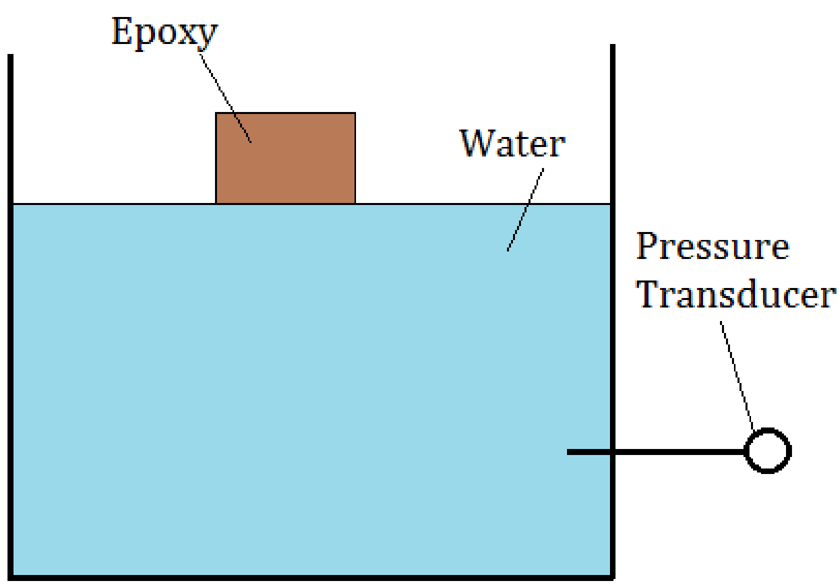

Fig. 64-Schematic of epoxy falling in a large tank.

In the case above the only change the pressure transducer will sense is the pressure change due to the increase of water height when the epoxy enters the water. If the same volume of epoxy was replaced with water the pressure transducer would not sense the difference. Going back to **Fig. 63** the situation is different. The difference is that in order for the epoxy to fall the water must be able to rise and therefore the pressure of the water will need to rise in order to be able to break through the epoxy. The difference between the two figures is that in **Fig. 63** the epoxy is much more concentrated. As the epoxy falls below the pressure transducer there is less epoxy above it and therefore less pressure is needed to force the water through the epoxy above. This concept is what causes the pressure to decline when the epoxy starts to fall below the pressure transducer. The pressure continues to decline until concentration of the epoxy above the pressure transducer is not significant enough to inhibit the water from flowing upwards. Therefore, the reason why the “time tail from pressure readings” in **Table 6** is not accurate is because some epoxy might still be above the pressure transducer but not causing significant pressure increase to be detected by the pressure transducer when they fall below it.

The proof that the pressure transducer does not sense the entire hydrostatic pressure of the epoxy comes by examining the difference in pressure when all the epoxy is above the transducer and when all of it is below it. For example, consider a heavy formulation falling in a 6”-3.5” annulus. The volume inserted is a little more than a gallon and therefore the height of epoxy is almost a foot in such an annulus. The hydrostatic pressure of a foot of 14.7 ppg is approximately 0.764 psi. Subtracting the hydrostatic pressure of a foot of water that will replace it when the epoxy drops then the difference in pressure between the epoxy above and below the transducer is 0.33 psi. The maximum pressure drop observed with such a formulation was 0.18 psi.

Table 7 below lists distances between different parts of the pipe that were used to calculate the epoxy’s speed.

TABLE 7-DISTANCES THE EPOXY TRAVELS DURING THE EXPERIMENT

cap to bottom of valve 4	292	in
cap to top of coupling	178	in
cap to pressure transducer	54	In
cap to middle of first tee	46	In

Based on the distances listed in **Table 7** and the times listed in **Table 6** average speed of the epoxy can be calculated. The speeds are listed in **Table 8** in ft/min for visual readings and readings from the pressure transducer. “Time Tail from pressure readings” was neglected as discussed earlier.

TABLE 8-EPOXY'S VELOCITIES					
Experiment Number	Speed from start to lead ft/min	Speed from start to Tail ft/min	Speed from coupling to lead ft/min	Speed from start to transducer ft/min	Speed from start to transducer by pressure readings ft/min
1 (13)	39.46	16.4	40.45	39.68	38.44
2 (3)	41.71	20	38.7	42.41	-
2' (4)	41.71	19.21	38.7	42.41	41
3 (14)	50.34	21.79	46.84	51.25	51.25
4 (12)	36.5	17.38	35.6	37.27	37.85
5 (11)	42.94	19.47	40.45	42.41	42.41
6 (10)	60.83	22.46	55.63	61.5	60
7 (8)	36.5	14.6	34.23	37.27	36.72
8 (6)	44.24	19.47	40.45	43.93	43.93
9 (9)	56.15	22.12	52.35	55.91	51.25
10 (15)	91.25	47.1	98.89	87.86	87.86
11 (16)	85.88	48.67	89	87.86	91.11

A lot of information can be derived from **Table 8**. First, it is clear that increasing the density of the epoxy increases its settling velocity which is expected. Although denser formulations are also more viscous, viscosity can only decrease settling by making it harder for the water to flow upwards. Therefore, the major contributor to the settling velocity is the density. The only way that the viscosity of the epoxy helps settling is by enhancing its ability to hold onto the barite and not allow it to separate. However, this was the case for the three formulations. Therefore this factor alone would not differentiate a formulation from another.

Another observation found in **Table 8** is that experiments 10 and 11 which were done at an angle are much faster than experiments performed vertical with the same formulation namely experiments 2, 5 and 8. In fact their speeds are more than double of those performed vertical which shows that this observation is neither a coincidence nor an experimental error. At first this seems to be against logical reasoning because at an angle the force pulling a settling particle in a vertical pipe is more than that in an inclined pipe as shown in **Fig. 65**.

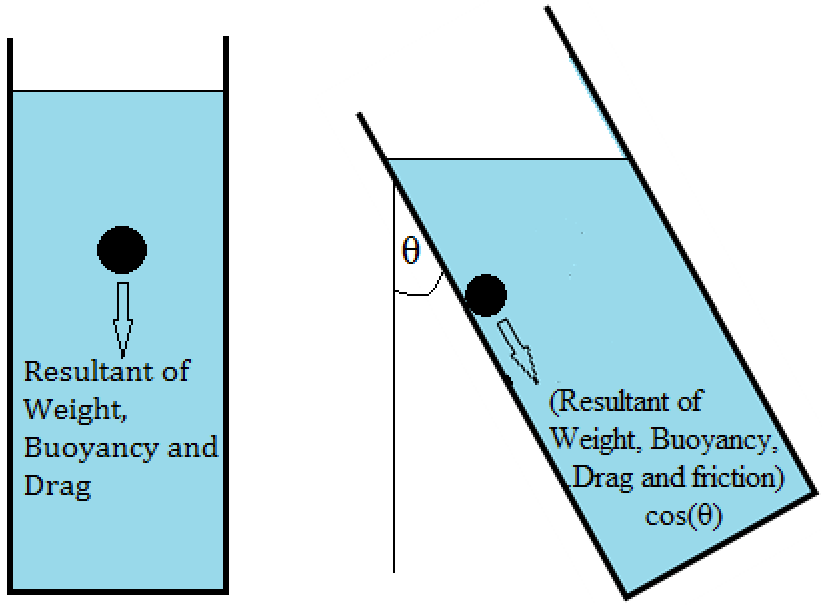

Fig. 65-Forces on a settling particle in vertical and slant pipe.

Fig. 65 clearly shows why at an angle the force is less. Not only there is friction from the pipe wall decreasing the resultant force but the resultant force is also multiplied by cosine the angle of inclination. However, there is another factor that comes into play causing this big difference in speed which is illustrated by **Fig. 66**.

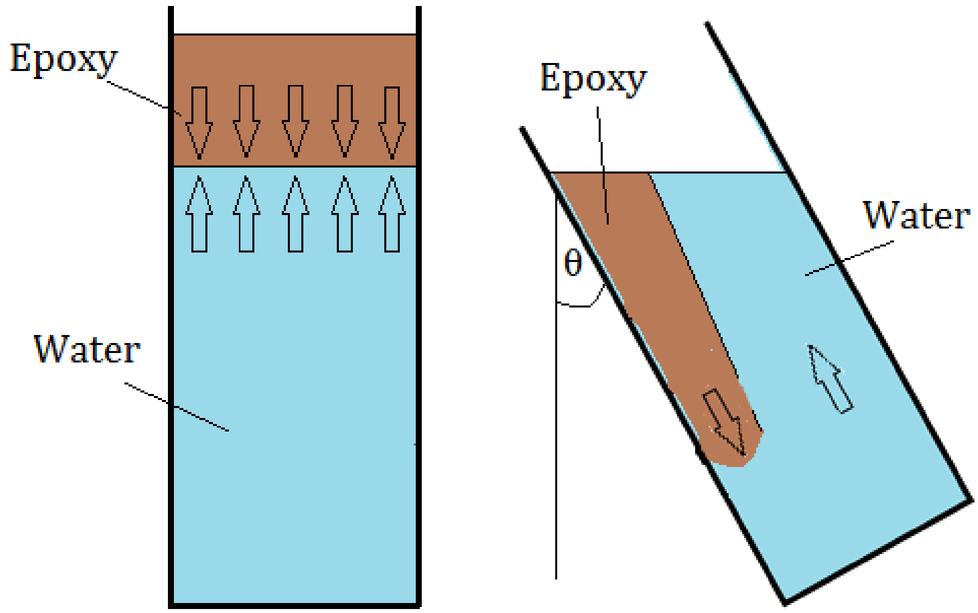

Fig. 66-Settling of epoxy in vertical and slant pipe.

For pipe on the left in **Fig. 66**, the water needs to rise and the epoxy needs to fall. The two motions oppose each other and therefore hinder the settling greatly. For the pipe on the right, the epoxy falls to the bottom side of the pipe first then starts to flow downwards. What makes the epoxy, for the pipe on the right, faster is that now the water has a big channel at the top side of the pipe to flow and therefore the epoxy can easily flow downwards at the bottom side and the water can easily flow upwards at the top side of the pipe. Another reason is as the epoxy starts to flow downwards its column gets longer and its hydrostatic pressure is increasing only on itself and not in the water which boosts the epoxy forward.

This latter phenomenon is caused by the placement method. Meaning, it is caused by dumping the entire volume of epoxy all at once in the water. This increases the concentration of epoxy in vertical pipes and inhibits the upward flow of water and the downward flow of epoxy. As a result, it is recommended to place the epoxy in small volume rates to prevent this phenomenon to occur in vertical pipes.

The annulus does not seem to cause any significant change in the settling velocity sometimes it makes the settling faster and sometimes slower and in both cases the change is not significant. It was expected that a smaller annulus would result in a slower settling velocity since the cross sectional area is smaller and there would be more friction from the pipe walls which is proportional to the hydraulic perimeter of the annulus. A possible reason why the annulus did not affect the settling velocity could also be the placement method. Injecting epoxy in small volume rates might show otherwise.

Table 8 also shows that the velocity of the epoxy is decreasing with depth for a vertical pipe. This is seen by comparing the "speed from start to lead" and "speed from coupling to lead". This is again the opposite of what is expected. It is expected that the epoxy would accelerate at first and then reach a terminal velocity and therefore the speed would increase and then stabilize. However, this expectation is opposite of what was observed for a vertical pipe. A possible reason might be that at first the epoxy is altogether and the layer of epoxy between the epoxy/water interface is seeing a big pressure difference between the epoxy above it and the water below it and therefore reaches a terminal velocity based on that pressure difference. As the epoxy spreads down the column of epoxy is not as significant on the lead as at the start of the experiment. Therefore there is a smaller pressure difference which causes the settling velocity to decrease. For experiments done at an angle the epoxy did accelerate as expected.

TABLE 9-Adhesion of epoxy on pipe walls

Experiment Number	Epoxy Formulation	Annulus	Angle °	Epoxy Entered (g)	Epoxy Lost (g)	Percentage Lost/Entered
1 (13)	Light	6" - 0"	0	5350	1007	18.8
2 (3)	Medium	6" - 0"	0	6278	1211	19.3
2' (4)	Medium	6" - 0"	0	6284	1029	16.4
3 (14)	Heavy	6" - 0"	0	7170	2033	28.4
4 (12)	Light	6"-1.9"	0	5345	1332	24.9
5 (11)	Medium	6"-1.9"	0	6323	1634	25.8
6 (10)	Heavy	6"-1.9"	0	7137	2242	31.4
7 (8)	Light	6" - 3.5"	0	5359	1390	25.9
8 (6)	Medium	6" - 3.5"	0	6320	1665	26.3
9 (9)	Heavy	6" - 3.5"	0	6920	2237	32.3
10 (15)	Medium	6" - 0"	30	6323	1384	21.9
11 (16)	Medium	6" - 0"	45	6339	1753	27.7

The epoxy entered and the epoxy lost shows how much of the epoxy entered have adhered to the pipes while falling down. As can be seen that the amount of epoxy adhered is quite significant. This might give an indication that for 7000 ft in real life application the entire volume of epoxy will adhere to the pipe before it reaches the bottom. However, there are very important factors that must be discussed before jumping to conclusions. It was noticed that most of the adhered epoxy was at the top and the adhesion decreases as the epoxy falls down. **Figs. 67** to **69** show the pipe from top to bottom respectively after the experiment is complete and the water is drained out. These figures were taken after experiment 9 with the heavy epoxy formulation. The heavy epoxy formulation was the most adhesive to the pipes as shown in **Table 9**. There are two possible explanations to why the adhesion decreases as the epoxy moves down. The first reason is that when the valve is open all the epoxy is released at once and therefore the concentration of epoxy at the top has more chance of bumping into the pipe walls and adhering to it. As the epoxy spreads down the concentration decreases and therefore has a less chance of bumping into the pipe walls. The second explanation is that at the top the epoxy is still slow and building up speed and therefore if it bumps into the pipe walls with no or small downward momentum it can easily stick to it. However, as the epoxy moves downward it builds up momentum and therefore becomes more difficult for it to adhere to the pipe walls.

From **Table 9** it can be seen that adhesion increases from the light formulation to the heavy formulation. The reason for this is not that the density has increased but is because that the viscosity increases significantly from one formulation to the next. This makes the epoxy have a stronger adhesion with the pipe walls and cohesion and therefore more epoxy is lost.

Also **Table 9** shows that adhesion increases with increasing the inner pipe diameter. This is perfectly logical because a smaller annulus means a smaller flow area which means that there is more chance for the epoxy to bump into the pipe walls. In addition, the smaller the annulus, the larger the surface area of the pipe walls which means more area for the epoxy to adhere to.

Lastly, **Table 9** also shows that increasing the angle of inclination increases adhesion. The reason for this is that the at an angle there is a smaller force pushing adhered epoxy down as explained in **Fig. 65**.

A recommendation to minimize adhesion of epoxy is to inject it at low volume rates so the concentration of epoxy relative to seawater in the pipe would be small. In addition, if the epoxy could be injected into the pipe while having an initial downward velocity that would also minimize adhesion. To enhance settling speed for vertical pipes epoxy could be introduced by a distributor to disperse the epoxy into droplets instead of one slug.

Fig. 67-Adhesion of epoxy for a vertical pipe at top section.

Fig. 68-Adhesion of epoxy for a vertical pipe at middle section.

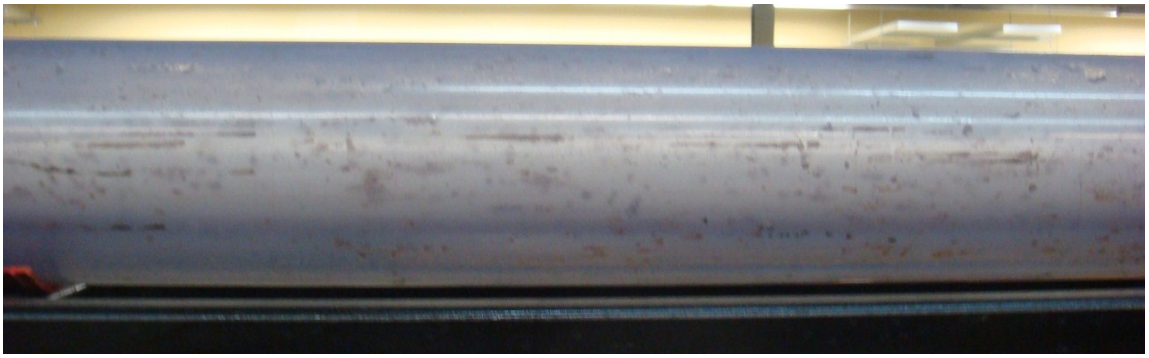

Fig. 69-Adhesion of epoxy for a vertical pipe at bottom section.

Experiments done at an angle showed the same concept of adhesion as in vertical pipe but the difference is that almost all of the adhesion took place at the bottom of the pipe. **Figs. 70** to **72** illustrate the adherence from top to bottom respectively after experiment 11 (16).

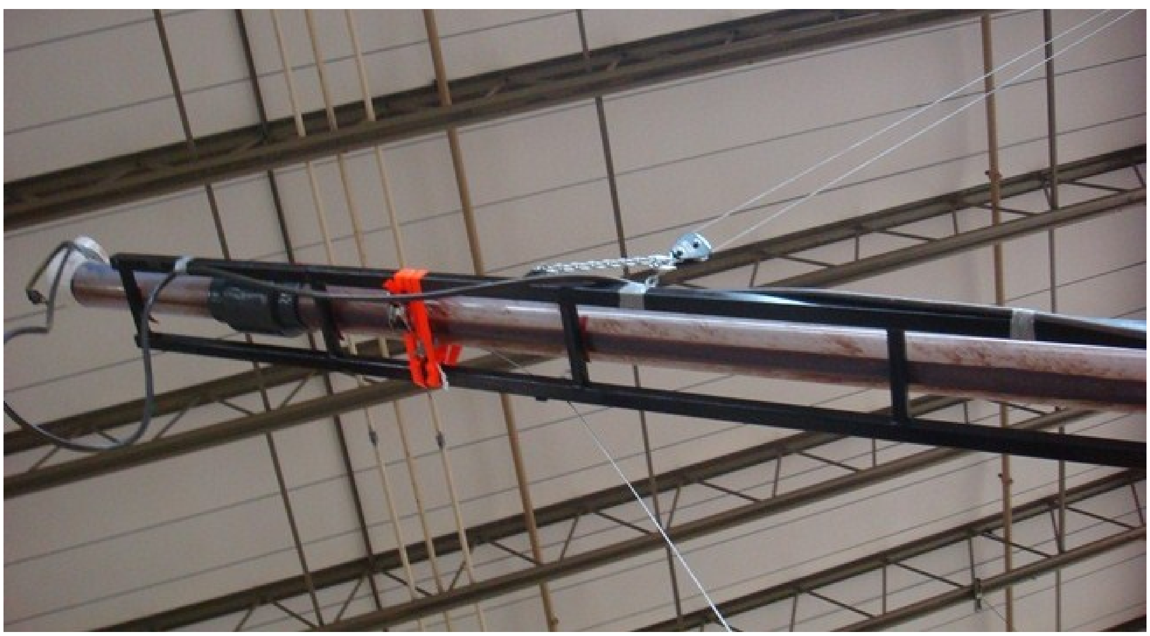

Fig. 70-Adhesion of epoxy for a slant pipe at top section.

Fig. 71-Adhesion of epoxy for a slant pipe at middle section.

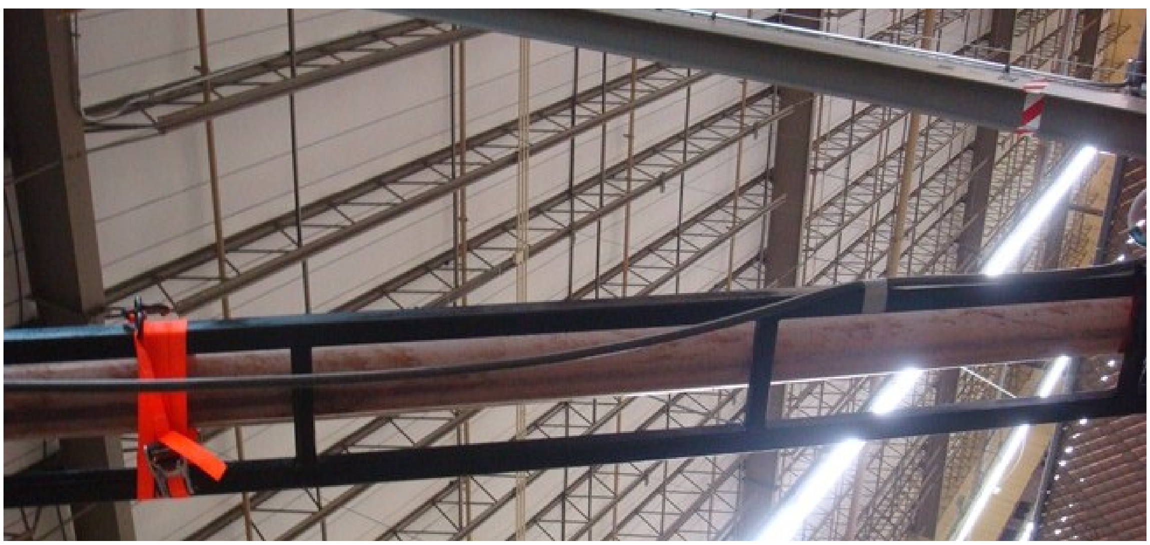

Fig. 72-Adhesion of epoxy for a slant pipe at bottom section.

Taking a look back at **Table 6** it can be seen that there were 4 experiments that were not reported by looking at the original experiment numbering. One of them was the first experiment which was omitted because it was done without video recording and therefore the timing was not recorded. It was the first experiment that led us to decide to video record the rest of the experiments. The remaining three omitted experiments were done using recycled epoxy which was recovered from an experiment that was already performed. They were omitted because their behavior was much different from the freshly made epoxy as can be seen in the experiments videos and the pressure recordings. There are two possible reasons for this. One when the epoxy is retrieved after an experiment some water must come along with it. Although the contaminant water volume is very small compared to the volume of recovered epoxy it can have significant effect on the formulation during the mixing stage affecting its viscosity. Another reason might be that the experiments were not performed on the same day. As a result, the barite in the epoxy settles to the bottom and clumps together. The mixer used might not have been strong enough to break the clumps of barite. **Tables 10** to **12** summarize the results for the recycled epoxies.

TABLE 10-RECYCLED EPOXY EXPERIMENT 12 (2)

Experiment 12 (2)		
density	10	ppg
Viscosity	R3	2
	R6	4
	R100	56
	R200	111
	R300	165
	R600	above maximum (300)
Epoxy used =	Recycled epoxy	
Epoxy entered =	4466 g	
Epoxy recovered =	3077 g	
Epoxy Lost=	1389 g	
Time lead =	59 secs	

TABLE 11-RECYCLED EPOXY EXPERIMENT 13 (5)		
Experiment 13 (5)		
density	13.2	ppg
Viscosity	R3	3
	R6	5
	R100	70
	R200	140
	R300	205
	R600	above maximum (300)
Epoxy used =	Recycled epoxy	
Epoxy entered =	4500 g	
Epoxy recovered =	2390 g	
Epoxy Lost=	2110 g	
Time lead =	24 secs	

TABLE 12-RECYCLED EPOXY EXPERIMENT 14 (7)		
Experiment 14 (7)		
density	13.2	ppg
Viscosity	R3	5
	R6	9
	R100	140
	R200	235
	R300	above maximum (300)
	R600	above maximum (300)
Epoxy used =	Recycled epoxy	
Epoxy entered =	4515 g	
Epoxy recovered =	2300 g	
Epoxy Lost=	2215 g	
Time lead =	was not recorded correctly	

Fig. 73 shows the pressure recording for experiment 7. Clearly the pressure behavior is different from that of a fresh epoxy.

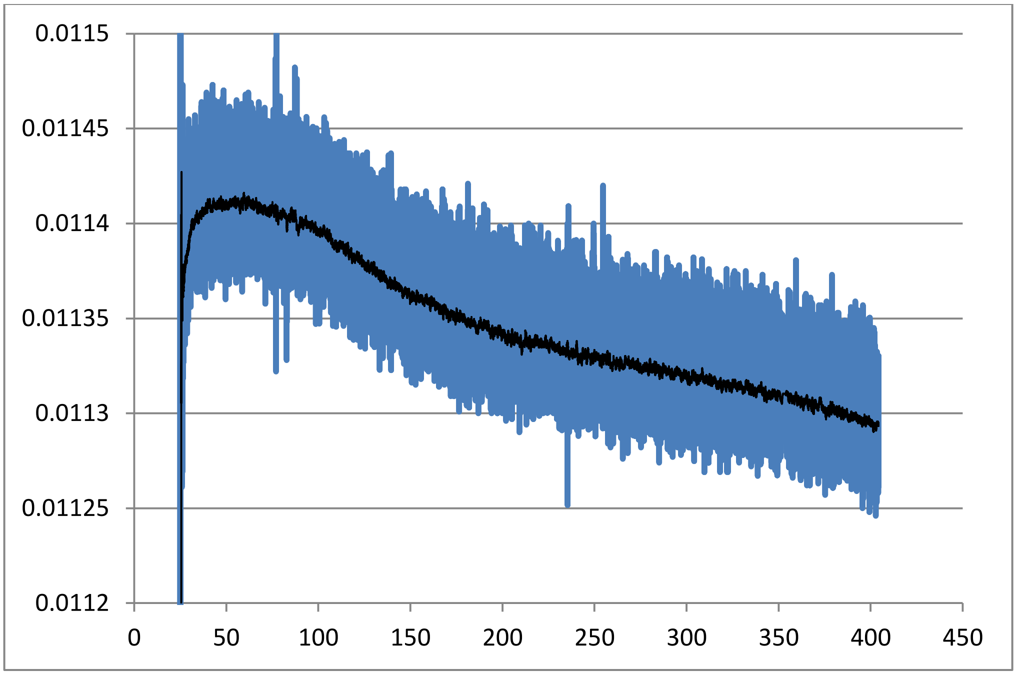

Fig. 73-Pressure readings for experiment 14 (7) which used recycled epoxy.

The pure epoxy that was used has a density that is less than water. Therefore, it was important to see if the epoxy could separate from the barite and float after it settles to the bottom. To test that, the medium formulation was kept in water after settling for a couple of hours. No significant floating of the barite was witnessed. For the heavy formulation it was noticed that most of the barite sags to the bottom of the epoxy column but there is still enough barite at the top keep it from floating. This is attributed to the strong adhesion properties of the pure epoxy.

8. CONCLUSION

The list below summarizes the conclusions of the experiments:

1. Denser formulations have a faster terminal velocity.
2. Experiments at an angle are much faster than experiments done at vertical position, almost double the terminal velocity.
3. The annulus has no significant effect on terminal velocity for vertical pipes.
4. The pressure transducer is a good way to measure the time from the experiment's start till the lead of the epoxy passes it.
5. The more the viscosity of the epoxy formulation the more the adhesion to the pipe walls.
6. The larger the angle of inclination the more the adhesion to the pipe walls.
7. The smaller the annulus the more the adhesion to the pipe walls.
8. Adhesion decreases with depth.
9. Recycled epoxy is not suitable to represent freshly mixed epoxy.
10. Although pure epoxy is less dense than water, it does not separate from the barite it is mixed with and therefore maintains a higher density and stays at the bottom.

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APPENDIX

The figures below are plots of pressure vs. time for the experiments taken by the pressure transducer.

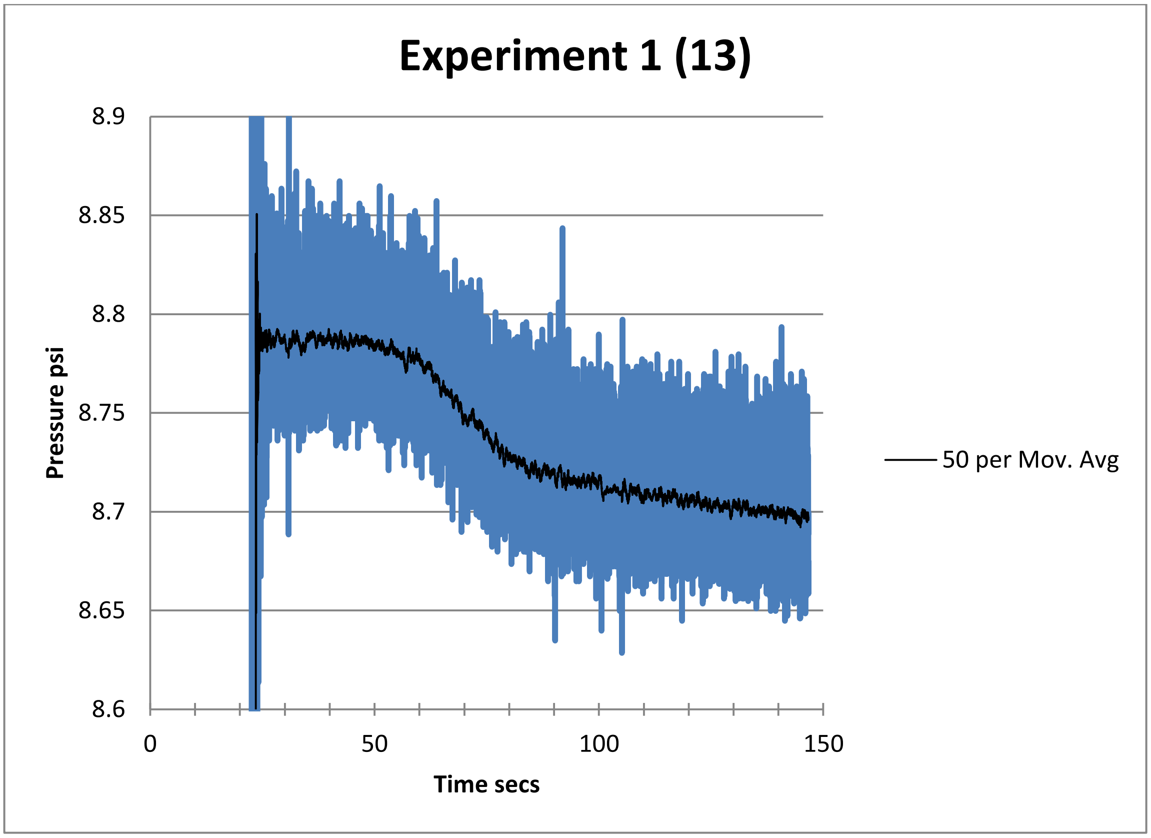

Fig. A1-Pressure Readings for Experiment 1 (13).

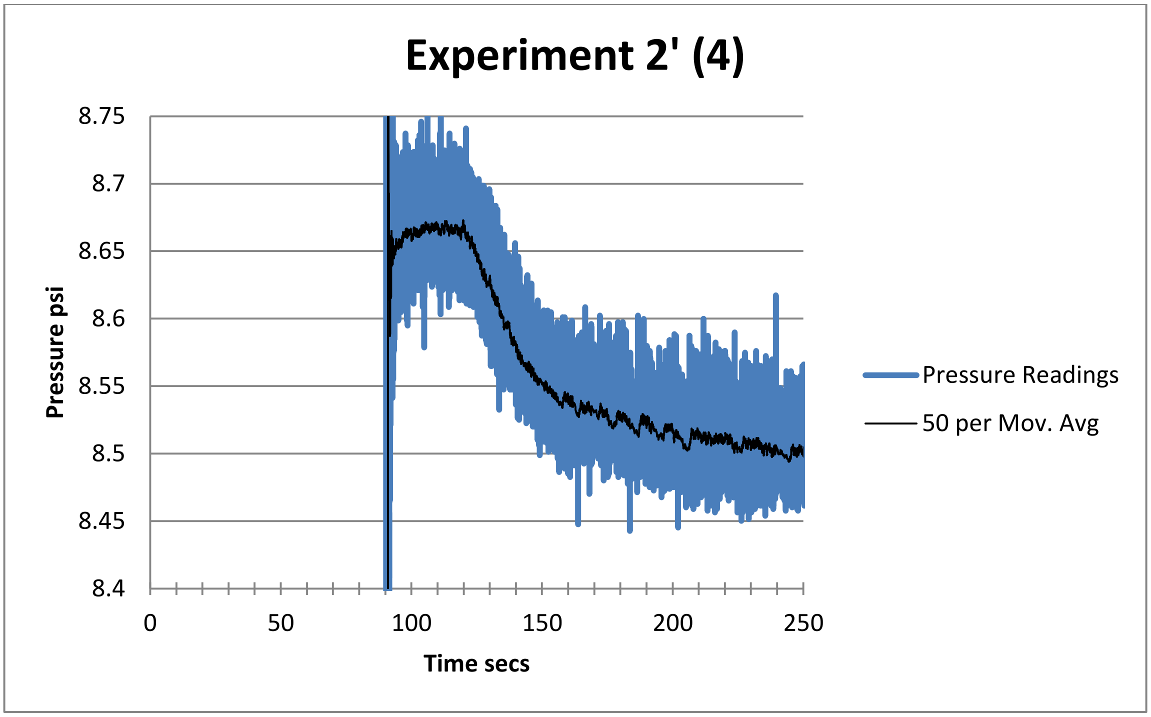

Fig. A2-Pressure Readings for Experiment 2' (4).

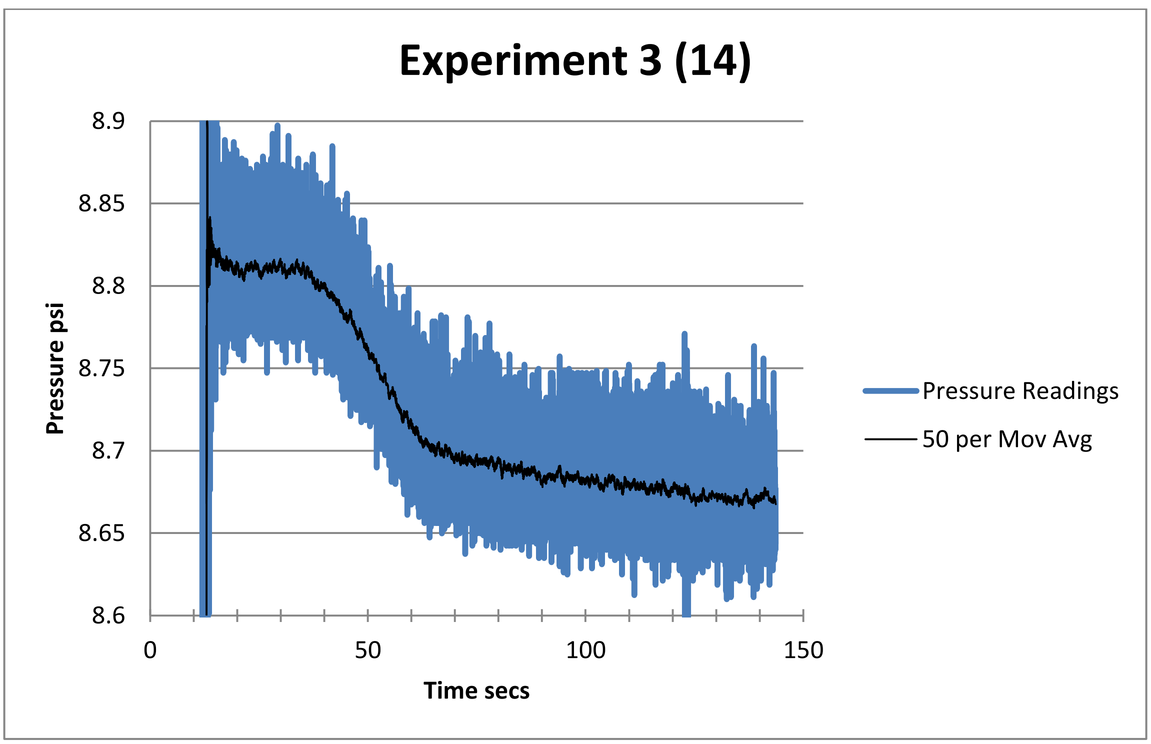

Fig. A3-Pressure Readings for Experiment 3 (14).

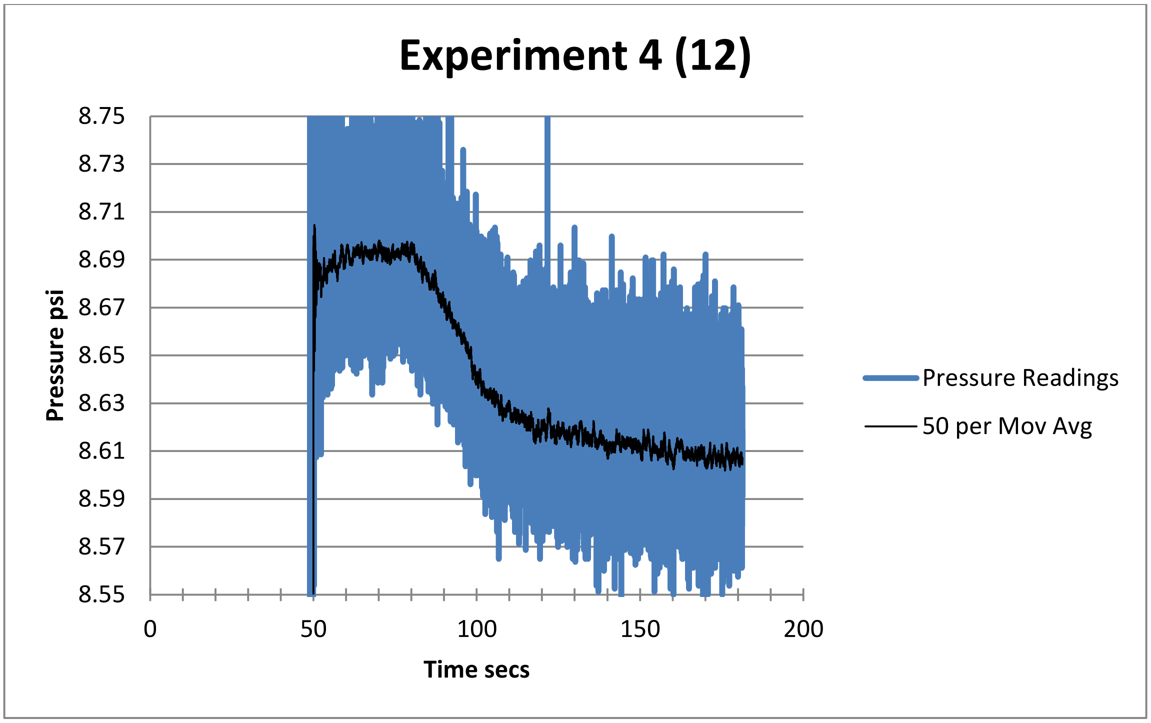

Fig. A4-Pressure Readings for Experiment 4 (12).

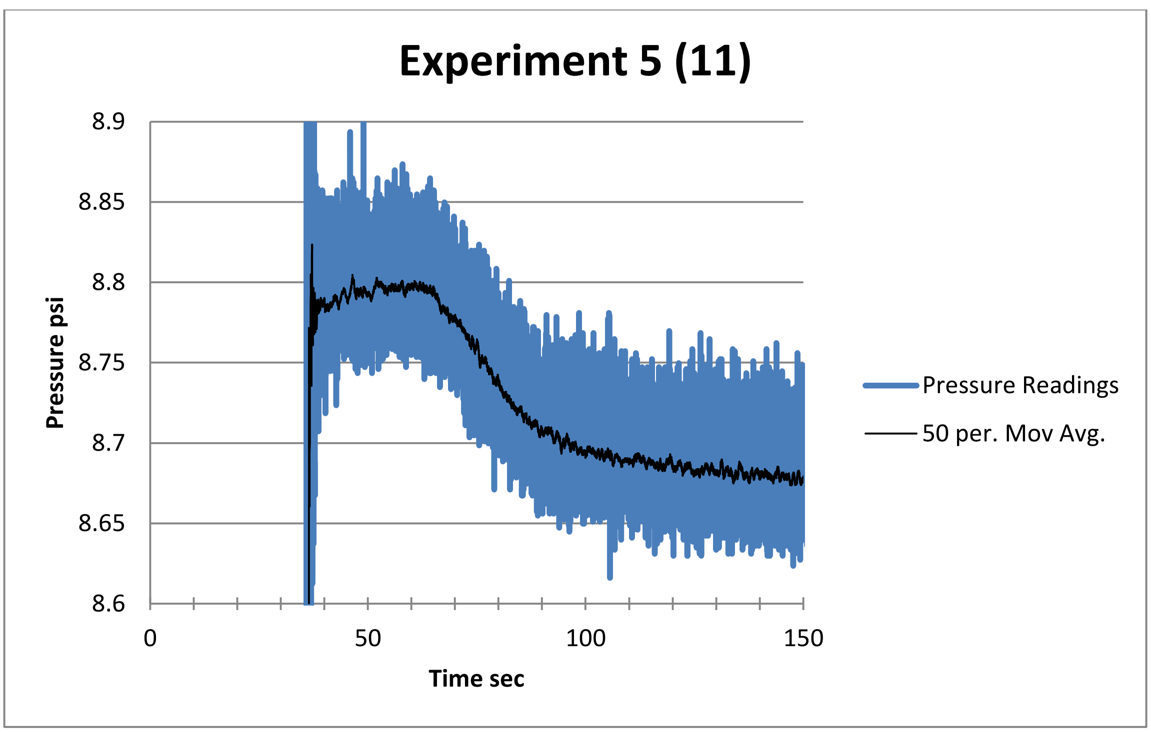

Fig. A5-Pressure Readings for Experiment 5 (11).

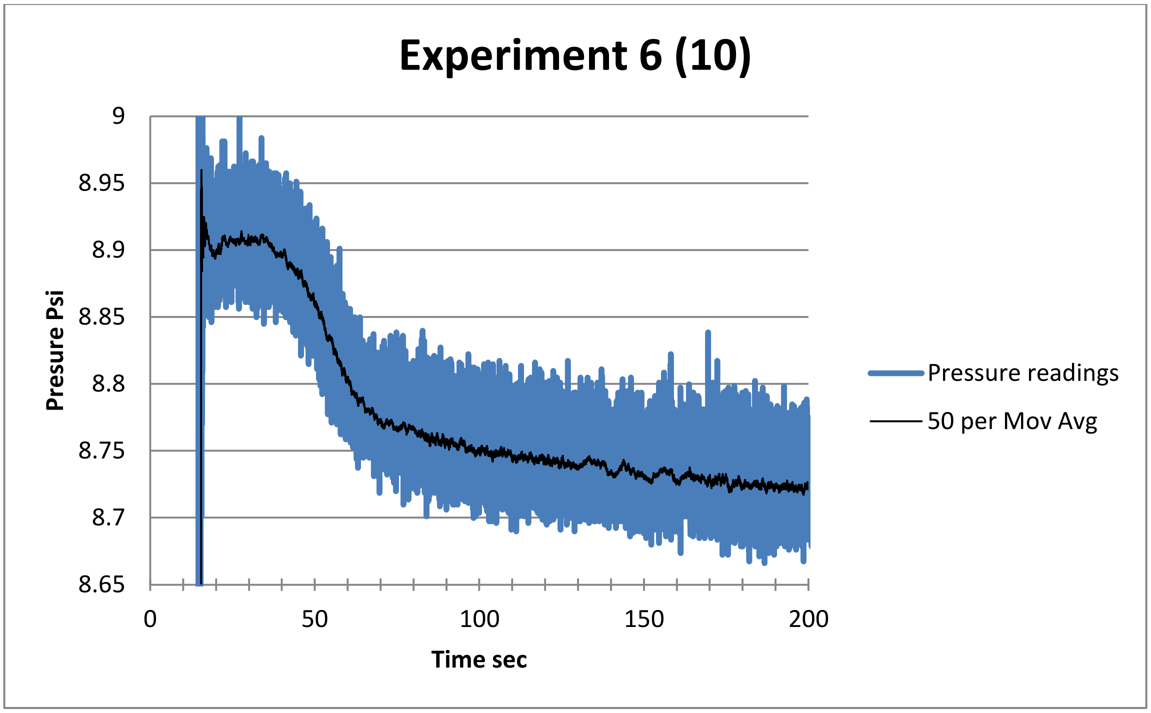

Fig. A6-Pressure Readings for Experiment 6 (10).

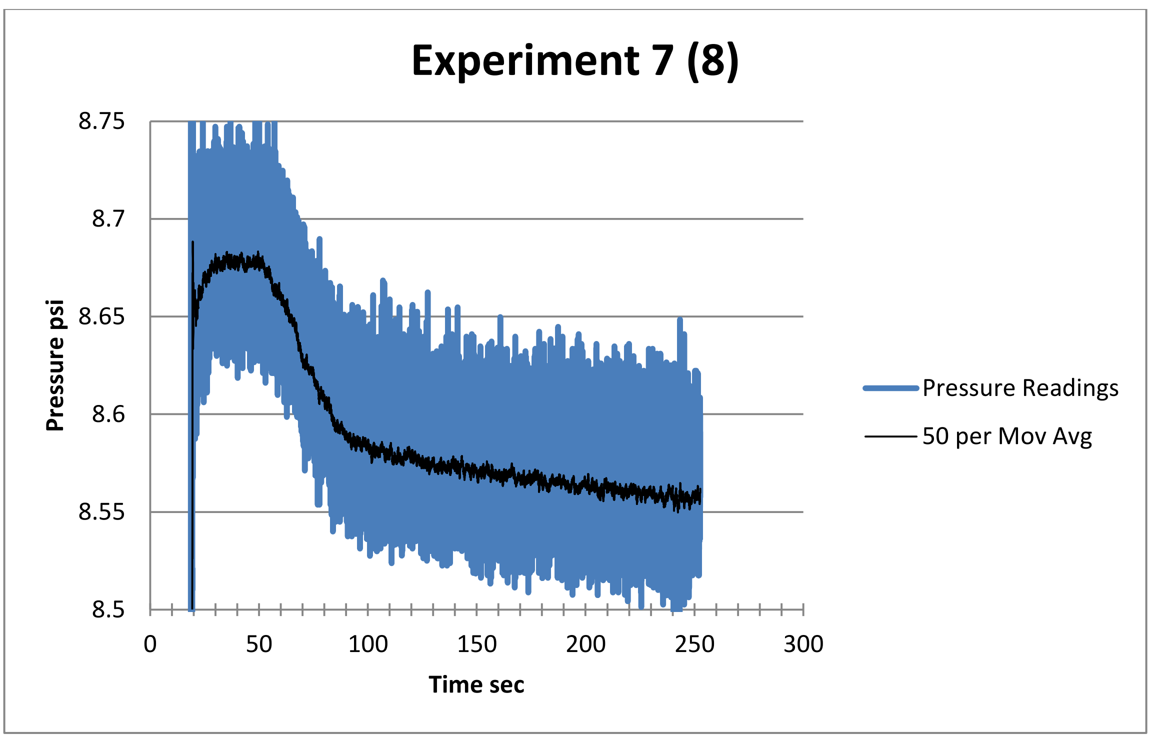

Fig. A7-Pressure Readings for Experiment 7 (8).

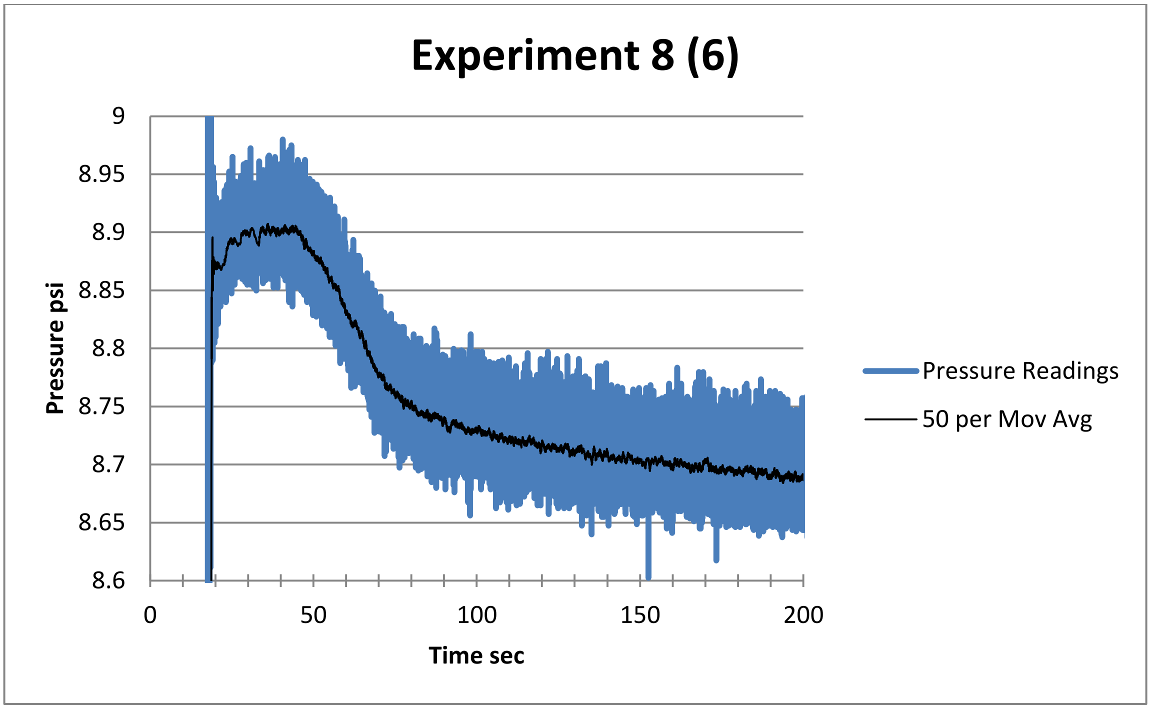

Fig. A8-Pressure Readings for Experiment 8 (6).

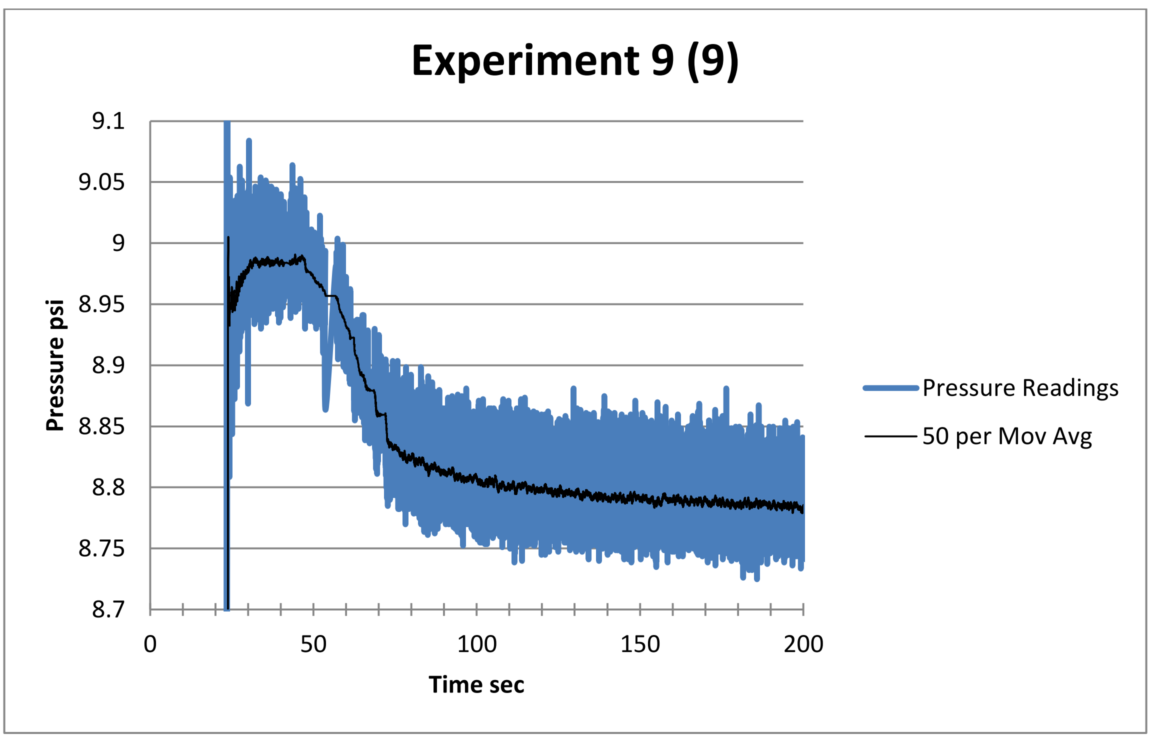

Fig. A9-Pressure Readings for Experiment 9 (9).

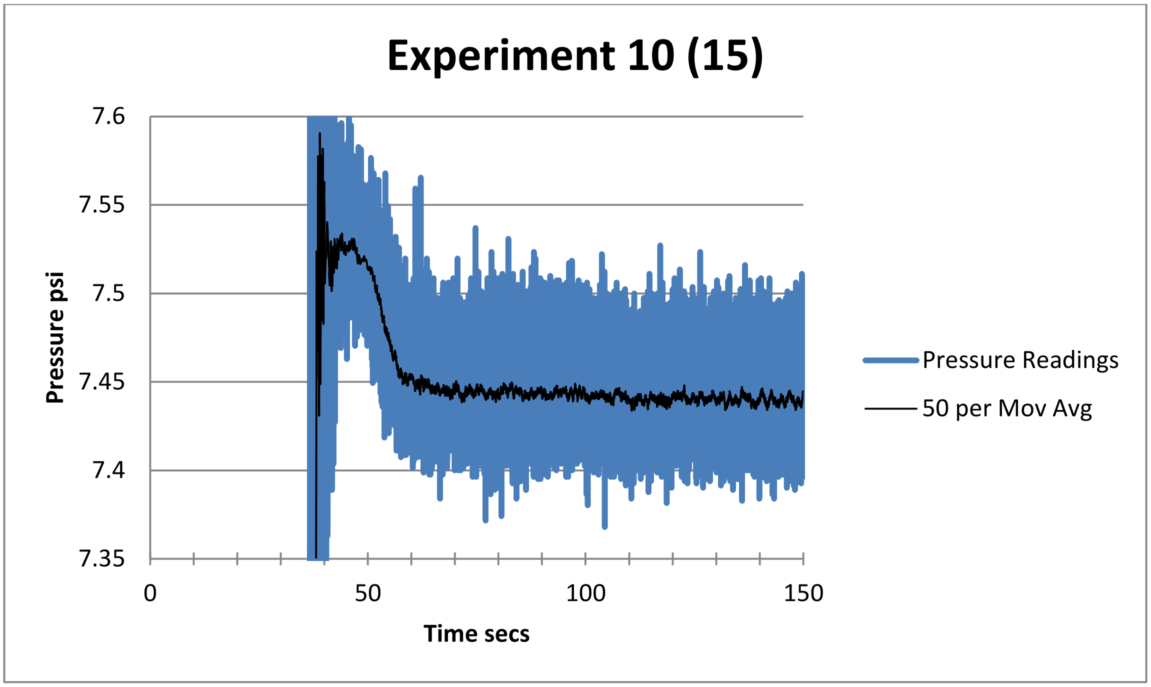

Fig. A10-Pressure Readings for Experiment 10 (15).

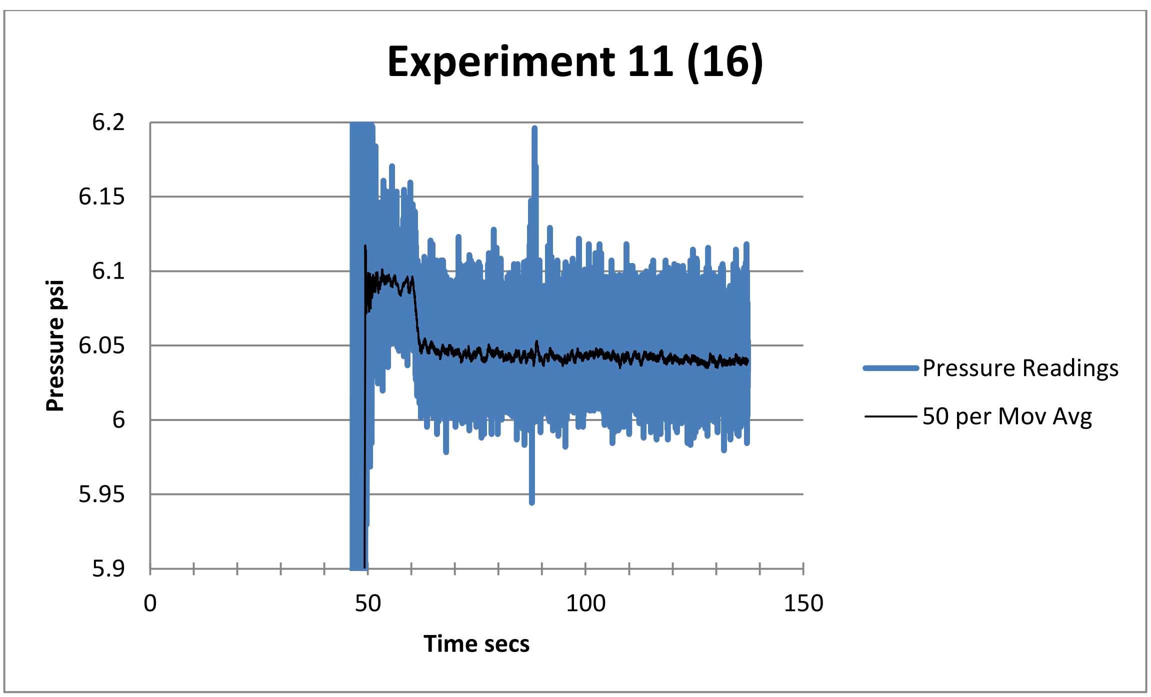

Fig. A11-Pressure Readings for Experiment 11 (16).

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