MASTER'S THESIS

Risk Identification and Risk Management in Pumping of Gel Fluids in Pipeline Application

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Acknowledgement

Abstract

The focus of this research work is to develop a model that will predict the pressure required to move a crosslinked gel plug in a pipeline in the hypothetical case of Halliburton Temblok 50 gel. In addition, this study seeks to carry out risk analysis on the experimental set up and procedure by using JSA and risk acceptance criteria to identify what can go wrong.

This study adopts a simplified theoretical model which was initially developed from Fanning equation in order to get pressure drops range which was used in setting the PSV on 2, 4 and 6 inches pipeline. In addition, an experiment was conducted in both Halliburton and IRIS test yard by pushing 50m, 100m and 150m gel plug into 2 inches pipeline at different times. Water was then pumped into the line until the gel plug started moving and pressure recorded. The experiment was repeated for the 4 and 6 inches pipelines and their pressures recorded.

The experiment was carried out based on two assumptions. First, that the flow rate, and the settling times are constant. Second, that the pipelines were smooth and that the topography in which these lines were laid was straight.

The theoretical and experimental results were then compared and graph of pressure drops against pipe diameters were plotted for 50m, 100m and 150m gel plug. From these graphs, a linear equation containing pipe diameter and gel plug length as input parameter was developed.

The result in this study points to a model which can be used in predicting the pressure required to set Temblok 50 gel in motion provided the gel plug length and the pipe diameter are known.

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Subscripts

1   Inlet pressure

2   Outlet pressure

g   Gel plug

y   Yield

Abbreviations

A	Event
ALARP	As low as reasonable practicable
API	American petroleum institute
C	Consequences
D	Pipe diameter
F	Force
FMECA	Failure, mode, effects and criticality analysis
FTA	Fault tree analysis
HAZID	Hazard identification
HAZOP	Hazard operability
HP	High pressure
HPPS	Halliburton Pipeline and Process Services
IRIS	International Research Institute Stavanger
JSA	Job safety analysis
K	Background knowledge
L	Length of gel plug
LP	Low pressure
MSDS	Material safety data sheet
P	Probability
P&ID	Piping and Instrumentation Diagram
PPE	Personnel protection equipment
PRD	Pressure relief devices
PSV	Pressure safety valves
R	Pipe radius
S	Sensitivity
U	Uncertainty
V	Velocity

W	Weight
X-linker	Crosslinker
ρ	Density
τ	Yield stress
ΔP	Pressure drop

Chapter one

1.0. BACKGROUND KNOWLEDGE

As the demand for oil and gas increases, so does the design and installation of new platforms and facilities increases in oil and gas industry. To save cost, the industry may perform repairs and modification of exiting platforms, facilities, templates, and pipeline so as to improve production instead of investing in new equipment. Such modification projects are sometimes carried out by using gel for component isolation.

Gel is, amongst other applications, used to prevent ingression of water into pipelines when repairs such as changing of valves, hoses, and others are being done. An example is the recent modification in the Statfjord field by Statoil. Gels are very useful in pipeline applications because of their complex rheological behavior which gives them a unique flow characteristic. However, gel usage in pipeline applications has some challenges.

A big problem associated with gel usage is the difficulty encountered in determining its specifications such as gel length, flow rate, pipe diameter, yield stress and pressure drop required to carry out the isolation activity without exceeding the maximum allowable pressure of the pipeline.

1.1. Study Objective

Halliburton Pipeline and Process Services (HPPS), Tananger, Norway has used gel for pipeline applications with great success for many years. The most common application is the placement of a gel slug across a subsea connection which is to be disconnected for repair/modification. Removing the gel from the pipeline after use might be an issue. This is because an accurate pumping pressure, flow rate and yield stress are required to set the gel plug in motion without exceeding the line maximum allowable pressure.

The primary objective of this research work is to develop a model to predict the restart pressure for a static gel plug in a pipeline without exceeding the pipeline design pressure. The underlying objective will be to analyze and identify the risk that can occur during the experiment.

The model in this study is developed using the results obtained from the experiments carried out at Halliburton test yard and International Research Institute of Stavanger (IRIS). The

experiment is extended to IRIS because more data is needed for the model to fit perfectly and describe a real life situation. IRIS has the 6 inches pipe in place.

1.2. Plan of the study

This study is divided ino six chapters. Chapter one has the background, objective and problem statement. The literature review is in chapter two which examines different fluid models in pipeline applications, describes gel and its application. Also, a presentation of mathematical flow model to predict restart pressure of static gel (crosslinked gel plug) in the pipeline is done in chapter two. Chapter three is the description of the pilot plant set-up and experimental procedure. Chapter four consists of a presentation of the risk analysis which includes what can go wrong, causes, consequences, counter measures and precautions that should be taken. Chapter five shows the analysis done using a mathematical model, presentation and discussion of results. Finally, chapter six supplies the conclusion and recommendation which were drawn based on the results.

Chapter two

2.0. FLUID MODEL IN PIPELINE APPLICATION

Fluid can be defined as a substance that cannot resist a shear force or stress without moving. They can be classified based on physical and chemical state. Fluids are classified based on their physical state as either gaseous, liquid or both. An example of fluid is linear gel (Halliburtion, 2011). A linear gel is a type of fluid which comprises of solvent and uncrosslinked polymers.

It is very important to understand fluid characteristics before it can be used in pipeline applications and service operations. Such pipeline applications and service operations include pipeline isolation, cementing, water and sand control, and in industrial cleaning. Fluids are known to exhibit properties that are largely dependent on flow conditions. These properties are studied in rheological laboratory conditions (Halliburton, 2011).

2.1. Rheological properties of fluid

Rheology is the study of deformation and flow of material, including liquids and solids (Cheremisionoff, 1986). The fluid rheological characteristics are critical in evaluating the ability of a fluid to perform a specific function in well operations and pipeline applications. The rheological properties of a fluid are numerous and some of these properties are discussed as below:

- *Laminar flow*: The nature of the type of fluid flow is determined by the value of the Reynolds number. We have laminar flow when the Reynolds number is lower than or equal to 2000. This indicates that the flow is calm and regular (Rume, 2009).

- *Turbulent flow:* Turbulent flow is a flow at a high rate with wider pipes. Its shear stress is a function of the density. We have turbulent flow when the Reynolds number is higher than 4000. This indicates that the flow is characterized by recirculation, eddies, and apparent randomness (Rume ,2009).

- *Viscosity:* This is defined as the ratio of shear stress to shear rate (Halliburton, 2011). An important property of any fluid is its resistance to flow. The fluid viscosity is the

physical property that characterizes the flow resistance of simple fluids[1]. The unit on viscosity is either Newton second per square meter or Pascal seconds. Another unit of viscosity is Poise (dyne. Second/centimeter). The expression for viscosity is as shown in equation (1).

$$\mu = \frac{\tau}{\gamma}$$
(1)

In equation (1), μ is viscosity, τ is the shear stress and γ is the shear rate.

- **Shear Stress and Shear Rate:** Shear Stress (τ) is defined as the force required to move a given area of fluid (Astaria, 1990). The unit of shear stress is Newton per square meter, which is also known as Pascal. On the other hand, shear rate (γ) is the rate of movement between fluid areas. It is determined by dividing the velocity difference (V) of the fluid between two boundaries by the distance (L) between them. This is called the velocity gradient. The unit is measured in reciprocal of seconds (sec^{-1}). The expression for both shear stress and shear rate are as shown in equation (2) and (3) respectively.

$$\tau = \frac{F}{A}$$
(2)

In equation (2), τ is shear stress, F is the force, and A is area

$$\gamma = \frac{V}{L}$$
(3)

In equation (3), γ is shear rate, V is the velocity difference, and L is the length between the two boundaries.

2.1.1. Types of fluid

There are basically two types of fluids. They are Newtonian fluids and Non-Newtonian fluids (Halliburton, 2011).

- **Newtonian fluids**

In these fluids, shear stress and shear rate are directly proportional (Cheremisionoff,1986).In other words, there is a linear relationship between shear stress and shear rate. The

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[1]Simple fluid is also referred to as Newtonian fluid

proportionality constant relating the shear stress to shear rate is known as viscosity. The expression for viscosity has been shown in equation (1).

- **Non- Newtonian fluids**

A non-Newtonian fluid is one whose apparent dynamic viscosity (that is, the ratio of shear to shear rate) is not constant at a given temperature and pressure, but is dependent on flow conditions. An example of such flow conditions are flow geometry and shear rate. Non-Newtonian fluid behavior is encountered in many chemical and process industries (Malin, 1997).

In addition, a Non-Newtonian fluid has flow properties that differ from that of a Newtonian fluid. These properties are not characterized by simple relationship between shear stress and shear rate. The flow curves for Non-Newtonian fluids are not linear and they do not pass through the origin.

Non-Newtonian fluids can be divided into three broad groups. These are:

- Time independent,
- Time dependent,
- Viscoelastic fluids

However, out of the above listed Non-Newtonian fluid groups, the time independent group will be looked at extensively in the next sub section. This is because it describes the properties of gel plug used in this research work.

2.1.2. *Time independent Non-Newtonian fluid*

The most common type of time-independent non-Newtonian fluid behavior is pseudoplasticity or shear-thinning. This is characterized by apparent dynamic viscosity, which decreases with increasing shear rate. Examples of fluids that exhibit shear-thinning are polymer melts and solutions, mayonnaise and suspensions. Suspensions include some dilute suspensions of inert particles, paint and pulp (Cheremisionoff, 1986).

The simplest and the most commonly used representations of shear-thinning behavior are the power-law model and Bingham plastic. For many years now, the oil industry has relied solely on these two models in determining fluid characteristic and hydraulic such as viscosity, density, and velocity and among others. These two models are discussed below.

- **Power Law**

This is the most widely used model because of its simplicity. The power law is

$$\tau = K\delta^n \tag{4}$$

In equation (4), K is the consistency index, δ is the shear rate or the velocity gradient perpendicular to the plane of shear, and n is the flow behavior index. K and n are functions of temperature and pressure. K Is more sensitive to temperature than n. Ideally, the power law models can only be applied to fluids that flow homogeneously and are not time and shear dependent. Newtonian and linear polymer fluids are the only fluids that meet these requirements.

- **Bingham plastic**

Bingham plastics are those fluids characterized by a straight line on a shear-shear rate diagram that does not pass through the origin (Malin, 1997). The positive intercept on the shear stress axis is called the yield stress. The equation describing a Bingham plastic is fluid

$$\tau = \frac{\mu}{g}(\gamma) + \tau_o \tag{5}$$

In equation (5), μ= plastic viscosity and τ_o is the yield stress.

2.2. Gel description

According to Ferry (1980), gels are defined as substantially dilute cross-linked system, which do not exhibit flow when in steady-state. Although gels are mostly liquid by weight, yet they behave like solids due to their three-dimensional cross-linked network within the fluid. It is these crosslinks within the fluid that give gels their hardness and sticky structure.

Gels are used in the oil and gas industries for different purposes like isolation, pipeline cleaning and among others depending on their chemical composition and condition.

2.2.1. *Application of gel in Pipeline and Process Services (HPPS)*

The general name for HPPS gel is `Temblok' (that is, Temblok 50 TM, and Temblok MEGA TM). Halliburton's Temblok system consists of a range of linear gels which are used for several applications. These applications are as listed below:

- To prevent seawater ingression into pipelines during underwater operations, for pigging and for fluid separation.

- To pick up debris within the pipeline system during transit through the system.

- To divert treatment fluids from one zone to another.

In the next two sub sections are discussions on Temblok gels used by HPPS.

2.2.2. *Temblok 50 gel*

Temblok 50 gel is a complex water base gel with an extremely tough cohesive structure originally developed to be used as a diverting material. This stable tough viscous gel fluid is formed by cross-linking a natural gum or its derivatives in alkaline pH conditions. The natural gum is hydrated in water prior to adding the complexing agent. Its gel life depends mainly on temperature. Laboratory test results show that this gel lasts for about a year. The base fluid can be prepared using fresh water, seawater, NaCl brine (or from fresh water mixed with a percentage Glycol). The Temblok 50 gel version containing Glycol is designed to prevent freezing during winter time in the North Sea area.

Advantages of Temblok 50 gel

- It can be made from a number of available gelling agents
- It is easy to mix with most conventional equipment.
- It can be mixed with a wide variety of base fluids.
- It is shear healing (it will re-crosslink after it is sheared)
- It has a very low freezing point when prepared with Glycol
- It is not corrosive
- It can be applied in all types of completion due to the absence of solid materials in the system
- It can be pumped through a small restriction while maintaining its gel strength
- All of its components are environmentally approved for use in the Norwegian sector of the North Sea SFT classification yellow or better.

2.2.3. Temblok MEGA gel

Temblok MEGA is based on 40% by volume of freshwater and 60% by volume of Mono Ethylene Glycol (MEG) for operations carried out at low temperatures and/or cases where the gel might contact air/gas in a pipelines in order to prevent formation of hydrates. The gel has a very high viscosity in its cross-linked state.

For the purpose of this research, more emphasis shall be laid on Temblok 50 gel.

2.3.   Research model

Numerous studies have carried out research on the prediction of the restart pressure for static gelled fluid in pipeline applications. These research works used different approaches and models to arrive at different methods of predicting pressure required to move gel plug in pipeline. Although most of them worked with gelled waxy crude, this can still be applicable to the use of cross-linked polymer.

More Recently, Davidson et al (2004) presented a model on the restart of a pipeline with compressible gelled waxy crude after shutdown. In their work, another fluid under pressure was used to displace the gelled oil so as to restart the flow in the pipeline. This fluid was assumed to display Bingham plastic behavior in the model. They stated that the applied pressure must exceed the operating pressure and must be sufficiently large to overcome the strength (yield stress) of gelled oil plug.

In Davidson et al (2004) model, the effect of both the yield stress and thixotropic behavior, and the compressibility of the gelled oil after a period of shut down were put into consideration. Meanwhile, in this research work, cross-linked polymer, yield stress, pipe diameter and length of gel plug are used.

Also, Feesa (2003) worked on non-Newtonian flows in pipelines. They used Herschel-Bulkley model for the flow model and assumed that the flow inside the pipeline is laminar. Feesa (2003) observed a restart problem of gelled oils in pipelines after shut down. This is because gelled oil has rheological behavior which is a function of temperature and formation history of the gel. However, this problem has led to considerable uncertainty associated with the fluid properties. It is based on these uncertainties that Feesa developed their model to predict the flows of gel in pipes. Feesa (2003) started the model from the first principle by carrying a simple force balance on the pipeline to arrive at the pressure drop equation.

The pressure drop equation adopted by Feesa (2003) is similar to the one used in this research work. But here, it is only used to calculate the theoretical pressure drop that is expected when carrying out the experiment.

In addition, Margarone et al (2010) had a study on the problem of restarting waxy crude in a pipeline and developed a one-dimensional model by modeling the waxy crude as Bingham fluid. The developed model which consists of yield stress, the Bingham plastic viscosity, the gel compressibility and the density as input parameters used to calculate the theoretical restart pressures. It was then compared with an experiment carried out in a model pipeline with multiple pressure taps at constant injection flow rates.

The approach of Margarone is adopted in this research work with the exception that, there is a major difference in the input parameters used. The input parameters used in this work are yield stress, gel plug length and the pipe diameter.

Also, Vinay (2009) examined the possibility of restarting gelled waxy crude for a pressure below the theoretical pressure drop by combining the effects of compressibility and thixotropy. They concluded that, it is possible to have flow when the pressure drop is below the theoretical minimum pressure $4\tau L/D$.

Although the aim of most of these studies is geared towards developing a model to predict restart pressure of either gelled waxy crude or gelled fluid in pipelines using the laboratory model, the restart pressures are however overestimated in most cases. This is because evaluating pressure drop (Δp) with $\Delta p = \frac{4\tau L}{D}$ using the yield stress (τ_y) measured with rotational rheometer[2] and pressure drop obtained directly from the pipelines differ.

However, this research work shall be carried out on a large scale so as to accurately determine the restart pressure for a gelled plug (HPSS Temblock) in a pipeline. By so doing, a thorough risk assessment and analysis on the set up will also be carried out to determine what can go wrong, the cause, consequence and the necessary measures to reduce or eliminate it.

Aven and Vinnem (2007) defined risk management as all measures and activities carried out to manage risk. They also stated that risk management deals with balancing the conflicts inherent in exploring opportunities on one hand and avoiding losses, accidents and disasters on the other.

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[2]A rheometer is a kind of viscometer that measure visco-ealstic properties of materials beyond just viscosity

Vinnem (2007) in his book titled `Offshore Risk Assessment', stated the principles and models for carrying out risk assessment on offshore activities. He analyzed some major accidents like Piper Alpha in the North Sea, lessons learnt from it and possible ways to reduce or eliminate the risk (hazard).

Aven (2008) stated in his book on Risk Analysis that, the objective of risk analysis is to describe risk. That is, to present an informative risk picture. He differentiated between the three categories of risk analysis methods and also explained the tools that can be used in various categories. The categories of risk analysis differentiated are: simplified risk analysis, standard risk analysis and model-based risk analysis. The approach of Aven (2008) to risk analysis has been adopted in this research work. More details on this are in chapter three of this study.

The knowledge gained from these books and other sources shall be used to analyze the likely hazards that can occur in the course of this research work.

2.3.1 Pressure drop Model

In this sub section is the derivation of pressure model equation. The derived pressure model equation is used in this study to calculate the theoretical pressure drop required to move a gel plug in a pipeline, so as to have idea about the actual pressure. This can be derived by carrying out a force balance on the pipe.

Consider a pipe of length L, diameter D, radius R, $(D = 2R)$ and plug gel of length L_g inside the pipe. When there is a fluid of density ρ flowing through the pipe, there exist shearing stresses in the boundary layer of flowing flow. These stresses are exerted in the opposite direction to the flow and, therefore, may be thought of as the forces resisting the flow (Cheremisionoff, 1986). For the gel plug to move, this shear stress must be overcome. The value of the stress which must be overcome for the gel plug to move or flow is called yield stress, τ_Y.
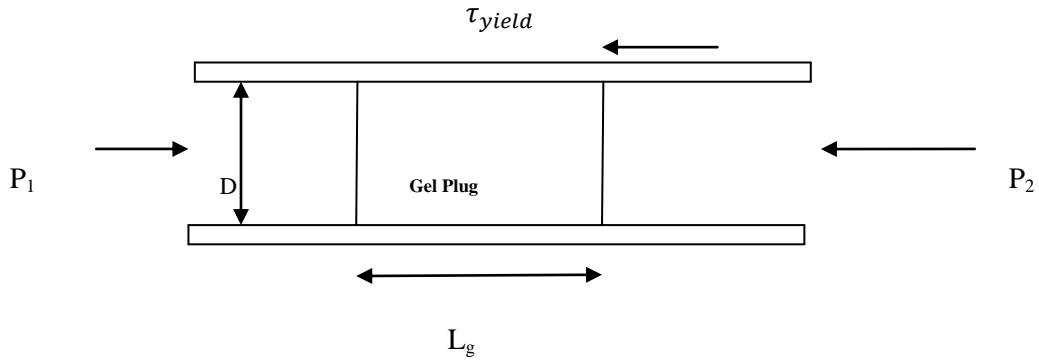
Figure.*2.1 Cross section of gel plug in a pipeline*

From the force balance over the length of the gel plug in the pipeline, we have equation (6).

F₁- F₂ -W-Fy = 0   (6)

Where F_1 is the force at the inlet, F_2 outlet force, W is the weight of the Gel plug and F_y is the force due to the yield stress at the wall.

Also from Force = Pressure *Cross sectional area

i.e $F = PA = P * \pi R^2$

And

$$Density = \frac{Mass}{Volume} \qquad \rightarrow \text{Mass = Density * Volume}$$

i.e mg $= \rho Vg = \pi R^2 L * \rho * g$

This implies that equation (6) can be

$$\pi R^2 P_1 - \pi R^2 P_2 + \pi R^2 \rho L_g\, g - 2\pi R L_g\, \tau_y = 0 \qquad (7)$$

Where P_1 and P_2 are inlet and outlet pressure respectively

Equation (7) can be rewritten as

$$\frac{\Delta P}{\rho} + L_g\, g = \frac{2L_g\, \tau}{\rho R} \qquad (8)$$

Where in equation (7), $\Delta P = P_1 - P_2$

Defining the sum of the friction forces to be $\Delta P/\rho$, then

$$\sum F = \frac{\Delta P}{\rho} = \frac{P_1 - P_2}{\rho} - L_g\, g \qquad (9)$$

Solving equation (7)

$$\Delta P\left(\frac{\rho R}{2L_g}\right) = \tau \rho \qquad (10)$$

$$\Delta P = \frac{2\tau L_g}{R} \qquad (11)$$

But $R = \dfrac{D}{2}$

At yield point, the gel plug begins to flow. Hence, shear stress (τ) become yield stress (τ_Y). This implies that equation (10) becomes

$$\Delta P = \frac{4\tau_y L_g}{D} \qquad (12)$$

Equation (12) is the pressure drop required to overcome the yield stress of the fluid.

Chapter three

3.0.   DESCRIPTION OF THE TEST SET UP

The experimental setup consists of equipment and instruments shown in the piping and instrumentation diagram (P&ID) which can be found in appendix 17. Some of these equipment and instruments used are as described below.

- *Gel Tanks*

This is a 4.5 m^3 pressurized tank used to store linear gel (that is, Temblok 50 gel in this research work) for the experiment. This tank is pressurized because of the gel's viscous nature. The tank is pressurized at 1 bar to force the linear gel out of the tank.

- *Fresh water tank*

This tank has a capacity of 4.5 m$^{3.}$ It is used for storing fresh water needed in this experimental set-up. The fresh water inside the tank is used as fluid to flow the gel plug in the pipeline. The stored fresh water is also used to flush the system and to dilute the gel plug, thereby, making it less viscous for easy disposal after usage.

- *Chemical Tank*

This tank has a capacity of 1.0 m^3. It contains the chemical known as the crosslinker which can also be referred to as X-linker. The crosslinker is used for crosslinking the linear gel to produce the crosslinked gel plug.

- *HT -400 pump*

This is a positive displacement pump with high flow rate and pressure over a short period of time. It pumps from 100 liter to 1500 liter per minute with a pressure range of 0 to 700 barg. It is used in this research work to fill the system initially with water and to prime the linear gel to the meeting point with the X-linker. The HT-400 pump is also used to move the gel plug to the required distance (say 10 meters) inside the test pipes of 2 inches, 4 inches and 6 inches before using the Haskel pump for the test. It has an adjustable pressure shutdown and pressure safety valve. For safety purpose, the pressure rating on the pump is set at a lower value than that of the pressure safety valve on the discharge side of the main line.

- *Haskel Pump.*

This is an air driven test unit for pressure and burst testing. It is a positive displacement pump with low pressure and flow rate over a short period of time. It has a pressure range of 420bar and pumps about 0.057 liters per stroke or 0.5 to 3 liters per minute. Haskel pump is used as the test pump in this research work because of its small pumping rate which allows the pressure for moving the gel plugs to be easily recorded. The Haskel pump is installed along the test line to move the settled gel plug in the pipeline (discharge line).

- *Chemical Injection Pump*

This is a small pump with 50 to 150 strokes per minutes. It is used to prime X – linker to the junction where it meets with the linear gel.

- *Pressure gauge*

This is an instrument used to measure pressure. There are various types of pressure gauges depending on their applications. The pressure gauge used for this research work is called 4 inches Stand-alone of pressure 0 to 400 bar. It is installed along the discharge sides of both the main line and the test line to determine and record the pressure required to move the gel plug.

In this research work, there is the local read-out pressure gauge mounted on the discharge side of both the main line and the test line.

- *Flow meters*

This is an instrument used for measuring the flow rate or movement of fluid in the pipe. According to Coleparmer (2011), selection of flow meters for a particular process depends on flow measurement type (volumetric or mass flow measurement), type of media (liquid, gas or slurry), media conditions (pressure and temperature), flow range (minimum and maximum reading required) and required accuracy of the readings.

The flow meter used for this research work is called turbine flow meter. Turbine flow meters use the mechanical energy of the fluid to rotate a "pinwheel" or rotor in the flow stream. It is calibrated in liter per minute and installed after the pump on both the main line and the test line. There is a local read-out mounted directly on the flow meter and another one inside the

test cabin. It is recommended that a straight line runs into and out of the flow meter to avoid turbulence. The presence of turbulence affects the readings of the flow meters.

- *Pressure safety valve*

Pressure Safety Valves (PSVs) which is sometimes called Pressure Relief Valves (PRVs), Pressure Relief Devices, (PRDs) or simply safety valves is primarily used in protecting life and properties. It is a mechanical valve that is designed to open when a certain pressure value is exceeded in a process pressure system. This action helps to protect life and all investments that have been put into such process plants, and also to prevent the occurrence of hazard or accident.

The PSV is able to perform the hazard preventive function by acting as a path of least resistance in the event that the system pressure exceeds the set pressure of the PSV. This would allow a portion of the fluid to be diverted through an auxiliary route connected to a flaring system. As the fluid is being diverted, the pressure within the pressure system drops and when the pressure drops below the valves reseating pressure, the valves closes.

In this research, the PSV is connected along the main line and the test line to prevent the set up from being over-pressurized. The pipe design pressure has been used to set the PSVs. This is taken as approximately 123% of the test pressure for the 2 inches pipe. The PSV on the discharge line is set at 345 barg for the 2inches pipe, 125barg for both the 4 inches pipe and the 6 inches pipe.

The PSVs are rigged up in such a way that they face down to prevent lateral movement during discharge.

3.1.   Operational Procedures

The experiment in this research work is carried out at Halliburton test yard and IRIS test yard. As below is the summary of operational procedure**.**

a. At the onset of this experiment, Lip test is carried out on linear gel in the tank in order to ensure that the linear gel is in good condition.
b. The experiment is rigged up according to the P&ID (see appendix 17)
c. The system is filled with fresh water using the HT- 400 pump
d. It is then pressurized to test for low pressure (LP) and high pressure (HP) of 340bars

e. A thorough leak test is conducted on the system by holding on the pressure for about 15 minutes

f. After this, the linear gel is the primed to the valve ML7 using the HT-400 pump

g. The X-linker (alkaline) is also primed to the junction where the chemical line meets the main line using the chemical injection pump

h. The linear gel and the X-linker are injected into the system in a steady and controlled manner according to table 3.1

i. After the desired length (e.g 50m) of gel plug has been produced, injection of linear gel and the X-linker is stopped

j. The HT - 400 pump is then used to push the gel plug to a certain distance inside the test pipe (say 2 inches pipe)

k. The produced gel plug is then allowed to settle for a while

l. The Haskel pump is switched on and then used to build up pressure in the test line by pumping in fresh water. Pumping continues and the pressure at which the gel starts to move is recorded

m. When the gel moves, pumping is suspended for some minutes to allow the gel plug settle down

n. Steps k to i are repeated as many times as the pipe permits to obtain more sets of data

o. Steps h to m are repeated for 100m and 150m gel plug.

p. The 2 inches pipe is replaced by 4 inches and step e to o is repeated on other lengths of gel plug

q. The entire procedure is repeated for the 6 inches pipe at IRIS test yard

Table 3.1: Injection rates for both linear gel and X-linker

HT 400 pump liter/min	X-linker pump liter/min
70	0,5
90	0,7
110	0,8
130	1,0
150	1,1
170	1,3
190	1,4
210	1,6
230	1,7
250	1,9
270	2,0
290	2,2
310	2,3
330	2,5
350	2,6
370	2,8
390	2,9
410	3,1

Chapter four

4.0   RISK ANALYSIS

According to Aven (2008), risk can be defined as two - dimensional combinations of (i) events A and the consequences of these events C, and (ii) the associated uncertainties U (about what will be the outcome), that is C, U.

Risk can also be defined as a combination between consequences and probabilities (C, P) (Aven, et.al, 2007). Comparing these two perspectives of risk definition, the later is obviously an inadequate description of risk because it has only probability in it definition. Probability is a tool for expressing uncertainty with respect to A and C. However, it is an imperfect tool, as it does not reflect the uncertainty associated with the risk hidden in the background knowledge K^3.

For example, consider a situation where probability is assigned to fatalities occurring on an offshore installation based on the assumption that the installation structure will withstand a certain accidental load. In real life situation, the structure could fail at a lower load level. However, the probability here does not reflect the uncertainty that the structure could fail when lower load is applied.

Another example is the one seen through the eye of an analyst in 1970s related to future health problems for divers working on offshore petroleum projects. An assignment is to be made for the probability that a diver would experience health problems during the next 30 years due to diving activities. Assuming that probability of 0.5% is made and this number is based on available knowledge at that time. There are not strong indications that the divers will experience health problems. However, it is known today that these probabilities led to poor predictions and many divers have experienced severe health problem (Aven, et.al, 2007). Uncertainty and risk are hidden when restricted to probabilities alone. Therefore, risk is not adequately described by A,C and P alone.

But the former definition adequately describes risk because it contains uncertainty U, which may be hidden in the background knowledge K. This definition can stand alone without the probability P to describe risk.

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[3] In this research work, background knowledge, historical data and experience gained over time means the same.

Risk analysis involves identifying the relevant initiating events and developing the causal and consequence picture. The main steps in risk analysis process are as shown in Figure 4.1. These steps have been used to analyze the risk in this research work.

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┌─────────────────────────────────────────────┐
│ Problem definition, information gathering and │      Planning
│         organization of the work             │
└─────────────────────────────────────────────┘
                     │
┌─────────────────────────────────────────────┐
│         Selection of analysis method         │
└─────────────────────────────────────────────┘
                     │
┌─────────────────────────────────────────────┐
│ Identification of initiating events (hazards, │   Risk Assessment
│          threats, opportunity)               │
└─────────────────────────────────────────────┘
        │                         │
┌──────────────────┐   ┌──────────────────────┐
│  Cause analysis  │   │ Consequence analysis │
└──────────────────┘   └──────────────────────┘
        │                         │
┌─────────────────────────────────────────────┐
│                 Risk Picture                 │
└─────────────────────────────────────────────┘
                     │
┌─────────────────────────────────────────────┐
│ Compare alternative, Identification and       │   Risk Treatment
│        assessment of measure                 │
└─────────────────────────────────────────────┘
                     │
┌─────────────────────────────────────────────┐
│   Management review and judgment, Decision   │
└─────────────────────────────────────────────┘
```

Figure 4.1: The main steps of the risk analysis process (Aven, 2008).

4.1. Planning

4.1.1. Problem Definition

Risk analysis has been decided to be conducted before carrying out the practical experiment of this study. The is due to several uncertainties which are associated to each of the hazards that can occur during this research work. These likely hazards are identified and categorized according to their severity in subsection 4.2.1 to 4.2.3.

In risk analysis, there are several decision makings tools which include risk acceptance criteria, cost benefit analysis, changes in the risk, cost-effectiveness and among others. In this study, risk acceptance criteria have been used for decision making for simplicity, information availability and easier usage.

4.1.2. Risk Acceptance Criteria

Risk acceptance criterion is a tool for risk management and a commonly used basis of judging risk analysis results in relation to setting acceptable working risk levels and identifying aspects of an operation for which some kind of risk reduction would be necessary (Wenche et al 2005).

 The objective of setting risk acceptance criteria is to express optimal levels of safety for this research work in terms of human safety, environmental safety and economic losses. The risk acceptance criteria set in this research work can be found in appendix 2.

In this study, risk acceptance criteria have been divided into three regimes with code 1, 2, and 3. Code 1 is the Unacceptable regime. Hazards that fall into regime 1 are termed as unacceptable. In regime 1, we have measures that should be implemented so as to reduce the hazards to a level that is As Low As Reasonable Practicable (ALARP). Code 2 is the ALARP regime and Code 3 is the Acceptable regime.

4.1.3. Selection of Analysis method

The risk analysis method used in this research work is standard risk analysis. This is because standard risk analysis is a more formalized procedure that involves the use of recognized method such as HAZOP, FMECA, Job Safety Analysis (JSA) and among others. It can also be carried out either qualitatively or quantitatively and can be used with risk matrix to present results.

The standard risk analysis method used in this study is JSA. JSA has been used to identify, analyze and record the operational procedure, the potential safety and health hazards associated with each step in the procedure and the recommended action that will eliminate or reduce these hazards and the risk of a workplace injury or illness.

4.2.   Risk Assessment

4.2.1   Hazard identification.

Hazard can simply be referred to as a situation that poses a level of threat to life, health, assets, or the environment. Hazard identification which is also known as HAZID involves identifying, categorizing and documenting the hazards that could affect a project. The potential hazards in this research studies have been identified using the JSA in appendix 2 and they are as follow:

- Missing of vital information regarding the valves alignment, pipes, hoses, pumps and other fittings could lead to hazard
- Project schedule delay leading to late thesis submission
- Human error leading to breakdown of equipment
- Delay in operation
- Injuries to personnel
- Electric shock to personnel on duty
- Exposure to chemicals by personnel and the environment
- Personnel falling down/out due to slippery floor
- Falling down from heights, ladder lead broken arms, legs and other injuries
- Explosion due to high pressure from the pipeline and pumps
- Chemical and gel spillage from the chemical injection pump and chemical tank
- Exposure to cold due closeness to the sea (Sea breeze) can cause flu
- Noise pollution from diaphragm pump, HT-400 pump and other noise equipment
- Leakages from pumps , lines, valve and among others
- Unsecured hoses to the floor at high pressure can be directed towards personnel on site thereby causing serious injuries
- Finger jam and cuts. Personnel fingers might be jam to rotating equipments like pumps, compressors and among others

4.2.2. Causes of hazards

These are the starting point of the potential hazards (accidents) or initiating events and if identified earlier, the occurrence can be prevented by putting the necessary barriers in place. Potential source of hazards for this research study based on the JSA and brainstorming are as follow:

- Inexperienced personnel

  The equipment might be operated by inexperience personnel. This might lead to complications and possible inability to fix any broken down equipment
- Unavailability of equipment /late delivery

  The late arrival or unavailability of equipment (most especially critical equipment) can lead to late submission of thesis.
- Unfamiliar equipment

- Wrong equipment and fittings specification during mobilization could lead to a delay in the project and as such lead to more cost to Halliburton and late thesis submission.

- Misunderstanding between personnel could lead to frequent quarrel and affect overall performance of the team

- Improper reference to material safety data sheet (MSDS) could lead either minor or major accident on site

- Improper use of the safety kits such as the ear plugs, hand gloves, goggles and among others could also lead to injuries.

- Malfunctioning of the PSV could lead to over pressurization of the line and later lead to explosion

- Poor calibration and low safety margin on the PSV could be dangerous

- Improper tightening of fittings valves ,hoses and pipes can cause accident during pressure test

- Presence of sand or dust particles on the O-ring could lead to leakages .This means that a lot time has to be spent rigging down

- Not making use of the valve status checklist before kickoff can lead to accident

- Inadequate or omitted leak test and pressure test can lead to serious explosion and injuries during test

This cause of hazard analysis is known to have a lot in common with traditional reliability analysis. Therefore, one of the reliability tools will be used to carry out a cause of hazard analysis in this study (Fig 4.3). The objective will be to show or identify the combination of causes that may lead to the initiating event or hazard (Peter, 1998).

The tool used here, is the fault tree analysis (FTA). A fault tree is logical diagram that shows the relation between system failure (specific undesirable event) and failures of the components of the system (Aven, 2008). The undesirable constitutes the top event of the tree and the different component failures constitute the basic events of the tree..

In this case, the single top event is leakages and explosion due to high pressure. Figure 3.1 shows a simple fault tree for testing procedure in this study.
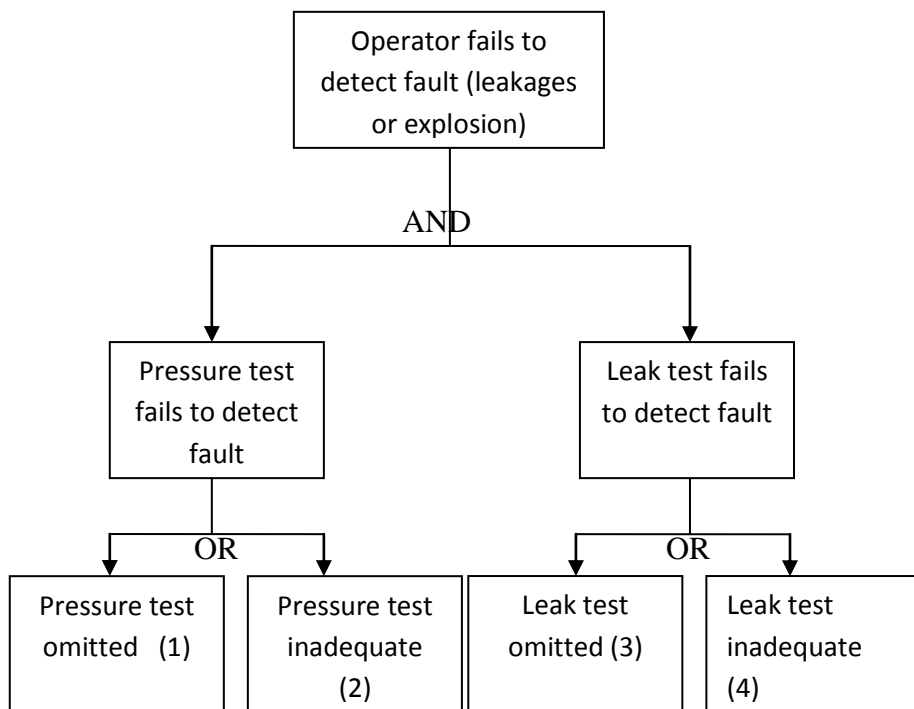
Fig 4.2   A simple fault tree for testing procedure

.
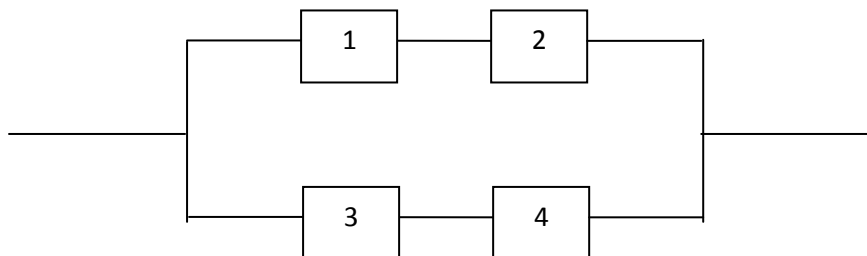
Fig 4.3: Reliability block diagram for the fault tree in Figure 4.2.

The minimum cut sets for the fault tree are [1, 3] [1, 4] [2, 3] and [2, 4].

A cut sets in the fault tree is a combination of causes that may lead to the hazard. A cut set is minimal if it cannot be reduced and still ensure the occurrence of the hazard (top event).

The reliability of the system (h) in figure 4.3 can calculated as shown below

System reliability $h = (1 - (1 - p_1 p_3)(1 - p_2 p_4)$

Where $p_1, p_2, p_3 \ and \ p_4$ are component reliabilities.

4.2.3. Consequences of hazard

Consequence describes the result of an accidental event and this can be evaluated for different categories. The consequences in this research work are based on the causes of hazard and they are evaluated for human safety (against personnel injury in this case), environmental impact and economic loss regarding the equipment used and the cost of experiment. They are ranked according to their severity from I (catastrophic) to IV (Negligible).

The consequences associated with each initiating events have been identified and presented on the JSA in appendix 1 and measures recommended based on the risk acceptable criteria in appendix 2.

The probability distribution associated with consequence, in this case personal injuries can be seen in figure 4.4 below.
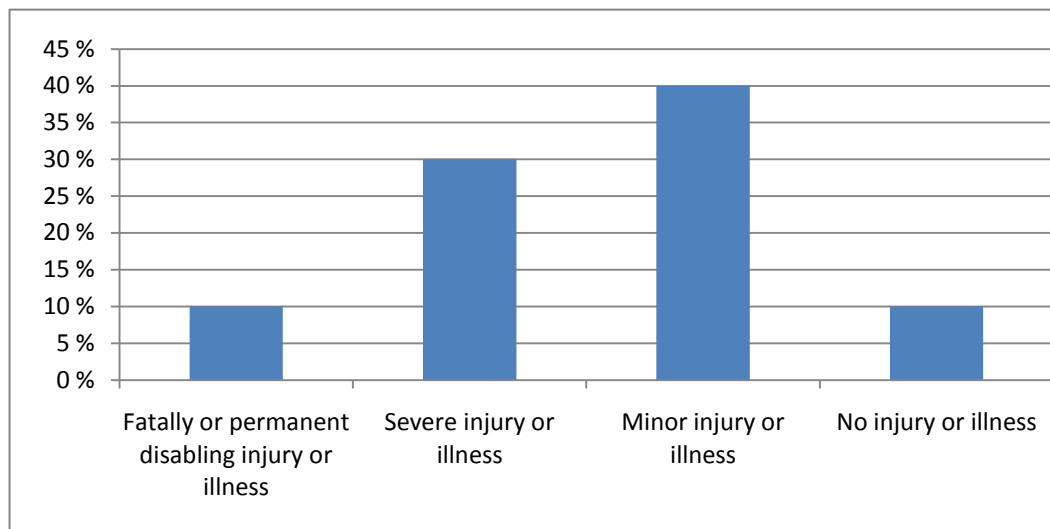
Figure 4.4: Probability distribution associated with the consequence (Personal injuries)

4.2.4. Uncertainty Assessment

In this research work, the deterioration of critical equipment is assumed not to cause hazard or break down problem by putting necessary barriers in place. However, experience gained during offshore projects (Real life project) has shown that expected problems do occur. The usage of critical equipment such as HT-400 pump, flow meter, pressure transducers and among others do deteriorate and spring up surprises over a long period of time.

In this research work, a probability of 20% has been assigned to these uncertainties that can spring up during the experiment. So, if the probability of HT-400 pumps not breaking down is

90% based on the background experience K, the probability of HT- 400 pump not breaking down equals 0,9*0,2.= 0,18. Hence, considering the uncertainties, the probability of HT-400 not actually breaking down is 18% and not 90%.

Uncertainty can be reduced to a great extent by performing an operational hazard and identification analysis (HAZID) early in the project. The operational procedure should be reviewed with all relevant personnel involved.

4.2.5   Sensitivity Analysis

There is high probability of having uncertainties in the experimental measured quantities that are used in equation (20) to determine the pressure drop. The measured quantities that are prone to uncertainties are length of gel plug in the line, flow rate, and pipe diameter amongst others. The uncertainty is either due to bias (related to accuracy) or the unavoidable random variation that occurs when making repeated measurements (related to precision). This uncertainty has to be addressed and that is why sensitivity analysis has been decided to be conducted.

According to Aven, sensitivity analysis in risk analysis context is the study of how a sensitive calculated risk index is with respect to changes in conditions and assumptions made. This is a type of uncertainty analysis. The sensitivity analysis in this research work looked at how a change in the parameters in equation (20) affects the predicted pressure drop.

Experience (background knowledge k) over the years has shown that there is likelihood of having an error in the measured value of gel plug length L in the pipeline.

In this regard, sensitivity analysis has been decided to be conducted on the pressure drop predicted by having a 50m gel plug in a 2 inches pipeline. Assuming that there is an error (uncertainty U) in the length of gel plug pumped in a 2 inches due to wrong calibration of measuring instruments and a that probability of ±5% has been assigned to this error. Also, that there is an error of ±5% in the diameter d, of the pipeline due to the same reason as the gel plug length.

Figure 4.5 and 4.6 show sensitivity analysis on the expected pressure drop in a line with a constant diameter d, and a varying gel plug length $(L + \Delta L)$ due to error in measured values and expected pressure drop for a constant gel plug length L, and varying diameter$(D + \Delta D)$ due to error in measurement respectively.

It can be seen from figure 4.5 that an error in the measured length of gel plug has a strong effect on the expected pressure drop. The error causes the results to deviate from the actual value. This implies that the model is very sensitive to the length of gel plug and as such, more effort should be geared towards obtaining accurate and precise measurement.

It is very fruitful to present results with probability P, sensitivity S and uncertainty U than using P alone because the former (the combination of P,S,U) gives a clearer picture and shows which of the independent variable is more sensitivity to changes than the later (P alone).
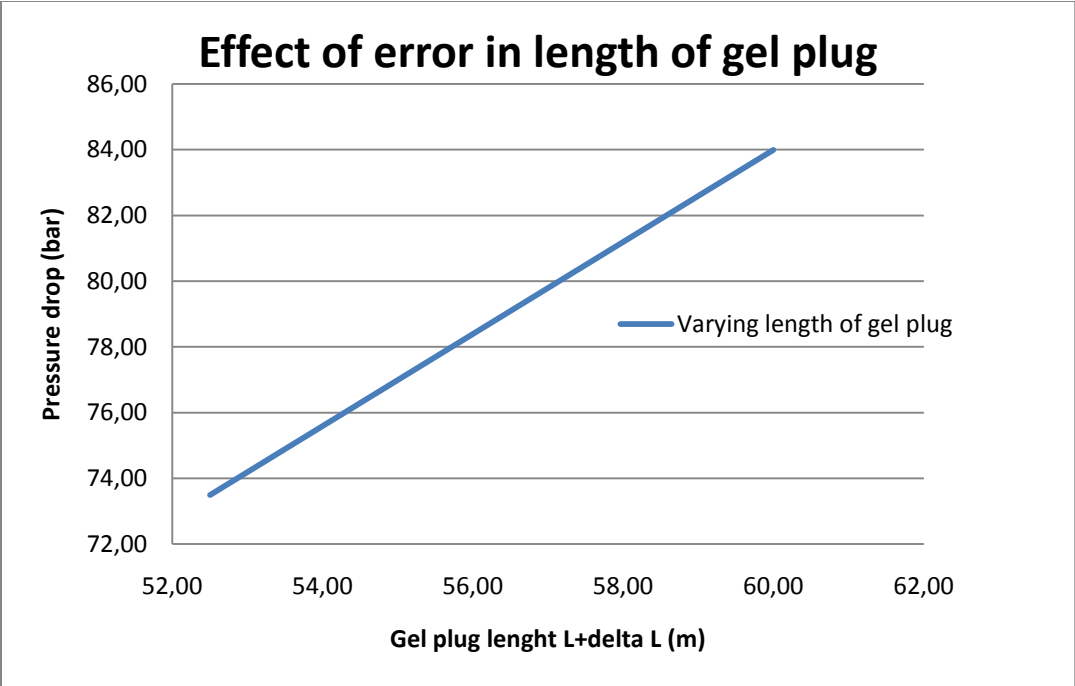
Figure 4.5: Sensitivity analysis on the pressure drop model equation with error in gel plug length measured
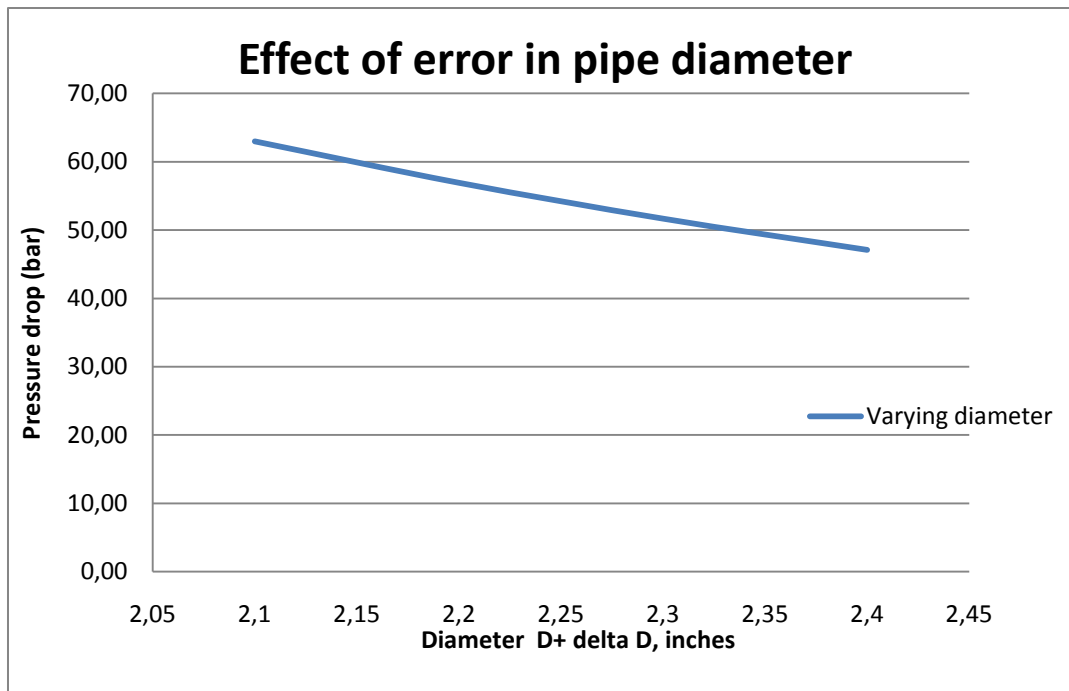
Figure 4.6: Sensitivity analysis on the pressure drop model equation with error in pipeline diameter measured

4.2.6 Risk reducing measures.

These are steps or procedures or barriers that should be in put place in order to reduce or eliminate the potential hazards in this research work. These precautionary measures are recommended based on the regime in which the hazards fall on the risk acceptance criteria in appendix 2. Below are some of the measures, though most of them have been included in the JSA.

- Educating the operators prior to the commencement of the experiment
- Carrying out the mobilization exercise on time
- A pre- check on the equipment lists before mobilizing
- Comparing the equipment list with the initial listed items
- Frequent communication between the students ,the operators and the supervisors
- Use of experienced personnel for the project
- Ordering of at least two extra items for each set of materials and equipment
- Use of proper PPE (personnel protection equipment)
- Reference to MSDS before and during experiment
- Perform leak test with water to avoid chemical and gel spillage
- Regular checks on machines, pumps among others to avoid break down

- High safety margins on PSVs
- Avoiding the presence of sands on the O-rings

Chapter Five

5.0   RESULTS

Presentation and discussion of results are as discussed in subsection 5.1 and 5.2 respectively while the assumptions made and problems encountered during the experiment are discussed in subsection 5.4 and 5.5 respectively.

5.1.   Presentation of results

Pipe Dimensions and Calculations

Table 5.1: Pipe types with their respective lengths and PSVs

Pipe	Length (m)	Pressure Safety Value(PSV) bar
2 "	350	345
4 "	280	125
6 "	700	125

Table 5.2: Volume of crosslinked gel plug needed for a single run of experiment

Volume of crosslinked gel plug (m^3)

Length of gel plug (m)/ Pipe diameter (in)	2	4	6
50	0,1014	0,4054	0,9121
100	0,2027	0,8108	1,8241
150	0,3041	1,2163	2,7362
Total (m^3):	8,51		
Total (liter):	8513,40		

The mixing ratio between the linear gel and X- linker is 1 - 0,0075. Therefore, the volume of linear gel and the crosslinker required to produce the above volumes of crosslinked gel plug are given in tables 5.3 and 5.4 below.

Table 5.3: Volume of linear gel required for each size of gel plug (single run) in the Table 5.2

Volume of Linear gel (m³)

Length (m)/Diameter(in)	2	4	6
50	0,1006	0,4023	0,9053
100	0,2012	0,8047	1,8106
150	0,3018	1,2070	2,7159
Total (m³):	8,45		
Total (liter):	8449,00		

Table 5.4 Volume of crosslinker required for each length gel plug in table 5.2

Volume of crosslinker (m³)

Length (m)/Diameter(in)	2	4	6
50	0,0008	0,0030	0,0068
100	0,0015	0,0060	0,0136
150	0,0023	0,0091	0,0204
Total (m³):	0,0634		
Total (liter):	63,37		

5.1.1. Theoretical pressure

These are the pressures calculated using model equation (equation 12) in chapter two. These calculated pressures are pressures required to move the crosslinked gel plugs in the pipeline. These pressures give idea of what to expect when carrying out test in the test yard (Halliburton test yard and IRIS test yard). Table 5.5 shows the theoretical pressures required to move each length of crosslinked gel plug in the 2 inches 4 inches and the 6 inches pipelines. The yield stress τ_y used for the calculation is 14,5 Ibf/ft^2

Table 5.5: Theoretical pressures required to move gel plug in pipelines

Pressure to move gel plug (bar)

Length of gel plug (m)/ Pipe diameter (in)	2	4	6
50	94	24	9
100	189	47	18
150	283	71	27

5.1.2. *Actual pressure*

These are pressures obtained directly from the experiment carried out at both Halliburton and IRIS test yards. The experiment was performed at least 3 times for each length of gel plug and an average has been taken. The actual pressures in table 5.6 below are the average of the experimental pressures found. The detailed experimental values are in appendix 19-21.

Length of gel plug (m)	Pressure (bar) in 2 inches	Uncertainty (%) ±	Pressure (bar) in 4 inches	Uncertainty (%) ±	Pressure (bar)in 6 inches	Uncertainty (%) ±
50	89,70	38,5	22,15	161	10,4	101,9
100	102,52	29,75	40,75	39	7,05	46
150	171,88	18,11	63,23	20	14,39	75

5.7: Presentation of actual pressure and % difference for 2" pipeline

2" Pipeline

Gel plug length (m)	Theoretical pressure (bar)	Actual pressure (Average) (bar)	% Difference in pressure
50	94	89,7	3,55
100	189	102,52	44,88
150	283	171,88	38,39

Table 5.8: Presentation of actual pressure and % difference for 4" pipeline

4" Pipeline

Gel plug length (m)	Theoretical pressure (bar)	Actual pressure (bar)	% Difference in pressure
50	24	22,15	3,70
100	47	40,75	13,30
150	71	63,23	9,67

Table 5.9: Presentation of actual pressure and % difference for 6" pipeline

6" Pipeline

Gel plug length (m)	Theoretical pressure (bar)	Actual pressure (bar)	% Difference in pressure
50	9	10,40	-14,15
100	18	7,05	61,31
150	27	14,38	47,39

5.2   Discussion of results

Table 5.1 presents the different pipe sizes used with their respective PSV. While table 5.2, shows the volume of crosslinked gel plug needed in the experiment for each pipeline. The values presented are for a single run.

Table 5.5 presents the theoretical pressures required to move each length of crosslinked gel plug in the 2, 4 and 6 inches pipeline and table 5.6 shows the pressures measured from the experiment for each crosslinked gel with their respective uncertainties.

The actual pressures presented in table 5.6 are average values of at least 3 runs on each gel length.

Table 5.7, 5.8 and 5.9 present the theoretical pressure, actual pressure and the percentage (%) difference between them for each length of gel plug in the three lines.

The average pressure value from the experiment when the Haskel pump was used to move 50m gel plug in the 2 inches line is 75,05 bar and that of HT-400 pump is 89,7bar with percentage difference of 19,30% and 3,55% respectively. It can be observed that, there is significant difference between these two values when compared. Because of the fact that HT-400 produced better results coupled with the fact that Haskel pump could not move gel plug of length 100m and above, it was decided that the HT-400 should be used for the entire test.

For the 4 inches pipeline, a percentage % difference of 3,70 to 13,30% was observed and for the 6 inches, a percentage (%) difference of -14 to 61,61 was observed. This large difference between the theoretical and the actual pressures is attributed to the topography of the line and uncertainties in the test. The 6 inches at IRIS test yard has large valley which gave fluctuating pressure drops values.
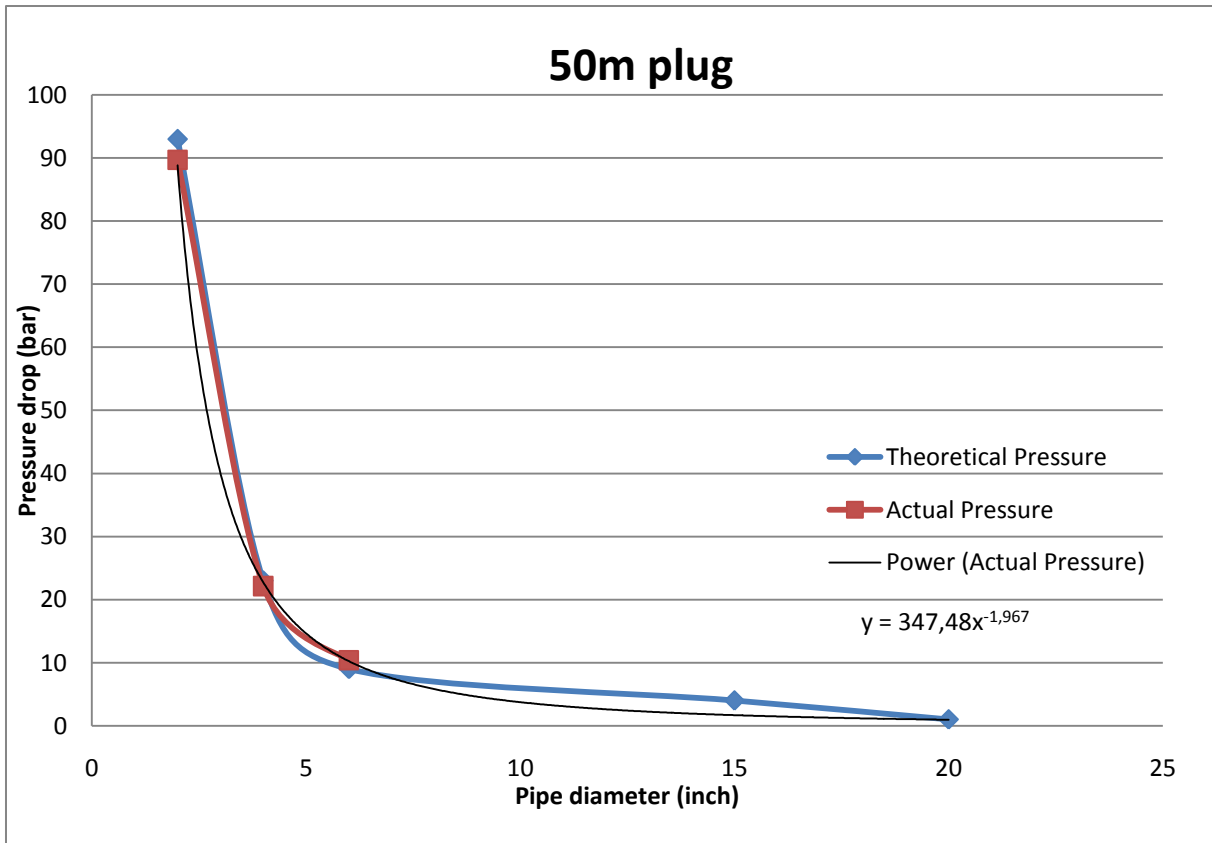
Figure 5.1: Pressure drop against pipe diameter for 50m gel plug

Figure 5.1 shows the graph of pressure drop against pipe diameter for 50m gel plug. A curve similar to the theoretical pressure was obtained for the actual pressure. After simulation, the actual pressure was observed to follow the power law model defined in chapter two of this research study. The power law equation generated from the actual pressure curve is given as:

$$\Delta P = 347{,}4\, D^{-1{,}96} \tag{13}$$

Where ΔP is the pressure drop, and D is the pipeline diameter. This model equation in equation (13) is only valid for a 50m gel plug.
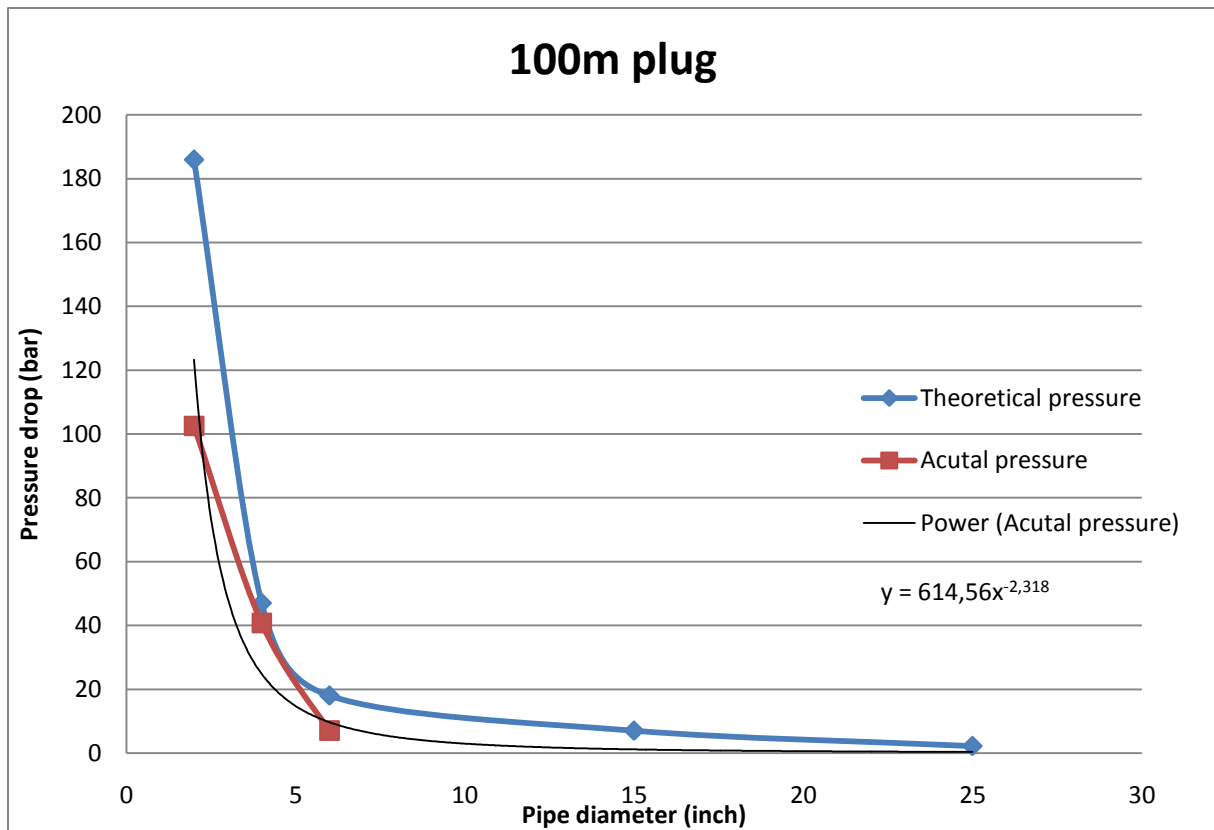
Figure 5.2: Pressure drop against pipe diameter for 100m gel plug

Figure 5.2 is the graph of pressure drop against pipe diameter for 100m gel plug. The actual pressure curve follows approximately power law model and the model is given below as:

$$\Delta P = 614,5 \, D^{-2,31} \tag{14}$$

Where ΔP is the pressure drop, and D is the pipeline diameter. This model equation in equation (14) is only valid for a 100m gel plug.
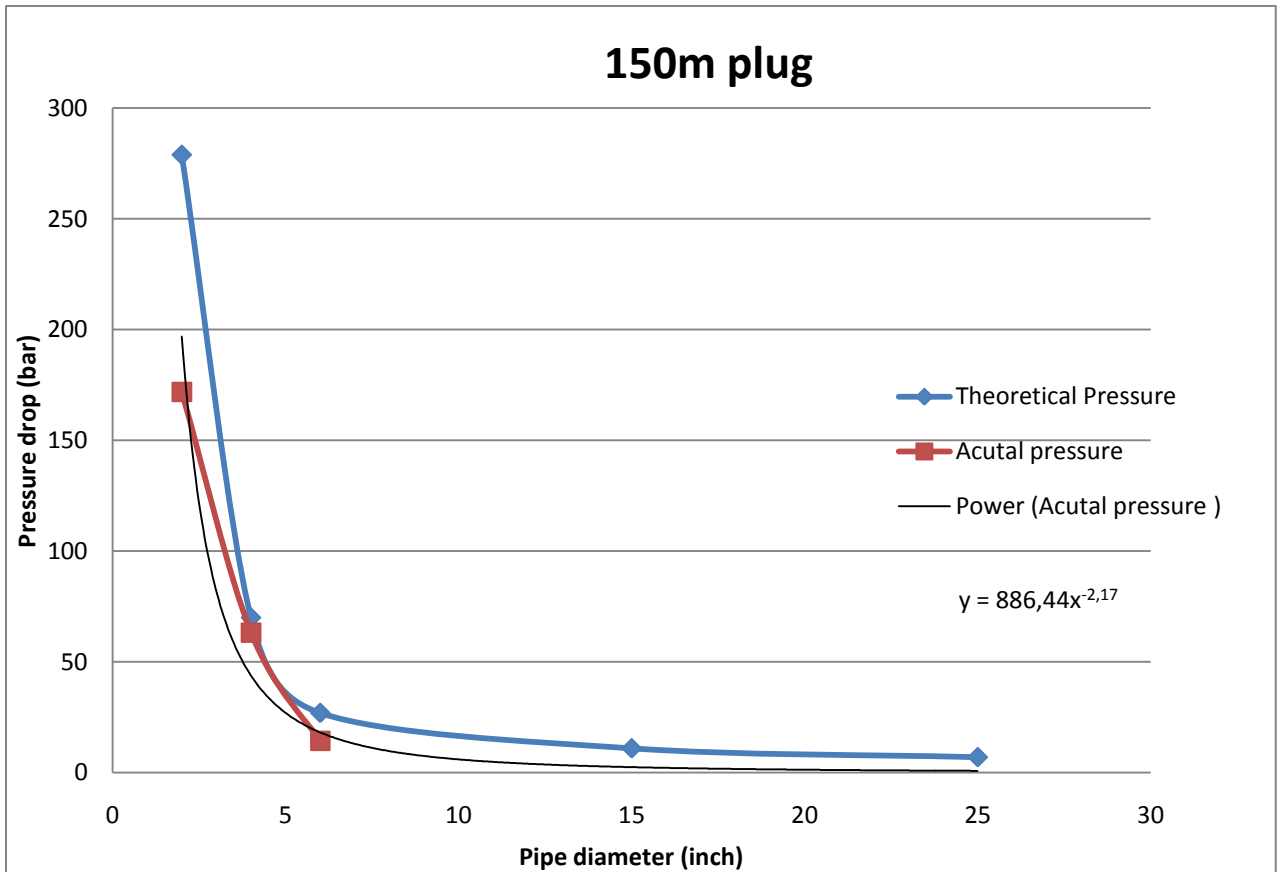
Figure 5.3: Pressure drop against pipe diameter for 150m gel plug

Figure 5.3 is the graph of pressure drop against pipe diameter for 150m gel plug. The actual pressure curve follows approximately power law model and the model is given in equation (15).

$$\Delta P = 886{,}4\ D^{-2{,}17} \tag{15}$$
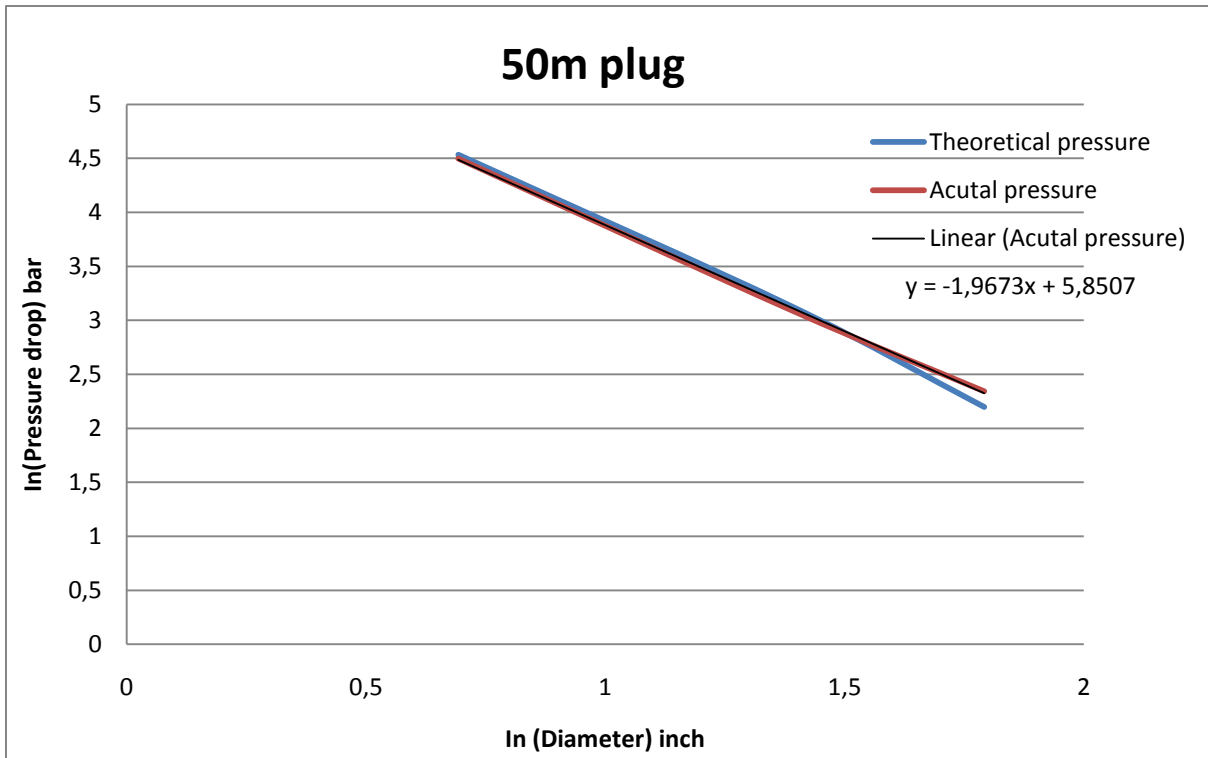
Figure 5.4: graph of Logarithm of pressure drop against logarithm of pipe diameter for 50m gel plug
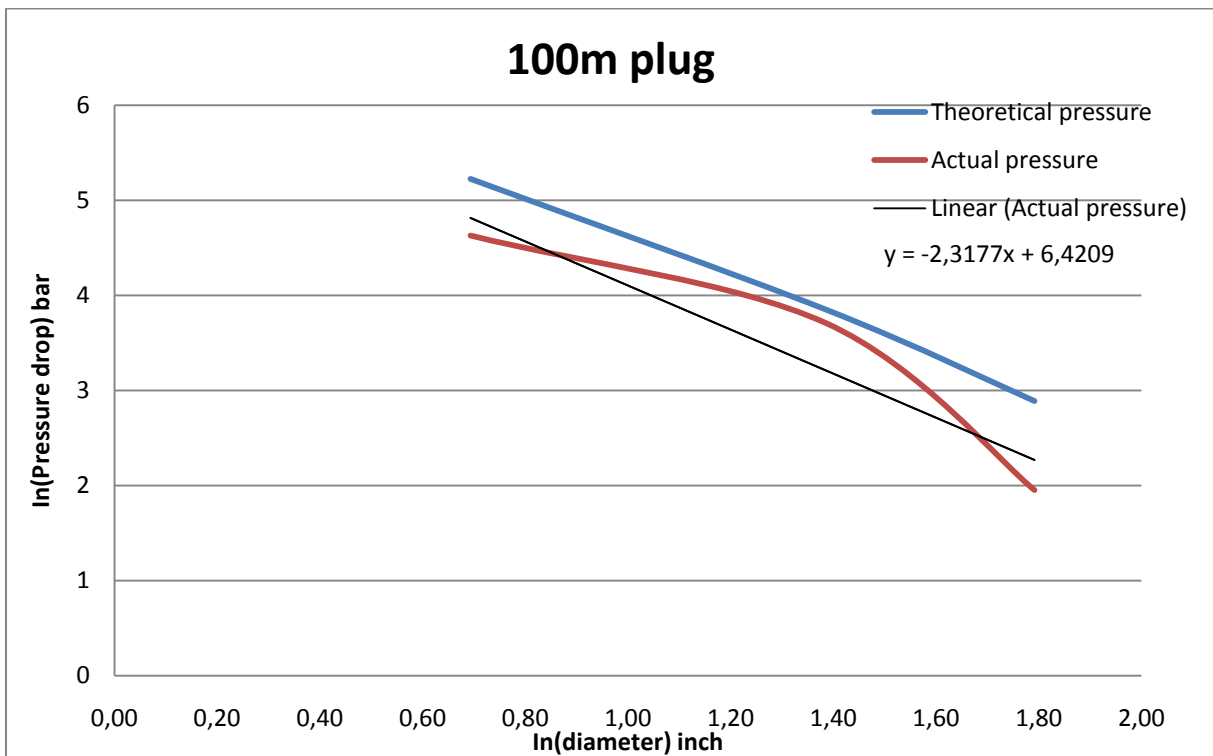
Figure *5.5: graph of logarithm of pressure drop against logarithm of pipe diameter for 100m gel plug*
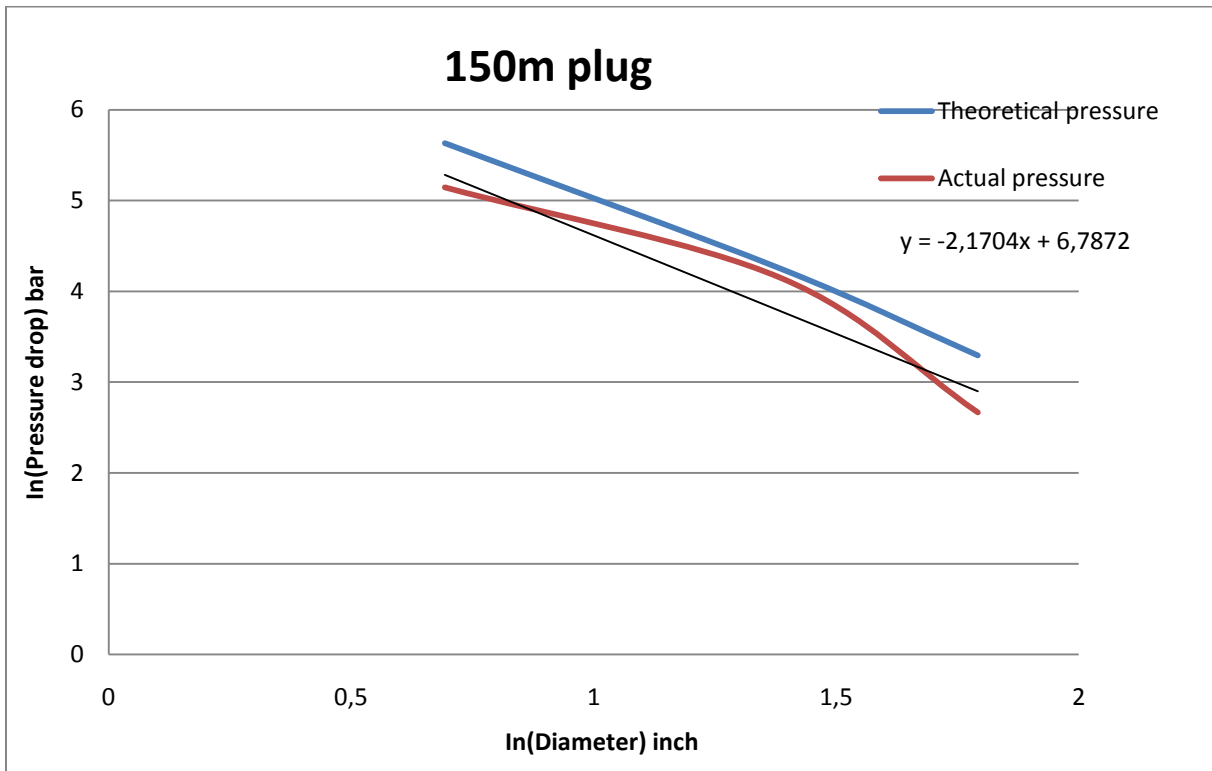
Figure 5.6: graph of Logarithm of pressure drop against logarithm of pipe diameter for 150m gel plug

Equations (13), (14) and (15) have been linearized by introducing natural logarithm (ln). This is done because linear graphs give higher accuracy than exponential graphs (Power law graph). The linearized graphs are as shown in figures 5.4, 5.5 and 5.6 and the corresponding linear equations are as shown in equations (16), (17), and (18) below.

From figure 5.4, we have the linear equation for 50m plug

$$ln\Delta P = -2,0lnD + 5,9 \tag{16}$$

From figure 5.5, we have the linear equation for 100m plug

$$ln\Delta P = -2,3lnD + 6,4 \tag{17}$$

From figure 5.6, we have the linear equation for 150m plug

$$ln\Delta P = -2,2lnD + 6,8 \tag{18}$$

Comparing equation (16), (17) and (18) as show in table 5.10, we see that the slope of each graph is approximately 2 while the intercepts on $\ln \Delta P$ axis increases with an approximate stepwise value of 0,4bar/inches for every 50m increase in gel plug length.
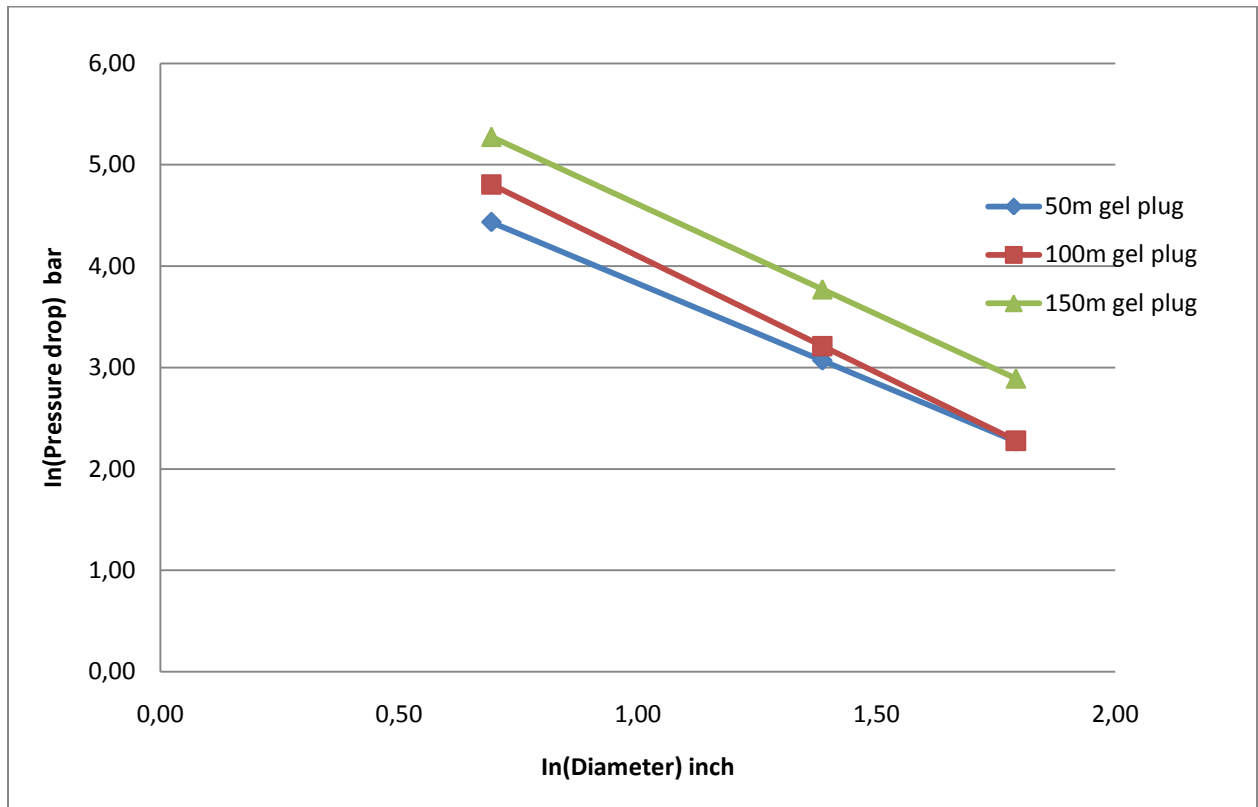
Figure 5.7 Combined results (Actual pressure) for 50m, 100m and 150m plug

Figure 5.7 is the combined graphs for 50m, 100m and 150m gel plug. Normally, the three lines in the graph were meant to be parallel, but due to experimental error and uncertainties the lines above were obtained.

Table 5.10: Average values for both slope and the intercept on $In\Delta P$ axis.

Plug length (m)	Linear Equation	Slope	Intercept on In(P) axis	$4\tau = \dfrac{e^{Intercept}}{L}$
50	$In\Delta p = -2,0InD + 5,9$	2,0	5,9	6,9
100	$In\Delta p = -2,3InD + 6,4$	2,3	6,4	6,1
150	$In\Delta p = -2,2InD + 6,8$	2,2	6,8	5,9
Average		2,17		6,3

From table 5.10, the average values for the slope and **4τ** are taken as 2,17 bar/inches and 6,3bar/m respectively .By substituting these values into the general equation of a linear graph, we have

$$ln\Delta P = -2,17 lnD + \ln(XL) \tag{19}$$

Where $X = 4\tau = 6,3$ bar/m. Equation 19 can be rewritten as

$$ln\Delta P = -2,17lnD + \ln(6,3L) \tag{20}$$

Equation (20) gives the model equation for this research work. Where D is in inches and length L is in meters. This equation can be used to predict the pressure drop in the pipeline given the diameters and length of gel plug.

Average values have been used for both the slope and the intercept on pressure drop axis (Y-axis) for the simplicity.

5.3. Validity of Equation 20 (Model Equation)

Equation (20) has been developed based on a lot of assumptions. The predicted pressure drop values will only be valid provided these assumptions hold and the values are within the range of theoretical pressure drop gotten from equation (12) and the actual pressure gotten from the experiment. If the values do not fall within this range then it is unacceptable.

That is $\Delta P_T \geq \Delta P_p$ and within the range of $\pm 35\%$ of actual pressure ΔP_p

Where ΔP_T is theoretical pressure, ΔP_p is predicted pressure using equation (20) and ΔP_A is actual pressure from experiment.

For instance, considering 2 inches pipe with gel plug of say L= 50m, the predicted pressure is as shown below

$ln\Delta P = -2,17\ln(2) + \ln(6,3*50)$

$\Delta P = $ **70 bar**

For L=100m we have,

$ln\Delta P = -2,17\ln(2) + \ln(6,3*100)$

$\Delta P = $ **139, 99 bar**

For L=150m we have,

$ln\Delta P = -2,17\ln(2) + \ln(6,3*150)$

$\Delta P = $ **209, 99 bar**

Comparing the 3 pressure drops gotten from equation (20), observations shows that they fall within the range of theoretical pressure and within the range ±26% of actual value from table 5.11. This makes the pressure drop values gotten from equation (20) to be acceptable based on all assumptions made in this research work.

The difference between the actual pressure and the predicted pressure from equation (20) is as a result of using average values for the slope and interception on ΔP axis.

The use of average values is very fruitful because it gives an estimate of the true value and it covers any uncertainty that might spring up during project execution. Some of these uncertainties and measures to reduce them have been discussed in subsection 4.2.4 and 4.2.5 of this research work.

Table 5.11: Tolerance (uncertainty) limit between the actual pressure and the pressure based on the model for 2inches pipe.

2 inches pipe

Gel plug length L (m)	Theoretical Pressure (bar) ΔP_T	Actual pressure ΔP_A (bar)	Pressure Based on model ΔP_p (bar)	Uncertainty ±%
50,00	94,00	89,70	70,00	25,54
100,00	189,00	105,52	139,99	-26,00
150,00	283,00	171,88	209,99	-25,80

Table 5.11 shows the pressure drop from the model equation for 2 inches pipe .The values predicted for 100 m and 150m are more reasonable compared to 50m plug. For the 50m plug, the theoretical pressure value should be considered because it is higher than the one gotten from the model.

Table 5.12: Tolerance (uncertainty) limit between the theoretical pressure and the pressure based on model for 4 inches pipe.

4 inches pipe

Gel plug length L (m)	Theoretical Pressure (bar) ΔP_T	Actual pressure ΔP_A (bar)	Pressure Based on model ΔP_p (bar)	Uncertainty ±%
50,00	24,00	22,15	15,55	35,19
100,00	47,00	40,75	31,22	33,81
150,00	71,00	63,23	46,66	34,28

Table 5.12 shows the pressure drop from the model equation for 4 inches. The values are very reasonable when compared to theoretical and actual pressures. Although these values are observed to be lower than the actual pressure values, but they can still be used; because the difference is as a result of uncertainties and limited data from the test.

Table 5.13: Tolerance (uncertainty) limit between the actual pressure and the pressure based on model for 6 inches pipe

6 inches pipe

Gel plug length L (m)	Theoretical Pressure ΔP_T (bar)	Actual pressure ΔP_A (bar)	Pressure Based on model ΔP_p (bar)	Uncertainty ±%
50,00	9,00	10,40	6,45	28,31
100,00	18,00	7,05	12,90	28,31
150,00	27,00	14,38	19,26	28,31

Table 5.13 also shows the predicted pressure for 50m, 100m and 150m gel plug in 6 inches line. The results are reasonable when compared to theoretical and actual pressure, except for 50m gel plug which has a lower predicted pressure value compared to theoretical and actual pressure value. In this case, the actual pressure should be considered.

Table 5.14: Tolerance (uncertainty) limit between the theoretical pressure and the pressure based on model for 8 inches pipe.

8 inches pipe

Gel plug length (m)	Theoretical pressure ΔP_T (bar)	Pressure based on model ΔP_A (bar)	Uncertainty $\pm$%
50	7	4,92	29,69
100	14	9,84	29,69
150	21	14,77	29,69

Table 5.14 shows simulated pressure drop values for 50m, 100m and 150m gel plug in 8 inches pipeline using the model equation. The values are very reasonable and acceptable because they are less than their respective theoretical pressure values. The actual pressure from the experiment will not differ much from predicted pressure in table 5.14 above.

 The simulation in this research work can be extended to different pipe diameters and different gel plug lengths L, but as stated earlier that, more data set will increase the model accuracy.

5.4.   Significance of the Model (Equation 20)

The importance of the model is to give idea of what pressure is needed to move a gel plug of certain length in a pipeline during design stage and to make decision based on the result.

For instance, if the maximum allowable design pressure that a pipeline can withstand is 100bar and from calculation, the pressure required to move a certain length of gel plug in a pipeline of diameter d turns out to be 110bar. Based on this, the engineer can quickly adjust his/her calculation by either reducing or increasing the length of gel plug.

5.5. Problems encountered during the experiment.

This has been divided into two based on where the experiment was carried out:

- *At Halliburton test yard*

- The experiment could not be started as scheduled due to delay in equipment mobilization
- There was a challenge in getting the accurate flow rate to set the gel plug moving without destroying it. At low flow rate, the water gets in-between the gel plug and destroyed it instead of overcoming the yield stress at the gel- wall interface. The flow rate was eventually increased until a value was obtained when the gel plug moved.
- There was a challenge in moving the 100m gel plug with the Haskel pump. The gel plug was destroyed rather than moving it with the Haskel pump.
- There was blockage of lines due to ice formation (drop in atmospheric temperature). This was as a result of drop in atmospheric temperature.

-At IRIS

- There was poor gel plug formation during the first 2 days
- There was a problem with the HT – 400 pump. The pump was not pumping accurate volume due to problem with one of the plunges. It was giving an output error of about 44- 50% in the pumped volume. The seal, seat and spring had to be changed
- There was also a challenge in getting the accurate flow rate that will move the gel plug without destroying it
- The problem encountered with pressure transducer gave faulty readings due to long usage
- There was problem in getting good pressure curves. This was due to the uneven nature of the site topography

5.6. Assumptions made in the experiment.

- That   all the lines are straight and smooth
- Settling time is the same
- That the flow rate is between the range of 90 – 340L/min with the HT- 400 pump

Chapter Six

6.0 Conclusion

In this research work, a mathematical model to predict the pressure required to pump a static gel in pipeline has been derived. The derivation is based on the results obtained from experiment carried out at both Halliburton test and IRIS test yard.

A thorough risk analysis was also carried out before the experiment. Although the experiment went well as planned, little delay was experienced during equipment mobilization.

The model developed is a linear equation and can be used to predict pressure drops in any pipeline provided the length of gel plug and diameter of the line are known.

6.1 Further Studies

A lot of assumptions have been made in this study. Firstly, it was assumed that the flow rate, and the settling times were constant. Also, it was assumed that the pipelines were smooth and that the topography in which these lines are laid is straight. Finally, average values were taken for actual pressures from experiment, slopes and intercepts of the graphs.

It is recommended that further studies should be carried out by using more pipelines of different diameters. This is because an average of five points will provide better results on the graph than three points.

The effect of settling time or flow rate should also be checked to see how it affects pressure drop in the line. The settling time or the flow rate should be varied to see the effect on the pressure drop. The two scenarios can also be considered simultaneously.

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Flow meters

Available at: http://www.coleparmer.com

Appendix

Appendix 1:Job Safety Analysis

ID from HSEQ activity plan	Activity	Aspects/Hazards	Potential Consequences					Nature of Controls	Consequences				Responsible Officer
			Personnel injury	Equipment Loss	Environmental	Schedule / Cost			Personnel injury	Equipment Loss	Environmental	Schedule / Cost	
	General Preperations												
1	Collect necessary information about the project.	Vital information regarding pressure limitations, test location, time,equipment and facilitities present at test site before moving in , pumps etc may be missing .	F IV	F IV	F IV	D III		Frequent communication between the Supersviors and the students	F IV	F IV	F IV	E IV	**Student**
2	Start the Project Schedule.	Delayed project schedule due unavailability / late arrival of equipment.	F IV	F IV	F IV	B I		Identify ongoing/planned Halliburton projects, agree on schedule for tests to ensure equipment and personnel are available.	F IV	F IV	F IV	C III	**Student & Supervisors**
3	Define clearly responsibilities.	Unclear responsibilities, who does what. Critical tasks is skipped.	C II	C I	C I	D I		Go through tasks and responsibilities on everyday if possible.	D II	D II	D II	D II	**Supervisor**
4	Define possibility for human error during the job.	Failure to follow procedures, misleading text, inexperienced personnel, missed milestones in procedure/ plan, important tasks that is not accurate planned, equipment failures, manufacturing defects.	B II	B II	B II	B II		Ensure procedures are followed , newly arrived personnel at test site should be briefed on how far the Job has gone.	D II	D II	D II	D II	**Student & Supervisors**
5	Evaluate Human-Machine interface (Human Factors) analysis of equipment package during the design phase.	Delay in operation due to unfamiliar equipment such as the chemical injection pump.	C II	C II	C II	C1		Ensure to mobilise dedicated personnel to operate special equipment.	D II	D II	D II	D I	**Student & Supervisors**
	Procurement												
6	Define equipment that is critical to success of the project.	Delay in project due to damage to critical equipment like HT-400 pump, chemical injection pump, can lead to late submission of Masters thesis report	E III	B I	E III	B I		Equipment should be tested before bringing to test site.if possible, spare for critical equipment should be made available. Experienced operators/mechanic should be among the personnel.	E IV	C III	E IV	C III	**Student & Supervisors**
7	Make sure appropriate and trained personnel are available with the students on site	Task unknown, unqualified personnel.	D I	D II	D II	C II		Use experienced personnel. Ensure personnel are familiar with gel pumping. Inform personnel coordinator if any changes in schedule.	E I	D II	D II	D II	**Surpervisor**
	Mobilisation of Equipment /Personnels												
8	Issue personnel request form.	Not enough experienced personnel available.	D I	D II	D II	C II		Personnel request form to be issued. Keep Personnel coordinator updated on any changes in the schedule.	E I	D II	D II	D II	**Surpervisors**
9	Perform necessary maintenance of equipment before mobilized. Check oil level, cool water level, function of emergency switch etc. On pumps and other equipment if required.	Equipment not maintained, not working as expected, missing equipment, wrong specifications.	E IV	C II	E IV	C II		Ensure equipment is maintained according to Halliburton proce	E IV	D II	E IV	D II	**Personnel**
10	Mobilisation lists.	Not accurate mobilisation lists, missing(wrong) equipment.	E III	E III	F IV	B II		Make sure that third party delivers equipment as ordered. Internal review of modem lists.	E IV	E IV	F IV	D III	**Student & Supervisors**
11	Define the need for backup equipment.	Break down of equipment during job.	E IV	C III	E IV	C I		Have back up of critical equipment available.	E IV	C III	E IV	D II	**Student & Supervisors**

	Rig Up process												
12	Prior to operation		F IV	F IV	F IV	F IV		Contact superior personnel on location to clarify any special precautions needed to do the operation	F IV	F IV	F IV	F IV	**Student**
13	Rig up hoses	leakages, slippery ground	C II	F IV	F IV	D III		Perform tool box talk where discussion on proper lifting techniques etc is included prior to rig up	C III	E IV	F IV	D IV	**Supervisor**
14	Rig up gel tanks, mixing and pumping of chemicals, transfer of Temblok to HP unit, use of chemical cleaners in confined areas,.	Exposure to chemicals	B II	E III	B II	E III		perform tool box talk prior to handling chemicals.	B II	F IV	B II	E IV	**Student & Supervisors**
15	Load/unload of equipment, (de-/)rigging of iron and instruments on HP/LP lines.	Finger jam, cuts	C II	F IV	F IV	C II		Proper PPE, JSA, use of lifting aids, assembly check. Good house keeping. Awareness of hazards. Do not place fingers/hands between or under heavy loads.	C III	F IV	F IV	F IV	**Student**
16	(Un)load equipment, (de-)rigging, carrying heavy load, manual handling, rigging up	Strain, stress posture, Ergonomic	C II	E III	E III	C II		Use correct PPE (safety kits) . Good house keeping. Awareness of hazards. Correct working positions when rigging up, use correct manual handling techniques .Know limitations, get help use mechanical lifting aids. Assess load - size, shape and weight before attempting to lift. Not manual lifting more than 25kg - use buddy system, get help, mechanical or personnel.	C III	F IV	F IV	F IV	**Student**
17	Working on heights (gel tanks, compressors, rigging), (dis-), use of ladders and scaffolding, hose deployment/ recovery	Fall down / out	C I	C III	C III	C III		Hold on to any strong rail or strong equipment around, keep hand(s)s free, be especially careful in wet and windy weather. Wear boots with non slip soles, housekeeping. Watch out for crane activities. . Perform Toolbox talk prior to job.	D II	F IV	F IV	F IV	**Student/ Supervisor**
18	Fill tank water	flood test site / wetting of tests site.Slippery floor	C III	F IV	F IV	F IV		Keep proper valves open and closed. Rope off area	E IV	F IV	F IV	F IV	**Student**
19	Function testing of equipment, leak testing of temporary iron/hoses, HP pumping, (de-) pressurization during HP test, derigging (residual HP)	High pressure	C I	F IV	C II	F IV		All hoses and temporary piping to be secured, area to be barriered off and no unauthorised persons to be inside barriered area, trained personnel only to operate equipment. Barrier off area during leak testing, ensure all pipework is vented off, particular attention to pump side of check valves. Never position right in front of pressure release direction. Relevant procedures to be strictly followed.	C II	D III	D III	D III	**Student & Supervisors**
20	Surrounding operations like depressurization of gel tank, hammering of line,noise from diaphram pump and among others.	Noise	C III	F IV	C III	F IV		Use of proper PPE (individually molded ear plugs), reduce working time in high noise areas.	C III	F IV	C III	F IV	**Student**
	Pumping Process												
21	pumping of water into the main line and test line	leakages, slippery ground	C III	F IV	F IV	F IV		Keep proper valves open and closed. Rope off area	E IV	F IV	F IV	F IV	**Student**
22	Pumping of gel and chemical	Exposure to chemicals	B II	E III	B II	E III		Read toxic data sheets. Use proper safety equipment. Keep proper valves open and closed, barrier off area. Wear appropriate PPE. Refer to MSDS for appropriate actions. Always be aware of other operations. Wear safety glasses at all times.	B II	F IV	D III	F IV	**Student**
	Clean up and end of project												
23	Identify the potential risk for spill during rig down.	Spill can occur during rig down, spill to environment, the crosslinker can cause injuries personnel.	D III	D III	D III	D III		Make sure appropriate flushing of equipment prior to rig down. Make sure to have appropriate spill kit available.	D III	D III	D III	D III	**Student & Supervisors**

Appendix 2: Risk Analysis Matrix

HAZARD SEVERITY CATEGORY	DESCRIPTIVE WORD	PERSONNEL ILLNESS/ INJURY	EQUIPMENT DAMAGE/ LOSS	POTENTIAL CONSEQUENCES ENVIRONMENTAL	SCHEDULE / COST	PROBABILITY RATING A Frequent	B Reasonably Probable	C Occasional	D Remote	E Extremely Improbable	F Impossible
I	Catastrophic	Fatally or permanent disabling injury or illness	> 200,000 NOK	Any Incident that potential harms or adversely effects the general public and has the potential for widespread public concern of Halliburton operations.	> 200,000 NOK	1	1	1	2	3	3
II	Critical	Severe injury or illness	100,000 to 200,000 NOK	Any Incident that potential harms or adversely effects trained employees and the environment at our facility. Requires specialised expertise or resources for correction.	100,000 to 200,000 NOK	1	1	2	3	3	3
III	Marginal	Minor injury or illness	25,000 to 50,000 1M NOK	Any Incident that presents limited harm to the environment and requires general expertise and resources for correction.	25,000 to 50,000 1M NOK	2	2	3	3	3	3
IV	Negligible	No injury or illness	<25,000 NOK	Any Incident that presents limited harm to the environment but requires minor corrective actions.	<25,000 NOK	3	3	3	3	3	3

PROBABILITY RATING

LEVEL   DESCRIPTION

A   **FREQUENT**: Likely to occur repeatedly during activity/operation

B   **REASONABLY PROBABLE**: Likely to occur several times

C   **OCCASIONAL**: Likely to occur sometime

D   **REMOTE**: Not likely, but possible

E   **EXTREMELY IMPROBABLE**: Probability of occurrence cannot be distinguished from zero

RISK PRIORITY CODE (RPC)

CODE   ACTION REQUIRED

1   **HIGH RISK: Imperative to suppress risk to lower level**

2   **MEDIUM RISK: Operation may require waiver endorsed by management**

3   Operation permissible

NOTE: RISK PRIORITY CODE OF LESS THAN 3 IS NOT ACCEPTABLE FOR HAZARDS THAT TARGET PERSONNEL

Appendix 3: water tank

Appendix 4: Gel tank and water tank at test site

Appendix 5: Chemical tank (Xlinker tank)

Appendix 6: T 400 pump

Appendix 7: Haskel pump

Appendix 8: Chemical injection pump

Appendix 9a: Pressure gauge

Appendix 9b: Pressure gauge

Appendix 10: Flow meter

Appendix 11: Pressure safety valve (PSV) at test site

Appendix 12: Double block and bleed valve at test site

Appendix 13a: Experimental set up at Halliburton test yard

Appendix 13b: Experimental set up at Halliburton test yard

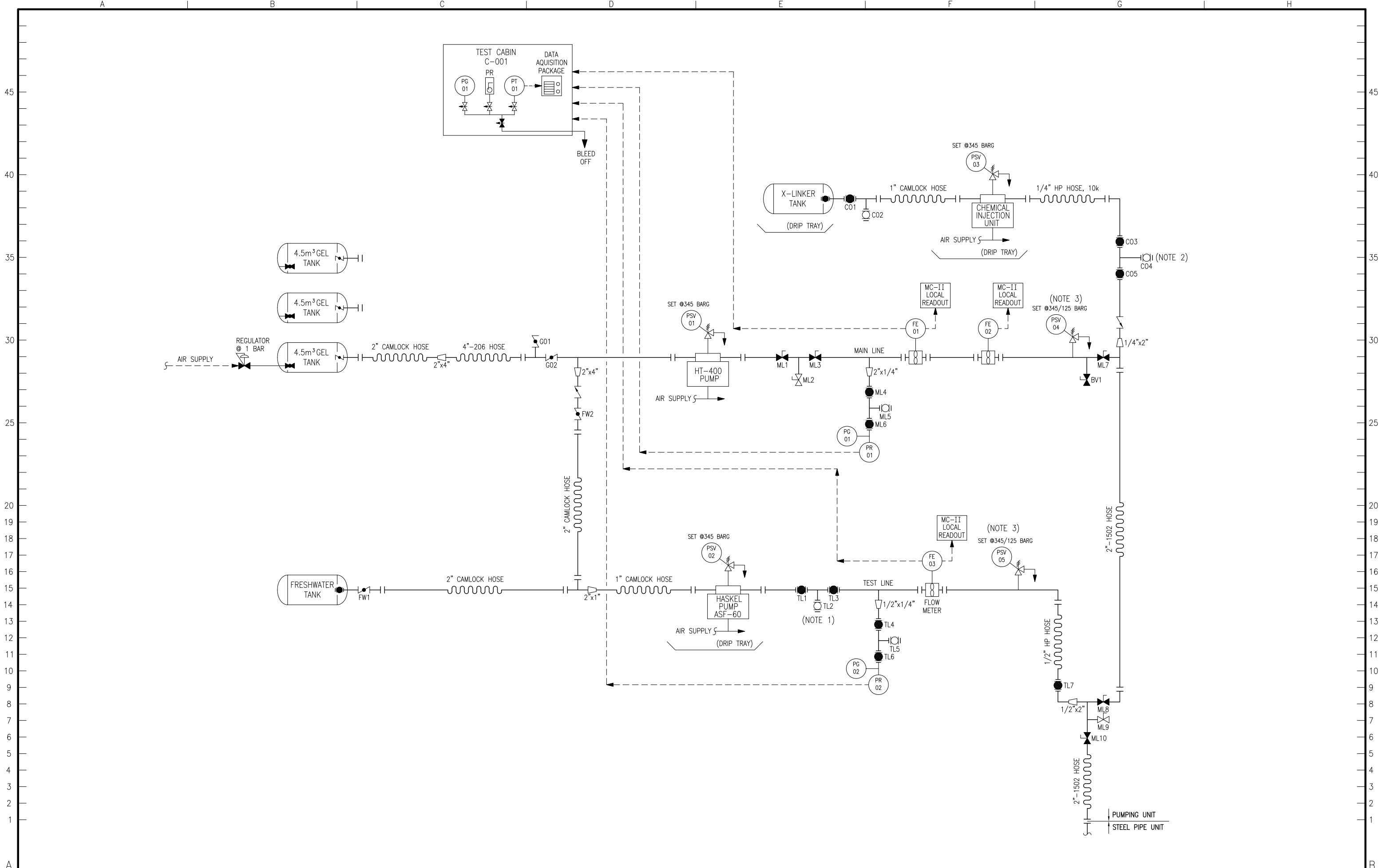*Appendix 14: Experimental set up at IRIS test yard*

Appendix 15: Double block and bleed, flow mater, pressure gauge and PSV set up IRIS test yard

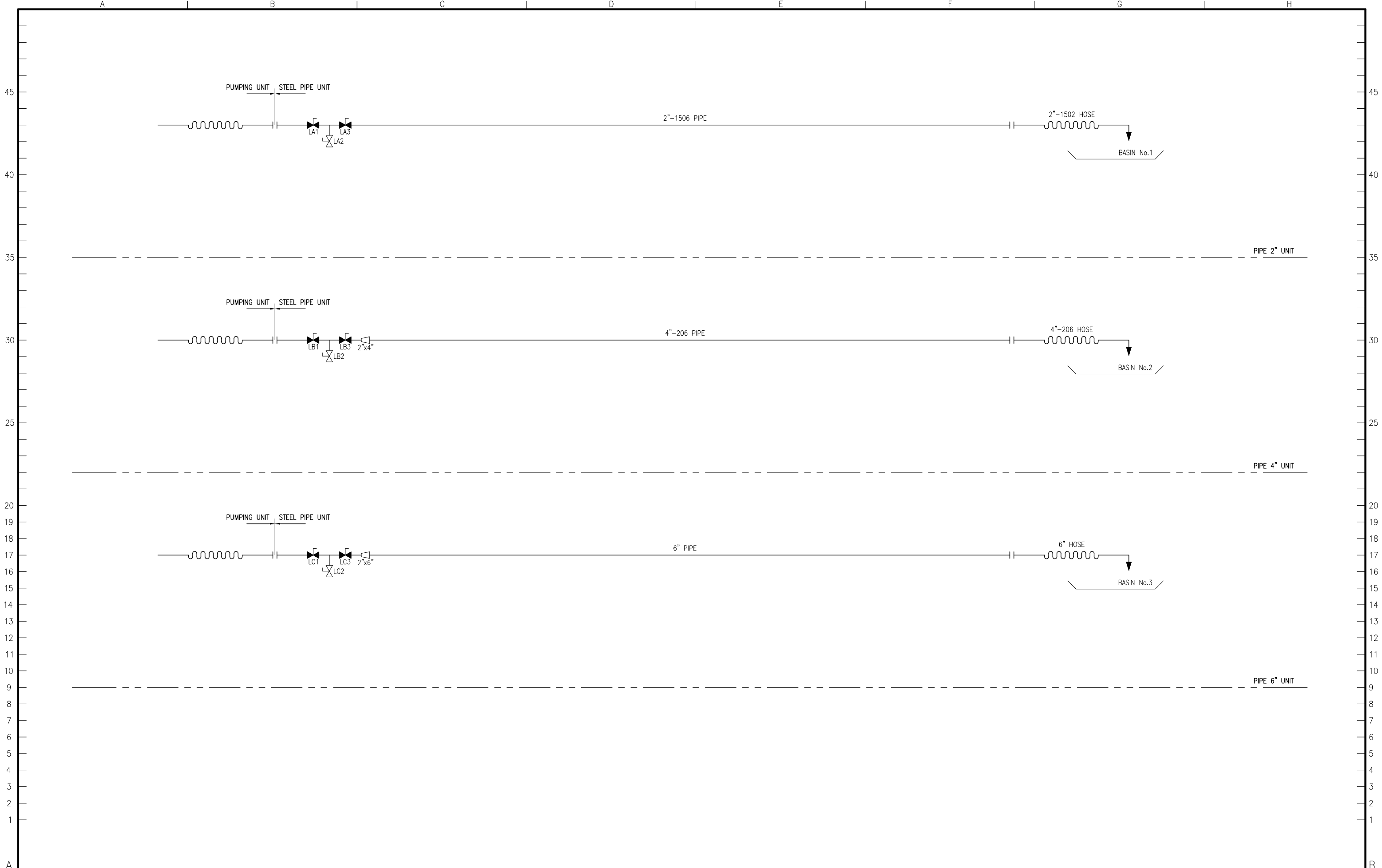*Appendix 16: HT- 400 control panel*

Appendix 17: Piping and instrumentation diagram *(P& ID)*

TEST CABIN
C-001

DATA AQUISITION PACKAGE

PG 01   PR   PT 01

BLEED OFF

SET @345 BARG
PSV 03

X-LINKER TANK
(DRIP TRAY)

CO01 CO02   1" CAMLOCK HOSE   CHEMICAL INJECTION UNIT   1/4" HP HOSE, 10k

AIR SUPPLY
(DRIP TRAY)

CO03
CO04 (NOTE 2)
CO05

4.5m³ GEL TANK

4.5m³ GEL TANK

MC-II LOCAL READOUT

MC-II LOCAL READOUT

(NOTE 3)
SET @345/125 BARG

SET @345 BARG
PSV 01

FE 01

FE 02

PSV 04

4.5m³ GEL TANK

REGULATOR @ 1 BAR

AIR SUPPLY

2" CAMLOCK HOSE   4"-206 HOSE

G01
G02

2"x4"

HT-400 PUMP

AIR SUPPLY

ML1 ML3   MAIN LINE

ML2

2"x1/4"

ML4
ML5
ML6

PG 01   PR 01

1/4"x2"

ML7

BV1

2"x4"

FW2

2" CAMLOCK HOSE

2"-1502 HOSE

MC-II LOCAL READOUT

(NOTE 3)
SET @345/125 BARG

SET @345 BARG
PSV 02

FE 03

PSV 05

FRESHWATER TANK

FW1   2" CAMLOCK HOSE   2"x1"   1" CAMLOCK HOSE

HASKEL PUMP ASF-60

AIR SUPPLY
(DRIP TRAY)

TL1 TL3   TEST LINE

TL2
(NOTE 1)

1/2"x1/4"   FLOW METER

TL4
TL5
TL6

PG 02   PR 02

1/2" HP HOSE

TL7

1/2"x2"

ML8
ML9

ML10

2"-1502 HOSE

PUMPING UNIT
STEEL PIPE UNIT

NOTES:

1. HIGH POINT FOR VENTING AIR.
2. CHEMICALS TO BE COLLECTED IN SUITABLE CONTAINER.
3. 125 BARG PSV TO BE USED DURING TESTS IN 2" PIPE.
   145 BARG PSV TO BE USED DURING TESTS IN 4" PIPE.

REV. No.	DATE	REASON FOR ISSUE	PREPARED	CHECKED	APPROVED	REVIEWED/VERIFIED	REVIEWED/VERIFIED
0	14.03.11	ISSUED FOR USE.	RK	EAS	DN		
2	11.03.11	ISSUED FOR CLIENT REVIEW.	ESt	KU	DN		
1	01.03.11	ISSUED FOR IDC.	ESt	TML	KU		
						CONTRACTOR	

HARDWARE GROUP/ SERVICE DEPARTMENT: DFO

DRAWING TITLE:
PUMPING GEL IN PIPELINE APPLICATIONS

P&ID

CONTRACTOR NAME
HALLIBURTON

DOCUMENT CATEGORY: RETENTION CODE:
CONTRACT No.:   TBC   CTR. No.:
SCALE: N.T.S.   PROJECTION   DWG. SIZE: A1

CAD FILE CODE: O:\CAD\GEL PROJECT\GEL-26-L-XP-001-01.dwg

DRAWING NUMBER:
GEL-26-L-XP-001-01

REVISION
0

DRAWING NUMBER   REFERENCE DRAWINGS   DRAWING TITLE

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PUMPING UNIT | STEEL PIPE UNIT

2"-1506 PIPE

2"-1502 HOSE

LA1 LA3
LA2

BASIN No.1

- - - PIPE 2" UNIT

PUMPING UNIT | STEEL PIPE UNIT

4"-206 PIPE

4"-206 HOSE

LB1 LB3 2"x4"
LB2

BASIN No.2

- - - PIPE 4" UNIT

PUMPING UNIT | STEEL PIPE UNIT

6" PIPE

6" HOSE

LC1 LC3 2"x6"
LC2

BASIN No.3

- - - PIPE 6" UNIT

REV. No.	DATE	REASON FOR ISSUE	PREPARED	CHECKED	APPROVED	REVIEWED/VERIFIED	REVIEWED/VERIFIED
1	23.02.11	ISSUED FOR IDC.	ESt	EAS			

CONTRACTOR

DRAWING NUMBER   REFERENCE DRAWINGS   DRAWING TITLE

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Appendix 18: Actual pressure for 50m gel in 2inches pipe using the Haskel pump

Haskel Pump

2" pipe 50m Slug	
Run	**Pressure to move Gel (bar)**
1	95,00
2	69,90
3	71,50
4	63,80
Average	**75,05**

Appendix 19a,19b and 19c:Actual pressure for 50m,100m and 150m gel in 2inches using the HT-400 pump

HT-400 pump

2" pipe 50m Slug	
Run	**Pressure to move Gel (bar)**
1	120,90
2	55,20
3	93,00
Average	**89,70**

Appendix 19b

2" pipe 100m Slug	
Run/	**Pressure to move Gel (bar)**
1	98,00
2	71,00
3	128,80
4	149,00
5	81,10
6	119,50
7	73,50
Average	102,52

Appendix 19c

2" pipe 150m Slug

Run	Pressure to move Gel (bar)
1	203,00
2	150,20
3	163,40
4	170,90
Average	131,03

Appendix 20a,20b and 20c: Actual pressure for 50m,100m and 150m gel in 4inches using the HT-400 pump

4" pipe 50m Slug

Run	Pressure to move Gel (bar)
1	58,00
2	16,60
3	8,40
4	5,60
Average	22,15

Appendix 20b

4" pipe 100m Slug

Run/	Pressure to move Gel (bar)
1	56,80
2	33,70
3	24,50
4	48,00
Average	40,75

Appendix 20 c

4" pipe 150m Slug

Run	Pressure to move Gel (bar)
1	76,50
2	52,00
3	56,40
4	68,00
Average	63,23

Appendix 21a,21b and 21c: Actual pressure for 50m,100m and 150m gel in 4inches using the HT-400 pump

6" pipe 50m Slug

Run	Pressure to move Gel (bar)
1	4,90
3	21,00
4	5,30
Average	10,40

Appendix 21b

6" pipe 100m Slug

Run	Pressure to move Gel (bar)
1	9,10
2	11,30
3	6,10
4	1,70
Average	7,05

Appendix 21c

6" pipe 150m Slug

Run/	Pressure to move Gel (bar)
1	17,20
2	21,00
3	19,30
Average	14,38