2013-06-20

Snubbing Field Operations - Potential Trapped Air and Explosive Hydrocarbon Mixtures on Surface

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Snubbing Field Operations - Potential Trapped Air and Explosive Hydrocarbon Mixtures on Surface

by

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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF CHEMICAL AND PETROLEUM ENGINEERING

CALGARY, ALBERTA

JUNE, 2013

Abstract

Snubbing is a widely used drilling, completion and work-over method. It is especially useful in HPHT reservoirs and in unconventional reservoirs such as the Marcellus, Haynesville, Bakken oil and Eagle Ford shale plays. During some operations, though very infrequent, powerful explosions have occurred on surface which have resulted in injuries to personnel and the destruction of surface equipment.

It is shown in this thesis that these explosions, could be internal explosions, that, based on the literature describing Low Temperature Oxidation (LTO) reactions, which occur in conjunction with in-situ combustion processes; in the presence of a trapped pocket of air which is in contact with immobile hydrocarbon liquids and in the case of gas wells, with natural gas.

There are three mechanisms that create this explosion. This first mechanism requires the presence of a trapped pocket of air to persists for a sufficient time for LTO reactions to create oxidized species, heat and volatile vapor products and bring the interface into the flammability zone. Subsequently, the second mechanism involves a rapid temperature rise from the fast compression of the pocket of air and immobile hydrocarbon sufficient enough to auto-ignite the volatile vapors and start a burn, the final mechanism involves this burn exhausting the oxygen supply within the air pocket and looking for oxygen internally from LTO oxidized species created prior ignition. Once the combustion reaction draws oxygen internally from these species, a powerful explosion occurs similar to conventional explosives.

This thesis also identifies the location and potential volume of trapped pockets of air on surface snubbing equipment that could lead to the explosion described above.

Furthermore a theoretical low pressure (8 MPa) snubbing simulation was conducted to illustrate the power of the LTO initiated explosion from a small trapped pocket of air (0.150L). This simulation shows the explosive pressure rise of the explosion and also illustrate the strength and damage potential of an explosive detonation shockwave resulting from the explosion described above.

Finally, this thesis recommends methods to reduce the likelihood of an internal explosion within snubbing surface equipment during operations.

It is hoped that the outcomes and recommendations within this thesis will reduce the likelihood of explosions during snubbing operations and ultimately save lives.

Acknowledgements

Firstly, my deepest gratitude goes out to my dear Mom and Brother for their support, countless sacrifices, patience and never-ending love.

I am also very grateful to the following people for their immense help and guidance: Dr. Gordon Moore and Dr. Raj Mehta my supervisors, Dr. Laurence Lines, Dr. Roberto Aguilera and Dr. Matthew Clarke, members of my supervisory committee, Mr. Walter Tersmette from Walter C. Tersmette and Associates Ltd., Mr. Adam Blazenko from Cenovus Energy, Mr. Aaron Huntley from Precision Well Servicing, Mr. Scott Ebert from Northern Snubbing Ltd and Ms. Kimberly Gulevich.

I would also like to show my appreciation to Devon Canada, DACC, CAPP, Enform Canada, all members of the Canadian Industry (Operators and Service Companies), Alberta OHS, Alberta Environment, ERCB, Government of Alberta, Government of Canada, (NSERC), and especially Mr. Matthew Ursenbach, Mr. Donald Mallory, Mr. Mark Hancock, Ms. Ericka Rios, Mr. Ehsan Panjeshahi, Mr. Mikhail Anisimov, Mr. Adam Connolly, Ms. Crystal King, Dr. David Lertzman, Mr. Domingo Alvarez, Mr. Zakir Gazizov, Mr. Dan Zilnik, Mr. Leor Rotchild, Mr. Igor Orlov, Mr. Pål Østebø Andersen, and all members of *In-Situ* Combustion Research Group (ISCRG), the Schulich School of Engineering and the University of Calgary and my colleagues and team at Statoil ASA Drilling and Well Technology, Troll Field MDUT, Norway for their support.

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List of Symbols

A	Cross Sectional Area of the Pipe (m^2)
a	Speed of Sound (m/s)
C_p	Constant Pressure Heat Capacity $\left(\frac{J}{mol \cdot K}\right)$
C_v	Constant Volume Heat Capacity $\left(\frac{J}{mol \cdot K}\right)$
E	Modulus of Elasticity (Pa)
I	Moment of Inertia ($kg \cdot m^2$)
F_D	Force of Drag on Casing(daN)
F_F	Force of Friction (daN)
F_{Snub}	Force of Snubbing (daN)
F_{WP}	Force of Well Pressure (daN)
P_1	Pressure Behind the Front (kPa)
P_{air}	Absolute Pressure of air (kPa)
P_o	Initial Pressure in Front of Shock (undisturbed by shock) (kPa)
R	Ideal Gas Constant (JK^{-1} mol^{-1}
S	Speed of Shockwave (m/s)
${SR_c}^2$	Critical Slenderness Ratio
T	Temperature of the Shock Fluid (K)
$T_{air\ 1}$	Absolute Temperature of Air Before Pressure Up (K)
$T_{air\ 1}$	Absolute Air Temperature Before Equalization of Surface Assembly (K)
$T_{air\ 2}$	Absolute Temperature of Air within the Wellhead Surface Assemble Following Pressure Up (K)
$T_{air\ 2}$	Absolute Air Temperature After Pressurization of Surface Assembly (K)
T_f	Absolute Temperature of Gas Within the Tank Following Pressurization (K)
T_i	Absolute Temperature of Gas Entering the Cylinder (K)
T_{sa}	Absolute Temperature of Gas Within the Wellhead Surface Assembly (K)
T_{well}	Absolute Temperature of Incoming Well Fluid (Natural Gas) from the Well (K)

Greek Symbols

σ_y	Yield Stress (kPa)
Π	Pi
γ_{air}	Specific Heat Ratio of the Air in the Well
γ_{well}	Specific Heat Ratio of the Gas in the Well
γ	Specific Heat Ratio

Abbreviations

BHA	Bottom Hole Assembly
BHP	Bottom Hole Pressure
BHT	Bottom Hole Temperature
BLEVE	Boiling Liquid Expanding Vapor Explosion
BOPs	Blow Out Preventors
BTU	British Thermal Unit
dB	Decibels
HPHT	High Pressure and High Temperature
HRA	Hydraulic Rig Assist/Rig Assist Snubbing unit
LCM	Lost Circulation Material
LTO	Low Temperature Oxidation
MD	Measured Depth
MIE	Minimum Ignition Energy
OD	Outer Diameter
TNT	Trinitrotoluene
SOP	Standard Operating Procedure

Chapter 1: Introduction

This first chapter will introduce a brief background on snubbing operations, applications, advantages and ideal reservoirs for use. The need and objectives of this study will also be introduced.

In today's competitive economic market for natural gas and conventional oil there is a need for well servicing methods to be quick, low cost, efficient and versatile. In order to maintain optimum production cost effectively, snubbing operations provide a very viable option (Snubco Pressure Control Ltd., 2010; Precision Well Servicing, 2011).

1.1 Snubbing Operations

Snubbing operations otherwise referred to as snubbing is a method of inserting tools and tubulars into wells under pressure. It is the process of tripping pipe in a well under live conditions in which the well has a surface pressure great enough to eject the pipe from the well if no restraining force is applied (Hodgson, 1995).

In Alberta, snubbing is typically used to enhance and maximize production mainly from fluid sensitive formations that are highly susceptible to formation damage. Snubbing can be used in a variety of conditions for conventional oil and for both conventional and unconventional gas. The operation is versatile enough to also be used in both under or over pressured reservoirs and in reservoirs with low or high permeabilities.

Snubbing in the past was typically used to re-establish well control (Schmigel, 2003). However, current day snubbing operations are used in a wide variety of applications such as perforating, milling scale removal and underbalanced drilling. A major advantage of snubbing is that it can conduct operations without the cost and need for completion, work-over, kill fluids or lost circulation material (LCM) (Snubco Pressure Control Ltd., 2010).

In Alberta, snubbing units are usually rated for well pressures at surface of up to 21 MPa (3,000 psig) for rig-less and up to 35 MPa (5,000 psig) for some standalone units (Huntley, 2011). Snubbing operations dealing with pressures below 21MPa are considered low pressure operations (DACC and Enform, 2007).

Snubbing units are rated and listed by the total amount of weight the snubbing hydraulic cylinders can lift. Typical lift ratings are from 54 000 kg (120 000 lbs) to 265 000 kg (600 000 lbs). However for operations, snubbing units are chosen for the amount of snub forces they can exert. Usually half the lift rating is a good estimate of snub exertion force available. Therefore, for the above mentioned lift ratings the snub force would be around 27 000 daN (60 000 lbf) and 130 000 daN (288 000 lbf) (Boots and Coots, 2011). See Appendix A for a range of specifications for snubbing unit lift and snub forces capabilities.

1.2 Snubbing Applications

Snubbing units can be employed in almost any operation done by conventional completions and work-over or drilling rigs. Some of the snubbing applications in conventional oil and gas and unconventional gas operations are included in Table 1.

• Asphalting, Paraffin and Scale Removal	• Completions, Single and Dual String
• Deploying and Retrieving Packers, Bridge Plugs and Other Down-hole Equipment	• Deploying and Retrieving Tubing Conveyed Perforating Guns
• Installing Sand Screens	• Deploying and Retrieving Acidizing Tools
• Fishing Lost Tools	• Milling Operations
• Underbalanced Drilling	• Blow-out Control and Re-entry Work
• Hydrate Washing	

Table 1: Snubbing applications (Snubco Pressure Control Ltd., 2010; DACC and Enform, 2007).

1.3 Advantages and Disadvantages of Snubbing

Traditionally in conventional operations for drilling, well completions and work-overs, fluids are pumped down-hole to hydrostatically overbalance the reservoir pressure so that tripping operations can be performed on a dead well. These fluids can cause formation damage to the reservoir.

In addition, in some operations wells cannot be completely killed and may take fluid quickly and lost circulation material (LCM) is needed to obtain a manageable fluid loss rate to begin or continue operations (Schmigel, 2003). After the use of fluids or LCMs a swabbing service operation is frequently needed to restart the well back into production. The use of kill fluids, LCM and swabbing add extra costs and time to operations.

The main advantages of snubbing units over conventional operations are that they do not require kill fluids or any invasive fluids for drilling or well servicing operations. As such there is less formation damage to the production reservoir and no additional costs for LCM.

Additionally, snubbing also allows for the ability to rotate the work string while under pressure which is an added advantage over coil tube technology. In some cases the well can still produce while being worked on, thus bringing revenue during operations (Precision Well Servicing, 2011). It saves cost and time as no swabbing is needed to bring the well back into production. Snubbing also protects the environment by reducing green house gas emission through reduced well site flaring from re-circulating gas and it avoids fluids and cuttings from invading the formation since no circulating fluids are used (Precision Well Servicing, 2011).

The major disadvantage of snubbing is the time it takes for making connections and tripping into and out of the hole. This is because snubbing units typically snub one joint at a time as there is no space to rack stands. This can add significant time to the operations. In addition each pipe joint needs to be raised over the snubbing basket and snubbed through the snubbing BOPs until a large OD pipe or pipe collar is encountered, then operations are stopped and a staging procedure commenced. A pipe collar is encountered on each stand. Therefore, the operation has a lot of stop and go and this process also adds considerable time to operations.

Proper supervision and pre-planning is critical before, during and after snubbing operations. Lack of proper supervision can lead to significant errors, down time and costs. Snubbing operations have a series of defined procedures (closing and opening of Rams and Annular BOPs, de-pressurization / re-pressurization) and if these multiple procedures are not followed correctly, failures occur.

For example in 2007 in the Shearwater platform in the North Sea, snubbing operations were being used to clean out a large obstruction (stone) which entered through a collapsed liner. During the pulling operation one of the stripping rams was not opened sufficiently and a collar caught the ram, excessive up weight was used and the pipe parted and fell down-hole. The fishing operation to retrieve the parted pipe failed. It was found that the large stone that was to be cleaned out originally, fell and had settled on top of the parted tubing, thereby making fishing impossible. Therefore, careful planning and supervision (up weight not to exceed tubing parting strength) is needed in all aspects of snubbing operations.

1.4 Ideal Reservoirs for Snubbing

Snubbing operations can be used in many reservoirs. However, there are certain ideal reservoirs and plays that potentially provide the most technical and economical benefit. These are as follows:

- Reservoirs that produce hydrocarbons from a fluid sensitive formation. This is especially true for reservoirs that contain water sensitive fines or clays that may swell in contact with commonly used completion or work-over fluids This swelling could reduce permeability to the reservoir. The use of snubbing operations in this case eliminates the need for expensive completion or work-over anti-swelling fluids to be used. In addition, by using the well's own fluids, the likelihood of swelling occurring during snubbing operation is reduced. Good candidates for snubbing are high volume, deep gas wells within reservoirs containing sandstone and clays that have the potential to swell (Precision Well Servicing, 2011).

- Conducting work-over, re-completion or new completion in a low pressure reservoir where the well production has reduced the *in-situ* reservoir pressure to below the original reservoir pressure and in naturally fractured reservoirs. Frequently, in under-pressured reservoirs large volumes of fluid can be lost to the formation during conventional completion or work over operations when the hydrostatic head of the fluid used is greater than the pressure of the reservoir. This is also true in high-permeability reservoirs and heavily fractured reservoirs. By using the wells own fluid and natural pressure, snubbing eliminates the need for costly LCM.

- In unconventional reservoirs especially in the Barnett, Marcellus, Haynesville Shales, Bakken oil Shales (North Dakota, Montana and southern Saskatchewan) and Eagle Ford (South Texas) shale plays (Wehrenberg, 2010). In these tight reservoirs, snubbing operations are ideal as they allow for the operators to keep producing the well while work-over operations are ongoing and no costly fluids are needed for drilling, completion or work-over operations. This is especially useful for the Bakken oil Shales play where the bottom hole pressure (BHP) in some areas can require equivalent mud densities up to 18 lb/gal (2.6 SG)

(Wehrenberg, 2010). With conventional drilling, completion, and work-over operations, high quality and expensive drilling and completion fluids would be needed to manage the high equivalent mud densities. In addition, if conventional work-overs are to be done in the future, there is a loss of revenue as the well would need to be shut in and most likely also killed prior to operation. Due to these cost and the further costs of collecting, transporting and disposing of contaminated cuttings and liquid wastes, coupled with the possibility of formation damage and the risk of hitting lost circulation zones, the overall economics for conventionally drilling, completion and work-over operations would be uneconomical for operators working within the unconventional plays in North America. In addition onshore snubbing operations leave a small footprint, all the equipment arrives by truck and everything is set up on the existing system, this is an advantage in unconventional plays that are near populated areas.

- In HPHT reservoirs, many of which are quite deep, these wells require large volumes of premium heavy, drilling, completion and work over fluids that are expensive, and similar to unconventional reservoirs these fluids could possibly be lost in lost circulation zones, there is a large risk of formation damage, and the fluids and cuttings are costly to dispose. Also these wells require very high pumping pressure, therefore extra costs for more equipment. In addition in some plays like the Haynesville Bossier shale play wells can be drilled from 3 658 m (12,000 ft) MD to greater than 4 572 m (15,000 ft) MD with bottom hole temperature (BHT) greater than 149^{o}C (300^{o}F) and pressure gradients in excess of

1.0 psi/ft (Wehrenberg, 2010). With such high pressures, conventional operations would require very heavy drilling, completion, work-over and killing fluids. Wells such as these in the past would have been completed with coil tubing operations. However, wells in the Haynesville Bossier shale play cannot use coil tube operations due to tubing fatigue / failure mainly from down hole mechanical friction resulting from wall to wall contact inherent in coil tubing operations in horizontal wells. This friction also limits the reach of coil tubing (Wehrenberg, 2010). In addition coil tubing cannot provide the needed weight on bit to mill up composite plugs typically used in completions. Due to limitations of coil tubing and the high pressure gradients exceeding 1.0 psi/ft, and the ability of snubbing operations to work into extended reach wells, rotate the drill pipe / tubulars, to give added weight on bit, and no requirement for costly drilling, completing and work-over fluids. Snubbing is the only preferred method for drilling, completion and work-over operations in the Haynesville Bossier HPHT shale play.

1.5 Motivation for Study

The current day use of snubbing is significant and the increase in demand for the use of snubbing on well sites is rising. While a majority of the snubbing operations are safe and occur without incident, in a small minority of cases there have been incidents in which explosions have occurred. The impact of the explosion has caused damage to property, and serious injuries including fatalities to on-site personnel. It is important to note that these incidents occur very rarely in relative terms.

Industry and those working within it generally understand the risks involved with snubbing, particularly during high pressure operations. However, sometimes during low pressure operations the same caution is not always applied. Therefore, for this study the focus will be on potential explosions in low pressure snubbing operations where well pressures are below 14 MPa (2,000 psig), primarily around 8 MPa (1,200 psig), as this is the lowest well pressure snubbing can be typically used. Of specific interest are relatively small trapped pockets of air and hydrocarbons mixtures in surface equipment during operations that could lead to explosions.

Small pockets of air and hydrocarbons can be trapped in many areas especially during snubbing operations when pressures are equalized or purged between the well bore, flare lines and surface assemblies. It is recognized that perfect mixing of air initially in the snubber and associated surface equipment with natural gas (assumed to be methane) introduced from the well would result in the average methane concentration within the gas phase being too fuel rich to burn. It is also recognized however that perfect mixing will not occur whenever air is present in "dead volumes" where there is no convective mixing of the air and methane. Within these "dead volumes", air will initially be trapped and mixing of the air with the natural gas will primarily be due to diffusion. The rate at which this occurs will depend on the geometry of the air pocket.

If the well gas in contact with an air pocket is pure methane, there is little danger of explosions unless the air pockets are located where there may be an internal spark or friction source. The reason is that pure methane has an auto-ignition temperature at atmospheric pressures which is in excess of 500^{o}C (Coward and Jones, 1952) and it is difficult to imagine how this level of temperature could be achieved in the absence of a spark within the surface equipment.

This is not the case if the well produces liquids such as natural gas condensates or hydrocarbon based work-over fluids which are often a diesel base (average carbon number around C_{13}). Coward and Jones (1952) report that the auto-ignition temperatures for fractions having carbon numbers in the excess of C_9 approach 200^oC at atmospheric pressures. Experience of the *In-Situ* Combustion Research Group (ISCRG) at the University of Calgary (Mehta and Moore: Private Communication, 2012) indicates that the auto-ignition temperatures reduces with increasing pressure and that a significant number of oils will undergo spontaneous ignition at temperatures in the range of 150 ^oC to 180 ^oC. Hence, if the air pocket is in contact with a heavy condensate or diesel based work-over fluid, then rapid re-pressurization of the surface equipment occurs as gas is introduced from the wellbore (often referred to as adiabatic compression), this can generate sufficiently high temperature to auto-ignite a combustion zone within the volume occupied by the air pocket.

Figure 1 illustrates an air pocket which could be present in a dead headed line. In this illustration, one end of the air pocket is in contact with an immobile hydrocarbon deposit while the other end is in contact with methane gas. Ignition of a burn within the gas phase has the highest probability to occur close to the interface between the immobile hydrocarbon and the air pocket, however once initiated, the localized temperature rise would be sufficient to ignite the methane within the transition zone where there hydrocarbon concentration of the methane-air mixture falls within the flammable range.

The air pocket illustrated in Figure 1 is located within a branch line from a tee , however cavities where air can be trapped can be found in the well's primary BOPs, snubbing BOPs, lubricators, spools, and lines leading to measurement gauges. The objective of this current study is to investigate and identify the location where trapped air pockets and immobile hydrocarbon may form. While Figure 1 assumes that one end of this air pocket is in contact with natural gas, the air may be trapped by liquids produced from the well.

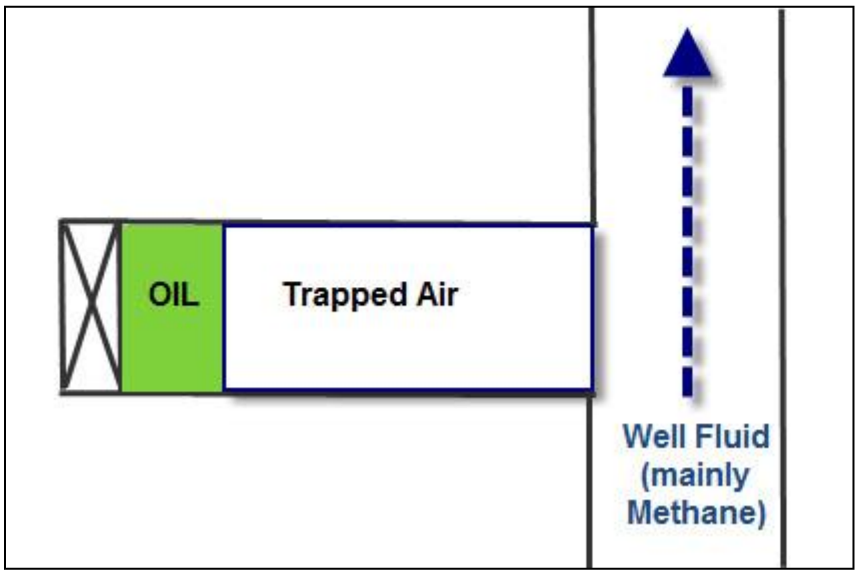


Figure 1: Trapped pockets of air and hydrocarbon during snubbing operations

These trapped dead volumes under the right temperature conditions such as during a hot summer day with direct sunlight light on the surface assembly, could raise the temperature of the air and hydrocarbon pocket high enough to begin the generation of heat and flammable vapour phase components through liquid phase oxidation of the liquid hydrocarbons. In *in-situ* combustion literature liquid phase oxidation reactions are normally referred to as "Low Temperature Oxidation or LTO" reactions. If the temperature is high enough the generated heat and flammable vapours from LTO reactions could supply enough ignition energy to lead to spontaneous ignition of the vapor phase.

Once LTO reactions begin the formation of oxidized species (organic acids, aldehydes, esters, ketones, alcohols), reactive hydrocarbon species in the liquid and semi-solid phases are of concern. These species are believed to be the ignition sources for an explosion. The accumulations of these oxidized species and hydrocarbons have the potential to behave like conventional explosives because these oxidized hydrocarbons will use their internal supply of oxygen to continue combustion once the external (to the liquid or semi-solid phases) supply of oxygen has been exhausted. When this occurs a detonation explosion subsequently follows.

In Figure 1, LTO reactions could begin due to a temperature rise on a hot summer day. The LTO reactions could be accelerated by rapid pressurization (from snubbing pressure equalization) thereby increasing the fluid temperatures and at a certain point, spontaneous vapour burn ignition may start from the oil/trapped air interface with the combustion front moving towards the well fluids. If at the oil/trapped air interface the amount and rate of heat generation is sufficiently high a secondary combustion zone at the interface between the trapped air and well fluid interface could begin as well. Once the trapped air oxygen source is exhausted, the combustion starts drawing on its supply of internal oxygen internally from its LTO oxidized species. The internal oxygen supply burn can have a very high rate of energy generation and is often confined into a relatively small volume. Since pressure is equivalent to energy per unit volume, high energy generation rates in a small volume leads to a large pressure rise known as a shockwave that moves out rapidly and can cause serious damage.

Good examples of this phenomenon are explosives such as gun powder or ammonium nitrate-diesel. Gun powder burns in a controlled manner with adequate external air supply, however if the burning powder is covered with a container thereby no longer making the external oxygen supply available, the combustion reaction will feed on the supply of internal oxygen and an explosion will occur.

Further, a study done by Shahbazi et al. (2005) provides an example of explosions from small amounts of air and hydrocarbons in an enclosure (Shahbazi et al., 2005). In this study a volume of diesel (112 mL in a 250 mL container) left for a period of time at a constant initial pressure of 13.5 MPa (1,960 psig) and initial temperature of 150^{o}C exploded with a large pressure rise. The charge air in this enclosure had an intial composition of 21.88% oxygen and 78.12% nitrogen (Shahbazi et al., 2005) as illustrated in Figure 2.

In Figure 2 it is believed that LTO reactions begin to occur as the diesel is left to sit and minutes before the large sudden pressure increase, the liquid temperature starts to rise, and pressure starts to decrease. It is believed that at this point the external oxygen uptake of the reaction starts to decrease and the reaction is starving of oxygen. The reaction then looks internally for oxygen from the LTO oxidized species and subsequently after this the explosion occurs.

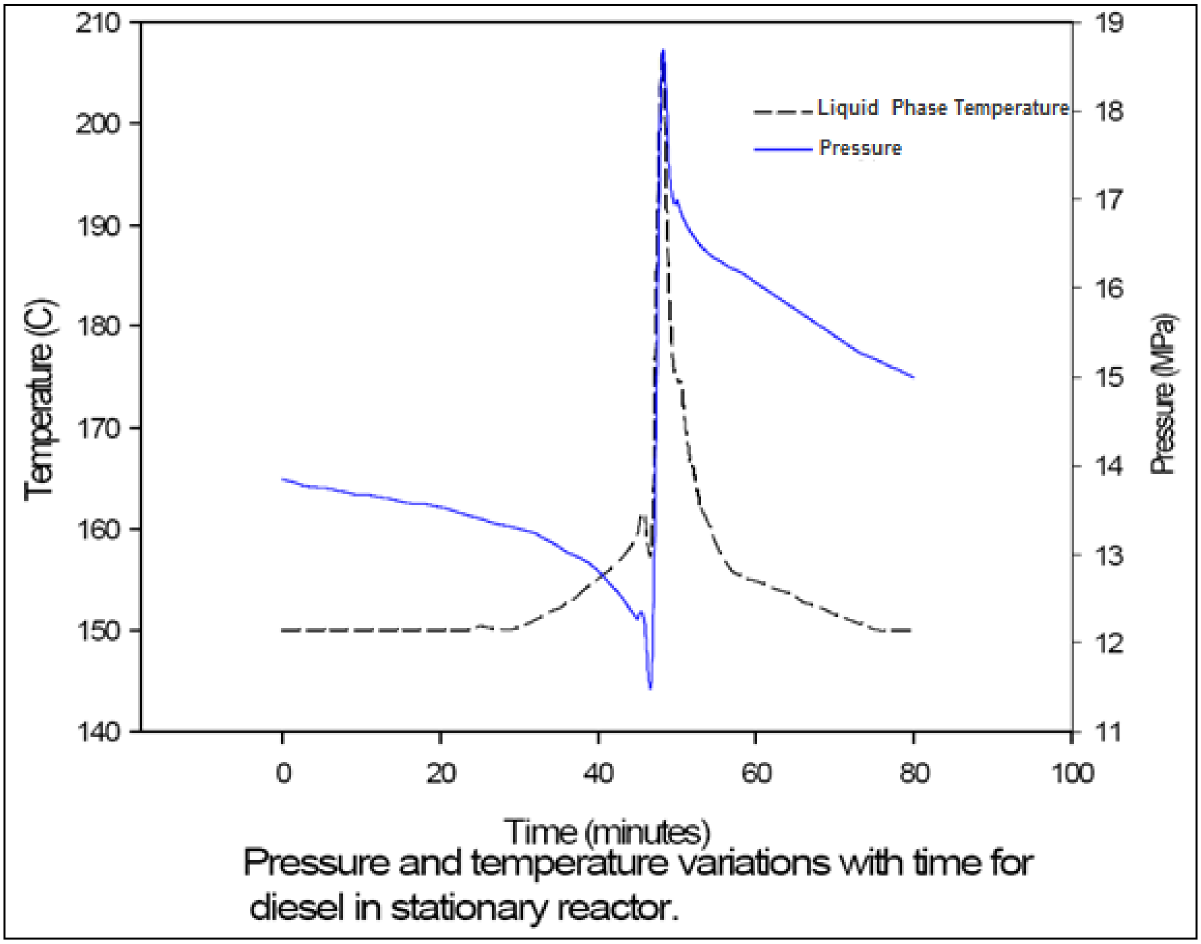
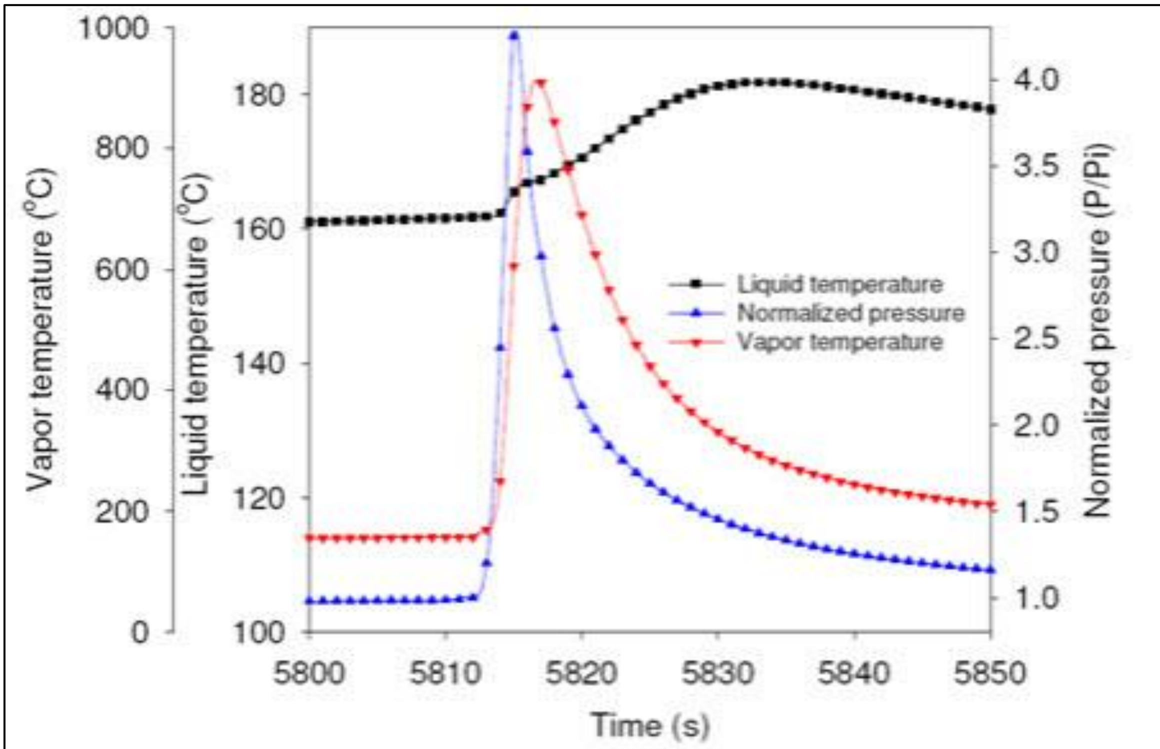


Figure 2: Diesel in stationary reactor experiencing an explosion due to auto-ignition from liquid phase (Shahbazi et al., 2005).

In Shahbazi's study, as the explosion occurs, the pressure increases from the initial pressure condition of 13.5MPa (1,960 psig) to approximately 18.5 MPa (2,700 psig). This is about 1.32 times the initial pressure. The liquid temperature also rises from 150^{o}C to approximate 205^{o}C, denoting an increase of 55^{o}C in temperature.

In another similar study with the same composition of charge air by Shahbazi et al., (2006) a synthetic drilling fluid used in Alberta drilling operations was tested (Shahbazi et al., 2006). This fluid was called ENVIRO-DRILL™ it is essentially a hydro-treated heavy petroleum naphtha, and it was mixed with commonly used oilfield additives in an enclosure at a constant initial pressure of 13.5MPa (1,960 psig) at a temperature of 150°C (Shahbazi et al., 2006).

After some time an explosion occurred. This was again attributed to LTO reactions leading to an internal burn of the LTO oxidized species. The maximum liquid phase temperature recorded in the system was 182°C while the vapour phase temperature attained was approximately 900 °C. As shown in Figure 3 the pressure rise was greater than four times the initial pressure.



Normalized pressure and vapor, liquid, and wall temperatures of Envirodrill +…+ calcite versus time just around rapid heating event.

Figure 3: ENVIRO-DRILL™ and various additives under constant pressure ignite due to liquid phase auto-ignition (Shahbazi et al., 2006).

In some experiments it has been noted that explosions can generate greater than 18 to 30 times the initial pressure conditions (Johnson and Vasey, 1996; Shahbazi, 2006). This is of particular concern to snubbing operations as the pressure ranges of typical operations are within or greater than the pressure in Shahbazi studies and there are areas in the surface equipment that air and hydrocarbon mixtures could potentially be trapped in dead volumes.

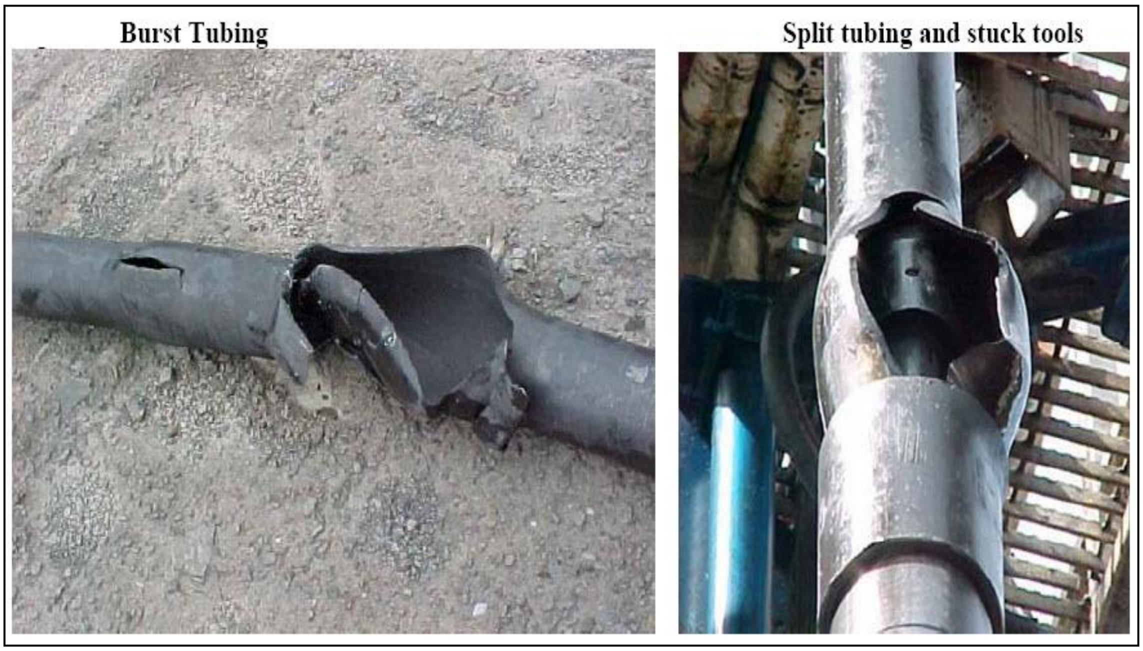


Figure 4: Burst tubing and split tubing damage from Petro-Canada's down-hole explosions during snubbing operations (Duncan, 2008).

In addition, similar fluids as used in Shahbazi's study could be present in snubbing operations and generally most equipment on-site will experience damage from an explosion if the pressure rise is greater than the maximum collapse or burst pressures of the equipment. This will result in the equipment failing possibly causing injury to personnel or damage to the surroundings. Of specific concern is surface equipment as any explosions on surface can have the greatest effect because of its close proximity to on-site personnel and equipment. Figure 4 illustrates the damage caused to tubing due to an explosion in snubbing operations (Duncan, 2008).

Therefore, this study will mainly focus on potential trapped air and hydrocarbons mixtures that could cause explosions due to internal ignition of LTO oxidized species and the resulting shockwaves generated within surface equipment during low pressure snubbing operations.

1.6 Objectives

The general objectives of this study are:

1. To get a better understanding of snubbing operations. Limited primary literature has been published on general equipment and procedures for snubbing operations. Most knowledge is learned in the field, passed on through word of mouth. Most source documents and open literature on the subject matter are geared towards personnel with previous operational snubbing experience. It is hoped this study can be used as a source document for those with little or no previous snubbing knowledge to learn and build upon,
2. To investigate and identify potential trapped pockets of air and hydrocarbons mixtures within surface equipment during low pressure snubbing operations that may lead to explosions.
3. To investigate and begin to understand the role of LTO in the explosion mechanism due to LTO reactions which is felt to be accelerated by rapid compression.

4. To obtain a basic understanding of explosive shockwaves, and their damage potential during an explosion within surface snubbing equipment and,
5. To provide key recommendations for safe snubbing operations free of fire and other hazards from explosion.

Chapter 2: Literature Review and Background

This chapter will provide information on snubbing operating fundamentals, snubbing procedures and background information on explosions.

2.1 Snubbing Fundamentals

Snubbing is done with snubbing units, these units can either be rig-less units called standalones or rig-assists sometimes referred to as hydraulic rig-assists (HRA). Rig-assists are modified units that go on existing rigs. Both standalone and rig-assist units contain similar equipment. Detailed figures of these units can be found in Appendix A.

2.1.1 Snubbing Units

Standalone units are self-contained free standing rigs that include all equipment required for snubbing operations including their own primary well BOPs. Standalone units like rig-assist units also come with their own snubbing crew, however the crews for a standalone operations are typically larger than rig-assists. Figure 5 illustrates a standalone unit.

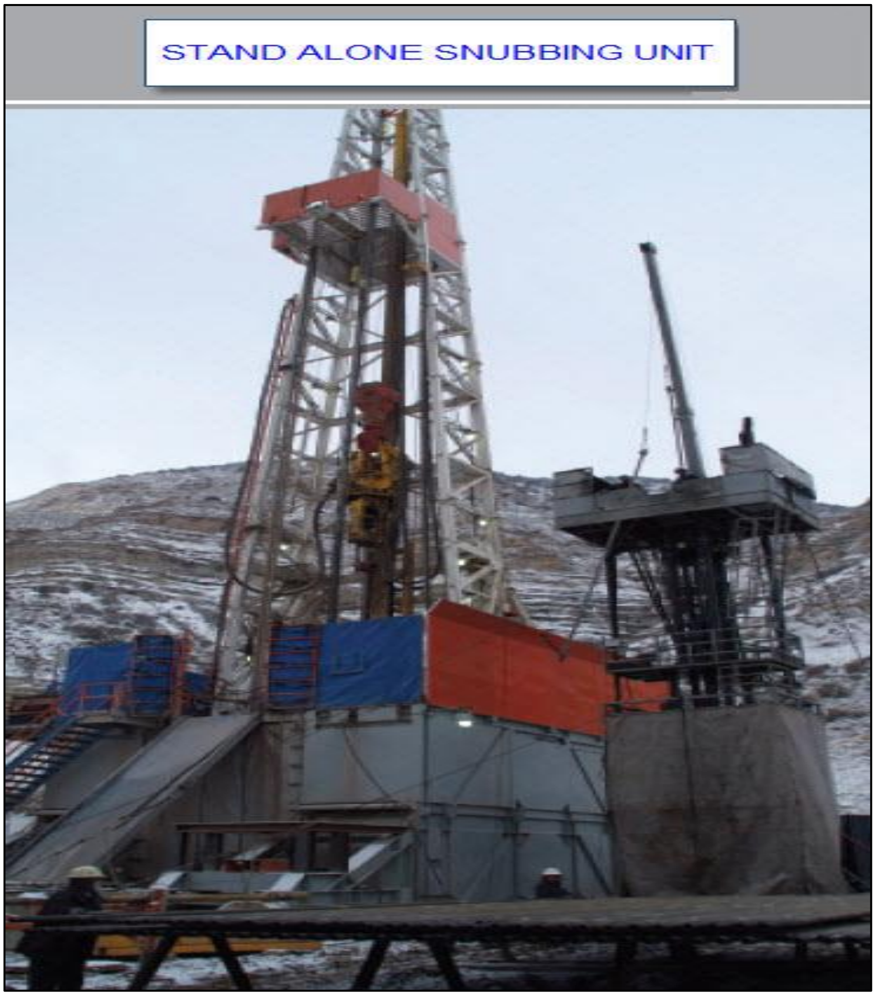


Figure 5: An example of a standalone snubbing unit (International Snubbing Services LLC, 2011).

Rig-assist units, as shown in Figure 6, are typically one large single piece of equipment that can fit and can be transported on the back of a truck. Once on site they can be mounted within the derrick of the drilling or work-over rig on site. The rig-assist unit utilizes the primary BOPs existing on the rig that it attaches itself to. The rig-assist transport truck provides the hydraulic power for the system. The rig-assist uses the existing rig systems for tripping operations and to make-up, rack or lay down pipe during the operations, which is a major advantage over standalone units as the latter units have little room to rack pipe.

Figure 6: An example of a rig-assist snubbing unit (International Snubbing Services LLC, 2011).

Both standalone and rig-assist units are commonly used in snubbing operations. An advantage of standalone units is increased safety because there is no risk of incompatibility of equipment between the drilling or work-over rig and the snubbing equipment. Also with the use of standalone snubbing units there is no need for a completion or work-over rig to be on site for other related operations. All aspects of completions or work-overs can be completed on a snubbing standalone unit. In addition compared to regular completion and work-over units, standalone snubbing units can reduce crew requirements and leave a smaller environmental footprint (Snubco Pressure Control Ltd., 2010).

However, standalone units typically take longer than rig assists to set up and do not have tubular standing capabilities. This requires them to pick up or lay down pipe as needed during tripping operations which slows down operations.

On the other hand rig-assist units are designed for quick mobilization. Their operations are typically faster as they use the draw works of the rig they attach to for tripping and stacking pipe. It usually takes a rig-assist unit 1 to 2 hours to rig up while a standalone can take 4 to 6 hours (Schmigel, 2003).

2.1.2 Snubbing Process

The process of snubbing involves the tripping of a pipe into and out of a well with surface pressure. When the surface pressure and the work string combination is such that if unrestrained the pipe would be ejected from the well, moving the pipe is termed snubbing or a pipe light situation.

When the weight of the pipe becomes greater than the force of pressure acting on the cross sectional area of the pipe, the pipe is considered pipe heavy and the process is called stripping (Snubco Pressure Control Ltd., 2010; Hodgson, 1995). Generally if F_w (force of the well) is greater than the W (weight of the work string) then snubbing force is needed, otherwise the situation is pipe heavy (Duncan, 2008; DACC and Enform, 2007) as illustrated in Figure 7.

During operations there is a also a point on the work string where the force of the well is equal to the weight of the work string. This point is called the neutral point. At this point the axial stress changes from compression to tension on the workstring. This point can change during operations due to a number of factors (weight on bit, buoyancy), but is usually limited to a certain zone, usually of few joints long. In this zone the work string experiences a lot of wear, as it can switch from being in compression to tension and back in a cyclic manner. In snubbing operations, particularly due to the pressures involved, thorough pre-planning is needed to identify this point / zone and ensure the work string is strong enough in this area, so as to prevent tubing failure. Figure 7, also illustrates the neutral point.

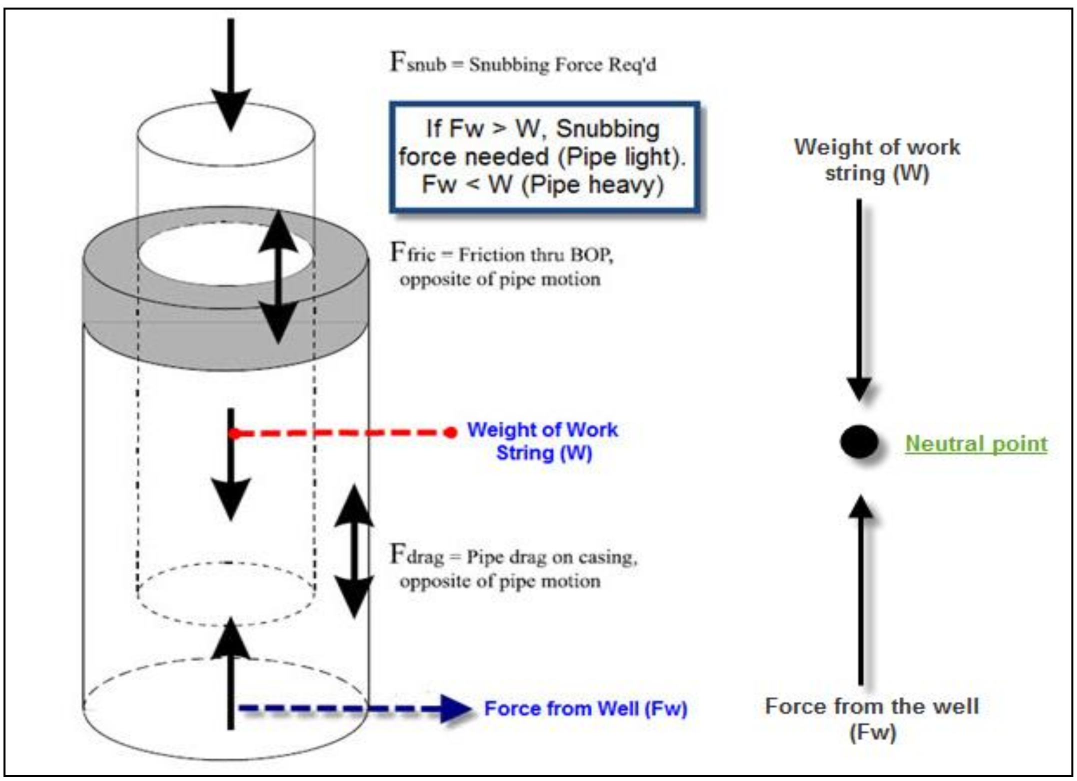


Figure 7: Summary of forces while snubbing (Duncan, 2008; DACC and Enform, 2007)

2.1.3 Snubbing Calculations

The fundamental calculations associated with snubbing operations are;

a) Maximum snubbing force F_{snub} required,

b) Critical buckling load and maximum unsupported length of tubing.

A series of other calculations are also used. A detailed list can be found in IRP 15. However, the above two calculations are the most critical.

2.1.3.1 Maximum Snubbing Force Needed

The maximum snubbing force F_{snub} occurs when the operation has just started as there is no weight to assist in running down-hole. The maximum well pressure force F_W occurs when a coupling is placed in the Annular Preventer, because a coupling has a greater cross sectional area than tubing. Therefore the maximum snubbing force can be calculated as shown in Equations 2.1 and 2.2 below.

$$F_{snub} = F_W + F_{fric} \approx F_W \times 1.2 \tag{2.1}$$

$$F_W = \frac{W \times A}{10\,000} \tag{2.2}$$

Where:

F_{snub}	Force of Snubbing (daN)
F_W	Force of Well Pressure (daN)
F_{fric}	Force of Friction (daN)
W	Well Pressure (kPa)
A	Cross sectional area of the pipe (mm^2)

According to DACC and Enform (2007) F_F can be assumed to be around 20% of the force of the well F_{WP}. This can be estimated because these forces, especially the force of friction in snubbing operations is the friction from the work string going through the annular BOPs. This is a function of hydraulic pressure (snubbing force), applied to the annular BOP which is a function of the well pressure (DACC and Enform, 2007).

2.1.3.2 Critical Buckling Load of Tubing

Under snubbing force tubing can buckle. This could result in tubing failure which may result in the work-string being ejected from the well or loss of pressure integrity at the surface (Duncan, 2008). Therefore, a calculation of buckling forces is needed to calculate the maximum allowable unsupported length from the snubbing pipe ram up.

There are two main types of buckling: local buckling (inelastic) and major axis buckling (elastic).

To begin, the following calculation as shown in Equation 2.3 is required:

$$L = R_g \times SR_c \tag{2.3}$$

Where:

L	Unsupported length value (mm). It is the transition point between local and major axis buckling
R_g	Radius of Gyration (mm)
SR_c	Critical slenderness ratio, used to determine the strength of a tubing/column

Actual unsupported length values below the unsupported length value calculated above indicate local buckling and any value above, major axis buckling. A graphical illustration of the unsupported length value (L) for a 60.30mm OD tubing with a tubing weight of 6.99 kg/m is shown in Figure 8.

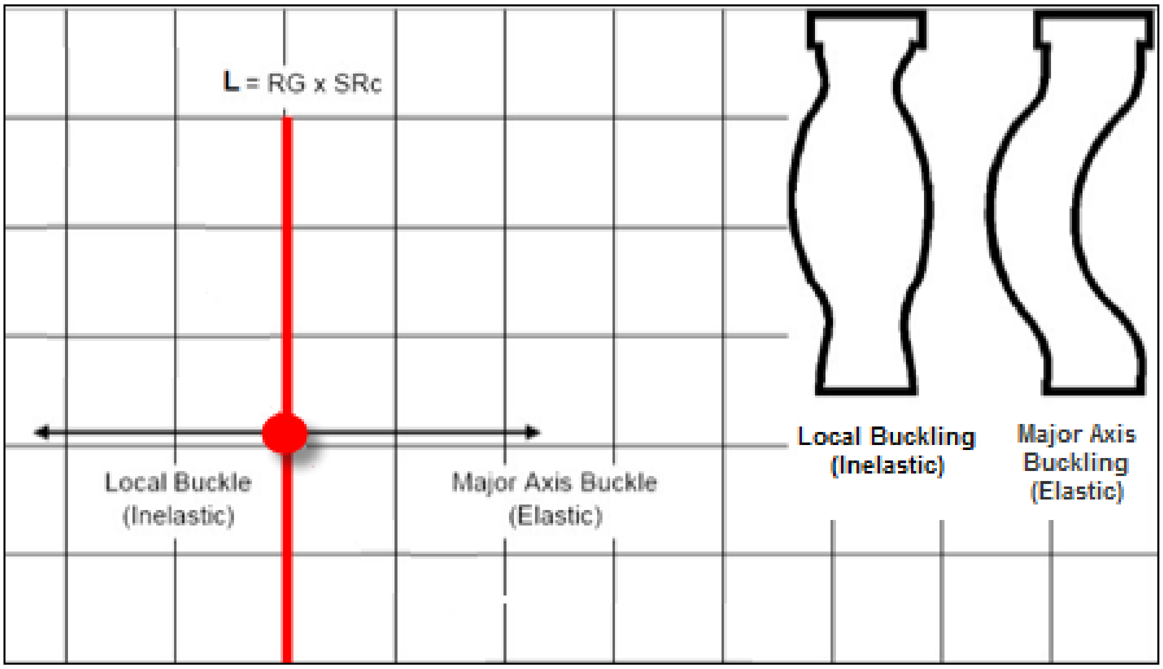


Figure 8: Buckling force vs. unsupported length with illustration of local and major axis buckling on a 60.30mm OD tubing (DACC and Enform, 2007).

Once a value for L has been calculated, next buckling force needs to be calculated.

For calculating local buckling the Johnson's Equation 2.4 is used. The equation is as follows:

$$F_{cr} = \sigma_y A \left(1 - \frac{\left(\frac{L}{R_g}\right)^2}{2 \times {SR_c}^2}\right) \qquad (2.4)$$

Where:

F_{cr}	Buckling Force critical (daN)
A	Cross sectional area (mm^2)
σ_y	Yield Stress of Steel (MPa)
L	Unsupported Length (mm)
R_g	Radius of Gyration (mm)
$SR_c{}^2$	Critical slenderness ratio

For calculating major axis buckling a modified Euler's Equation 2.5 is applied:

$$F_{cr} = \frac{\pi^2\, EI}{L^2} \tag{2.5}$$

Where:

F_{cr}	Buckling Force critical (daN)
π	Pi
E	Modulus of Elasticity of the Material (GPa)
I	Moment of Inertia (mm^4)
L	Unsupported Length (mm)

The yield stress (σ_y) and the modulus of elasticity (E) can be looked up according to the tubing type that will be used. The moment of inertia, radius of gyration and critical slenderness ratio can all be calculated from the procedure and details set out in Appendix B.

An example from DACC and Enform (2007) for a well pressure of 17 500kPa is illustrated in Figure 9 and Figure 10 below. First tubing snubbing force and coupling force is calculated based on Equation 2.1 (Note couplings have larger ODs than tubing) for a range of well pressures in this case from 0 to 50 000kPa. The well pressure of 17 500kPa is then marked with a vertical line. Next the buckling force can be calculated using Equation 2.4 for local buckling and Equation 2.5 for major axis buckling, the results are illustrated in Figure 10. Figure 10 is then placed beside Figure 9. On Figure 9 a horizontal line (coupling) is extended from the intersection points of the wellbore pressure and snubbing force to the 60% IJ connection green line located on Figure 10 and the data for maximum allowable lengths is read. There are two lines in Figure 10. The 100% red line indicates a line with no safety factor the 60% green line is the line with a 60% safety factor. The green line is used for operations. Further details on calculations for Figure 9 and Figure 10 are found in Appendix B (DACC and Enform, 2007) .

Figure 9: Snubbing force vs. well pressure for a tubing and coupling (collar) with an OD of 33.4mm and grading of J-55. Tubing weight was 2.56 kg/m (DACC and Enform, 2007).

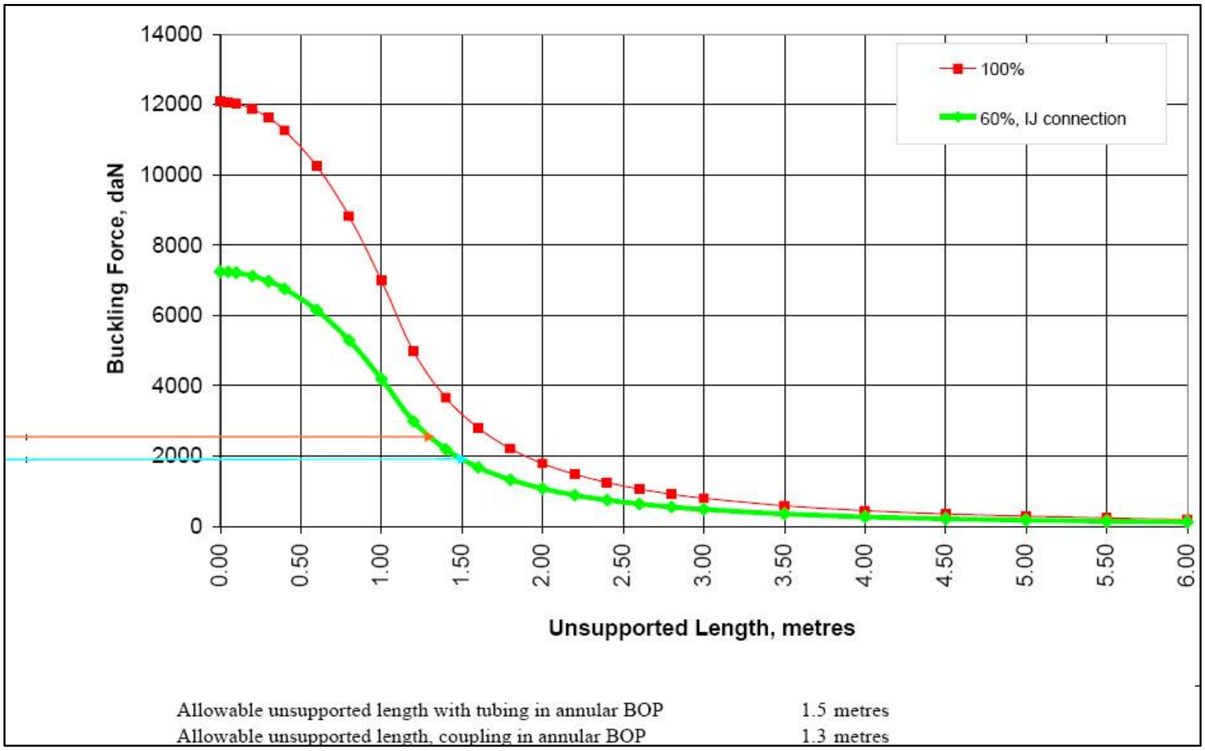


Figure 10: Buckling force vs. unsupported length for a tubing and coupling with an OD of 33.4mm and grading of J-55. Tubing was 2.56 kg/m (DACC and Enform, 2007).

The unsupported lengths in Figure 10 give an indication of the maximum safe allowable lengths that can be left unsupported during operations without major buckling incidents.

Generally buckling occurs over a short distance on the unsupported length of the pipe above the snubbing unit's pipe rams. An operator may need to adjust his equipment to ensure that the unsupported lengths are taken into consideration for safe operations.

2.1.4 Snubbing Well Control

In most conventional oil and gas drilling, completion and work-over operations, well control is primarily achieved through maintaining a column of fluid with sufficient hydrostatic pressure to prevent the well from flowing uncontrollably. The BOP system is also used mainly as a secondary barrier or fail safe if the fluid column fails to maintain pressure. In snubbing operations a combination of BOP's (both on the snubbing unit and the well BOPs) including wireline plugs are mostly used to maintain well control. The surface BOPs are the primary form of well control in snubbing operations.

2.1.5 Snubbing Equipment

Snubbing equipment is specialized. They are primarily needed for two main functions (DACC and Enform, 2007) in order to:

1. Provide well control, specifically of annular pressure through the use of stripping components or working blowout preventer stacks, and,
2. Allow for the movement of tubulars in and out of a well controlled by mechanical means with enough ability to overcome the force the well pressure exerts.

Snubbing unit equipment for both the standalone and rig-assist's are very similar. The main difference is that the rig-assist uses the drilling or work-over rig's draw works for its lifting force. In addition standalone units provide both the primary and snubbing unit BOPs, primary and snubbing unit accumulators, and come with flare stacks, a doghouse and kill fluids, pumps and tanks if required.

For rig-assist operations the existing rigs BOP stack is used. In some cases additional BOPs may be needed depending on the conditions such as high hydrogen sulphide gas content. (Snubco Pressure Control Ltd., 2010).

Table 2 below lists the main parts of a snubbing unit. These parts are common to both standalone and rig-assist operations. (Snubco Pressure Control Ltd., 2010; Huntley, 2011)

• Travelling Heavy Slips / Heavies	• Jack Plate	• Passive Rotary
• Travelling Snubbing Slips	• Power Tongs	• Hydraulic/ Jack Cylinders
• Hydraulic Control Panel/Control Panel	• Work Basket/ Upper and Lower Basket	• Equalize/Bleed off Spool
• Stationary Light Snubbing Slips	• Stationary Heavies/ Heavy Slips	• Annular Preventer
• Work / Equalizing Spool	• Top Stripping Pipe Rams	• Lower Stripping Pipe Rams
• Hoses / Lines	• Power Pack	

Table 2: Equipment and components on snubbing units

The snubbing units that are skid mounted have been illustrated in Figure 11. Appendices A4 – A9 have additional schematics on snubbing skids and the BOP stack.

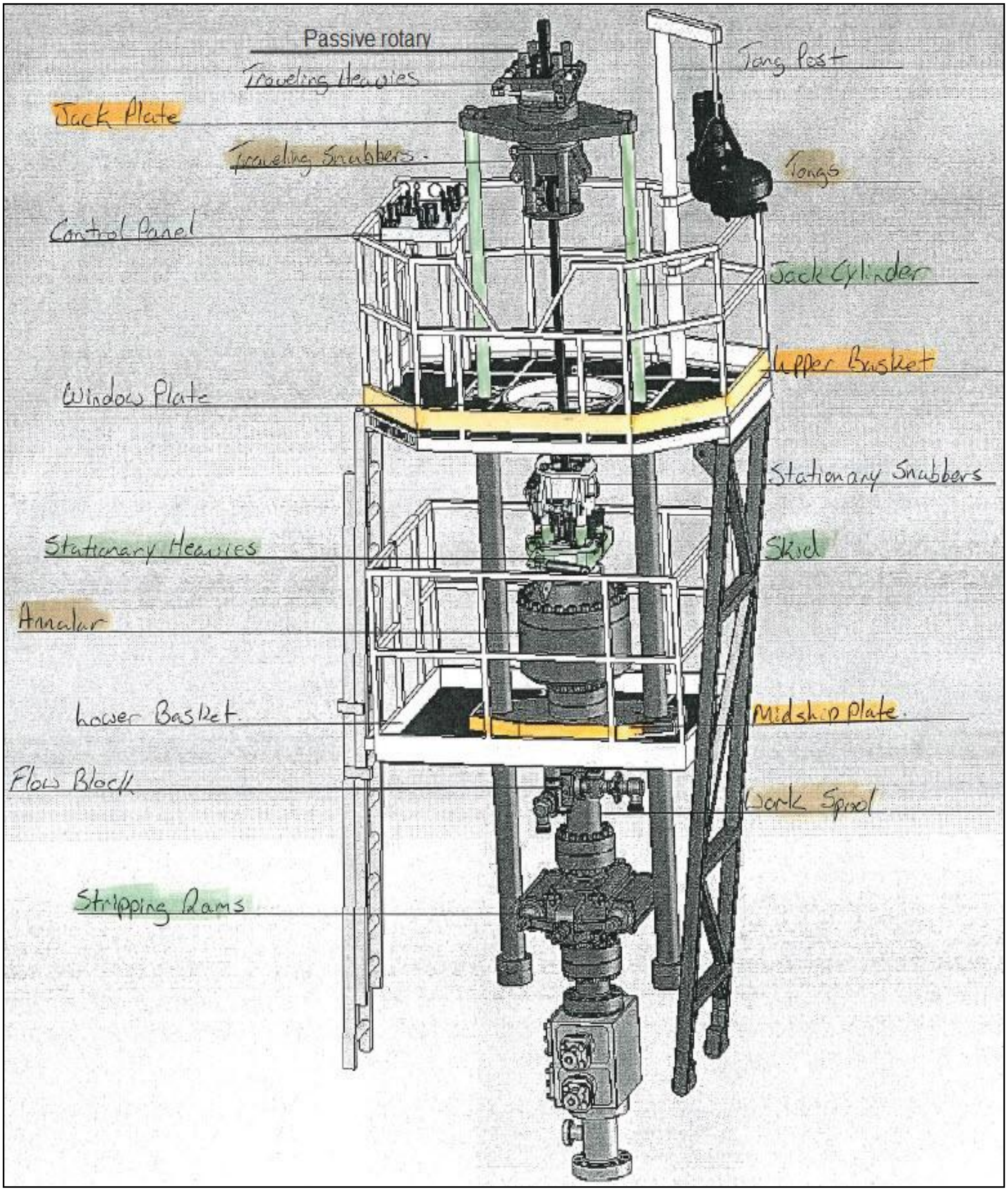


Figure 11: Rig-assist snubbing unit with essential equipment labeled (Huntley, 2011).

The components of the snubbing equipment and their function are summarized below:

Travelling Heavies / *Heavy Slips* are a set of slips used during stripping operations to stop pipe from falling down-hole especially during the transition from pipe light to pipe heavy. They are attached near the top of the rig, on the passive rotary.

Jack Plate is a plate of high strength steel that physically ties the snubbing unit's two hydraulic cylinders together. It is designed for quick removal to facilitate other operations such as wireline and or access to the BOP contained on the subbing unit. Most times the passive rotary and travelling slip attachment points are contained within the plate (Snubco Pressure Control Ltd., 2010).

The *Passive Rotary* allows for the rotation of the string during pipe light/ snubbing operations. It gives the unit the ability to set tools requiring rotation or to perform drilling/milling operations in snubbing pipe light mode when coupled with a power swivel (Snubco Pressure Control Ltd., 2010).

Travelling Snubber / Snubbing Slips are a set of slips that grip the pipe during snubbing operations. The equipment is mounted in an inverted position to prevent pipe from being ejected from the wellbore while pipe light/snubbing. These slips are attached to the bottom of the unit's passive rotary or jack plate and travels up and down with the units hydraulic cylinders.

Tongs / Power Tongs typically operated by the snubbing assistant, these are of varying sizes depending on the operations. They are large capacity, self-locking wrenches used to grip drill/work string components and apply torque. The tongs are held by the tong post.

Jack / Hydraulic Cylinders these cylinders provide the necessary force to lift the pipe into and out of the hole during snubbing operations. Each snubbing unit's cylinders are rated on the maximum force that it can exert. The cylinders are controlled by the control panel.

Control Panel contains all the hydraulic operation for the units such as the snubbing BOPS, slips and hydraulic jacks. Closing pressures for annular, slips and stripping rams can be controlled and set as per the required safety of different operations.

Work Basket - Upper and Lower Basket. Each basket is a work platform and there are typically two platforms mounted on the snubbing unit. The upper basket is used during tripping operations and serves as a mounting point for the control panel of the unit. The lower work platform allows the crews to access to stationary slip / snubbers and the annular preventer for maintenance and repair if needed.

Window Plate, the window plate is an opening on the upper basket that allows for tubing and the travelling heavies and snubbers to go through.

Stationary Snubbers /Light Slips, are a set of slips that holds the pipe from ejecting from the well during snubbing operations. They are engaged in order to release the travelling slips and allow the traveling snubbers, jack plate and travelling heavies to be lifted back to the top of the upper basket to be loaded with the next drill pipe / work-string.

Stationary Heavies/ *Heavy Slips* are similar to the above slips and are engaged to prevent the drill pipe from falling down-hole during stripping operations. This set of slips gives the snubbing unit the ability to provide pipe movement when in heavy mode operations independent from the rig draw works (Snubco Pressure Control Ltd., 2010).

Annular Preventer, is a BOP under the stationary heavies that can provide a rapid seal on any kind of pipe in the well. It can also provide seals on wireline or even seal on itself if the hole is open (Enform, 2011). In snubbing operations this annular preventer is used during tripping operations.

Within an annular preventer is a flexible elastomer element that can conform to virtually any shape. A hydraulic system is used to operate the preventer and is designed to allow quick reaction times to changes in the pipe diameter, such as tool joins or collars. This hydraulic system is powered by the snubbing unit. The hydraulic fluid is frequently a petroleum based product.

This BOP has a typical pressure rating of 5 000 psi or 35 000 kPa. (Snubco Pressure Control Ltd., 2010). As per Alberta regulations the annular preventer must close fully in less than sixty seconds (Enform, 2011). Figure 12 illustrates an annular BOP. See Appendix C for detailed diagrams on annular BOPs.

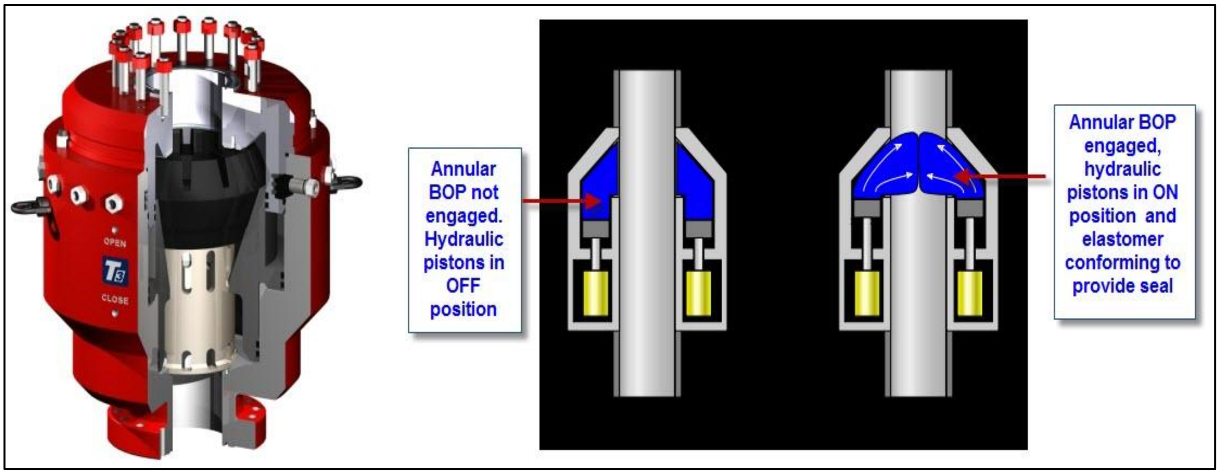


Figure 12: Annular BOP, and description of its use when engaged and non-engaged through the use of hydraulic pistons pressured through the accumulator (T3 Energy Services Inc, 2011).

Work / Equalizing Spool is a spool component typically installed to allow for pumping of fluid into the well and for allowing fluid to flow out of the well when the BOPS are closed. These spools are equipped with side outlets to which the kill line or return line are attached. Typically these spools are used in snubbing to equalize the pressure of the drill string / work string to well conditions before they are tripped in.

Top Stripping Pipe Rams or main Stripping Rams in low pressure snubbing operations, are placed below the annular BOP. They contain two rams which seal on the tubing when engaged. A hydraulic system is used to close them. However, they can also be manually closed, but they can only be opened with hydraulic pressure. It is important to note that this BOP will only hold pressure from the lower side up, so if it is installed incorrectly up-side down it will not hold pressure.

The stripping rams only closes to a specific outer diameter size of pipe, some pipe rams such as a variable pipe ram can close to different diameters depending upon what the crew has prepared the devices for. These BOPs are used in situations where the annular preventer is unable to safely contain the well pressure or as a backup to the annular BOPs. See Figure 12. These BOPs as per Alberta regulations need to close fully in less than thirty seconds (Enform, 2011).

In low pressure snubbing operations only one stripping ram is used. During high pressure operations both a top and lower stripping ram is used. Figure 13 illustrates pipe rams. See Appendix A for a high pressure snubbing configuration.

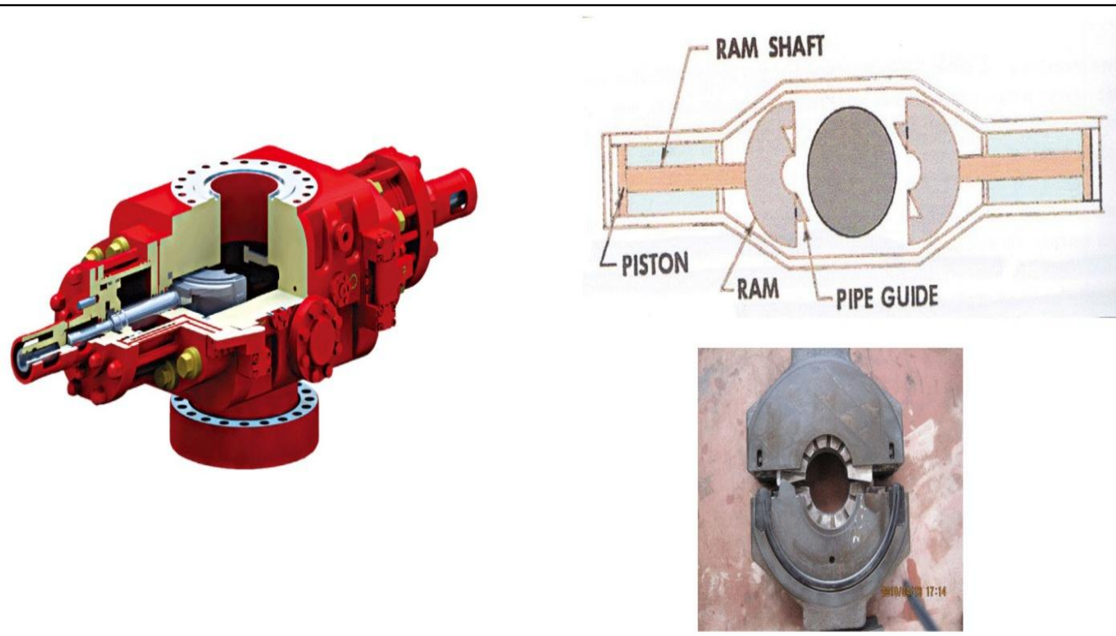


Figure 13: Pipe Rams and illustration of the piston and the ram shaft that closes the ram onto the pipe (Enform, 2011; Cameron International Corporation, n.d.).

Lower Stripping Rams, are typically only used in high pressure snubbing operations and installed below the work/ equalizing spool and functions similar to the top stripping pipe rams. The configuration of using a top and lower pipe ram with an equalizing spool in between allows for a technique called "ram to ram" (Huntley, 2011). In "ram to ram" the top and lower stripping rams can be opened and closed and used for added support for purposes of snubbing or stripping. By Alberta regulations this can only be done on the snubbing unit BOPs, Alberta regulations prevent stripping or snubbing of pipe thorough pipe rams or annular BOPs on the primary well BOPs.

Hoses/Lines, various hoses and lines are needed for operation. The hoses and lines provide the flow path for the fluids (hydraulic, power, kill). They can either be rubber like hoses or metal pipes. Figure 14 below illustrates.

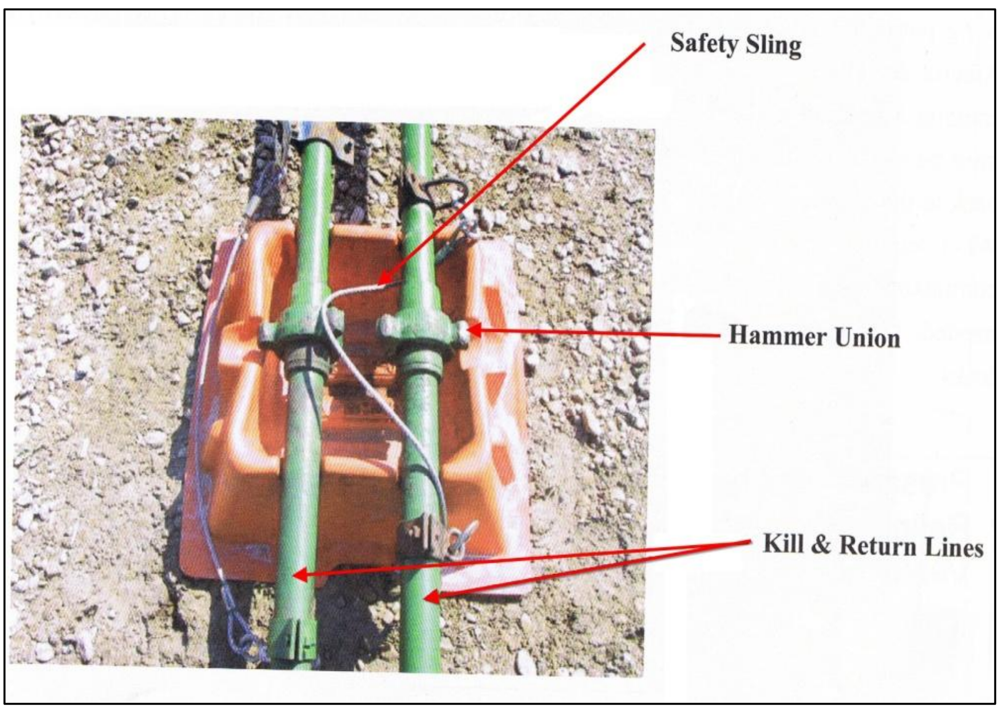


Figure 14: Lines used in operations (Enform, 2011).

Carrier / Power Packs, are typically a truck or multiple trucks that provide both transport and power to the hydraulic system for the snubbing unit. The truck also serves as the mounting point for the accumulator snubbing unit BOP system (pipe rams). The above listed components are the main equipment used in snubbing. They are components common to both standalone and rig-assist units.

During snubbing operations in addition to the above equipment, primary annular, primary pipe rams and primary blind/shear rams are needed. The primary annular and pipe rams are similar to the snubbing annular and pipe rams. However, they are not used for stripping purposes and have controls located at the top of the work basket and remotes located on the ground (Snubco Pressure Control Ltd., 2010).

Blind Rams are sometimes used as primary BOPs. These are designed to close when the pipe is out of the hole. The rams seal on each other and shut in the well.

Shear Rams, may also be used as primary BOPs. They are modified blind rams that are designed to shear off any pipe or wireline that may be in hole. When engaged they cut through whatever is in the hole, then seal on themselves to shut in the well. The lower tubing that is sheared off is lost down-hole (Enform, 2011).

Frequently in operations shear rams are more commonly used. See Figure 15 and Figure 16 . This is because when there is nothing in the hole the shear rams act like blind rams. For snubbing operations with surface well pressures over 21 000 kPa shear rams are mandatory. The BOP Stack configuration with a triple gate rams and annular preventer for a large wellbore operation is illustrated in Figure 17.

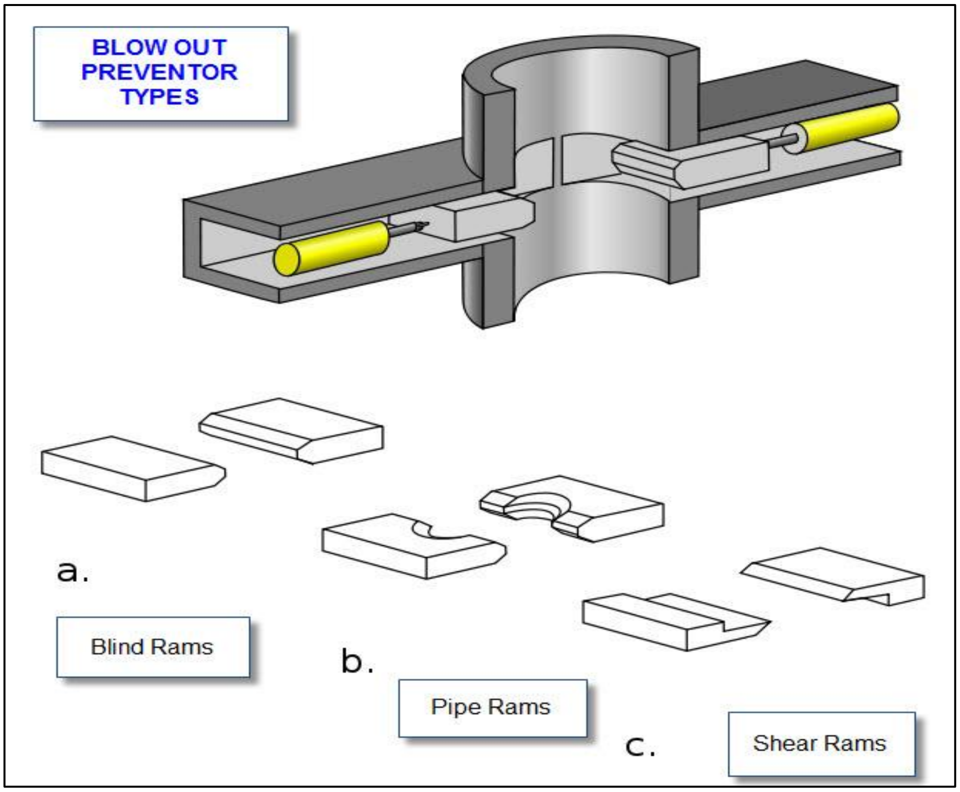


Figure 15: Blind, pipe and shear ram BOPs and their respective rams.

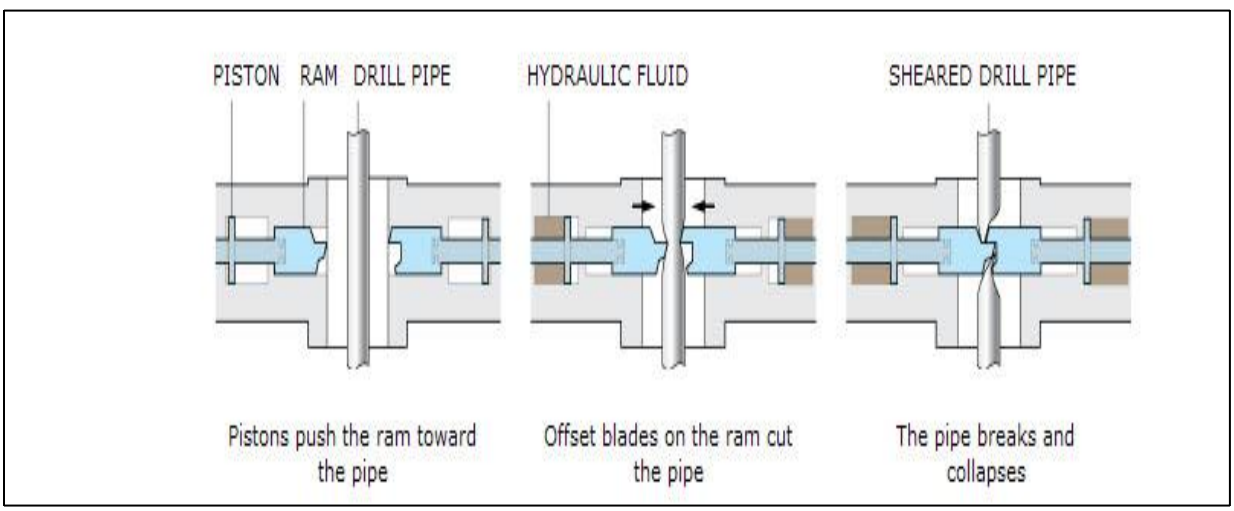


Figure 16: Illustration on how shear rams cut the tubing. Shear rams are needed during high pressure snubbing operations (Werner Sölken, 2011).

Figure 17: BOP stack configuration with a triple gate rams and annular preventer for a large wellbore operation (Cameron International Corporation, n.d.).

2.2 Low and High Pressure Snubbing Procedures

Snubbing units can do a multitude of operations. A general common low pressure snubbing operation will be discussed in this section. A low pressure snubbing operation is one in which the well is under 21 000 kPa (DACC and Enform, 2007). High pressure snubbing operations are very similar to low pressure operations but have a slightly different snubbing configuration, mainly two snubbing stripping rams are used instead of just one. For a high pressure snubbing configuration refer to Appendix A.

Once a snubbing unit arrives on location the snubbing crew rigs up the snubbing equipment either on the existing site's primary BOP stack (rig-assist) or on the snubbing units primary BOP stack (standalone). The snubbing crew ensures that the primary BOP's blind rams are closed and if needed any well fluid or pressure is bled off.

After the snubbing unit is rigged up and placed on the primary BOPs the snubbing units stripping pipe rams are closed, but the snubbing unit's annular BOP is left open.

The bottom hole assembly (BHA) is then made up. In most snubbing operations a snubbing plug is set on the bottom of the BHA.

Once the BHA is made up, it is picked up with the pipe handling system and lowered into the snubbing stack till the plug is just above the primary rig's BOP blind / shear rams.

The snubbing unit stationary snubbers, travelling snubbers and travelling heavies are engaged onto the pipe. At this point the hydraulic cylinders are holding the weight of the tubing. The snubbing units annular BOP is then engaged and closed on the joint. Then the equalization line located on the casing bowl is opened creating an equalizing loop that equalizes the work string to well pressures. The unit is then checked for leaks of fluid.

After this check is complete the snubbing units stripping pipe rams and the rig's primary blind/shear rams are opened, and the stationary snubbers are disengaged. The hydraulic cylinders through the travelling snubbers and travelling heavies force the pipe downwards. The travelling heavies and snubbers push the pipe downwards moving with the pipe until they reach the stationary snubbers. The stationary snubbers are then engaged and hold the weight of the pipe as the travelling heavies and snubbers are disengaged and travel upwards towards the upper basket where a new connection is made using the power tongs on the upper basket. The travelling heavies and snubbers are then re-engaged and the stationary snubber are then subsequently disengaged. The pipe is then forced downwards and this process repeated until the operation experiences a large outer diameter (OD) pipe or collar. When this occurs a staging process is conducted.

The staging process occurs when any large OD pipe needs to go through the snubbing annular such as a collar or when placing a packer or while landing a tubing hanger. The process begins with the collar or large OD pipe being brought to slightly above the snubbing annular. The snubbing stripping rams are then closed and the pressure and well fluids between the snubbing stripping rams and the annular BOP is bled off to the flare stack. Then the annular BOP is opened and the large OD pipe fed through to just above the snubbing stripping ram. The snubbing annular is then closed, the area equalized to well pressure and the stripping ram opened and the snubbing process continued.

This process is repeated each time a collar or large OD pipe has to be staged through the snubbing annular BOP. This process can add significant time to operations, and is quite tedious. This process is subject to a lot of human error (Huntley, 2011).

The above snubbing process continues until the operation becomes pipe heavy. Once the operations becomes pipe heavy the snubbing unit's stationary heavy slips take control from the stationary snubber for tripping operations. Since the operation is pipe heavy no force needs to be exerted by the hydraulic cylinders. Well control is maintained with the snubbing units annular preventer.

Sometimes during low pressure snubbing operations when the pressure is below 14 000 kPa snubbing crews will leave the stripping pipe rams open, and the snubbing annular BOP is engaged throughout all processes including staging of collars (Huntley, 2011).

This procedure creates a lot of wear on the stripping pipe rams and if this procedure is done constant checks need to be done on the snubbing equipment BOP to ensure they still function properly (Huntley, 2011).

During some high pressure snubbing operations the pipe is stripped both through the annular BOP and the lower and/or upper pipe rams, until a collar is encounter. Once a collar is encountered the staging process takes place.

2.2.1 Low Pressure and High Pressure Snubbing Guidelines

IRP 15 suggests low or high pressure snubbing arrangements on three sizes of common wellbores. They are (DACC and Enform, 2007; Duncan, 2008):

- 60.3 mm, annular BOP at pressure less than 13 800 kPa, annular and stripping ram rated between 13 800 and 21 000 kPa
- 73.0 mm, annular BOP at pressure less than 12 250 kPa, annular and stripping ram rated between 12 250 and 21 000 kPa
- 88.9 mm, annular BOP at pressure less than 4 000 kPa, annular and stripping ram between 4 000 and 21 000 kPa
- At pressures above 21 000 kPa, a high pressure configuration is used with the stripping rams as the upper BOP

IRP 15 Snubbing considers any snubbing operations over 21 000 kPa as high pressure (DACC and Enform, 2007).

Also according to IRP 15 on wells greater than 1% H_2S and over 21 000 kPa the following must occur (DACC and Enform, 2007; Duncan, 2008):

- A shear ram must be installed as the lowermost primary BOP and/or
- Pump and tank must be connected to the wellbore with a minimum of one hole volume of fluid on location
- The kill fluid cannot be an aromatic hydrocarbon

Chapter 3: Theory and Snubbing Challenges

This chapter will provide information on the dangers of trapped pockets of air and hydrocarbon mixtures, and the relevant theories that serve as a background for a study on explosions in snubbing operations.

Snubbing operations are generally a safe procedure, however due to the presence of hydrocarbons, oxygen and air and various ignition sources, explosions can occur. During snubbing operations all three elements of the fire triangle can be present, especially on surface equipment.

In order for explosions to occur all three elements of the fire triangle have to be met as illustrated in Figure 18. These are sufficient fuel, energy source and oxygen.

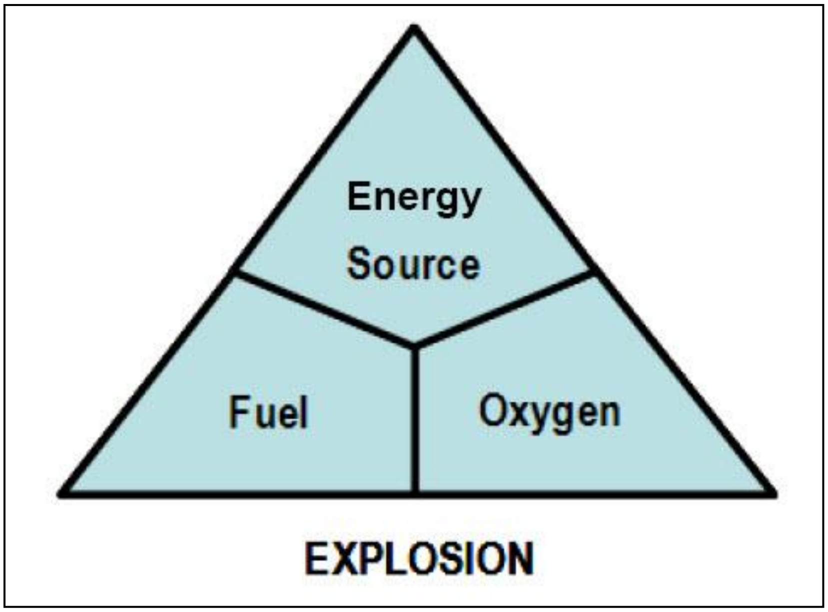


Figure 18: Fire Triangle (Garcia, 2008).

3.1 Trapped Pockets and Explosive Hydrocarbon Mixtures

During snubbing operations the well fluid consist of many components including non-oxidized hydrocarbons and perhaps oxygen containing hydrocarbons, CO_2, H_2S, air, water and other fluids. These fluids especially hydrocarbons and air mixtures can be trapped within various enclosed areas and within snubbing surface equipment. Under the right conditions these mixtures could cause explosions.

An explosion is defined as a rapid transformation of internal or chemical energy into mechanical energy and involves the expansion of gasses (Martin, 2000; Shahbazi et al., 2006). A flammable air, oxygen and vapour mixture can result in an explosion. Explosions are characterized by the speed at which the shock front travels. A further explanation of shockwave is provided in next chapter. (Martin, 2000; Shahbazi et al., 2006).

Hydrocarbons can be classified in the following main groups; gases, liquid and vapour, chemicals and solids. The sustained combustion of the above only occur within certain flammability ranges (Garcia, 2008).

3.1.1 Gases

In order for gas to be explosive, an oxygen/air and hydrocarbon vapour combination is required. The greatest potential of energy release within gases are when they are at stoichiometric conditions, or when the oxygen and mixture is completely chemically balanced. It can generally take a small concentration of hydrocarbon fuel in a hydrocarbon – air mixture for a flame to start.

3.1.2 Liquids and Liquid Vapours

Un-oxidized liquids generally do not ignite on their own but are the ignition source for hydrocarbon vapours. Hydrocarbon vapours given off from liquid surfaces do ignite. Liquids will give off vapours at a rate related to temperature (Garcia, 2008). For liquids, the flashpoint temperature is needed for an explosion. Below the flashpoint temperature typically the liquid will not ignite.

Other characteristics of liquids typically encountered in snubbing operations include (Garcia, 2008; Della-Giustina, 2003) the following:

- Crude oils and condensates. These substances have a wide variety of properties and densities. Flash points for these vary. These are of particular concern in snubbing oil operations

- Hydrocarbons that are liquids at reservoir temperature and pressure conditions, but become vapours at surface conditions. These are referred to as gas condensates. These condensates tend to be composed mainly of C_5 and C_6 hydrocarbon chains and tend to have a low flash point. They are extremely flammable and are commonly encountered in snubbing operations
- Gasoline, Diesel, Lubrication fluid, Hydraulic fluid (usually a low viscosity oil) used in both the accumulators, annular BOP, and in the snubbing unit jacks/hydraulic cylinders contain a wide variety of hydrocarbons usually between the C_3 to C_{10}+ hydrocarbon range (Enform, 2011; Garcia, 2008). If these fluids come into contact with oxygen over a prolonged period of time and or if they are compressed suddenly they can spontaneously ignite and cause an explosion Shahbazi et al. (2005) showed this in his experiments.

3.1.3 Solids

Solids can cause explosions if heated and the solid undergo pyrolysis, a chemical degrading that results in the release of vapours that could cause explosions. If the solid contains oxygenated fractions, oxygen induced cracking can occur at temperatures much less than the 350^{o}C which is the rule of thumb temperature where pyrolysis reactions become important (Shahbazi, 2006).

Solids of interest during snubbing operations include:

- Lubricants
- Sealants
- Paints and Coatings

Generally, the flammability risks of these solids are quite high.

3.1.4 Flammability

An air and gas mixture can be burned over a wide range of concentrations either at elevated temperatures or at ambient temperatures when exposed to a catalytic surface at the right conditions (Zabetacis, 1965). However, most homogenous combustible air-gas mixtures are flammable propagating freely within a limited range of compositions (Zabetacis, 1965).

A good example is methane in air. Even a trace amount of methane can be readily oxidized on a heated surface but the flame will propagate from an ignition source at ambient temperatures and pressure only if the surrounding mixture contains at least 5% but less than 15% volume of methane, Figure 19 illustrates this (Zabetacis, 1965).

A dilute (in terms of hydrocarbons) combustible mixture is known as the lower limit or combustible lean limit mixture, and a more concentrated mixture is known as the upper limit or combustible rich limit mixture. These upper and lower limits define the flammability or the range of concentration of a fuel gas or vapor in air that can be ignited (Kuchta and Lambiris, 1962; Coward and Jones, 1952).

In operations the limits of flammability are affected by temperature, pressure, direction of flame propagation, and its surroundings. Limits for substances are obtained experimentally by determining the limiting mixture compositions between the various substances. Each well fluid has varying compositions. For safety considerations it is advised that each different composition be tested in order to understand the lower and upper limits of flammability. Any compositions outside of these limits of flammability cannot be ignited. Figure 19 illustrates the flammability limits of some substances.

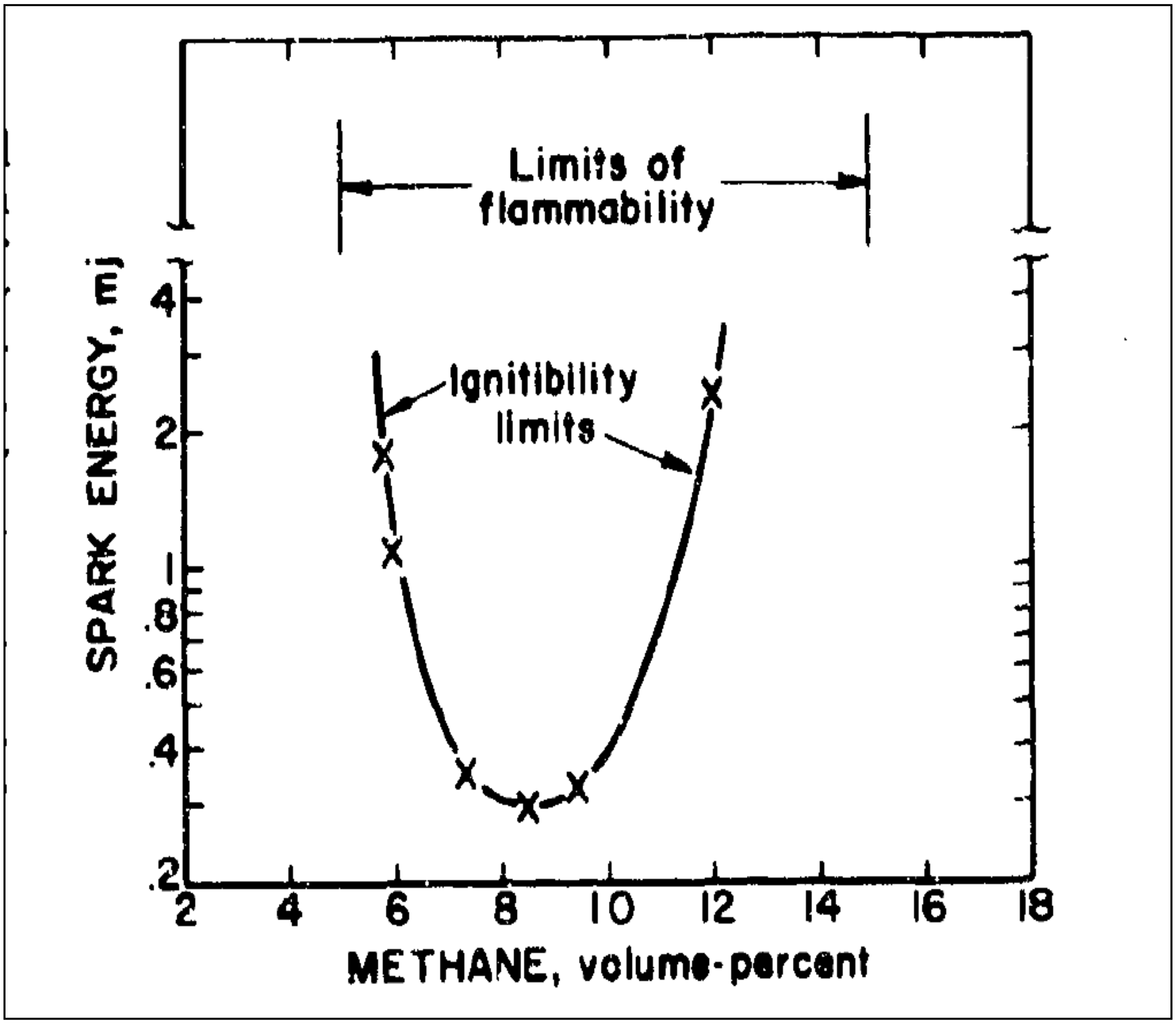


Figure 19: Ignitibility curve and limits of flammability for methane-air mixture at atmospheric pressure and 26 ^{o}C (Zabetacis, 1965)

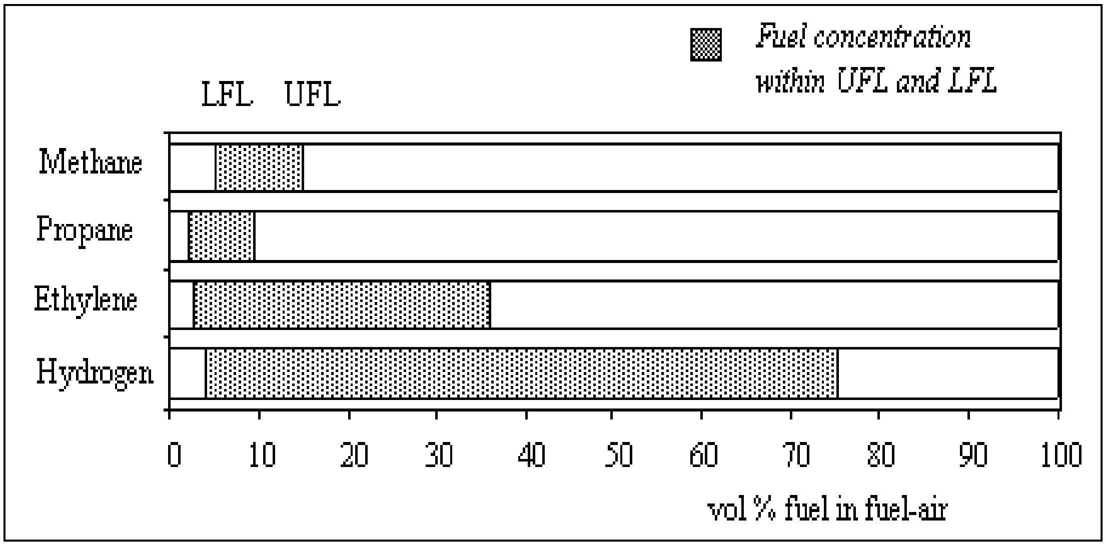


Figure 20: Flammable range for fuel-air mixtures at 1atm and 25^{o}C (Bjerketvedt et al., n.d.)

It is also known that as pressure and temperature increase the flammability limit also widens (Mehta et al., 1998; Mehta et al., 1996; Coward and Jones, 1952) . The presence of H_2S, CO, hydrogen, and moisture can also widen the limit (Shahbazi, 2006; Mehta, et al., 1998; Sutherland, et al., 2007; Mehta, et al., 1996). Pressure especially lowers the auto-ignition temperature (Sutherland et al., 2007; Garcia, 2008; Shahbazi, 2006). Turbulence and sloshing of fluids has an effect of narrowing flammability limits (Garcia, 2008).

Figure 12 shows the effect of increasing pressure on the flammability limit of methane/air mixtures.

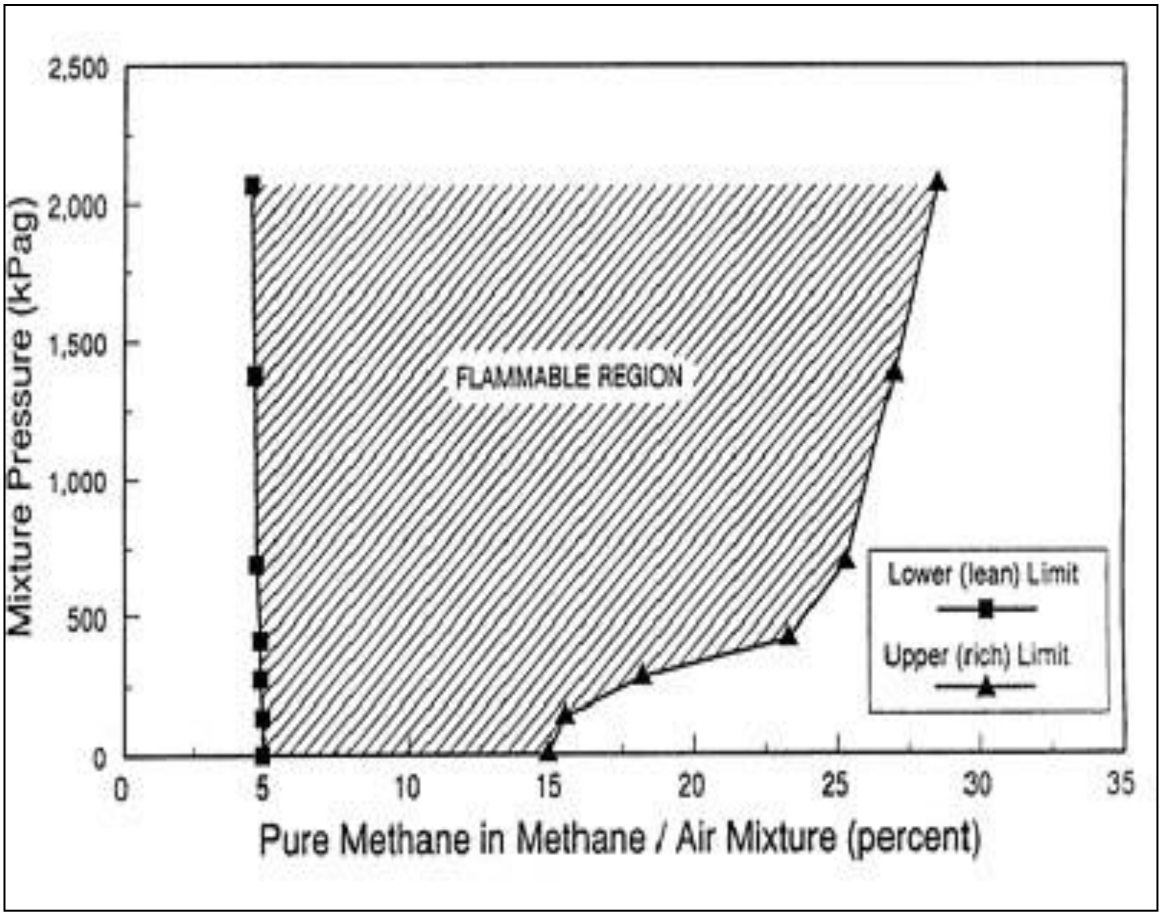


Figure 21: Pressure increase on flammability limits for methane/ air mixture at a constant temperature of 21^{o}C (Mehta et al., 1998).

3.1.5 Flashpoint

The minimum or lowest temperature that a liquid gives sufficient vapors to support a flame across its surface is considered its flash point (Jones and Pujado, 2006). Flashpoints are related to the vapour pressure of the liquid. Generally, a low vapour pressure corresponds to a high flashpoint and a high vapor pressure corresponds to a low flash point. The lower the flashpoint the greater the volatility of the substance and the greater the risk of the substance becoming explosive. The flashpoint of methane is -188^{o}C and gasoline is -45^{o}C at atmospheric conditions (Engineering Toolbox, n.d.).

3.1.6 Auto Ignition Temperature (Spontaneous Ignition)

Auto ignition temperature (AIT) or spontaneous ignition is normally defined as the lowest temperature at which a mixture gives off vapours that can ignite without an ignition source. The higher the number of carbons present in the hydrocarbon the lower the auto ignition temperature. Figure 22 illustrates this.

Generally, heavier hydrocarbons will auto-ignite before lighter hydrocarbons and hydrocarbons that have been heated will ignite if exposed to air (Lottermoser et al., 2003; Shahbazi, 2006; Enform, 2007). Also an increase in pressure reduces the spontaneous ignition temperature (Coward and Jones, 1952). In addition the greater the fuel concentration in the vapour phase the lower the auto-ignition temperature based on the dependence of AIT with the equivalence ratio (fuel/air) (Griffiths and Gray, 1990).

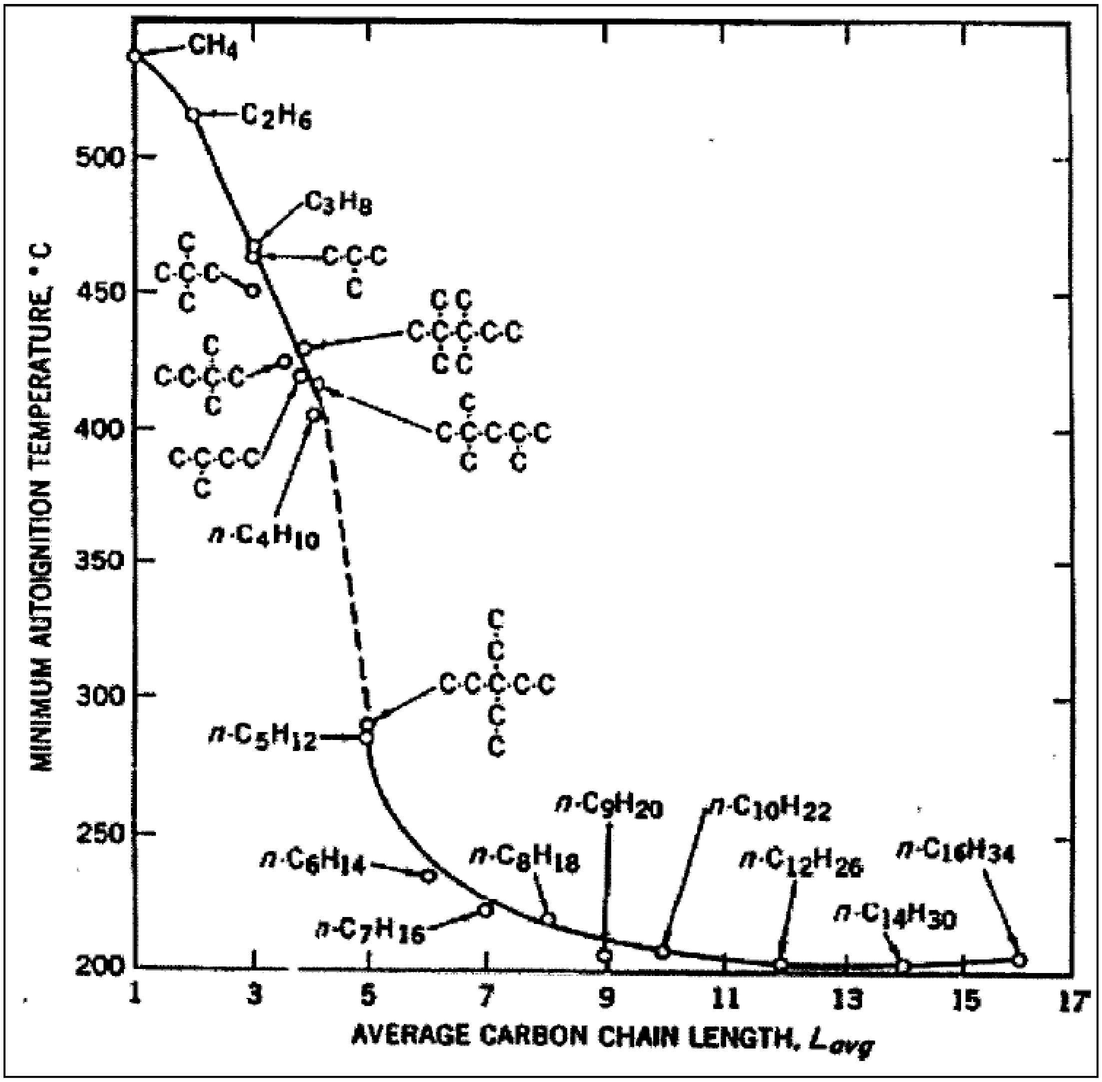


Figure 22: Minimum auto-ignition temperature of various hydrocarbons at atmospheric conditions (Coward and Jones, 1952).

3.1.7 Minimum Ignition Energy (MIE)

The minimum ignition energy is the least amount of energy needed to cause ignition of a combustible mixture (Garcia, 2008). It is a measure of the required energy for a localized ignition source, like a spark to successfully ignite a fuel and air vapour mixture (Kuchta, 1985). The mixture has to be within its upper and lower flammability limits. The minimum ignition energy for combustible mixtures vary with composition, for most combustible fuels the minimum ignition energy is between 0.1 and 0.3 mJ in normal ambient air (Kuchta, 1985). However substances such as hydrogen, acetylene and carbon disulphide typically have one order of magnitude lower minimum ignition energy (Kuchta, 1985).

This concept of minimum ignition energy is of particular importance because mixtures could be ignited from a small ignition source with minimal amounts of energy, such as the heat release associated with the liquid phase oxidation of a hydrocarbon. This concept also helps to realize that extreme care is needed when dealing with trapped pockets of air which come in contact with liquid hydrocarbons, especially those which contain oxidized fractions.

3.1.1 Trapped Air / Oxygen

Oxygen content of the air is always of major concern. It is known that oxygen in air (approximately 21% oxygen by volume) when mixed with hydrocarbons can form an explosive mixture (Garcia, 2008; Mehta et al., 1998).

Studies done by Mehta et al. (1998) on various mixtures of gas, condensate and drilling mud at various pressure for operations in the foothills sour gas /condensate fields suggested that a maximum of 5 percent by volume oxygen ensures fluids do not enter the flammability range and prevents fires mainly due to external ignition sources (Mehta, et al., 1996; Mehta, et al., 1998).

During snubbing operations, air/oxygen can become temporarily trapped in various cavities of the well's primary BOPs, snubbing BOPS, lubricators, lines, spools and lines to measurement gauges due to the cyclic nature of snubbing operations specifically the pressurization and purging of well fluids during staging collars and other functions. The areas where trapped pockets of air and hydrocarbons could accumulate are further described in the next chapter.

Typically these pockets of air and hydrocarbon are not of a concern if the temperature is low. However, when trapped or immobile hydrocarbons are in long term contact with air (even if the air is not present on a continuous basis) they can under the right conditions, generate heat and flammable vapor phase components from LTO reactions

Of specific concern is air and immobile oil that can be trapped in any deadheaded line, spools, junctions, and especially lines to measurement devices such as gauges and cavities within equipment. Trapped/immobile oil under the right conditions of rapid compression from typical pressurization and purging snubbing operation could lead to explosive events. This is further explained in the next section.

3.1.2 Ignition Sources

During snubbing operations there are multiple sources of ignition for external fires or explosions including hot lines (equalization lines) and surfaces, heat caused by friction and mechanical sparks and static electricity.

Depending on the amount and distribution of oxygen within the well, primary wellhead equipment, snubbing equipment or lubricator, ignition of an internal fire or explosion may be caused by the previously recognized ignition sources which include friction (rubbing pipes or tubulars sliding through annular BOP), static electricity or sparks associated with particles which are transported in the flowing gas. Another ignition source which is not generally recognized in the open literature is the generation of heat and flammable vapour phase components associated with LTO reactions of liquid or solid hydrocarbons which are momentarily trapped in dead volumes within the primary wellhead equipment, snubbing equipment or lubricator and associated piping on surface.

3.1.3 LTO Initiated Ignitions

LTO reactions according to Burger and Sahuquet (1972) are described as partial oxidation reactions which generate oxygen contained species such as organic acids, aldehydes, esters, ketones, alcohols and hydroperoxides. With the exception of hydroperoxide formation, the heats of reaction per unit volume of air consumed approach those associated with high temperature combustion of a typical hydrocarbon (nominally 3 716 kJ/m^3 (ST) air or 100 BTU /SCF air).

Oxidized components are believed to concentrate in the liquid or semi-solid phase, however the LTO reactions involving a typical crude oil are generally of limited extent at ambient temperatures but become significant at temperatures exceeding approximately 80^{o}C and are sufficiently fast at temperatures in the range 150 - 180 ^{o}C to generate a rapid temperature rise, which on its own can generate a rapid pressure rise, but can also lead to spontaneous ignition of a vapor phase burn at the interface exposed to the air.

Heat generation associated with the continuous contact of air with a hydrocarbon at temperature where LTO reactions occur is not considered to be a significant ignition source when considering the initiation of an explosive event within the primary wellhead equipment, snubbing equipment or lubricator assemblies. The reason for this is that trapped/immobile pockets of hydrocarbon will not be continuously exposed to air due to the cyclic nature of the snubbing operations.

This is of course not the case when dealing with external fires where the hydrocarbon based fluids like drilling muds can be exposed to the air under direct sunlight as they circulate in open mud tanks. LTO reactions can certainly lead to the ignition of a vapor phase burn starting at the fluid-air interface and the resulting energy will vapourize more hydrocarbons leading to a major fire. A useful analogy to LTO reactions involving crude oil is the spontaneous ignition of Linseed oil.

Linseed, as well as other vegetable oils, contains a significant fraction of oxidized species. It is well known that rags soaked in Linseed can ignite spontaneously when exposed to direct sunlight. Linseed oil is often injected with air for the ignition of *in-situ* combustion oil recovery processes. Depending on the crude oil with which it is mixed the temperature at which measurable heat generation occurs can be lowered to the range of $60^{o}C$.

Typically light oils especially are more susceptible to partial oxidation at low temperatures than their heavier oil counterparts (Dabbous and Fulton, 1974; Lukyaa et al., 1994).

While heat generation by LTO reactions due to continuous exposure to air is not considered to be responsible for initiating internal explosions during snubbing operations, the formation of oxidized species in the liquid and solid phases as well as the generation of reactive hydrocarbon species and hydrogen in the vapor phase will occur whenever air contacts an immobile accumulation of hydrocarbon. The hydrocarbon in question may be a light condensate, crude oil or it may be lubricating grease.

The extent of these LTO reactions will depend on the temperature within the localized space where the hydrocarbon is located, the duration of time and the pressure at which the trapped hydrocarbon is exposed to air following the introduction of well fluids (mainly natural gas) from the well. Both the temperature and pressure histories are important whenever air is contacting the trapped/ immobile hydrocarbon. For a given contact time, the amount of oxygen incorporated in the hydrocarbon due to LTO reactions increases with increasing temperature and pressure.

It is often assumed that the air is purged out of the primary wellhead equipment, snubbing equipment, lines or lubricator piping when the pressure are equalized between the well bore and surface assemblies.

This will be true in the sections of the well head assemblies where well fluids from the well displace air by convection. The concern is that air can be temporarily trapped in any deadheaded line or cavity which is not directly swept by a purge. Trapped air pockets will persist until counter diffusion of the air and well fluids (mainly natural gas) transforms the gas mixture within this region to a fuel rich state. It is noted that this is the state that would exist in the major portion of the surface assembly following the introduction of gas from the well. This is illustrated in Figure 23.

As implied in the previous sentence, under equilibrium conditions the average air/fuel mixture within the overall surface assembly will be on the fuel rich side of the flammability range when the assembly is pressurized with well gas.

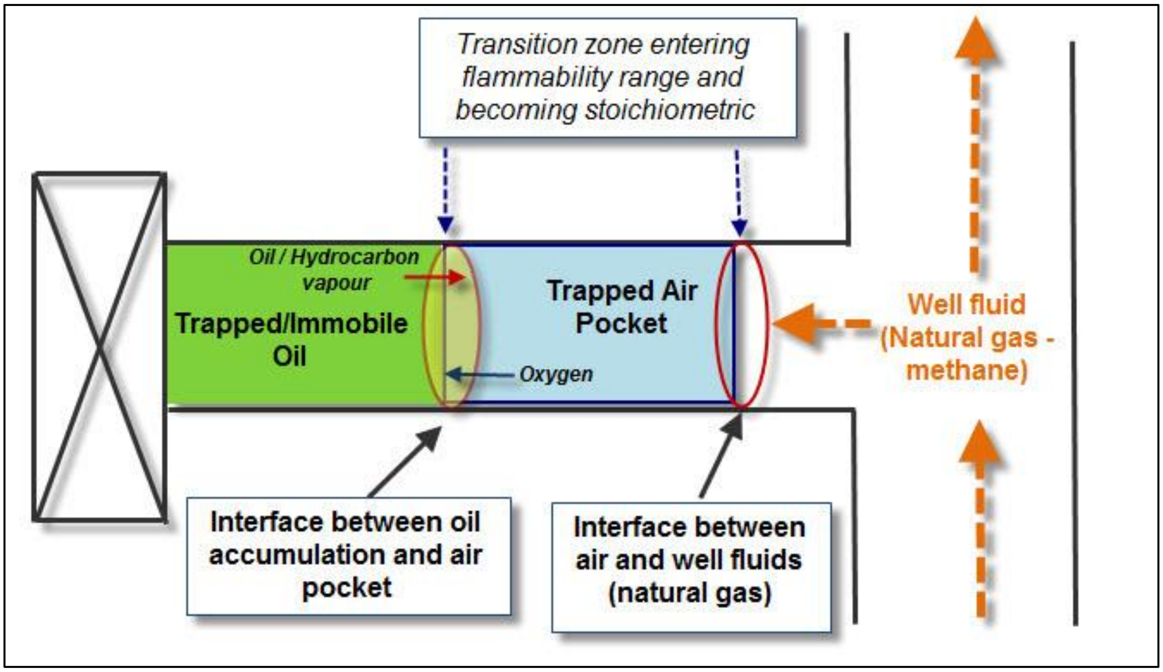


Figure 23: Trapped oil and air pocket at a deadend line before rapid compression during operations

What does not appear to be nearly as well recognized is that there is a time period between initial pressuring up the surface assembly with well gas until the dissipation of trapped air pockets. It is during this transient time period that there is a very real potential for initiating an explosive event. A sudden temperature rise, such as that which is generated when gas at high pressure is allowed to rapidly pressurize the surface assembly from a low to high pressure state is one of the triggers for igniting an internal burn. The reason for this is that sudden pressurization of the surface assembly with gas from the well both traps the air pockets and causes the temperature to rise rapidly.

The rise in temperature when an ideal gas is allowed to rapidly (adiabatic) fill an evacuated rigid tank is given by:

$$T_f = \gamma T_i \tag{3.1}$$

Where:

T_f	Absolute temperature of gas within the tank following pressurization (K)
γ	Specific heat ratio of the gas
T_i	Absolute temperature of gas entering the cylinder (K)

Looking first at the temperature of the well fluids (natural gas) following sudden pressurization of the surface assemblies with well gas, Equation 3.1 would become:

$$T_{sa} = \gamma_{well} T_{well} \tag{3.2}$$

Where:

T_{sa}	Absolute temperature of gas within the wellhead surface assemble (K)
γ_{well}	The specific heat ratio of the gas in the well
T_{well}	Absolute temperature of incoming well fluid (natural gas) from the well (K)

The specific heat ratio (γ) for methane gas is 1.32 at 300 K (Cengel and Boles, 2010). Note that T_{well} corresponds to the temperature of the incoming gas, hence it will depend on the relative volumes of the natural gas entering the surface assembly which originates from above surface and below surface. For the gas which is above surface the temperature will be related to the ambient air temperature and the radiation energy delivered to the piping from exposure to sun light.

Generally the average incoming gas temperature will be lower than the temperature of the air which can occupy the surface assembly volume. This is especially true if the sun is shining directly on the assembly and the ambient temperature is high. If one concentrates on the pocket of air which is formed immediately following pressure up, the temperature of the rapidly pressurized air can be estimated from the same relation but written for air:

$$T_{air\ 2} = \gamma_{air}\, T_{air\ 1} \tag{3.3}$$

Where:

$T_{air\ 2}$	Absolute temperature of air within the wellhead surface assemble following pressure up (K)
γ_{air}	The specific heat ratio of the air in the well
$T_{air\ 1}$	Absolute temperature of air before pressure up (K)

The value of γ for air at 300 K is 1.40 (Cengel and Boles, 2010) and it is not unreasonable that on a hot summer day with direct sunlight on the surface assembly that the initial temperature of the air which ultimately constitutes the air pocket is in the range of 50°C (323.15K).

$$T_{air\ 2} = (1.40)(323.15k)$$

$$= 452K\ or\ 179℃$$

The estimate of temperature immediately following pressure up would be predicted to be 179^oC which is within the range (approx.. 150^oC to 180^oC) for initiating vapour phase combustion reactions for hydrocarbon condensates even if they have not been previously oxidized. The temperature is certainly sufficient to initiative vapour phase burns for the vapor in equilibrium with oxidized hydrocarbon. The Table below shows various initial air temperatures and estimated temperature after pressure up. Most temperatures above 30 ^oC are within the range for initiating vapour phase combustion reactions.

Temperature of Air before Pressure up (^oC)	Temperature of Air at Wellhead Surface Assembly after Pressure up (^oC)
30	150
40	165
50	179
60	193
70	207

Table 3: Estimated temperatures of air at wellhead surface assembly before and after pressure up

The rapid pressurization process is often termed "adiabatic compression", however it is acknowledged that this term may be somewhat misleading. The temperature rise associated with adiabatic reversible (isentropic) compression of an ideal gas is described by the relationship:

$$\frac{T_{air\ 2}}{T_{air\ 1}} = \left(\frac{P_{air\ 2}}{P_{air\ 1}}\right)^{\frac{\gamma-1}{\gamma}} \tag{3.4}$$

Where:

$T_{air\ 2}$	Absolute air temperature after pressurization of surface assembly (K)
$T_{air\ 1}$	Absolute air temperature before equalization of surface assembly (K)
$P_{air\ 2}$	Absolute pressure following pressurization, well pressure (kPa)
$P_{air\ 1}$	Absolute pressure at ambient conditions: barometric pressure (kPa)
γ	The specific heat ratio of the air in the well

Equation 3.3 is felt to provide a better estimate of the temperature within the air pocket which can be achieved by rapid re-pressurization of the surface assembly. What it indicates is that there is a good probability that the temperature of the trapped air may achieve levels in the range of 150 - 180 ^{o}C. At these elevated temperatures, and at elevated pressures, LTO reactions are sufficiently fast to generate energy at a sufficient rate to supply the ignition energy required to ignite a vapour burn. This could occur whether the trapped oil is oxidized or un-oxidized, however it is more likely to occur for the oxidized hydrocarbon due to the generation by the LTO reactions of reactive gas phase components like H_2, ethylene and propylene.

The duration and intensity of the vapour burn will be controlled by the amount of trapped air and by the concentration distribution of the flammable components within the trapped air pocket. If by chance the concentration of the flammable components within the air pocket is near stoichioemteric at the interface between the trapped oil and air, which is the most probably location for ignition of the vapour burn to occur, the amount and rate of energy generation may result in the ignition of a secondary combustion zone at the interface between the well fluid (natural gas) and air. At this interface, there is a transient transition zone from fuel rich (in the main portion of the surface assembly) to fuel lean (within the air pocket), hence there will always be a location where the air/fuel ratio is stoichiometric and hence the burning rate is at a maximum. Figure 24 illustrates the process. At the maximum burning rate, the rate of energy generation rate is high and the energy generation occurs within a relatively small volume.

As will be illustrated in Chapter 5, since pressure is a measure of energy per unit volume, high energy generation rates in a small volume can generate a pressure rise which may cause destruction of the piping at the localized location or may lead to the onset of a shockwave. Trapped pockets of oxidized fuel are generally believed to contribute to the ignition process through the energy generated by LTO reactions and perhaps more importantly, the reactive vapor phase components (seed components) transferred to the vapor phase. It is also important to note however that when the oxygen within the air pocket becomes depleted the combustion reactions will look for oxygen internally from the oxidized hydrocarbons formed by LTO reactions and an explosion can occur which in itself can lead to a strong and destructive shockwave.

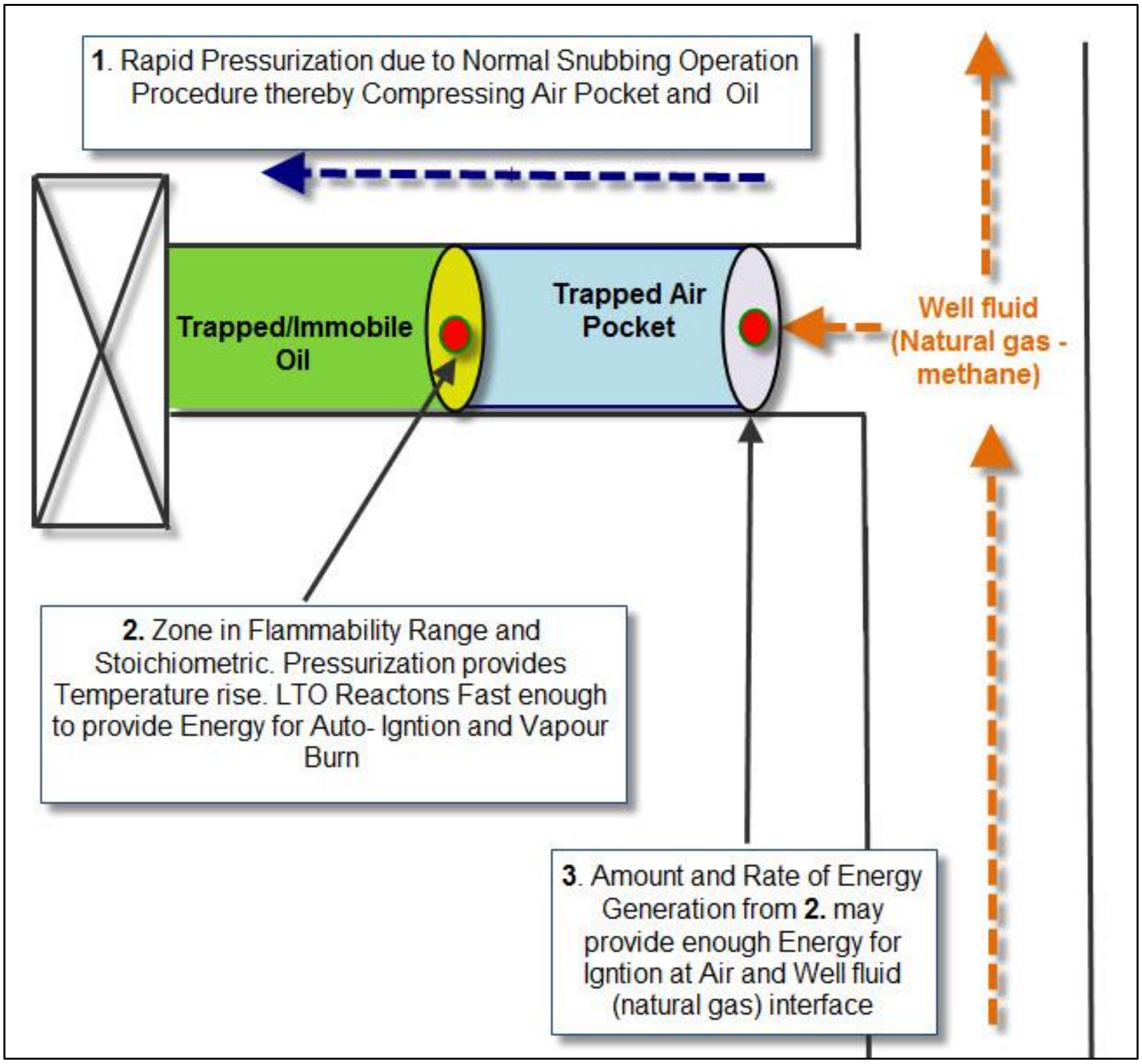


Figure 24: Description of ignition process in a deadend line within snubbing operations after rapid pressurization

In the scenario, described in the previous paragraph, the significance of the trapped hydrocarbon deposits concentrates on their role in providing volatile components to the air pocket. It is the vapour phase fractions which are the fuel for the ignition of the initial vapor phase burn. It is however recognized that an accumulation of oxidized hydrocarbons has the potential to behave like conventional explosives. This is because, like explosives, oxidized oil has an internal supply of oxygen.   In explosives such as gun powder when an adequate external oxygen source is available it burns in a controlled fashion, but if the powder is covered and the external source of oxygen is interrupted the combustion reaction draws on its supply of internal oxygen and an explosion occurs.

Explosives are designed with pre-designed ratios of oxygen to combustible fuel and this is not the case when an accumulation of trapped oil is exposed over time to oxygen. It is therefore unlikely that the total mass of oxidized oil will suddenly auto-decompose, but there are fractions such as the hydroperoxides which are relatively unstable and are capable of generating energy and reactive vapour phase fractions at a rate sufficient to initiate an explosive event.

Further experimental work is obviously required to better understand the reactions involved in the auto-decomposition of oxidized oils and greases, however this research is beyond the scope of the current study.

Chapter 4: Research Investigation: Potential Trapped Pockets of Air and Shockwave Characteristics

This chapter will identify the general areas of explosions during snubbing operations; summarize the research investigation conducted in identifying the areas in snubbing equipment where air and hydrocarbons can come into contact to form potentially explosive mixtures and finally describe explosions and shockwave characteristics.

4.1 Areas of Potential Explosions in Snubbing

During snubbing operations the current literature reports that there are two primary possibilities for potential explosions involving air and hydrocarbon mixtures, Case 1 and Case 2 (DACC and Enform, 2007). Also in this study another mechanism not generally recognized in open literature described in the Chapter 3 is also listed, Case 3.

The cases are listed below:

Case 1: When uncontrolled gas or liquid vapours are brought to surface or escape to atmosphere and are ignited mainly due to an external ignition source,

Case 2: When air contacts well gas or liquid vapours or other fuels at surface and sub-surface at a concentration that forms an explosive mixture with an external ignition source,

Case 3: When dead volumes of air in contact with immobile solid or liquid hydrocarbons and well fluids (natural gas) under the right temperature conditions, after rapid pressurization, generate heat and flammable vapour phase components from LTO reactions that provide sufficient energy to cause ignition and then an explosion.

4.1.1 Case 1: Uncontrolled Well Gas or Liquid to Surface (External Ignition)

Case 1 illustrates one area of potential explosion specific to external ignition. Well fluids can be brought to surface from various failures such as; snubbing plug failure, tubing failing in compression or tension from pulling or pushing into a closed ram or slip, and from well flows out of the annulus due to deterioration of ram elements and seal elastomers due to the prolonged exposure of well fluids at elevated pressures (DACC and Enform, 2007). This leads to explosion or fires generally at surface. The external ignition sources could include static electricity, sparks during operation (due to friction), hot surfaces and many other sources.

To mitigate some of these risks snubbing plugs should always be correctly deployed and at the initial signs of possible failure, BOPs should be engaged and then the tubing tripped out of the hole. If fluid is in excess it should be flared and/or an emergency kill fluid used. To avoid failures due to errors in the snubbing operational procedures, the snubbing personnel should be diligent during operations and have had the adequate amount of rest. In order to mitigate the deterioration of BOPs, they need to be checked daily during operations and the accumulators checked weekly (Huntley, 2011).

4.1.2 Case 2: Air Contacts Well Gas or Liquid Vapours (External Ignition)

Explosive mixtures on surface and sub-surface can accumulate especially in underbalanced conditions if the casing is swabbed dry before it is perforated, which would leave an air-filled casing (air can enter the casing once the swabbing tool is removed on surface) that once perforated allows for contact with well gas. If the swabbed air filled casing is perforated and the well is then shut in, the pressure of the well gas and air mixture inside the casings increases and if the well is opened again and tubing run in and out for snubbing work-over operations the potential for an explosion from a traditional external ignition source both at surface and sub-surface is extremely high (DACC and Enform, 2007).

A method to mitigate this risk is to flow the well at a controlled rate after perforation and flare the contents until air is dissipated within the casing then the well can be shut in and/or snubbing workover operations begun. This way there is no/little air in the casing as a result explosions at surface and sub-surface/down-hole is significantly reduced (DACC and Enform, 2007).

Explosions could also occur on surface or sub-surface when the tubing is snubbed into the well and before the snubbing plug is pulled. The explosive mixtures could be created if well gas or fluid from the annulus is introduced into the tubing to equalize the pressure from above before the snubbing plug is pulled.

In order to mitigate this a fluid spacer should be pumped into the well tubing before annular gas is used to equalize. The spacer will keep the air under the fluid from contacting the gas used to equalize. This also provides a barrier for the possible explosive mixtures while removing the plug both at surface or sub-surface/down-hole (DACC and Enform, 2007).

Another method instead of using a liquid spacer is the use of nitrogen gas. Nitrogen gas can be feed into the air rich tubular to displace the air. However, it is important to note that the mixing of air and nitrogen takes time and premature equalization and inadequate mixing may still result in an explosion at surface or sub-surface/down-hole.

4.1.1 Case 3: Trapped Air in Contact with Immobile Solid or Liquid Hydrocarbons and Well Fluids, due to LTO Reactions energies, Ignite

Potential explosions within the surface equipment could occur due to the ignition of flammable vapour phase components generated from LTO reactions trapped in dead volumes. This ignition process was described in the Chapter 3. The subsequent explosion creates a detonation shockwave that can cause substantial damage.

In order to mitigate trapped pockets of air and hydrocarbons within surface equipment proper design and purging of surface equipment is needed. This will entail educated and proper equipment design, stringent on-site equipment inspection and field management protocol along with corresponding frequent equipment operating and maintenance schedules. Potential areas for trapped air will be further analyzed in section 4.2 and shockwaves in section 4.3.

4.2 Examination of Areas of Trapped Air and Explosive Hydrocarbon Mixtures

The examination of areas where trapped air pockets may come in contact with immobile hydrocarbons that form explosive hydrocarbon mixtures during snubbing operations involves a detailed analysis of a low pressure snubbing operation as illustrated in Figure 25.

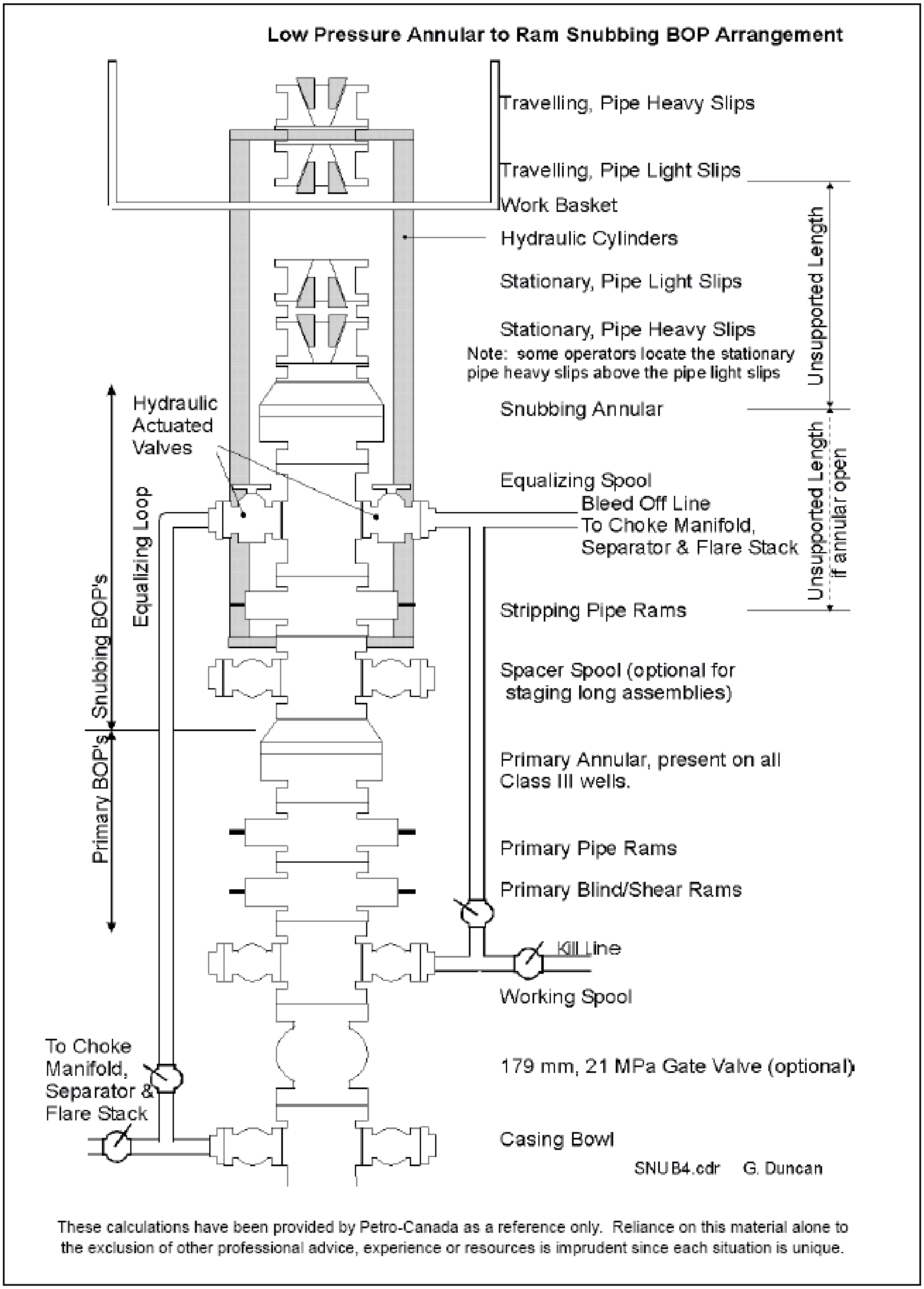


Figure 25: Low pressure configuration for a snubbing unit (DACC and Enform, 2007; Duncan, 2008).

The overall areas of potential trapped air which can lead to explosive hydrocarbon mixtures is in equipment found during a) rigging up (pre-job), b) during operations and c) post job operations. However the focus of this study is on trapped pockets of air during operations.

The detailed analysis during operations revealed three main areas of potential trapped air and explosive hydrocarbon mixtures as listed below:

1. In the equipment such as the snubbing primary BOPs and the lubricator when used
2. In valves within the spools such as the casing bowl, working spool and equalization spool
3. In the lines and at junction points such as the:
    a. Line to the choke manifold, separator and flare stack, and, the kill line
    b. Equalization loop line from the casing bowl, with a T-junction to the choke manifold, separator and flare stack to the equalization spool
    c. Working spool with a T-junction to the kill line and connected to the equalization spool
    d. T-Junction from the equalization spool to the bleed off line
    e. Junction(s) for the pressure/measuring gauge reading valves

The main equipment where these pockets could exist are the snubbing and primary BOPs associated with the lubricator when used, valves within the spools, lines and junction points. These pieces of equipment are enclosed and have direct exposure to well fluids.

Other equipment such as the snubbing and associated slips and areas around the work basket are not considered in this study as they are open to atmosphere and a large out flow of uncontrolled well fluids would create risks for external fires or explosion.

4.2.1 Annular BOPS

Both the primary and snubbing annular BOPs, refer to Figure 26, have the potential of trapped pockets of air as depicted in Figure 27. Air can become trapped between the annular elastomer and behind the annular seals, if the elastomer or the seals experience wear and tear. It is important to note that this wear and tear could be compounded by prolonged exposure to varying pressures and temperatures and well fluid composition especially if the well contains H_2S acid gas. The acid gas will produce iron sulphides by deteriorating the metal and this may accelerate accumulation of air in and around the elastomer or seals and may create an explosive mixture.

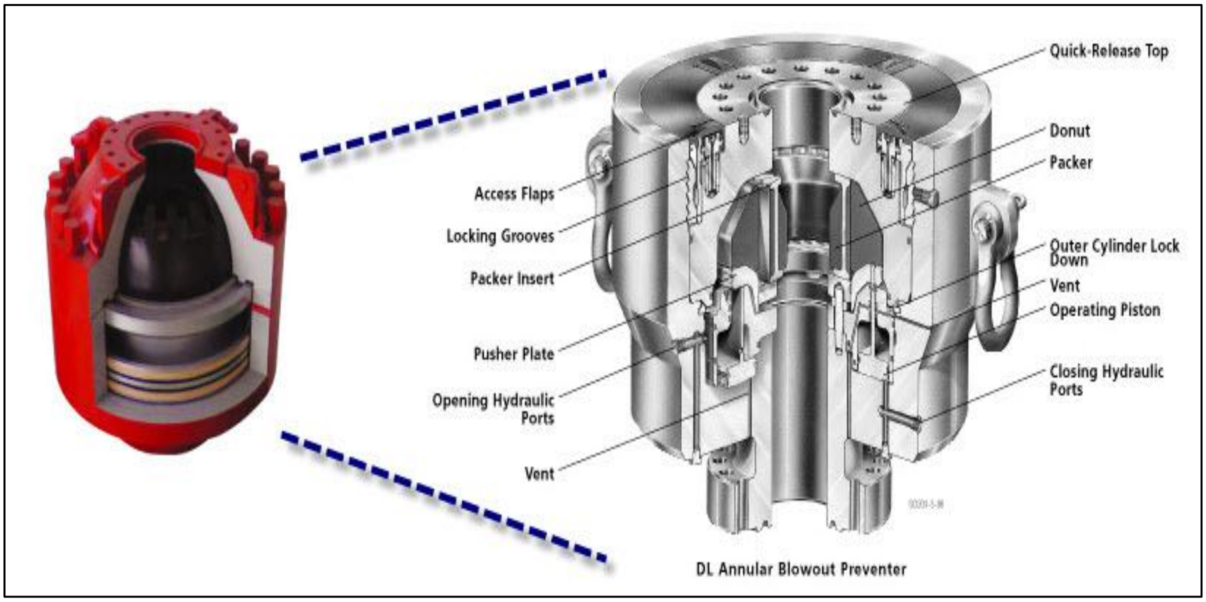


Figure 26: Focused schematic of annular BOP and parts within (Bejing Lanfeing Energy Equipment CO. Ltd., n.d.; Cameron International Corporation, n.d.).

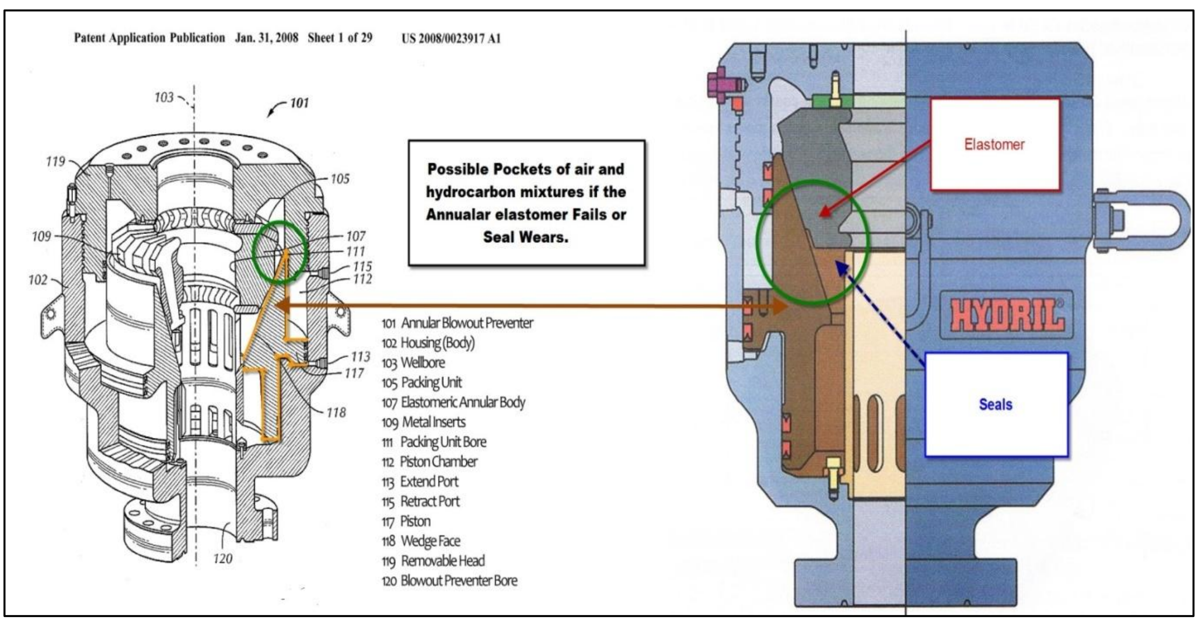


Figure 27: Possible trapped pockets of air in Snubbing or Primary Annular BOPS (Hydril Pressure Control, n.d.; Enform, 2011).

As shown above pockets of air are mainly due to elastomers and seal failures in the annular BOP. When this occurs there is also a possibility of the well fluids infiltrating into the hydraulic and accumulator system of the unit. This is a potentially dangerous situation because frequently the hydraulic fluids are petroleum based and a mixture with well fluids and trapped air from seal failures represents an explosion risk. From field experience it has been shown that elastomers and seal failures do occur on jobs and as such seals and annular elastomers are changed out typically after every two jobs (Ebert, 2011) to prevent explosions.

The volume of potential air trapped within these spaces is dependent on the size of the annular BOP. The potential maximum capacity of a pocket of air was calculated by subtraction which was through the difference between the liters to close and the the liters to open for a variety of annular BOPs. The result provided the displacement volume needed to close or open the annular BOP. A few selected BOPs sizes are illustrated in Table 4 with their maximum potential air pocket size (Enform, 2011).

BOP Model	BOP Size (mm) Minimum	Vertical Bore (mm) Maximum	Liters (L) to Close	Liters (L) to Open	Potential Maximum Size of air pocket (L)
Spher BOP	103.1	103.1	7.8	6.3	1.5
Spher BOP	152.4	179.4	17.3	12.2	5.1
MSP	203.2	227	17.3	11.2	6.1
GK	254.0	279.4	28.1	21.0	7.1

Table 4: Potential air pocket sizes in annular BOPS. BOP models are from Enform 2011: Well Servicing Blowout Prevention (Enform, 2011)

4.2.2 Pipe Rams, Blind Rams and Shear Rams

Snubbing and primary stripping pipe rams, pipe rams and shear rams also have potential for trapped air. The potential areas are behind the rams in the area ahead of the piston assembly during operations when the rams are activated and in front of the ram when it is not activated.

Air and well fluids may potentially accumulate in areas behind the ram if the rams deteriorate and do not provide a seal from the well fluids. This is of particular concern when working in H_2S environments as it can deteriorate the metal components of the rams significantly and form iron sulphides. This will corrode the metal rams and open up the passage for air and well fluid infiltration which at the right conditions as described in the preceding text could result in explosions. Please see Figures 28, 29 and 30.

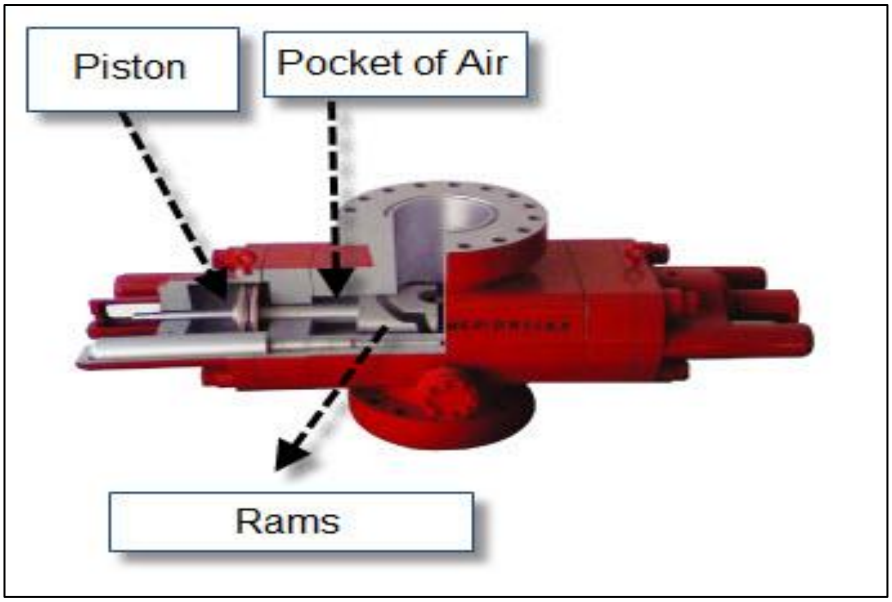


Figure 28: Potential pockets of trapped air in ram type BOPS behind the ram and in the piston pockets (Bejing Lanfeing Energy Equipment CO. Ltd., n.d.).

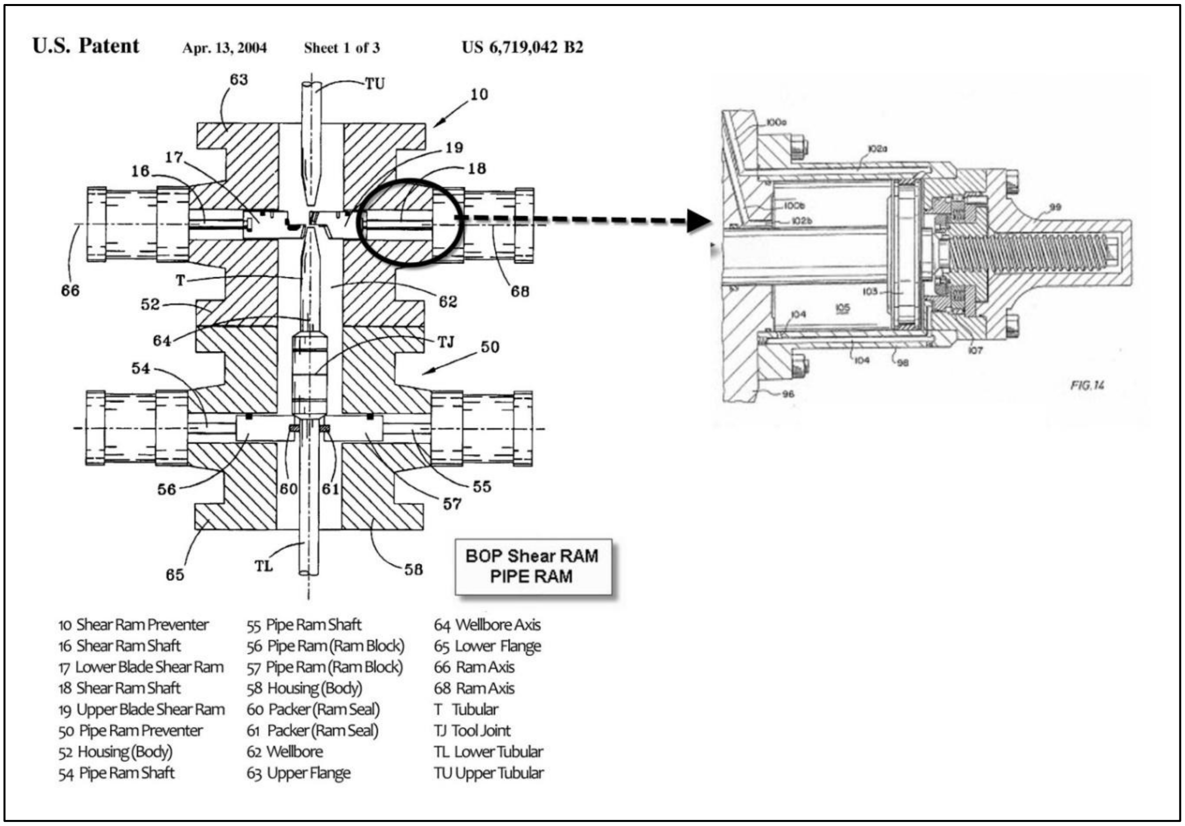


Figure 29: BOP pipe ram schematic focusing on piston (Varco International, 2004).

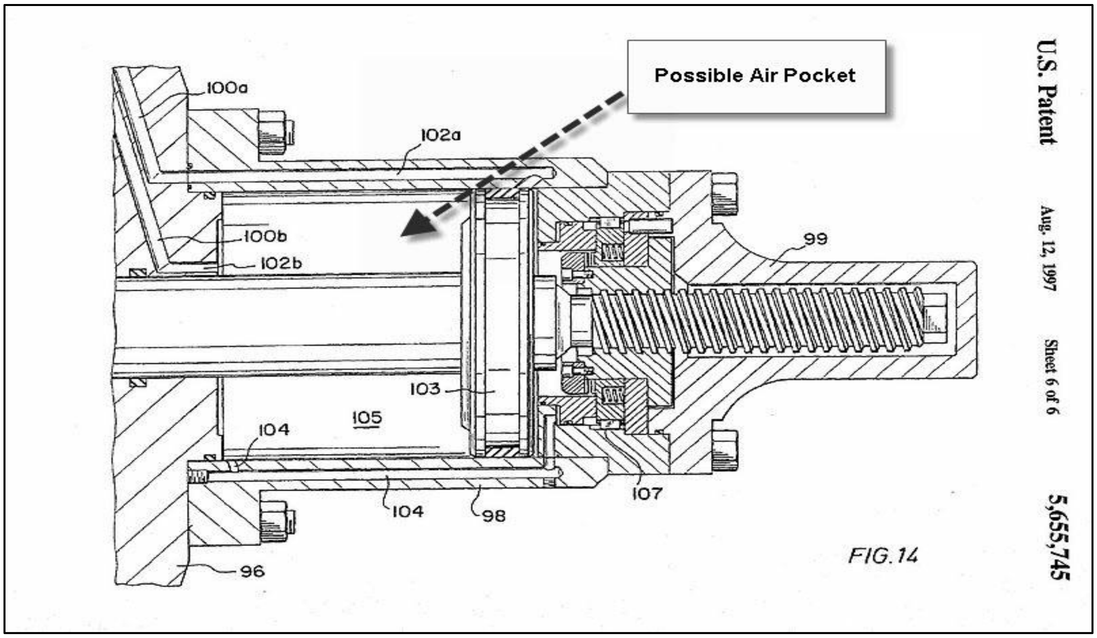


Figure 30: Focused piston on BOP pipe ram and areas of trapped pockets air (Varco International, 1997).

Trapped air in front of non active rams are a concern as well. However, there is a greater potential of trapped air pockets behind the rams than in front. This is because the area for accumulation is small compared to that of the air pockets behind the rams. Table 5 presents the potential volume of trapped air that could accumulate from a variety of pipe ram BOPs (Enform, 2011).

BOP Model	BOP Size (mm) Minimum	Vertical Bore (mm) Maximum	Liters (L) to Close	Liters (L) to Open	Potential Maximum Size of air pocket (L)
47034	103.2	103.2	1.6	1.3	0.3
U	152.4	179.4	5.0	4.8	0.2
SS	203.2	228.6	5.7	4.9	0.8
U	254.0	279.4	12.7	12.1	0.6

Table 5: Potential air pocket sizes in ram type BOPS

If air accumulates in these areas and experiences a sudden change in pressure, an explosion could occur due to adiabatic compression auto-ignition. This is of specific concern for snubbing rams that experience pressure changes due to staging of collars.

4.2.3 Lubricator

Lubricator's are an assembly of high pressure tubing used to place tools run on wireline into pressurized wells and in many cases they form a barrier for well control purposes. Lubricators also help to centralize the wireline as it goes down. Lubricators are typically placed downhole above or within the BOPs and the wireline line tools and wireline are feed through the lubricator into the pressurized hole. Sometimes the lubricator contains a grease injection assembly above it and most lubricators contain sealing elements within.

Pockets of air can be potentially trapped within the lubricator unit, specifically in the areas where the well fluid is injected and the end tubing section exposed to the BOPs. Pockets of air could be let into the well fluid injection area due to inadequate purging or a stall in operations when the well pressure line is inadvertently turned off and then on again. Trapped air can accumulate in end tubing section if the tubing below is not properly purged. These air pockets could then be pressurized by the well fluid and can lead to an explosive mixture.

In addition, in many wireline operations a grease assembly is placed above the lubricating assembly, this grease assembly applies petroleum based grease to the wireline running in hole. This high carbon petroleum product is very flammable and in combination with pockets of air trapped within the lubricator assembly, this can be a very dangerous situation. The volume of potential trapped pockets of air is hard to determine as the lubricator sizes vary and are dependent on the tubing sizes or operations planned for the well. Figure 31and Figure 32 illustrate areas of trapped air.

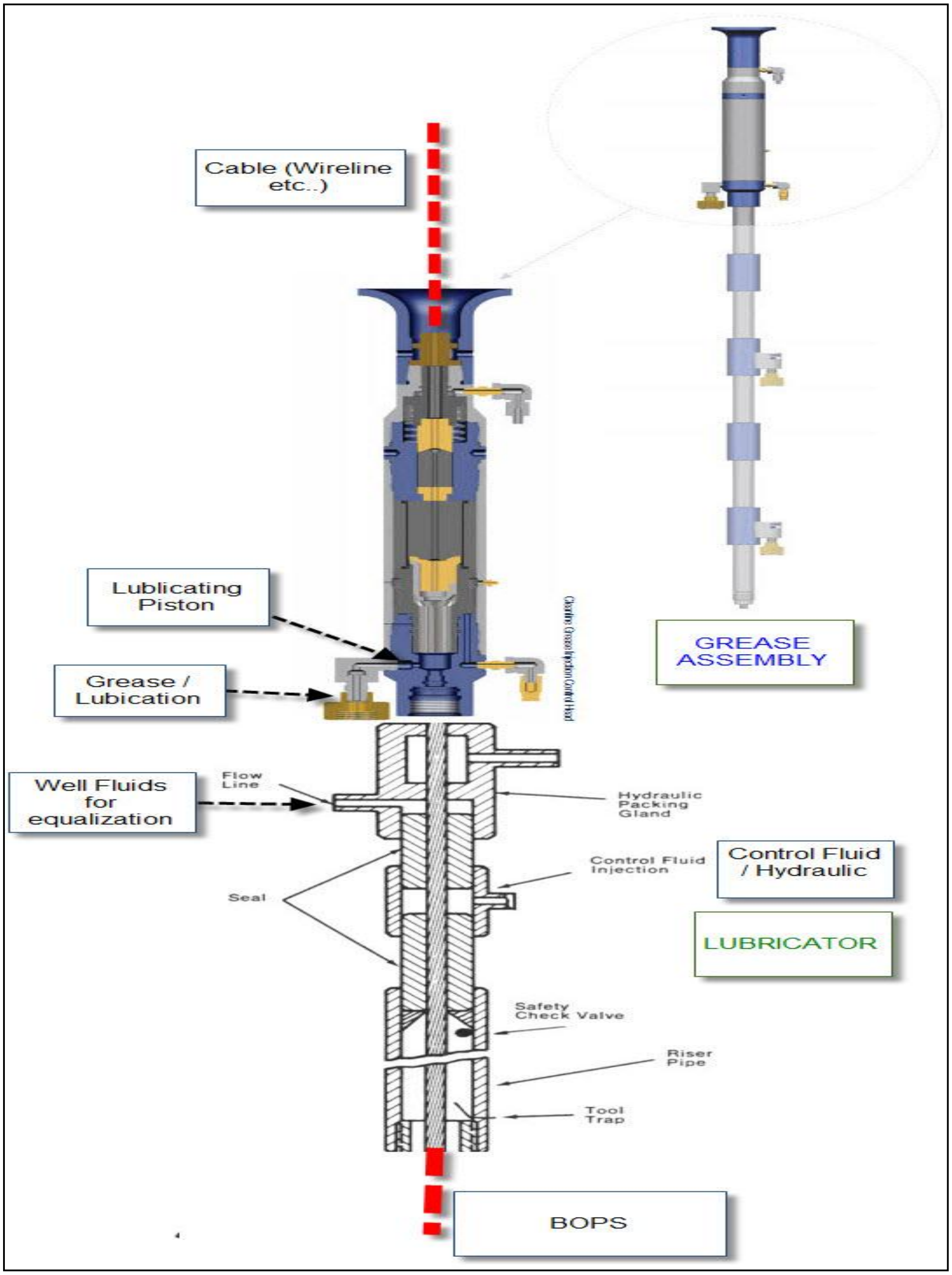


Figure 31: Illustration of grease and lubricator assembly (Hunting Energy Services, 2010; Schlumberger Limited, 2011)

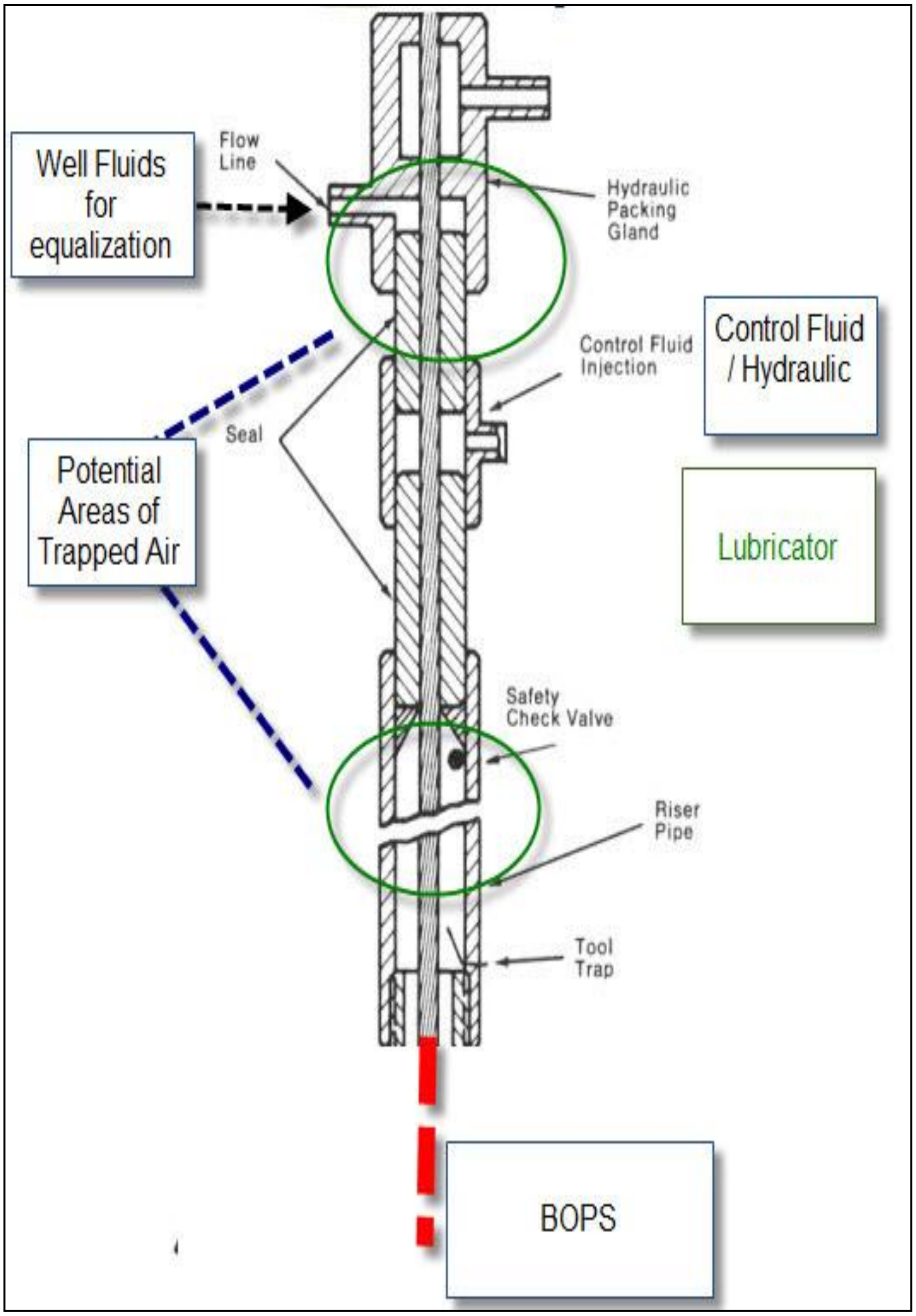


Figure 32: Potential pockets of air within lubricator (Schlumberger Limited, 2011).

4.2.4 Spools

Most valves and spools used on the BOP stack and snubbing stack are similar. The areas of potential pockets of air are the spaces between the work spool outlets and the main hole as shown in Figure 33.

These areas can accumulate pockets of air through the snubbing operations. In particular during collar staging operations where the snubbing unit is purged of well fluid, air is allowed to enter and then pressured through with well fluid again. The air trapped within these regions when mixed with well fluids along with the associated pressure has the potential for an explosion. The volume of trapped air within these spools are dependent on the spool sizes and are typically greater than 150 mL.

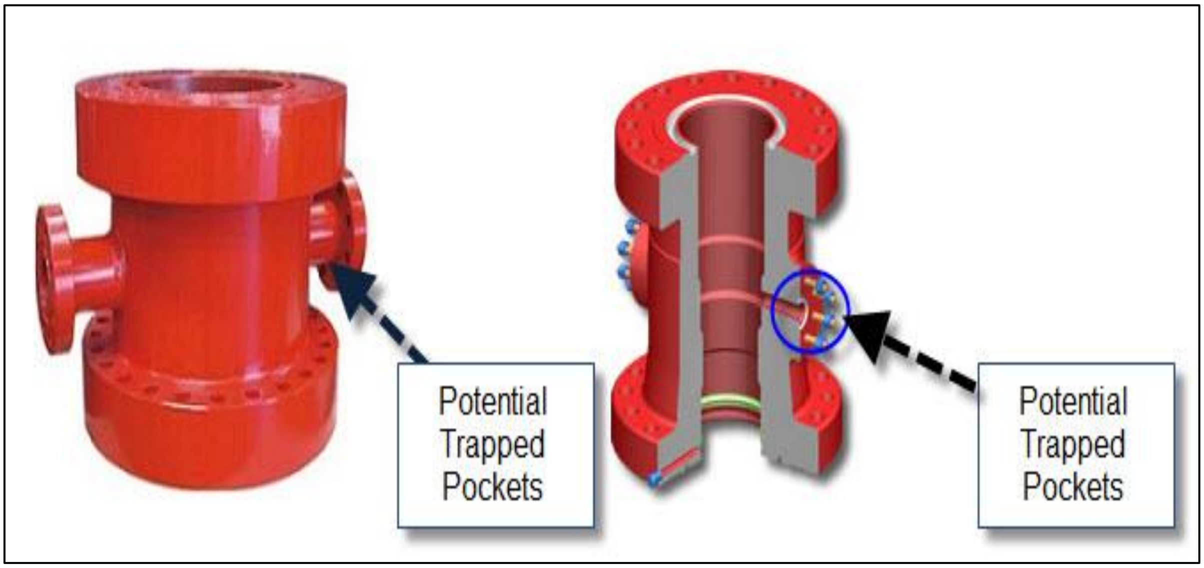


Figure 33: Potential pockets of trapped air in spools (Sunry Petroleum Equipment Co. Ltd., 2009).

4.2.5 Lines

Trapped pockets, especially air/oxygen can be a problem. The lines can trap pockets if they are improperly purged. Even a slight pocket of air can cause an explosive mixture. Junctions specifically T-intersection are good candidates for trapped pockets of air/oxygen or hydrocarbons. This is especially true during purging operations. Trapped pockets can accumulate in the branches off the lines that are used for purging

Junctions as shown in Figure 34 where tubing changes diameter are areas of concern. Air can be trapped in these areas. These changes in diameter are also areas of failure where shockwaves can inflict damage.

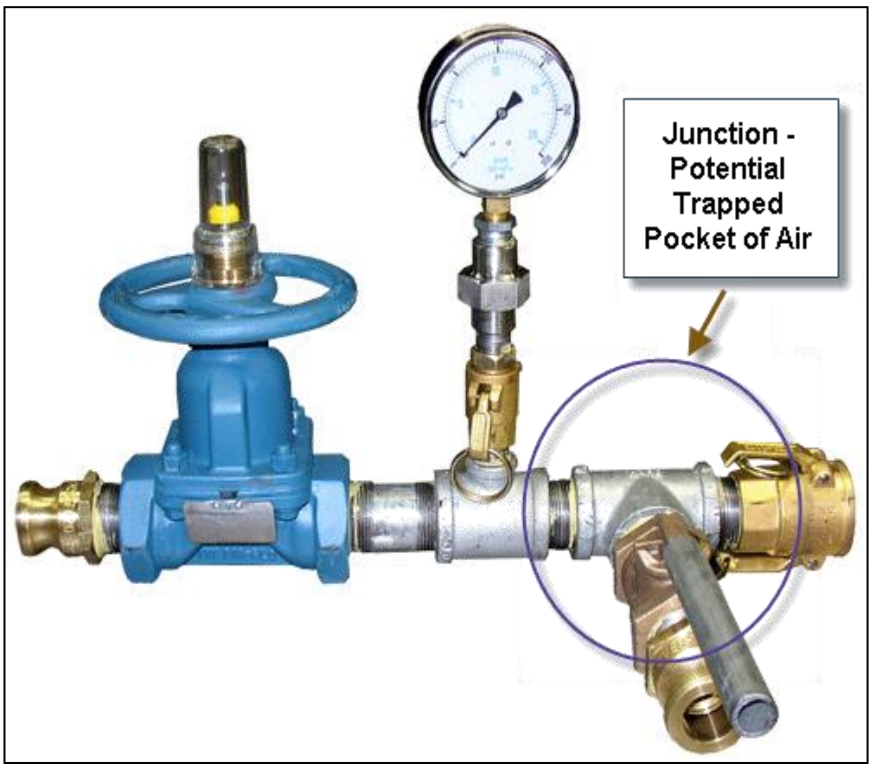


Figure 34: Pockets of trapped air in T- junctions (ChemGrout Inc. , n.d.).

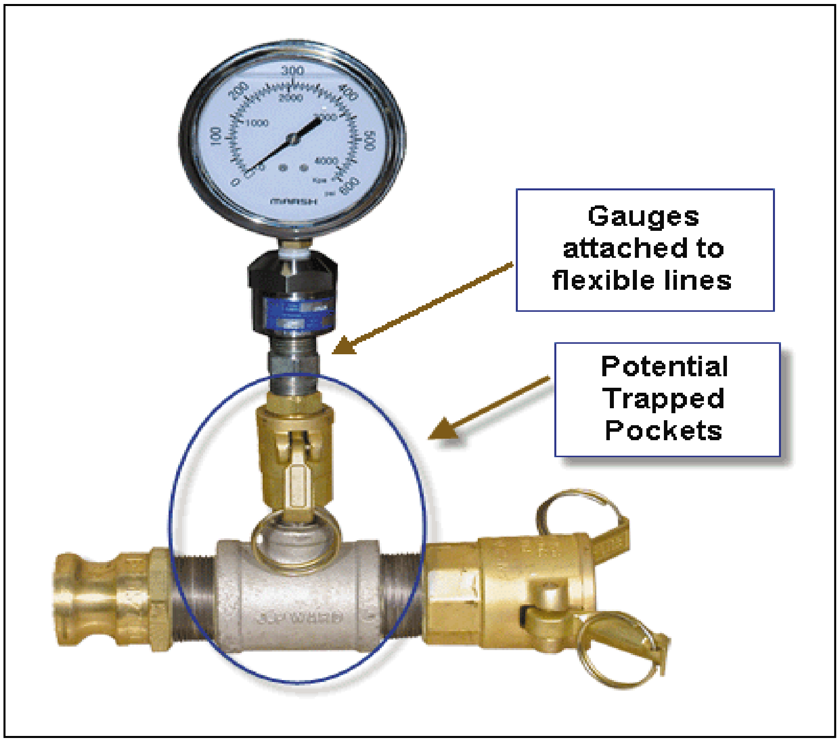


Figure 35: Pockets of trapped air in pressure and measurement gauges (ChemGrout Inc. , n.d.)

The areas of particular concern for lines are the choke manifold, separator and flare stack, bleed off and kill line. The junction areas (see Figure 25) of particular concern are the equalization loop line from the casing bowl, with a T - junctions to the choke manifold, separator and flare stack to the equalization spool, the two T - junctions one from the working spool to the kill line and back to the equalization spool and the other T- junction from working spool line and the bleed off line to the equalization spool. These areas can accumulate dead volumes of air and hydrocarbon mixtures, dead headed branches off purge lines are especially susceptible of this.

Other areas include pressure and measuring gauges or lines to the gauge measuring device as shown in Figure 35. These areas are particularly susceptible as they can trap pockets of air and hydrocarbons and if overly pressurized due to an explosion, can lead to situations where debris can fly off rapidly. Typically on site personnel are relatively close to gauges making this situation a very significant hazard on site.

The junction pressure and measurement gauge integration areas of concern are on the equalization loop to the choke manifold, separator and flare stack and pressure gauge reading valve from the working spool to the kill line and bleed off lines. The volumes of air in these areas depend on the tubing or gauge sizes. They can be of 150 mL and higher.

4.3 Explosions, Shockwaves and Shockwave Characteristics

An explosion is defined as a rapid transformation of internal or chemical energy into mechanical energy and involves the expansion of gasses (Martin, 2000; Shahbazi et al., 2006). An explosion involves a rapid expansion in which energy is transmitted outward as a shockwave. A flammable air or oxygen and vapour mixture can result in an explosion. Some of these types of explosions lead to a BLEVE, which is a boiling liquid expanding vapor explosion. These explosions lead to deadly fireballs and flying fragments (Lottermoser et al., 2003).

Explosions are characterized by the speed at which the shockwave travels and can be characterized into two main forms, deflagration and detonation.

Deflagration is defined as combustion reaction in which the velocity of the shockwave through the fuel medium is less than the speed of sound (Lottermoser et al., 2003). Detonation is when the reaction shockwave velocity is equal to or greater than the speed of sound (Lottermoser et al., 2003).

This segment of the study will focus on explosions due to ignition of trapped/immobile hydrocarbons vapours within trapped pockets of air assisted by rapid compression and LTO reactions within the surface equipment during snubbing operations. The resulting explosion creates shockwaves that are in the form of detonation waves. These detonation shockwaves are relevant because they have the most destructive impact for causing harm to personnel, damage to equipment and surrounding environment.

4.3.1 Shockwave Characterization

A shockwave according to Krehl (2011) is a mechanical wave characterized by a surface of discontinuity in which particle velocities and all thermodynamic quantities (velocity, pressure, density, temperature and entropy) change abruptly (Krehl, 2011; John and Keith, 2006). The exact processes taking place inside the waves itself are quite complex, and not well understood. However, the focus of shockwaves are on the net changes in the fluid properties taking place across the entire wave (John and Keith, 2006). These waves are of finite but large amplitude and generally the faster a wave propagates the stronger the wave becomes (Zuker, 1977). The energy within shockwaves unlike other non-linear waves dissipates relatively quickly with distance. Therefore, generally the closer the object, the stronger the impact of the wave (Krehl, 2011).

The majority of the force within a shockwaves is at its shock wave front. Figure 41 shows the approximate shape of a shock wave and its shock front.

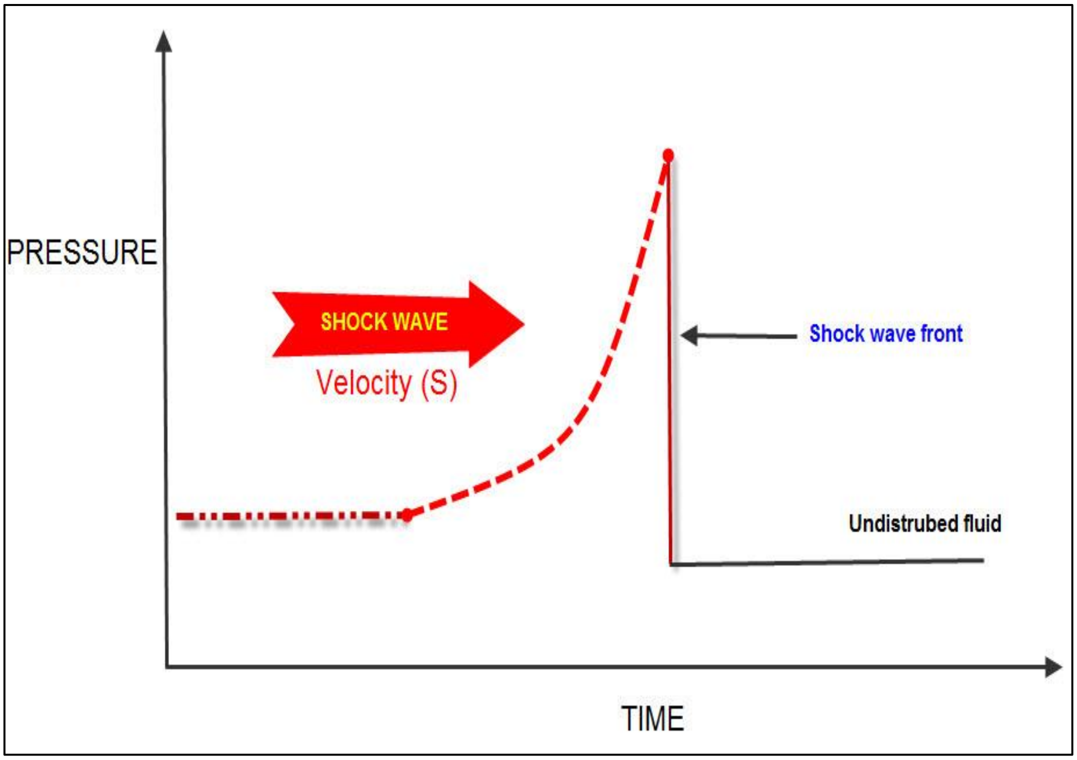


Figure 36: Approximate shape of a shock wave.

Typically, when a strong shock front experiences an object or a corner in an enclosed space it transfers the majority of its energy directly on that object and in a strong shockwave the waves can cause total destruction to any object with little apparent change in the velocity of the shock wave itself (Lottermoser et al., 2003). Figure 37 demonstrates the damage from a strong shockwave at a corner of tubing.

Figure 37: Damage due to a shockwave experiencing a corner tubing (Moore et al., 2011).

Under very high shock pressures, the shock front can transform a solid into a liquid (shock liquefaction or shock melting) and a shock compressed liquid into a solid (shock solidification or shock freezing). The powers of the shock front can be exceptionally damaging, even a small shock wave can be potentially fatal to humans.

Of particular interest in this study is the shockwave produced and propagated following ignition of a hydrocarbon vapour when the temperature of the air/fuel mixture is suddenly increased due to rapid compression. The hydrocarbon vapour may be condensate produced from the well or it may be low carbon number (C_5 to C_{10}) fractions generated by LTO reactions. Once ignition of a vapour phase burn occurs, auto-decomposition of the liquid and semi-solid products of the LTO reactions can generate additional energy at a rapid rate by involving the oxygen previously incorporated into the hydrocarbon molecules.

Following the ignition process described in an earlier chapter, the resulting explosion creates a combustion wave (Enform, 2007; Lee, 2008). This combustion wave transforms reactants into products, releasing the potential energy stored in the chemical bonds of the reactant molecules. This energy is then converted into internal (thermal) and kinetic energy of the combustion products (Lee, 2008). These chemical reactants within the combustion wave propagate through at high supersonic speeds as a denotation wave, the most destructive type of waves.

4.3.2 Detonation Wave Characteristics

A detonation is a shock wave that moves in the same direction as that of the fluid motion (Lee, 2008). Once a detonation shock wave starts to propagate, the leading shock front can ignite the reactants directly ahead of the front by adiabatic compression (Lee, 2008). As the front moves forward it can lead to subsequent auto-ignition by the leading shock front. This can increase the strength/speed of the shock and compounded over time results in a front more damaging than the initial. This process continues until the internal effects within the wave, mainly the heat of conduction and viscosity hold back the shock velocity (John and Keith, 2006) . This compounding effect is illustrated in Figure 38.

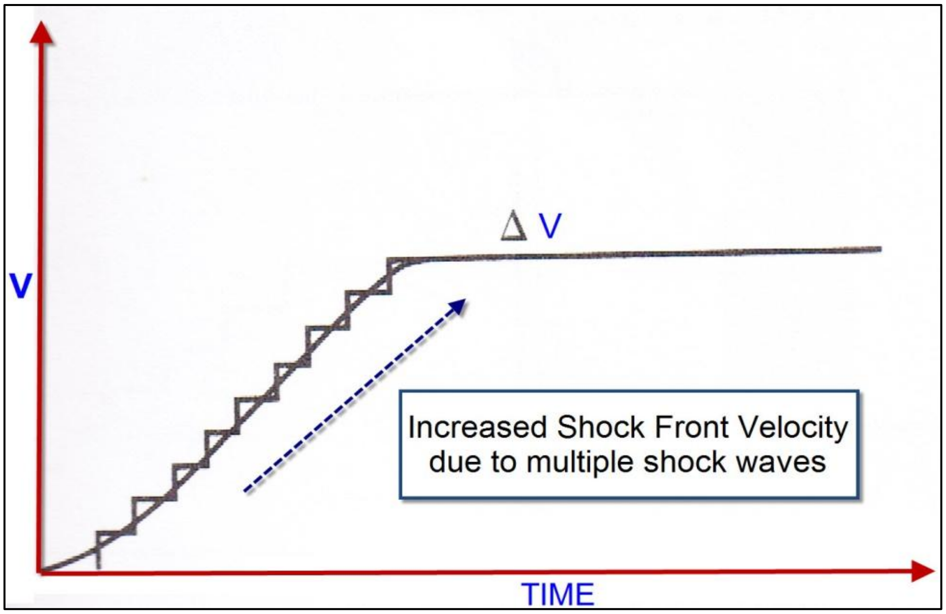


Figure 38 Increased shock front velocity due to multiple shock waves due to adiabatic compression auto-ignition (John and Keith, 2006).

Detonation shockwaves can travel in any direction and when experiencing a corner or change in tubing or pipe diameter, they are not impeded or restricted by the direction of fluid flow (Lottermoser et al., 2003).

If a combustion explosion produces a denotation wave in a confined volume, a large rise pressure will be observed due to the high temperature of the combustion reaction products and the restriction of the gases ability to expand. Typically, the rate of pressure rise decrease as vessel size increases. A slow rate of pressure rise creates a pushing or bulging type of damage and a rapid pressure rise damages by shattering, producing shrapnel.

4.3.3 Pressure and Other Conditions Resulting from a Shockwave

The pressure within a shockwave is an important characteristic. Stoner and Bleakney (1948) and Zabetacis (1965) have presented work on combustion reactions shockwaves that closely relate to those experienced in the oilfield. It has been noted in these studies that the pressure rise due to explosions are about 20 to 30 times greater than initial pressure pre-explosion.

However, the explosion field is quite complex and the equations presented in their work and in various open literature do not model the explosion behaviour accurately compared to those found in experimental results. A general formula and series of formulas do however work to give an estimate of the damage potential from an explosion's shockwave. These formulas and calculations are presented in the next chapter.

Chapter 5: Simulation Results: Explosion and Shockwaves

The following section illustrates the damage potential within an explosive shockwave for a 150 mL trapped pocket of air during low pressure snubbing operations (21 MPa and below) on a warm summer day (ambient outside temperature 25 ^{o}C to 30^{o}C) . A snubbing pressure of 8 MPa will be used for calculations as this is the lowest pressure typically used for field snubbing operations. Pressures under this usually use other well servicing methods. The purpose of these results is to show the significance and destructive impacts possible from the smallest trapped pocket of air under the right snubbing operating conditions.

The ignition and explosion source will be as described in the Chapter 2, due to the ignition of flammable vapour phase components generated from LTO reactions between dead volumes of hydraulic oil, crude oil, light condensate or other hydrocarbons, and trapped air. Ignition would most likely occur during/after rapid pressurization by a well fluid. The explosion would most likely occur after the ignition. However, for calculations purposes the well fluid will be assumed to be natural gas mostly methane gas.

5.1 Pressure Rise and Temperature Calculations

Consider a trapped pocket of air of volume (V_{air}) as measured at atmospheric pressure (P_{air}) and the localized temperature within the volume where the air is trapped ($T_{air\ 1}$). The mass of air (m_a) within the pocket is given by:

$$m_{air} = \frac{P_{air}\, V_{air}}{R\, T_{air}} \tag{5.1}$$

where :

P_{air}	Pressure at Atmosphere (kPa)
V_{air}	Volume where air is trapped (m^3)
R	Specific Gas Constant (0.2870 kJ/ kg K)
T_{air}	Temperature of the trapped air (K)

When gas from the well is suddenly introduced to the surface assembly, the resulting temperature of the air within the pocket can be estimated using Equation (3.3)

$$T_{air\ 2} = \gamma_{air} \times T_{air\ 1}$$

which as described in Chapter 3, predicts a temperature for

$$T_{air\ 1} = 50^{o}\text{C} = 323\ \text{K}$$

$$\gamma = 1.40$$

$$T_{air\ 2} = 452\text{K} = 179\ ^{o}\text{C}$$

This would be the temperature of the air within the air pocket moments before the initiation of the combustion reaction. The pressure at this moment would be close to the pressure of the gas in the well.

Assuming a well pressure of 8 000 kPa, then:

$$P_{air\ 2} = 8\ 000 kPa$$

and the volume occupied by the air pocket a moment before the onset of the explosion would be:

$$V_{air\,2} = \frac{m_{air}\, R\, T_{air}}{P_{air\,2}}$$

$$= \; V_{air}\, \frac{P_{air}}{P_{air\,2}} \frac{T_{air\,2}}{T_{air\,1}} \tag{5.2}$$

If it is assumed V_{air} = 150 cm^3 = 150 x 10^{-6} m^3 and P_{air} is 100 kPa then

$$V_{air\,2} \; = \; (150\; x\; 10^{-6}\; m^3)\; \frac{(100kPa)(452K)}{(8000kPa)(323K)}$$

$$= 2.62 \text{ x } 10^{-6} \text{ m}^3 = 2.62 \text{ cm}^3$$

If it is assumed that all of the air contained in the original air pocket is consumed (which implies turbulent mixing of air with surrounding fuel once self ignition occurs) then the heat generated by the reaction can be estimated based on 3 716 kJ/m^3 (ST) of air reacted (Mehta : Private Communication, 2012).

i.e.

$$\Delta h_{reaction} \; = 3\;716\; \frac{kJ}{m^3 (ST)_{air}}$$

Which on a mass basis is:

$$\rho_{air}\;(STP) = \left(\frac{101.325\; kPa}{\left(0.2870\; \frac{kJ}{m^3 (ST)_{air}}\right)\; 288.15K} \right) \left(\frac{1\; kJ}{1\; kPa\; m^3} \right) = 1.225\; \frac{kg}{m^3 (ST)}$$

Hence $\Delta h_{reaction}$:

$$\left(3\ 716\ \frac{kJ}{m^3(ST)_{air}}\right)\left(\frac{1\ m^3(ST)_{air}}{1.225\ kg}\right)$$

$$= 3033\ \frac{kJ}{kg\ air}$$

The heat of reaction is the enthalpy change on reaction, however if the calculations are based on a fixed mass of air, then the internal energy change on reaction is:

$$\Delta u_{reaction} = \Delta h_{reaction} - RT_{ref} \tag{5.3}$$

Where it is assumed that T_{ref} = 298 K (25°C), which is the temperature where heats of reaction are normally measured. If it is assumed that the gas mixture before and after the combustion event can be assumed to behave like air then:

$$u_{\ reaction} = \left(3033\frac{kJ}{kg\ air}\right) - \left(0.2870\ \frac{kJ}{kg\ K}\right)(298K)$$

$$= 2947\ \frac{kJ}{kg\ air}$$

If one notes that pressure is equivalent to energy per unit volume (i.e. 1 kPa = 1 kJ/m^3), then the anticipated pressure rise associated with the ignition event is:

$$\Delta P(kPa) = \frac{m_{air}\ \Delta u_{reaction}}{V_{a_2}}$$

$$\Delta P(kPa) = \left(\frac{P_{air_2}}{RT_{air_2}}\right)(\Delta u_{reaction}) \tag{5.4}$$

$$= \left(\frac{8000\ kPa}{0.2870\,\frac{kJ}{kg\ air}{*}452\ K}\right)\left(2947\ \frac{kJ}{kg\ air}\right) = 181\ 739\ \text{kPa}$$

or

$$\frac{\Delta P(kPa)}{P_{air_2}} = 22.7$$

It is important to note that the predicted pressure rise is independent of the actual volume of the air pocket, hence even a small air pocket can result in the generation of an exceptionally high localized pressure.

The above calculation for pressure rise based on equivalent energy generation per volume may be though to be too simplistic, however it should be of the correct order of magnitude.

If the analysis of the ignition event is based on a fixed mass of air (i.e closed system analysis), the first law of thermodynamics is :

$$Q - W = m_{air}\Delta u_{\,reaction} = mC_v(T_{air\,3} - T_{air\,2}) \tag{5.5}$$

Where:

Q	Heat transfer to gas (assume zero due to short duration of ignition event)
W	Work at moving boundary (kJ)
$T_{air\,3}$	Absolute temperature following release of energy (K)
m_{air}	Mass of air in pocket (kg)

The work term can be estimated by assuming a moving boundary between the air under analysis and the gas within the surface assembly.

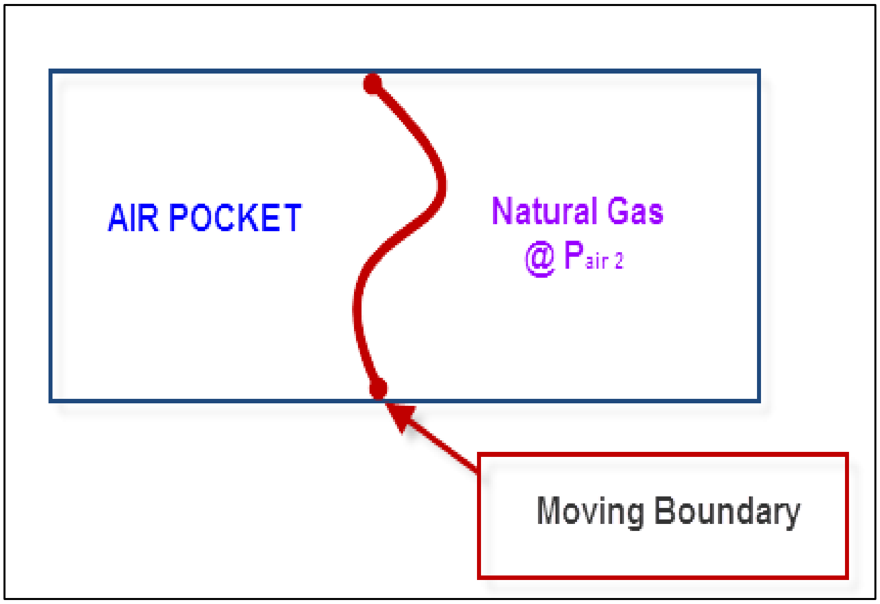


Figure 39 Moving boundary between air pocket and natural gas

i.e.

$$W = P_{air\,2}\,(V_{air\,3} - V_{air\,2})$$

$$= (m_{air})\ (R\,)(P_{air\,2})\left(\frac{T_{air\ 3}}{P_{air\,2}} - \frac{T_{air\,2}}{P_{air\,2}}\right)$$

Hence the first law for the fixed mass m_{air} of air is:

$$= -(m_{air})\ (R\,)(P_{air\,2})\left(\frac{T_{air\ 3}}{P_{air\,3}} - \frac{T_{air\,2}}{P_{air\,2}}\right) + m_{air}\Delta u_{\ reaction} = mC_v(T_{air\,3} - T_{air\,2})$$

Noticing that the mass cancels out, upon re-arrangement the first law equation become:

$$-T_{air\,3}\left(\frac{R\,P_{air\,2}}{P_{air\,3}}\right) + \Delta u_{\ reaction} = C_vT_{air\,3} - C_vT_{air\,2}RT_{air\,2}$$

or

$$T_{air\ 3}\left(C_v + \left(\frac{R\ P_{air\ 2}}{P_{air\ 3}}\right)\right) = \Delta u_{\ reaction} + C_p T_{air\ 2}$$

Where $C_p = C_v + R$

For the purpose of calculation, C_v and C_p are taken at 1000 K (Cengel and Boles, 2010).

i.e. $C_v = 0.855\ \frac{kJ}{kg\ air}$ and $C_P = 1.142\ \frac{kJ}{kg\ air}$

If the ignition process is assumed to be reversible and adiabatic (i.e. isentropic).

$$\frac{T_{air\ 3}}{T_{air\ 2}} = \left(\frac{P_{air\ 3}}{P_{air\ 2}}\right)^{\frac{\gamma-1}{\gamma}} \tag{5.6}$$

Where γ = 1.336 at 1 000 K

Hence:

$$\left(\frac{P_{air\ 3}}{P_{air\ 2}}\right) = \left(\frac{T_{air\ 3}}{T_{air\ 2}}\right)^{\frac{\gamma}{\gamma-1}}$$

$$= \left(\frac{T_{air\ 3}}{T_{air\ 2}}\right)^{3.976} \tag{5.7}$$

For $T_{air\ 2}$ = 452K

The first law equation is:

$$T_{air\ 3}\left(0.855 + \left(\frac{1.036}{T_{air\ 3}{}^{3.976}}\right)\right)\frac{kJ}{kg\ air} = 3465\ \frac{kJ}{kg}$$

Solving by trial and error yields:

$$T_{air\ 3} = 4\ 050K$$

If the work term in the first law had been assumed negligible, then :

$$\Delta u_{\ reaction} = C_v(T_{air\ 3} - T_{air\ 2})$$

$$T_{air\ 3} = 452K + \frac{2947\ \frac{kJ}{kg\ K}}{0.855\ \frac{kJ}{kg\ K}}$$

$$= 3\ 899K$$

The higher temperature following ignition implies that the external gas does work on the system which reflects the reduction in the volume of the fixed mass of gas at the elevated pressure predicted based on the ignition process being isentropic. The predicted pressure is:

$$\left(\frac{P_{air\ \ 3}}{P_{air\ 2}}\right) = \left(\frac{4\ 050\ K}{452\ K}\right)^{3.976} = 6115$$

$$P_{air\ \ 3} = (8\ 000\ kPa)(6115) = 48.9\ x\ 10^6\ kPa$$

This pressure would far exceed the design strength of most piping, however the validly of assuming the ignition process to be isentropic must be questioned.

Neglecting the work at the moving boundary is equivalent to assuming the initial mass of the air is contained in a rigid vessel. If this were the case, then:

$$\left(\frac{P_{air\ \ 3}}{P_{air\ 2}}\right) = \frac{T_{air\ \ 3}}{T_{air\ 2}}$$

$$P_{air\ 3} = (8\ 000\ kPa)\left(\frac{3\ 899K}{452K}\right)$$

$$= 69\ 008\ kPa$$

This would imply a pressure rise of:

$$\left(\frac{P_{air\ 3}}{P_{air\ 2}}\right) = \frac{69\ 000\ kPa}{8\ 000\ kPa} = 8.6$$

Detailed analysis of the ignition event and subsequent formation of a shockwave is beyond the scope of this thesis, however if one assumes the pressure rise based on the $\frac{energy}{volume}$ concept, i.e.

$$\left(\frac{P_{air\ 3}}{P_{air\ 2}}\right) = 22.7$$

And then evaluate temperature $T_{air\ 3}$ based on the first law for fixed mass if air, the value would be:

$$T_{air\ 3}\left(0.855 + 0.287\left(\frac{1}{22.7}\right)\right) = 3\ 465$$

$$T_{air\ 3} = 3\ 992\ K$$

What the above analysis implies is that the temperature of the gas (assumed to be air but will actually be a mixture of nitrogen and combustion gasses) is known with a much higher level of certainty than the actual pressure rise. The pressure rise based directly on the $\frac{energy}{volume}$ concept appears to be reasonable, hence conditions of the air contained in the original air pocket are estimated as:

$$T_{air\ 3} = 3\ 992\ K$$

$$P_{air\ 3} = (22.7)(8000\ kPa)$$

$$= 181\ 739\ kPa$$

Immediately following the ignition event.

This sudden pressure rise is not the only area of concern. The true destructive power of this pressure rise is within the following shockwave that results. The typical transition time between a shockwave and normal air is from 10^{-10} to 10^{-15} seconds (Hamby, 2004; Kinney, 1985).

5.2 Shockwave Wave Calculations

The study of shockwaves and its resulting effects are a very complex field of study. Therefore, the following general equations are presented to give an approximation of the significance of shockwaves and an indication of their damage potential.

In order to calculate shockwave characteristics the following assumptions for simplicity will be used:

- The shockwave will occur in one dimensional compressible flow
- The fluids involved will be ideal gases with constant specific heats
- The shock wave propagates through the fluid starting from the point where the energy is released
- The shockwave will be calculated with no reflective shockwave

The speed (S) a shockwave travels at is given by (John and Keith, 2006):

$$S = a\sqrt{\left(\frac{\gamma+1}{2\,\gamma}\right)\frac{P_{air\,3}}{P_{air\,2}}+\frac{\gamma-1}{2\,\gamma}} \tag{5.8}$$

where :

a Speed of sound in air (m/s)

$$a = \sqrt{\gamma R T_{air\,2}} \tag{5.9}$$

R Ideal Gas Constant (J/ kg K)
$T_{air\,2}$ Temperature of fluid (K)

Where γ = 1.336 at 1 000 K

$$a = \sqrt{(1.336)(287)(452K)} = 416.3\ \frac{m}{s}$$

The shockwave front velocity is then:

$$S = (416.3)\sqrt{\left(\frac{1.336+1}{2\,(1.336)}\right)\frac{(181\,739\ kPa)}{(8000\ kPa)}+\frac{1.336-1}{2\,(1.336)}} = 1861.15\ \frac{m}{s}$$

Frequently, the shock speed is noted in relation to the Mach number. The calculation of the shock Mack number (M) is given by Equation 5.10 (John and Keith, 2006):

$$M = \frac{S}{a} \tag{5.10}$$

Generally if M > 1 and $P_1 >> P_0$, then it is considered a strong compressive shock. A weak shock is generally when M< 1 or near unity and where jumps in flow variables between conditions before and after the shock front are small (Ya and Yu, 1968). Most detonations and explosions are strong compressive shocks.

The Mach number is calculated by (5.10):

$$M = \frac{S}{a} = \frac{1861.15\ \frac{m}{s}}{416.3\ \frac{m}{s}} = 4.47$$

This is an extremely fast shock speed. The shockwave itself has a very thin thickness that can be approximated by (Granger, 1995):

$$t_{shock\ thicknes} = \frac{\nu_{air}}{a\ M} \qquad (5.11)$$

where :

ν_{air}	Kinematic Viscosity of air before the shockwave (m^2/s)
a	Speed of sound in air (m/s)
M	Mach number

ν_{air} at 452K is 27.47 x 10^{-6} m^2/s (Engineering Toolbox, n.d)

$$t_{shock\ thicknes} = \frac{27.47 \text{ x } 10^{-6}\ \frac{m^2}{s}}{\left(416.3\ \frac{m}{s}\right)(\ 4.47)} = 1.477\ x\ 10^{-8}\ m$$

Next an equation representing instantaneous intensity of a shockwave is needed.

Sadovsky (1952) established some general equations to measure the shockwaves /blast waves from a TNT explosion in air (Silnikov, 2004; Gelfand, 2004; Gibson, 1994). After analyzing some of this work, the work done by Gelfand (2004), Gibson (1994), the works of Hamby (2004) and Kinney (1985), and considering the conditions in this study the following approximate equation for instantaneous intensity of a shockwave expressed in Watts per square meter:

$$\frac{Watts}{m^2} \cong \frac{S^2\,\rho_{air}\;a}{100} \tag{5.12}$$

Where ρ_{air} is 0.375 $\frac{kg}{m^3}$ at 1 000 K

$$\frac{Watts}{m^2} = \left(1861.15\ \frac{m}{s}\right)^2 (0.375\ \frac{kg}{m^3})(\ 416.3\ \frac{m}{s})\ (\frac{1}{100}) = 5.407 *\ 10^6 \frac{Watts}{m^2}$$

Watts per square meter can be converted to decibels. Decibels are typically used to measure sounds waves. Shockwaves are sounds waves, but they are of higher energy, speed, temperature and have a quicker release of energy than normal sounds waves. All shock waves degenerate into normal sound waves after a certain distance (Hamby, 2004; Kinney, 1985).

The softest sound typical heard by humans is at 0 decibels (dB). The dB scale is a logarithmic scale and 0 dB = 10 $^{-12}$ $\frac{Watts}{m^2}$

Therefore the conversion from Watts per square meter to decibels is as follows (Hamby, 2004; Kinney, 1985):

$$dB = 10\log(\ \frac{x}{10^{-12}\ \frac{Watts}{m^2}}) \tag{5.13}$$

$$dB = 10\log\left(\frac{5.41 * 10^{6}\,\frac{Watts}{m^2}}{10^{-12}\,\frac{Watts}{m^2}}\right) = 187.33\ dB$$

The value of 187.18 dB can create a shockwave that will destroy all objects and fatally injure humans that are within its shockwave range.

To approximate the general shockwave radius for dB measurements under 210.6 dB (Hamby, 2004; Kinney, 1985):

$$Shockwave\ radius = \left(10^{\left(\frac{dB-210.6}{20}\right)}\right)\ (3.57\ m) \tag{5.14}$$

The shockwave radius is the distance that the shockwave will have full power, any objects in it is way will act near transparent, that is the shockwave will pass right through them with no apparently loss in energy.

$$Shockwave\ radius = \left(10^{\left(\frac{187.33-210.6}{20}\right)}\right)\ (3.57) = 0.245\ m$$

A 187.18 dB shockwave will cause catastrophic and fatal damage to any structures and humans within a 0.245 m distance in all directions from where the explosion is initiated.

The time it will take for shockwave to reach this distance can be calculated from:

$$T_{Shockwave\ at\ Full\ power} = \frac{Shockwave\ distance}{S} \tag{5.15}$$

$$T_{Shockwave\ at\ Full\ power} = \frac{0.245\ m}{1861.15\ \frac{m}{s}} = 1.31\ x\ 10^{-4}\ seconds$$

The decibel calculation above gives a good indication of the significance of a shockwave speeds, power and severity. To further understand the energy and damage within a shockwave, a conversion will be made between the approximated shockwaves decibel measurement and a TNT equivalent. A TNT equivalent measurement is a typical method used to quantifying the power of an explosion.

A general approximation for TNT equivalent measurement relevant to this study can be approximated for dB measurements under 210.6 dB by (Hamby, 2004; Kinney, 1985):

$$TNT\ (metric\ tons) = 10^{\left(\frac{dB-210.6}{6.67}\right)} \tag{5.16}$$

In this case:

$$TNT\ (metric\ tons) = 10^{\left(\frac{187.33\ dB-210.6}{6.67}\right)}$$

$$= 3.24\ x\ 10^{-4}\ tons\ or\ 324.53\ grams\ of\ TNT\ equivalent$$

Table 6 illustrates a reference table of TNT and its energy equivalent.

Grams TNT	Symbol	Tons TNT	Symbol	Energy
gram of TNT	g	microton of TNT	μt	4.184×10^3 J
kilogram of TNT	kg	milliton of TNT	mt	4.184×10^6 J
megagram of TNT	Mg	ton of TNT	t	4.184×10^9 J
gigagram of TNT	Gg	kiloton of TNT	kt	4.184×10^{12} J
teragram of TNT	Tg	megaton of TNT	Mt	4.184×10^{15} J
petagram of TNT	Pg	gigaton of TNT	Gt	4.184×10^{18} J

Table 6: Reference table for weights of TNT and energy output (Cooper, 1996)

From the above: $324.53\ \ grams\ of\ TNT\ equivalent = (324.53\ g)(4.184 * 10^3 J)$

$$= 1.35\ x\ 10^6 J\ or\ 1.35\ MJ\ of\ energy\ released$$

Further:

$$W = F * D \tag{5.17}$$

Where:

W	Work (MJ)
F	Force (MN)
D	Distance (m)

$$F = \frac{W}{D} = \frac{1.35\ MJ}{0.245m} = 5.54\ MN$$

Therefore, an air pocket volume of 2.62 cm^3 (150 mL at atmospheric conditions) under the right conditions for an explosive event gives rise to a pressure of 181 739 kPa from an initial pressure of 8 000 kPa and temperature of 452K. The temperature of this fluid at the time of the explosion is approximated to be 3 992K. The shockwave velocity is 1861.15 m/s, which gives a Mach number of 4.47. This shockwave produces 187.33 dB of energy which is equivalent to 324.53 grams of TNT which releases 1.35 MJ of energy or 5.54 MN of force that can completely destroys any object within a range of 0.245 m in all direction, and significant damage after that distance.

5.3 Calculation Results

Further calculation for different temperatures for a 2.62cm^3 (150 mL at atmospheric conditions) air pocket under an initial pressure of 8000 kPa are listed in Table 7, Table 8, Table 9 and Table 10.

Initial Temperature, $T_{air\ 1}$ (^oC)	After Pressure up $T_{air\ 2}$ (^oC)	Pressure due to Explosion(P_3) (kPa)	Pressure Ratio ($\frac{P_3}{P_2}$)
30	150	1.94×10^{5}	24.27
40	165	1.88×10^{5}	23.44
50	179	1.82×10^{5}	22.72
60	193	1.76×10^{5}	22.03
70	207	1.71×10^{5}	21.39

Table 7: Pressure rise during an explosion for varying temperatures of an air pocket volume of 2.62 cm^3 at an initial pressure of 8 000 kPa

After Pressure up $T_{air\ 2}$ (^oC)	Temperature of the shockwave (K)	Shockwave velocity ($\frac{m}{s}$)	Mach number	Thickness of shockwave (m)
150	3957.06	1860.78	4.62	1.428×10^{-8}
165	3974.89	1860.97	4.54	1.451×10^{-8}
179	3991.53	1861.15	4.47	1.477×10^{-8}
193	4008.15	1861.33	4.40	1.496×10^{-8}
207	4024.75	1861.52	4.34	1.518×10^{-8}

Table 8: Shockwave properties at varying temperatures for an air pocket volume 2.62 cm^3 at an initial pressure of 8 000 kPa

After Pressure up $T_{air\ 2}$ (^oC)	Shockwave $\frac{Watts}{m^3}$	Shock wave (dB)	Shock Wave TNT Equivalent (g)	Energy of Shock wave (MJ)	Shock wave Force (MN)	Shock wave Destructive Distance (m)	Time (s)
150	5.229×10^{6}	187.18	308.60	1.29	5.36	0.240	1.29×10^{-4}
165	5.322×10^{6}	187.26	316.87	1.32	5.45	0.243	1.30×10^{-4}
179	5.407×10^{6}	187.33	324.53	1.35	5.54	0.245	1.31×10^{-4}
193	5.491×10^{6}	187.39	332.13	1.38	5.63	0.246	1.32×10^{-4}
207	5.574×10^{6}	187.46	339.68	1.42	5.71	0.248	1.33×10^{-4}

Table 9: Shockwave energy, TNT equivalent and destructive force at varying temperatures for an air pocket volume 2.62 cm3 at an initial pressure of 8 000 kPa

A conversion to Imperial units/oil field units is needed to demonstrate the impact of an explosion to oilfield drill pipe burst pressures and strengths.

After Pressure up (°C)	Pressure Rise due to Explosion (kPa)	Pressure Rise due to Explosion (Psi)	Force (MN)	Force (lbs)
150	1.94×10^{5}	2.82×10^{4}	5.36	1.20×10^{6}
165	1.88×10^{5}	2.72×10^{4}	5.45	1.23×10^{6}
179	1.82×10^{5}	2.64×10^{4}	5.54	1.25×10^{6}
193	1.76×10^{5}	2.56×10^{4}	5.63	1.27×10^{5}
207	1.71×10^{5}	2.48×10^{4}	5.71	1.28×10^{5}

Table 10: Shockwave pressure and force in Imperial units at varying temperatures for an air pocket volume 2.62 cm^3 at an initial pressure of 8 000 kPa

Table 11 illustrate the properties of sample drill pipe that could be used in snubbing operations. The lowest explosion pressure rise (2.48×10^{4} psi) in Table 10 exceeds the highest burst pressure (1.55×10^{4} psi) in Table 11. Therefore when an explosion occurs the drill pipe most likely will rupture.

Tool Size	Weight per foot (ft·lb)	Burst Pressure (psi)	Maximum Tensile Strength (lbs)
2⅜	6.650	1.55×10^{4}	1.38×10^{5}
2 ⅞	10.400	1.65×10^{4}	2.14×10^{5}
3 ½	13.300	1.38×10^{4}	2.72×10^{5}
4	14.000	1.08×10^{4}	2.85×10^{5}
4 ½	16.600	9.83×10^{3}	3.31×10^{5}
5	19.500	9.50×10^{3}	3.96×10^{5}
5 ½	21.900	8.61×10^{3}	4.37×10^{5}
6 ⅝	25.200	6.54×10^{3}	4.89×10^{5}

Table 11: Properties of drill pipe (Grade E-75) sizes used in snubbing operations (VAM Drilling, 2007)

Lines, junctions and gauges coming from the snubbing unit typically have a burst pressure much lower than drill pipe, especially lines to gauges, and if they experience a pressure rise due to an explosion, they would rupture much easier and will cause significant damage to their surrounds.

Chapter 6: Result Summary: Explosions and Damage Potential of Shockwaves

This chapter will summarize how a possible explosion could occur during snubbing operations, the severity of such an explosion through its pressure rise and shockwave and its damage potential.

Explosions can occur mainly during snubbing operations in three difference cases.

Case 1: When uncontrolled gas or liquid vapours are brought to surface or escape to atmosphere. The main ignition source is external (static electricity, sparks from friction, heated surfaces). Location of fuel leaks could be due to:

- Snubbing plug failure
- Uncontrolled well flows due to snubbing tubing failing in compression or tension from pulling or pushing into a closed ram or slip
- Uncontrolled well flows out of the annulus due to deterioration of ram elements and seal elastomers due to the prolonged exposure to well fluids at elevated pressures.

These explosions and fires are external to the snubbers and surface equipment.

Case 2: When air contacts well gas or liquid vapours or other fuels at surface and sub-surface at a concentration that forms an explosive mixture with a traditional ignition source (sparks or friction) or rapid compression:

- On surface and subsurface when tubing is snubbed into the well and well fluids from the annulus is introduced into the tubing to equalize the pressure before removal of the snubbing plug
- Sub-surface in casing if the well is swabbed dry before it is perforated and the well fluid flows into the air-filled casing

These explosions and fires are internal to the wellbore and are due to an obvious oxygen supply being present.

Case 3: The focus of this study, when dead volumes of air in contact with immobile solid or liquid hydrocarbons under the right temperature conditions generate flammable vapour phase components from LTO reactions that most likely after rapid pressurization provide sufficient energy to cause ignition, that then leads to an explosion.

Trapped volumes of air can be found in equipment such as the snubbing primary BOPs and the lubricator when used. The volumes of air can be estimated as follows:

- Annular BOPs from 1.5 L to 7.1 L of potential trapped air
- Pipe, blind or shear rams from 0.3 L to 0.6 L of potential trapped air
- Lubricator greater than 0.150 L of potential trapped air
- In valves within the spools such as the casing bowl, working spool and equalization spool. Trapped pockets are stack size dependent and will be greater than 0.150 L
- In the lines, T- junction points and junction(s) for the pressure/measuring gauge reading valves. Trapped pockets of air are tubing depended on line size and typically greater than 0.150 L.

The pressure rise and shockwave from even a 0.150 mL air pocket (at atmospheric conditions) can be quite devastating. As Table 7, Table 8, Table 9 and Table 10 show, the pressure rise ratio from an explosion is from 21 to 24 times initial pressure. The pressure rise of this explosion will exceed the burst pressure of most tubing.

The temperature of the fluid rises to approximately 3957K to 4024K and the shockwave has a velocity is around 1861 m/s. The resulting shockwave has energy from 5.23 x 10^6 $\frac{Watts}{m^3}$ to 5.57 x 10^6 $\frac{Watts}{m^3}$ and produces a shockwave from 187.1dB to 187.4dB. This shockwave decibel reading is deadly and extremely damaging. A shockwave over 183 dB can cause total destruction of all objects within their range. Table 12 illustrates the damage potential of various explosion levels in terms of decibels.

dB	Significance
0	BEGINNING OF HEARING, A MOSQUITO 10 FEET AWAY
10	ABSOLUTE SILENCE IN A "QUIET ROOM"
15	A PIN DROP FROM A HIEGHT OF 1 CENTIMETER AT A DISTANCE OF 1 METER
35	ANECHOIC HEARING TEST ROOM
40	A WHISPER, A NORMAL CONVERSATION = 60 DB, NORMAL SOUND 70 DB
85	BEGINNING OF HEARING DAMAGE, EARPLUGS SHOULD BE WORN
100	NORMAL AVERAGE CAR OR HOUSE STEREO AT MAXIMUM VOLUME
107	THE BEGINNING OF PAIN AT THE MOST SENSITIVE FREQUENCY OF 2750 HERTZ
116	HUMAN BODY BEGINS TO PERCIEVE VIBRATION IN THE LOW FREQUENCIES
120	ONE PURE SOUND WATT FLOWING THROUGH 1 SQUARE METER, YOUR ELECTRIC AMP
127	HUMAN TINNITUS (RINGING IN THE EARS) BEGINS
133	GUNSHOT- EAR LEVEL, MAY VARY GREATLY TO SIZE AND TYPE OF GUN
135	LARGE TRAIN HORN
137	HUMAN BODY VIBRATION IS STRONG
140	HUMAN EAR ALL FREQUENCIES ARE PAINFUL EXTREMELY DAMAGING TO HEARING
141	HUMAN BODY BEGINS TO FEEL NASUEA AFTER A FEW MINUTES
142	HUMAN BODY CHEST POUNDING
147	FORMULA 1 RACE CAR, 700 HORSEPOWER
158	HUMAN BODY VIBRATION IS VIOLENT
163	GLASS WINDOWS ON BUILDING START TO BREAK
165	JET AIRPLANE, BOEING 727-15,000 LBS OF THRUST
180	DAMAGE TO STRUCTURES IS CATASTROPHIC WHEN WITHIN SHOCKWAVE RANGE
180-200	HUMAN DEATH FROM SHOCKWAVE WITHIN SHOCKWAVE RANGE
183	TOTAL DESTRUCTION OF ALL STRUCTURES WITHIN SHOCKWAVE RANGE
190	RICHTER SCALE 0 (ZERO) EARTHQUAKE
200	63.24 POUNDS OF T.N.T., RICHTER SCALE 1.0
210	EARTHQUAKE RICHTER SCALE 2.0
210	1 TON OF T.N.T. AND A 23.40 FOOT CRATER
215	SPACE SHUTTLE LAUNCH EXHAUST, APPROXIMATELY 3 MILES PER SECOND
215	BATTLESHIP NEW JERSEY FIRING ALL 9 SIXTEEN INCH GUNS
220	SATURN 5 ROCKETSHIP, MELTS CONCRETE AND BURNS GRASS ONE MILE AWAY
229	SEAFLOOR VOLCANIC ERUPTION
230	EARTHQUAKE RICHTER 4.0
235	EARTHQUAKE RICHTER 5.0
286	MT. SAINT HELENS VOLCANO ERUPTION
320	TAMBORA INDONESIA VOLCANO ERUPTION IN1815, EJECTED OBJECTS STRAIGHT IN THE AIR APPROX 36 MILES

Table 12: Decibel equivalence table (Hamby, 2004; Kinney, 1985)

The explosive shockwave has a full force blast zone radius from 0.24 m to 0.248 m from the source. In this range nearly all structures are completely destroyed. The explosive shockwave also occurs exceptionally fast typically reaching its full force destruction blast zone radius in 1.29 x 10^{-4} s to 1.33 x 10^{-4} s or in less than 0.129 ms to 0.133 ms.

The explosion produces an equivalent shockwave of between 308.6 to 339.6 g of TNT. To give a general perspective, 250 g of TNT is approximately the amount of explosives in a MK 3 US concussion grenade. This hand thrown type of grenade produces a large blast, with high destructive power, limited to a short range.

The resulting force of the shockwave is around 5.35 MN to 5.71 MN. Therefore the damage from a small air pocket of 150 mL (atmospheric pressure) and initial temperature of 30 ^{o}C to 70 ^{o}C after pressurization to 2.62 cm^3 at 8 000 kPa will destroy and be fatal for any equipment or personnel within the blast zone radius.

Typically in snubbing operations, as shown earlier in this chapter, pockets of trapped air can accumulate in most surface snubbing equipment from a volume of 0.150 L to 7.0 L.

In general, the greater the trapped air volume the greater the likelihood of an explosion occurring.

Chapter 7: Conclusions and Recommendations

The deliverable of this study was to get a better understanding of snubbing operations and investigate a possible explosion mechanism not generally recognized in the literature; explosions through the ignition of flammable vapour phase components initiated by LTO reactions especially during/after rapid pressurization. This study also identified areas of potentially trapped pockets of air and hydrocarbon mixtures in snubbing operations where such explosions could occur and demonstrated the severity and damage potential of such an explosion's resulting shockwave.

The conclusion summary has been presented in Section 7.1 and the recommendations are contained in Section 7.2

7.1 Conclusions

1. Snubbing is generally a safe oil and gas operation that involves multiple steps of pressurizing and de-pressurizing between well and atmospheric pressure. These procedures especially during staging large OD pipes or collars can lead to pockets of trapped air.
2. A trapped pocket of air on a hot summer day (approximate outside ambient temperature 25 ^oC to 30^oC) after rapid pressurization by the well fluid during low pressure snubbing operations can reach temperatures of 150 ^oC to 180 ^oC. This trapped pocket of air in contact with an immobile hydrocarbon (hydraulic oil, crude oil, light condensate or other hydrocarbons) can through LTO reactions provide sufficient energy for ignition which subsequently can initiate an explosion on surface snubbing equipment.

3. Trapped pockets of air can accumulate in most surface snubbing equipment. The amount of trapped air can range from 0. 150 L to 7.0 L. The area's most prone are:
    a. Snubbing annular BOP if the seals or elastomers wear or fail
    b. Snubbing pipe/ram or shear BOPs behind the pistons
    c. Lubricator in areas where the chamber is pressurized and exposed to petroleum grease
    d. Within the spools, junctions, lines, especially lines which are dead headed and not purged like lines to pressure / measurement gauges
4. An LTO initiated explosion from a small trapped pocket of air, in contact with an immobile hydrocarbon, can cause an explosion which results in significant damage. A small trapped air pocket initially at 0.150 L (atmospheric conditions) when pressured to 8 000 kPa (a typical occurrence for low pressure snubbing operations) becomes compressed to a volume of 2.62 cm^3 (0.00262L) and has the potential to create:
    a. An explosive pressure rise of 21 to 24 times initial pressure that will exceed the burst pressure for tubing used in snubbing operations
    b. An instantaneous increase in the temperature of the air / product gas to between 3957K to 4024K
    c. A shockwave around 1861 m/s or a Mach number of around 4.6
    d. A shockwave energy from 5.23 x 10^6 $\frac{Watts}{m^3}$ to 5.57 x 10^6 $\frac{Watts}{m^3}$ which gives a shockwave dB between 187.1dB to 187.4 dB respectively.
    e. A shockwave force in the range of 5.35 MN to 5.71 MN.

f. A shockwave that has a TNT mass equivalent of between 308 g to 339 g of TNT with a blast zone distance of approximately 0.25m from the source.

g. A shockwave that occurs in less than from 1.29 x 10^{-4} s to 1.33 x 10^{-4} s (0.129 to 0.133 ms.) and has the damage potential equivalent close to that of a MK 3 US concussion grenade

Therefore the damage potential from a small trapped air pocket, of 0.150 L under atmospheric conditions in contact with an immobile hydrocarbon, which is then pressurized to 8 000 kPa, will be catastrophic for any equipment and fatal for any personnel within the blast zone radius.

Snubbing operations can have trapped pockets of air from 0. 150 L to 7.0 L. This study shows the damage potential of a small air pocket of 0.150 L at atmospheric conditions. The greater the trapped air accumulation the greater the likelihood and occurrence of a devastating explosion.

It is hoped the results of the study provides snubbing operators with an appreciation of the potential of trapped pockets of air during operations and its destructive potential due to explosions, which could cause serious injury to humans, wildlife, surrounding equipment, infrastructure and the environment, even in low volume amounts during low pressure snubbing operations.

7.2 Recommendations

The results of this study have identified the potential source and size of trapped air pockets and provided an estimate of the potentially destructive pressure rise and impact of shockwaves during an explosion. However, future work is necessary to investigate the explosion mechanism described and more specific equations are needed to determine the explosion energy released in snubbing operations.

Prior to snubbing operations, potential areas of trapped pockets of air should be identified, and procedures for purging or additional purge piping should be designed to directly sweep the lines with well gas. To ensure added safety it is recommended that all tubing and equipment should also be purged with an inert or non-combustible gas, such as Nitrogen especially in low pressure snubbing, pre and post operation.

Future snubbing rig designs should include improved designs to minimize volumes in lines, junctions points and anywhere air can be trapped. For example, bleed lines should also be placed as close to the base of the snubbing annular as possible.

Lines, junction points especially T- junction points and pressure and measuring gauges should be rated for the right well conditions for the operations and routinely checked to ensure integrity. If a trapped pocket of air is suspected in a pressure and measuring devices as evident by an unreasonably off pressure reading, it is imperative that the line should be purged thoroughly and in some case this will also mean that the hydraulic fluids contained within the gauge, be changed out as well.

BOPs need to be thoroughly checked frequently especially the annular BOPs seals and the pipe/ram and shear blades for integrity to ensure no wear has occurred that may allow well fluids or air into the well control devices.

Proper cleaning of snubbing equipment is essential to prevent the accumulation of greases and degraded hydrocarbon solids.

During operations it is recommended to avoid using well work-over fluids that have been used before in operations or have been oxidized in surface tanks. Also work-over fluids should be chosen with the least manufactured oxygen containing components.

Additionally, operators need to be aware that in some cases during operations when the snubbing unit and the surface equipment becomes flooded with well liquids and when these liquids are then drained to surface tanks, during this process there is a possibility that a vacuum could be created in the snubbing unit and/or surface equipment, which would result in some liquids coming back in and being trapped.

Finally, it is recommended that during field operations that any pressurizations is done in a controlled fashion (avoid rapid pressurization) so as to limit the possibility of sudden temperature rises resulting from rapid filling of the surface equipment with gas from the well.

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APPENDIX A

SNUBBING UNIT

STAND ALONE SNUBBING UNIT

150K/150K Quick Rig

150K

- Lift Capacity – 150,000 lbs
- Snub Capacity – 66,000 lbs
- 10 ft Stroke
- Stand Alone
- Unit Thru Bore – 7 1/16"
- Rotary Torque 1,500 ft /lbs
- Rotary RPM – 90
- 20,000 psi Surface Pressure Capacity
- Work Window 6' or 10' with Work Basket
- HD Tong Pole
- Hydraulic Gin Pole 45'
- Land or Offshore Operations
- Quick Rig Version Available

The ISS 150k and 150k Quick rig stand alone snubbing units are designed and custom built to perform live or dead well operations on or offshore. The quick rig model which is land based is truck mounted and offers the customer an extremely quick rig up time for a fully equipped stand alone snubbing unit. These units are perfectly designed to work on: long horizontal wells, highly deviated wells where coil tubing is limited due to push or friction issues, through tubing work, and velocity strings predominately seen throughout the US Shale.

ISS

A SUPERIOR ENERGY SERVICES COMPANY

Source: International Snubbing Services, 2011

RIG ASSIST SNUBBING UNIT

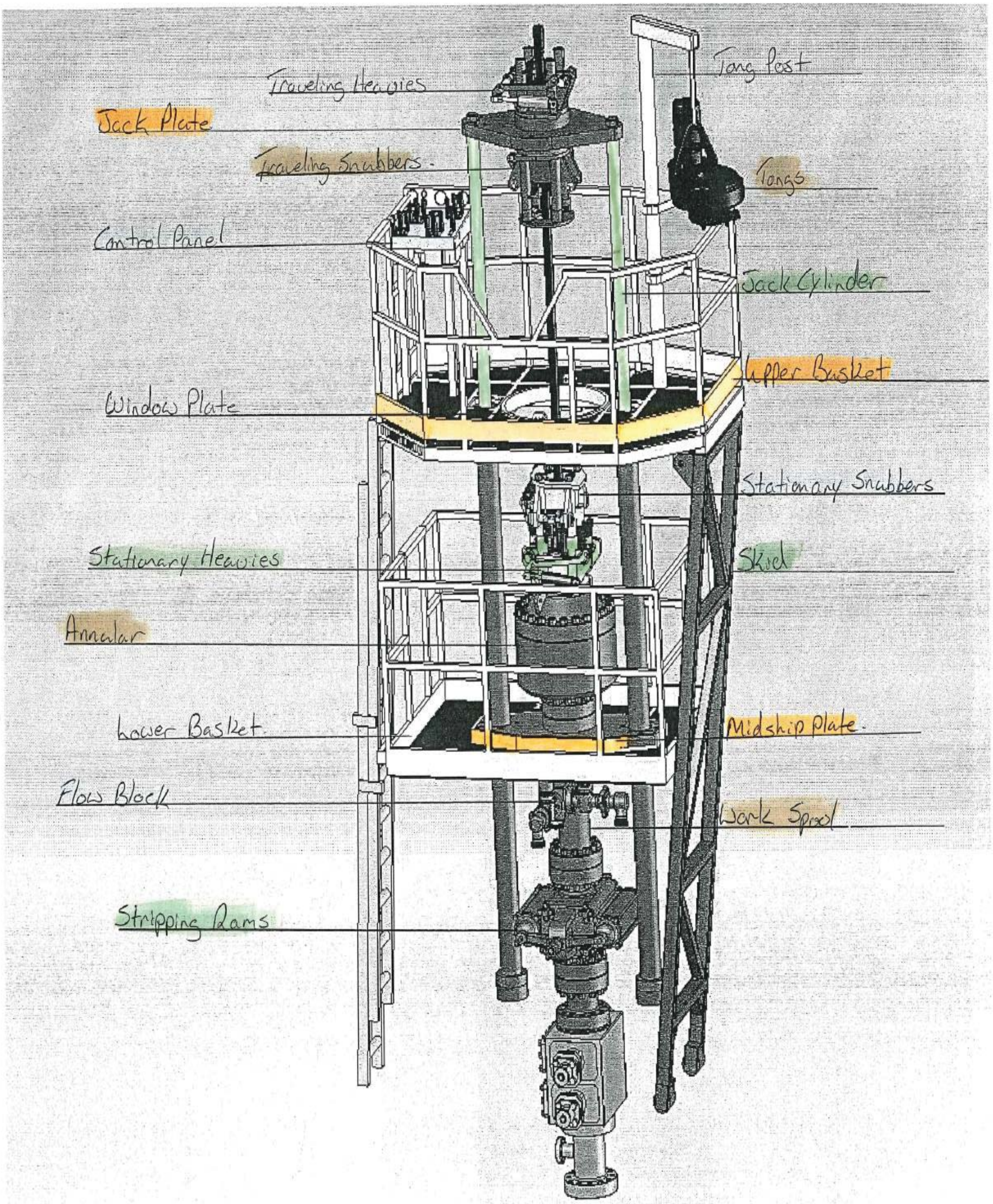
95K Rig Assist Unit

95K
Lift Capacity – 95,000 lbs
Snub Capacity – 46,000 lbs
8 ft Stroke
Rig Assist Unit/Space Saver
3 Man Crew
7¹⁄₁₆" 5M or 10M Stack

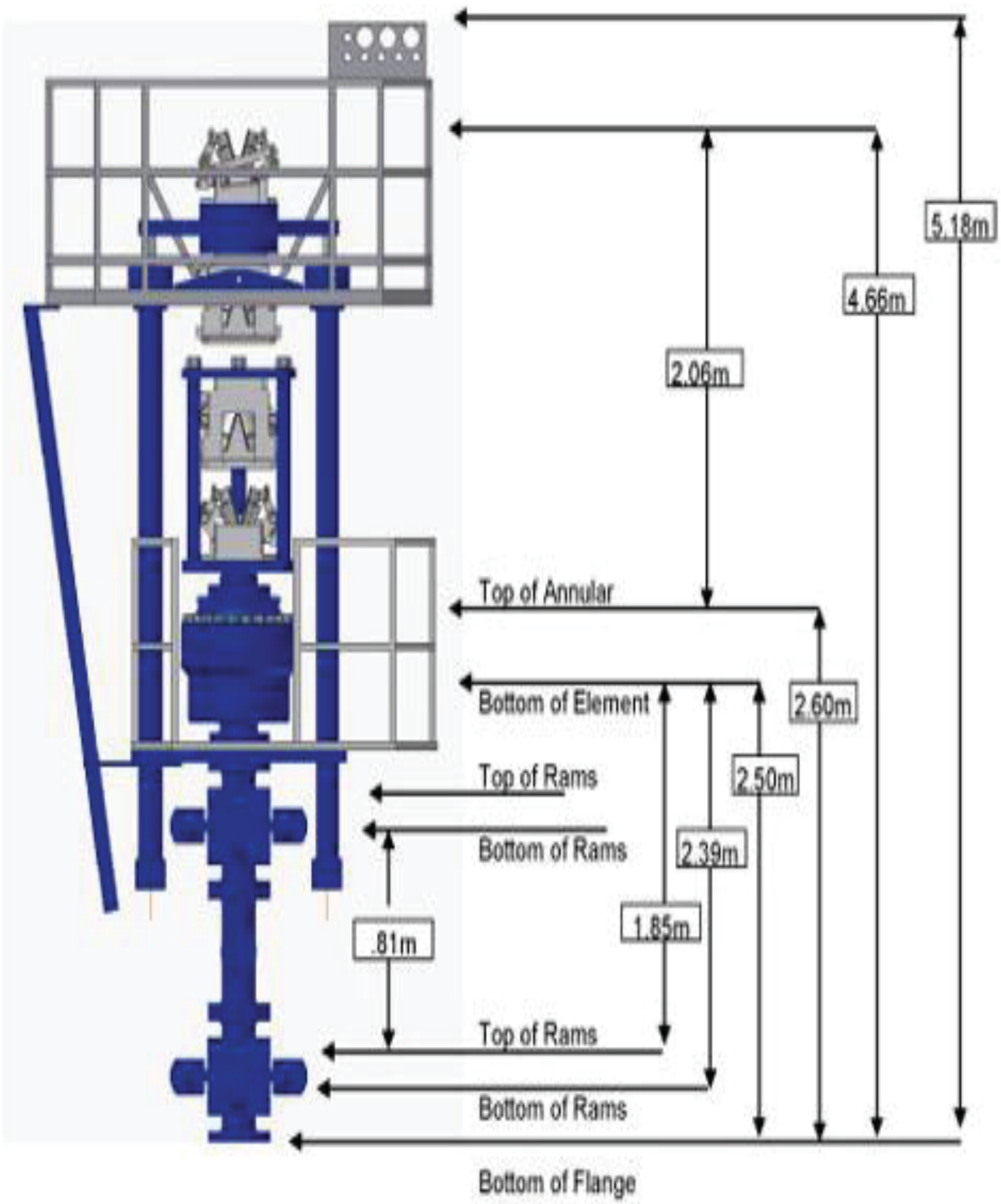
The 95k Rig Assist Unit was designed to provide land based conventional workover and drilling rigs the ability to snub pipe into the well until the pipe weight overcomes the wellbore pressure. When the pipe is considered heavy, the drilling or workover rig then takes over running tubing.

ISS
A SUPERIOR ENERGY SERVICES COMPANY

Source: International Snubbing Services, 2011

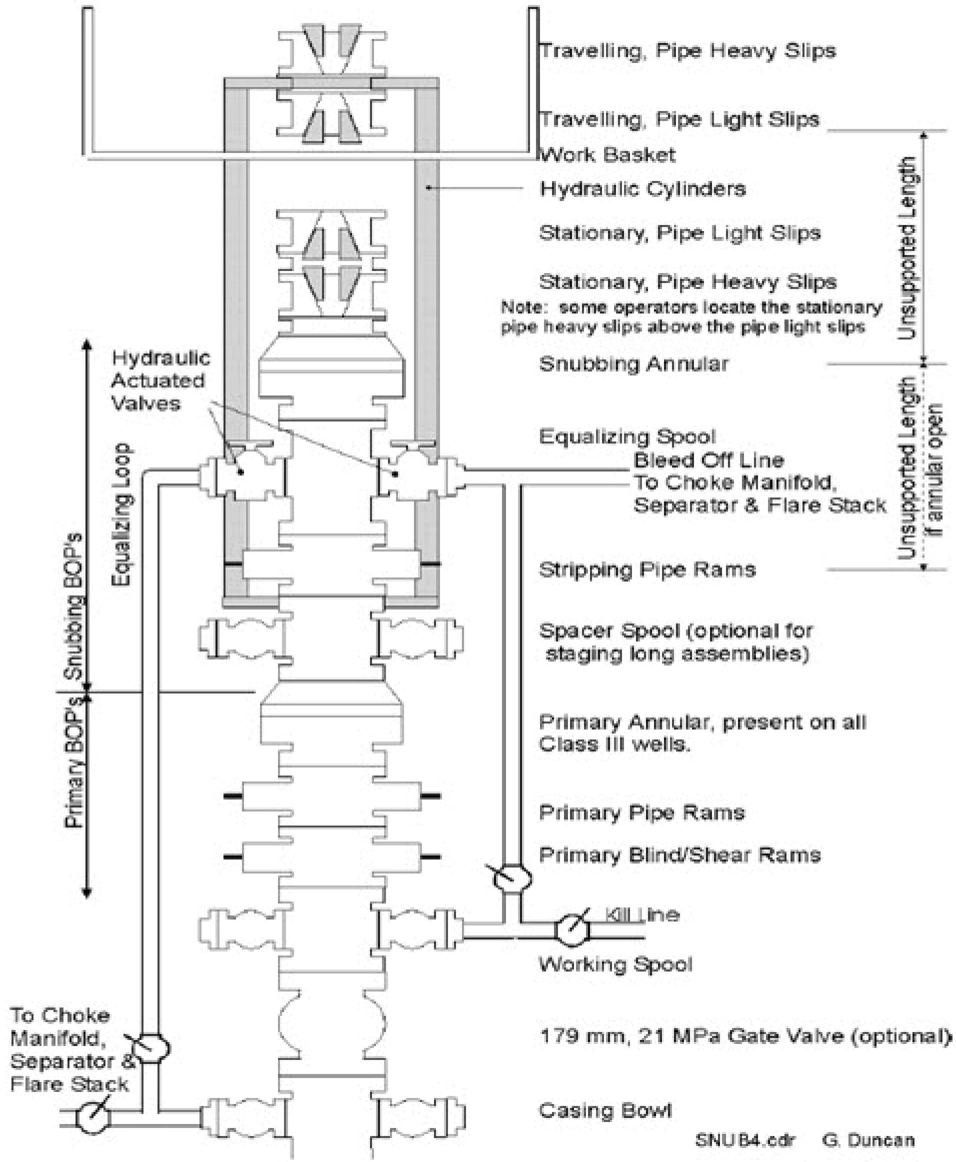


Source: Huntly, 2007: Private Conversation



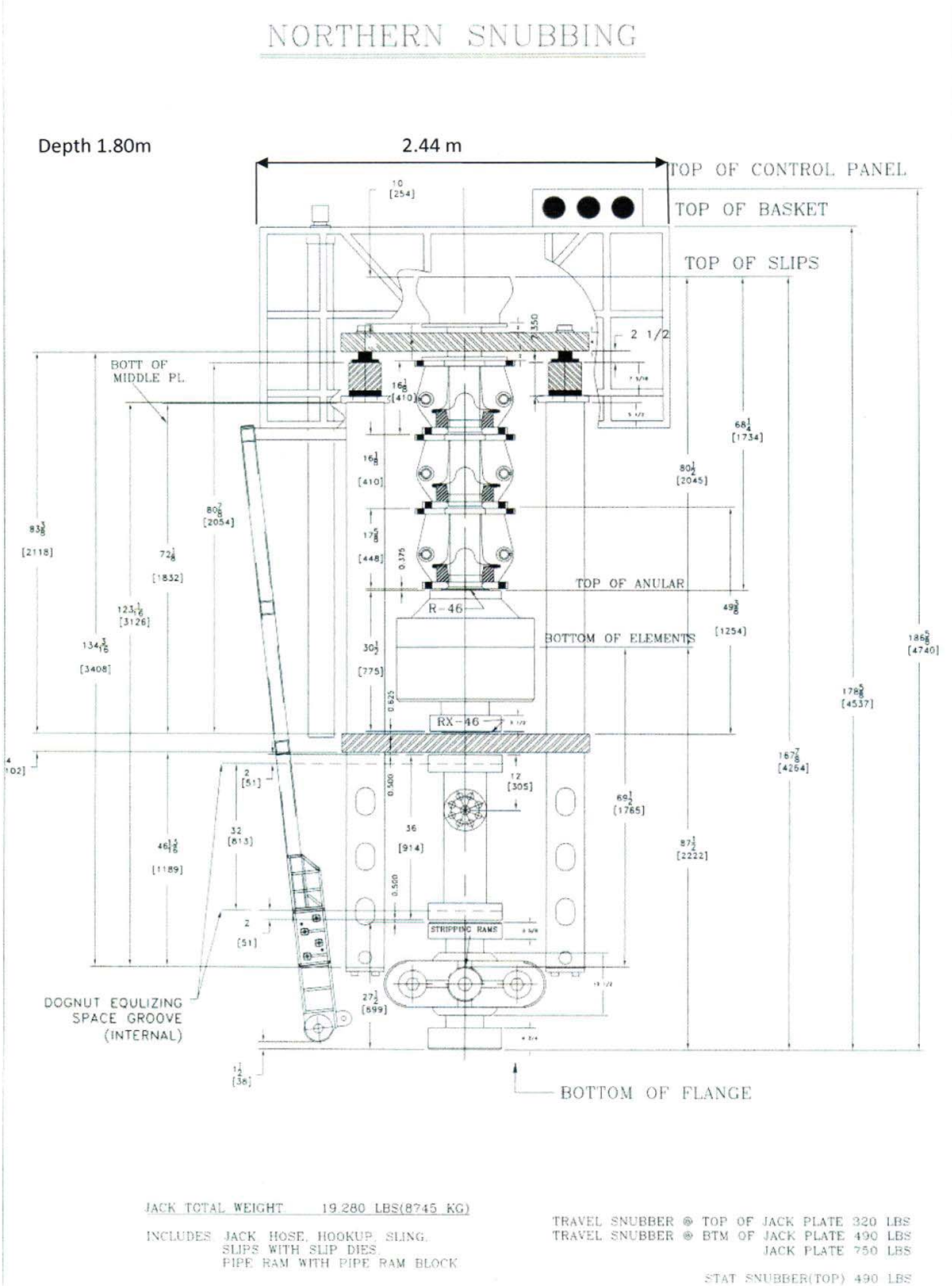
Source: Northern Snubbing Inc. (Ebert, S., 2011)

Low Pressure Annular to Ram Snubbing BOP Arrangement



These calculations have been provided by Petro-Canada as a reference only. Reliance on this material alone to the exclusion of other professional advice, experience or resources is imprudent since each situation is unique.

Source: DACC and ENFORM, 2007: Duncan, 2008



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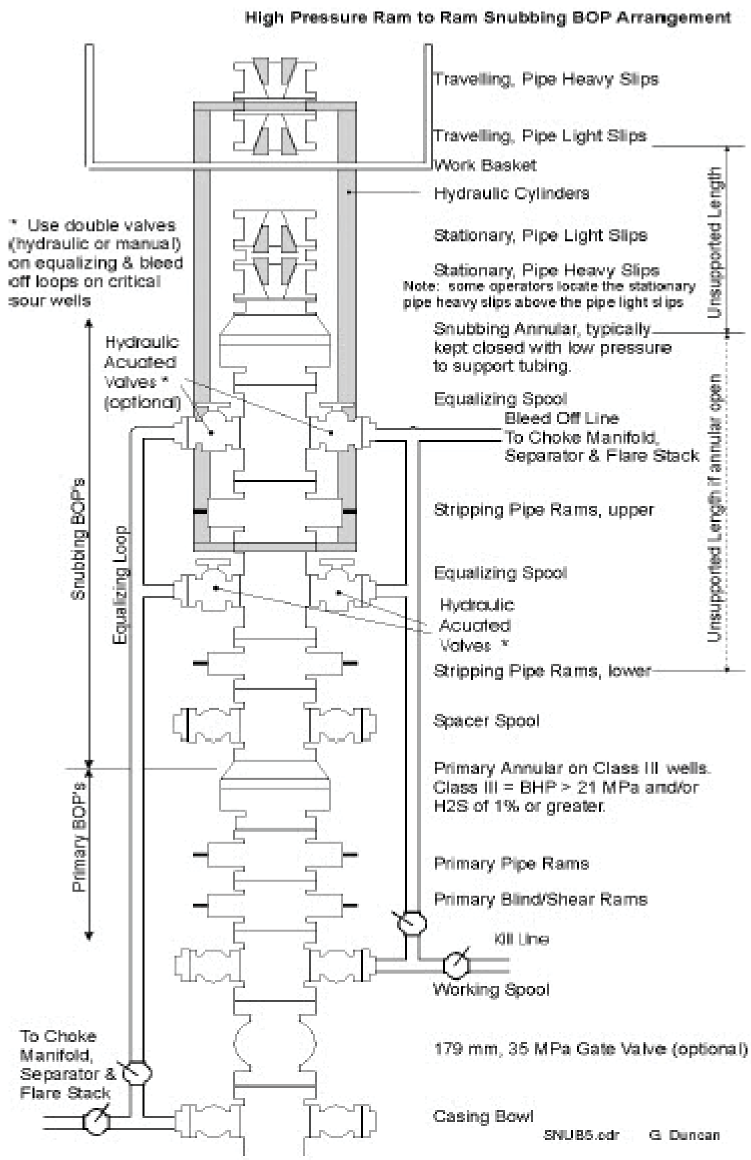

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Source: DACC and ENFORM, 2007: Duncan, 2008

Snubbing Unit Capabilities Onshore

HWO Snubbing Unit Capabilities*

Unit Nominal Capacity	Unit Type	Bore Size Inches	Pipe Range Inches	Stroke Feet	Lifting Capacity Pounds	Snubbing Capacity Pounds	Rotary Torque ft/lb
120K	Stand Alone / QR	4-1/16	1 – 2-7/8	10	117,000	60,000	2,235
120K	Rig Assist	11-1/8	1 – 9-5/8	10	117,000	60,000	N/A
150K	Stand Alone / QR	8	1 – 2-7/8	10	150,000	66,000	2,800
170K	Rig Assist	7-1/16	1 – 5-1/2	10	169,000	95,000	N/A
200K	Stand Alone / QR	7-1/16	1 – 5-1/2	10	199,000	103,000	3,400 - 4,800
200K	Stand Alone	11-1/8	1 – 9-5/8	10	199,000	103,000	4,800
225K	Stand Alone	11-1/8	1 – 5-1/2	10	225,000	120,000	5,000
235K	Stand Alone	11-1/8	1 – 9-5/8	11	235,000	117,500	7,500
300K	Stand Alone	11-1/8	1 – 9-5/8	10	300,000	150,000	12,000
340K	Stand Alone	11-1/8	1 – 7-5/8	10	340,000	188,000	6,600
400K	Stand Alone	11-1/8	1 – 9-5/8	12	381,000	182,000	6,400 - 10,500
460K	Stand Alone	11-1/8	1 – 8-5/8	10	460,000	220,000	6,600 - 12,000
600K	Stand Alone	15	1 – 8-5/8	14	600,000	260,000	6,600 - 12,000
600K	Stand Alone	11-1/8	1 – 9-5/8	10	580,000	288,000	10,500 - 20,000
600K	MDU - Drilling	30	1 – 30	56	600,000	NA	28,300

*List is not all inclusive of available HWO units

Source: Boots & Coots 2011

APPENDIX B

SNUBBING CALCULATIONS

SOURCE: DACC AND ENFORM, 2007

Chart 15: Tubing OD 33.4 mm Grade J-55 Tubing Wt. 2.56 Kg/m Connection IJ

Tubing OD	**33.40** mm	Tubing weight	**2.56** kg/m
Grade	**J-55**	Connection	**IJ**

Pipe Buckling Calculations

	INPUT		
Pipe OD	OD	**33.40**	mm
Pipe ID	ID	**26.64**	mm
Cplg OD	CplgOD	**39.40**	mm
Pipe yield stress	Sy	**379**	MPa
Modulus Elasticity	E	**200**	GPa
	CALCULATED		
Area, pipe OD	Ao	876	mm^2
Area, pipe ID	Ai	557	mm^2
Area, steel	As	319	mm^2
Moment of Inertia	I	36346	mm^4
Radius of Gyration	RG	10.68	mm
Critical Slenderness Ratio	SRc	102.0	
Cplg x-sect area	Acplg	1222	mm^2
	EQUATIONS		
Area, pipe OD	Ao	=3.14*(OD^2)/4	
Area, pipe ID	Ai	= 3.14*(ID^2)/4	
Area, steel	As	=Ao-Ai	
Moment of Inertia	I	=3.14*(OD^4-ID^4)/64	
Radius of Gyration	RG	=(I/As)^.5	
Crit.slenderness ratio	SRc	=3.14*(2*E/Sy)^.5	
Slenderness ratio	SR	=L/r	
Local Buckle (Johnson's Eqn, short column)	Flb	=Sy*As*(1-(L/RG)^2/(2*(SRc)^2))	
Major Axis Buckle (Euler Eqn, long column, pinned ends)	Feb	=(3.14)^2*E*I/(L)^2	
Buckling Load	Fb	=IF(SR>SRc,Feb,Flb)	

Snubbing Force vs Wellbore Pressure

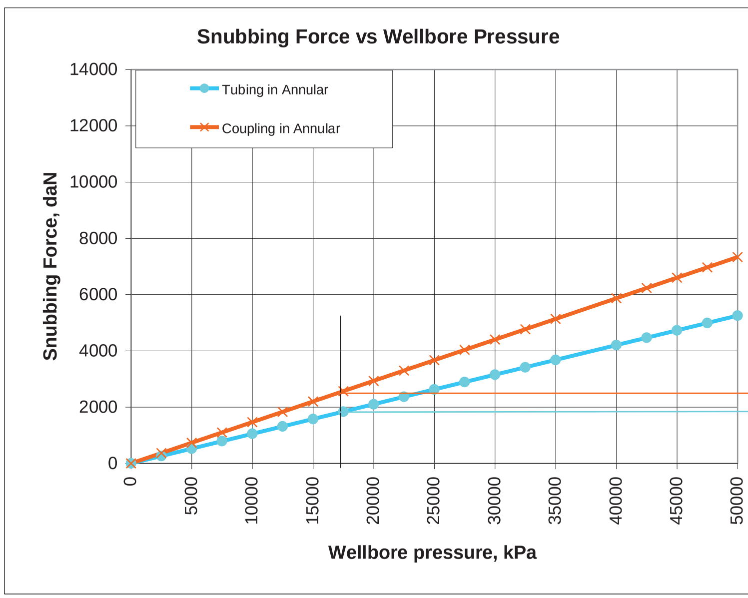
Wellbore Pressure kPa	Snubbing Force: Tubing in Annular, daN	Snubbing Force: Coupling in Annular, daN	Transition to pipe heavy, m.	Length at which cplg. neutral, m.
0	0	0	0.0	0.0
2500	263	367	104.6	146.0
5000	525	733	209.2	292.1
7500	788	1100	313.8	438.1
10000	1051	1467	418.4	584.1
12500	1314	1834	523.1	730.2
15000	1576	2200	627.7	876.2
17500	1839	2567	732.3	1022.2
20000	2102	2934	836.9	1168.3
22500	2364	3301	941.5	1314.3
25000	2627	3667	1046.1	1460.3
27500	2890	4034	1150.7	1606.4
30000	3153	4401	1255.3	1752.4
32500	3415	4768	1359.9	1898.4
35000	3678	5134	1464.5	2044.5
40000	4203	5868	1673.8	2336.6
42500	4466	6235	1778.4	2482.6
45000	4729	6601	1883.0	2628.6
47500	4992	6968	1987.6	2774.7
50000	5254	7335	2092.2	2920.7

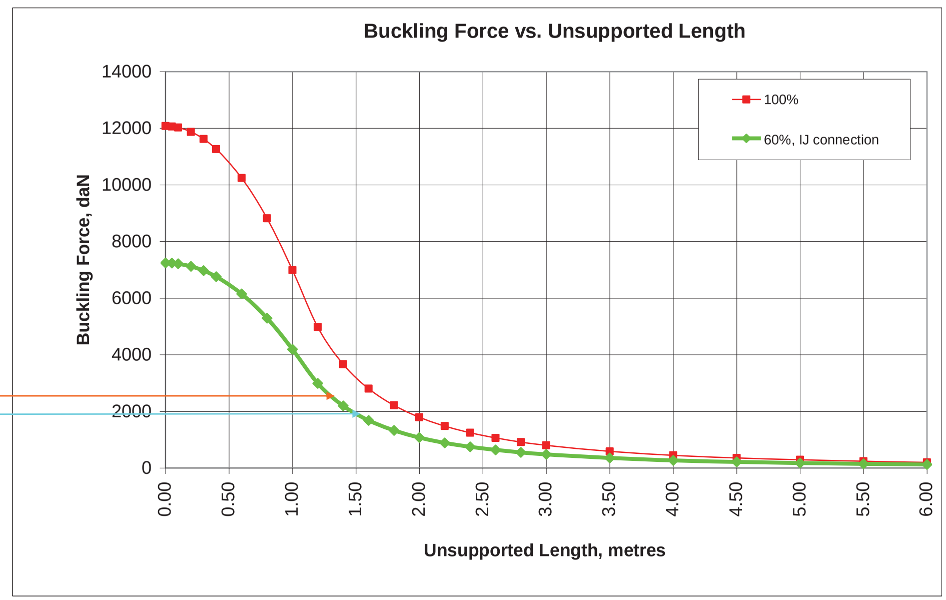
Note: Above snubbing forces include 20% for friction through the annular BOP
Fwp = WP (kPa) * X-area (mm^2) / 10000
Fsnub = Fwp + Ffric = 1.2 x Fwp
units: decaNewtons

Above calculations assume annulus gas has a specific gravity = 1.0 (air sg = 1.0)

Buckling Force as a Function of Unsupported Length

Unsupported Length (mm)	Unsupported Length (metres)	Slenderness Ratio	Buckling Force, daN 100%	Buckling Force, daN IJ 60%
0	0.00	0.00	12075	**7245**
50	0.05	4.68	12063	**7238**
100	0.10	9.36	12024	**7215**
200	0.20	18.73	11872	**7123**
300	0.30	28.09	11618	**6971**
400	0.40	37.45	11261	**6757**
600	0.60	56.18	10244	**6147**
800	0.80	74.90	8820	**5292**
1000	1.00	93.63	6989	**4193**
1200	1.20	112.35	4977	**2986**
1400	1.40	131.08	3657	**2194**
1600	1.60	149.80	2800	**1680**
1800	1.80	168.53	2212	**1327**
2000	2.00	187.25	1792	**1075**
2200	2.20	205.98	1481	**888**
2400	2.40	224.70	1244	**747**
2600	2.60	243.43	1060	**636**
2800	2.80	262.15	914	**549**
3000	3.00	280.88	796	**478**
3500	3.50	327.69	585	**351**
4000	4.00	374.51	448	**269**
4500	4.50	421.32	354	**212**
5000	5.00	468.13	287	**172**
5500	5.50	514.95	237	**142**
6000	6.00	561.76	199	**119**





Example:	Wellbore pressure = 17,500 kPa	Tubing snubbing force =	1839 daN	Allowable unsupported length with tubing in annular BOP	1.5 metres
		Coupling snubbing force =	2567 daN	Allowable unsupported length, coupling in annular BOP	1.3 metres

These calculations have been provided by Petro-Canada as a reference only. Reliance on this material alone to the exclusion of other professional advice, experience or resources is imprudent since each situation is unique.

APPENDIX C

BOP EQUIPMENT

SOURCE: US PATENT OFFICE

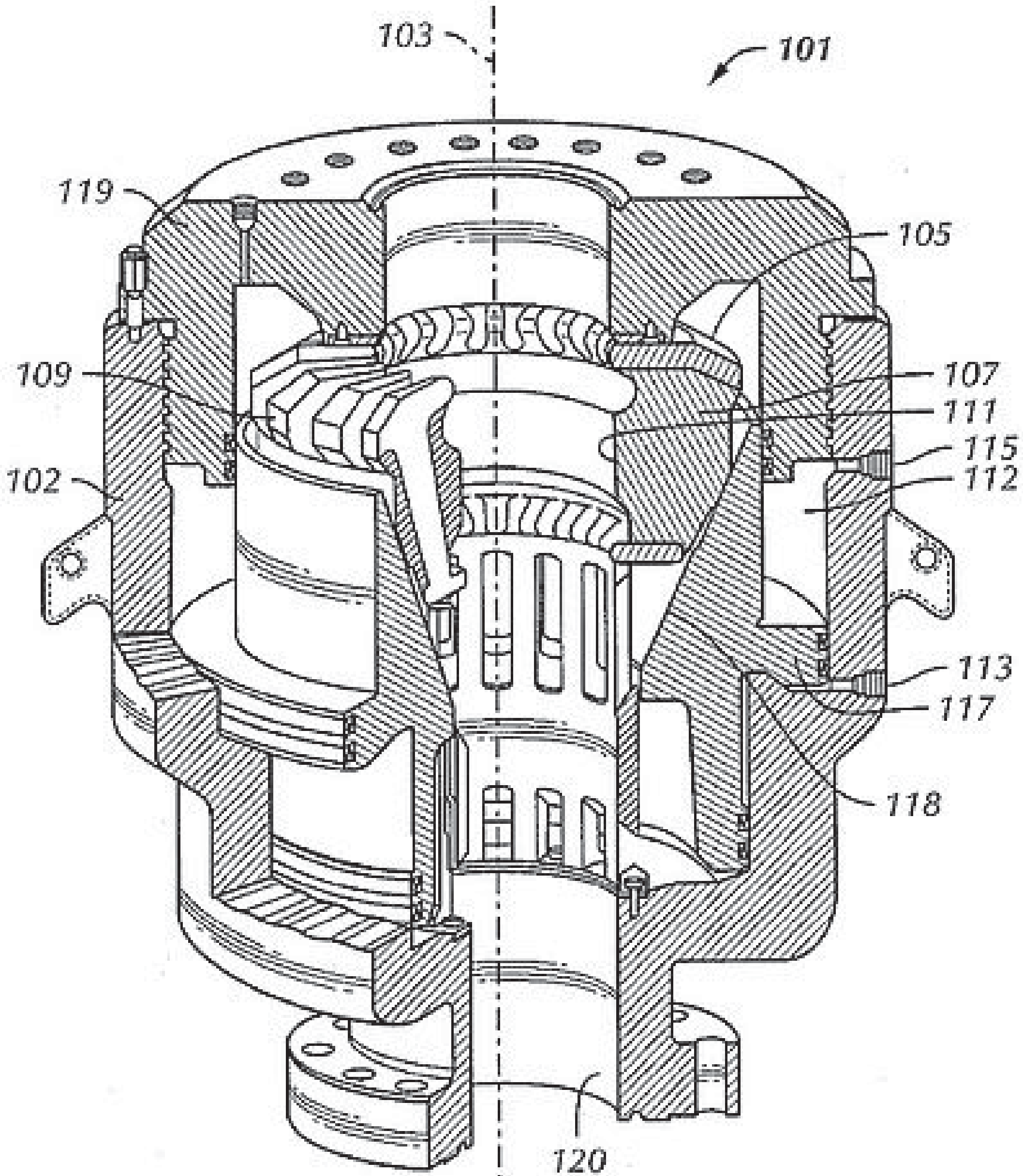


FIG. 1

101 Annular Blowout Preventer
102 Housing (Body)
103 Wellbore
105 Packing Unit
107 Elastomeric Annular Body
109 Metal Inserts
111 Packing Unit Bore
112 Piston Chamber
113 Extend Port
115 Retract Port
117 Piston
118 Wedge Face
119 Removable Head
120 Blowout Preventer Bore

Fig. 1

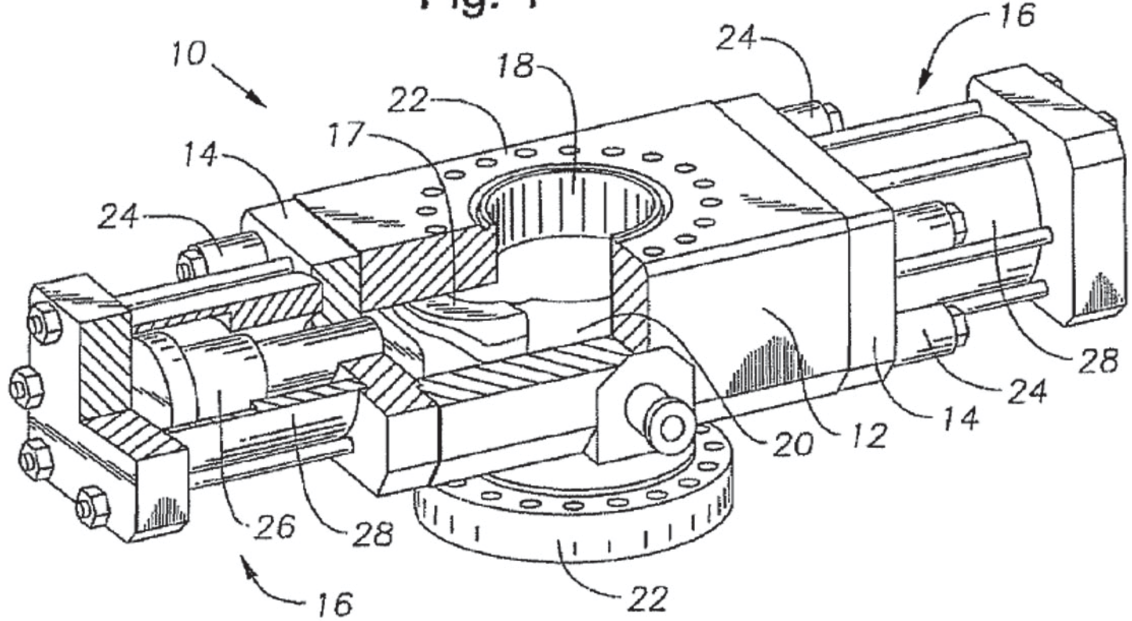
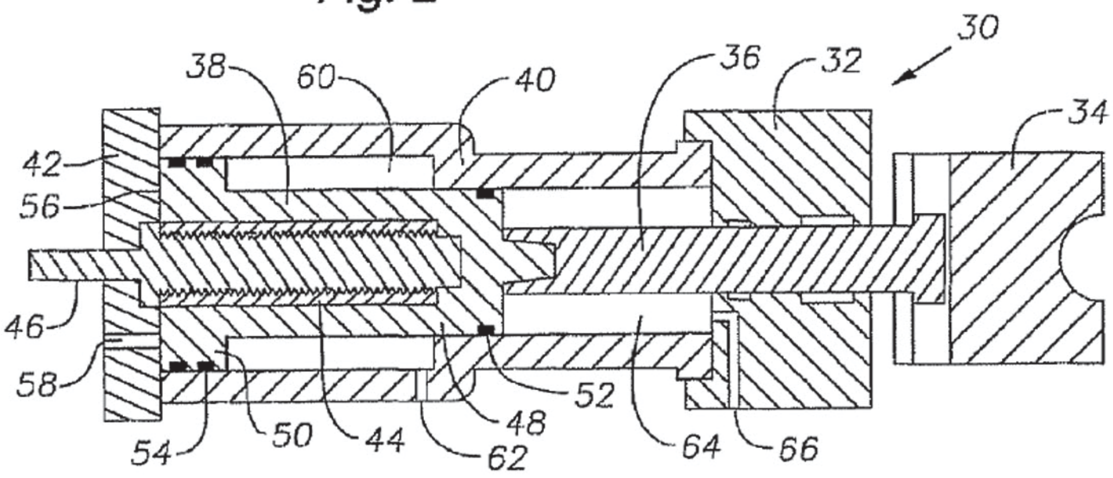


Fig. 2



10 Blowout Preventer (BOP)
12 Housing (BOP Body)
14 Bonnet
16 Actuator Assembly (Operator System)
17 Ram (Closure Member / Ram Block)
18 Well Bore (Bore)
20 Ram Guide Chamber (Ram Cavity)
22 Bolted Connection
24 Bonnet Connectors
26 Piston
28 Cylinder (Operator Housing)
30 Actuator Assembly (Operator System)
32 Bonnet
34 Ram (Closure Member / Ram Block)
36 Ram Shaft (Piston Rod)
38 Piston
40 Cylinder (Operator Housing)
42 Head
44 Sliding Sleeve
46 Lock Rod
48 Piston Body
50 Piston Flange
52 Piston Body Seal
54 Piston Flange Seal
56 Extend Chamber
58 Extend Port
60 Slack Fluid Chamber
62 Slack Fluid Port
64 Retract Chamber
66 Retract Port

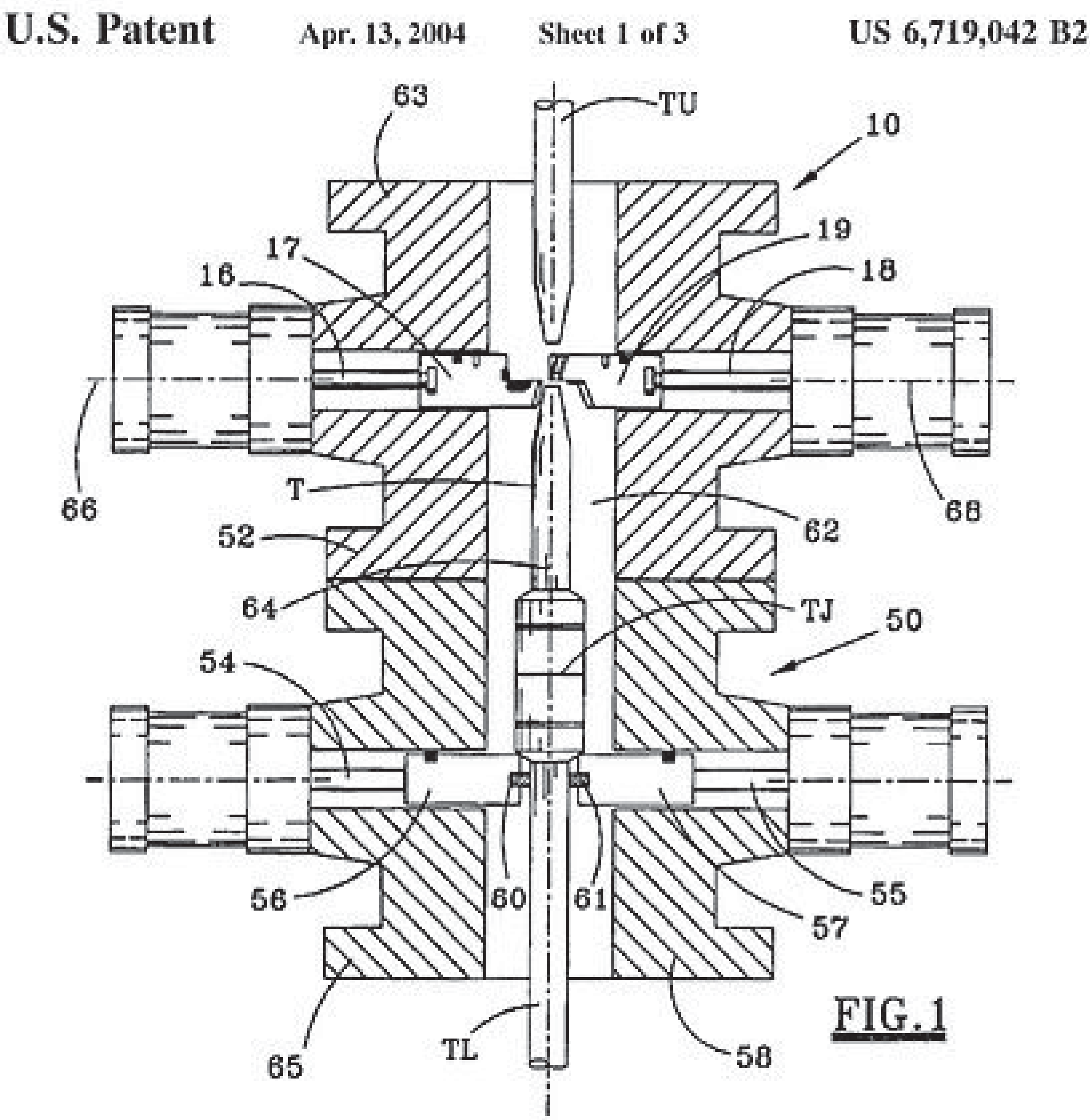


FIG.1

10 Shear Ram Preventer	55 Pipe Ram Shaft	64 Wellbore Axis
16 Shear Ram Shaft	56 Pipe Ram (Ram Block)	65 Lower Flange
17 Lower Blade Shear Ram	57 Pipe Ram (Ram Block)	66 Ram Axis
18 Shear Ram Shaft	58 Housing (Body)	68 Ram Axis
19 Upper Blade Shear Ram	60 Packer (Ram Seal)	T Tubular
50 Pipe Ram Preventer	61 Packer (Ram Seal)	TJ Tool Joint
52 Housing (Body)	62 Wellbore	TL Lower Tubular
54 Pipe Ram Shaft	63 Upper Flange	TU Upper Tubular

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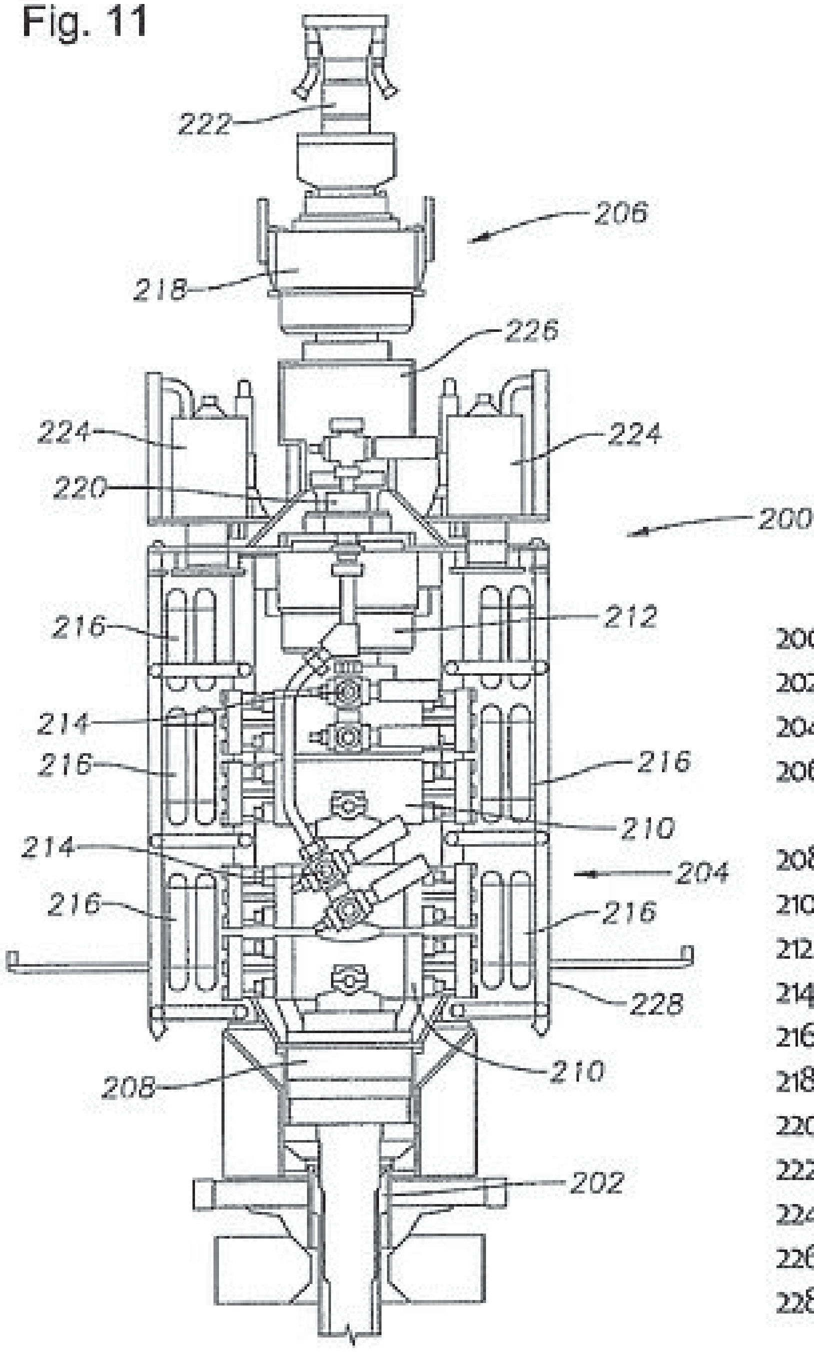
Fig. 11



200 Blowout Preventer Stack
202 Wellhead
204 Lower Stack Assembly
206 Upper Stack Assembly
(Lower Marine Riser Package)
208 Wellhead Connector
210 Ram Blowout Preventers
212 Annular Blowout Preventer
214 Choke and Kill Valves
216 Hydraulic Accumulators
218 Annular Blowout Preventer
220 Choke and Kill Connectors
222 Riser Adapter (Flex Joint)
224 Control Pods
226 Collet Connector
228 Frame