ASSESSMENT OF SUSTAINED CASING PRESSURE ON WELL INTEGRITY

by

Darren Wong Vun Nyap

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Petroleum Engineering)

MAY 2012

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CERTIFICATION OF APPROVAL

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A Project dissertation submitted to the
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BACHELOR OF ENGINEERING (Hons)
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Approved by,

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Project Supervisor

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May 2012

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

DARREN WONG VUN NYAP

ABSTRACT

Sustained casing pressure (SCP) is commonly known as one of the well integrity problems in oil and gas industry. In fact, the term of ‘annular pressure’ implies a similar definition to SCP (Attard, 1991) if the annular pressure is unmanageable or leaking in well components. The leaking problem can be due to tubing/casing leak, poor primary cementing job and interuption to cement integrity due to the pressure and temperature changes when the well starts to produce hydrocarbon. Hence, there is a necessity to manage SCP effectively in order to ensure the integrity of well. This project is based on modeling approach, where the objective is develop a series of computer codes with the reference of existing pressure bleed-off time Mathematical model. The results generated from the model is based on effect of temperature, type of gases filled in annulus and depth of well. These 3 type of parameters can affect the pressure bleed-off time in annulus itself, provided the condition where the size of needle valve is fixed. From the model generated in Wolfram Mathematica 8.0, it is able to notify engineer to receive any early sign of warning if the well is suspected a leakage. Meanwhile, based on the matching process of field data and modeled data, engineers will be able to aware and determine whether the occurence of annular pressure is due to thermal induced annular pressure buildup or it is because of the leakage in well components. Finally, this model is economic and able to save cost until the well is needed for any further confirmation. In addition, the project also studied the effect of SCP on the well integrity. With this, the well will eventually loss in production, severe failure in well’s integrity or consider the worst case scenario, the excessive of SCP may cause an underground blowout at subsurface. Currently, the report was referred 18 documents as references in this research topic.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Saeby J. (2011) defines Sustained Casing Pressure (SCP) as an excessive casing pressure in the wells persistently rebuild after bleed-down procedure was conducted. According to *Well Risk Management Guideline* from PETRONAS Carigali Sdn Bhd, it states that SCP is the pressure which results from the well component leak (tubing leak, packer leak or casing leak) that allows the flow of fluid across the well control barrier, the uncemented formations or damaged cement after setting. Furthermore, R. Xu (2002) explained during primary cementing, gas in the formation invade cement while the cement is in hardening stage, thus created a flow channel in cement and allowed gas flow to wellhead then accumulated (with this, SCP formed) as illustrated in **Figure 1**.

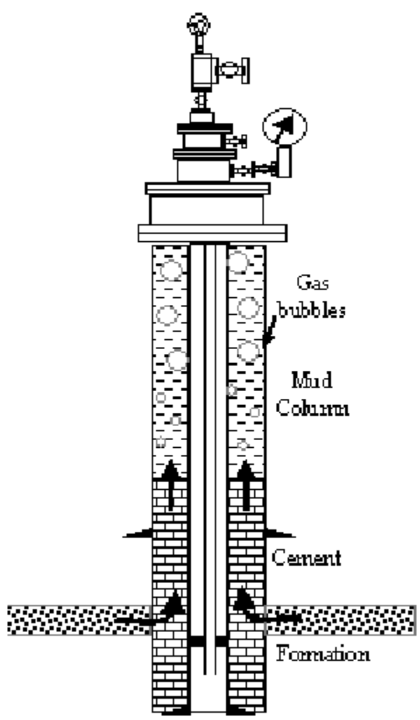


Figure 1: Gas Flow Path Formation to Wellhead

When the well is experiencing SCP, there is certain potential risk in resulting underground blowout (Bourgoyne et. al., 1999). Thus, a close monitoring job is mandatory in order to manage SCP effectively since SCP not able to fully mitigate. If operator company failed to manage SCP effectively, there is a potential risk in losing production, on-site pollution and endanger crews' working safety as well as jeopardizing wellbore integrity.

In diagnostic SCP, Bourgoyne et. al.(1999) were listed out several methods in analyzing SCP which the data can be obtained from Fluid sample analysis, well logging, monitoring fluid levels, pressure testing, pressure bleed-down and build-up performance and wellhead maintenance. Furthermore, the authors were listed out three methods to remediate the excessive pressure. One of the methods is periodic bleeding of excessive pressure which will be studied in this project. Following is the equation shows to determine the time taken to bleed the annulus to atmospheric pressure via bleed valve and assume this is gas well and annulus full of gas due to tubing leak:

$$t(p_f) = \frac{V_a}{A_n\sqrt{2RT}} \int_{\bar{p}=\frac{p_i}{p_{atm}}}^{\frac{p_f}{p_{atm}}} \frac{d\bar{p}}{\beta\sqrt{\overline{\bar{p}(\bar{p}_t - \bar{p})}} - \sqrt{\overline{\bar{p}(\bar{p}-1)}}},\ p_t \geq p \geq p_{atm}$$

After bleed down pressure process was done, R. Xu & Wojtanowicz (2003) were identified two patterns of SCP testing pressure behaviour namely pattern of instant bleed-down and pattern of prolonged bleed down. **Figure 2** shows the casing head pressure was release rapidly and the well liquid is also removed with the gas in the same time. While Figure 3 shows the prolonged process of pressure bleed down in order to minimize the removal of fluid in the casing annulus.

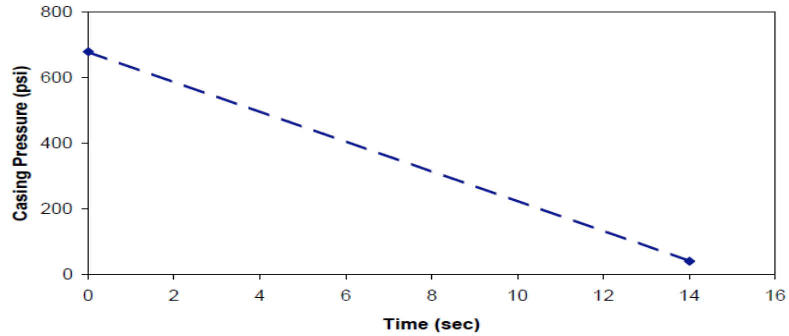


Figure 2: Instant Bleed-Down Pressure Pattern

Source: *Diagnostic Testing of Wells with Sustained Casing Pressure –An Analytical Approach, Paper 2003-221*

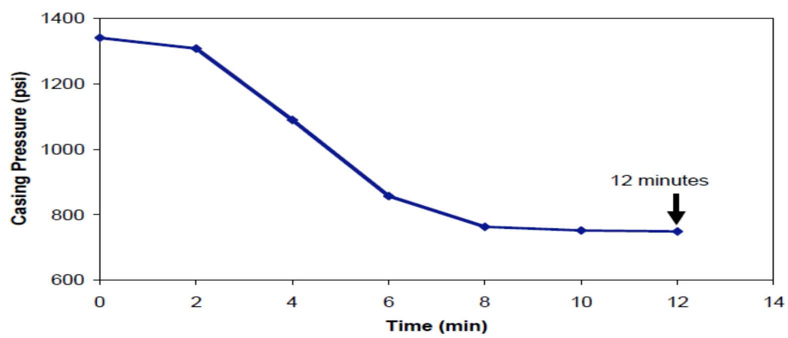


Figure 3: Prolonged Bleed-Down Pressure Pattern

Source: *Diagnostic Testing of Wells with Sustained Casing Pressure –An Analytical Approach, Paper 2003-221*

1.2 Problem Statement

There is high number of wells in Gulf of Mexico area are developing potentially risk of SCP (Bourgoyne et. al., 1999). Apart from Gulf of Mexico, an oilfield named Bakau Field in Malaysia, Sarawak Water Region is reported one of the wells exhibiting a high casing pressure. Based on this observation, it is able to forecast that other wells in any part of the world might develop the same issue as developed in Gulf of Mexico; Periodic Bleed-off pressure is one of the methods to relief the SCP into minimum risk level.

Sathuvalli & Suryanarayana (2001) stated that data obtained from periodic bleed-off pressure can contribute or provides utmost important information regarding the magnitude of leak in wellbore components and SCP problem. In addition, the data indicate that bleeding to zero pressure is not necessary a solution in mitigating SCP. Besides, Kinik & Wojtanowicz (2011) were claiming bleeding to zero pressure might causing hydrostatic pressure in the column decreased and thus induce influx of gas flowing into annulus column.

Since the periodic bleed-off pressure method was introduced, there is a need to develop computer codes from periodic bleed-off method in order make engineer's life easier so that he/she can receive an early warning signal while monitoring 'A' annulus pressure. In addition, he/she has more extra time to analyze SCP problem, modelling and more effective in managing SCP before the problem become worst.

1.3 Objectives and Scope of Study

The objectives of this study are:

- To study the detrimental effect of sustained casing pressure in 'A' annulus on well integrity, as shown in **Figure 6**.
- To convert and utilise the existing mathematical model of periodic bleed-off the sustained casing pressure into computer code.
- To develop a work flow in monitoring SCP via *Wolfram Mathematica 8.0*

The scope of study includes:

- Conducting research on the theory and definition of terms related to the study.
- Conducting research in developing a computer code for modelling the periodic bleed -off pressure.
- Familiarization the usage of *Wolfram Mathematica 8.0* programs.

CHAPTER 2

LITERATURE REVIEW

2.1 Causes of Sustained Casing Pressure (SCP)

The causes of SCP or referred as Sustainable Annulus Pressure (Attard, 1991) were casing leaks, insufficient isolation of cement and failure of completion string. In addition, Bourgoyne et al. (1999) were claiming that damage of primary cement after setting due to temperature cycles and casing contraction also were one of the causes to exhibit SCP. Meanwhile, for Casing Leaks and completion string failure factor, Bourgoyne et al. (1999) were stated that leaks happened due to the poor thread connection, corrosion, thermal-stress cracking or any mechanical failure of the inner string. However, the cause due to insufficient isolation of cement is referring to poor primary cementing job during completing the casing into the well. It is because the invasion of gas from formation into cement while the cement is in setting process. After cement was hardened, it will form a micro channels in the cement itself (Bourgoyne et al., 1999).

If the cementing job was performed perfectly, yet it still has a possibility to exhibit SCP in the future once the well put on production phase. During the production phase, the changes in pressure and temperature are causing expansion and contraction of the casing and the cement sheath, thus resulting micro annulus in the cement. This finding was based on the experiment in examining the effect of increasing internal casing pressure who conducted by Jackson and Murphey (1993).

2.2 Annular Pressure

The effect of fluid temperature can lead to Annular Pressure buildup (APB) in the well’s annulus. The high pressure reading at the surface might be due to APB which induced by thermal effect, once the pressure is bleed-off, ideally the pressure will not return unless there is a leak. Thus, Attard (1991) claiming that this could be temporary effect and did not present any hazardous situation to well integrity.

In modelling Annular Pressure, Oudeman & Bacarreza (1995) were stated that, according to equation of state, the pressure at any point in the annulus is a function of mass of fluid m, volume V_{ann} and temperature T:

$$\boldsymbol{p_{ann} = p_{ann}\,(m,\,V_{ann},\,T\,)}$$

In addition, Oudeman & Bacarreza (1995) were obtained an expression to describe the changes of annular pressure as the following:

- Mass Influx or efflux from annulus volume
- Volume changes of annulus due to physical changes in annular volume
- Temperature Changes of the fluid

Below is the expression in mathematical equation of Annular Pressure changes, Δp:

$$\Delta p = \left(\frac{\partial p}{\partial m}\right)_{V,T} \cdot \Delta m + \left(\frac{\partial p}{\partial V_{ann}}\right)_{m,T} \cdot \Delta V_{ann} + \left(\frac{\partial p}{\partial T}\right)_{m,V} \cdot \Delta T.$$

Below is the expression in mathematical equation of Annular Volume changes:

$$\Delta V_{ann,F} = \frac{\pi}{2} \cdot L_{ann,F} \cdot (d_o \cdot \Delta d_o - d_i \cdot \Delta d_i)$$

When the well is in shut in condition, following is the equation used to estimate the increase in the pressure on primary annulus:

$$\Delta p_{ann} = \frac{1}{1 + \frac{fE_t}{B_{ann}}} \Delta p_t$$

Where

$$f = \frac{1}{2}\left[\left(\frac{r_c}{r_t}\right)^2 - 1\right]\left(\frac{r_t}{t} - \nu\right)^{-1}$$

2.3 Annuli Pressure Monitoring

It is important to monitor the annuli pressure in ensuring the well integrity; the following are the criteria in identifying the well which is potentially unsafe due to SCP as mentioned by Attard (1991):

- There is a direct pressure communication between annuli.
- The inability to bleed down the annulus pressure to a designated minimum pressure.
- There is a breakdown of casing shoe where the annulus pressure drops suddenly for no any valid reason.
- Continuous of pressure build up where the pressure exceed the maximum pressure limit, even after bleed-off procedure was done.

In pressure monitoring process, a workflow model was developed by Attard (1991). Please refer to **Appendix A.**

2.4 Pressure Bleed-down

It is essential to perform bleed-down pressure test in each well. According to *Well Risk Management Guideline* from PETRONAS Carigali Sdn Bhd, the guideline is mentioned the bleed-off test should be conducted for each of the well once, in every six months. From this statement, it clearly states that the company is highly emphasizing on well safety issue. In addition, Saadon K. et al. (2008) stated that bleed-downs activity is routinely completed in ensuring the well integrity of 781 offshore wells in Malaysia, based on this justification, Saadon K. et al. (2008) were developed pressure bleed down guideline for "A , B and C" annulus. For further reading, please refer **Appendix B.** From the bleed-off test, Riggs et al. (2001) explained the pressure bleed-down test is able to provide an important bleed down signature which can results the magnitude of leak. Furthermore, he is also claiming it is not recommended to bleed pressure to zero value because it might lead to casing collapse due to low hydrostatic pressure at inner casing string.

2.4.1 Model in Annular Bleed-off Time

Following is the description on model to estimate time taken to bleed a closed volume which containing gas as suggested by Riggs et al. (2001).

There are 3 assumptions were made in the following equation which is:

- It is an ideal Gas
- Bleed-off annulus without influx
- The annulus filled with Gas (Air) instead of liquid

Below is the equation of dimensionless time estimating for pressure bleed-down process based on the above 3 assumptions:

$$\bar{t} = \frac{t}{t_o} = \ln\left[\sqrt{\frac{p_i}{p_{atm}}} + \sqrt{\frac{p_i}{p_{atm}} - 1}\right]$$

Following is the equation which shows the time taken to bleed the annulus to atmospheric pressure if the effect of leak influx is considered:

$$t(p_f) = \frac{V_a}{A_n\sqrt{2RT}} \int_{\bar{p}=\frac{p_i}{p_{atm}}}^{\frac{p_f}{p_{atm}}} \frac{d\bar{p}}{\beta\sqrt{\bar{p}(\bar{p}_t - \bar{p})} - \sqrt{\bar{p}(\bar{p}-1)}}, \; p_t \geq p \geq p_{atm}$$

Where β = ratio of the leak path area to nozzle area

If β is assume to be zero:

$$t(p_{atm}) = \frac{V_a}{A_n}\sqrt{\frac{2}{RT}} \ln\left[\sqrt{\frac{p_i}{p_{atm}}} - \sqrt{\frac{p_i}{p_{atm}} - 1}\right]$$

2.5 Well Integrity Issue

As the topic mentioned “Well Integrity”, what is so important of well integrity in oil and gas production? From the well integrity studies obtained from SINTEF Petroleum Research, the integrity of wells at Norwegian Continental Shelf is at risk due to several type leakages: leakage from tubing to ‘A’ Annulus, leakage at Wellhead and leakage at Downhole Safety Valve. In addition, the number of leakage in wells also increasing by years as illustrated **Figure 4**.

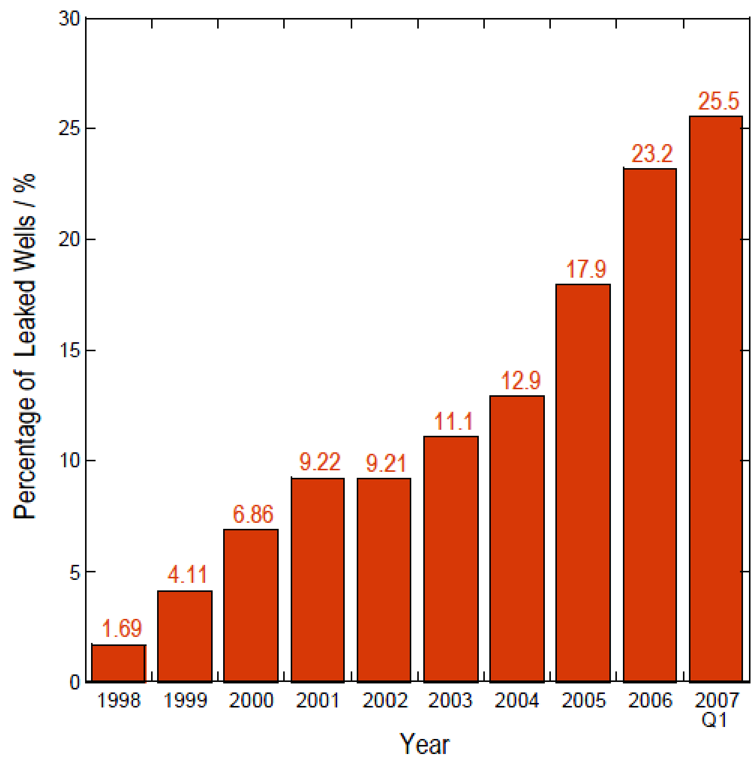


Figure 4: Percentage of leaked wells Versus Year from 1998 to 2007
Source: Assessment of Well Integrity on Norwegian Continental Shelf by SINTEF Petroleum Research

If the leaks in wells are not taken seriously, eventually it will become a SCP in well and slowly deteriorating the integrity of wells as well as the safety of personnel crew.

The NORSOK-101 guideline defines well integrity is the application of technical, operational and organization solutions to reduce risk of uncontrolled release of formation fluids throughout the life cycle of a well. Basically it is all about the Safety which including personnel crew on board, well's equipments located from subsurface until topside facility as well as the company's business function. Nevertheless, the well integrity issue in this report will be focusing from subsurface until surface wellhead.

Attard (1991) mentioned there are four potential hazards if annulus pressure is not able control with a proper procedure. Consequently, the high pressure below the wellhead could damage the wellhead itself and causing failure to contain all the fluids from subsurface. Secondly, pressure communication with formation can result in formation's breakdown or fracturing. For instance, if the breakdown occurs in shallow formation, the fracture in the formation could transmit all the way to surface formation. It is indirectly providing an alternative channel to let the subsurface fluids escape to the atmosphere and provide an unnecessary contingency plan in order to isolate the problem. Thirdly, casing collapse could be happened if the pressures build up accumulate at 'B' or 'C' annulus where the pressure at 'A' annulus had been bleed off. Meanwhile, it may also damage the production tubing. The last but not least, there is a possibility lead to casing burst when hydrostatic pressure of completion fluid inside the annulus is extremely high. Hence, the effect of casing collapse and casing burst will potentially to let reservoir fluids escape from the wellbore; this incident can further exacerbate the well's rehabilitation programme such as Well Workover.

If the integrity of well is jeopardized, it may lost its daily production and indirectly generate a negative impact to company's business operation. Hence, Mineral Management Services (MMS) in U.S.A. was setting up the Self-departure regulation in observing SCP. Self-departure means the well will be freed from SCP observation and continue its own production. Following is the self-departure's condition if SCP fulfill the below requirements:

- SCP less than Minimum Internal Yield Pressure (MIYP)
- SCP will bleed down to zero psi within 24 hours through ½ in. needle valve.

However, Kinik & Wojtanowicz (2011) were stated that the pressure bleeding process may reduce fluid's hydrostatic pressure; it may induce more gas influx flowing into annulus. Hence, pressure bleed-down to zero psi is not an ideal option to relieve pressure in well.

Nowadays, it is the industry’s common practices in temporary remediation of SCP by implementing periodic bleed off and/or lubricating with high density completion fluid such as zinc bromide (Kinik & Wojtanowicz, 2011). With lubricate a high density completion fluid, it also increase the hydrostatic pressure which applied to casing shoe, high pressure at casing shoe resulting casing shoe breaching. Furthermore, D’Alesio et al (2010) were developed an operational methodology to assess the well integrity through eliminating, at least reducing the risk in the presence of SCP in the well. First of foremost, the calculation needed to be calculated is Maximum Allowable Pressure (MAP) of each annular space in SCP well or it also can be referred as Maximum Allowable Wellhead Operating Pressure (MAWOP) according to API recommended practice 90. The MAWOP is measured relative to the ambient pressure at the wellhead for certain part of annulus.

The implementation of diagnostics tests to detect the location and sizes of leakage on the critical well is crucially important. Once completed the diagnostic test, the team will starts to analyze the risk level to the well before they select the most appropriate remedial action to restore the integrity of well. **Figure 5** shows a simple workflow diagram in diagnosis SCP in ‘A’ annulus who developed by Riggs et al. (2001).

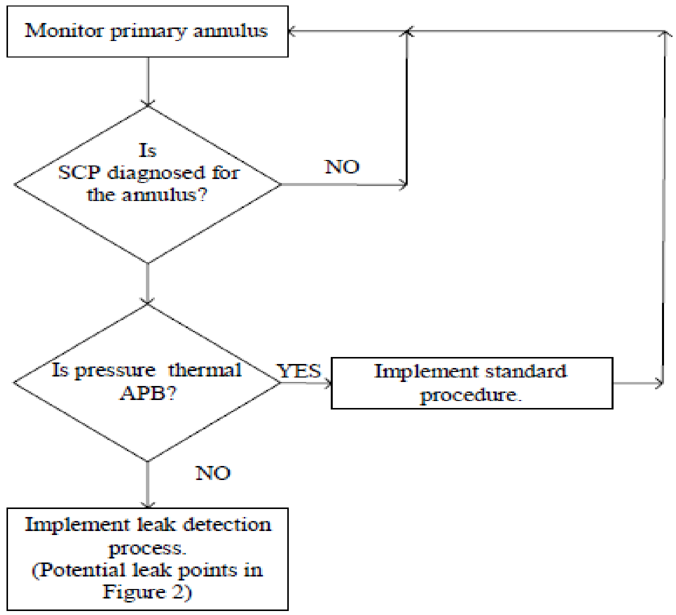


Figure 5: Diagnosis of 'A' Annulus

Source: *Best Practices for Prevention and Management of Sustained Casing Pressure*. Stress Engineering Services Inc, Houston, USA.

CHAPTER 3

METHODOLOGY

3.1 Research Methodology

The sources of research are from books and technical papers. UTP IRC has become the main location to provide main source of research for books, while the ONE PETRO website under Society of Petroleum Engineers (SPE) is the main source of research for technical papers.

The main objective of this research will be focusing on converting existing Mathematical model of pressure bleed-off time into computer code and perform sensitivity analysis by using software *Wolfram Mathematica 8.0.* Next objectives will be analyzing the detrimental effect of SCP on Well Integrity as well as developing a workflow in diagnostic SCP via software *Wolfram Mathematica 8.0*. Other than that, in order to have a better understanding of SCP on well integrity, such as the behavior of annular pressure in the function of changes in pressure, temperature, volume, basic understanding in casing design such as burst, collapse and formation breakdown will be studied as well so that the author will have a better idea on the effect of SCP which acting on Well integrity.

After the computer code was developed, there is a need to validate the modeled data using hypothetical well parameters, with this it is able to evaluate the model developed from *Wolfram Mathematica 8.0* is convincing and valid.

3.2 Scope of Research

The study is focusing on sustained casing pressure in 'A' Annulus which is the annulus between the production tubing and production casing instead of 'B' and 'C' Annulus which is the annulus between casings. Why focusing on 'A' annulus instead of 'B' and 'C' Annulus? According to Bourgoyne et al. (1999), they observed the trends of exhibiting SCP in production casing is 50% compare other type of casing such as intermediate casing (10%), surface casing (30%) and conductor casing (10%) as shown in **Appendix F**. Furthermore, SINTEF Petroleum Research shows in Norwegian Continental Shelf, the percentage of leaking from production tubing to 'A' annulus is the second highest which is 30% compared to other type of leakage. Hence, the author realized that it is more important to focus at 'A' annulus as the frequency of leakage to occur is higher compare others leakage in 'B' and 'C' annulus. Basically, it is essential to know the behaviour of annular pressure, interpretation of Bleed-down pattern and the effect of Sustained Casing Pressure (SCP) on well integrity. **Figure 6** below showing the location of 'A' , 'B' and 'C' annulus in well.

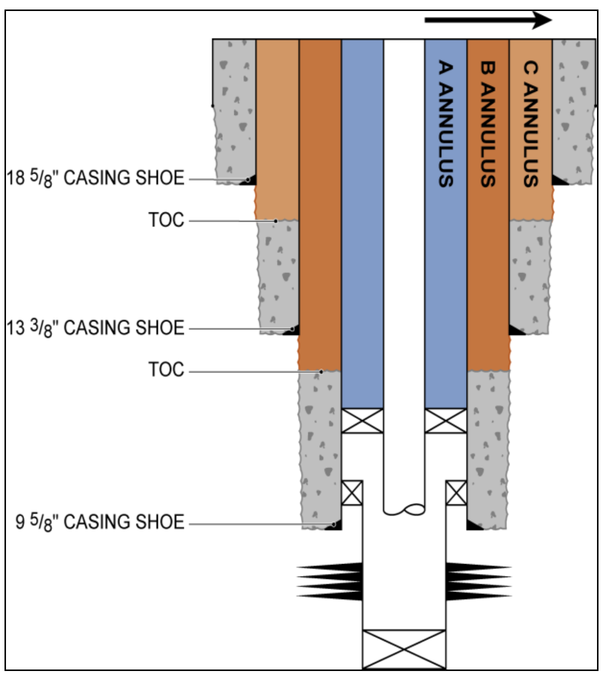


Figure 6: Well schematic showing 'A',' B', 'C' Annulus

3.3 Theoretical Analysis and Derivation of Equation

In estimating the bleed off time while reducing the pressure in an annulus, it is the problem where involve pressure driven fluid migrate from one volume to another volume via a nozzle. This migration phenomenon is involved the principle of unsteady Bernoulli equation for incompressible flow. In this thesis, only gas phase is selected for the scope of study. For two phase flow study, it is required a longer period to research compare to the author's research period (2 semesters).

In this case, method that will be discussed is the method derived by Riggs et al. (2001) to estimate the time taken to bleed-off a closed volume which containing gas. Assuming that the bleed-off takes place at constant temperature and gas is perfect.

Where $$p(t) = \rho(t)RT \qquad \text{(T1)}$$

ρ (t) denotes the gas density in the annulus during bleed off and R stand for the gas constant for the gas. R is given by

$$R = \frac{\Lambda}{M_{gas}}$$

Where Λ denotes to universal gas constant (49,720 $ft^2/s^2/^oR$) and Mgas is its molecular weight. By multiplying both sides with the volume of the annulus, V_a . Thus, it will become

$$V_a p(t) = (\rho(t)V_a)RT$$
$$= m_a(t)RT$$

Where ma(t) refer to the mass of the gas in the annulus at time *t.* Differentiating both sides with respect to time, then it will become

$$\frac{dp(t)}{dt} = \frac{RT}{V_a}\frac{dm_a}{dt} \qquad \text{(T2)}$$

The RHS of above equation is the instantaneous mass of gas in the annulus and its depend on the influx and efflux of the mass into the volume.

$$\frac{dm_a}{dt} = \overline{m}_{in} - \overline{m}_{out} \qquad \text{(T3)}$$

Where $\overline{m}_{in}$ and $\overline{m}_{out}$ are the mass flow rate of gas into and out of annulus. The $\overline{m}_{out}$ is given by

$$\overline{m}_{out}(t) = A_n \rho(t) v(t) \qquad \text{(T4)}$$

Where A_n = flow area of nozzle,

v(t) = Instantaneous velocity through the nozzle.

The v(t) applying Bernoulli's equation for isentropic isothermal flow from pressure p(t) to atmospheric pressure, p_{atm} . By neglecting the gravitational effects, the velocity of efflux through the nozzle is given by

$$v(t) = \sqrt{\frac{2(p - p_{atm})}{\rho}} \qquad \text{(T5)}$$

Substituting (T5) into (T4) and then into (T2), after simplifying, it will get

$$\frac{dp}{dt} = \frac{RT}{V_a}\overline{m}_{in} - A_n \frac{\sqrt{2RT}}{V_a}\sqrt{p(p - p_{atm})} \qquad \text{(T6)}$$

By introducing dimensionless pressure and time,

$$\overline{p} = \frac{p}{p_{atm}} \qquad \text{(T7)}$$

$$\bar{t} = \frac{t}{t_o} = \frac{t}{\frac{v_a\sqrt{\frac{2}{RT}}}{A_n}} \quad \text{(T8)}$$

Introducing (T7) abd (T8) into (T5), then it will become

$$\frac{d\bar{p}}{d\bar{t}} = \sqrt{0.5RT}\,\frac{\bar{m}_{in}}{Ap_{atm}} - \sqrt{\bar{p}(\bar{p}-1)}$$

And used G = $\sqrt{0.5RT}\,\frac{\bar{m}_{in}}{Ap_{atm}}$ which is the dimensionless mass influx. In this study, it is assume there is no in influx (no leakage) from any well's components, thus it is assumed G is equal to zero.

Therefore, the time taken to bleed off from initial pressure, p_i to atmospheric pressure, p_{atm} is given by

$$\bar{t} = \frac{t}{t_o} = \int_{\bar{p}=\frac{p}{p_{atm}}}^{1} \frac{d\bar{p}}{G - \sqrt{\bar{p}(\bar{p}-1)}} \quad \text{(T9)}$$

After (T9) expression is integrated and G is equal to zero, below is the expression for bleed-off from a closed annulus without influx.

$$\bar{t} = \frac{t}{t_o} = \ln\left[\sqrt{\frac{p_i}{p_{atm}}} + \sqrt{\frac{p_i}{p_{atm}} - 1}\right]$$

To get the time, *t* estimated value (non-dimensionless value) via bleed-off pressure expression,

$$t = \bar{t} \times t_o$$

$$t = \frac{v_a}{A_n}\sqrt{\frac{2}{RT}}\ln\left[\sqrt{\frac{p_i}{p_{atm}}} - \sqrt{\frac{p_i}{p_{atm}} - 1}\right] \quad \text{(T10)}$$

3.4 Parameters involved and Formula

The following formula will be used in modelling the time during bleed-off pressure in annulus by Riggs et al. (2001).

$$t = \frac{v_a}{A_n}\sqrt{\frac{2}{RT}}\ln\left[\sqrt{\frac{p_i}{p_{atm}}} - \sqrt{\frac{p_i}{p_{atm}} - 1}\right]$$

Please refer to **Nomenclature** section for the parameters involved in above equation.

The parameters involved in above equation which are V_a, R, and T will be conducted a sensitivity analysis in order to observe the time required to bleed off with the changes of these parameters. Furthermore, according to API recommend practice 90 (2006), the parameter of A_n will be kept at constant value which is 0.5inc in this research study. In addition, the 0.5in needle valve is also typically used in the industry nowadays' practice.

According to Bellarby J. (2009), after the production stops, it is unavoidable that annulus pressure will drop below atmospheric pressure at surface. Furthermore, he also claiming that if the annulus was exposed or opened, or the valves are vacuum tight, air can enter the annulus and this can lead to corrosion problem in the future. Hence, the atmospheric pressure will be assumed more than 14.7 psi in the model.

To observe the effect of gas constant in affecting time during bleed-off pressure test; several types of gases were selected. Table below is showing the molecular weight of gas with the respective of gas type filled in annulus.

Type of gases	**Molecular Weight**	**Gas Constant, ft lb/slug ^{0}R**
Carbon Dioxide, CO_2	44.01	1129.743
Oxygen, O_2	32.00	1553.75
Air	28.97	1716.258
Nitrogen, N_2	28.02	1774.45
Methane, CH_4	16.04	3099.75
Helium, He	4.003	12420.68
Hydrogen, H_2	2.016	24662.70

Table 1: Value of gas constant with various types of gases filled in annulus

3.5 Project Flow of Work

Figure 7 shows the process flow of the Final Year Project:

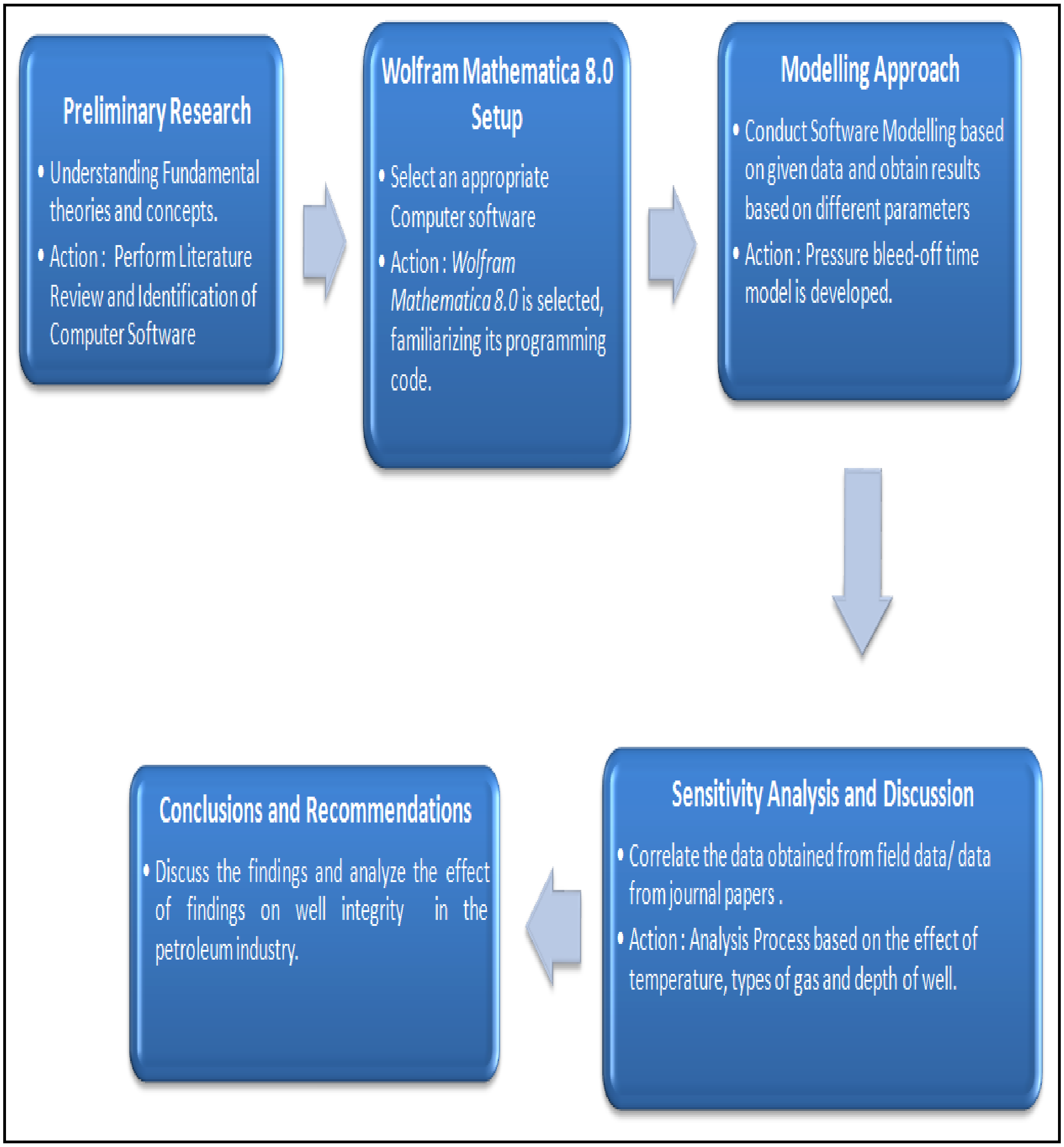


Figure 7: Process flow of work

3.6 Gantt Chart and Key Milestone

Table 2 shows the Gantt chart to schedule the implementation of FYP I:

FINAL YEAR 1st SEMESTER (SEPT 2011)															
No.	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Project title selection								Mid-semester break							
2.	Preliminary research work															
3.	Extended Proposal submission															
4.	Study on fundamental concepts related to the project & familiarize the usage of Software tools															
7.	Proposal Defence															
8.	Study on mathematical model which involved in calculating bleed off annular pressure according to time.															
9.	Preparation of interim report															
10.	Submission of interim report															

Table 2: Gantt chart for the First semester project implementation

Table 3 shows the Gantt chart to schedule the implementation of FYP II:

	FINAL YEAR 2nd SEMESTER (January 2012)																	
No.	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15	16
1	Development of Computer Code and manipulate different parameters.								Mid-semester break									
2.	Submission of Progress Report																	
3.	Seeking advice and meeting with Industry Professionals.																	
4.	Conduct Sensitivity Analysis and validation between simulated data and field data.																	
6.	Create Workflow in accessing SCP.																	
7.	Preparation of Final Report																	
8.	Pre-EDX & Submission of Final Report(Softcopy)																	
9.	EDX(if selected)																	
10.	Preparation of Oral Presentation																	
11.	Final Oral Presentation																	
12.	Submission of Hardbound Copies																	

Table 3: Gantt chart for the Second semester project implementation

3.7 Tool required

In order to complete this project, the end product would be modeling of this time estimating in pressure bleed-off via computation software. The software is needed to translate the mathematical model into computer codes. Besides that, the software also used to develop a workflow diagram in diagnostic SCP.

The computational software chosen is *Wolfram Mathematica 8.0*. This software was developed by Wolfram Research. This software is the world's only fully integrated environment for technical computing. **Figure 8** below illustrated the interface of *Wolfram Mathematica 8.0.*

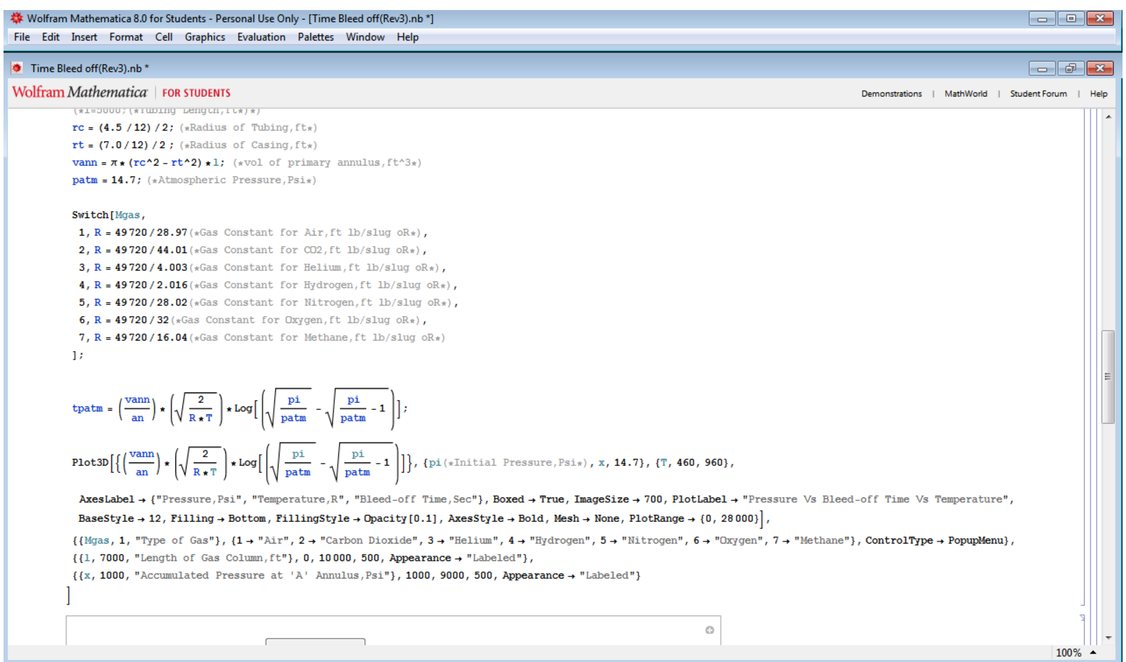


Figure 8: Interface of *Wolfram Mathematica 8.0*- Student Version

CHAPTER 4

RESULT AND DISCUSSION

Based on the model developed from *Wolfram Mathematica 8.0*, an extensive analysis were made and compared.

4.1 Computer Code

Below is the Computer code developed for 2D plot or it can be referred as '*input*':

```
Manipulate[Clear["Global'*"];



rc = (4.5 /12)/2; (*Radius of Tubing*)
rt = (7.0/12)/2 ; (*Radius of Casing*)
vann = \[Pi]*(rc^2 - rt^2)*l; (*vol of primary annulus*)
patm = 14.7; (*atmospheric pressure*)
(*Below is the Gas Constant where 49720 the Universal Gas Constant divided
by \
Molecular Gas *)



 Switch[Mgas,
  1, R = 49720/28.97 (*Gas Constant for Air, ft lb/slug °R*),
  2, R = 49720/44.01 (*Gas Constant for CO2, ft lb/slug °R*),
  3, R = 49720/4.003 (*Gas Constant for Helium, ft lb/slug °R*),
  4, R = 49720/2.016 (*Gas Constant for Hydrogen, ft lb/slug °R*),
  5, R = 49720/28.02 (*Gas Constant for Nitrogen, ft lb/slug °R*),
  6, R = 49720/32 (*Gas Constant for Oxygen, ft lb/slug °R*),
  7, R = 49720/16.04 (*Gas Constant for Methane, ft lb/slug °R*)
  ];

an = \[Pi]*((0.25/12)/2)^2; (*nozzle area*)


(*Formula*)
tpatm = (vann/an)*(Sqrt[2/(R*T)])* Log[(Sqrt[pi/patm] - Sqrt[pi/patm -
1])];


(*Plot the graph in 2D*)
Plot[{tpatm}, {pi, x, 14.7},
  AxesLabel -> {"Pressure,Psi", "Bleed-off Time,Sec"},
  ImageSize -> 600, PlotLabel -> "Pressure Vs Bleed-off Time",
  AxesStyle -> Bold, Background -> Lighter[ColorData[1][3], 0.9]],
```

```
(*Variable needed to declare to create manipulation interface*)
 {{Mgas, 1, "Type of Gas"}, {1 -> "Air", 2 -> "Carbon Dioxide",
   3 -> "Helium", 4 -> "Hydrogen", 5 -> "Nitrogen", 6 -> "Oxygen",
   7 -> "Methane"}, ControlType -> PopupMenu},
 {{T, 460, "Temperature,oR"}, 460, 960, 50, Appearance -> "Labeled"},
 {{l, 7000, "Length of Gas Column,ft"}, 0, 10000, 500,
  Appearance -> "Labeled"},
 {{x, 1000, "Accumulated Pressure at 'A' Annulus,Psi"}, 1000, 9000,
  500, Appearance -> "Labeled"}
 ]
```

4.2 Analysis on well's parameters

4.2.1 The effect of temperature

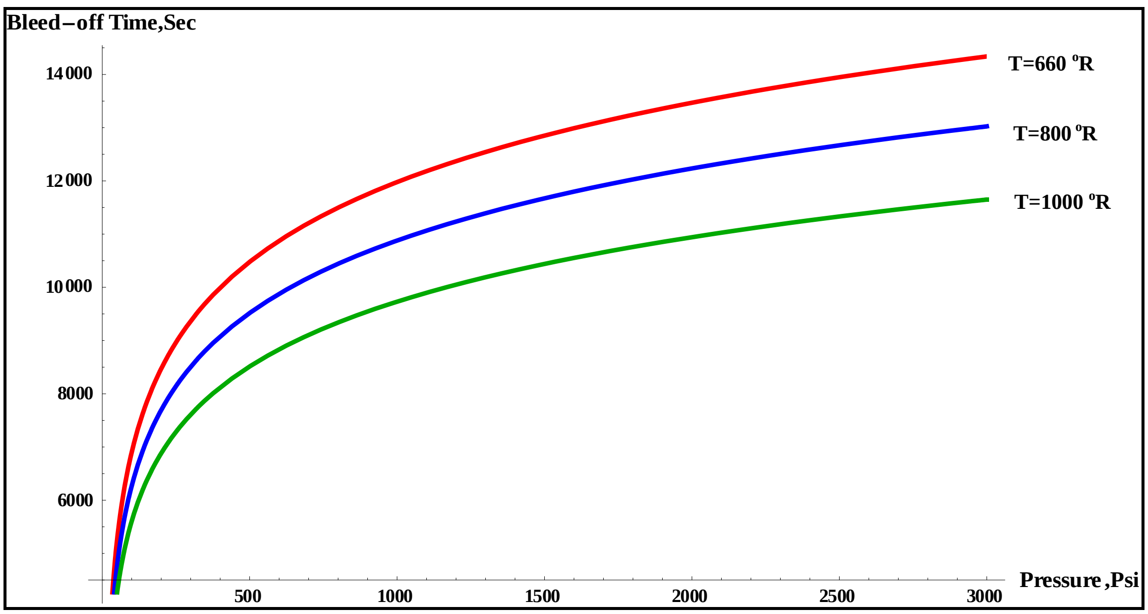


Figure 9 : Time Bleed-off Pressure model for varying temperature at 3000psi

From **Figure 9**, the estimated time in seconds to bleed-off the annular pressure is decreased when the average temperature of well is increased. At 660 ^{o}R, the time required to bleed-off is the highest compared to the other two temperature at 800oR and 1000 ^{o}R.

This effect can be explained based on the physical understanding of gas law, as the average temperature in ‘A’ annulus higher, the energy of the fluid particles increase as well. As a result, the particles will travel with high speed of velocity in the confined space, the ‘A’ annulus. Therefore, when the needle valve at the surface is opened, the high energy of particles will flow and vent out from the valve with higher flow-rate.

Given by $$PV = nRT \quad \textbf{(A1)}$$

Where $$P = \frac{F}{A} = \frac{ma}{A} \text{ and } a = \frac{v}{t}$$

Thus, $$P = \frac{mv}{tA} \quad \textbf{(A2)}$$

Where P is the pressure of fluid particles, A is cross section area, a is acceleration, v is velocity of particles and t is time.

By substituting equation **(A2)** into equation **(A1)**,

It will become $$\frac{mv}{tA}V = nRT \quad \textbf{(A3)}$$

From the equation (**A3)**, it is clear that when the relationship of temperature and time is inversely proportional, when the temperature increasing, the time required to bleed off is decreasing with the increasing of speed travel of particles via needle valve.

*Please refer **Appendix C** for the Computer Code to generate **Figure 10**.

4.2.2 The effect of Gas Type filled in annulus

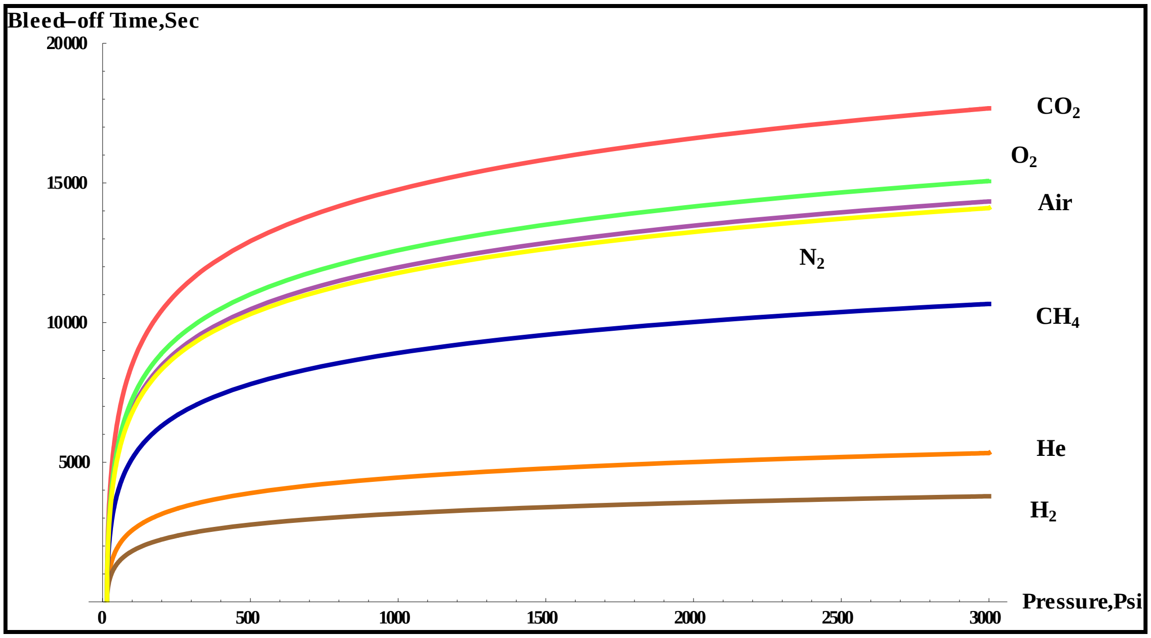


Figure 10 : Time Bleed-off Pressure model for different types of gases at 3000psi

Different types of gas may result into different time estimated to bleed-off pressure at 'A' annulus. As **Figure 11** shows, annulus filled with Carbon Dioxide (CO_2) gas required longest time to bleed-off the pressure, whereas the shortest time required bleed-off is Hydrogen (H_2) gas. In addition, the results also showing that increasing in molecular weight of gas would increase the time bleed-off and vice versa. Furthermore, there is very close result of pressure bleed-off time between the Air and Nitrogen gas (N_2). This is due to the Air contained about 78.1% of Nitrogen gas and both gases have also the same number of molecular weight. Hence, the pressures bleed-off time almost similar for Air and N_2 gas. According to Bellarby J. (2009), gas is a good insulator due to low conductivity and limit-free convection compare to liquid. Nowadays, Nitrogen gas is commonly used as packer fluids to fill in the annulus of some wells. This is due to Nitrogen has a very stable triple-bonded molecular structure.

Oxygen gas (O_2) is not recommended to use as packer fluids based on the best level of author's knowledge, as O_2 gas is one of the essential elements for ignition.

Meanwhile, the well is producing hydrocarbon and the hydrocarbon is the main sources to fire in order to continue burning, also add with the third element, *Heat*. Hence, Fire will be occurred. From the discussion above, this will definitely jeopardize the well's integrity and meanwhile, the utmost important concern is the safety of the crew on board. Furthermore, according to Riggs et. al. (2001), they were claimed that O_2 gas is commonly known as corrosion agent, this type of gas may result in high corrosion rates in steels material such as casing or tubing. Therefore, it is not recommended to inject O_2 gas into well's annulus based on the justification as discussed above.

*Please refer **Appendix D** for the Computer Code to generate **Figure 10**.

4.2.3 The effect of Height of annulus column

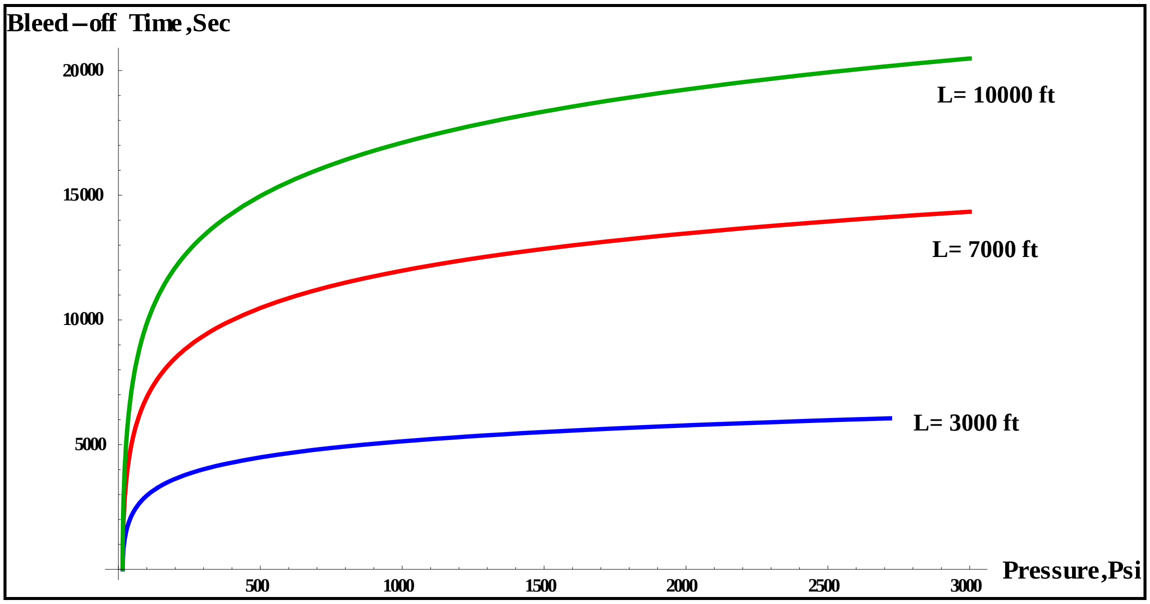


Figure 11: Time Bleed-off Pressure model for different height of gas column at 3000psi

The depth of well is also one of the factors in alternating the estimated time for pressure bleed-off. As shown in **Figure 11**, with the radius of annulus is fixed through a fixed tubing size and casing size in this model of study; the deeper well is required longer time to bleed-off compare to shallower well. For instance, **Figure 11** shows the bleed off time at 10,000 feet of Well is the highest compare to the other depth of Well which located at 7000ft and 3000ft. From the observation, this is due to the volume of gas column increase with length, the deeper the well, the capacity to cater a huge quantity of gas is higher and vice versa. Thus, it is request a longer time to bleed-off.

*Please refer **Appendix E** for the Computer Code to generate **Figure 11**.

The following 3D plot, **Figure 12** is generated to improve the visualization and better understanding the relationship among bleed-off time, pressure in annulus and well's temperature.

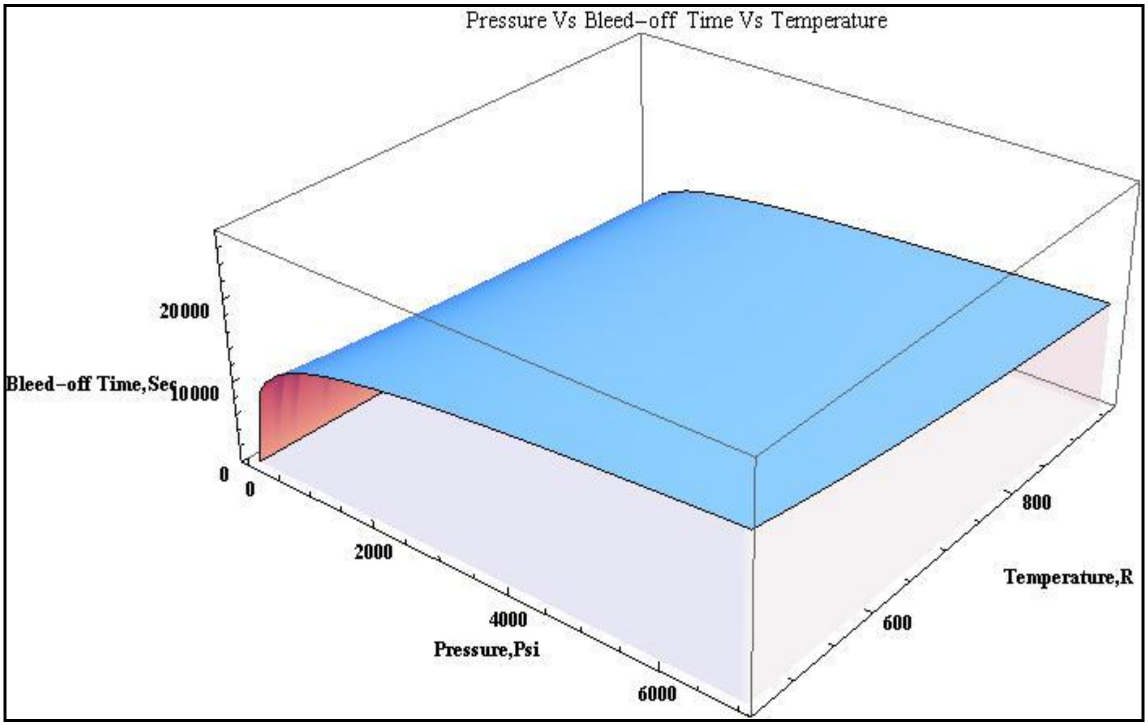
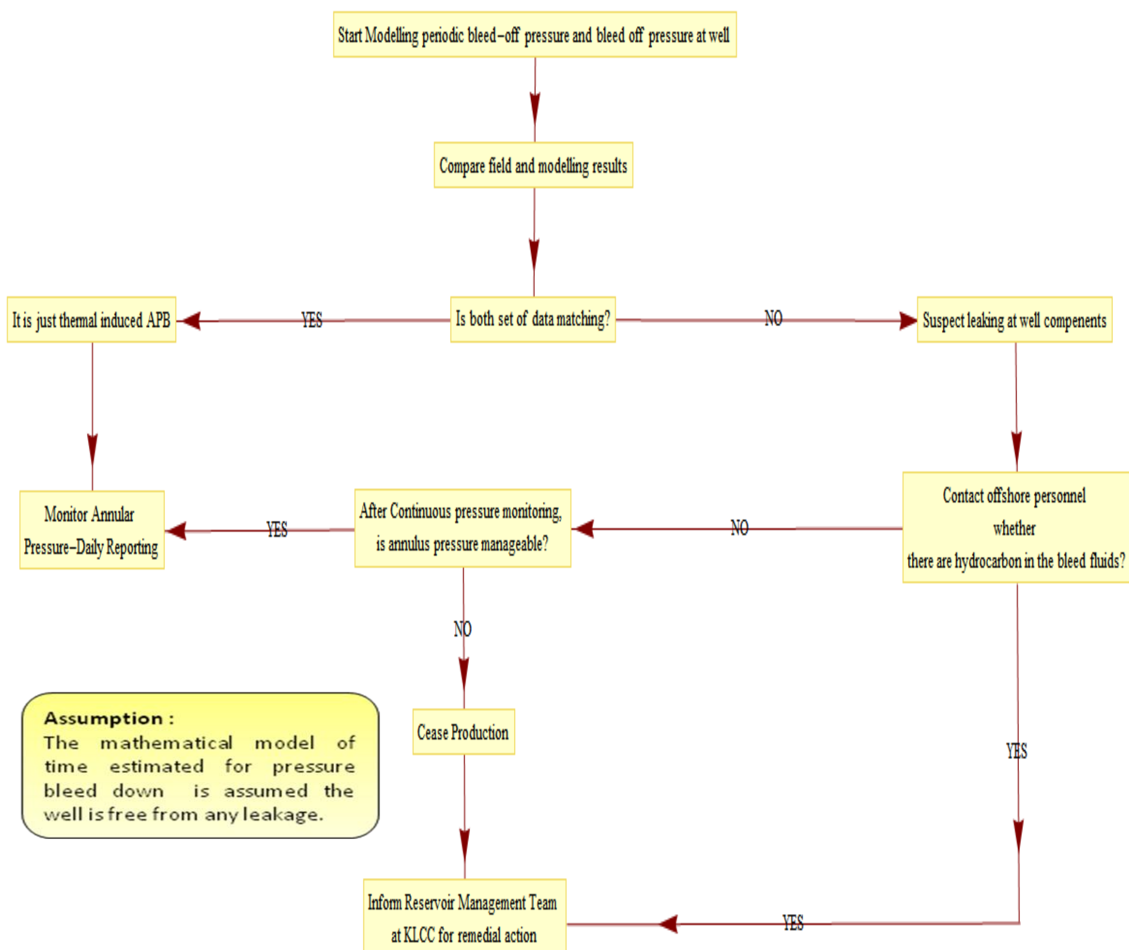


Figure 12: 3D View of Pressure Vs Bleed-off Time Vs Temperature

The figure above can be rotated 360degree in *Wolfram Mathematica 8.0.* From the 3D view above, the relationship between bleed-off time and temperature of well can be described effectively. As the Temperature,^{o}R increase, the required time to bleed-off is decreasing. On the other side, it shows the bleed-off curve according to initial pressure in the well.

4.3 Workflow Diagram on diagnostic SCP in Wells

Via using *Wolfram Mathematica 8.0,* the workflow diagram on diagnostic SCP was developed in order to get our users to have a better visualization on the estimated time pressure bleed-off while diagnosing the SCP in wells.



Note: The mathematical model of time estimated for pressure bleed down is assumed the well is free from any leakage. With this assumption made, following are the procedure in diagnostic SCP.

Once the engineer obtained the annular pressure report from site personnel, the data from the report need to be compared with the modelling data after the model is generated with provided well parameters. Then, he/she need to start matching process from the both set of data. If both data is matched, it means the well only exhibits thermal induced APB (Annular Pressure Buildup). Hence, it just needs to bleed off the pressure in ‘A’ annulus in order to relief the pressure. After that, continue back to daily monitor annular pressure.

On the other side, if both set data is not matching, it means the well is suspect leaking, thus engineer should contact back to site personnel and request them to observe whether there is any hydrocarbon in the bleed fluids or not. If there is no any hydrocarbon fluid observed in bleed fluid, engineer should inform them to continue monitor the annular pressure. If the annular pressure is manageable, then continue back to daily monitoring process. Otherwise, immediately stop the production and report to reservoir management team. However, if there is any hydrocarbon fluid observed in bleed fluid during the observation, immediately contact reservoir management team at KLCC for any necessary remedial action.

4.4 Validation of Pressure Bleed-off Model

The validation of pressure bleed-off model is using hypothetical well data provided from Riggs et al. (2001) in *Best Practices for Prevention and Management of Sustained Casing Pressure* report.

Given the hypothetical Well data as below:

Well Depth, **ft**	700
Tubing OD, **in**	4.5
Casing ID, **in**	7.0
Initial Pressure, **psi**	3000
Temperature, $^{\mathbf{o}}$**F**	200
Diameter of Bleed Nozzle, **in**	0.25

The graphs generated from *Wolrfram Mathematica 8.0* as shown in **Figure 9, 10** and **11** are exactly similar with the **Figure 13**. Hence, it is concluded that the graphs are valid and convincing. Nevertheless, the only dissimilarity is **Figure 13** shows dimensionless Value for Pressure and Bleed-off Time, whereas the graphs generated from *Wolrfram Mathematica 8.0* have dimensional value for pressure (Unit : Psi) and bleed-off time (Unit : Seconds).

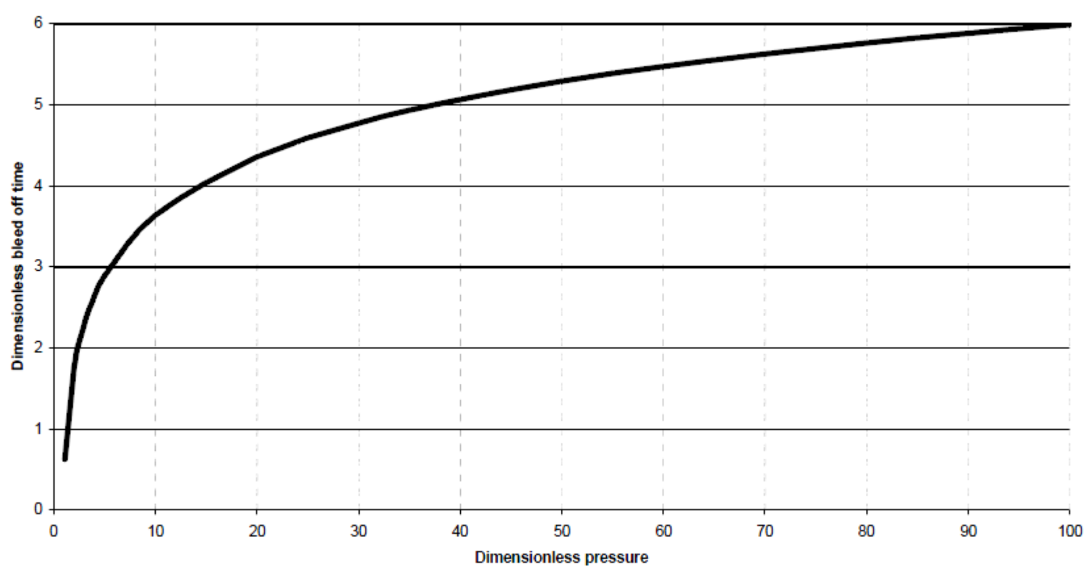


Figure 13: Dimensionless Bleed-off Time with zero mass influx

Source: *Best Practices for Prevention and Management of Sustained Casing Pressure*. Stress Engineering Services Inc, Houston, USA.

4.5 Case Study: Occurrence of High Casing Annulus Pressure issue in Baram Delta, Sarawak Malaysia.

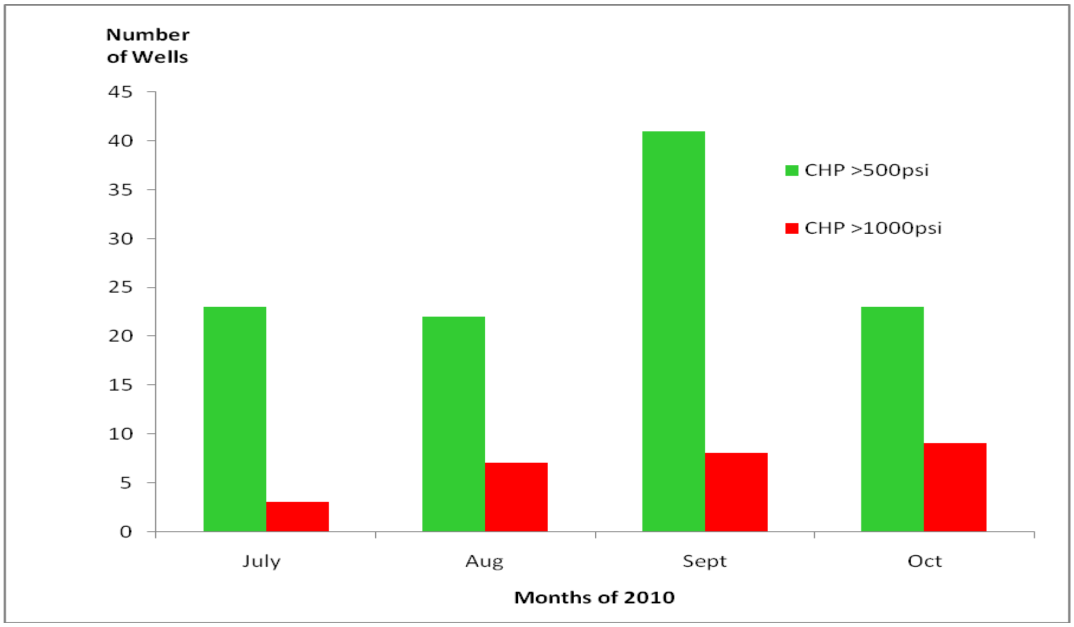


Figure 14 High Casing Head Pressure in Baram Delta, Sarawak, Malaysia

The author had done a research on the trend of high casing head pressure issue happening in Baram Delta, Sarawak, Malaysia. **Figure 14** shows the number of wells exhibiting high casing head pressure. From the observation by months in the year of 2010, the number of wells which are more than 1000psi is increasing steadily from 3 wells to 9 wells within 4 months. Moreover, every month there are at least more than 20 wells which are exhibiting more than 500psi. In September 2010, there are 41 wells exhibits more than 500psi of casing head pressure.

It can be interpreted there is an increasing trend of casing head pressure in the future time and it is same goes to wells which more than 1000psi. Since some of the wells in Baram Delta are one of the longest history in producing oil and gas, it may indicates probably there will be certain number wells is aging well and this also increase the possibility of leakage in well components. Hence, from the trend there will be more number of wells will exhibit high casing head pressure in the future period and this phenomena perhaps will apply into another region in Malaysia such as Sabah oilfield and oilfield at East peninsular of Malaysia.

CHAPTER 5

CONCLUSION

5.1 Conclusions

The idea of proposing this project is due to the operation engineer in oil and Gas Company rarely performs and emphasis on this bleed off practice. Hence, the author believes that this is important to practice in contributing higher safety factor in wellbore and crew on board, so this practice should be practiced for the benefit of the company and its people.

The findings shows that it is important to monitor annulus pressure in order to further ensure well safety. The bleed-off test is performed to ensure well safety. The mathematical model for time estimated to bleed down pressure is assumed that the well is free from any leakage. Based on the bleed off curve, it is useful for well integrity engineer to identify whether the pressure is caused by thermal annular pressure buildup (APB) or the leaking in well's components. With this, the company able to save the pre-diagnostic cost until the well is needed for further confirmation. If the data matched the bleed-off curve, then it can be assumed as a thermal APB. Otherwise, this it can be assumed there is a sign of leakage in any well components. Furthermore, this method can be very useful for unmanned offshore platform, where the engineers can directly perform bleed-off pressure using automatic remote system and they can perform real time pressure monitoring in the office without any site visit. Besides that, this research study has given a holistic idea on SCP's physical phenomena and its detrimental effect on Well Integrity.

5.2 Recommendations

There are still further works that need to be done for this project. Following are the recommendation for any future references:

- It is suggested to have a Close Collaboration with PCSB/PRSB for further research to obtain field data in order to make sure the simulated data are more convincing and reliable.
- It is suggested to further research on Two phase and Multiphase flow in well's annulus. This may take longer time to complete.
- It is recommended to obtain field data in order to make sure the simulated data are more convincing and reliable. Thus, it is suggested to organize a trip to visit an oil and gas operating company in order to extract any relevant data set.
- It is recommended to develop a pressure build up pattern in order to further improve the diagnostic process.

NOMENCLATURE

A_n	=	Nozzle Area
B_{ann}	=	Fluid bulk Modulus in Annulus
β	=	Ratio of flow area of the leak to flow area of nozzle
D_o	=	Outer diameter
D_i	=	Inner diameter
E_t	=	Modulus of elasticity of tubing
L_{ann}	=	Uncemented length of annulus
$\overline{p}$	=	Ratio of tubing pressure to atmospheric pressure
$\overline{p}_t$	=	Ratio of Annular Pressure to atmospheric pressure
P_{atm}	=	Atmospheric pressure
P_i	=	Initial Pressure
P_f	=	Final Pressure
p_{ann}	=	Annulus Pressure
R	=	Gas constant
r_t	=	Outer radius
r_c	=	Inner radius of casing
t	=	Time
T	=	Average Temperature of the gas
V_a	=	Volume of the gas in annulus

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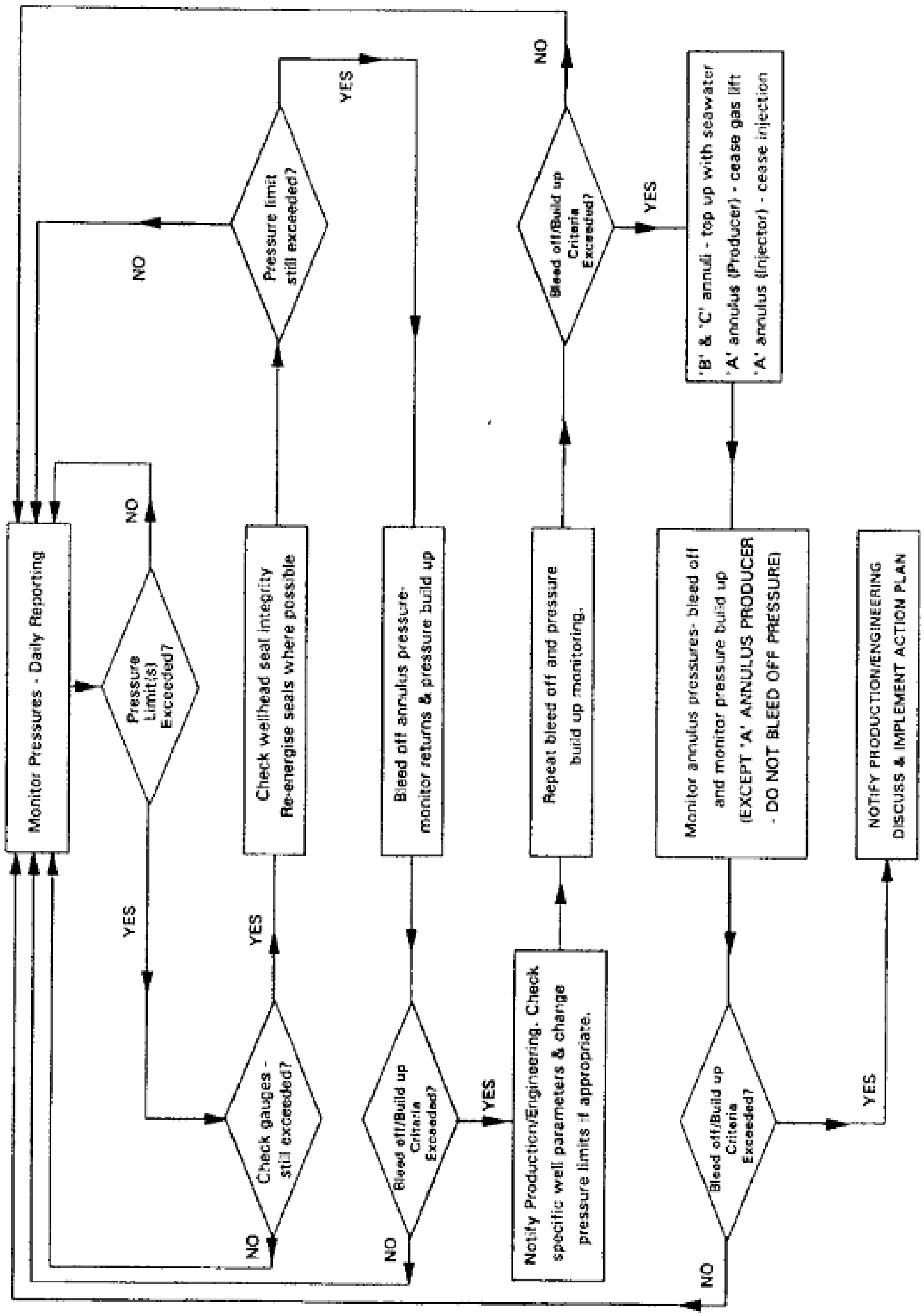
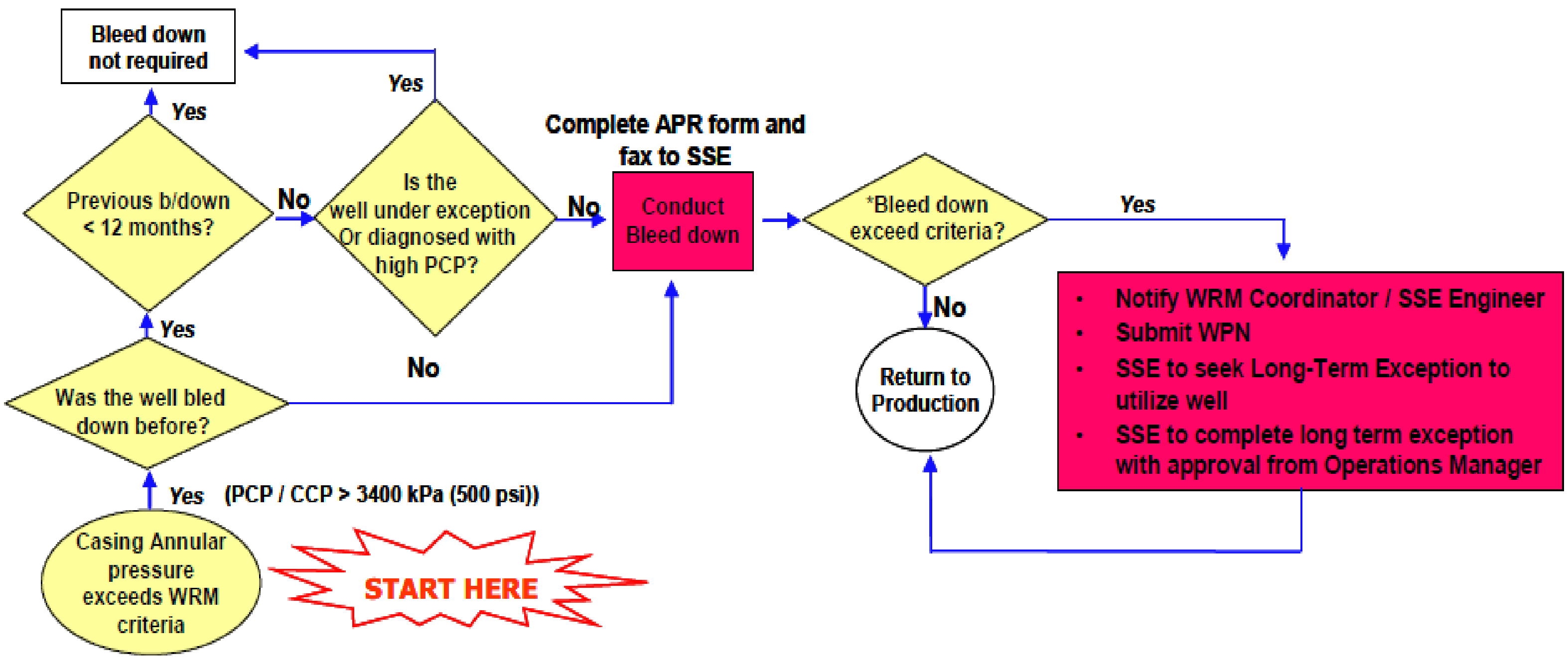
18) Xu R., Wojtanowicz A.K. (2003). *Diagnostic Testing of Wells with Sustained Casing Pressure-An Analytical Approach*. Paper 2003-221, Canadian International Petroleum Conference, Canada.

Appendix A



Source: The Occurrence of Annulus Pressure in the North West Hutton Field: Problem and Solutions .SPE 23136

Appendix B



(*) The following criteria will be used to determine if a well requires further diagnostic or remedial action

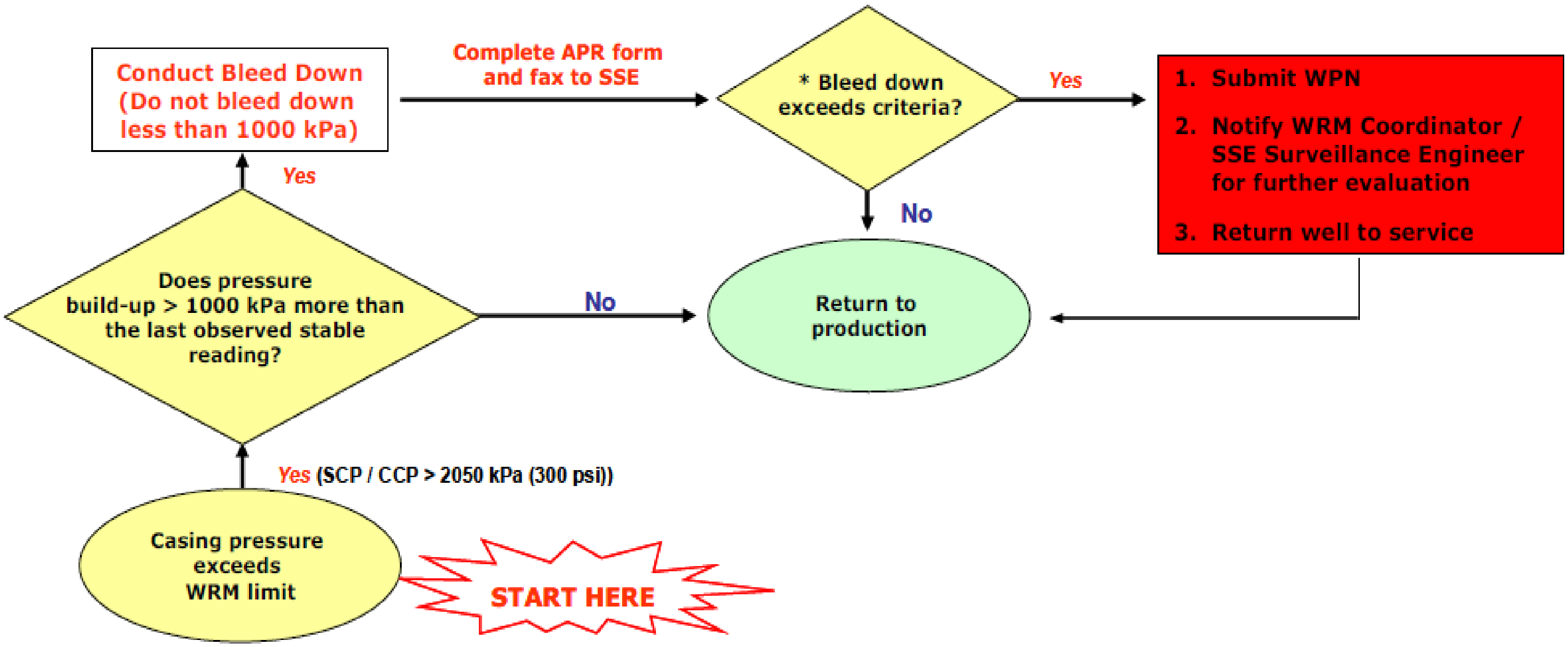
1. The annulus pressure build-up after 24 hours is greater than 3400 kPa (500 psi)
2. The annulus pressure build-up after 24 hours exceeds 50% of the pressure bled down.
3. During bleed-down, an adjacent annulus has a change in pressure indicating potential communication between strings
4. Oil is bled from the annulus.

Note:

- Any well which meets one of the above four criteria requires immediate action.
- Do not bleed a continuous stream of liquid more than ½ bbl (80 liters)

Production Casing Annulus Pressure Bleed-Down Guideline

Source: Optimizing Well Integrity Surveillance and Maintenance. IPTC 12624



(*) The following criteria will be used to determine if a well requires further diagnostic or remedial action

1. The annulus pressure build-up after 24 hours is greater than 2050 kPa (300 psi)
2. The annulus pressure build-up after 24 hours exceeds 50% of the pressure bled down.
3. During bleed-down, an adjacent annulus has a change in pressure indicating potential communication between strings
4. Oil is bled from the annulus.

Any well which meets one of the above four criteria requires further evaluation / action

Surface and Conductor Casing Annulus Pressure Bleed-Down Guideline

Source: Optimizing Well Integrity Surveillance and Maintenance. IPTC 12624

Appendix C

Effect of Temperature

```
Clear["Global'*"];(*Time needed to bleed off*)
l=7000;(*Tubing Length*)
rc=(4.5 /12)/2;(*Radius of Tubing*)
rt=(7.0/12)/2 ;(*Radius of Casing*)
vann=π*(rc^2-rt^2)*l; (*vol of primary annulus*)
an=π*((0.25/12)/2)^2;(*nozzle area*)
Mgas=28.97 ;(*molecular gas,Air at 25celcius and it is
constant*)
R=1716.258198 ;(*Gas Constant for Air*)
```

$$g1=(vann/an)*\left(\sqrt{\frac{2}{R*660}}\right)*Log\left[\left(\sqrt{\frac{pi}{patm}}-\sqrt{\frac{pi}{patm}-1}\right)\right];$$

$$g2=(vann/an)*\left(\sqrt{\frac{2}{R*800}}\right)*Log\left[\left(\sqrt{\frac{pi}{patm}}-\sqrt{\frac{pi}{patm}-1}\right)\right];$$

$$g3=(vann/an)*\left(\sqrt{\frac{2}{R*1000}}\right)*Log\left[\left(\sqrt{\frac{pi}{patm}}-\sqrt{\frac{pi}{patm}-1}\right)\right];$$

```
Plot[{g1,g2,g3},{pi,3000,16},AxesLabel→{Style["Pressure",Fo
ntSize→14,Black],Style["Bleed-off
Time",FontSize→14,Black]},AxesStyle→Bold,ImageSize→600,
PlotStyle→{{Red,Thickness[0.005]},{Blue,Thickness[0.005]},{
Darker[Green],Thickness[0.005]}}]
```

Appendix D

Effect of Different types of gas

```
Clear["Global'*"];(*Time needed to bleed off*)
l=7000;(*Tubing Length*)
rc=(4.5 /12)/2;(*Radius of Tubing*)
rt=(7.0/12)/2 ;(*Radius of Casing*)
vann=π*(rc^2-rt^2)*l; (*vol of primary annulus*)
an=π*((0.25/12)/2)^2;(*nozzle area*)

T=660;(*Wellbore Average Temperature*)

g1=(vann/an)*(Sqrt[2/(1716.258*T)])*Log[(Sqrt[pi/patm]-Sqrt[pi/patm-1])]; (*Air*)
g2=(vann/an)*(Sqrt[2/(12420.68*T)])*Log[(Sqrt[pi/patm]-Sqrt[pi/patm-1])];
(*Helium*)
g3=(vann/an)*(Sqrt[2/(24662.7*T)])*Log[(Sqrt[pi/patm]-Sqrt[pi/patm-1])];
(*Hydrogen*)
g4=(vann/an)*(Sqrt[2/(3099.75*T)])*Log[(Sqrt[pi/patm]-Sqrt[pi/patm-1])];
(*Methane*)
g5=(vann/an)*(Sqrt[2/(1129.743*T)])*Log[(Sqrt[pi/patm]-Sqrt[pi/patm-1])]; (*CO2*)
g6=(vann/an)*(Sqrt[2/(1553.75*T)])*Log[(Sqrt[pi/patm]-Sqrt[pi/patm-1])]; (*O2*)
g7=(vann/an)*(Sqrt[2/(1774.45*T)])*Log[(Sqrt[pi/patm]-Sqrt[pi/patm-1])]; (*N2*)

Plot[{g1,g2,g3,g4,g5,g6,g7},{pi,3000,16},AxesLabel→{Style["
Pressure,Psi",FontSize→12,Black],Style["Bleed-off
Time,Sec",FontSize→12,Black]},PlotRange→{0,20000},AxesStyl
e→Bold,ImageSize→600,
PlotStyle→{{Lighter[Purple],Thickness[0.005]},{Orange,Thick
ness[0.005]},{Brown,Thickness[0.005]},{Darker[Blue],Thickne
ss[0.005]},{Lighter[Red],Thickness[0.005]},{Lighter[Green],
Thickness[0.005]},{Yellow,Thickness[0.005]}}]
```

Appendix E

Effect of Height of Annulus Column

```
Clear["Global'*"];(*Time needed to bleed off*)
l1=7000;(*Tubing Length*)
l2=3000;
l3=10000;
rc=(4.5 /12)/2;(*Radius of Tubing*)
rt=(7.0/12)/2 ;(*Radius of Casing*)
vann1=π*(rc^2-rt^2)*l1;
vann2=π*(rc^2-rt^2)*l2;
vann3=π*(rc^2-rt^2)*l3;(*vol of primary annulus*)
an=π*((0.25/12)/2)^2;(*nozzle area*)
Mgas=28.97 ;(*molecular gas,Air at 25celcius and it is constant*)
R=1716.258198 ;(*Gas Constant for Air*)
T=660;
```

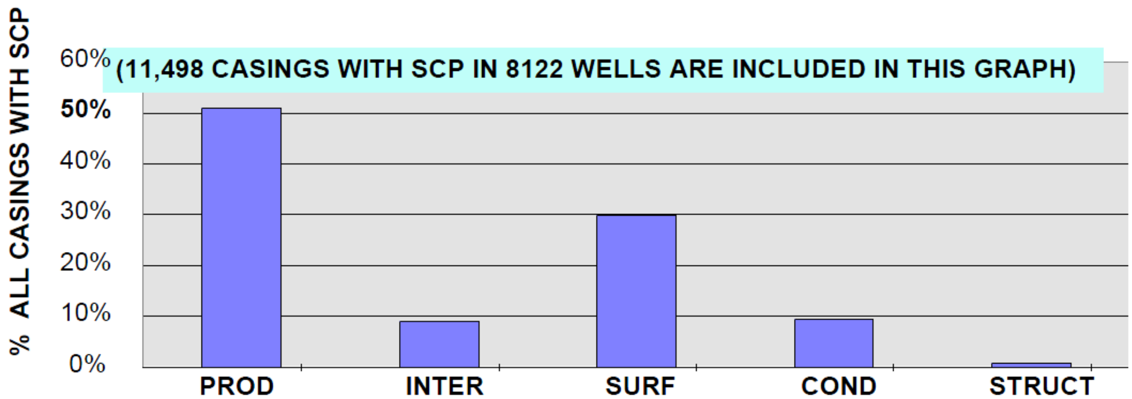
$$g1=(vann1/an)*\left(\sqrt{\frac{2}{R*T}}\right)*Log\left[\left(\sqrt{\frac{pi}{patm}}-\sqrt{\frac{pi}{patm}-1}\right)\right];\ (*Red*)$$

$$g2=(vann2/an)*\left(\sqrt{\frac{2}{R*T}}\right)*Log\left[\left(\sqrt{\frac{pi}{patm}}-\sqrt{\frac{pi}{patm}-1}\right)\right];(*Blue*)$$

$$g3=(vann3/an)*\left(\sqrt{\frac{2}{R*T}}\right)*Log\left[\left(\sqrt{\frac{pi}{patm}}-\sqrt{\frac{pi}{patm}-1}\right)\right];(*Green*)$$

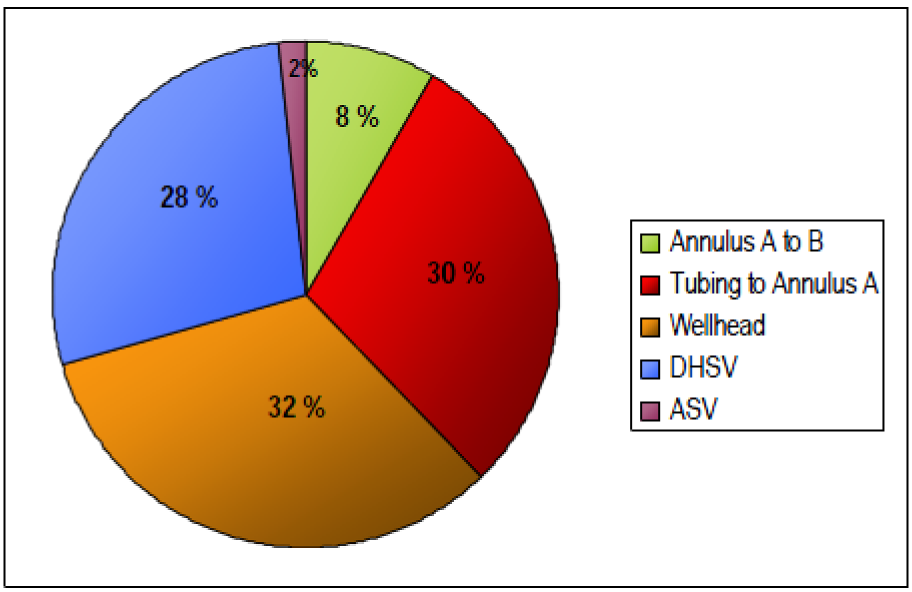
```
Plot[{g1,g2,g3},{pi,3000,16},AxesLabel→{Style["Pressure,Psi",FontSize→14,Black],Style["Bleed-off Time,Sec",FontSize→14,Black]},AxesStyle→Bold,ImageSize→600,
PlotStyle→{{Red,Thickness[0.005]},{Blue,Thickness[0.005]},
{Darker[Green],Thickness[0.005]}}]
```

Appendix F



Occurence of SCP in GOM by Casing String

Source: *Sustained Casing Pressure in Offshore Producing Wells*. OTC 11029, Offshore Technology Conference, Houston, Texas.



Type of Leakage

Source: *Assessment of Sustained Well Integrity on the Norwegian Continental Shelf*, SINTEF Petroleum Research, Norway