EFFECT OF TEMPERATURE AND Z-FACTOR ON CASING DESIGN USING KICK TOLERANCE

by

Abu Bakarr Sidiq Jalloh

Dissertation submitted in partial fulfilment of
the requirement for the
MSc. Petroleum Engineering

JULY 2012

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CERTIFICATE OF APPROVAL

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Approved by

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Dr. Reza Ettehadi Osgouei

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TRONOH, PERAK

July 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 reference and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

ABU BAKARR SIDIQ JALLOH

ABSTRACT

The appropriate selection of casing shoe depth is an important aspect in the casing design of an oil well. It significantly impact on the well cost and safety during drilling. As the search for oil moves into challenging territories such as deep water, where there is a narrow window between pore pressure and fracture pressure, the determination of casing setting depth using kick tolerance needs to be more robust. The current industry practice for predicting casing setting depth using kick tolerance assumes a constant geothermal gradient and ideal gas behavior in the calculations.

The focus of this research is to study the effect of geothermal temperature variations and compressibility (Z) factor on the casing setting depth design process. Such study is important in order to evaluate how these parameters affect the selected depths especially for HP/HT wells. The research method adopted to achieve this aim involves developing an iterative excel macro program for casing setting depth prediction using kick tolerance which takes in to account Z-Factors and temperature gradients variations across subsurface formations. Four cases with different combination of geothermal temperature gradients and Z-Factor are studied to evaluate the effects. The setting depth for each case is predicted by comparing the fracture pressure equivalent density with the pressure generated inside the wellbore during influx circulation.

The results from the study shows that variations in geothermal formation gradients and the incorporation of real gas behavior has an impact on the circulation influx volumes and internal pressures generated during well control procedures and hence affects the selection of casing setting depths. The main conclusions from this study are correcting for Z-Factors and varying geothermal gradients gives lower influx volumes during circulation, thereby reducing the risk of fracturing the formation, Z-Factors and varying geothermal gradients have significant effect on the predicted setting depth at high temperatures but little or no effect at low temperatures; accounting for these effects especially in conventional wells makes it possible to drill longer hole section, thereby reducing the casing sizes to be run, hence lowering well cost considerable. This dissertation recommends that these effects be taken into account during the casing design process for safe and cost effective drilling.

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ABBREVIATIONS

TVD = True Vertical Depth
TD = Total Depth
OH = Open Hole
DC = Drill Collar
DP = Drill Pipe
BHA = Bottom Hole Assembly.
ppg = Pounds per gallon
Fig = Figure
Cir = Circulating

NOMENCLATURES

W_n= New mud weight (ppg)

W_{ex}= Existing mud weight (ppg)

P_{cmax}= Maximum allowable shu-in casing pressure (psi)

D_h= True vertical depth of hole (ft)

K_{in}= Kick tolerance including effect of influx (lbm/gal)

P_{cMax}= Maximum allowable shut-in casing pressure (psi)

G_i= Gradient of influx (psi/ft)

L_i = Length of influx (ft)

D_h = True vertical depth of hole (ft)

D = Final well depth (ft)

D_{cs} = Casing shoe setting depth (ft)

ρ_{frac} = Fracture equivalent density (ppg)

ρ_m= Mud density (ppg)

H_k = Height of kick calculated (ft)

ρ_k= Kick density (ppg)

ρ_{cir} = Equivalent circulating density at casing shoe setting depth (ppg)

V_g= Normalised gas velocity

C_o= Fluid distribution coefficient

V_h= Homogenous Velocity (m/s)

V_s= Slip velocity (m/s)

P= Pressure

V= Volume

T= Temperature

n= number of moles (mass divided by molecular weight)

R_g = Universal gas constant.

T_c = Critical Temperature

P_c = Critical Pressure

P_{bh}= Pressure at the bottom hole (psi)

ρ_{pp}= Pore pressure at TD (ppg)

D= TVD of well (ft)

ρ_m= Mud weight (psi/ft)

h_k= Height of kick (ft)

D_k= Casing shoe depth (ft)

P_{hg}= Hydrostatic pressure of influx (psi)

γ_g= Influx gas gravi

T= Temperature (^{0}R)

Z= Gas compressibility (Z) Factor

V_k= Influx Volume (bbl)

C_s= Annulus Capacity factor (bbl/ft)

V_{ki}= Initial influx volume at TD (bbl)

$P_{bh,}T_{bh,}Z_{bh}$= Pressure (psi), Temperature and Z-Factor at the bottom hole

P, T, Z= Pressure (psi), Temperature and Z-Factors at the depths

CHAPTER 1

INTRODUCTION

1.1 Background

The appropriate selection of casing setting depths for a well is one of the most important aspects of a well design. It is essential for various reasons. Among these reason includes for isolating troublesome hole sections, reducing torque and drag, completion purposes, regulatory requirements and well control considerations. Casing setting depths are traditionally selected based on mud weights. In this method, the pore pressures, fracture pressure and mud weights are used together to select casing setting points. The mud weights are derived by adding an appropriate overbalance to the pore pressure to maintain primary well control but they are also maintained below the fracture gradient to prevent fracturing the formation. In essence, casing seats are selected so that the minimum mud density does not exceed the allowable maximum density. The application of this method relies greatly on accurate estimations of pore and fracture pressures. Selecting casing seat based on mud weights will not provide sufficient fracture integrity to control a gas kick, meaning there is a danger that the pressure generated during the process of circulating the kick out of well will exceed the fracture gradient of the weakest formation in the open hole presumable the formation at casing shoe or at any other critical depth leading to loss of well control and possibly an underground blowout. Hence, the current industry practice of selecting casing setting depths has included well control consideration through the kick tolerance concept.

Kick tolerance is a fundamental concept in well design. Its applications on well design for casing setting depth selection purposes have made drilling much more safe and economical. It defines the number of casing in a well and also indicates whether it is safe to continue drilling or a new casing string should be run in order to reach the target depth. In as much as the concept is fundamental in well design it has been defined in various ways by different operators. Some of the definitions used are highlighted below[1]:

-The largest volume of influx that can be removed from the well safely based on the results of either a Leak off test (LOT) or formation integrity test (FIT or limit test).[1]

•The capability of the wellbore to withstand a state of pressure generated during well control operations without fracturing the weakest formation.[1]

•The maximum increase in mud weight allowed by the pressure integrity test (LOT or FIT) of the casing shoe with no influx in the wellbore.[1]

•The maximum allowable pore pressure, expressed in equivalent mud density such that if a kick with specified volume occurs at a particular depth with a specific drilling fluid the well could be closed down and the kick circulated out safely without fracturing the weakest section in the open hole. [1]

•Maximum influx to equal the Maximum Allowable Annular Surface Pressure (MAASP).[1]

•The maximum kick volume that can be taken into the wellbore and circulated out without fracturing the formation at the weakest point (commonly the casing shoe), given the difference between pore pressure and mud weight in use (kick intensity).

•The maximum volume of a swabbed kick that can be circulated out without fracturing the previous casing shoe

•An estimate of the volume of gas influx at bottomhole condition that can be safely shut in and circulated out of the well.

•The maximum kick intensity that a well can tolerate before lost circulation is experienced at the last casing seat.

The conventional approach of selecting casing setting depth based on kick tolerance assumes a bubble of gas influx into the wellbore and uses it to calculate the pressure generated inside the wellbore when the gas is circulated out of the well assuming constant geothermal gradient and ideal gas behavior. The ideal gas law is thus used to calculate the volumes at various depths in the well. The influx height can then be calculated using the annular capacity factor. The driller’s method (worst case scenario) of kick circulation is then employed to compute the internal pressure generated during the kick circulation process. These pressures are then compared to the fracture gradients at different depths to determine the casing seat depth. The internal pressure prediction is done on a look forward basis as drilling proceeds into area of changing pore pressure regimes. The Driller’s method equation of calculating the internal kick circulation pressures depends on the pore at next TD, the mud weight, the geometry of well and the nature of influx fluid.

The method that assumes gas influx enters as slug into the well and remains as slug during circulation is a simple model that leads to a conservative solution as compared to those obtained by using a gas kick simulator. For this reason Gas kick simulators were developed in order to accurately represent what happens in the wellbore during kick circulation so that accurate internal pressures would be calculated thereby minimizing the risk of fracturing the formations at the casing shoe or any other critical depth.

1.2 Problem Statement

The current industry practice of estimating casing setting depths using kick tolerance assumes a constant geothermal gradient and uses ideal gas law to model the gas as it moves up the wellbore. The issues with this approach is that, the geothermal gradient might not be constant from one formation to another and also in order to model accurately what happens in a well during well control procedures requires that the deviation from ideal behavior (real gas behavior) be considered. Neglecting the effects of such variations will have a significant impact on whether a casing should be set shallower or deeper in a well.

As wells are now drilled in more challenging environments such as HT/HP wells in which there is a small window between pore and fracture pressure, variations on how kick tolerance is calculated can lead to dangerous drilling environment and can also lead to expensive well design.

1.3 Objectives

The main objectives of this project are:

a) To understand gas behavior in terms of PVT relationship as it is circulated out of a well during well control procedures.

b) To develop a procedure for casing setting depth design that takes into account the effect of geothermal temperature changes and real gas behavior and study how these effects affect the selection of casing setting depths

1.4 Scope of Study

The purpose of the project is to study what effects gas compressibility factors and subsurface geothermal temperature variations has on calculation of casing seats using kick tolerance concept. A model that is based on a single gas bubble of an influx will be built on excel macro. The model will be used to study the how the influx volume will change as it moves up the well bore as a real gas in a varying formation geothermal gradient and then highlight the differences when a model of ideal gas behavior and constant geothermal gradient is applied instead. The model will then be used to calculate casing seats using real gas law and changing subsurface formation geothermal gradients and compare the results obtained from the ideal gas behavior and constant geothermal gradients model, in order to quantify the effects the compressibility factors and varying geothermal gradients has on the design.

CHAPTER 2

LITERATURE REVIEW AND THEORY

Kick tolerance has been a controversial subject defined in different ways by different operators. This controversy has led to the publication of lots of technical papers to address the subject. This chapter summarises the pertinent literature found on kick tolerance. It contains an overview of the kick tolerance concept, a review on gas kick simulation models to model and predict gas kick volumes and bottomhole pressure behavior. An overview on the use of equations of state to calculate compressibility (Z-factors) will also be presented.

2.1 The Kick Tolerance Concept

Kick tolerance defined as the maximum difference between the pore pressure and existing mud weight that can be allowed for safe circulation of the influx during well control without fracturing the weakest formation in the open hole is a fundamental concept in well design. It specifies the number of casing strings to be used in a well as well as indicating whether it is safe to continue drilling or to run a casing. The use of kick tolerance in well design and operational well control to avoid kicks or lost circulation and blow outs is been critical to the successful drilling of wells. In light of its significance in well design and drilling, lots of literature has been published on this topic to make it more understandable and reduce the controversies surrounding it.

Early works by K.P Redmann [2], Otto Santos [3] , Antonio Carlos et al [4]were concerned about highlighting the significance of kick tolerance in well design and how it can be used to determine casing setting depths. Adetola, Isaac and Olayinka [5] proposed a stochastic model for selecting the appropriate kick tolerance for a given region. Further works by Oumer, Taufiqurranchman, Perrucho and Yunnus [6] dealt with the use of kick tolerance to design wells in a shallow gas field.

Helio Santos, Catak and Sandeep[1] highlighted the Misconceptions associated with the kick tolarnce concept and the consequences they bring to well design.

In order to enhance the understanding on kick tolerance, Redmann [2] presented a new method for calculating kick tolerance. In the past kick tolerance has been defined based on zero pit gain as the maximum increase in mud weight allowed by the pressure integrity test at the casing shoe with no influx (zero pit gain) in the well bore. Based on this definition the kick tolerance equation is written as;

$$W_n - W_{ex} = \frac{P_{cmax}}{(0.052D_h)} \text{.................................Equation 1}$$

Where

W_n= New mud weight (ppg)

W_{ex}= Existing mud weight (ppg)

P_{cmax}= Maximum allowable shut-in casing pressure (psi)

D_h= True vertical depth of hole (ft)

From this definition a new equation was developed that considers influx into the wellbore. The derivation assumed worst case well control that is influx enters the bottom of the well as slug and is gas. This will cause a substantial increase in the maximum allowable casing shoe pressure during shut-in and hence reduces the kick tolerance allowable in the wellbore. The kick tolerance at shut in conditions is calculated using equation 2. It is given as a function of maximum pit gain expected, given an assumed gas kick density, the existing mud weight, well depth, the fracture gradient at the weakest formation and the depth of the weakest formation

$$K_{in} = (P_{cMax} - \{(0.052W_{ex}) - G_i)L_i\}/0.052D_h \text{.......Equation 2}$$

Where

K_{in}= Kick tolerance including effect of influx (lbm/gal)

P_{cMax}= Maximum allowable shut-in casing pressure (psi)

W_{ex}= Existing or current mud weight (lbm/gal)

G_i= Gradient of influx (psi/ft)

L_i= Length of influx (ft)

D_h= True vertical depth of hole (ft)

The pressure of the influx when it is circulated to the casing shoe is calculated using the driller's method of well control. Maximum shoe pressure will occur at the shoe when the top of the influx has been circulated to the casing shoe. The pressure generated at the weakest formation presumable the casing shoe is calculated in an iterative manner using the pressure/volume equation to predict both the pressure and volume of the shut-in influx as it is circulated to the casing shoe. The equivalent mud weight W_{eq}, at the shoe may then be determined and a new kick tolerance value computed from:

$$K_c = s - W_{eq} \text{……….............Equation 3}$$

Where,

K_c= Circulation Kick Tolerance

s= Shoe test (ppg)

W_{eq}= Equivalent mud weight (psi)

The value of kick tolerance computed from equation (2) is compared to that from equation (3), the lesser of the two values is used as the kick tolerance.

Drilling parameters affect kick tolerance for a given hole section as shown in Fig 1. Kick tolerance decrease with the following: Increase in true vertical depth, increase in mud weights, increase in pit gains, increase in drill collar lengths as well as with influx expansion during circulation as shown in the Fig 2.

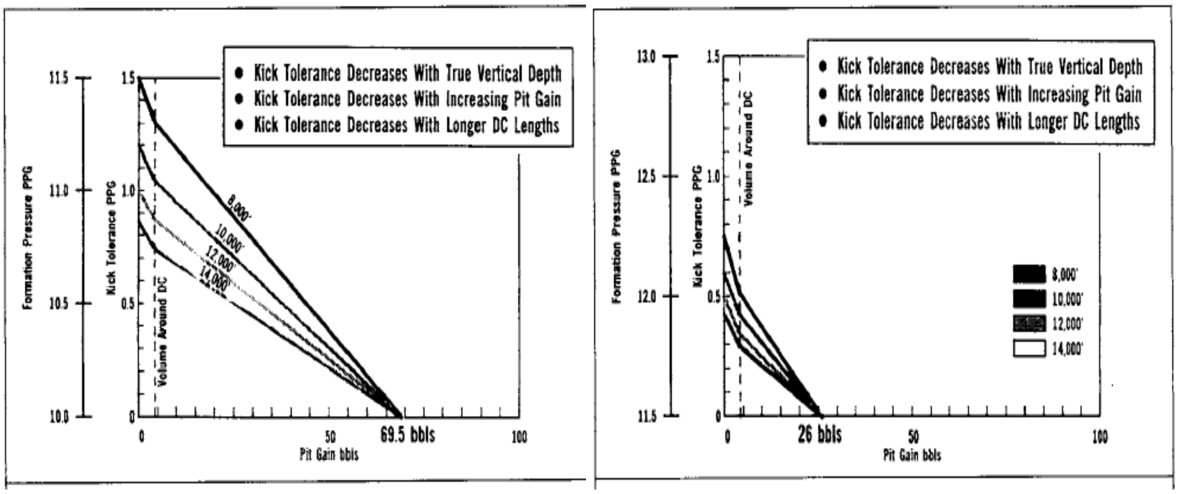

Fig.1: Kick tolerance at initial shut-in conditions and with mud weight increased [2]

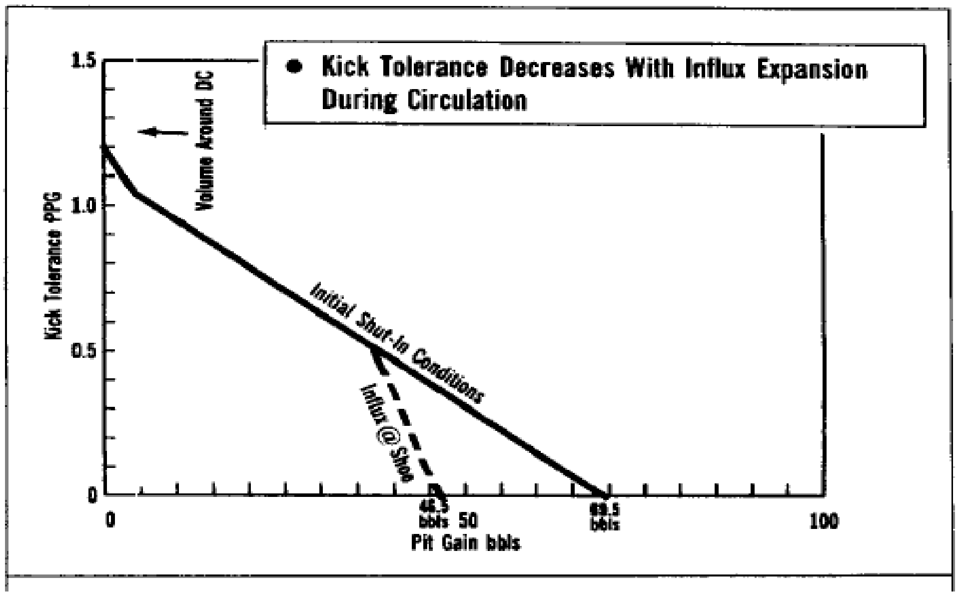

Fig.2: Kick tolerance with influx at shoe [2]

During well planning, kick tolerance must be considered in selecting the casing setting depths incorporating all the factors mentioned above. Fig 3 shows the impact of kick tolerance on casing shoe selection. It is important to note that the effect of temperature and z-factor have not been considered in this work.

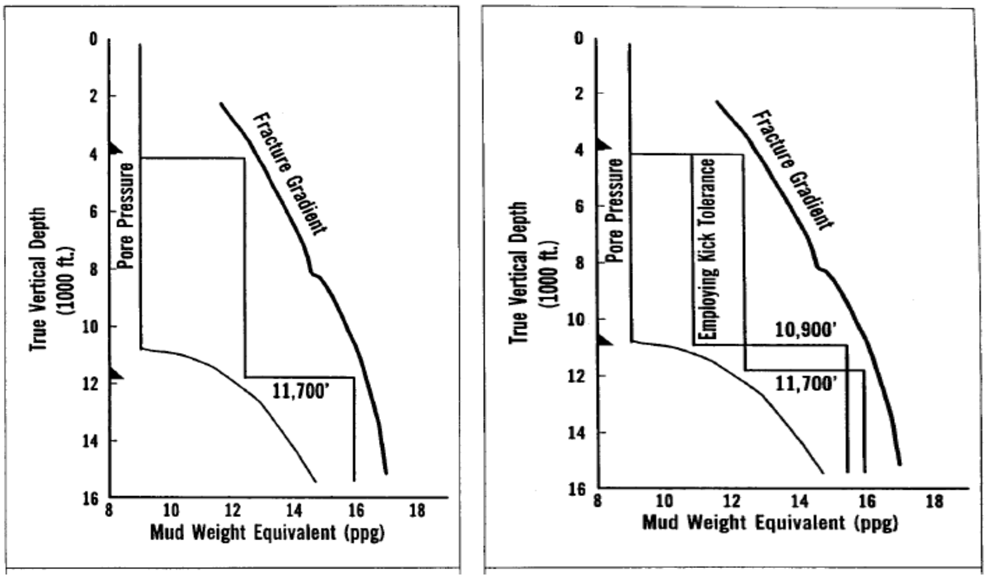

Fig.3: Choosing casing setting depths with and without kick tolerance [2]

Santos [3] developed the concept presented by Redmann [2] and proposed a methodology which provides a faster and accurate way of defining casing setting depths in oil wells based on kick tolerance concept. An algorithm which uses an iterative procedure defines the shallowest casing shoe setting depth using the kick tolerance concept. Kick tolerance for the state of pressure inside the wellbore after shut in is given by:

$K_{t-wc} = \frac{(\rho_{frac}-\rho_m)}{D} * D_{cs} - \frac{(\rho_m-\rho_k)}{D} * H_k$………………Equation 4

Where,

D= Final well depth in feet

D_{cs} = Casing shoe setting depth in feet

ρ_{frac}= Fracture equivalent density at D_{cs} in ppg

ρ_m= Mud density in ppg

H_k = Height of kick calculated using the maximum kick volume assumed for the calculations and the bottomhole geometry.

ρ_k= Kick density in ppg

The casing shoe setting depth should satisfy the following design criteria

$$\rho_{casing\ shoe\ at\ shut\ in\ time} \leq \rho_{frac}$$

Replacing ρ_{frac} in equation (4) by the maximum pressure generated at the shoe and using a 0.5 ppg kick tolerance for well containment, equation (4) becomes

$$\rho_{max} = \rho_m + \frac{0.5\,.D + H_k\,.(\rho_m - \rho_k)}{D_{cs}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \text{Equation 5}$$

To determine the casing setting depth the fracture gradient of the formation is compared to the pressure generated inside the wellbore during a well control operation. The procedure involves guessing a casing setting depth, then calculating the maximum pressure in the wellbore after shut-in, a kick tolerance of 0.5 ppg is then added to this value, if the resulting value is equal to or less than the fracture equivalent density then the guessed setting depth is the shallowest casing setting depth. This procedure is continued until the optimum depth is obtained. The procedure was applied to determine casing setting depth during kick circulation using the driller’s method. For this situation, kick tolerance is given by the equation:

$$K_{t-cir} = \rho_{frac} - \rho_{cir} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots. \text{Equation 6}$$

Where

ρ_{cir} = Equivalent circulating density at casing shoe setting depth in ppg

In this method, the pressure generated inside the wellbore at every depth is predicted and compared to the fracture pressure at the same depth. The procedure is similar to the one used for well containment. The model showed that the higher the kick tolerance volume the greater the shallowest casing setting depth.

Antonio Carlos [4] presented new criteria for casing setting depth design for unconventional well based on modified kick tolerance margin for HT/HP exploration wells in deep water. HT/HP wells are charactersied by rapid rising pore pressures, convergence of pore and fracture gradients and long sections of openhole which makes the well design restrictive. For wells of this nature the conventional setting depth criteria would greatly increase well cost and would make it difficult to reaching the target due mainly to borehole size constraints. These limitations required a new basis of applying the kick tolerance concept. Previous work [2],[3] on kick tolerance specifies the tolerance margin based on mud weigh allowed for a give hole section, that is the difference between kick tolerance and the mud weight. However this concept is only valid where the formation pressure forms the unique basis for defining mud weights. Other constraints may require an increase in mud weight, thereby reducing the kick tolerance margin leading to a casing been set shallower than necessary. In order to address this problem, a new criterion was formulated where the kick tolerance was compared with the estimated pore pressure to determine the kick tolerance margin. When this new criteria was applied it shows a casing will be set deeper than specified by the old criteria for wells where increase in the mud weight is required to address difficulties in drilling.

Selection of the appropriate kick tolerance is critical in well design and involves various techniques and practices, the most common been the use of gas kick simulation models to quantify the selected value and another is to use historical kick data. Both methods depend on historical well control data. It was on this note Adetola, Isaac and Olayinka [5] carried out their work because it was noted that the problem does not lie with the data but the manner in which it has been transformed into usable forms. The authors use a stochastic analysis procedure to transform historical well control data into usable probabilistic models for reliable prediction of kick tolerance within a given geological setting. The stochastic procedure of analysis consists of essentially using probabilistic techniques to model occurrence of sequence of events based on statistical analysis of historic data as compared to the historical approach which involves a simplistic prediction based on worst case scenario. The model is represented as normal frequency distribution curve of historical kick intensities for a field. Based on this distribution a prediction of maximum kick intensity of 5 ppg was made and was compared to distribution generated using results from a gas kick simulation model which incorporates data from the same field. The results from both predictions were consistent thus validating the model. The historical and the stochastic approaches were applied to determine kick tolerance for the drilling of the 8 ½’’ hole section of a horizontal well, it was found that the stochastic approach gave a lower volume allowing the well to drilled to the target depth as compared to the historical approach which gave a higher volumes thus requiring an extra casing string to reach the target depth and as such increasing the well cost. The stochastic approach provides a more realistic method for selecting appropriate kick tolerance to be used in the design of wells. However the stochastic approach is only valid for regions whose data have been used to generate it.

In equation (5) the height of the gas in the open hole is calculated by dividing the volume of gas influx by the annular geometry between hole and drill pipe. Oumer, Taufiqurrachman and Perruchot [6] showed that well design based on kick tolerance is greatly affected by bore hole size. They were faced with creating a well design for the shallow gas reservoirs in the Tunu Field with a low LOT at the 9 5/8’’ surface casing shoe. Two Architectures were proposed as shown in Fig 4.

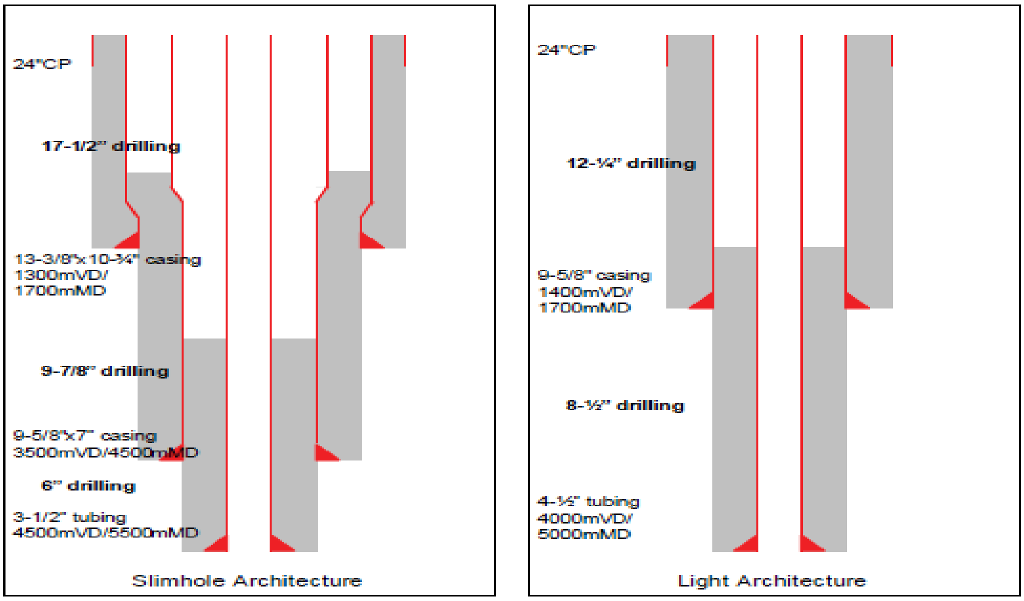

Fig.4: Proposed well Architectures [6]

Both designs were investigated for casing setting depth that can permit the circulation of 5 m^3 of influx gas. From the results it was found that the first architecture gave satisfactory results for all depths investigated but the second architecture gave limitations in setting depths with regards to kick tolerance, hence showing that the reduction on the hole size in the second architecture have impacted on the design. It is important to note that when the kick tolerance was reduced to 3 m^3 the second architecture gave satisfactory results in terms of maximum TD drilled.

The concept of kick tolerance have been defined and applied in different ways by different operators in well design and drilling implementation as was mentioned earlier in the background. Santos, Catak and Sandeep [1] carried out a review of the fundamental concepts in the application of kick tolerance and they found that few misconceptions that have been made in applying the kick tolerance concept. They also studied the consequences they bring to well design. Amongst the misconceptions is the assumption that an approach utilizing a single bubble model ignoring the effect of temperature and gas compressibility factor in the final calculations will always result in a conservative solution. The current approach for calculating kick tolerance for a given hole section does not take into account the effect changes in temperature along the wellbore. In this study the effect of temperature changes on the influx volume was taken into account by using Charles Law. The results show that the effect of temperature resulted in a higher kick tolerance volumes as compared to the current approach which assumes constant temperature in the well bore. The effect of compressibility factor was also investigated. The Z-factor is used to allow for using the ideal gas law to model the behavior of real gases. Compressibility factor were for conditions along the openhole and the results shows that the smaller the Z-factor the higher the kick tolerance. It must be stressed here that the temperature been used is that of the constant geothermal gradient, in this project the effect of varying temperature gradients across different formation types in the kick tolerance calculations will be studied coupled with changes in the compressibility factors for the stated temperatures and pressures in the formations.

2.2 Gas kick Simulation Models

The previous discussions on the use of the kick tolerance concept in well design assume the influx as slug and remains as slug during circulation. This method gives a conservative solution to the kick tolerance calculations. The flow of gas influx in the wellbore is a complex process which involves the interaction of internal sub-processes as well as external factors such as well geometry, mud and gas properties, reservoir conditions etc. that defines the character of the kick. In order to accurately describe this flow process in the wellbore, gas kick simulators are needed. A lot of work has been done on this subject that has resulted in the publication of many technical papers.

D.B White and Walton [7] developed a computer gas kick model for kicks in water and oil based mud. The model is based on the full mass (mud and gas) and momentum (gas-mud mixture) equations. The mathematical representation of the model took into account wellbore hydrodynamics by modeling the distribution of drilling mud, dissolved gas and free gas at different times and different positions, it also accounted for flow of gas from the formation by deriving an equation from the combination of the equation of conservation of mass, an equation of state of the fluid and Darcy’s law for flow in porous medium. Equations accounting for Gas dissolution, variation of rheological parameters of the mud with pressure and temperature (Casson Model), frictional pressure losses, dispersion of dissolved gas and an empirical correlation for gas rise in the drilling mud were used. The model also considered well plan geometry and took into account the variation of downhole temperatures during circulation. The model was validated with experimental data for both oil-based and water-based mud. When a simulation was run using criteria of 10bbl pit gain, gas kick detections in oil-based mud took longer to detect as compared to water based mud. During the kill process in the two cases (water and oil based muds) there is an earlier arrival of gas in the water based mud test as transport is dominated by the rise of free gas. In the oil based mud, the initial pit gain is at a lower rate as the gas expansion is less significant. This has an implication on the bottomhole pressure generated during circulation which in turn determines appropriate casing setting depths for safe drilling.

The early part of the petroleum industry in dominated by conventional wells and as such most of the well control procedures were developed for such wells, but the success of the horizontal well technologies over the past several years have warranted research on many aspects on the subject. Santos [8] in his work presented a model for well control in horizontal well. The mathematical gas kick model proposed assumes a two-phase mixture of gas and water based mud flow under unsteady state conditions. Beggs and Brill correlation was used to account for important two phase flow characteristics such as gas slip velocity, liquid-hold up and two-phase friction factor. A constant temperature gradient is used and the Driller's method of kick circulation is employed. The model could predict the pressure behavior in the annulus during the circulation of the kick in the well. The model was used to compare the pressure development in vertical and horizontal wells and it shows that pressure development in the annulus of a horizontal well is less severe as compared to a vertical well for the same kick tolerance. This implies that a horizontal well has a larger kick tolerance during well shut-in than a vertical well. A theory for swabbing effect during drill string pull out and the risk of taking a kick during suck operations was also studied. It was found that gas kick due to swabbing is more critical in horizontal wells because during swabbing the formation pressure remains constant whilst the pressure drop due to swabbing increase with increase in measured depth of drill string tripped out.

The use of kick simulators to model gas influx into wellbore gives realistic results but only if the simulation model is accurate and as such it needs to be verified with a real gas kick data. To provide confidence of using the gas kick simulator as an engineering tool, Rommetveit and Verring [9] compared the performance test carried out with a gas kick simulator with those obtained from a full scale experimental gas kick well. The mathematical model considers fluid flow as a combined single and two-phase flow problem in both oil and water based muds. The main equations in the mathematical model are those expressing conversation of mass (Free gas, dissolved gas and oil) and conservation of total momentum. The model incorporated a gas rise velocity model. The kick experiment was performed in a 2000 m long and 60^0 inclination well. Surface and downhole data were recorded from the experiment. Real data from the experiment was entered into to the model in order to simulate the kick experiment. Results from the simulator model indicate that a correct gas rise model is critical in order to simulate accurately the kick process.

The determination of the gas rise velocity in the annuli for various well conditions is crucial and fundamental to the development of a more accurate kick tolerance calculation. Experiments to determine these gas rise velocities have to be conducted A.B Johnson and D.B White [10] reported an experiment in which they examined gas rise migration rate in drilling mud. The rate at which free gas rises up the wellbore is a key parameter in the development of a gas kick in a well. Previous work [7],[8],[9] on two-phase flow is based on air/water flows. To represent real drilling condition, air was used as the gas phase and Xanthan gum as the liquid phase. Gas rise velocity from the two flow systems were compared and was found that gas rise velocity in air/water flows depended on void-fraction but independent of void-fraction in air/mud flow system. Predictions from a simulator using air/water as well as air/mud gas rise models were conducted. The gas rise velocity and gas flow rate from the well are higher in air/mud model as compared to air/water model. This has an implication on the kick tolerance volume of the well, for the air/water system. There is a tendency that the tolerance volume would be exceeded before the gas is detected at surface and as such the use of an air/mud model is essential in simulating gas kicks in wells.

Frank Hovland and Roiv Rommetveit [11] reported a gas kick experiment performed on a research well to study gas rise velocities in oil-based and water-based mud. This research reflects real results unlike those performed in laboratories as was discussed in the previous reference. The research was conducted on a 2020 m long research well with a maximum inclination of 63^0. Gas was injected using a coil tubing unit to simulate gas kick. Data was recorded using surface and subsurface sensors to study the development of the kick. The data obtained was then analyzed. According to the results, the free gas velocity is a function of the homogeneous velocity, the flow distribution coefficient and slip velocity. It is given by the following equation

$$V_g = C_o V_h + V_s \text{...} \text{Equation 7}$$

Where

V_g= Normalised gas velocity

C_o= Fluid distribution coefficient

V_h= Homogenous velocity (m/s)

V_s= Slip velocity (m/s)

The results also show that the free gas velocity is not significantly dependent on gas void fraction, well inclination, mud density, viscosity and surface tension.

A.B Johnson and Steven Cooper [12] investigated the effect of deviation and wellbore geometry on the rate at which gas rises up the wellbore. The research was conducted on an experimental scale at the SCR multiphase flow test centre, the facility is described in [10]. The facilities allows for the test of fluid flows in pipes at different elevations for both Newtonian and Non-Newtonian fluids. The test was reported for a well with deviation up to 60^0. To simulate drilling conditions, realistic drilling fluids were employed, air was used as the gas phase and an aqueous Xanthum solution was used as the liquid phase to reflect real drilling muds. From the results it was shown that, in a vertical orientation the flows in the pipe and annulus are almost identical and that the distribution factor (C_o) is the same for the two flows but the gas slip velocity is slightly greater in the annulus. For all deviations investigated, the gas slip velocity is larger in the pipe whist the gas distribution factor is larger in the annulus. The significance of this study reveals that for air-mud flows in pipe geometry, small pipe deviations increases the slip velocity as the deviation is increased past 45^0 slip velocity tends toward the vertical value. For the effect on annular flow, the slip velocity remains unchanged up to deviation of 45^0 after which it starts to fall.

Gas kick into a wellbore can be extremely dangerous leading to loss of life, destruction of property and significant environmental damage. Hence it is very important that a kick be detected and circulated safely to surface. Well control procedures used to maintain safe kick circulation rely on very simple calculations to calculate kick density, formation pressures and maximum casing shoe pressure from hydrostatic calculations using surface measurements of pit gains, difference between stabilized surface pressures in the drill string and the annulus, stabilized drill pipe pressure and change in hydrostatic pressure as the influx moves up the well. However, these calculations are subject to major errors. To address these errors, Billingham, Thompson and White [13] reported a new method to analyse these surface measurements and developed equations for pit gain and drill pipe pressures. These equations were fitted to surface measurements to reveal important downhole quantities. One such quantity is the maximum casing shoe pressure that would be generated when circulating out a gas kick. Standard methods of predicting such pressures assume gas exist as a single bubble and ideal gas behavior. These calculations overestimated the true pressure. The gas influx was treated as a distributed bubbly mixture of gas and mud which occupies a greater length of the annulus. Down hole gas distribution was estimated using a rise cloud of influx gas in drilling mud model instead of a function of void fraction. Gas was assumed to have ideal gas behavior. These assumptions were incorporated into the model to improve prediction of maximum casing shoe pressure and it gave a lower pressure than that estimated using standard method. From the results it is seen that a good model of the gas dynamics during kick enables the estimation of the distribution of the influx which allows for a more accurate estimation of maximum casing shoe pressure as compared to the single bubble approximation.

As was mentioned earlier, the successes of the application of the horizontal well technologies for reservoir development have seen many research and investigation conducted on the subject. Zhihua , Peden and Lemanczyk [14] performed simulation studies on gas kick displacement in horizontal and conventional wells. The simulation model was based on mass and pressure balance equations of mud and gas as well as empirical correlations relating gas velocity to the average mixture plus the relative slip velocity and equations of state for gas and mud. Their work is an extension of previous works [7],[8],[10],[12],[13] done on the gas kick simulation. The model was used to simulate kick in a horizontal well and vertical well to enable comparison. The results show that the delta flow (flow-out minus flow-in at surface) used for kick detection remains to be a sensitive parameter in horizontal wells, it was also revealed that the effect of gas migration is considerably smaller in horizontal wells particular those with long horizontal sections. The most important finding shows that horizontal wells demonstrate a larger kick tolerance at the moment of well closure and can be shut longer without fracturing the weakest formation but swabbed kicks are a major concern in such wells.

As the most easily accessible oil becomes even harder to get, the search for the precious resource has moved into more challenging environment (Deep water). Drilling activities in these environments requires different forms of well designs and well control procedures. Nunes, Bannwart and Ribeiro [15] reported a mathematical model to predict pressure behavior in the annulus during gas-kick circulation out of the well in more challenging deep water environment. In the mathematical formulation of the model, considerations regarding the effects of wellbore geometry, frictional pressure losses, influx expansion and two-phase flow models have been implemented using different forms of equations. The model with its codes was validated by comparing it to other simulators using different codes and results were found to be satisfactory. The model was then used to investigate the effect of different surface measurements on the choke pressure. Results shows that, the larger the pit gain the larger is the choke pressure to maintain a constant bottomhole pressure, the choke pressure reduces with increased in water depth due increase in friction pressure losses inside the choke line, also it was observed that the higher the pump flow rates during circulation the lower the lower the choke pressure profiles due to increased friction pressure losses. Mud density was also found to have a significant impact on the choke pressure profile.

2.3 Theory on Gas Behaviour

In well control techniques, the nature of the gas and how it reacts to change in wellbore condition is critical to maintaining a desirable constant bottomhole pressure. Well control procedures are designed to move gas influx up the wellbore while circulating at a constant bottomhole pressure. To achieve this, the expansion and compressibility nature of the gas must be accounted for during kick circulation.

In the process of killing a well, the influx goes through phase changes. Understanding these phase changes is important for predicting reasonable annulus pressure generated during the well killing process. Fig 5 shows a pressure /temperature phase diagram for a pure gas. The line separating the liquid phase and the gas phase is defined as the vapour pressure curve and the line separating the solid phase and the liquid phase is defined as the melting point curve. The liquid and gas phase are the most important portion in the diagram to petroleum engineers. At point C, the temperature (T_c) for pure gases refers to the critical temperature; a point at which only gases exist while (P_c), the critical pressure is a pressure above which liquid and gas co-exist.

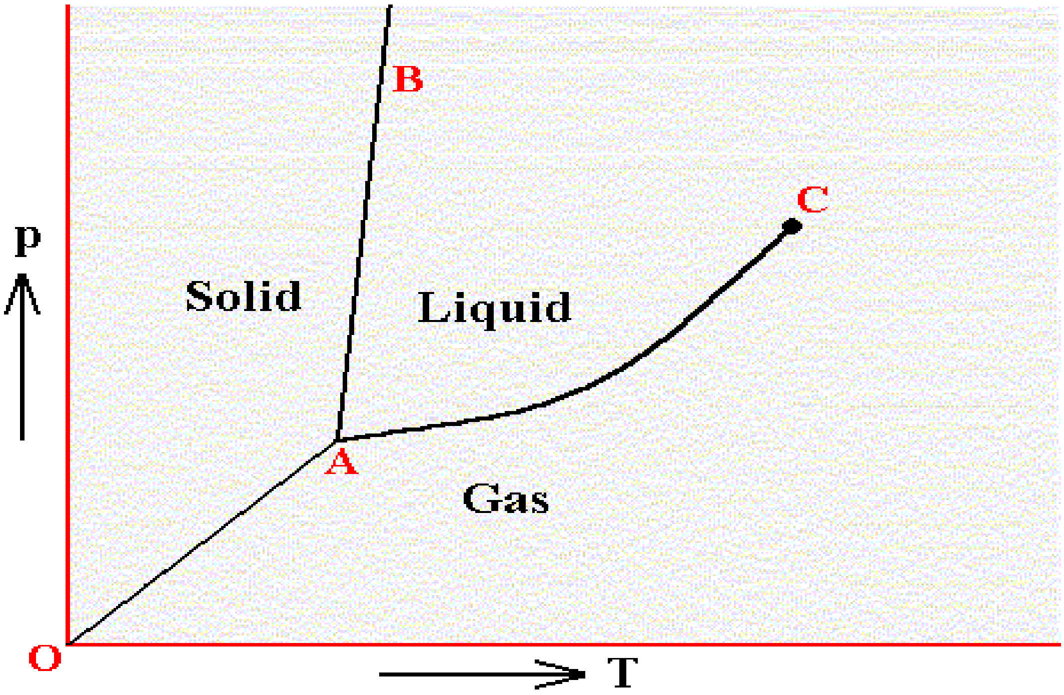

Fig.5: Pressure/Temperature phase diagram for pure gases [19]

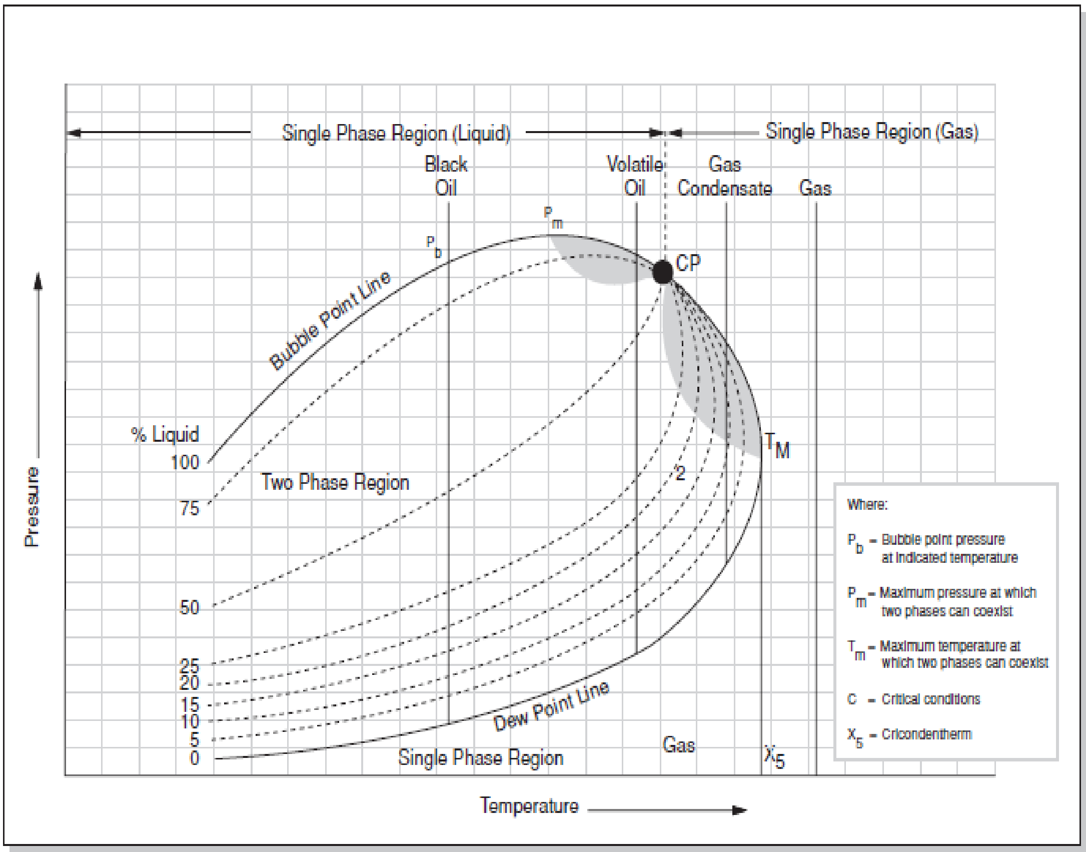

Fig.6: Pressure/Temperature phase diagram for mixtures [16]

However, in reality produced reservoir fluid are rarely pure gases or liquids but a combination. The phase diagram of a mixture is shown in Fig 6. Increase liquid concentration in the envelope is seen at increasing pressure and at decreasing temperature. From the diagram if an influx enters the wellbore at bottomhole conditions where influx is all gas. As the influx is circulated out, it goes through phase changes, liquid starts falling out of the gas mixture at reduced pressure and temperature, this liquid concentration increase further when the gas reaches the surface. This shows that during kick circulation, conditions exist in the wellbore where the gas concentration increase as the influx approaches the surface.

Gas law principles describe the Pressure/Volume/Temperature (PVT) relationship of gas influx as they are moved up the wellbore.

Robert Boyle [19] found by experiment that at constant temperature, the volume of a quantity of gas is inversely proportional to its pressure

$$P_1V_1 = P_2V_2 \text{……………………………………..Equation 8}$$

Where,

P and V are the pressures and volumes of the gas at condition 1 and 2.

Charles [19] also found that the Temperature and Volume of a given quantity of gas are direct proportional

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} \text{……………………………………..Equation 9}$$

Where,

V and T are volume and Temperature at condition 1 and 2.

Absolute Temperatures and Pressures are used in these equations

Another law, the Avogadro's Law [19] states that under the same conditions of temperature and pressure equal volumes of an ideal gas contains the same number of molecules.

An equation of state for ideal gas is obtained by combining Boyle's Law, Charles's Law with Avogadro's Law, given as;

$$\frac{PV}{T} = nR_gT \text{…………………………………Equation 10}$$

Where,

P= Pressure

V= Volume

T= Temperature

n= Number of moles (mass divided by molecular weight)

R_g = Universal gas constant.

For an influx into the wellbore, n is constant, hence

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \text{……………………………………Equation 11}$$

The gas density is given by mass per unit volume

$$\rho = \frac{m}{V} = \frac{nM}{V} \text{…………………………………….Equation 12}$$

Density of an ideal gas is given by

$$\rho_g = \frac{pM}{R_gT} \text{…………………………….Equation 13}$$

Specific gravity for gas is given by the ration of its molecular weight to that of air (M_g)

$$\gamma_g = \frac{M}{M_g} \text{………………………………..Equation 14}$$

From equation (13) and equation (14), Gas density is given by

$$\rho_g = \frac{29\gamma_gP}{R_gT} \text{………………………….Equation 15}$$

Gas specific gravity is usually assumed between 0.6 and 0.7 for well control purposes.

Ideal gas behavior was found to be valid only under limited range of pressure and temperature conditions. For this reason compressibility factors or Z-Factors were introduced to account for non-ideal gas behavior. The equation for non-ideal gas behavior is given by

$$\frac{P_1V_1}{Z_1T_1} = \frac{P_2V_2}{Z_2T_2}$$ ……………………………Equation 16

The compressibility factors vary with changes in gas composition, temperature and pressure. Z-Factors have been determined experimentally for various pure gases. The curves in the plot have similar shapes but the actual Z values are component specific. However, through the law of corresponding states all gases are shown to have common values. The law of corresponding states, states that all pure gases should have similar Z-Factor when the Pressure and Temperature are referenced to the critical pressure and temperature of the gas. The reduced Temperature and reduced Pressure makes this possible.

Reduced Temperature $T_r = \frac{T}{T_c}$…………………………Equation 17

Reduced Pressure $P_r = \frac{P}{P_c}$……………………………Equation 18

Where,

T_c = Critical Temperature

P_c = Critical Pressure

Having obtained the reduced temperature and reduced pressure, Z-Factors can be obtained from the Standing and Kartz chart shown in Fig 7 [16].

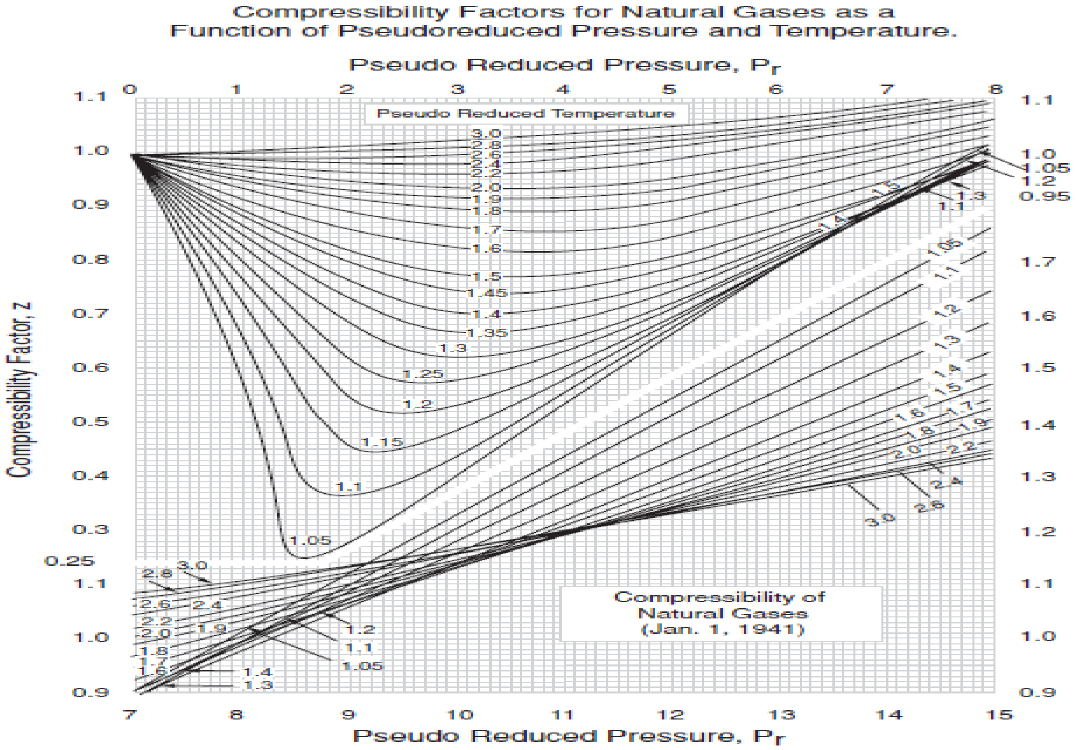

Fig.7: Compressibility factors for natural gas (Standing and Kartz chart) [16]

The Standing and Kartz chart is incorporated into many computer programmes but this chart is specific to the condition at which it was prepared. It was on this note it was deemed necessary to develop equations that allows for extrapolating to conditions outside the region of the chart. These equations are referred to as Equations of State. These equations are developed by fitting the chart with experimental data; the fitted equations are then used to calculate the Z-Factor. Many technical papers have been published on this subject.

Dranchuk and Abou-Kassem [17] verified the use of an equation of state to calculate Z-factors. The relevant equation is the Starling equation of state. This equation was fitted with 1500 data points used in the Dranchuk et al. After fitting the equation, it was used to make a comparison with the Hall and Yarborough and Dranchuk et al equations of state using different forms of data. From the results of the comparison, the authors revealed that the fitted Equations of Hall Yarborough, Dranchuk and Startling equation presented in this paper are within engineering accuracy regions of

$0.2 \leq P_r \leq 30$, $1 \leq P_r \leq 3$ and $P_r \leq 1$, $0,7 \leq T \leq 1$ but are not accurate in the region $T_r = 1$; $P_r \leq 1$.

R.P Sutton [18] examined the effect of high molecular weight gases on the calculation of compressibility factors and presented an equation for the calculation of critical Temperature and critical Pressures for heptane plus gases. Compressibility factors calculations are referenced to critical temperatures and pressures (single gas) and pseudo-critical temperatures and pressures from Kay’s molar average combination rules (gas mixtures). This rule gave inaccurate values for pseudo-critical temperatures and pressures for heptane plus gases hence inaccurate Z-factors. Using a data bank of laboratory measured natural gas composition and PVT properties, it was found that the Lee-Kessler correlation gave more accurate results and hence was recommended for calculating critical properties for heptane-plus gases. The Stewart, Burkhardt and Voo (SBV) combination rules together with empirical adjustments factors related to the presence of heptane plus greatly improved the calculations of pseudo-critical temperatures and pressures and in essence leading to a more accurate calculation of compressibility (Z) factor.

CHAPTER 3

METHODOLOGY

This chapter presents the methodology that will be used in this project to study the effect of changes in geothermal temperature gradient and compressibility factor (Z-Factor) in casing design. The study is done using excel macro programme.

The following algorithm will be adopted for the casing design using the kick tolerance concept.

3.1 Algorithm

1. Specify the setting depth for the first casing (Conductor) and well total depth (TD).
2. Assume a casing setting depth between the first casing shoe and well TD
3. Add a kick intensity of 0.5 ppg to the mud density at the assumed depth (Assumption Mud density = Pore pressure at assumed depth)
4. Assume a minimum kick tolerance influx volume at TD
5. Estimate the temperature and compressibility (Z) factor at the assumed depth as well as at well TD and use real gas equation to calculate the influx volume at assumed depth
6. Use annular capacity between drillpipe/BHA to calculate influx height
7. Using the influx heigh and an assumed influx gradient at the bottom of the gas bubble, calculate the influx pressure at the top of the gas bubble
8. Calculate the maximum pressure at the casing shoe using Driller’s method.
9. Determine the equivalent density at the casing shoe and compare to the fracture density.
10. Adjust the casing setting depth based on the result
11. Repeat steps 2 through 10 until equivalent density of annulus pressure generated pressure equals fracture density.
12. Once shoe depth is fixed, the same calculations are repeated to get next casing shoe assuming this depth as the well TD till the first casing setting depth is reached.

The flow chart describes the steps in the process

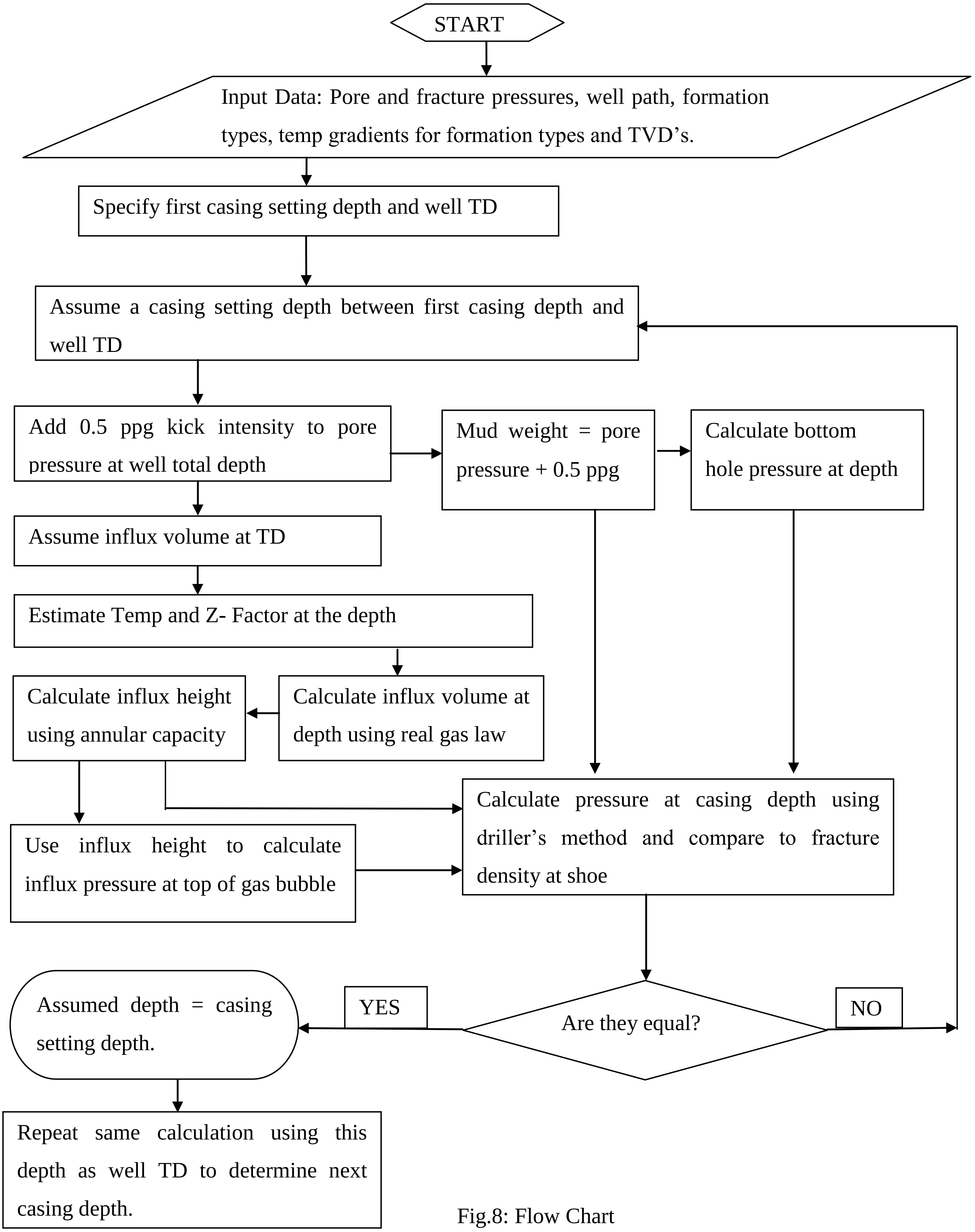

Fig.8: Flow Chart

3.2 Mathematical Equations used in the Modeling.

The mathematical equations used to estimate the annulus pressure and expansion characteristics of the gas while circulating out a gas influx can be obtained by combining the Gas Laws and hydrostatic pressure of the mud and influx at various depths.

Consider that while drilling a hole section of a well a gas influx into the wellbore occurs, the following equations[19] are used to estimate the annulus pressure whilst the influx is removed from the well in order to estimate casing setting depth

The pressure at the bottomhole is given by:

$$P_{bh} = \left(\rho_{pp} + 0.5\right) * 0.052 * D \text{……………………..Equation 19}$$

Where,

P_{bh}= Pressure at the bottomhole (psi)

ρ_{pp}= Pore pressure at TD (ppg)

D= TVD of well (ft)

The pressure at the top of the gas bubble is the bottomhole pressure (P_{bh}) less the combined hydrostatic pressure of the gas influx and the underlying mud given by:

$$P_{top} = P_{bh} - \rho_m(D - h_k - D_k) - P_{hg} \text{………………………Equation 20}$$

Where

ρ_m= Mud weight (psi/ft)

D= TD of well (ft)

h_k= Height of kick (ft)

D_k= Casing shoe depth (ft)

ρ_{hg}= Hydrostatic pressure of the influx gas column (psi)

Hydrostatic pressure of the influx gas column= Influx Hydrostatic gradient X influx height

$$P_{hg} = \frac{\gamma_{g*P*h_k}}{53.29*ZT} \text{……………………Equation 21}$$

Where,

P_{hg}= Hydrostatic pressure of influx (psi)

P= Pressure at the depth (psi)

h_k= Influx height (ft)

γ_g= Influx gas gravity

T= Temperature (^{0}R)

Z= Gas compressibility (Z) factor

The influx height h_k is calculated by dividing the gas volume at the point of interest by the annulus capacity factor

$$h_k = \frac{V_k}{C_s} \text{…………………………..Equation 22}$$

Where,

h_k= Influx height (ft)

V_k= Influx volume (bbl)

C_s= Annulus capacity factor (bbl/ft)

Gas volumes at every depth is calculated from the real gas law

$$V_k = \frac{P_{bh} V_{ki} Z T}{P Z_{bh} T_{bh}} \text{……………………..…Equation 23}$$

Where,

V_k= Influx Volume (bbl)

V_{ki}= Initial influx volume at TD (bbl)

$P_{bh,} T_{bh,} Z_{bh}$= Pressure (psi), Temperature and Z-factor at the bottomhole

P, T, Z= Pressure (psi), Temperature and Z- factors at the depths

The gas compressibility (Z) factors are calculated numerically using the Dranchuk and Abou-Kassem correlation shown below along with the Newton-Raphson iterative method. The calculations are programmed in excel macro for conditions along the openhole. The Code is given in appendix.

Dranchuk and Abou-Kassem correlation for calculating gas compressibility factors.

$$Z = [1 + C_1(T_r)\rho_r + C_2(T_r)\rho_r{}^2 - C_3(T_r)\rho_r{}^5 + C_4(\rho_r,\ T_r)]$$

$$C_1(T_r) = 0.3265 - \frac{1.07}{T_r} - \frac{0.5339}{T_r{}^3} + \frac{0.01569}{T_r{}^4} - \frac{0.051615}{T_r{}^5}$$

$$C_2(T_r) = 0.5475 - \frac{0.7361}{T_r} + \frac{0.1844}{T_r{}^2}$$

$$C_3(T_r) = 0.1056\left(\frac{-0.7361}{T_r} + \frac{0.1844}{T_r{}^2}\right)$$

$$\rho_r = \frac{0.27 P_r}{Z T_r}$$

$$C_4\left(T_{r\,,}\,\rho_r\right) = 0.6134(1 + 0.721\rho_r{}^2)\left(\frac{\rho_r{}^2}{T_r{}^3}\right) exp^{(-0.721\rho_r{}^2)}$$

After obtaining these values, they are then substituted into equation (20) to calculate the annulus pressure generated inside the wellbore during kick circulation. This pressure is then compared to the fracture pressure at the desired depth to determine the casing setting depth based on the following criteria.

$$\rho_{at\ casing\ shoe\ during\ circulation} \leq \rho_{frac}$$

Where,
$\rho =$ Fracture density equivalent.

This process is repeated at different depths starting from well TD upwards to determine the casing setting depth as described in fig 18.

These mathematical equations will be programmed on excel macro using the procedure described in the flow chart (Fig 8). The developed code will then be used to carry out study of the effect of Temperature variations and Z-Factors on Casing design using kick tolerance.

CHAPTER 4

ANALYSIS, RESULTS AND DISCUSSIONS

This chapter contains the analysis done on the project in order to achieve the objectives. It also presents the results and discusses their significance.

4.1 Model Input Data

To account for the kick tolerance in casing setting depth selection for an oil well, the following data are required:

1. The well geometry, comprising of the MD, inclinations and TVD.
2. The formation pressure at TD of the hole section considered.
3. The mud weights for the next hole section
4. The maximum kick volumes that can be circulated out
5. The fracture equivalent density curve of the formation.

The data used for the analysis is from a real field well. It is a deviated well with a build- up rate of 3^0/100ft and a final inclination angle of 77.69^0. The MD of the well is 15653 ft. with a corresponding TVD of 5404 ft. The well trajectory is given in Fig 9.

A summary of the hole sizes, casing sizes and mud weights of the well use in the simulation is given in Table 1. The table also gives the mud weights used in the different hole sections.

Table 1: Well Parameters for Simulation

Wellbore Diameter (in)	**Casing Sizes (in)**	**DrillCollar OD (in)**	**DrillPipe OD (in)**	**Mud weight (ppg)**
12.25	13.375	9	5	11.75
8.5	9.625	6.25	5	10.7

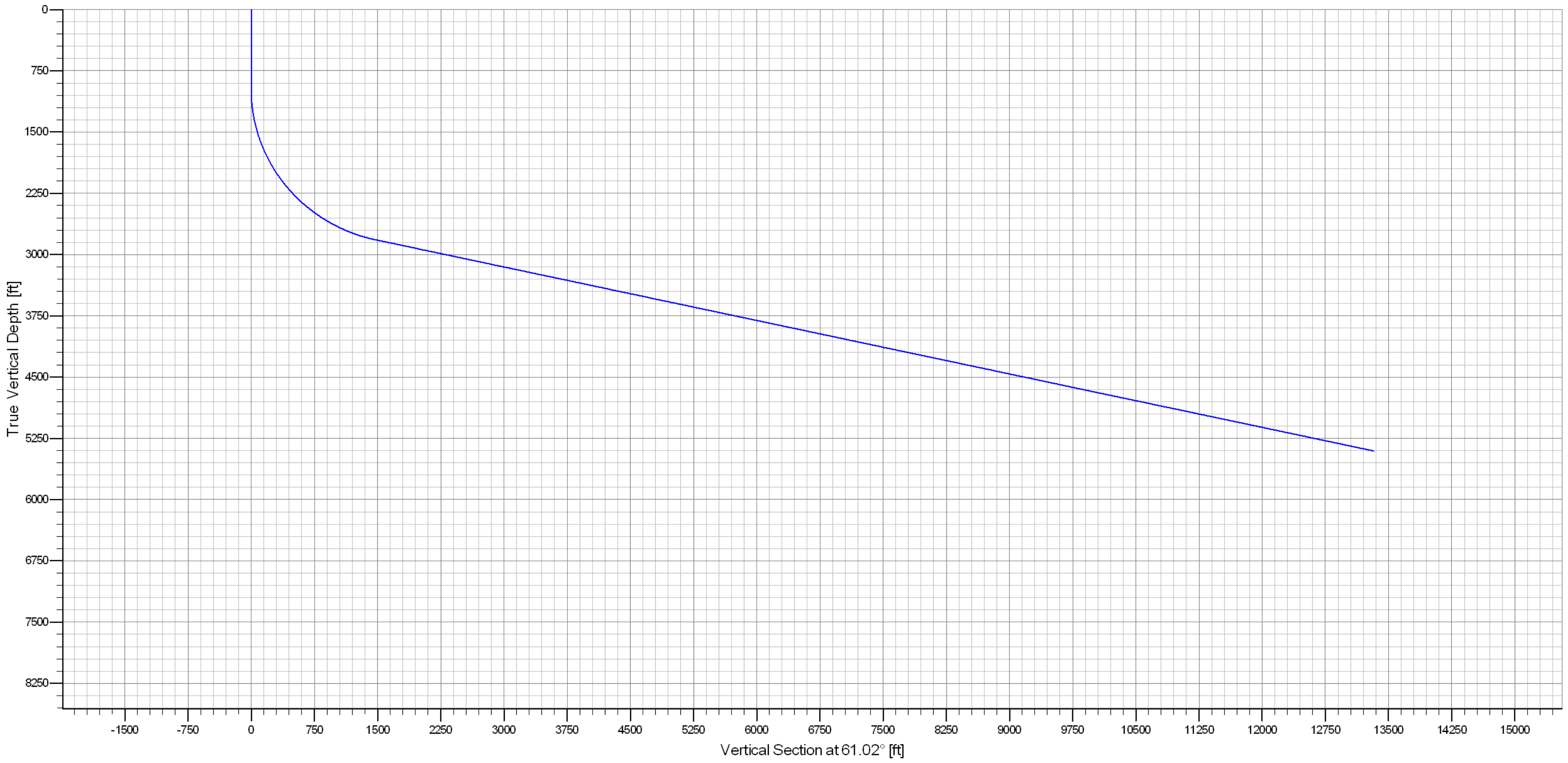

Fig.9: Well Trajectory

The pore pressures and fracture pressures of the area are given in the table below

Table 2: Pore and Fracture Pressure Data

TVD (ft)	Pore Pressure (psi/ft)	Pore Pressure (ppg)	Fracture Pressure (psi/ft)	Fracture Pressure (ppg)
394	0.436	8.38	0.576	11.08
574	0.436	8.38	0.584	11.23
984	0.436	8.38	0.602	11.57
1565	0.436	8.38	0.625	12.01
2008	0.436	8.38	0.640	12.30
2679	0.436	8.38	0.651	12.51
2822	0.436	8.38	0.661	12.72
3032	0.436	8.38	0.665	12.79
3704	0.436	8.38	0.674	12.96
3914	0.436	8.38	0.675	12.98
4163	0.436	8.38	0.675	12.99
4364	0.436	8.38	0.675	12.98
4459	0.436	8.38	0.675	12.98
4498	0.436	8.38	0.675	12.97
4537	0.436	8.38	0.674	12.97
4902	0.435	8.36	0.671	12.90
5154	0.434	8.36	0.667	12.83
5236	0.434	8.34	0.666	12.80
5256	0.438	8.41	0.667	12.82
5404	0.438	8.42	0.664	12.77

The pore pressure and fracture pressure profiles are given in Appendix 1.

4.2 Study Cases

In order to achieve the main objective of the study, that is to study the effect of formations geothermal variations and Z-Factors on selection of casing setting depths, four cases are studied.

CASE 1: Constant geothermal gradient and ideal gas behavior (Z=1) which is the normal industry practice.

CASE 2: Constant Geothermal Gradient and real gas behavior (Effect of Z-Factor)

The temperature profile for case 1 and case 2 is given in Fig 10.

CASE 3: Varying Geothermal gradients across formations and ideal gas behavior (Effect of Varying Geothermal gradient (Z=1)).

CASE 4: Varying geothermal gradients across formations and real gas behavior (Effect of varying of varying geothermal gradients and Z-Factor).

The temperature profile for Cases 3 and 4 is given in Fig 11.

Prediction of the setting depths for casing is done for all the cases mentioned above using a casing setting depth code programmed on excel macro as described in the methodology chapter.

The procedure involves calculating the internal wellbore pressure generated when circulating out a gas influx from a well at various depths. The density equivalent of the calculated pressure is plotted on the same graph with the fracture gradient of the area in order to determine the setting depth which is the point of intersection of both curves.

Methane gas of 0.6 S.G, critical pressure of 667.8 psi and critical temperature of 343^0R is assumed to be the influx gas. The other simplifying assumptions used in carrying out the calculations are given below:

1. Influx enters the well and resides in the annulus as a slug of gas.

2. Influx does not mix with mud i.e it remains as a slug during circulation.

3. Free influx gas does not slip or migrate through a circulating or static mud column.

4. The influx is a consistent fluid in one phase

5. No free gas dissolves in the mud

6. Annulus friction losses are negligible

7. The influx does not change phases during the displacement process
.

All depths used in the hydrostatic calculations are True Vertical Depths (TVD).

The Z-Factors along the borehole wall for the different temperature profiles are calculated using the Abou-Kaseem and Dranchuk correlation combined with Newton-Raphson iterative method. This was programmed on Excel Macro. The code is given in Appendix 2.

4.3 Temperature Profiles

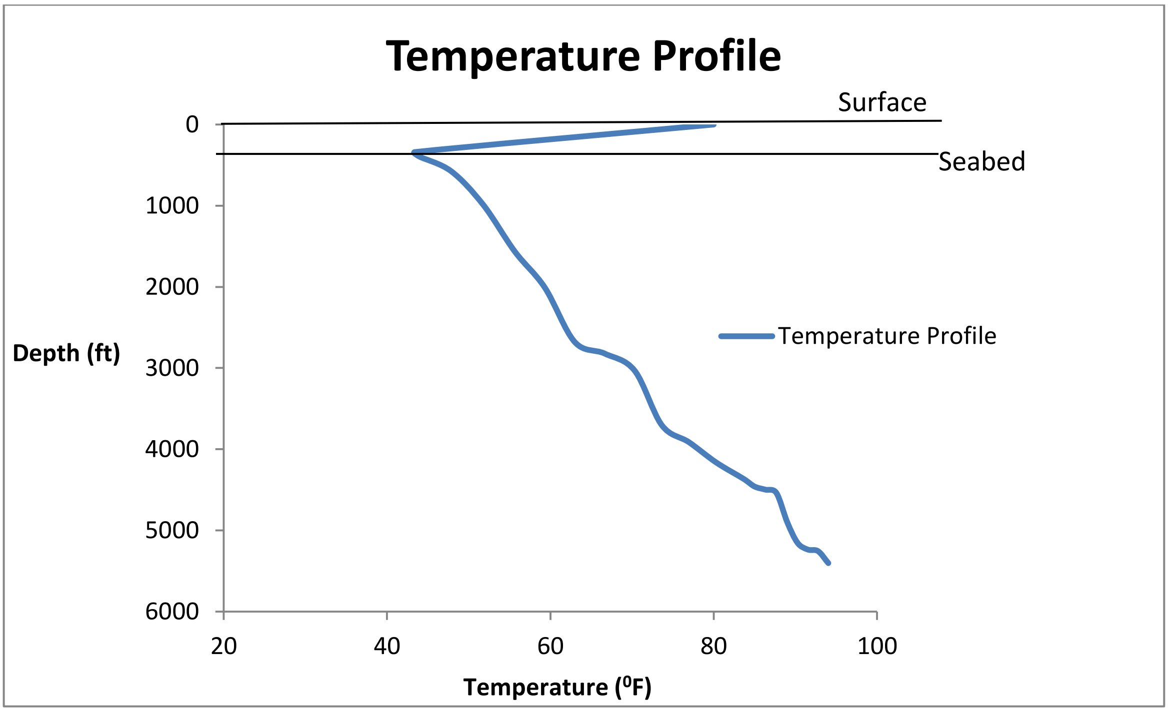

Fig.10: Nearly Constant Temperature Gradient Profile

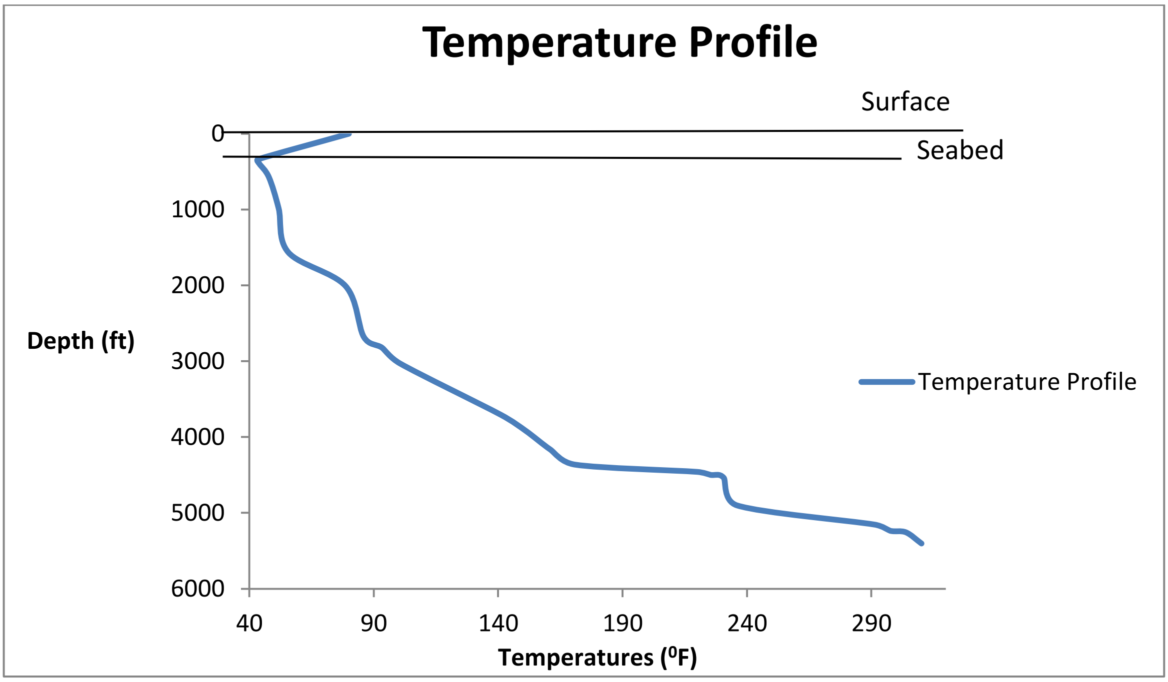

Fig.11: Varying Temperature Gradients Profile

4.4 Results and Discussions

4.4.1 Case 1: Industry Approach

For the developed code to be used for the analysis, it has to be validated to establish the engineering confidence of its applicability. To achieve this, the developed code was used to predict the casing setting depths for the well described using the industry approach that is Case 1 (with a geothermal gradient of 0.01^0F/ft). The results for the casing setting depth from this analysis are given in Figure 13 and 15, compared to the setting depths of the real well which are 4167 ft. and 2612 ft. for the 9 5/8’’ and 13 3/8’’casings setting depths, the calculated setting depths are within an error of 5% with those from the real well.

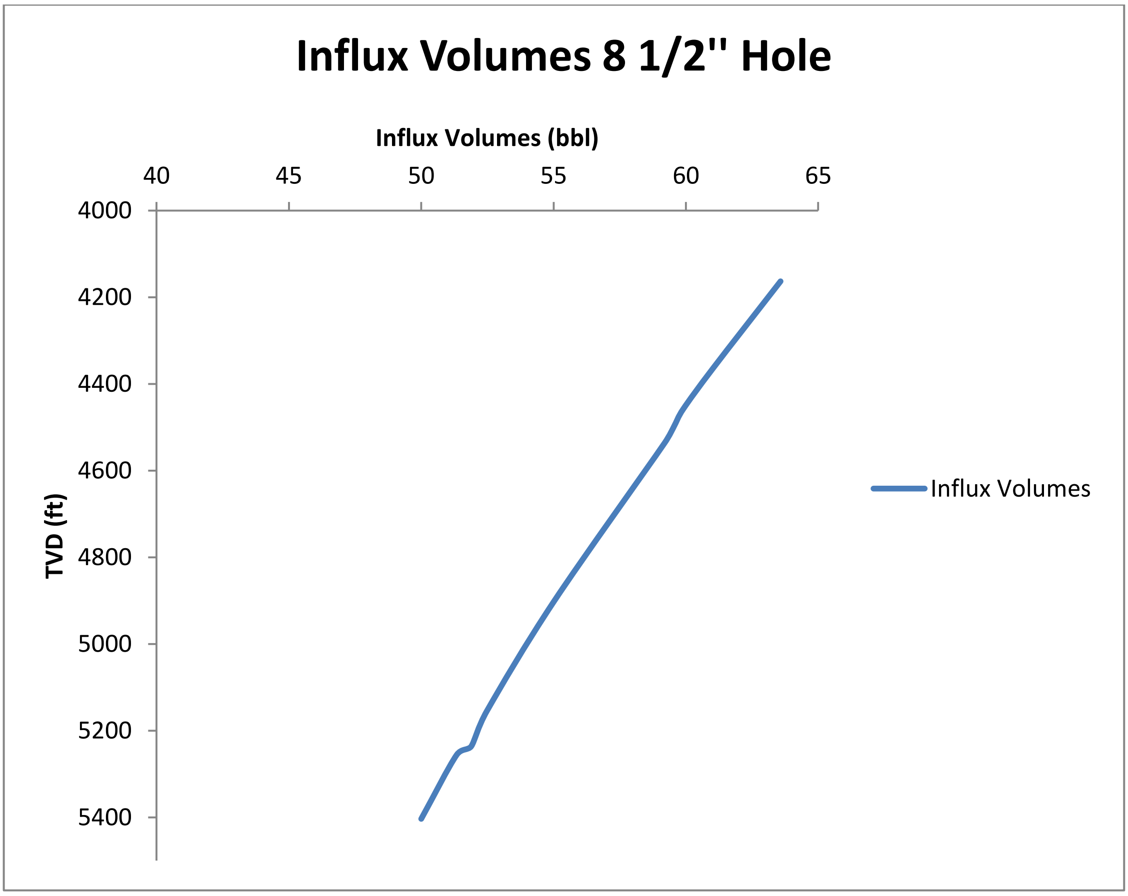

Fig.12: Influx Volumes along 8 ½ " Hole (Case 1)

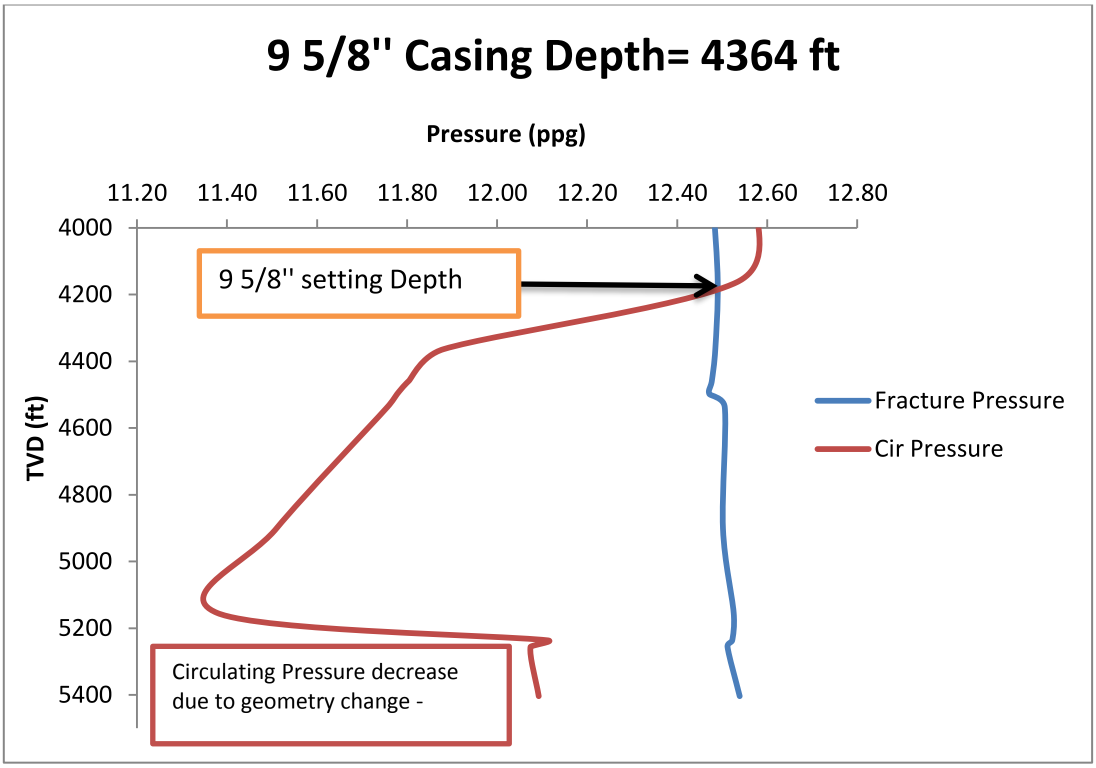

Fig.13: Casing Setting Depth Calculated Using Kick Tolerance (Case 1)

Having established the confidence of the engineering applicability of the code, it will now be used to study the effect of temperature variations and compressibility factors on the design. Case 1 is used as the base for the comparison.

The results from case 1, that is using ideal gas behavior (Z=1), the influx volumes in the 8 ½ inch hole section Fig 12, used to calculate the influx which in turn is used determine the annulus circulating pressure used in predicting the setting depth for the 9 5/8'' casing increases with decrease in temperature along the borehole wall.

Fig 13, used to predict casing setting depth for the 9 5/8 inch casing, the circulation pressure is higher in the annulus between OH/DC because of the higher influx height created in this section. As the influx enters the OH/DP annulus, there is a reduction in the influx height which subsequently leads to a decrease in the circulation pressure. Further up the wellbore, as temperature reduces, the influx volume keeps increasing for the same OH/DP annulus resulting in a higher influx height thus an increase in the circulation pressure.

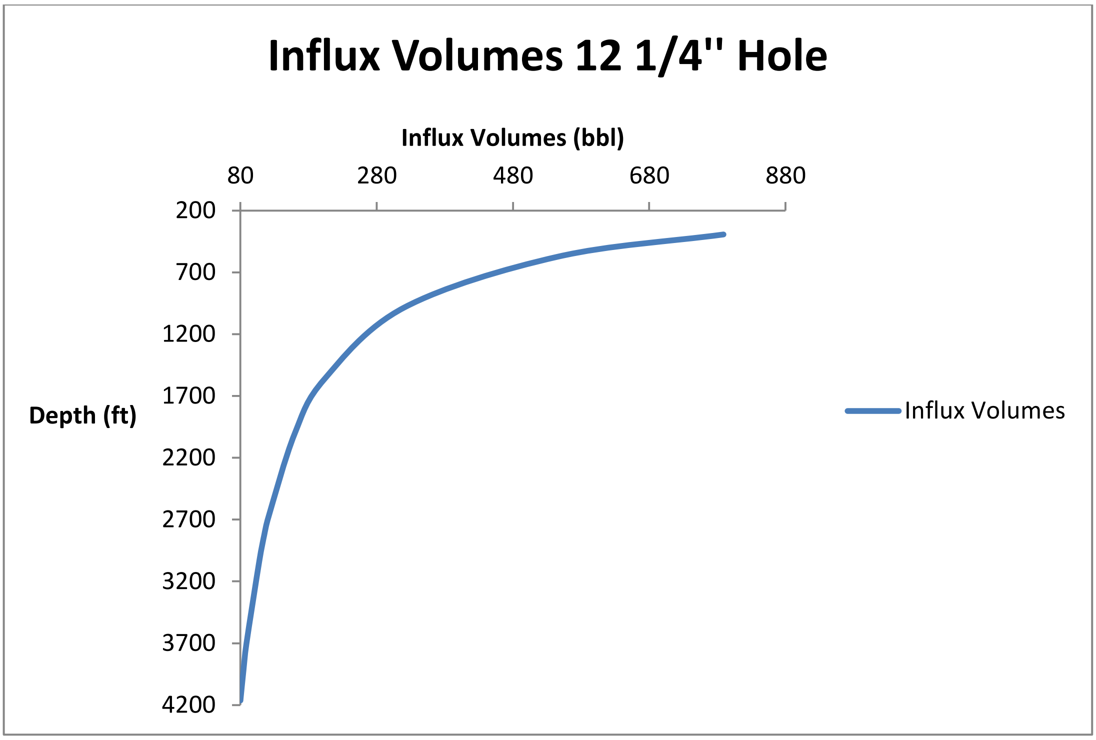

Fig.14: Influx Volumes along 12 1/4" Hole (Case 1)

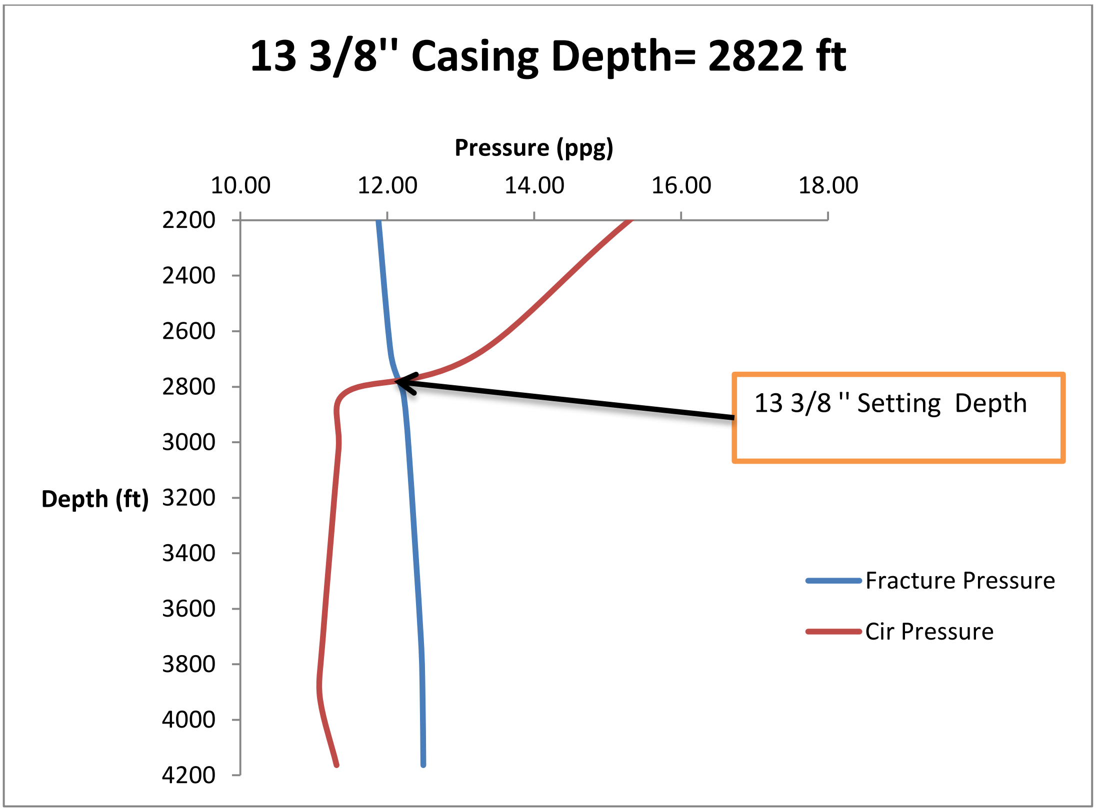

Fig.15: Casing Setting Depth Calculated Using Kick Tolerance (Case 1)

For the 12 ¼ inch hole which starts at the shoe of the 13 3/8 inch casing and ends at the 9 5/8 inch casing, Fig 14 shows the trend of the influx volumes along the open hole. The influx volumes increases as influx migrates up the wellbore where there is a decrease in temperatures. The influx volumes increase is significant at very low temperatures which are found at shallow depths.

In Fig 15 used to estimate the casing setting depth, the same argument put forward for the 9 5/8 inch casing is valid here as well but only that the decrease in the circulation pressure at the OH/DP annulus is not as evident as that for the 9 5/8 inch casing. This is probably due to the higher influx volumes that have resulted because of the low temperatures at these depths.

4.4.2 Case 2: Effect of Gas Compressibility (Z) Factor

This case is used to study the effect of the gas compressibility (Z) Factor on the design. The Z-Factor for the temperatures and pressures at every depth along the borehole is calculated using Abou-Kassem and Dranchuk correlation assuming Methane gas of 0.6 S.G as the influx fluid

Gas compressibility factor, is a parameter that allows for using the ideal gas equation to model real gas behavior.

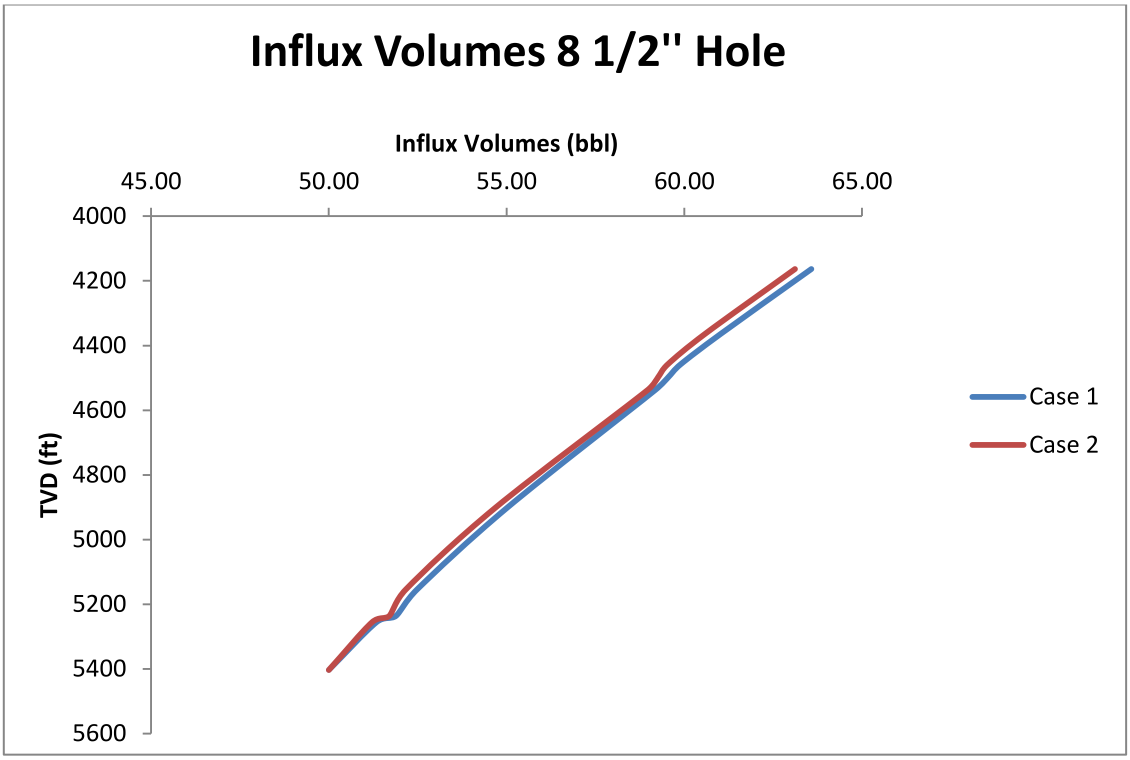

Fig.16: Effect of Z-Factor on influx Volumes along 8 1/2" Hole

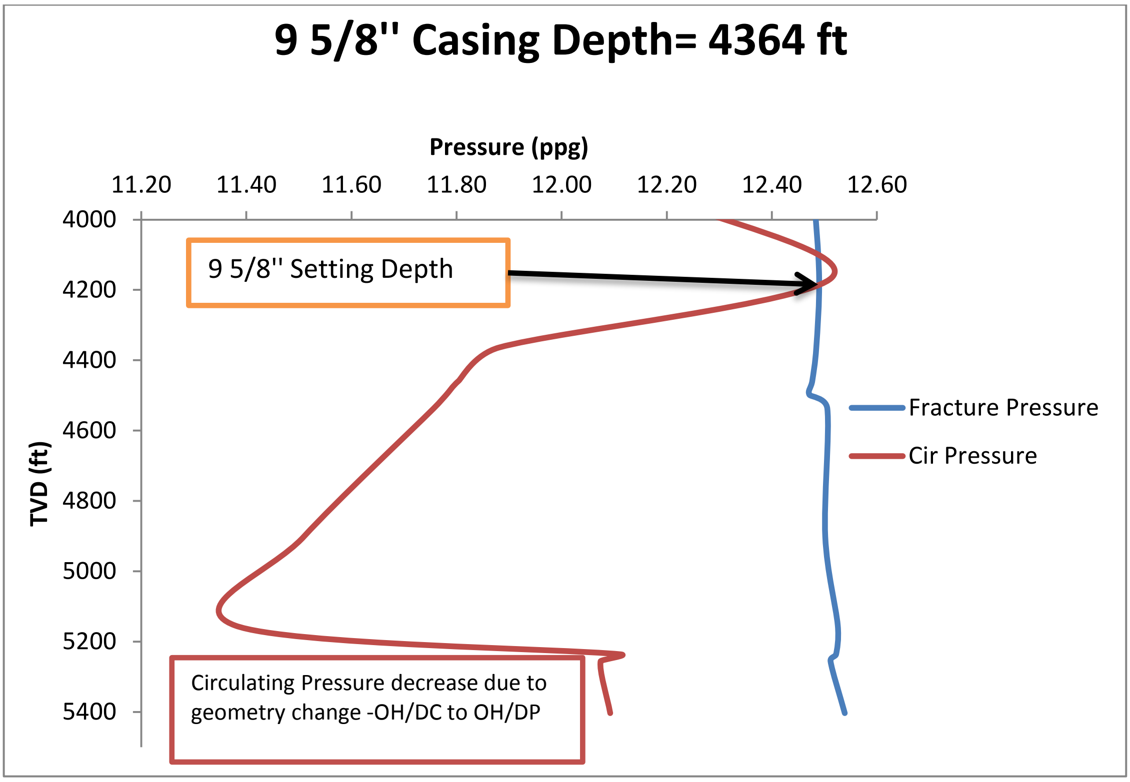

Fig.17: Effect of Z-Factor on Calculated Casing Setting Depth

Using real gas equation to model the influx gas behaviour, the influx volumes in the 8 ½ inch hole section increases with decrease in temperature along the borehole wall just like in case 1 but the influx volumes are lower than those from case 1 as shown in Fig 16.

The predicted setting depth for the 9 5/8 inch casing Fig 17 for case 2 did not change from that of case 1 even though there is a difference in volume between case 1 and case 2. The Z-Factors for case 2 decreases at low temperatures, later it starts increasing at temperatures higher than 90 ^{0}F as shown in Fig 18.

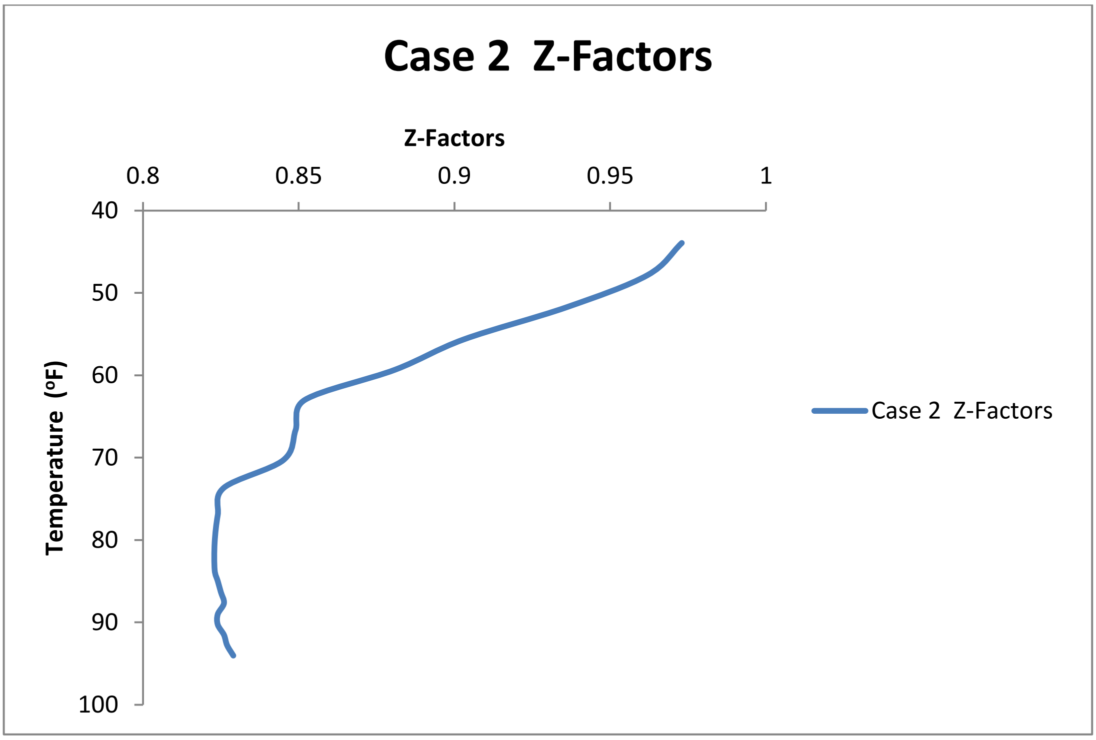

Fig.18: Z-Factor Variation with Temperature (Case 2)

The decrease in Z-Factors along the borehole wall with reference to the Z-Factors at TD for the 8 ½ inch hole have resulted in lower volumes for this case as compared to case 1 where the Z-Factors are constant throughout. This change is significant because it shows that for the same casing setting depth, the kick tolerance when Z-Factors are included in the calculations will be higher than when it is ignored.

Another significance it shows is that for HT/HP wells where the window between Pore pressure and fracture pressure is small, the inclusion of Z-Factors in the calculations reduces the risk of fracturing the weakest formation during influx circulation.

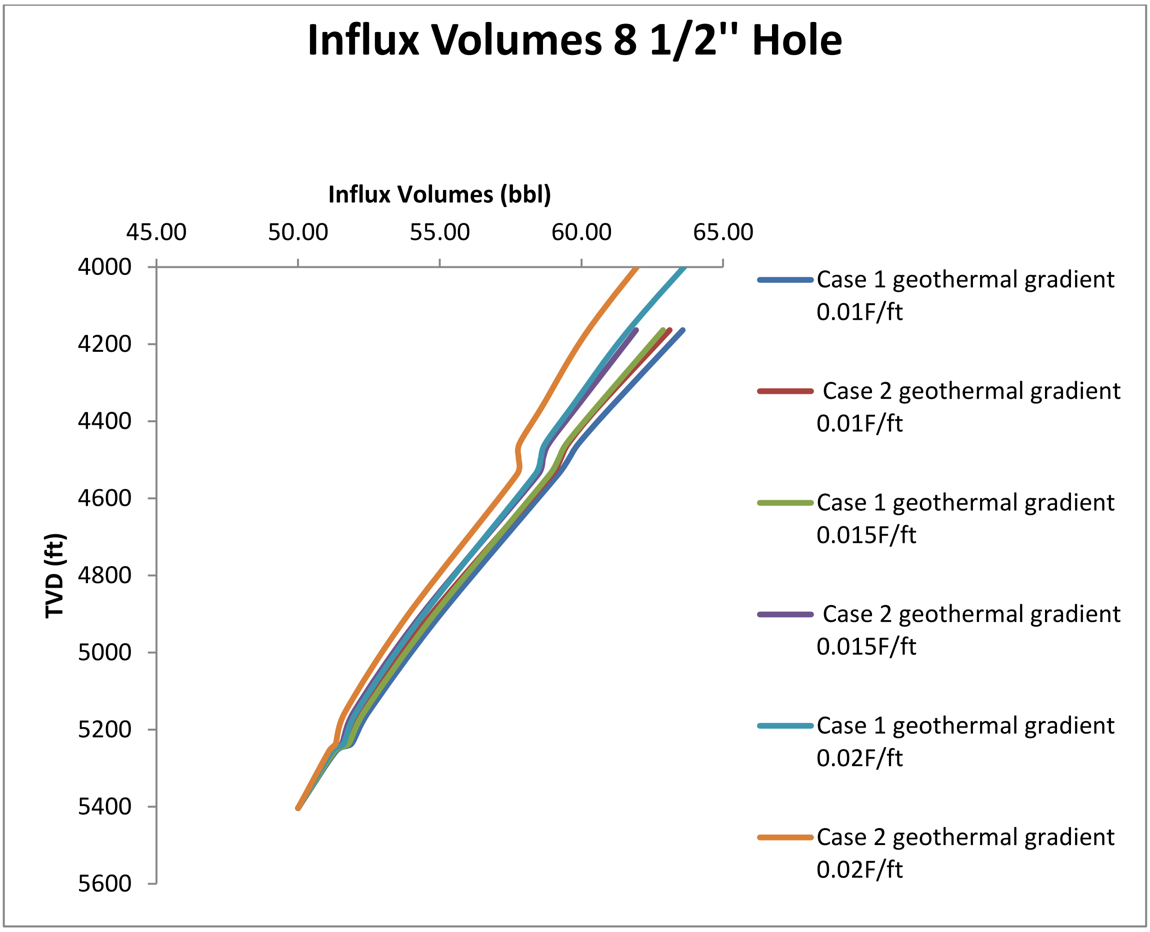

Fig.19: Effect of Increase in Geothermal Gradients on Influx Volumes

Fig 19 above shows the variation in influx volumes at the 8 ½ inch hole when the constant geothermal temperature gradient is 0.01 ^{0}F/ft, 0.015 ^{0}F/ft and 0.02 ^{0}F/ft for both case 1 and Case 2. It is evident that the difference in influx volumes between case 1 and 2 is wider at a constant geothermal temperature gradient of 0.02 ^{0}F/ft. In fact when this temperature gradient was used for the analysis, the setting depth in case 2 was found to be 4163 ft. which is 201 ft. shallower than that for the same temperature gradient used in Case 1 (Z=1). This shows that at increased bottomhole temperatures, the Z-Factors have an effect on the predicted casing setting depth. This further highlights the significance of the Z-Factor inclusion in the calculation especially for HT/HP wells where the correction for Z-Factor in the calculations gives lower gas influx volumes along the borehole wall during circulation, thereby reducing the risk of fracturing the weakest formation.

On the other side if the influx volumes in the calculations is not corrected for Z-Factors, there is a high risk that the fracture pressure of the weakest formation will be exceeded during circulation because of the high influx volumes generated.

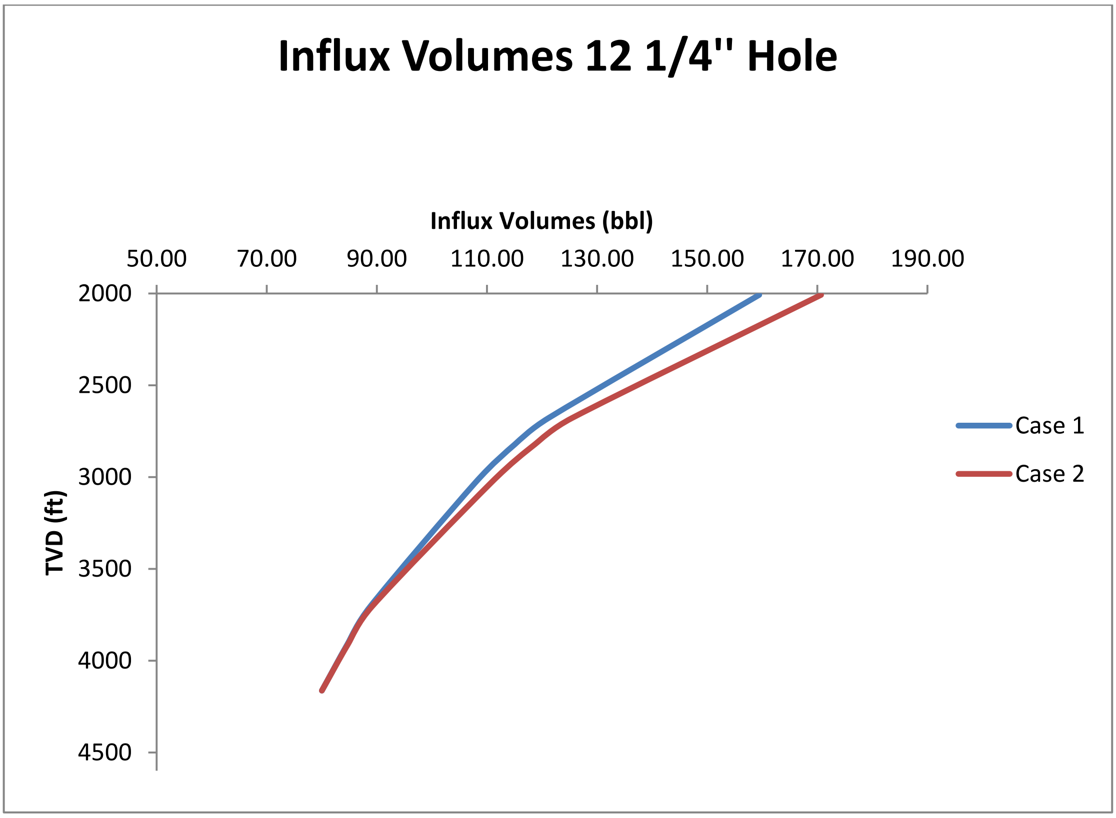

Fig.20: Influx Volumes 12 1/4 " hole for Case 1 and Case 2

For the 12 ¼ inch hole section in case 2, the influx volumes curve is similar to that obtained for case 1 (Fig 14) but the absolute values are greater than those from case 1 as shown in Fig 20. This is because influx volumes increase as the Z-Factors with respect to the Z-Factor at TD increase along the wellbore as seen in Fig 18.

The predicted setting depth for the 13 3/8 inch casing for Case 2 did not vary from that of Case 1, 2822 ft shown in Fig 15 even after increasing the constant geothermal gradient as was mentioned earlier. This further shows that gas Z-Factors have little or no effect on the design at low temperatures.

4.4.3 Case 3: Effect of Variations in formations geothermal gradients

This case is used to study the effect of formations geothermal temperature variations on the design. The temperature profile for this case is shown in Fig 11.

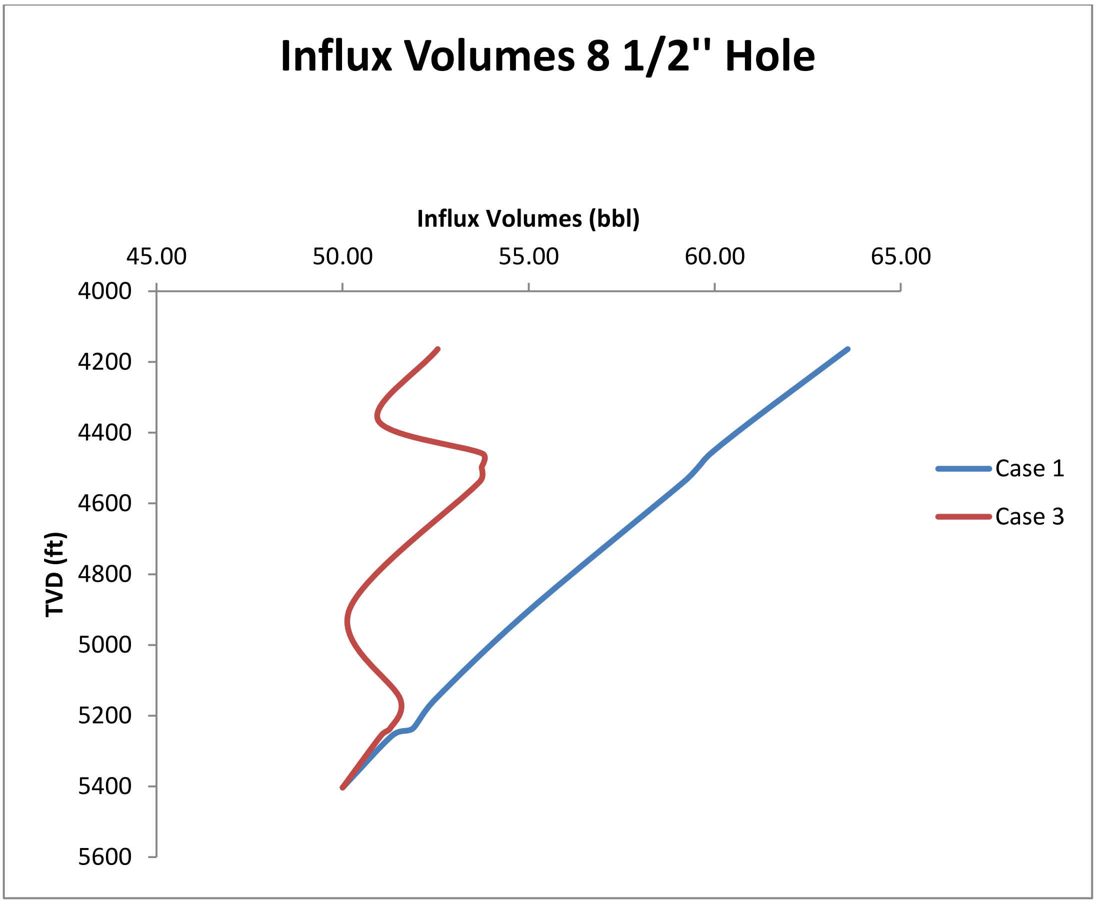

Fig.21: Effect of varying Geothermal Gradients on Influx Volumes (8 ½'' Hole)

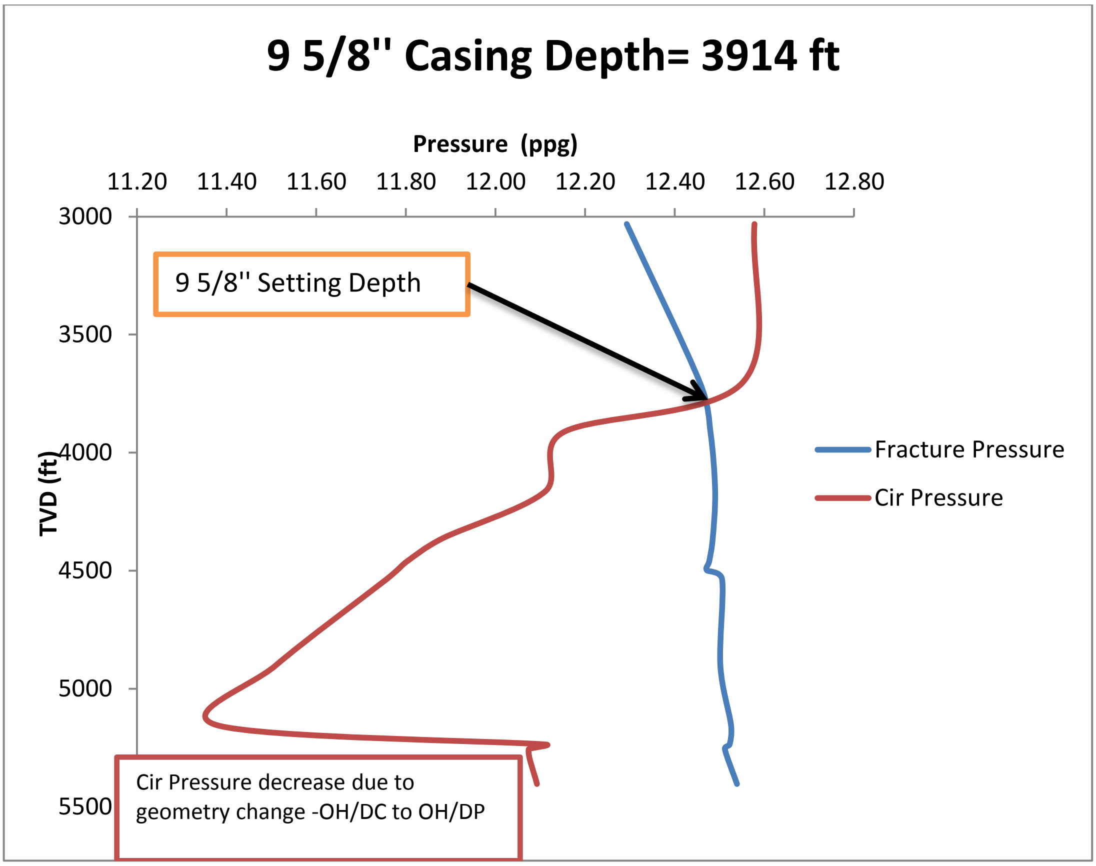

Fig.22: Effect of Varying Geothermal Gradients on Calculated Setting Depth

For this case, the influx volumes in the 8 ½ inch hole section are lower compared to those from case 1 as shown in Fig 21. The influx volumes in case 3 increase from TD moving up the wellbore but decreases at the transition between formations of different geothermal gradients.

The increase in temperature in case 3 is believed to be responsible for the reduction in the influx volumes as compared to case 1 which has lower temperatures for this hole section.

Because of this, the casing setting depth predicted in case 3 shown in Fig 22 is found to be 3914 ft. which is 450 ft. shallower than that obtained from case 1. This is expected because at lower influx volumes which translates to a lower influx height for the same hole size and BHA, the length of open hole section that can be drilled safely without fracturing the weakest formation at shoe when circulating out a gas influx will be greater than when the influx volumes are higher. Hence, the increase in geothermal gradient leads to reduced influx volumes during circulation compared to Case 1 there by giving a shallower predicted setting depth for the 9 5/8 inch casing.

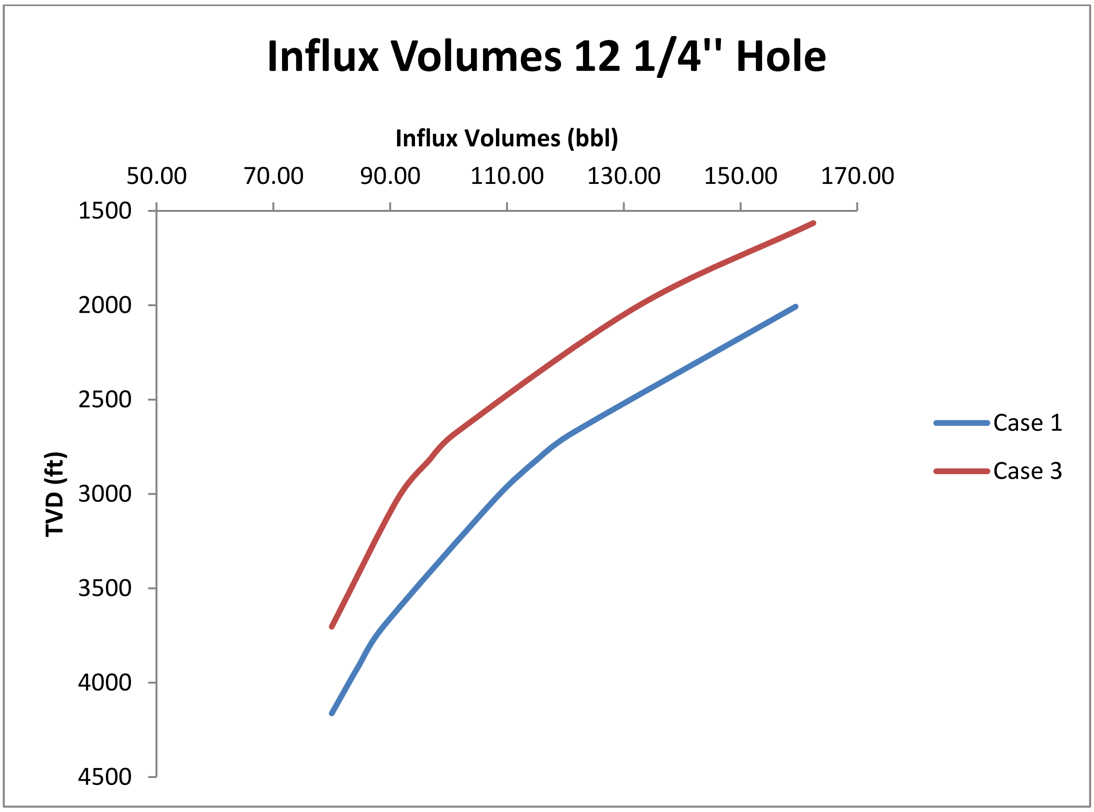

Fig.23: Effect of Varying Geothermal Gradients on Influx volumes (12 1/4" hole)

For the 12 ¼ inch hole section, the influx volumes increases as it moves up the wellbore from TD. But unlike the 8 ½ inch hole, the volumes curve for this hole section did not show any abrupt change between formation of varying geothermal gradients. This is probably due to the fact that temperatures at these depths are lower. The volumes for this case is lower than those from case 1 for the same hole section as shown in Fig 23.

Even though there is a difference in influx volumes at this hole section between case 1 and case 3, the volume changes did not result in any change for the predicted 13 3/8 inch casing shoe depth from that obtained for case 1 shown in Fig 15. This discovery shows that at shallow depths, variation in formation geothermal gradients does not have a significant impact on the setting depth prediction. This is probably due to the fact that at shallow depths variation in geothermal gradients does not lead to significant change in temperatures from those of constant geothermal gradients.

4.4.4 Case 4: Effect of varying geothermal gradients and Z-Factor

This case is used to study the effect of real gas behavior on the design of case 3 when the temperature profile of Fig 11 is used. For this case just like in case 2, the gas compressibility factors for every pressure and temperature at every depth is calculated using the Abou-kaseem and Dranchuk correlation combined with the Newton-Raphson iterative method.

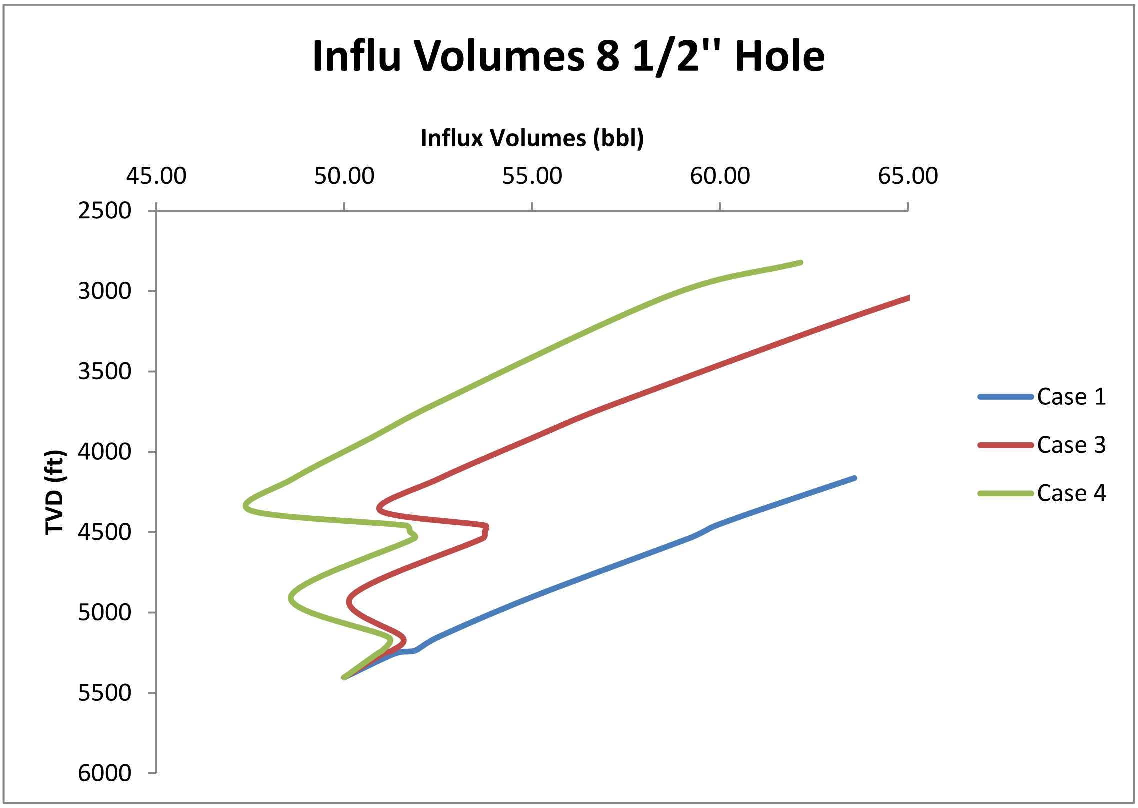

Fig.24: Effect of Z-factor and Varying Geothermal Gradient on Influx Volumes (8 1/2" hole)

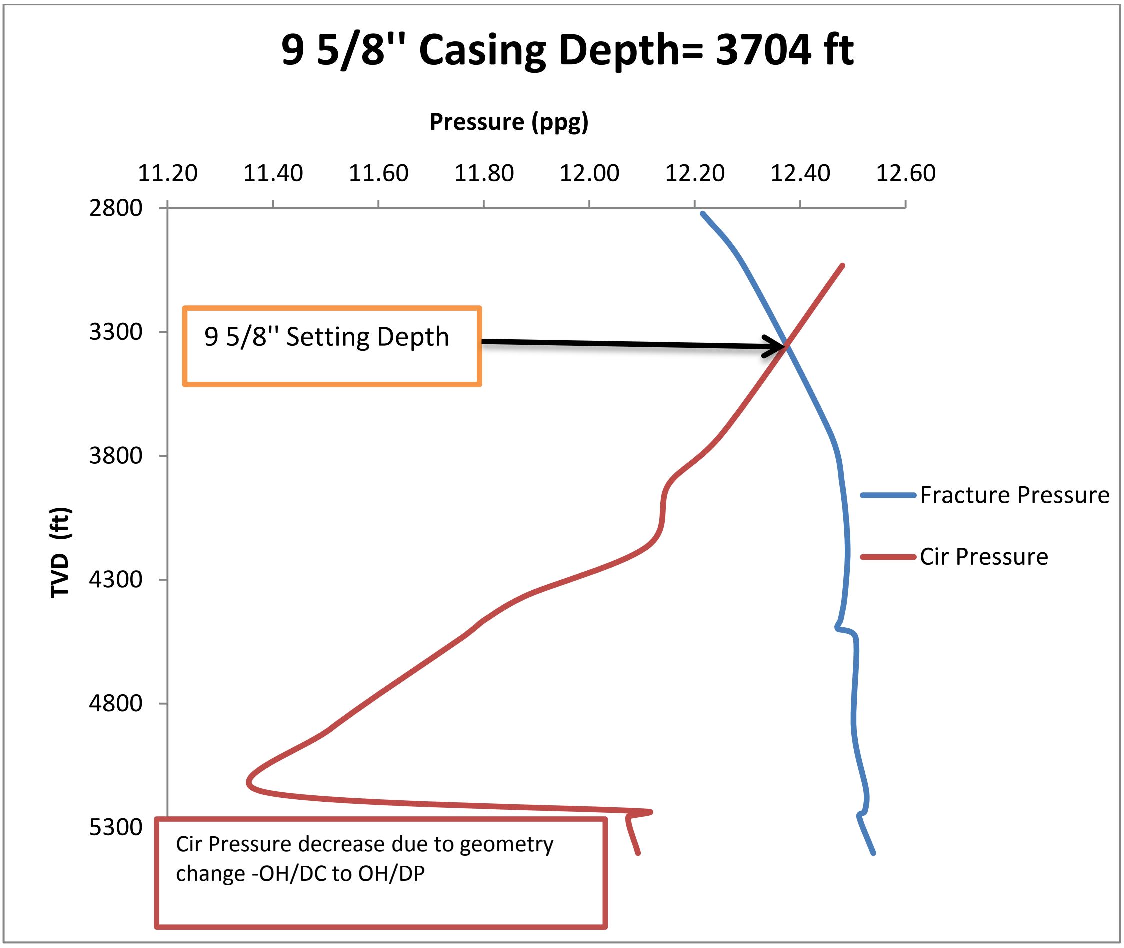

Fig.25: Effect of Z-Factor and Varying Geothermal Gradient on Calculated Casing Setting Depth.

The influx volumes along the 81/2 inch hole section in Fig 24, used to estimate the setting depth for the 9 5/8 inch casing shoe has a curve similar to that obtained in case 3 but with lower influx volumes as compared to case 1 and case 3. The reduction in influx volumes is as a result of decrease in the Z-Factors for this case, unlike in cases 1 and 3 were the Z-Factors remains constant throughout.

The 9 5/8 inch casing setting depth predicted for this case Fig 25 is shallower than those obtained for case 1 and case 3. This is expected because of the lower influx volumes generated during influx circulation as was explained earlier in case 3.

The influx volumes for the 12 ¼ inch hole section shown in Fig 26 for this case shows that the influx volumes for case 4 are as well lower than those from case 1 and 3

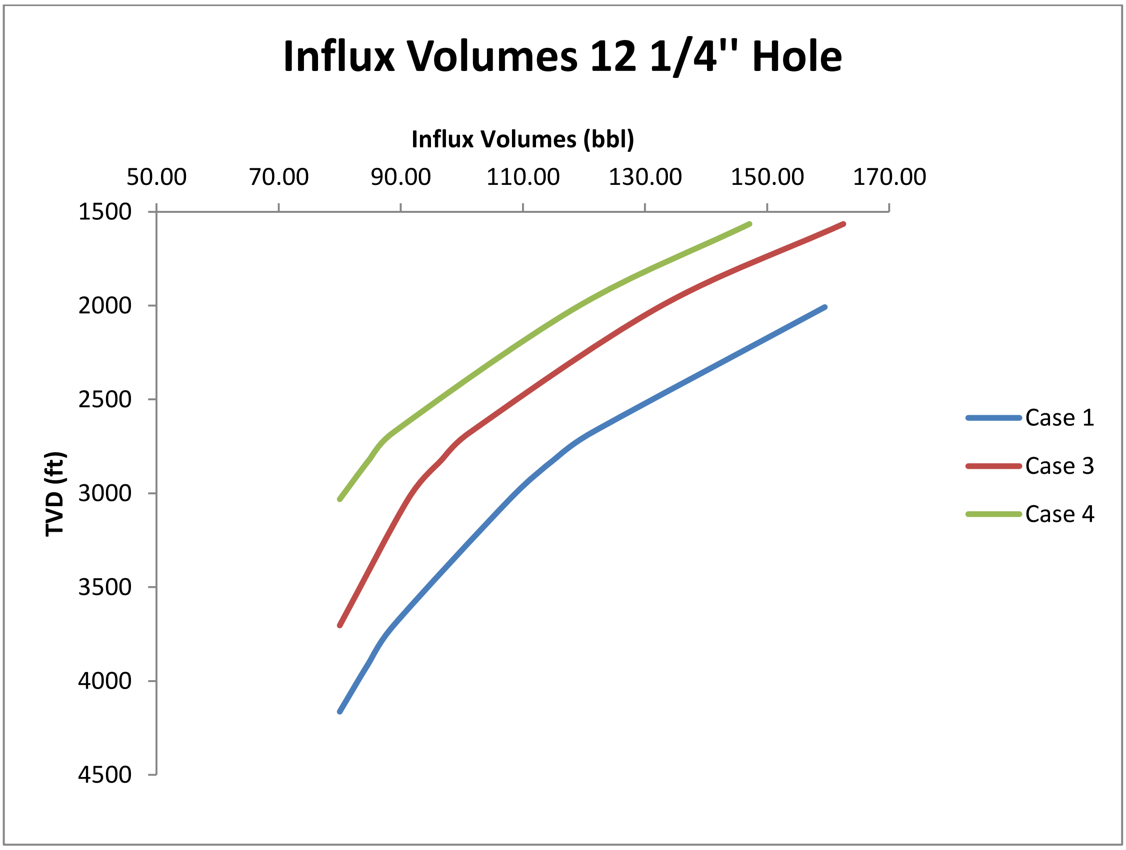

Fig.26: Effect of Z-Factor and Varying Geothermal Gradients on Influx Volumes (12 1/4" hole)

The influx volumes even though lower did not create any change on the predicted casing setting depth for the 13 3/8 inch casing. Hence the casing setting depth is same as that for case 1 shown in Fig 15. This further strengthens the earlier claim that the effect of Z-Factors is more pronounced at depths of high temperatures.

Fig 27 shows the Z-Factors vs Temperature plot for this case. It shows that the Z-Factors decreases at low temperatures up to a value of about 90 ^{0}F and then starts increasing thereafter onto TD. The reason for this is that at shallow depths which are characterized by low temperatures and pressures, the pseudo-reduced pressures (equation 18) and pseudo-reduced temperatures (equation 17) for constant critical temperatures and critical pressures are low resulting in low values of Z-Factors. As the temperatures and pressures increases with depth, there is a corresponding increase in the pseudo-reduced temperatures and pressures which leads to an increase in the Z-Factors.

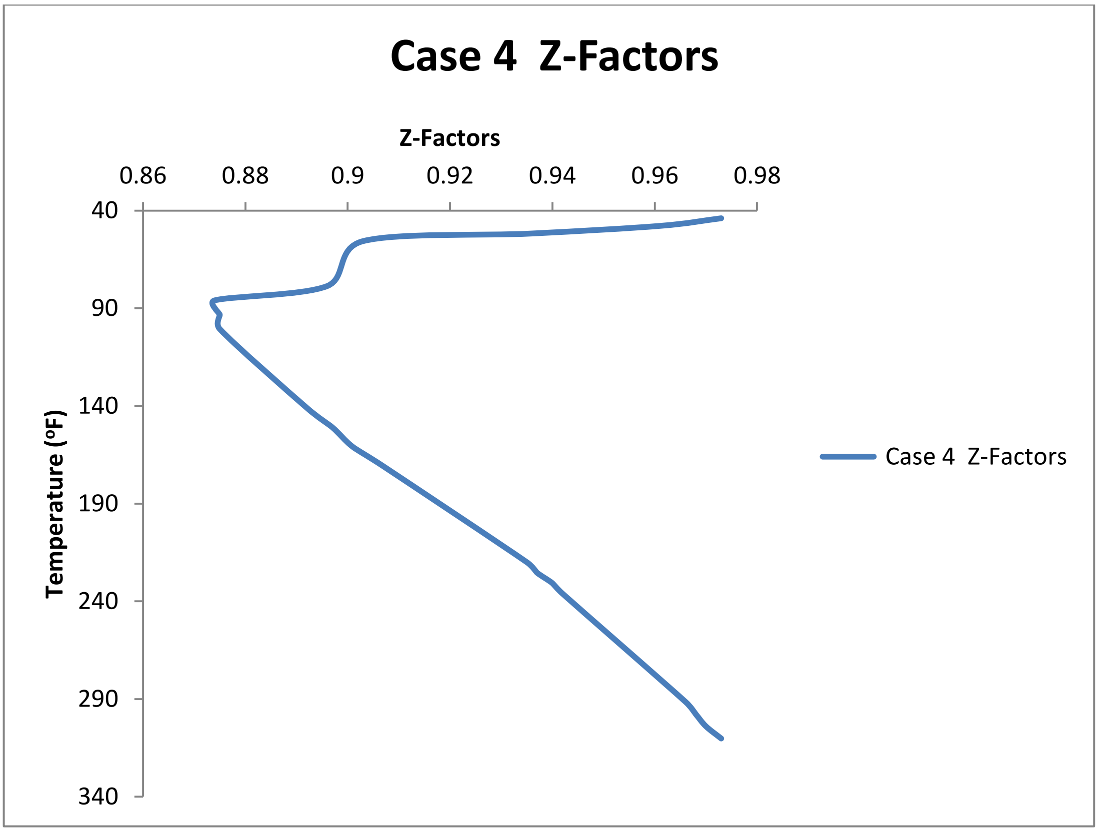

Fig.27: Z-Factor Variation with Temperature for Case 4

The plots of Z-Factors variations with depth for both Cases 2 and 4 are given in Appendix 1.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this study, it has been shown that:

1. Correcting for Z-Factors in the calculation of influx volumes results in lower influx volumes compared to those obtained from the industry approach where Z-Factors are ignored. This implies that correcting for Z-Factors reduces the risk of fracturing the weakest formation during influx circulations. This is particularly important when dealing with HT/HP wells where the window between pore pressure and fracture pressure is narrow.

2. For the same Casing Setting depth and hole section, Z-Factor corrected calculations gives a higher kick tolerance than that obtained when Z-Factors are ignored. For conventional wells, this means that longer hole sections can be drilled safely before running casing. This reduces the casing strings to be run in the well, consequently reducing the well cost.

3. Z-Factors have little or no effect on the prediction of casing setting depth at low temperatures and pressures, but become very significant at very high temperatures and pressures. This is because of the large difference in influx volumes between the real gas behavior case (Z-Factor corrected for) and ideal gas case (Z=1)

4. Accounting for variations in geothermal gradients across subsurface formations results in lower influx volumes than those obtained when a constant formation geothermal gradient is used in the calculations.

5. Casing setting depth prediction is affected by high temperatures. This conclusion was arrived at when variations in geothermal gradient was accounted for, the setting depth for casing at depths of very high temperatures gave a shallower predicted depth than that obtained for the same casing size but with constant geothermal gradients.

5.2 Recommendations

It is recommended that the effects of subsurface temperature changes and Z-Factors be taking into account in the casing design process in order to ensure safe and cost effective drilling operation.

In order to fully investigate the effect of Temperature variations and Z-Factor on the design, many other parameters should be accounted for in the calculations. For future research the following recommendations are made:

1. Frictional pressure losses in the annulus should be included and the ECD of the mud calculated.

2. Gas should be modeled as two-phase flow of mud and gas taking into account dissolutions of free gas into the mud.

3. Free gas slip velocity should be calculated and included in the annulus pressure prediction calculations

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APPENDICES

APPENDIX 1: AREA PRESSURES AND Z-FACTOR PLOTS

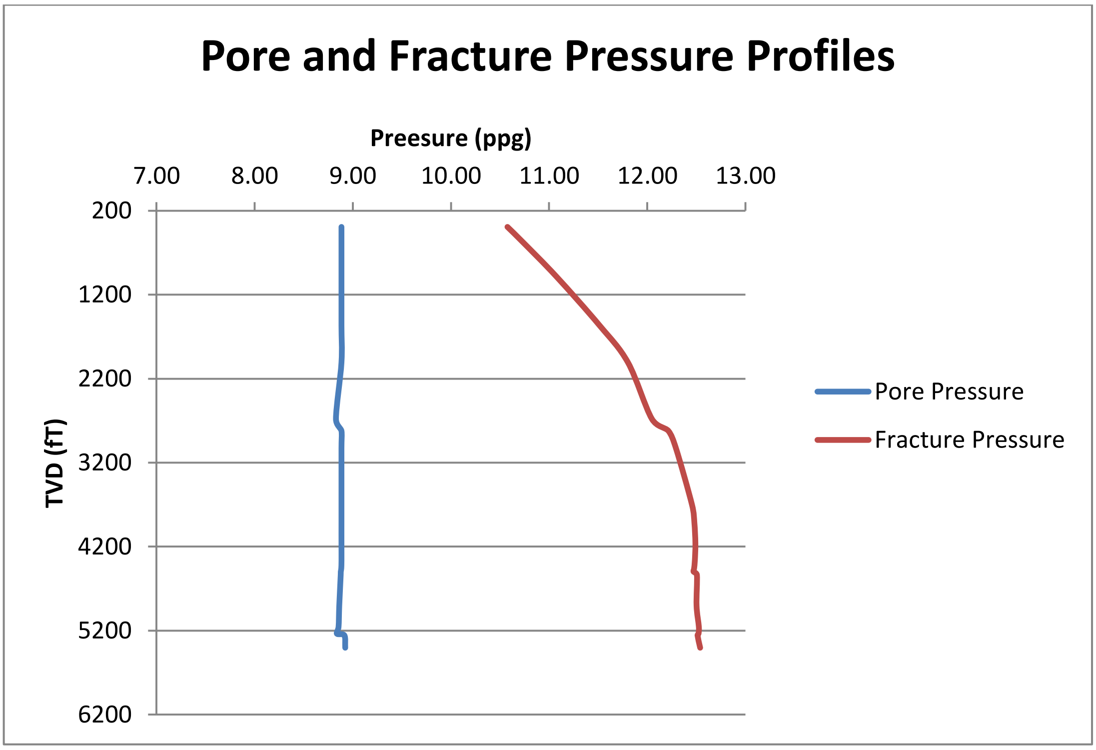

Fig.28: Pore Pressure and Fracture Pressure Profiles

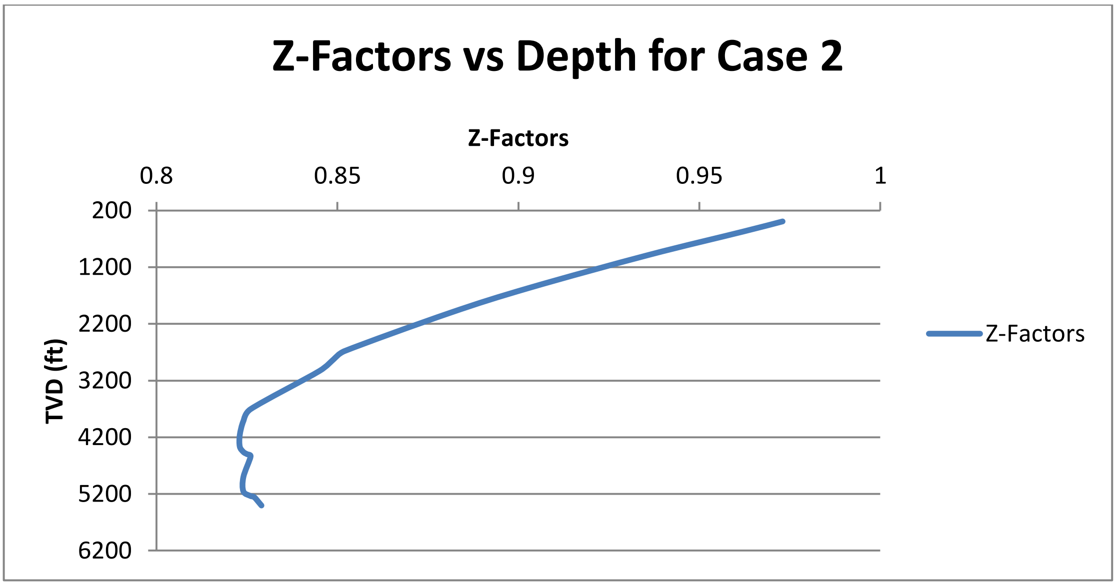

Fig.29: Z-Factors against TVD

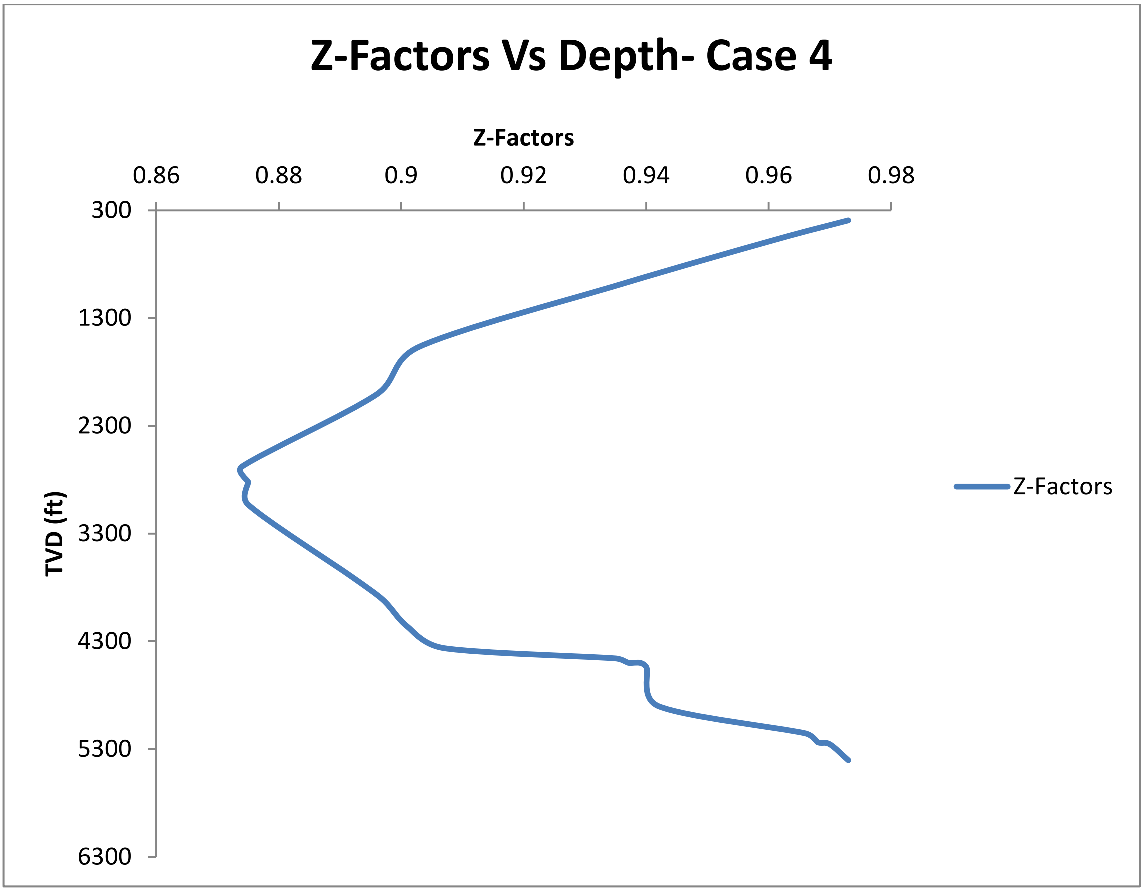

Fig.30: Z-Factors against Depth

APPENDIX 2: CODES

Code for calculating Z-Factors

```
Dim redT, redP, C1, C2, C3, C4, RuR, FZ, FPZ, ZNewAs Double

Sub CommandButton1_Click ()

redT = (temp.Value + 460) / CT.Value……………………….Reduced Temperature

redP = pressure.Value / CP.Value…………………………………Reduced Pressure

C1 = 0.3265 - (1.07 / redT) - (0.5339 / (redT * redT * redT)) + (0.01569 / (redT * redT * redT * redT)) - (0.051615 / (redT * redT * redT * redT * redT))..C1 Constant

C2 = 0.5475 - (0.7361 / redT) + (0.1844 / (redT * redT))……………….C2 Constant

C3 = 0.1056 * ((-0.7361 / redT) + (0.1844 / (redT * redT)))……………C3 Constant

RuR = 0.27 * redP / (assumeZ.Value * redT)………………………Reduced Density

C4 = 0.6134 * (1 + (0.721 * (RuR * RuR))) * ((RuR * RuR) / (redT * redT * redT)) * Exp(-0.721 * RuR * RuR)

FZ = assumeZ.Value - (1 + (C1 * RuR) + (C2 * RuR * RuR) - (C3 * RuR * RuR * RuR * RuR * RuR) + C4) ……………………………………………Function of Z

FPZ = 1 + ((C1 * RuR) / assumeZ.Value) + ((2 * C2 * RuR * RuR) / assumeZ.Value) - ((5 * C3 * RuR * RuR * RuR * RuR * RuR) / assumeZ.Value) + ((1.2268 * RuR * RuR) / (redT * redT * redT * assumeZ.Value)) _
* ((1 + (0.721 * RuR * RuR) - ((0.721 * RuR * RuR) * (0.721 * RuR * RuR))) * Exp(-0.721 * RuR * RuR))……………………………………….. Differential of FZ
```

```
ZNew = assumeZ.Value - (FZ / FPZ)

Do

assumeZ.Value = ZNew

RuR = 0.27 * redP/ (assumeZ.Value * redT)……………………Reduced Density

C4 = 0.6134 * (1 + (0.721 * (RuR * RuR))) * ((RuR * RuR) / (redT * redT * redT))
* Exp(-0.721 * RuR * RuR)……………………………………...…C4 Constant

FZ = assumeZ.Value - (1 + (C1 * RuR) + (C2 * RuR * RuR) - (C3 * RuR * RuR *
RuR * RuR * RuR) + C4)…………………………………………...Function Of Z

FPZ = 1 + ((C1 * RuR) / assumeZ.Value) + ((2 * C2 * RuR * RuR) /
assumeZ.Value) - ((5 * C3 * RuR * RuR * RuR * RuR * RuR) / assumeZ.Value) +
((1.2268 * RuR * RuR) / (redT * redT * redT * assumeZ.Value)) _
 * ((1 + (0.721 * RuR * RuR) - ((0.721 * RuR * RuR) * (0.721 * RuR * RuR))) *
Exp (-0.721 * RuR * RuR)) ……………………………………….Differential of FZ

ZNew = assumeZ.Value - (FZ / FPZ)

Loop While (ZNew - assumeZ.Value> 0.0001)


End Sub
```

Casing Setting Depth Prediction Code

```
Dim  VolTDAs Double
Dim TempTDAs Double
Dim PTDAs Double
Dim ZFTD As Double

Private Sub CommandButton1_Click()

'9 5/8 casing Calculations

PTD = Cells (31, 6) ……………………….Pressure at well TD

VolTD = Cells (50, 6)……………………..Assumed influx volume at TD

ZFTD = Cells(31, 13)……………………...Z-Factor at TD

TempTD = Cells(31, 12)…………………..Temperature at bottom hole

MD = Cells(31, 4)………………………….Measure Depth at TD

DC = Cells(49, 6)…………………………….Drill collar length

HID = Cells(45, 6)…………………………….Hole size below 9 5/8 casing

F47 = Cells (47, 6)…………………………………Drill pipe OD

F48 = Cells(48, 6)…………………………………..Drill Collar OD

MW = Cells(46, 6)…………………Allowable mud weight for next hole section

TVD = Cells(31, 5)…………………..True Vertical Depth at well TD

GasG = Cells(5, 7)……………………….Influx gas specific gravity
```

```
PP = Cells(31, 7)………………………………..Pore Pressure at TD

For i = 31 To 12 Step -1

Cells(i, 20) = (PTD * VolTD * Cells(i, 13) * Cells(i, 12)) / (Cells(i, 6) * ZFTD * TempTD)……………………………………………….'Influx volumes at other depths

If MD – Cells (i, 4) <= DC Then

Cells(i, 21) = Cells(i, 20) / (((HID * HID) - (F48 * F48)) / 1029.4)…………………… 'Influx height Hole/Drill collar annulus



Else

 Cells(i, 21) = Cells(i, 20) / (((HID * HID) - (F47 * F47)) / 1029.4)………………….    'Influx height at Hole/Drill pipe annulus

End If

   Cells(i, 22) = Cells(i, 21) * (Cos(Cells(i, 15) * WorksheetFunction.Pi / 180))….Influx height in TVD

 Cells(i, 23) = (MW * 0.052 * TVD) - ((MW * 0.052) * (TVD - Cells(i, 22) - Cells(i, 5))) - ((GasG * Cells(i, 6) * Cells(i, 22)) / (53.29 * Cells(i, 12) * Cells(i, 13)))…. 'Pressure at the top of gas influx at different depths

 Cells(i, 16) = ((GasG * Cells(i, 6) * Cells(i, 22)) / (53.29 * Cells(i, 12) * Cells(i, 13)))...    'Hydrosatic pressure of gas influx at all depths

Next i

Dim result As Double
```

```
For j = 31 To 12 Step -1

 If (Cells(j, 23) / (0.052 * Cells(j, 5))) > Cells(j, 9) Then

 Cells(j, 24) = (Cells(j, 23) / (0.052 * Cells(j, 5)))………….. 'Influx circulating pressure mud weight equivalent

Cells (68, 4) = Cells (j, 5)…………………….'Depth at which influx circulating pressure is greater than fracture gradient

 Cells(68, 5) = (Cells(j, 23) / (0.052 * Cells (j, 5)))……………..' Influx circulating pressure mud weight equivalent at depth

Cells (68, 6) = Cells (j, 9)………………….' Fracture Pressure at depth where circulating pressure is greater than fracture pressure

'13 3/8 casing TD data

Cells (89, 4) = Cells (j, 6)…………………………………'Pressure at TD

Cells (90, 4) = Cells (j, 4)…………………………………'Measured Depth at TD

 Cells (91, 4) = Cells (j, 5)…………………………………'TVD at TD

 Cells (92, 4) = Cells (j, 7)………………………………'EMW pore pressure at TD

 Cells (93, 4) = Cells (j, 13)………………………………..'Z-factor at TD

 Cells (94, 4) = Cells (j, 12)………………………………. 'Temprature at TD

      Exit For

 End If
```

```
Next j

‘13 3/8 Casing setting depth calculation

P_TD = Cells (89, 4)………………………………………………'Pressure at well TD

Vol_TD = Cells (50, 14)………………………………….'Assumed influx volume at TD

Z_FTD = Cells (93, 4)………………………………………………'Z-Factor at TD

Temp_TD = Cells (94, 4)…………………………………..'Tempreture at bottom hole

MD_TD = Cells (90, 4)…………………………………………….. 'Measure Depth at TD

DCL = Cells (49, 14)……………………………………………….. 'Drill collar length

H_ID = Cells (45, 14)……………………………………'Hole size below 13 3/8 casing

F_47 = Cells (47, 14)…………………………………………………….'Drill pipe OD

F_48 = Cells (48, 14)…………………………………………………….'Drill Collar OD

M_W = Cells (46, 14)……………………'Allowable mud weight for next hole section

TVD_TD = Cells (83, 4)………………………………….'True Vertical Depth at well TD

PP_TD = Cells (92, 4)………………………………………………'Pore Pressure at TD

Dim jj As Integer

jj = j

For k = j To 12 Step -1
```

```
Cells(k, 26) = (P_TD * Vol_TD * Cells(k, 13) * Cells(k, 12)) / (Cells(k, 6) * Z_FTD * Temp_TD)……………………………………………'Influx volumes at other depths

If MD_TD – Cells(k, 4) <= DCL Then

Cells(k, 27) = Cells(k, 26) / (((H_ID * H_ID) - (F_48 * F_48)) / 1029.4)………… 'Influx height Hole/Drill collar annulus

Else

Cells(k, 27) = Cells(k, 26) / (((H_ID * H_ID) - (F_47 * F_47)) / 1029.4)………….. 'Influx height at Hole/Drill pipe annulus

End If

Cells(k, 28) = Cells(k, 27) * (Cos(Cells(k, 15) * WorksheetFunction.Pi / 180))…..Infux height in TVD

Cells(k, 29) = (M_W * 0.052 * TVD_TD) - ((M_W * 0.052) * (TVD_TD - Cells(k, 28) - Cells(k, 5))) - ((GasG * Cells(k, 6) * Cells(k, 28)) / (53.29 * Cells(k, 12) * Cells(k, 13)))…………………………………'Pressure at the top of gas influx at different depths

Next k

Call Iterations(jj, 12, -1)

End Sub


Sub Iterations(starting As Integer, ending As Integer, stp As Integer)

For j = starting To ending Step stp
```

```
 If (Cells(j, 29) / (0.052 * Cells(j, 5))) > Cells(j, 9) Then

 Cells(69, 4) = Cells(j, 5)……………………………'Depth at which influx circulating pressure is greater than fracture pressure

Cells(69, 5) = (Cells(j, 29) / (0.052 * Cells (j, 5)))………………….' Influx circulating pressure mud weight equivalent at depth

Cells (69, 6) = Cells (j, 9)……………………………………….' Fracture Pressure at depth where circulating pressure is greater than fracture pressure

  Exit For

    End If

Next j

End Sub
```