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Model for Kick Tolerance

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Master Thesis

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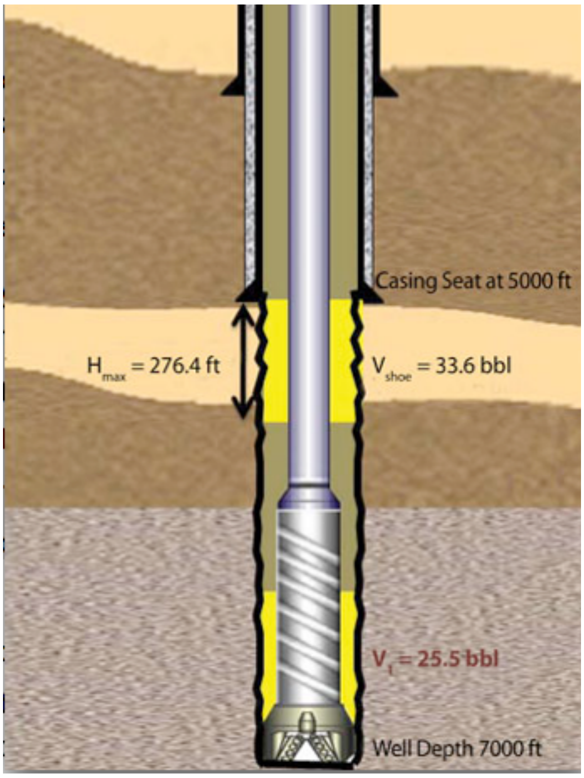

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Front page picture: Well Control Incident

Source: http://safekick.com/

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Studieprogram i Geofag og petroleumsteknologi

Faculty of Engineering and Technology
Study Programme in Earth Sciences and Petroleum Engineering

Institutt for petroleumsteknologi og anvendt geofysikk
Department of Petroleum Engineering and Applied Geophysics

HOVEDOPPGAVE/DIPLOMA THESIS/MASTER OF SCIENCE THESIS

Kandidatens navn/The candidate's name: *Carla Acosta Hernandez*
Oppgavens tittel, norsk/Title of Thesis, Norwegian: Modell for brønnspark-toleranse
Oppgavens tittel, engelsk/Title of Thesis, English Model for kick tolerance
Utfyllende tekst/Extended text:

Background:

Kick tolerance is a governing factor for key properties as:

- Mud weight
- Section start and end
- Number of sections and,
- Influence the BHA design.

API states the recommended kick tolerance for each section size and the operators in the industry are careful not to exceed these. Failure to ensure kick tolerance is acceptable can lead to an underground blowout.

Kick tolerance is a concept well described in the literature. However, all operators work with their own spread sheet type model and run these calculations for each sections of the well.

Many of the models are subjected to some margin of error from assumptions of:

- Z factor
- Depth of BHA (kick taken while drilling or POOH)
- Accuracy in describing the well path (often simplified) and
- Other factors.

Task:

1) Map what parameters kick tolerance influence and describe the magnitude of error the assumptions have (where could the existing models be improved – if necessary)
2) Build a model (spreadsheet type software tool) and compare with similar models from the oil industry.
3) Evaluate and compare the model with existing calculation methods.

Supervisor *Sigbjørn Sangesland*
Co-supervisor *Bjorn Brechan*
Studieretning/Area of specialization: *Petroleum Engineering, Drilling Technology*
Fagområde/Combination of subject: *Drilling*
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……………………………….
Sigbjørn Sangesland

1 Summary

Kick Tolerance is an important factor in the industry, that allows drilling engineers to establish several parameters in the development phase of a well, such as casing depths, open hole lengths, etc. It can also be considered a valuable safety factor to prevent well control problems.

Several different definitions and calculation approaches were found for this term, and when you have something as dynamic and fast-paced as it is the oil & gas industry it is an important issue, since this lack of standardization leads to confusion and miscommunication.

In chapter 3 and 4 the current calculation method, industry approach and knowledge of the term is quickly reviewed. Different kick tolerance software was analyzed in order to outline assumptions, compare results and calculation methodologies. Two main groups were distinguished: VBA macros for Microsoft Excel and standalone applications. The software presented in this work is developed in an attempt to overcome the main difficulties and disadvantages found during the initial analysis of the previously mentioned programs.

Well: “Thesis work”, analyzed in chapter 5, presents real data from an exploration well that, when planned, was expected to be an easy to accomplish task by the drilling crew, not at all troublesome. In the original analysis, pre-development, an extremely high kick tolerance was found (≈90bbl or ≈15 m^3), and drilling and casing designs were made accordingly.

Operations for the 8.5” section where estimated to last 5 – 8 days with a specific budget. Several small kicks were presented during the drilling operations, and about 100m before TD was reached, a gas kick occurred, even though the original analysis showed a high margin before trouble was supposed to be encounter, once killing operations started, it became clear that control was not going to be easily regained, ultimately leading to the abandonment well.

Many different reasons could have led to this much trouble, i.e. using data from nearby wells without later updating this information with the real data found, for this specific well, not taking into consideration all the factors involved on the calculation, etc. This would have helped readjust different parameters before the incident happened, with high probabilities of a different, more positive, outcome.

Appendix C gives a review on the safety importance of kick tolerance; Appendix D better explains the calculations required to find a proper kick tolerance.

The developed software is presented in further detail in Appendix E.

2 Acknowledgement

I would like to acknowledge the help of my Professor Sigbjørn Sangesland at the Department of Petroleum Engineering and Applied Geophysics, NTNU, first of all for the opportunity to research and develop this thesis work, furthermore for your understanding and for giving me the chance to work independently but being there in my time of need.

Special thanks to Bjorn Brechan from the same department, who was of immense help in the progress of this work and was available even when geography was against us.

A small mention to my lower back, for turning what started as a pleasant journey into a very uncomfortable race against the clock, I appreciate the understanding and support of all the people involved in the project.

A mis papas, mis hermanos y mis sobrinos, nada de esto hubiera sido posible sin su amor y apoyo incondicional.

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3 Introduction

Now days, the oil & gas industry is faced with an increasingly difficult challenge, the complexity of drilling operations is greater every day and this is an irreversible tendency. This trend, associated with extreme pressure and temperature conditions, remote and harsh operating environments, combined with associated risks due to small margins, high investments and a very much-needed strong focus on safety, calls for more detailed well planning.

As defined by NORSOK D-010, Well Integrity is the: *“Application of technical, operational and organizational solutions to reduce risk of uncontrolled release of formation fluids throughout the life cycle of a well”*

The ability to ensure well integrity requires a throughout understanding of the corresponding well behaviour and how it is affected by the different operational regimes it is subjected to, during all phases of a drilling operation. To achieve best possible well integrity, through planning, good software tools are essential.

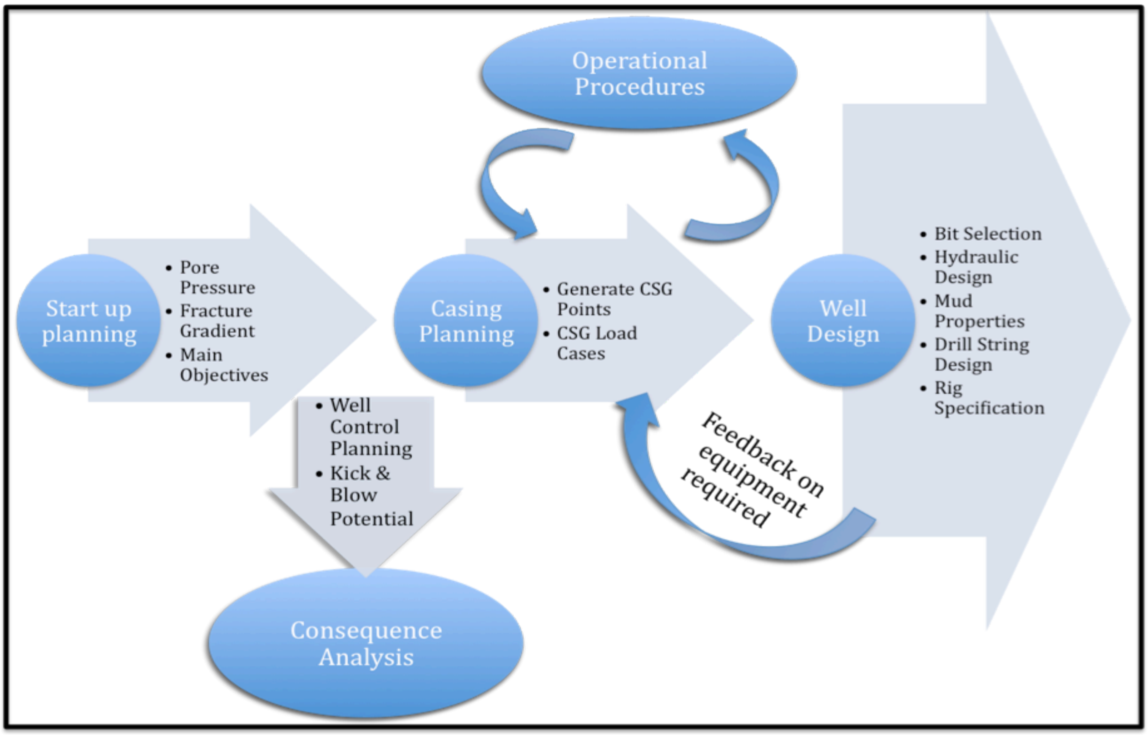


Figure 1. Exploration/Delineation Well Planning

Figure 1 shows a simplified model of the steps involved in the planning of a well, it start with the knowledge of the different formation pressures and the original objectives of the drilling campaign, all this information then is taken into consideration as the design team moves forward to advanced stages of the development.

Kick tolerance is a key element when establishing a well design. The number of sections will rely on the engineered data from the set of regulations governing the safety (kick tolerance) for each section.

4 Kick Tolerance in the Industry

Correctly calculating and understanding kick tolerance is essential to safe well design and drilling. There are numerous guidelines related to drilling, these describe best practices and recommendations in detail, however the research performed for this thesis work showed that even though kick tolerance is a critical and fundamental concept for the drilling industry, no uniformity was found to be used by all operators and drilling contractors and neither the API publications nor the IADC Drilling Manual seem to provide a method.

Additionally, the concept is not widely employed or understood to help essential decision-making during drilling. This often leads to discussion during operations on whether it is safe or not to continue drilling. As wells are drilled in more challenging environments, it takes only a small variation in kick tolerance calculations to lead to a premature abandonment of the well if a more conservative approach is used or, in other cases, to be against safety when the kick tolerance calculated is higher than what it should be.

Even the definition of the term shows lack of standardization, which can lead to confusion and the wrong use of this factor as a safety barrier. Some of the many different definitions found were:

1. Kick tolerance is the maximum allowable pore pressure, expressed in equivalent mud density such that if a kick with certain volume occurs at a particular depth with a specific drilling fluid, the well could be closed down and the kick circulated out safely – that is, not fracturing the weakest formation in the open hole.

2. Kick tolerance is the maximum increase in mud weight allowed by the pressure integrity test of the casing shoe with no influx in the wellbore.

3. Kick tolerance can be understood as the capability of the wellbore to withstand the state of pressure generated during well control operations (well

closure and subsequent gas kick circulation process) without fracturing the weakest formation.

4. Kick tolerance is the maximum height of a gas column that the open hole section can tolerate, i.e., without formation fracture occurring. This height is then converted to a volume using the cross sectional area and geometry of the wellbore and drill string to derive a limited 'Kick Tolerance' in barrels or ppg equivalent.

5. Kick tolerance is the largest volume of influx that can be removed from the well safely and is again based on the results of either a LOT or FIT. When kick tolerance is calculated the result could be best described as a measurement of well control risk when drilling the current hole section.

NORSOK standard 3.1.50 define a kick as an unintentional inflow of formation fluid from the formation into the wellbore, and standard 3.1.14 describe kick tolerance as the maximum influx to equal MAASP and mark some mandatory parameters for it’s calculation:

- The choke line friction shall be included when calculating kick tolerances for subsea wells. The MAASP shall be reduced with a value equal to the choke line friction.
- Standard 5.6.2 establish that when preparing the casing design the Experience from previous wells in the area or similar wells shall be assessed in regards to the maximum allowable setting depth with regards to kick margin.

Many different definitions and the confusion between kick tolerance and maximum allowable pit gain, derived from the additional formation flow into the wellbore after the well is shut in (afterflow), could be the beginning of an explanation on the lack of standardization and consistency among the different methods and assumptions used by different drilling operators.

Another important mistaken belief is the assumption that an approach utilizing a single bubble model and ignoring effects like temperature, influx density and gas compressibility factor in the final calculation will always result in a conservative solution.

4.1 Industry Practice

Frequently used spreadsheet type tools present several assumptions, in order to simplify the calculation process, but these assumptions, both individually or a combination of them might not be applicable to all particular scenarios. These simplifications could produce an extremely conservative volume, hence an unnecessary budget increases, or on the other hand an unsafe value, that could put in jeopardy the achievement of the drilling and safety objectives.

Unlike some “in-house” build applications, run mainly by operators on a Microsoft Excel platforms, there is available commercial “standalone” software. Some of these programs show to be extremely powerful and well thought, taking into consideration most of the different variables, giving the kick tolerance calculation a very high level or reliability.

More details about the developed application, the spreadsheet type tool often used by the operators and the state of the art available software can be found in Appendix E.

4.2 Calculation of Kick Tolerance

As previously mentioned the fundamental concept of kick tolerance is frequently misunderstood and among those misconceptions are issues related to the calculation of the kick volume.

The procedure found in some operators spread sheets and in the available literature is presented here:

Maximum pressure allowed at the shoe or fracture gradient:

$$p_{shoe,max} = h_{csg\_shoe} \cdot p_{LOT} - p_{safety} \tag{4.1}$$

Where equilibrium must apply:

$$p_{shoe,max} = p_f - \rho_{mud} \cdot (h_{TD} - h_{csg\_shoe} - H_{shoe}) - \rho_{i,shoe} \cdot H_{shoe} \tag{4.2}$$

And from these the height of the kick at the shoe:

$$H_{shoe} = \frac{p_{shoe,max} - p_f + \rho_{mud} \cdot (h_{TD} - h_{csg\_shoe})}{\rho_{mud} - \rho_{i,shoe}} \tag{4.3}$$

When a LOT has not been performed, the value of H_{shoe} can also be calculated using an adjusted MAASP, MAASP subtracted by a safety margin, at the casing shoe, assumed to be the weakest point in the open hole, based on:

- Fracture gradient
- Mud weight
- Kick fluid density
- Predicted pore pressure

V_{shoe} is calculated from H_{shoe} using annular capacity across the drill pipe

$$V_{shoe} = H_{shoe} \cdot A_{csg\_shoe} \tag{4.4}$$

The influx volume at the shoe, is then taken to bottom as shown in ***Figure 2***, using Boyle's Law and it correspond to:

$$V_{kickzone,1} = V_{shoe} \cdot \frac{p_{shoe,max}}{p_f} \tag{4.5}$$

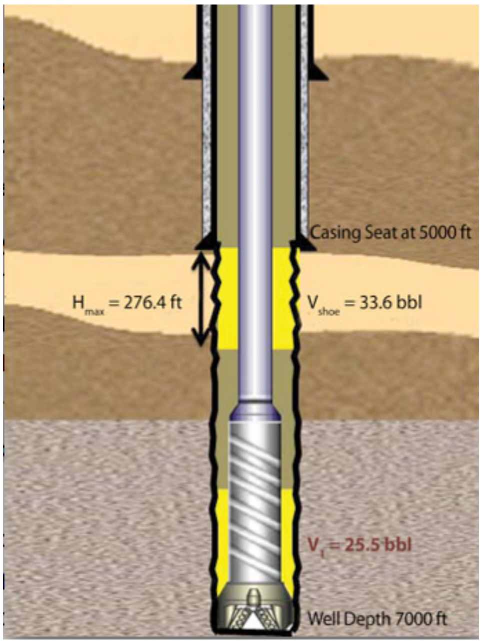


Figure 2. Volume Kick Zone 1

This is the influx volume at the kick zone, which will cause the pressure at the shoe to reach the maximum allowable value when the kick reaches the shoe. Is important to note that some sources stop calculations at this point and consider this the final value for kick tolerance.

The allowable value when the kick enters the wellbore might be higher due to inclination or smaller due to the decrease in the annular capacity.

$$p_{shoe,max} = p_f - \rho_{mud} \cdot (h_{TD} - h_{csg\_shoe} - H_{kickzone}) - \rho_{i,kickzone} \cdot H_{kickzone} \tag{4.6}$$

And from these the height of the kick at the kick zone:

$$H_{shoe} = \frac{p_{shoe,max} - p_f + \rho_{mud} \cdot (h_{TD} - h_{csg\_shoe})}{\rho_{mud} - \rho_{i,kickzone}} \tag{4.7}$$

$$V_{kickzone,2} = H_{kickzone} \cdot A_{kickzone} \tag{4.8}$$

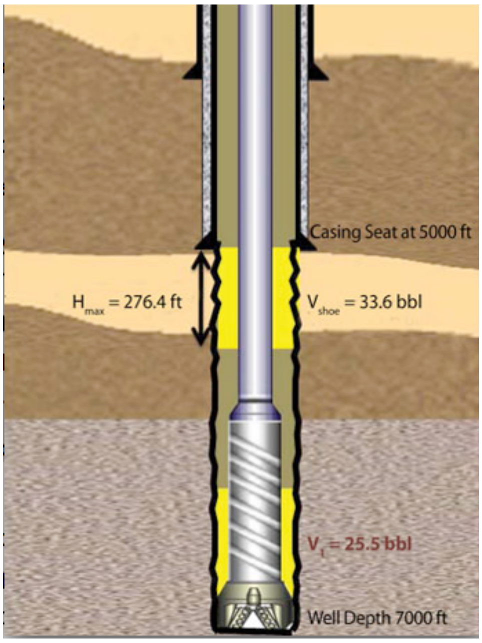


Figure 3. Volume Kick Zone 2

In order to define Kick Tolerance:

$$\begin{aligned} &\text{If } V_{kickzone,1} \geq V_{kickzone,2} \\ &\text{then } KickTolerance = V_{kickzone,2} \\ &\text{else } KickTolerance = V_{kickzone,1} \end{aligned} \tag{4.9}$$

The volumes are compared and the assumption is that the smaller value will create a more conservative, hence safer, kick tolerance.

4.3 Kick Tolerance Parameters

Some important factors are neglected in the analysis previously presented, each one of these generate different change in the calculation of kick tolerance.

The parameters discussed here are:

- BHA length
- BHA geometry and annular capacities
- Influx density
- Temperature change
- Frictional losses
- Swabbing
- Zero gain
- Compressibility factor
- Single bubble
- Casing shoe as the weakest point
- Other parameters:
  - Mud rheology
  - Solubility
  - Dispersion
  - Migration
  - ECD
  - Velocity of the influx

In order to present and review how these different parameters affect and modify the analysis of kick tolerance for a well a real life case would be shown with the support software.

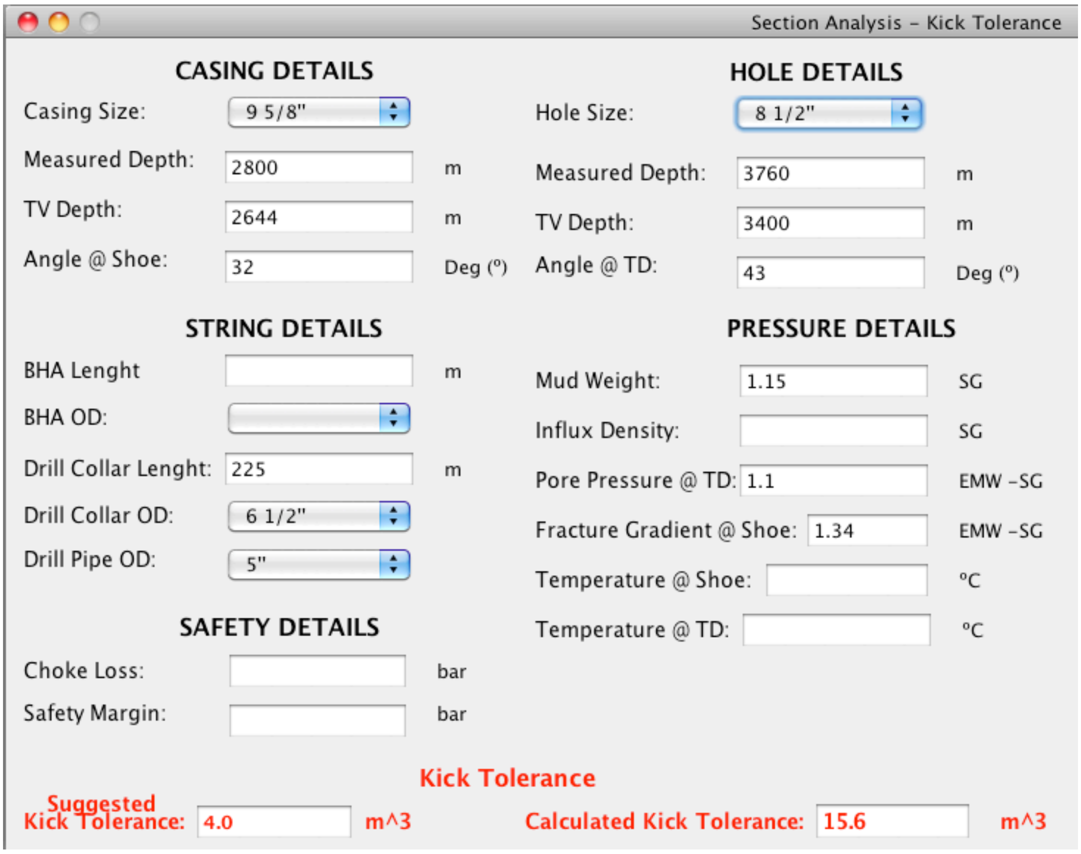
5 Kick Tolerance Support Software

Well Information RT Data Set#5				
Drilled Interval	2800 - 3760 mMD			
Well Name / Date	"Well Thesis Work" / 27-Jan-05 – 13-Feb-05			
Tie in Point	2794.00 m MD	2641.03 m TVD	31.78° Inc	
Top of Reservoir	3698 m MD Mean Sea Level			
Pore Pressure Gradient	1.1 SG			
Fracture Gradient*	1.34 SG			
Mud Type	Oil Based Mud			
Surface Temperature	15 ºC			
EBHT	123 ºC			
Temperature Gradient	0.0318 ºC/m			
Mud Density	1.15 SG to 1.24 SG			
Formation Fluid	0.24 SG			
Casing Record	9 5/8"	2800m MD	2644m TVD	32º
Borehole Record	8 ½"	3760m MD	3400m TVD	43º
BHA	8"	26.55m		
Drill Collar	6 ½"	225m		
Drill Pipe	5"			

Table 1. *Kick Tolerance Data*

*FIT performed in neighboring wells @ 2800mMD

Table 1. Shows all the relevant data for the analysis.



Section Analysis – Kick Tolerance

CASING DETAILS

Casing Size: 9 5/8"
Measured Depth: 2800 m
TV Depth: 2644 m
Angle @ Shoe: 32 Deg (º)

HOLE DETAILS

Hole Size: 8 1/2"
Measured Depth: 3760 m
TV Depth: 3400 m
Angle @ TD: 43 Deg (º)

STRING DETAILS

BHA Lenght m
BHA OD:
Drill Collar Lenght: 225 m
Drill Collar OD: 6 1/2"
Drill Pipe OD: 5"

PRESSURE DETAILS

Mud Weight: 1.15 SG
Influx Density: SG
Pore Pressure @ TD: 1.1 EMW -SG
Fracture Gradient @ Shoe: 1.34 EMW -SG
Temperature @ Shoe: ºC
Temperature @ TD: ºC

SAFETY DETAILS

Choke Loss: bar
Safety Margin: bar

Kick Tolerance

Suggested Kick Tolerance: 4.0 m^3
Calculated Kick Tolerance: 15.6 m^3

Figure 4. Initial Data in Support Software

	Capacity		Annular Volume	
Open Hole – Drill Collar	15.2	l/m	3.4	m^3
Open Hole – Drill Pipe	23.9	l/m	17.6	m^3
Casing – Drill Pipe	29	l/m	81.1	m^3
Distance top Drill Collar to Casing Shoe			735	m
Temperature Gradient			0	ºC/30m
Fracture Pressure @ Casing Shoe			347.6	bar
Fracture Gradient @ Total Depth			366.9	bar
Allowable Influx Height			584.7	m TVD
Lenght of Kick @ Casing Shoe			689.4	m MD
Lenght of Kick @ True Depth			799.4	m MD
Kick Size on Shut in			17.2	m^3
Kick Size @ Shoe			16.5	m^3
Gas – Shoe Back to Total Depth			15.6	m^3
MAASP			49.3	bar

Acceptable Kick Tolerance

Figure 5. Extra Calculations in Support Software

The initial analysis, with the available data in this well shows an acceptable value for kick tolerance, later, once operations started, this demonstrated to be different from what was expected.

5.1 BHA Length

It is conceptually wrong to neglect the BHA length. If $BHA_{length} \geq H_{shoe}$ the kick will most likely not be circulated out of the wellbore, or it will create an unsafe and very hard task for the drilling crew, as it will reach the top of the drill collars with a kick height greater than H_{shoe}, which in consequence would induce losses at the shoe.

When $BHA_{length} \geq H_{shoe}$ some other calculations have to be performed in order to have a more accurate value for kick tolerance, where the calculations must be done for the volume across the top of drill collars

$$V_{DC} = H_{Kickzone} \cdot A_{DC} \tag{5.1}$$

V_{DC} must be taken to the bottom of the wellbore using Boyle's Law

$$V_{kickzone,2}' = V_{DC} \cdot \frac{p_{shoe,max}}{P_f} \tag{5.2}$$

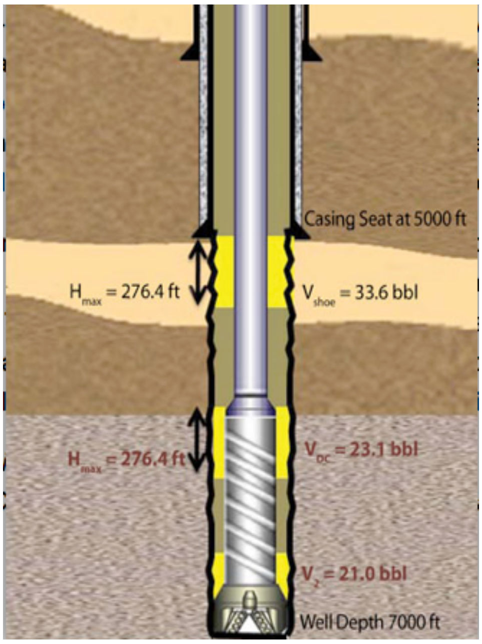
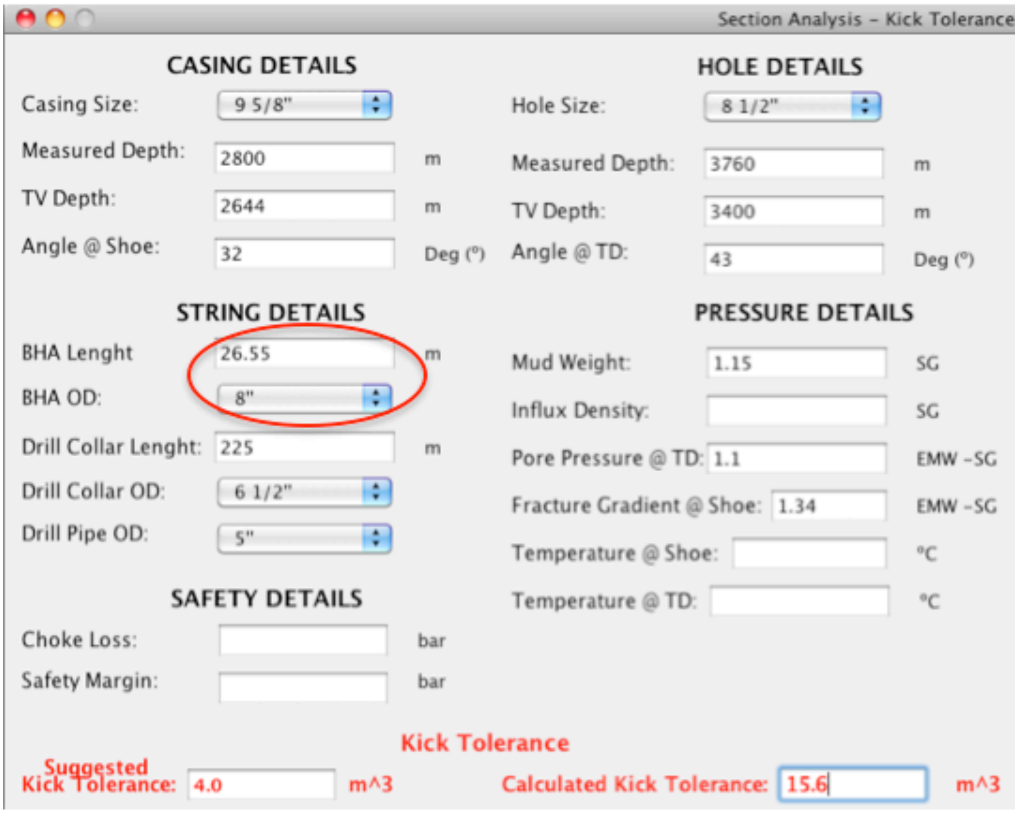


Figure 6. Volume Kick Zone 2'. Corrected for BHA Length

Kick tolerance is determined in the same way as for the conventional method

$$\begin{aligned} &\text{If } V_{kickzone,1}' \geq V_{kickzone,2}' \\ &\text{then } KickTolerance = V_{kickzone,2}' \\ &\text{else } KickTolerance = V_{kickzone,1}' \end{aligned} \tag{5.3}$$



Section Analysis – Kick Tolerance

CASING DETAILS

Casing Size: 9 5/8"
Measured Depth: 2800 m
TV Depth: 2644 m
Angle @ Shoe: 32 Deg (º)

HOLE DETAILS

Hole Size: 8 1/2"
Measured Depth: 3760 m
TV Depth: 3400 m
Angle @ TD: 43 Deg (º)

STRING DETAILS

BHA Lenght 26.55 m
BHA OD: 8"
Drill Collar Lenght: 225 m
Drill Collar OD: 6 1/2"
Drill Pipe OD: 5"

PRESSURE DETAILS

Mud Weight: 1.15 SG
Influx Density: SG
Pore Pressure @ TD: 1.1 EMW -SG
Fracture Gradient @ Shoe: 1.34 EMW -SG
Temperature @ Shoe: ºC
Temperature @ TD: ºC

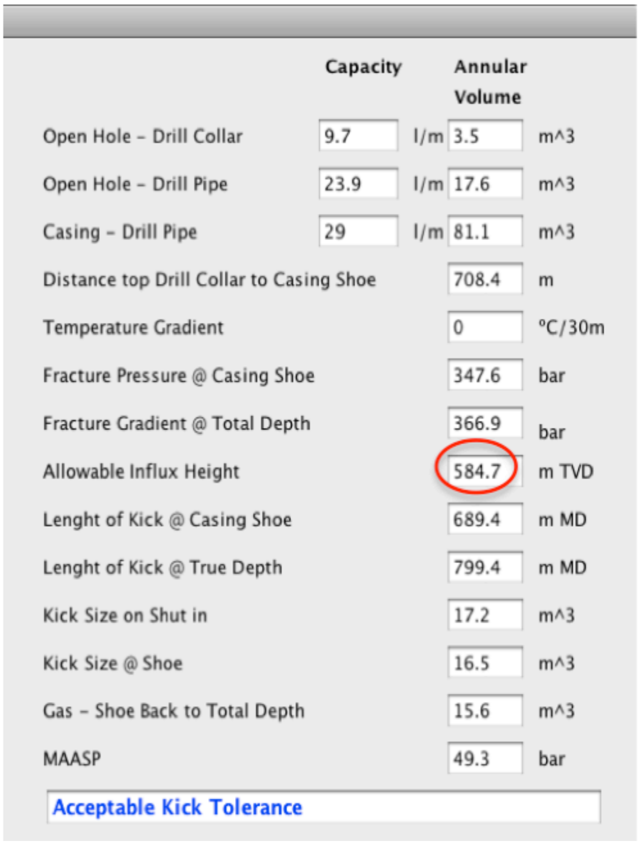
SAFETY DETAILS

Choke Loss: bar
Safety Margin: bar

Kick Tolerance

Suggested Kick Tolerance: 4.0 m^3
Calculated Kick Tolerance: 15.6 m^3

Figure 7. BHA Data



	Capacity		Annular Volume	
Open Hole – Drill Collar	9.7	l/m	3.5	m^3
Open Hole – Drill Pipe	23.9	l/m	17.6	m^3
Casing – Drill Pipe	29	l/m	81.1	m^3
Distance top Drill Collar to Casing Shoe			708.4	m
Temperature Gradient			0	ºC/30m
Fracture Pressure @ Casing Shoe			347.6	bar
Fracture Gradient @ Total Depth			366.9	bar
Allowable Influx Height			584.7	m TVD
Lenght of Kick @ Casing Shoe			689.4	m MD
Lenght of Kick @ True Depth			799.4	m MD
Kick Size on Shut in			17.2	m^3
Kick Size @ Shoe			16.5	m^3
Gas – Shoe Back to Total Depth			15.6	m^3
MAASP			49.3	bar

Acceptable Kick Tolerance

Figure 8. BHA Extra Calculations

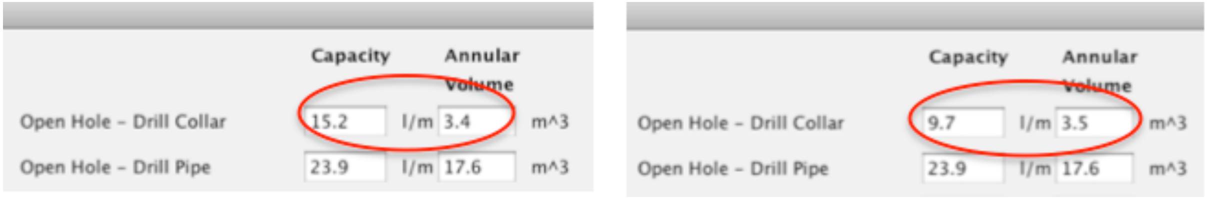
For this case $BHA_{length} \leq H_{shoe}$, which is the reason, no extra calculations were required, but it's very important for the used analysis to take this into consideration, since the losses at the shoe resulting from ignoring $BHA_{length} \geq H_{shoe}$ correction could be significant, especially for certain scenarios, i.e. short open hole sections.

5.2 BHA Geometry and Annular capacities

Most of the time when $H_{shoe} \geq BHA_{length}$ the difference in annular volume compensates the expansion of the gas when it travels upwards, reducing the chances of creating a problem. Ideally the analysis tool should take into account all BHA geometries to minimize any error in the final result.

BHA#8 Listing					
Element	Length (m)	OD (in)	ID (in)	Max OD	Total Length (m)
PDC Bit	0.30	8.00	-	8.00	0.30
PD675	4.10	6.75	2.63	8.0	4.40
NM Stab	1.72	6.75	2.50	8.0	6.12
ARC6	6.05	6.75	2.81	6.75	12.17
PowerPulse	8.30	6.75	5.1	6.75	20.47
ADN6	6.08	6.75	2.25	8.0	**26.55**

Table 2. *BHA Information*



	Capacity		Annular Volume	
Open Hole - Drill Collar	15.2	l/m	3.4	m^3
Open Hole - Drill Pipe	23.9	l/m	17.6	m^3

	Capacity		Annular Volume	
Open Hole - Drill Collar	9.7	l/m	3.5	m^3
Open Hole - Drill Pipe	23.9	l/m	17.6	m^3

Figure 9. BHA capacity and annular volume change

For this well the annular volume shows almost no effect when adding the BHA configuration, in comparison to assuming the entire string as a drill collar, 0.1 m^3 that show no effect in the computation for the allowable influx height. This does not mean this computation should be avoided; other wells could show bigger impact i.e. upper sections with larger annulus.

The remaining challenge is to know the real hole size with certain level of precision along the entire annulus to calculate the real volume capacities with a higher accuracy. This is no easy task; it is one of the main challenges for different operations in the industry. Some of the options available are listed in appendix D.

Not all scenarios allow an operator to make use of the high end technologies needed to modify, in real time, the actual annular volume generate by drilling. For some wells the investment might be considerably higher than the reward, and in some other cases, such as deep and near horizontal wells, real time measurements from LWD will hardly provide the necessary data density to have an accurate image of the hole's diameter and recorded data might only be useful as a reference for other operations, such as cementing and casing, but not to the modification of the kick tolerance value.

5.3 Influx Density

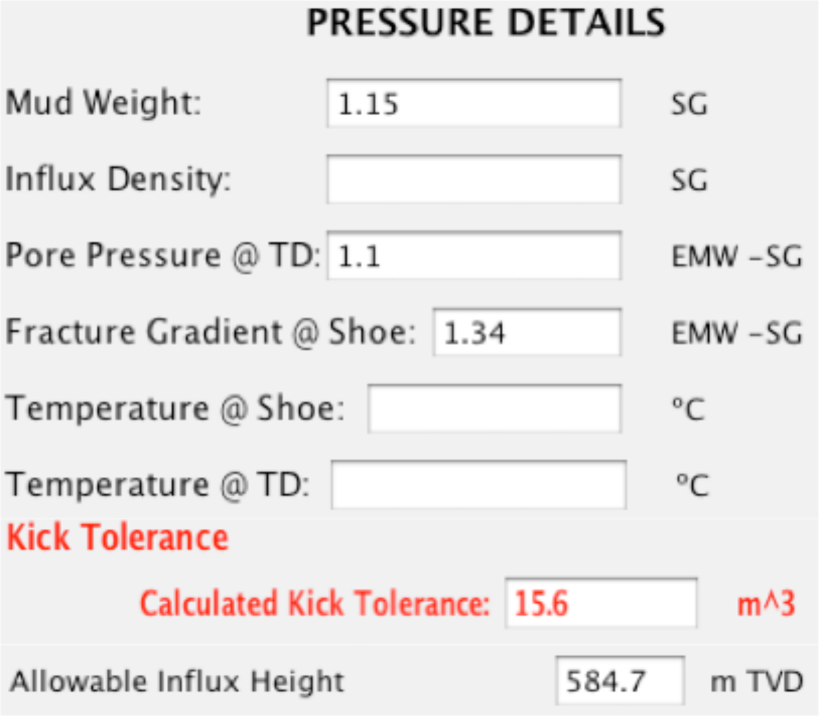
The kick fluid density is usually assumed, not calculated, and consider constant along the open hole. Part of the importance of the computation of the compressibility factor is that it can simplify the calculation of the influx density.

$$\rho_{i,kick} = \frac{29 \cdot \gamma_g \cdot p_{TD}}{z_{TD} \cdot R \cdot T_{TD}} \tag{5.4}$$

where $\gamma_g = 0.6$ for hydrocarbon gas.

This same formula can be used for all different point of interest where the kick influx might be expected.

The calculation of H_{shoe} in **formula 4.7** show that the greater the gas density the more influx the well can tolerate, as a result when influx density is used in the H_{shoe} calculation it not only affect its result but also the consequent volume calculations. In this example, the annular capacity is very small and a change in the allowable influx can have a considerable impact.



PRESSURE DETAILS

Mud Weight: 1.15 SG

Influx Density: SG

Pore Pressure @ TD: 1.1 EMW -SG

Fracture Gradient @ Shoe: 1.34 EMW -SG

Temperature @ Shoe: °C

Temperature @ TD: °C

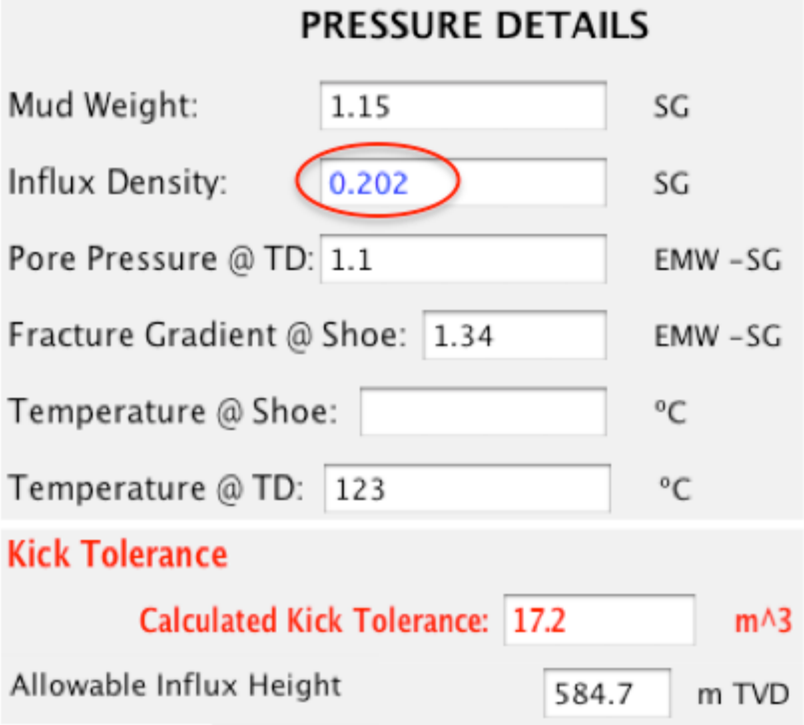
Kick Tolerance

Calculated Kick Tolerance: 15.6 m^3

Allowable Influx Height 584.7 m TVD

Figure 10. Kick Tolerance without influx density

Figure 10 shows the result of the analysis without the consideration of the influx density.



PRESSURE DETAILS

Mud Weight: 1.15 SG

Influx Density: 0.202 SG

Pore Pressure @ TD: 1.1 EMW -SG

Fracture Gradient @ Shoe: 1.34 EMW -SG

Temperature @ Shoe: °C

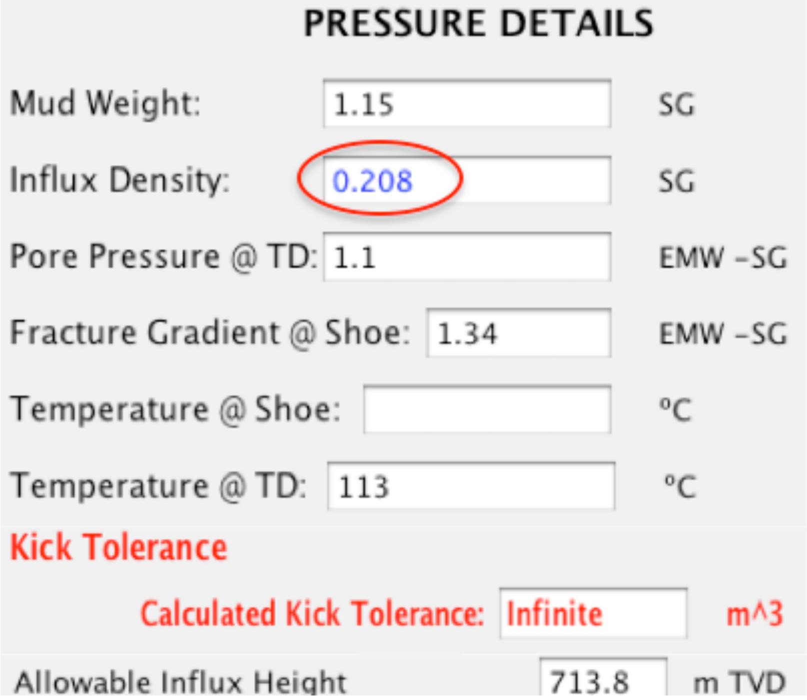
Temperature @ TD: 123 °C

Kick Tolerance

Calculated Kick Tolerance: 17.2 m^3

Allowable Influx Height 584.7 m TVD

Figure 11. Influx Density 2 (0.202)



PRESSURE DETAILS

Mud Weight: 1.15 SG

Influx Density: 0.208 SG

Pore Pressure @ TD: 1.1 EMW -SG

Fracture Gradient @ Shoe: 1.34 EMW -SG

Temperature @ Shoe: °C

Temperature @ TD: 113 °C

Kick Tolerance

Calculated Kick Tolerance: Infinite m^3

Allowable Influx Height 713.8 m TVD

Figure 12. Influx Density 3 (0.208) in Support Software

Figures 11 and ***12*** show how a small increase in the calculated influx density (in this case due to a down hole temperature adjustment), can change the outlook from a loose kick tolerance value to a well which open hole volume would be entirely filled by the influx of a kick.

5.4 Temperature Change

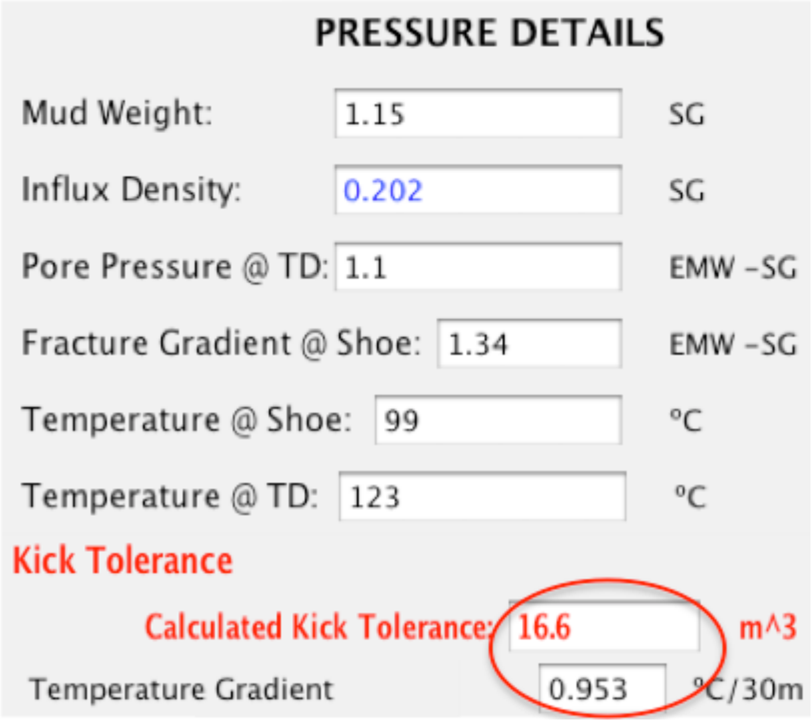
The simplified method assumes that the temperature in the open hole section is constant, thus no correction to the volume calculation is applied, but in reality the change in temperature will have effect in the mud characteristics (rheology and density). Once the volumes have been calculated, this effect can be easily corrected using Charles Law.

Charles Law states that the volume of the gas is directly proportional to the absolute temperature

$$T_{csg\_shoe} = T_{surface} + T_{gradient} \cdot h_{csg\_shoe} + 460^{\circ} \tag{5.5}$$

$$T_{TD} = T_{surface} + T_{gradient} \cdot h_{TD} + 460^{\circ} \tag{5.6}$$

$$\frac{P_1 \cdot V_{kickzone,1}}{T_1} = \frac{P_2 \cdot V_{kickzone,2}}{T_2} \tag{5.7}$$



PRESSURE DETAILS

Mud Weight: 1.15 SG

Influx Density: 0.202 SG

Pore Pressure @ TD: 1.1 EMW -SG

Fracture Gradient @ Shoe: 1.34 EMW -SG

Temperature @ Shoe: 99 °C

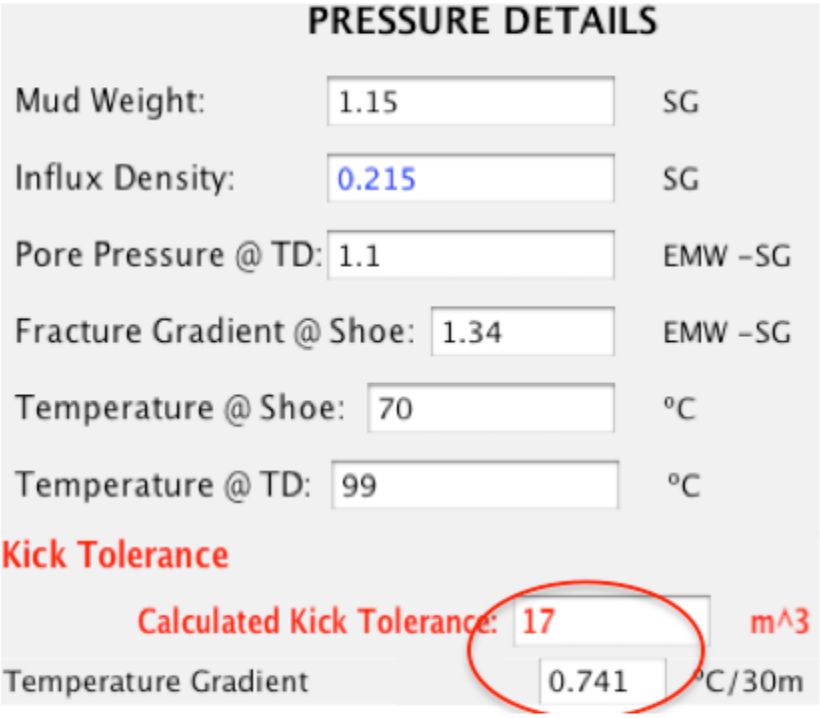
Temperature @ TD: 123 °C

Kick Tolerance

Calculated Kick Tolerance: 16.6 m^3

Temperature Gradient 0.953 °C/30m

Figure 13. Original temperature data



PRESSURE DETAILS

Mud Weight: 1.15 SG

Influx Density: 0.215 SG

Pore Pressure @ TD: 1.1 EMW -SG

Fracture Gradient @ Shoe: 1.34 EMW -SG

Temperature @ Shoe: 70 °C

Temperature @ TD: 99 °C

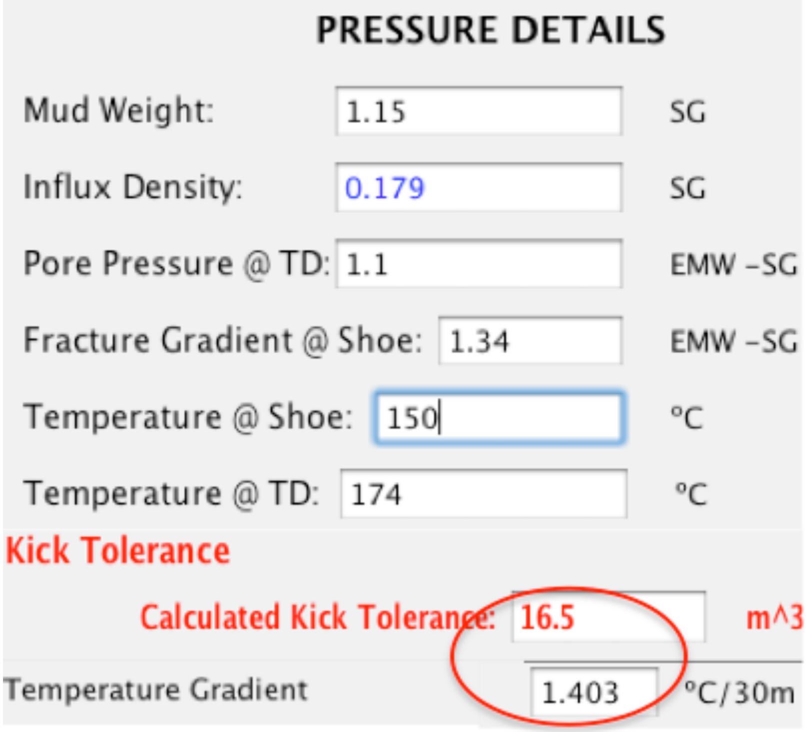
Kick Tolerance

Calculated Kick Tolerance: 17 m^3

Temperature Gradient 0.741 °C/30m

Figure 14. Smaller temperature gradient data

Figure 14 shows lower temperatures, hence a smaller temperature gradient, this generates a more conservative solution than the original data.



PRESSURE DETAILS

Mud Weight: 1.15 SG

Influx Density: 0.179 SG

Pore Pressure @ TD: 1.1 EMW -SG

Fracture Gradient @ Shoe: 1.34 EMW -SG

Temperature @ Shoe: 150 °C

Temperature @ TD: 174 °C

Kick Tolerance

Calculated Kick Tolerance: 16.5 m^3

Temperature Gradient 1.403 °C/30m

Figure 15. Larger temperature gradient data

Figure 15 present the opposite example, increased temperatures, an enlarged temperature gradient, giving as a result a slightly reduce kick tolerance calculation.

This temperature correction also relies on whether $V_{kickzone,1}$ or $V_{kickzone,2}$ is the dominating volume, depending on this the real effect of temperature on kick tolerance will vary.

$$EffectV_{kickzone,2} \geq EffectV_{kickzone,1} \tag{5.8}$$

As previously shown taking temperature into consideration also affects the density of the influx calculation. This added to the fact that all non-Newtonian fluids change from surface to downhole conditions while being pumped, and this also alters the density of the mud depending on it's rheology.

5.5 Frictional losses

Friction loss in the choke line and annulus will be generated every time there is fluid circulation in the well. Given the physical principle behind annular and choke line friction loss, they are frequently grouped together and used as a term better known as safety margin. Some misconception can be found in the application of this term, at times leading to an overly conservative solution, that as we mentioned before in some particular wells i.e. deepwater, can lead to unnecessary casing and liners.

$$SafetyM\,arg\,in = FrictionLoss_{annular} + FrictionLoss_{choke} \qquad (5.9)$$

Even though most wells, and each section, possess different characteristics, there are widely used fixed values, usually between 150-200 psi(10.3-13.8 bar) that is applied to the value of MAASP, in an attempt to reduce the chance of inducing fractures during a well control event. This is not necessarily the right approach since the magnitude of the induced losses are dependant on the well geometry, length and diameter of the choke line.

SAFETY DETAILS

Choke Loss: bar

Safety Margin: 6.89 bar

Kick Tolerance

Calculated Kick Tolerance: 14.9 m^3

Figure 16. Suggested value for safety margins (100psi)

SAFETY DETAILS

Choke Loss: bar

Safety Margin: 10.34 bar

Kick Tolerance

Calculated Kick Tolerance: 14 m^3

Figure 17. Industry minimum standard for safety margins (150psi)


SAFETY DETAILS
Choke Loss: bar
Safety Margin: 13.78 bar
Kick Tolerance
Calculated Kick Tolerance: 13.2 m^3

Figure 18. Industry maximum standard for safety margins (200psi)

As we can see in ***Figures 16-18*** the safety margin value has an important effect in the calculation of kick tolerance, the standard values shown to be more applicable to more challenging wells with larger and narrower the choke lines, where the losses would be considerably larger.

Figure 16 shows the proposed safety margin for this well, according to its particular specifications.

Another value that has been "standardized" is the choke error, this was a value originally designed to compensate for the human error factor that could occur with a poor choke operation. Problem is that nowadays, with the existence of new technologies, rigs with automated rig equipment have a much higher control degree and the commonly used rate, 100 psi (6.9 bar), could be an excessive assumption that generate an over conservative design.


SAFETY DETAILS
Choke Loss: 3.45 bar
Safety Margin: bar
Kick Tolerance
Calculated Kick Tolerance: 14 m^3

Figure 19. Suggested value for Choke error (50psi)

SAFETY DETAILS

Choke Loss: 6.89 bar

Safety Margin: bar

Kick Tolerance

Calculated Kick Tolerance: 13.2 m^3

Figure 20. Industry minimum standard value for choke error (100psi)

SAFETY DETAILS

Choke Loss: 10.34 bar

Safety Margin: bar

Kick Tolerance

Calculated Kick Tolerance: 12.2 m^3

Figure 21. Industry maximum standard value for choke error (150psi)

Figures 19-21 choke error will as well be an important factor that should be careful considered according to the particular characteristics of the well, which this in mind, ***Figure 19*** shows the proposed choke error to be considered for this well.

SAFETY DETAILS

Choke Loss: 3.45 bar

Safety Margin: 6.89 bar

Kick Tolerance

Calculated Kick Tolerance: 14 m^3

Figure 22. Suggested values for this particular well

SAFETY DETAILS

Choke Loss: 6.89 bar

Safety Margin: 13.78 bar

Kick Tolerance

Calculated Kick Tolerance: 11.2 m^3

Figure 23. Industry standard values for safety parameters

The combination of both errors can have considerable effects in the final result, although estimating an accurate value for this friction loss is difficult, given the well design improvements that can happen with a better approach for this value, it would be beneficial for the industry to investigate it more deeply in order to take advantage of the potential economical benefits, that for some wells could be substantial.

5.6 Swabbing

If swabbing occurs and the pressure is reduced sufficiently for the well to be underbalanced, reservoir fluids may enter the wellbore and flow towards the surface. This initial swabbing action compounded by the reduction in hydrostatic pressure (from formation fluids entering the well) can lead to a significant reduction in bottom hole pressure and a larger influx of formation fluids.

This makes swabbing harmful in drilling operations, because it can lead to kicks and wellbore stability problems. And although it is recommended, for operations, to control tripping velocities in order to decrease the chances of swabbing on trips, for some scenarios, such as the presence of high viscosity and gel strengths, the use of large ODs tools (packers, scrapers, fishing tools, etc.) and especially ultra deepwater drilling, this is an almost unavoidable effect; therefore, early detection of swabbing on trips, by closely monitoring hole fill-up volumes during trips, is critical to minimizing the size of a kick and avoiding well control problems.

There are several computer and calculator programs that can estimate surge and swab pressures, but it has been shown that computation of swab pressures on the basis of steady-state flow is often incorrect, from this we can deduce that the best way to include this effect into the calculation of kick tolerance is by recalculating a new value when, during operations, swab or surge is detected.

A big issue here is that even when swabbing is avoided while pulling out of hole, the temperature equilibrium between mud and it's surroundings will be reached (temperature of the mud will increase) and there is a chance that the new ESD will not be sufficient to keep the well overbalanced.

5.7 Zero Gain

Even when a kick is quickly detected and the well opportunely shut-in the formation continues to flow until the casing pressure increases enough to equilibrate the bottom hole pressure to the sand face pressure at the depth of the influx. This contradicts the practice of ignoring the afterflow effect.

Even though this simplification can lead to a conservative result not taking into account this effect may be exposing the operations to potentially dangerous situations, especially for deep wells with large bores. When determining maximum allowable pit gain the additional flow taken into the well after shut in must be considered.

The estimation of the after flow after shut in can be a demanding task to achieve, but considering it to be equal to the well's total compressibility leads to a more valid result than ignoring it all together. The result will depend on the system compressibility, but a low compressibility will lead to smaller values of kick tolerance.

5.8 Compressibility Factor

The compressibility factor, also know as z factor, takes account for real gas behaviour according to the particular gas composition of the influx. A common assumption is to utilize z=1, as if the influx behaved according to the ideal gas law. The approach used to estimate this factor is not straightforward and requires several different methods for the numerical calculation, this makes it a hard task to perform without computer power.

The pseudocritical properties are calculated using Katz's correlations, and the factor requires Newton-Raphson iterative method combined with Dranchuk-Abou-Kassem or Hall-Yarborough correlations (best fit for single phase) or the Beggs-Brill correlation when multiphase is considered.

It is complicated to asses the exact composition of the gas influx, and studies show that taking this factor into account in most of the situations only present a variation of 1-2% in the final result. But deviation from ideal behavior becomes more significant the closer a gas is to a phase change, the lower the temperature or the larger the pressure.

5.9 Single Bubble

A simplified approach has traditionally employed a single bubble model, and this allows the calculations to be done without any computer help. Although computer power is not a problem and multiphase flow models are available to reproduce gas behaviour inside the wellbore.

5.10 Casing shoe is the weakest point

The assumption that the fracture gradient is lowest at the previous casing shoe is not necessarily true; fracture gradients vary with the in-situ stresses (overburden, pore pressure, etc) superimposed tectonic stresses and formation type. Hence the lowest fracture gradient in an open hole section is not always found at the previous casing shoe. This can have severe implications for the well control practice and casing setting depth.

5.11 Other Parameters

Other factors such as:

- Mud rheology
- Solubility
- Dispersion
- Migration
- ECD
- Velocity of the influx

Can also be taken into consideration, in order to produce the most accurate result possible. None of these factors are independent; they are all related to other variables such as the different drilling parameters, accurate influx chemical properties and mud characteristics and composition. Hence all this values need to be monitored in real time, after the drilling operation has begun, before they can be considered and taken into account for the kick tolerance calculation.

6 Conclusions

Many different parameters have influence on the calculation of kick tolerance; the most important ones were presented here. Many are neglected based on the misconception that doing so will lead to a more conservative approach, hence safer drilling. As mentioned here, this could be the case in some wells but is definitely not a rule that applies for all developments.

The main goal of this project was to create a standalone application that could be as user friendly as a commonly used Excel macro, with the capability to be used in any computer, just like the state of the art software, but simple, easily editable and with the ability to be updated an improved in the future. Another desirable characteristic for the program is that it can be reach remotely, which means that all personnel interested in updating or reviewing the data made for the analysis can do it as long as they have access to a secure network, where the analysis can be stored. Capabilities and functionalities of the support software build for this work is explained in depth in appendix E, along with a user guide.

Every well shows different characteristics, and it becomes very difficult to generalize which parameters can be neglected or ignored and which cannot. Neglecting temperature and z-factor for a shallow well can have extreme consequences and change in calculations, while it almost makes no difference in long reach, horizontal or deepwater wells. Instead the latter wells experience extreme changes when it comes to frictional losses.

This proves the importance of taking as many parameters (the final goal, would be all) into consideration as possible, leading not only to a more precise value for kick tolerance, but also to a better understanding of the concept and all the factors that are involved in it’s calculation. This will as well, improve the future ability to deal with a well control problem, if it happens.

The complication with the current methodology relies on the lack of standardization, between different operators and service companies, not to mention between particular developments. As mentioned it is hard to create a uniform protocol that includes all the different scenarios, since the diversity is big and the information during planning is not always as reliable as desired.

That is why, with kick tolerance is not only the final calculation number what should be of concern to the industry, but also a broad understanding on how the different factors will affect a specific well, and how leaving assumptions on the side, even when the effect is “negligible”, could under certain circumstances, be of greater trouble than originally considered.

For the example presented in Chapter 5, the length of the open hole section, the mud weight, or some other different drilling parameters could have been readjusted, when operations were on their way, and a new kick tolerance re-calculated. In our analysis, small changes in factors like influx density generate different scenarios that could have led to the undesired result of this project.

7 Further Work

One of the main advantages of the way the support software is build, lies on the development architecture used. In the future, new modules can be build and be easily integrated into the main program, with this all the assumptions not yet taken into consideration can be researched and adopted into a new model.

A couple of functionalities have been thought of by the author to improve the developed software:

a. With more research and access to more information on many different fields, a database could be created, and the software could have an algorithm that finds a field with similar characteristics and present it to the engineer. This could reduce the chances of repeating a safety hazard.

b. With further analysis the software could have an option to make more specific analysis, selecting rig characteristics, water depth, more detailed gradients, etc.

c. Enable a graphic display of the solutions, this will make the analysis and result clearer to the engineers in charge of the study.

d. If a standardization protocol could be developed within 3rd party companies providing: LWD/MWD, Mud Engineers and Mud Logger services, etc. the software may expand to generate automatic updates as the measurements are being taken.

e. Configure a safe protocol to have remotely access to the application.

All this upgrading would be the ultimate goal to make use of kick tolerance to its full potential, for better planning, increased revenues, but more importantly: to increase the safety of operations and ultimately of the personnel involved in it.

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Appendix A. Abbreviations and Nomenclature

API	American Petroleum Institute
BHP	Bottom Hole Pressure
BHT	Bottom Hole formation Temperature
BOP	Blow Out Preventer
CCs	Control Centers
CCRs	Central Control Rooms
CHDP	Chip Hold Down Pressure
CSIP	Casing Shut-in Pressure
DFU	Defined Situations of Hazard and Accidents
DGS	Dual Gradient System
DST	Drill Stem Test
EBHT	Estimated Bore Hole Temperature
ECD	Equivalent Circulating Density
ESD	Equivalent Static Density
EUB	Energy and Utilities Board
FBG	Formation Breakdown Gradient
FIT	Formation Integrity Test

GoM	Golf of Mexico
HF	Human Factor
HPES	Human Performance Enhancement System
HPHT	High Pressure High Temperature
HTO	Human, Technology and Organization
LRRS	Low Riser Return System
LWD	Logging While Drilling
MAASP	Maximum Allowable Annular Surface Pressure
MTO	Man Technology Organization
MPD	Manage Pressure Drilling
MWD	Measuring While Drilling
NCS	Norwegian Continental Shelf
POOH	Pulling Out Of Hole
PWD	Pressure While Drilling
RFT	Repeat Formation Tester
ROP	Rate Of Penetration
RPM	Revolutions Per Minute
SICP	Shut-in Casing Pressure

SIDPP	Shut-in Drill Pipe Pressure
SPI	Safety Performance Indicator
V_{kick}	Represents the quantity of the formation fluid entering the wellbore
VB	Visual Basic
VBA	Visual Basic for Applications
WOB	Weight On Bit

Appendix B. Definitions

BOP	Large, specialized valve used to seal, control and monitor oil and gas wells. Developed to cope with extreme erratic pressures and uncontrolled flow (formation kick) emanating from a well reservoir during drilling.
Casing Shut-in Pressure	A measure of the difference between the formation pressure and the hydrostatic pressure of the mud in the annulus when a kick occurs.
Diagenetic Process	Chemical and physical changes sediments undergo, due to increasing pressure and temperature.
Diaparism	Is the piercement of a formation by a plastic, mobile, less dense underlying formation, typically salt.
Drag	Excess force, which is necessary to pull the string up, whether this happens on a connection or a trip.
Drill Stem Test	Is a method of testing formations for pressure and fluid.
Faulting	Sedimentary beds are broken up, moved up and down or twisted due to tectonic activities.
Fill	The settling of cuttings and/or caving at the bottom of the hole.
Flow Rate	Volume of fluid which passes through a given surface per unit time.
Folding	Tectonic compression of a geological basin.
FBP	The pressure required to rupture the walls of the wellbore.
FIT	Test to determine the fracture gradient of a formation.

Fracture Gradient	May be defined as the minimum horizontal in-situ stress divided by the depth.
Fracture Gradient Test	A test carried out to the leak off point and beyond until the formation around the wellbore fails.
In-situ Stress	Define the local forces acting on lithologic layers in the subsurface.
Leak off Test	A test carried out to the point where the formation leaks off.
Limit Test	A test carried out to a specified pressure value always below the fracture gradient of the formation.
Matrix Stress	Stress under which the rock material is confined in a particular position in the earth's crust.
Mud Weight	Is the density (weight) of the drilling fluid.
Overbalance	The difference between the mud hydrostatic pressure and pore pressure; also known as CHDP.
Overburden Pressure	The pressure exerted by the total weight of overlying formations above the point of interest.
Pressure Gradient	The rate of increase in pressure per unit vertical depth i.e., psi per foot (psi/ft)
Pressure While Drilling	Tool that can directly measure the change in pressure at the bottom of the well caused by total annulus friction that occurs when pumping is started.
Repeat Formation Tester	Is a wireline run tool designed to measure formation pressure and to obtain fluid samples from permeable formations.

SPI	A means for measuring the changes in the level of safety (related to major accident prevention, preparedness and response), as the result of actions taken.
Shoe Bond Test	Analysis carried out to test strength of the cement at the casing shoe.
Standpipe Pressure	Is equal to the total hydraulic friction that must be overcome to move the fluids through the well.
Swabbing	To reduce pressure in a wellbore by moving the pipe, wireline tools or rubber-cupped seals up the wellbore.
Undercompaction	Process whereby abnormal pressure is developed as a result of a disruption of the balance between rate of sedimentation of clays and the rate of expulsion of the pore fluids as the clays compact with burial.
Uplift	When a formation is being moved to a lesser depth.
Wellhead	Component at the surface of an oil or gas well that provides the structural and pressure containing interface for the drilling and production equipment.
Xmas Trees	Assembly of valves, spools, and fittings used for an oil well, gas well, water injection well, water disposal well, gas injection well, condensate well and other types of wells.

Appendix C. Safety Importance of Kick Tolerance

The world has seen a number of disasters resulting from industrial accidents during the last decades. Many of these accidents are related to human errors and factors. A human error is more than just operators or engineers performing or planning a task unsatisfactory. Rather than occurring due to one cause only, accidents are viewed as the outcome of a set of causes including human, technical and organizational factors and the interaction between them.

Existing literature suggests that there is a trend towards an understanding and acknowledgement than the role of human errors plays an ever more important role in accidents, while e.g. mechanical failures play a decreasingly important role in accidents.

The Petroleum Safety Authority in cooperation with SINTEF has been working on an investigation methodology: “Man – Technology – Organization”, the objective of this has been to map out relevant communities of expertise in the fields of accident investigation, and status with regard to the use and further development of investigation methodology.

The principal focus has been directed at methods that are related to human factors and MTO thinking barriers. This method is based on Human Performance Enhancement System HPES for the nuclear industry. Another terminology used to study the human factors and errors is “Human, Technology and Organization”.

The analysis focuses in the examination of which technical, human or organizational barriers have failed or were missing during the accident in progress. The basic questions in the analysis are:

- What may have prevented the continuation of the accident sequence?
- What may the organization have done in the past in order to prevent the accident?

An organizational barrier refers to all the systems-related, physical and administrative safeguards existing within the organization, and aspects of the individuals work to prevent errors and mistakes or to limit it's consequences, i.e. rules and security systems, cargo fire doors, procedures, guidelines, etc.

In 1999 The Norwegian Petroleum Directorate (NPD), initiated the Risk Level Project, RNNP, for the Norwegian oil and gas industry. It studies the safety climate, barriers and undesired incidents, and discusses its relevance to drilling, paying particular attention to deepwater wells worldwide. Aspects related to well integrity and the two barriers principle, well planning, schedule and cost, undesired incidents, and well monitoring/intervention are discussed.

An essential part of the investigation is related to the number of kicks during an operation, and it is remarked as one of the most important indicators for the whole drilling industry, because it is an incident with the potential to cause a blowout.

An important principle in the Norwegian Petroleum Safety Authority (PSA) activities (AR Sec. 76) and Facilities (FAR Sec. 47) regulations is the concept of the well barriers and their control. If a barrier fails, no other activities should take place than those to restore the well barrier. Activities regulations (AR Sec.77) states that if well control is lost it shall be possible to regain the well control by direct intervention or by drilling a relief well. The operator is also required to have an action plan on how well control can be regained.

Barriers are vital for maintaining safety in day-to-day operations. A well should have at least two barriers. The primary well barrier is the first obstacle against undesirable flow from the source (kick) and proper kick tolerance is the first barrier between safety and a blowout.

Well integrity is the application of technical, operational and organizational solutions to reduce risk of uncontrolled release of formation fluids throughout the life cycle of a well.

The main undesired incidents related to well operations are:

1. Unintentional well inflow
2. Well leakage
3. Blowout.

The first is an unintentional flow of formation fluid into the wellbore (kick). The second is characterized by unintentional fluid flowing up through the BOP for a limited period of time until stopped by the existing well equipment or by defined operational means. A kick is instability in the well as a result of the well taking in gas, oil or water and may lead to a blowout. A blowout in turn is defined as an unintentional flow of formation fluid from the well to the surrounding or between the formation layers after the defined technical barriers, and the operation of those, have failed.

Barriers are required to ensure well integrity during drilling. Safety barriers are physical or non-physical means planned to prevent, control, or mitigate undesired incident or accidents, may be passive or active, physical, technical, or human/operational systems and have been defined in terms of three characteristics:

1. Barrier function: A function planned to prevent, control, or mitigate undesired incidents or accidents.
2. Barrier element: Part of barrier, but not sufficient alone in order to achieve the required overall function.
3. Barrier influencing factor: A factor that influences the performance of barriers.

There is also a requirement for a systematic application of two independent and tested well barriers in all operations and the operator shall establish barriers and know the barrier functions (Management Regulation Section 1 and Section 2).

Those barriers shall be established to reduce the probability of undesired incidents and the major points of the Norwegian barrier principle, legislation and guidelines for wells are:

1. Integrity status of the barrier shall be known at all times when such monitoring is possible.

2. The well should withstand the maximum anticipated differential pressure it may become exposed to.

There are two different groups of indicators for major hazard risk in RNNP:

1. Incident indicators; i.e. indicator based on the occurrence of incidents and precursor incidents (“near-misses”)

2. Barrier indicators; i.e. indicator that measure the performance of barriers installed to protect against major hazards and their consequence potential.

C.1 Defined Situations of Hazard and Accidents

In RNNP, categories of hazard precursor incidents are denoted “DFUs” which may be translated as, “Defined situations of hazard and accidents”. The DFUs were selected according to the following criteria:

- The DFU is an undesired incident/situation, which has led, or may lead, to loss (of life and other values), and hence represents a risk contribution.

A survey, to determine the main categories of the DFUs related to major hazards, was completed by the RNNP; this includes all the oil and gas production installations and mobile drilling units, which have operated on the Norwegian Continental Shelf between 2003 and 2008.

Major hazard precursor incident (DFU)	Frequency (Annual average 2003-08)
Non-ignited hydrocarbon leaks	16.7
Ignited hydrocarbon leaks	0
Well kicks Loss of well control	16.2
Fire Explosion in other areas, flammable liquids	2.5
Vessel on collision course	33
Drifting object	0.8
Collision with field-related vessel Installation Shuttle tanker	0.7
Structural damage to platform Stability Anchoring Positioning failure	7.8
Leaking from subsea production systems Pipelines Risers Flowlines Loading buoys Loading hoses	2.8
Damage to subsea production equipment Pipeline system Diving equipment caused by fishing gear	2.2

Table 3. *DFUs frequencies in the NCS 2003-2008*

An overview of the results is presented in ***Table 3***, and we can see that well kicks and lost of well control are the 3rd major hazard precursor of incident just after vessel on collision course and non-ignited hydrocarbon leaks. Even though it wasn't correlated in the RNNP research, there were 15 blowouts in the Norwegian Sector in the period 1999-2009, 14 of them being gas blowouts, and 1 shallow gas blowout, where the main precursor incident to these blowout was the loss of well control, including kicks.

The Golf of Mexico frequency of deepwater kicks is high. The overall frequency of kicks is approximately 2.7 times higher in the US GoM deepwater wells than the overall Norwegian Continental Shelf experience. That said, the NCS kicks in deep wells, and especially HPHT wells, have occurred frequently.

SINTEF performed in 2001 a study of deepwater kicks in the GoM, it showed that the most significant contributors to the kick occurrences were:

- Too low mud weight (23)
- Gas cut mud (17)
- Annular losses (9)
- Drilling break (9)
- Ballooning (7)
- Swabbing (5)
- Poor cement (2)
- Formation breakdown (1)
- Improper fill up (1)

This high occurrence is justified mainly due to the fact that many prospect in the deepwater GoM pose a unique combination of challenges when compared to deepwater wells in other parts of the world:

- Water depths of 3000m
- Shut-in pressures of more than 690 bars
- Bottom hole pressures higher than 195ºC
- Problematic formations with salt zones and tar zones
- Deep reservoir at more than 9000m TVD
- Tight sandstone reservoirs (<10 mD)
- Fluid with extreme flow assurance issues.

This present some new and important challenges such as:

- Increased costs
- Complex casing programs
- Narrow drilling margins
- High pressure and high temperatures (HPHT)
- Uncertain seismic

It is documented that 11% of all wells drilled on the U.K. continental shelf from 1988 to 1998 have experienced reportable kicks during well construction operations, this statistic increasing to 22% when considering HPHT wells alone. Other sources claim that HPHT operations show 1 to 2 reportable kicks per well, a much higher frequency when compared to non-HPHT, which only reported 1 kick per 20-25 wells.

Some of the most frequent causes to kicks in U.K. drilling wells were also found in U.S. wells, such as:

- Lost circulation in the same hole section with potential flow zones
- Too low mud weight
- Uncertainty in flow zone existence
- Uncertain flow potential, location, or other important characteristics

A study performed in 2009, showed that most kicks experienced on the UK are indirectly linked to the geological conditions, at the well location, and most involve conditions difficult to detect before the well is drilled. Other incidents are indirectly linked to the geological conditions, such as the challenges related to cementing casing in halite formations or in keeping the mud weight sufficient to prevent the well from flowing, but not so heavy that losses are induced. The latter challenge is not limited to HPHT wells in the GoM but is also encountered in the complex reservoirs of the Northern North Sea and the Lower Permian sands in the Southern North Sea. According to this research a significant, though small, proportion of kicks are due to human error.

Data shows a considerable lower kick occurrence in onshore wells. The Alberta Energy and Utilities Board (EUB) reports 1 kick every 70 wells, but even with the differences between offshore and onshore, it regards the number of blowouts and kicks as a primary indicator of industry‘s drilling and servicing performance and pays particularly close attention to industry‘s response to these incidents.

Different sectors present different statistics, with the probability of kicks depending on geological conditions, but kicks can be prevented by proper well planning, design, and performance monitoring, and although it is hard to extrapolate this data and make a valid comparison, there is a common understanding among the regulatory authorities in Norway, UK, Canada and the U.S. that kicks are precursor incidents and should be avoided.

All this research shows that the most pressing issue is human error as a continuing factor in well incidents. If drilling activity levels and increased difficulty continues as in recent years, appropriate well-control training of personnel engaged in both rig site operations and in operational planning needs to be accorded the highest priority, and although the number of kicks and blowouts are relevant indicators, there is a pressing need for developing a set of deepwater drilling indicators for precursor incidents leading up to those kicks and blowouts. Often, a major challenge is that there is not enough data to support a basic set of reliable and valid safety indicators.

The relationship between schedule and cost, and assessment and prioritization of risks, is an essential element of risk management. Better understanding can be achieved by collecting data related to schedule and cost and compare with supplementing safety indicators.

The following are typical problems that occur if time is not spent on well design and planning:

- Lack of knowledge of overall geology and basin mechanics
- Not understanding why previous wells got in trouble
- Lack of “immersion” in data available
- Cost sensitivity mentality.

Appendix D. Deduction of Kick Tolerance – input/output

D.1 Open Hole Size Measurement

D.1.1 Ultrasonic Caliper.

A pulse-echo tool where a transducer sends and receives an ultrasonic signal.

$$S\tan doff = \frac{RoundTripTravel \cdot VelocityofWaveThroughMud}{z} \tag{D.1}$$

With single axis tools you have problems, such as a high dependence on the tool centralization and the location of the sensors in the well hole, where the blade might be too close or the body could be too far and generate an eccentric measurement.

Nowadays there are 3-axis and 4-axis tools, this tools eliminate the problem and compute a much more reliable hole and shape measurements, especially in the memory data store on the tool, not so much in the Real Time Data. The problems for this tools lie on the fact that the calculation needs an accurate knowledge of mud velocity, and the position on the tool in the BHA defines how well centralized the measurement, hence reliable, will be.

D.1.2 Sonic Caliper

Better used for cementing data acquisition in large wellbores, but it is found to be unreliable.

D.1.3 LWD Density Data

Works well when the hole is not significantly over-gauged and the density of the formation and the borehole fluid are different enough for the tool to distinguish it.

D.1.4 Resistivity Data

This method does not generate a direct measurement, it relies on assuming all separation of the resistivity curves in a drilling log is due to the borehole size, from there an iteration is required to find out the real diameter of the borehole. The accuracy of this is highly dependant on the number of resistivity sensors being monitored.

D.2 Background for Formation Input Data

D.2.1 Pore Pressure or Formation Pressure

Normal pore pressure is equal to the hydrostatic pressure of a column of formation fluid extending from the surface to the subsurface formation being considered, this is not constant, the magnitude of normal pore pressure varies with the concentration of dissolved salts, type of fluid, gases present and temperature gradient. For example, as the concentration of dissolved salts increases the magnitude of normal pore pressure increases.

Subnormal pore pressure is defined as any formation pressure that is less than the corresponding fluid hydrostatic pressure at a given depth. This is often developed long after the formation is deposited and may have natural causes related to the stratigraphic, tectonic and geochemical history of an area, or may have been caused by the production of reservoir fluids, i.e.:

- Depositional Effects
    - Undercompaction of shale
- Diagenetic Processes
- Tectonic Effects
- Structural Causes; and
- Thermodynamic Effects

Abnormal pore pressure is defined as any pore pressure that is greater than the hydrostatic pressure of the formation water occupying the pore space. The cause of abnormal pore pressure is attributed to a combination of various geological and mechanical changes. For any abnormal pressure to develop there has to be an interruption to or disturbance of the normal compaction and de-watering process, i.e.:

- Depositional Effects
    - Undercompaction of sediments
    - Deposition of evaporites
- Diagenetic Processes
- Tectonic Effects
    - Folding
    - Faulting
    - Uplift
- Structural Causes; and
    - Reservoir Structures
        - Lenticular
        - Diping
        - Anticlinal
- Thermodynamic Effects
    - Organic matter transformation (Thermal Cracking)
    - Aquathermal effects
    - Osmosis
    - Permafrost

D.2.2 Measuring Pore Pressure

There are basically three methods for detecting and measuring pore pressure:

1. Mud logging methods
    a. Measure drilling parameters; i.e. ROP, WOB, RPM, flow rate.
    b. Measure properties of drill cuttings from samples collected at the shale shaker
    c. Measure gas level from well

2. Measurement While Drilling (MWD), logging while drilling (LWD) and wireline logging methods

3. Direct methods
    1. Drill Steam Test (DST)
    2. Production test
    3. Repeat Formation Tester (RFT)

When collecting pore pressure data for a new well, it's imperative to label the data points according to the source used to measure or calculate them. Hence the data may come from mud logging, LWD or RFT and DST sources. Any one parameter taken in isolation can lead to misleading and possibly incorrect conclusions, when the combination all the available data is evaluated, pore pressure can be estimated accurately.

Mud programme and casing seat selection have to be based on the parameters that are more definitive and have the least uncertainty associated to them, these are usually RFT and DST pore pressure values.

When the formation present characteristics that are not suitable for RFT and DST, such as largely impermeable shale sections, the estimation has to come form different sources. Out of the various logs available, sonic log data is considered to be the most accurate, as it is largely unaffected by borehole size, formation temperature and pore water salinity.

D.2.3 Formation Integrity Test

A Formation Integrity Test is an analysis usually used to determine the fracture gradient of a formation, this test encompasses:

1. Limit Test

2. Leak off Test

3. Fracture Gradient Test

The main reasons to perform any of these tests are to:

1. Investigate the strength of the cement bond around the casing shoe

2. Ensure that no communication is established with higher formations

3. Determine the fracture gradient around the casing shoe and therefore establish the upper limit of primary well control for the open hole section below the current casing

4. Investigate wellbore capability to withstand pressure below the casing shoe in order to validate the well engineering plan regarding the next casing shoe depth

5. Collect regional information on the formation strength for optimization of well design for future wells.

As the well is drilled, FITs are carried out to determine the approximate value of fracture gradient beneath each casing shoe. However, it is not always possible, practical or desirable to repeat FITs at every formation change.

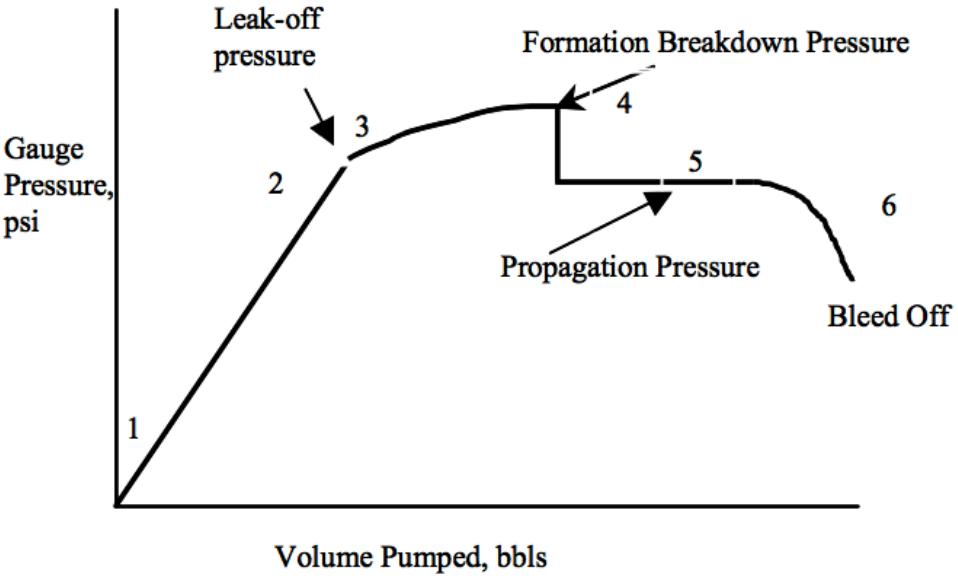


Figure 24. Formation Integrity Test Graph

The creation of a well in the ground will disturb the in-situ earth stresses and induce stresses around the wellbore and if the formation is being artificially pressurized it will, in theory, be fractured once the pressure reaches the minimum horizontal stress, however with the presence of the wellbore it will take pressure in excess, to fracture the wellbore, as seen in ***Figure 24*** this pressure is known as Formation Breakdown Pressure (4). Once this point is reached, the pressure required to maintain the fracture will be less and the minimum horizontal stress or Fracture Propagation Pressure (5) will be required to propagate the fracture.

In practice once the rock is fractured, the shut-in pressure value is taken as equal to the minimum horizontal stress, also known as the Fracture Gradient.

In directional wells, the formation breakdown pressure can occur at values higher or lower than the fracture propagation pressure (minimum horizontal stress) depending on the hole inclination and azimuth.

When planning exploration or wildcat wells, where there is little or no reliable offset well data, the fracture gradient can be estimated using various predictive techniques. In addition when drilling a well, fracture gradient should be calculated for each new lithology drilled.

The fracture gradient estimates should be used to establish a predicted leak-off pressure prior to conducting a FIT. When the predictive fracture gradient is dangerously close to the maximum anticipated mud weight, consideration should be given to performing a repeat FIT test. In some critical wells, several open hole FITs are carried out as the hole section is being drilled.

D.2.4 Formation Breakdown Gradient

The FBG is of paramount importance during kick situation when the casing shut-in pressure, CSIP, is being monitored. The sum of the hydrostatic pressure of fluids on the annulus and CSIP is always kept below the FBG at the casing shoe. It may be argued that for added safety, control should be based on the fracture propagation pressure (=σ_3) rather than the FBG. However, in deviated wells and in areas where σ_3 is considerably different from σ_2, the calculated FBG can be lower than σ_3.

The FBG is given by:

$$FBG = 3\sigma_3 - \sigma_2 + T - p_f \tag{D.2}$$

Where T = rock tensile strength
p_f = Formation Pressure

This equation was modified by Haimson and Fairhurst to take into account the effect of fluid penetration, to obtain FBG:

$$FBG = \frac{3\sigma_3 - \sigma_2 + T}{2 - \alpha \dfrac{1-2\nu}{1-\nu}} - p_f \tag{D.3}$$

Where; $$\alpha = 1 - \frac{C_r}{C_b} \tag{D.4}$$

C_r = Compressibility of the rock matrix
C_b= Compressibility of the bulk rock.

As the hole starts deviating from the vertical, the overburden stress starts contributing to the fracture pressure, thereby reducing the magnitude of the formation breakdown pressure:

$$FBG = \sigma_3 \cdot (3 - cos^2 \alpha) - \alpha_1 \, sin^2 \alpha + T - p_f \tag{D.5}$$

D.2.5 Casing Seat Selection

Pore pressure and fracture gradient plays a major role in the selection of proper casing seats that allow the drilling of each successive hole section without fracturing. Pore pressure, mud weight and fracture gradient are used collectively to select casing seats.

D.2.6 Kick

Kicks derive their name from the behavior of the resulting flow observed at the surface. Mud is “kicked” out of the well. Whenever the pore pressure of a formation becomes higher than the well pressure (and the pores are permeable) an influx from the formation will occur, referred to as a kick, as in the following situations:

1. Mud density is too low due to gas cut mud or due to encountering of high pore pressure

2. Lowering mud level in the annulus due to loss circulation or to removal of drill pipes from the well during tripping out

3. Drilling onto neighbouring producing wells

4. When pulling the drill string out of the well too fast a suction pressure arises called swabbing pressure.

Every 100th kick turns into a blowout. Kicks may develop into blowouts for one or more of the following reasons:

1. Failure to detect potentially threatening situations during the drilling process

2. Failure to take the proper initial action once a kick has been detected

3. Lack of adequate control equipment or malfunction of it.

The most troublesome blowouts are those that blow out below the surface. If the pressure in the annulus exceeds the fracture pressure of the formation, the tensile stress of the sedimentary formation has been surpassed and fractures open up and mud may flow into the formation. Possible repercussion could be:

1. If only a short string of casing has been set, a fracture can extend to the surface causing a blowout around the rig.

2. Downhole or underground blowout, when fluid from a high-pressure zone flows though the well bore and into a fracture located higher up in the well where the formation is weaker.

Because salt water and oil are incompressible, these fluids are not as troublesome to handle as gas. A small volume of gas at the bottom of a well is potentially dangerous because it expands when approaching the lower pressure near the surface. At low pressure it will expand and displace a corresponding amount of mud from the well, thus reducing the bottom hole pressure, which in turn allows more gas to flow in from the pores.

In order to create a new overbalance in the borehole, a drilling fluid with a greater density must be pumped into the hole. This operation is called the killing operation or killing procedures.

D.2.7 Killing Procedures

There exist a number of different killing methods, the two main methods being the Driller's and the Engineer's Method. The Engineer's Method is also called the Wait & Weight Method (W&W). The most common method of restoring an overbalanced situation after a kick has occurred is the Driller's Method.

Once a kick has been detected, and the well has been closed, it is time to start planning the killing of the well. First deciding what circulation rate should be used to kill the well. In the Driller's Method the pore fluid is displaced before kill mud is injected. This simplifies the operation but also induces higher pressure in the in-cased annulus, and the choke nozzles erode quicker. This could also lead to fracturing the casing shoe.

If the surface pressure rises above the Maximum Allowable Annular Surface Pressure, MAASP, the formation below the casing shoe will fracture.

$$MAASP = (\rho_{frac} - \rho_2)\cdot h_{csg\_shoe}\cdot g = p_{LOT} - (\rho_2 - \rho_1)\cdot h_{csg\_shoe}\cdot g \tag{D.6}$$

Where ρ_{frac} is the equivalent density that balances the fracture pressure.

For a shut-in well, the new formation pressure is assumed:

$$p_f = p_{SIDP} + \rho_{mud}\cdot h_{well}\cdot g = \rho_{kill}\cdot h_{well}\cdot g \tag{D.7}$$

Where we assume that the liquid composition inside the drill string is uncontamined, and hence the required mud weight to balance the pore pressure is:

$$\rho_{kill} = \rho_{mud} + \frac{P_{SIDP}}{h_{well}\cdot g} \tag{D.8}$$

A safety margin has to be added; an industry accepted and commonly used value is 0.05 kg/l, this margin has to at least be sufficient to avoid swabbing during the subsequent tripping operations. An often-used empirical formula:

$$TripMargin = \frac{0.01 \cdot \tau_y}{(d_{bit} - d_{drill\_collar}) \cdot g} \quad \text{(D.9)}$$

In offshore operations a Riser Margin is also used, in case the well is abandoned and the riser disconnected, in this case the mud weight column would be replaced by sea water and an air gap, this affect has to be taken into consideration, and the necessary mud weight would be:

$$p_f = \rho_{balance} \cdot g \cdot h_{disconected\_well} = \rho_{kill} \cdot g \cdot h \quad \text{(D.10)}$$

The Riser Margin is the excess mud weight required above the original density of the kill mud.

As previously mentioned it is always of importance to check what type of fluid has entered the well. If only liquid (oil, water or mud) has entered the well, the displacement procedure is simplified and will, by far, not be so critical as for a gas kick.

D.3 Planning

Much time in the well design process is devoted to the pressure and temperature profiles, mechanics (burst, collapse, axial loads, etc), data acquisition from previous wells, and other “conventional” processes of well design, but events such as 2010 spill from the Deepwater Horizon rig alert the industry on how “conventional” practices might not be enough to prevent a hazardous situation.

The casing represents a central part of the safety barriers. A number of elements are involved in the selection of the depth of a casing. The elements relate to pore pressure, geomechanics and well control, but kick tolerance is key and a fundamental concept used to constrain how casing is planned. It defines the appropriate number and setting depth of casing strings that are required to achieve the drilling objectives. It is also used during drilling to determine whether it is safe to continue drilling or if there is a need to run a casing string. Alternatively, it is used to indicate whether it is safe to circulate a kick out of the well or whether bullheading is necessary.

However, a direct trade-off exists between kick tolerance and well cost. Specifying “higher than necessary” minimum acceptable kick tolerances can increase the well cost because additional casing strings will be required, specifying “smaller than necessary” minimum acceptable kick tolerances can lead to costly well-control incidents.

Accurate values of formation pressures and the proper use of this information are vital to the safe planning of a well. These values are main parameters an engineer encounters at the beginning of planning a well program.

They are used to design safe mud weights, within the narrow margin to overcome fracturing the formation but still prevent well kicks, to plan and select the casing, cementing, and well control programs (kick control, wellhead, Xmas trees, BOPs, etc), and even the rig rating selection is dependent on the formation pressures encountered.

Appendix E. Support Software Development and User Guide

E.1 Kick Tolerance Software

E.1.1 Current Programs

Different kick tolerance software was analyzed in order to outline assumptions, compare results and calculation methodologies. Two main groups were distinguished:

- The most commonly used applications run as a visual basic for applications, VBA, macro in Microsoft Excel.

Not to confuse VBA with Visual Basic, VB, which is a programming language that lets you create standalone executable programs, while VBA can only be transferred to other Excel programs, meaning that when an engineer is trying to make kick calculations in a different computer than usual, for example offshore, or in a different platform or version/upgrade of Microsoft Excel the code could or could not work properly.

Other people who need to use your VBA programs must have their own copies of Microsoft Excel, and it would be extremely efficient if you could press a button that transforms a VBA/macro application into a standalone program, but that is not part of it’s capabilities.

Microsoft has released over 15 different versions of Excel in the last 10 years, plus different upgrades for each one of them, where the macro capability has not always been included, which make VBA a moving target that does not present as much availability as one would hope, and that certainly evolves with the running platform, Excel, which creates unnecessary trouble.

The reason this software is frequently used is the fact that is one of the easiest programming languages for new developers and works in parallel to a powerful spreadsheet software, such as Excel.

- There are state of the art standalone applications.

Unlike some “in-house” build applications, run mainly by operators, there is available commercial software. Some of this programs show to be extremely powerful and well thought taking into consideration most of the different variables, giving the kick tolerance calculation a very high level or reliability.

Some of these developments take kick tolerance calculations to the next level. The job of this tools stat with well design evaluation before operations begin, real time update of physical characteristics measured while drilling, and sensitivity analysis after the well has been concluded, creating an strong database for nearby future wells and making it easy to analyze and prevent future mishaps.

The first difficulty with this tools start with the added cost that a company has to take into account, this can become problematic especially for appraisal wells where the revenue is still uncertain or in areas where the amount of dry holes found, is very high.

Such high level of sophistication is rarely found with in a user-friendly shell, and in the applications found this is not exception. The ability to monitor in real time becomes hard and time consuming, since many of the inputs have to be updated manually from time to time, and it depends on the 3rd party companies involved in each particular project, and the compatibility with said programs. So even once the software is purchased, the involved engineers will require fair amount of training to feel comfortable enough to trust their calculations.

As an ideal of standardization and safety, these standalone software are the suggested applications for common developments and optimal, if not mandatory, applications for HTHP, deepwater, ultra deepwater or some other wells with particular characteristics.

E.1.2 Development of the Kick Tolerance Support Software

As previously mentioned the identified disadvantages of current software were that when simplicity was found compatibility and availability were lacking, and vice versa, the program that delivered better characteristics was found complicated, non editable and not necessarily user friendly.

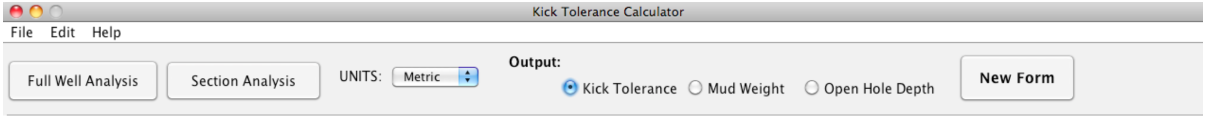
In a humble attempt to tackle these complications and meet some of the found industry needs, support software was designed and a quick review of its capabilities will be shown here.

The first task was to determine the right programming language where the standalone program was to be developed, one that would reach the original objectives and would allow in the future, if desired, the expansion of the tool.

After some research it came down to C++ and Java Script, where the first prove to be a more powerful software with no need to run from a virtual machine, unlike Java Script which consumes more memory resources while running it. But Java Script is one of the best, if not the most, portable programming languages available, which would give us the opportunity to make use of it without the need of the software installed on the computer, and the application can be converted into a simple applet and uploaded on a public access or private website.

E.2 Software User Guide

The executable file for the support software is available in a zip file together with this document. The file is called: “Kick Tolerance Calculator.jar”, the only necessary step is to double click on it and the main window will open.



UNITS: Metric

Output: ● Kick Tolerance ○ Mud Weight ○ Open Hole Depth

Figure 25. Main Menu in Support Software

Once “Section Analysis” is selected, (“Full Well Analysis” is not fully functional, future work), Units and Output need to be specified, and the next step is to load the proper form by clicking “New Form”.

This will open the full form that for the Kick Tolerance Sections is divided into 5 input panels:

1. Casing Details
2. Hole Details
3. String Details
4. Pressure Details
5. Safety Details

And 2 output panels:

1. Kick tolerance results
2. Extra information

E.2.1 Casing Details

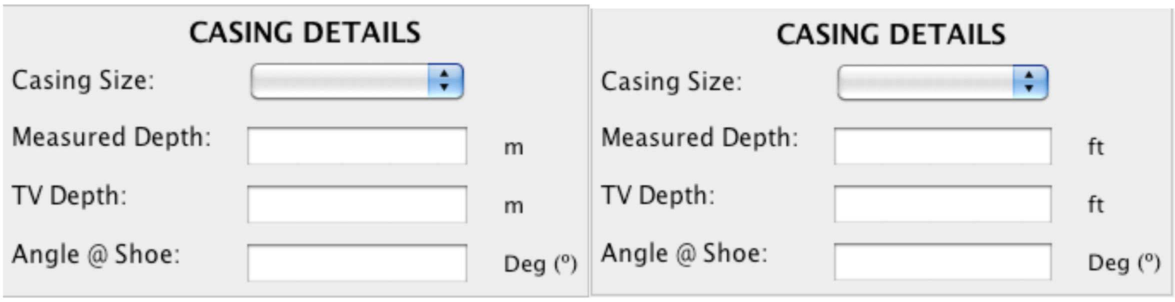


Figure 26. Casing Details Panel. Metric units(left), US units(right)

E.2.2 Hole Details

Figure 27. Hole Details Panel. Metric units(left), US units(right)

E.2.3 String Details

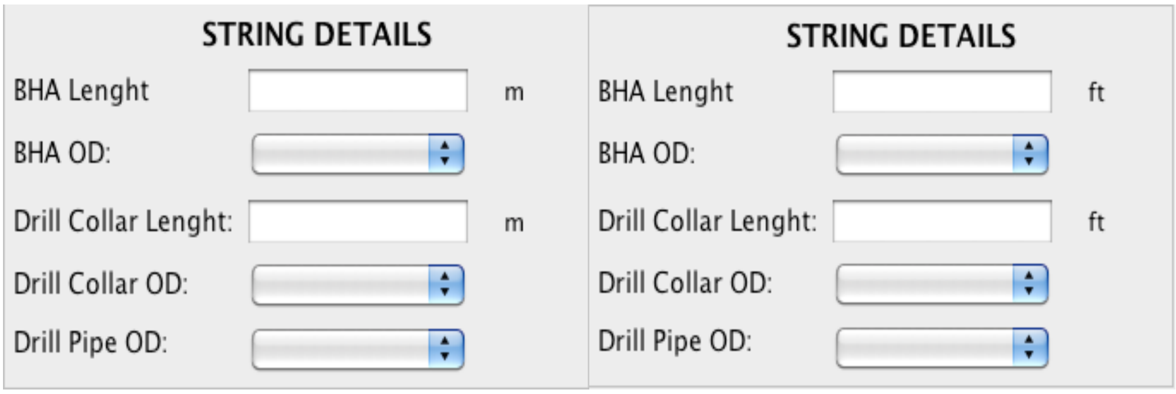


Figure 28. String Details Panel. Metric units(left), US units(right)

E.2.4 Pressure Details

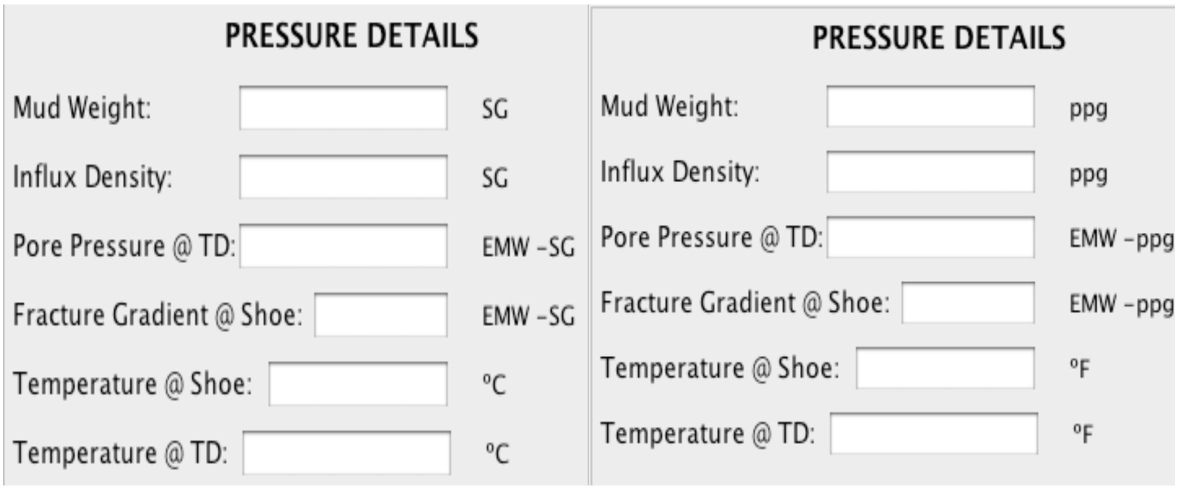


Figure 29. Pressure Details Panel. Metric units(left), US units(right)

E.2.5 Safety Details

Figure 30. Safety Details Panel. Metric units(left), US units(right)

E.2.6 Kick tolerance results

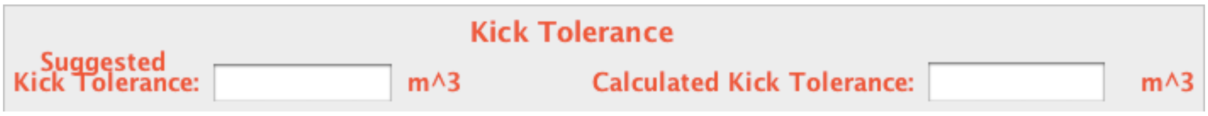


Figure 31. Result (Kick Tolerance) Panel. Metric units.

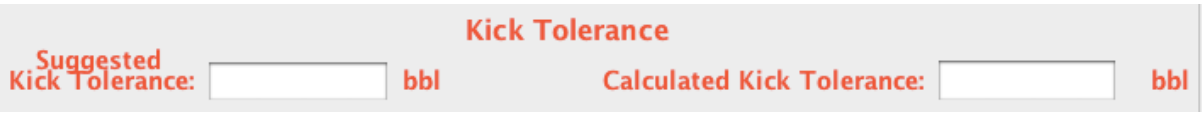
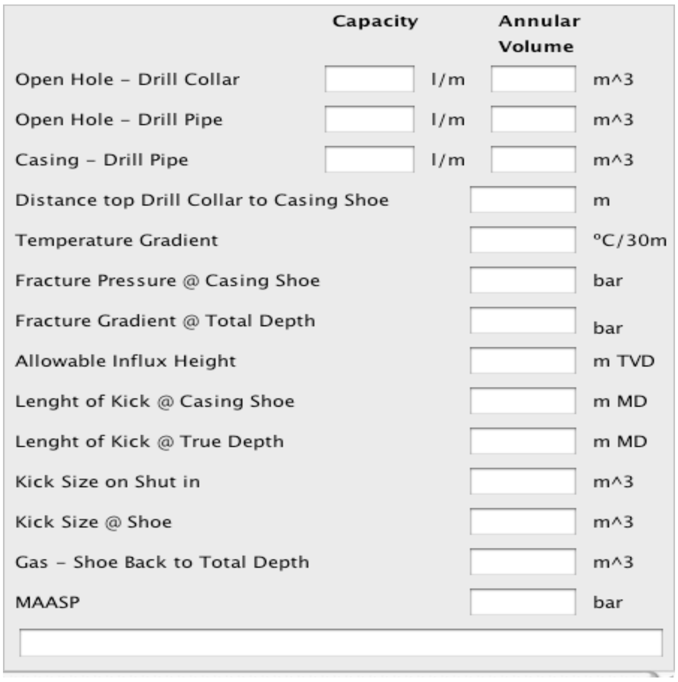


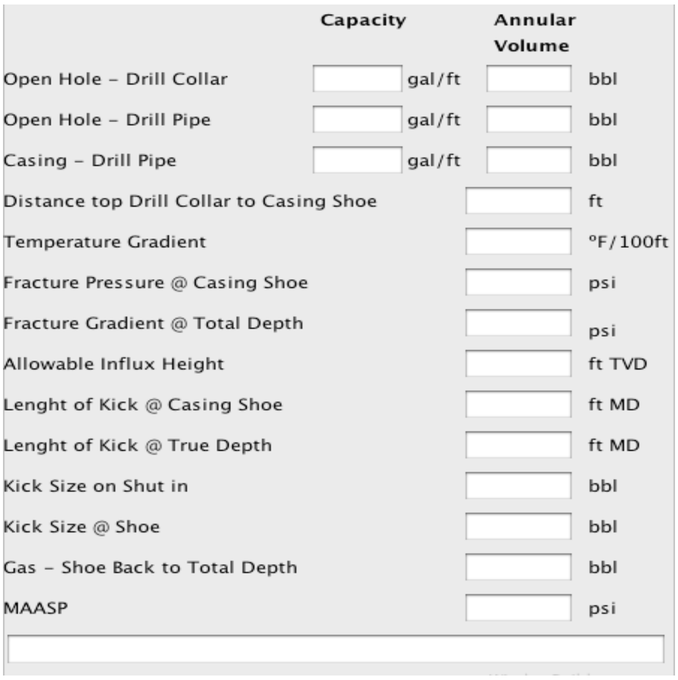
Figure 32. Result (Kick Tolerance) Panel. US units.

E.2.7 Extra Information



	Capacity		Annular Volume	
Open Hole – Drill Collar		l/m		m^3
Open Hole – Drill Pipe		l/m		m^3
Casing – Drill Pipe		l/m		m^3
Distance top Drill Collar to Casing Shoe				m
Temperature Gradient				°C/30m
Fracture Pressure @ Casing Shoe				bar
Fracture Gradient @ Total Depth				bar
Allowable Influx Height				m TVD
Lenght of Kick @ Casing Shoe				m MD
Lenght of Kick @ True Depth				m MD
Kick Size on Shut in				m^3
Kick Size @ Shoe				m^3
Gas – Shoe Back to Total Depth				m^3
MAASP				bar

Figure 33. Extra Information Panel. Metric units.



	Capacity		Annular Volume	
Open Hole – Drill Collar		gal/ft		bbl
Open Hole – Drill Pipe		gal/ft		bbl
Casing – Drill Pipe		gal/ft		bbl
Distance top Drill Collar to Casing Shoe				ft
Temperature Gradient				°F/100ft
Fracture Pressure @ Casing Shoe				psi
Fracture Gradient @ Total Depth				psi
Allowable Influx Height				ft TVD
Lenght of Kick @ Casing Shoe				ft MD
Lenght of Kick @ True Depth				ft MD
Kick Size on Shut in				bbl
Kick Size @ Shoe				bbl
Gas – Shoe Back to Total Depth				bbl
MAASP				psi

Figure 34. Extra Information Panel. US units.

Appendix F is presented digitally (attached zip file) and it contains 132 pages of the programming code for the support software.