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Excel Sheet Program to Select Optimum Well-Kill Method during Drilling

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Abstract
Well control is an extremely critical operation that requires a lot of good planning and professional implementation. The selection of the proper kill method that is required to kill the well safely and efficiently either drilling or production well is a tedious decision. It requires a lot of accurate data from the current well conditions which will help the decision makers in their selections. Selecting the wrong kill method may end up with an unsafe and a high costly operation. This paper introduces an excel sheet program to select optimum well kill method that will help the engineering team as well as the operation team to take the proper decision regarding the optimum well control method to be applied.
This paper provide a program built using simple excel sheet in which input data are well information. This information is analyzed and used to answer some questions. The answers for these questions have different weights. The system will select the highest score for these answers which will choose the optimum kill method based on the input data and the weighted value and provide kill sheet for the well according to the selected method. The program is tested in two different cases for drilling oil and gas wells. The system selected different kill methods based on each well criteria. The outputs were compared with a commercial simulator and the results are comparable which indicate that such a cheap excel program can be used easily and economically.

I. Introduction

The main objective of any drilling program is to help assure a well to be drilled, completed, and produced safely economically and efficiently. Due to the complications that are added to the drilling and production processes, a lot of challenges are caused to the operation. A lot of blowouts have been caused because of not following the proper kill method or the proper procedures. These blowouts caused a lot of fatalities, loss of rigs, loss of equipment, damage to environment and loss of production. Recent blowouts and well known in the industry are the blowout happened in the Gulf of Mexico in 2010 (Macondo well) and the blowout happened in Temsah field in 2004. [1]

Well Control in drilling wells may be controlled by different kill methods. Each method has different applications. The Driller’s method is preferred if the kick size is lower than the kick tolerance volume, deviated and horizontal wells, the string is on bottom, and in case of gas migration where the kill mud is not ready. The wait and weight method is preferred if the kick size is within the kick tolerance calculations, no gas migration is encountered, vertical wells where the volume of the string is lower than the volume of the open hole section. The volumetric method is preferred than the other methods in case the drill string is off bottom, drill string washout, gas migration, hole pack off, totally plugged string or no string is in the well bore. After the volumetric method, lubricate and bleed method has to be used to get rid of the gas. The stripping operation is preferred if the string is off bottom, and the gas is not migrating, and the gas volume is within the kick tolerance calculations. And in case of gas migration, the combined volumetric and stripping operation can be used.

The selection of the proper kill method is challenging and will depend on a lot of factors. These factors are necessary to help and guide the operation team to select the required kill method. However, it will be a critical decision as it will require the knowledge of the different conditions currently in the well. Commercial software are introduced to the industry, but they offer the calculation of the kill sheet and steps to be followed and amount to be monitored during applying the selected technique. Therefore, the need for computerized program to select the optimum method quickly and efficiently is obviously interested for the industry that will help the operation team to select the proper kill method to bring well back under primary control condition as well as the kill sheet calculations.

Background

The flow of the formation fluid from the formation into the wellbore is called "kick". It is also called "influx" if the well still overbalance. If the kick is not controlled, it may led to a blowout. Well control procedures are intended to safely prevent or handle kicks and reestablish primary well control conditions by regaining the hydrostatic overbalance of the mud. During the drilling operation, well control barriers should be in place to control the well. The primary well control barrier during conventional drilling is the hydrostatic pressure of the mud that provides overbalance on the formation being drilled which prevents formation fluid flowing into the well. For example, as shown in Figure 1, if the hydrostatic pressure is 5,200 psi at 10,000 ft (10.0 ppg mud) and the pore pressure is 4,650 psi. The difference between the hydrostatic and pore pressure is 550 psi; so, the well will be static, and this state is identified as overbalance condition. To control the well, the well should be overbalanced, and this to be planed based on each company policy. [2]

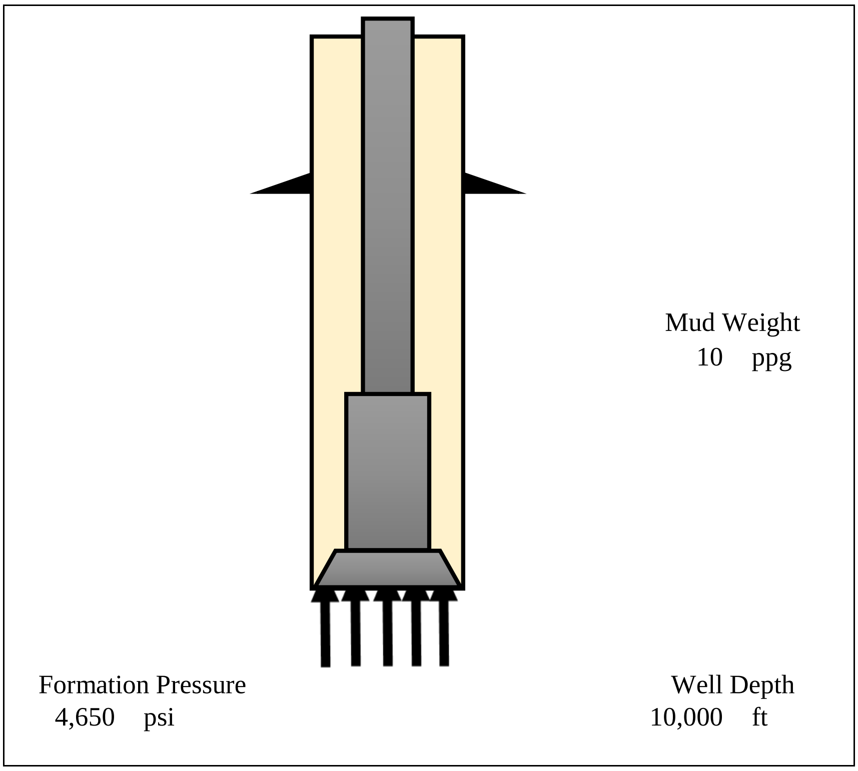


Figure 1: Primary well control concept [1]

An overbalance should be maintained during the drilling and tripping operation. The value of the overbalance depends on company policy (normally in a range between 100 to 300 psi). If the hydrostatic pressure fails to maintain the overbalance and fails to prevent formation fluids from entering the wellbore, the well will flow and kick is occurred. This process is stopped using the secondary barrier which is the blow out preventers (BOP) to prevent the escape of the wellbore fluids from the well. This is the first stage of the secondary well control. BOP should be tested regularly as per API and/or company policy to make sure that its reliability in case of any well kick and control operations. If the formation cannot be controlled by the primary or secondary well control, tertiary well control will be considered as the third line of defense. Drilling a relief well is considered one of the tertiary well control processes. [2-11]

In order to implement plan, drill and complete the well safely, it is necessary to have some knowledge of the fracture pressures of the formations to be encountered. The maximum kick size to the wellbore depends on some factors, these factors are the kick intensity "KI" and the fracture pressure of the weakest formation in the wellbore. [2]

If the wellbore pressure (hydrostatic pressure) is equal to or exceed this fracture pressure, the formation would break down as induced fracture would be initiated, followed by loss of mud, loss of hydrostatic pressure and loss of the primary control. Fracture pressure is a function of the weight of the formation matrix and the fluids occupying the pore space within the matrix, overburden pressure of the formations above the zone of interest. These three factors are combined to produce what is known as the fracture pressure. [1-10]

In onshore locations, since the sediments tend to be more compacted, the overburden gradient can be taken as being close to 1.0 psi/ft. While in offshore, the overburden gradients at shallow depths will be much less than 1.0 psi/ft due to the effect of the seawater depth and the large thicknesses of unconsolidated sediment. This makes surface casing seals in offshore wells much vulnerable to breakdown and is the reason why shallow gas kicks is difficult to be shut in. [2]

Maximum Allowable Annular Surface Pressure (MAASP)

The formation strength normally determined from the leak-off test below the casing shoe using the following Equation 1. MAASP is the maximum allowable annular surface pressure that can be tolerated before the formation at the shoe tend to fracture. MAASP can be determined using one of the following Equations (Equations 2, 3 or 4). It is only valid if the casing is full of the original mud, if the mud weight inside the casing is changed, MAASP must be recalculated. The calculated MAASP is no longer valid if the influx fluids enter into the casing. [3]

$$P_{F@shoe} = P_s + P_{h@shoe} \qquad 1$$

$$MAASP = P_{F@shoe} - P_{h@shoe} \qquad 2$$

$$MAASP = (FG - MG) \times TVD_{Shoe} \qquad 3$$

$$MAASP = (MAMW - MW_{current}) \times 0.052 \times TVD_{Shoe} \qquad 4$$

Kick Tolerance

Kick tolerance can be defined as the maximum kick size at a certain kick intensity that the well can be safely shut in and circulated out of the well without fracturing the formation at the weakest point in the open hole. In critical sections, it is important to calculate kick tolerance on a regular basis. A lot of factors can affect the kick tolerance size. These factors are the mud density, the bottom hole assembly, the hole depth, the pore pressure, the type of the kick, etc. [5]

The drilling engineer must calculate the volume of gas influx that can be safely shut in and circulated to the previous casing shoe for each open hole section. These calculations should consider the maximum expected pore pressure, and this will be used to calculate the maximum kick size. The worst-case scenario for a kick occurring is at the greatest depth – when the next casing point has been changed (section TD). To determine the minimum shoe strength required to reach this, some assumptions are made. For a development well, assume that the kicking formation may have a pore pressure equal to the virgin pressure of the first well drilled in that field. During this study the formation pressure is driven from the SIDPP and the hydrostatic pressure inside the drill string. Once the fracture gradient is known, calculate the maximum gas influx volume at the next casing point (section TD). [4]

To calculate the kick tolerance, Engineering or operation engineers have to calculate the maximum kick length which may be encountered at initial shut in or when the top of the gas is at the shoe. This length can be calculated using Equation 6. Then they have to convert the length calculated in the previous step into volume. This volume will be calculated two times, one time around the BHA and the second around the drill pipe below the casing shoe. Using Boyles law in Equation 7, will help to convert the calculated volume at shoe into the downhole condition assuming constant temperature and ideal gas. [4]

$$L_{max} = \frac{\text{MAASP} - \text{SIDPP}}{\text{MG} - \text{IG}} \qquad 6$$

$$P_1 \times V_1 = P_2 \times V_2 \qquad 7$$

$$V_1 = L_{max} \times C_{DP\&OH} \qquad 8$$

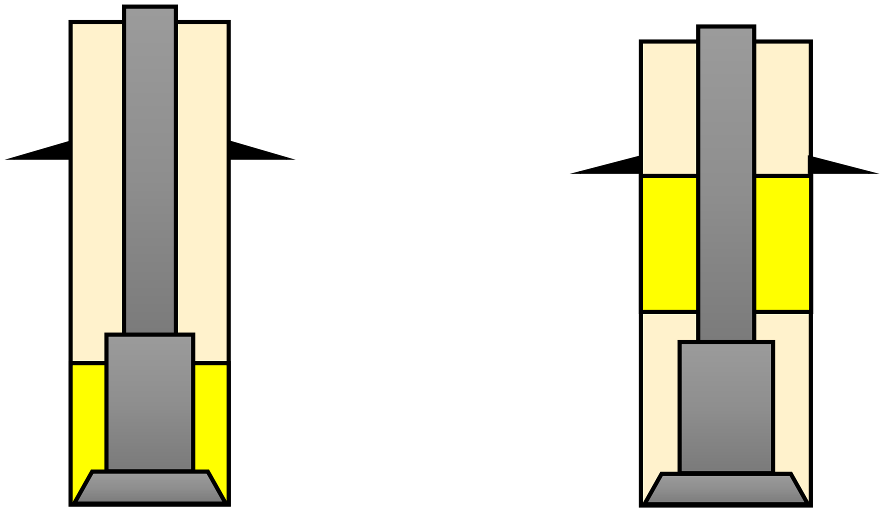
At initial shut-in,

$$V_1 = L_{max} \times C_{BHA\&OH} \qquad 9$$

Note: Kick Tolerance will be the smaller of the two volumes (V_2 calculated from Equation 7 and V_1 calculated from Equation 9).

As shown in Figure 2, two scenarios that will give the maximum shoe pressure. The maximum shoe pressure will be either at initial shut-In (Figure 2a) as the gas will be around the drill collars taking high length, or when the gas is at the shoe of the last casing string (Figure 2b) where it will take a different length due to the gas expansion. As mentioned in the previous paragraph, it is recommended to calculate the two lengths and then calculate the gas volume in each case, then compare the initial volumes in each case and the lowest volume will be the kick tolerance volume. [9]

Kick tolerance will always be calculated at the well design stage as it is one of the drivers towards the selection of casing seat and casing specifications. The company policy should be followed before the acceptance of the drilling program and before the drilling operation. [3]



a) gas around BHA @ Initial Shut-In

b) top of gas @ shoe

Figure 2: Kick tolerance [2]

Causes of Kick

There are a lot of causes that may end up with a well control situation due to the loss of the overbalance situation. These causes can include, and are not limited to, improper hole filling during tripping out of the hole, swabbing during the pipe movement, loss of circulation, the usage of insufficient mud weight, drilling through abnormal formation pressure, and some other special operations like Drill Stem testing, drilling into an adjacent well and/or excessive drilling rate through a gas sand. Surveys in the past have shown that the major portion of well control problems have occurred during tripping. This is due to reduction in the BHP due to; diminishing of annular pressure loss with pumps off, drop in the annulus levels when pulling the drill string out of hole and not filling the hole with the proper displacement and/or, due to swabbing effect. [2-9]

The pressure differential between the formations and wellbore, degree of underbalance, is proportional to the influx flow rate and kick volume for a given flow period. The situation can only deteriorate with time because the less-dense formation-fluid volume enters the hole and reduces the buttonhole pressure and thereby serves to increase flow rate into the well. Permeability is another significant factor as well as exposed thickness and fluid viscosity. It is difficult to control permeability or reservoir fluid properties, but the amount of exposed rock is governed by how long the driller continue to drill with kick entry. Gas influx in the well can be expected using the following equation and depends on the exposure time. [4]

$$q_{gsc} = \frac{703\ K_g\ h\ (P_e{}^2 - P_{wf}{}^2)}{\mu_g\ T_Z\ (\ln\ (r_e/r_w) - 0.75} \qquad 5$$

Insufficient mud weight is the main cause of underbalance and eventually kicks while drilling. The ECD is considered one of the causes that may end up with well control situation. If the ECD exceeded the formation fracture pressure, downhole losses will occur and cause the fluid level to drop resulting in the reduction of the hydrostatic pressure above the formation and initiating underbalance. If the well becomes underbalanced, it will start to flow and kick generates. The ECD may increases due to increase in the mud weight, increase in the mud rheology, small annular clearance between the bottom hole assembly size and the open hole diameter, increase in the pumping rate, increase in depth or due to increase in ROP and loading the annulus with cuttings. Proper planning should be in place to make sure to drill different formations within the same mud window and to control the mud weight and ECD as planned. Failure to prevent such kicks often leads to underground blowouts. [8]

Kick Indicators

During the normal drilling or tripping operation, operating parameters should be recorded and analyzed for any anomalies. Kick warning signs are considered some of these anomalies. Observing the warning signs will help to secure the well in case of kicks or even it will reduce the kick size as low as possible. The warning signs can vary from one situation to another. The warning signs are summarized as following: increase in rate of penetration, increase in torque and drag trends, decrease in shale density that can be captured from the downhole logs, changes in mud property, changes in cuttings size and shape, increase in the trip gases, increase in the connection and/or background gas during drilling, increase in the temperature of the return drilling mud and/or, decrease in D-exponent. The observation of positive indicators is a clear message that the well is underbalance and a kick is in progress. Positive indicators are increase in the return flow percentage, increase in the active tank volume and/or flow while pumps are off. The right decision to the observation of any of the positive indicators is to check for flow. If well flow while the pump is off, shut in the well using the proper shut-in procedures as per the company policy. After that choose the kill method and start performing killing procedures. [10-19]

Kick Behavior

Well kick may consist of water, oil, gas or any combination of them. The mud weight is usually heavier than the kick. The killing operation should proceed to remove the kick from the wellbore or pushed back to the formation. [9]

Gas Influx

Kick types have different compressibility. One of the conditions affecting the wellbore pressure is the kick compressibility. Gas is one type of the expected kick fluids. The gas compressibility is high compared with the other kick fluids, the temperature and pressure affect the gas volume while being circulated out of the wellbore. For example, a well is shut in on 1 bbl gas kick at 10,000 ft. The current mud weight is 9.0 ppg. The BHT is 170 °F. The hydrostatic pressure of the current mud is 4,680 psi. If the gas is allowed to expand, its size will increase to 280 barrels at surface under atmospheric conditions (assuming 0.6 specific gravity gas at 80 °F and 14.7 psia). If that barrel of gas is not allowed to expand in a controlled manner as it is circulated up the well bore, it will nearly maintain its initial pore pressure as it moves up the annulus and may create excessive well bore pressures. This excessive pressure may cause formation fracture resulting in downhole losses, and underground blowout. [20-30]

In OBM, Gas has high solubility and the kick detection is challenging which requires good training and special awareness of rig crew. The gas will come out of solution when it approaches the bubble point pressure. The gas expansion will be very fast when gas is near to the surface. The main factors affecting the solubility are fluid type, temperature and pressure. [2]

Well Control Procedures

Many well control procedures have been developed over the past years. The aim of these methods are to bring the well to its original normal case to continue drilling safely, Figure 3. The constant bottom-hole pressure concept was developed in which the total pressures (mud hydrostatic pressure, casing pressure, etc.) at the bottom of the hole would be maintained at a value slightly greater than the formation pressure to prevent further influxes of formation fluids into the wellbore. This concept can be implemented in two ways. [9]

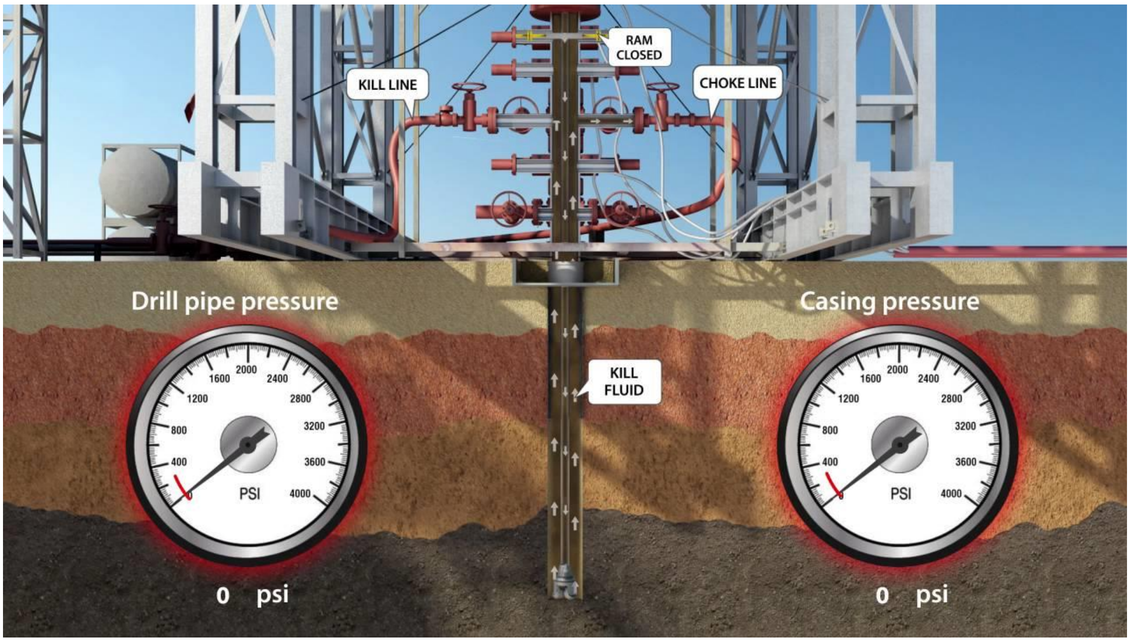


Figure 3 Results of kill method [31]

The kill method can be done through one circulation or what is called the Wait and Weight method. After the well has been shut in, the kill mud will be prepared based on the recorded data. A drill pipe pressure schedule should be prepared. The formation fluid and the original mud will be displaced with the kill mud in one circulation. (An alternate name often applied is the engineer's method). Another method will include two circulations, or what is called the Driller's Method. The first circulation will be at least bottom's up and during this circulation the original mud will be used to displace the kick outside the well. The second circulation will be a total cycle which will include displacing the original mud with the kill mud. Both methods will apply a constant BHP which is slightly higher than the pore pressure and named kill circulation methods, Figure 2. [2]

In some cases, Driller's Method and Wait & Weight method are not applicable. An alternative method should be used based on the well conditions. Unconventional, non-circulation, methods include the volumetric method, Lubricate and bleed method, stripping operation, combined volumetric and stripping operation, and Bullheading. [13]

Building the Excel sheet

During the drilling operation, it is crucial to maintain enough overbalance to keep the formation fluid inside the formation. This can be accomplished by selecting the proper mud weight that will provide the required overbalance. There are a lot of causes that will end up with underbalance situation where the well have to be secured and proceed with the killing operation in order to regain the required overbalance. As mentioned in the previous chapters, there are different types of well control (killing) methods that can be used to regain the primary well control (overbalance).

The selection of the proper killing method is essential to control the well safely and to be able to continue drilling as planned. The selection process for the preferred kill method for drilling operations at different conditions will be justified. This study is based on building an expert system that depend on the advantages and disadvantages of each kill method. The system is built on Excel sheet program.

The Excel sheet program will be mainly based on input data provided by the user. These data will be justified in the form of questions answered by yes or no and based on the actual well data during the well control operation. The program is going to select the proper kill methods based on the input data. The required calculation for the selected kill method will be provided by the sheet program. The user can use this program to control the well and regain the overbalance. It is highly recommended to input all the required data which will help to get the best outputs from the system. The system is divided into inputs that is required from the user and outputs that will be used by the user to control the well.

For the program depends on 12 questions that will be answered based on the input data provided by the user. The weight for each question is generated based on more than 200 trials done on the program and confirmed the optimum weights. The questions need to be answered by Yes or No. These questions are:

1. Is the bit on bottom?
2. Is circulation valid through drill string?

3. Is the well vertical?
4. Is the well deviated?
5. Is the well horizontal?
6. Is the open hole volume less than drill string volume?
7. Is the kick gas (gas migration)?
8. Is the kick water?
9. Is the kick oil?
10. Is the Influx volume below kick tolerance?
11. Is the kick has a potential of H2S?
12. Is the formation has good injectivity?

Program Input

The main input requirements are the existing well data as shown in Figure 4. These information input data includes:

1. Field Data
2. Formation Strength Data
3. Pump Data
4. Well Data
5. Shut-in Data

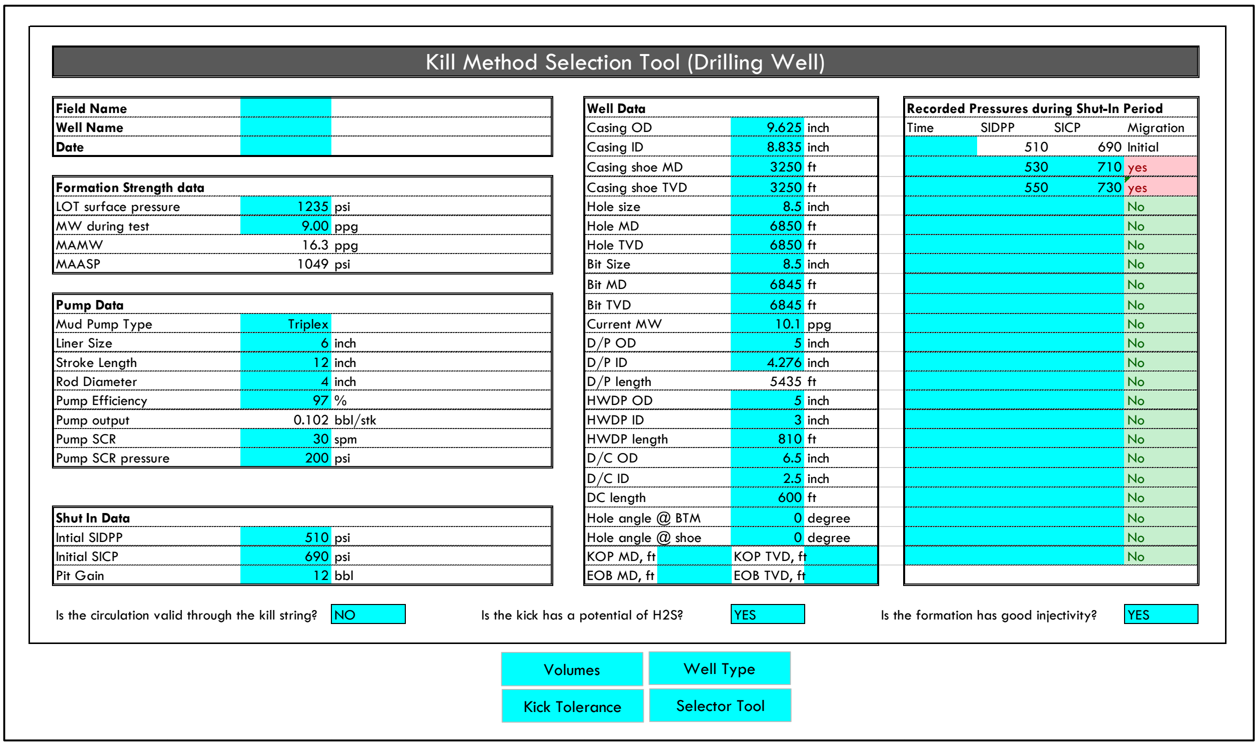


Figure 4: Well information inputs in the program

Program Processing

The program is going to calculate the well volumes, kick tolerance, kill method selector tool and different calculations for each kill method. The kill methods covered for the drilling wells' well control are, Driller's method, Wait and Weight method, Volumetric method, Lubricate and Bleed method, Stripping method, Combined Volumetric and Stripping method and Bullheading method.

Based on the current string (dimensions and length) and well information, the ESTOK system is going to calculate the different volumes inside the wellbore as shown in Figure 5. The kick tolerance section is going to calculate the maximum allowable kick size based on the current well design, SIDPP and current mud weight. It is going to calculate two values. The first value will be based on the initial shut-in when the kill is around the Bottom Hole Assembly (BHA). The second value will be based on the maximum gas expansion in the open hole and this will be when the top of gas reaches the shoe. The maximum kick size will be the lower of the previous two values. The kick tolerance calculations is shown in Figure 6.

Well Volumes				
Drill Pipe volume	96.54	bbl	948.05	stks
HWDP volume	7.08	bbl	69.55	stks
DC Volume	3.64	bbl	35.78	stks
Drill String Volume	107.26	bbl	1053.37	stks
Ann. Open Hole volume	155.31	bbl	1525.23	stks
Open hole	0.35	bbl	3.45	stks
D/C & OH	17.49	bbl	171.72	stks
HWDP & OH	37.18	bbl	365.12	stks
D/P & OH	100.29	bbl	984.93	stks
Ann. Cased Hole volume	167.51	bbl	1645.06	stks
Total Annulus volume	322.82	bbl	3170.29	stks
Total Well Volume	430.08	bbl	4223.66	stks

Input | Well Type
Kick Tolerance | Selector Tool

Figure 5: Well volumes calculations from the program

Kick Tolerance calculations			
Expected Influx grad.	0.088	psi/ft	
Pform	4107.6	psi	
Hmax	1233.22	ft	
Vinflux	35.94	bbl	at initial shut-in
Vinflux	37.98	bbl	Top of gas @ shoe
Kick Tolerance volume	**35.94**	bbl	
Kick intensity	**1.43**	ppg	

Input | Well Type
Volumes | Selector Tool

Figure 6: Kick tolerance calculations from the program

The kill method selector tool section, Figure 7, is going to show the most likely kill method that can be used to kill the well according to the provided data in the input section. This section mainly depends on twelve questions which already captured from the input data. These questions are: is the drill string on bottom? Is circulation valid through the string? Is the well vertical, deviated or horizontal? Is the drill string volume bigger than the open hole volume? Is the kick type gas, oil or water? Is the kick volume below the kick tolerance volume? Is the kick has a potential of H_2S? Is the formation has good injectivity? Based on the weight of each question. Each question is answered automatically by yes or no. The program gives a value for each kill method depends on the user input data. The values are summed up for each kill method. The highest score of the answers will determine the optimum kill method.

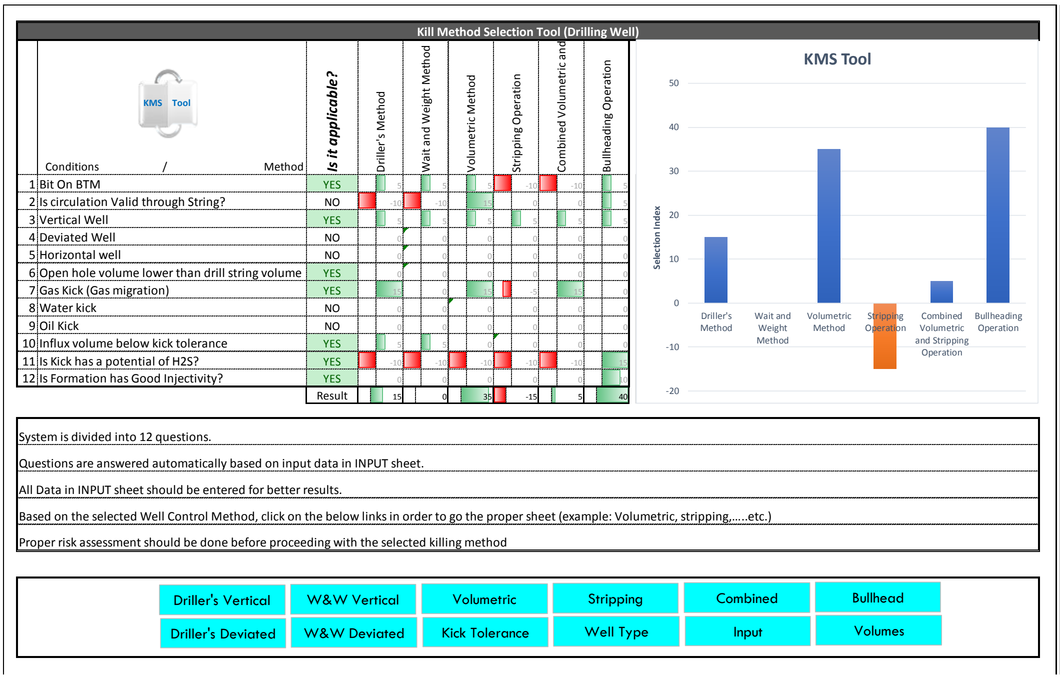
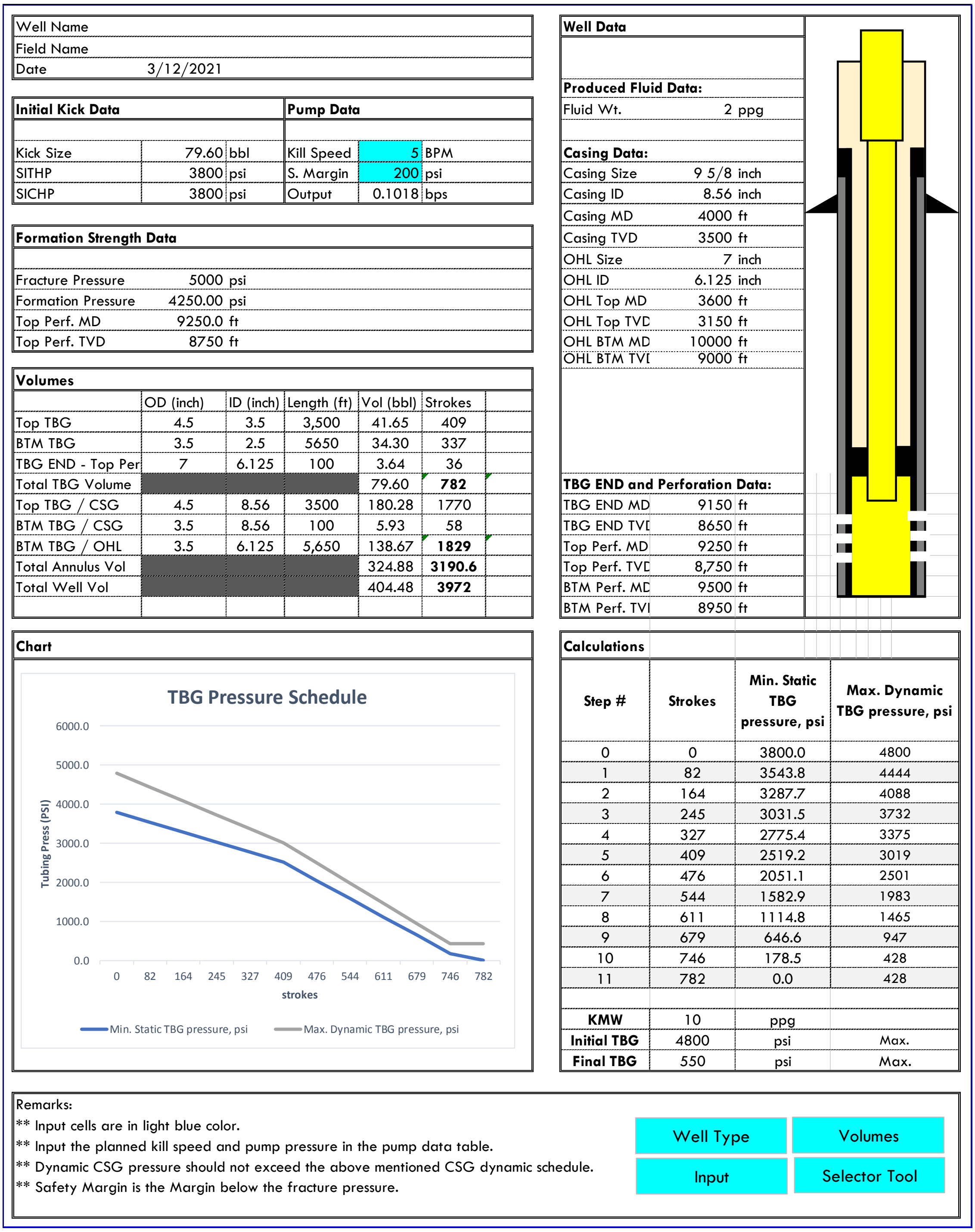


Figure 7: Kill method selection tool input information processing.

In the Kill method selection tool section, the user will check the provided graph that shows the maximum selection index as shown in Figure 7. Based on the selected method, the user will click on the proper link for this selected method where the link will direct him to the final calculations for this method. For example, bullheading operation is selected kill method shown in Figure 7.

Program Output

The system will provide the user with the required calculations for the optimum kill method as shown in Figure 8 which is named kill sheet of the well.



Well Name	
Field Name	
Date	3/12/2021

Initial Kick Data			**Pump Data**		
Kick Size	79.60	bbl	Kill Speed	5	BPM
SITHP	3800	psi	S. Margin	200	psi
SICHP	3800	psi	Output	0.1018	bps

Formation Strength Data		
Fracture Pressure	5000	psi
Formation Pressure	4250.00	psi
Top Perf. MD	9250.0	ft
Top Perf. TVD	8750	ft

Volumes	OD (inch)	ID (inch)	Length (ft)	Vol (bbl)	Strokes
Top TBG	4.5	3.5	3,500	41.65	409
BTM TBG	3.5	2.5	5650	34.30	337
TBG END - Top Per	7	6.125	100	3.64	36
Total TBG Volume				79.60	**782**
Top TBG / CSG	4.5	8.56	3500	180.28	1770
BTM TBG / CSG	3.5	8.56	100	5.93	58
BTM TBG / OHL	3.5	6.125	5,650	138.67	**1829**
Total Annulus Vol				324.88	**3190.6**
Total Well Vol				404.48	**3972**

Well Data		
Produced Fluid Data:		
Fluid Wt.	2	ppg
Casing Data:		
Casing Size	9 5/8	inch
Casing ID	8.56	inch
Casing MD	4000	ft
Casing TVD	3500	ft
OHL Size	7	inch
OHL ID	6.125	inch
OHL Top MD	3600	ft
OHL Top TVD	3150	ft
OHL BTM MD	10000	ft
OHL BTM TVD	9000	ft
TBG END and Perforation Data:		
TBG END MD	9150	ft
TBG END TVD	8650	ft
Top Perf. MD	9250	ft
Top Perf. TVD	8,750	ft
BTM Perf. MD	9500	ft
BTM Perf. TVD	8950	ft

Chart

Calculations

Step #	Strokes	Min. Static TBG pressure, psi	Max. Dynamic TBG pressure, psi
0	0	3800.0	4800
1	82	3543.8	4444
2	164	3287.7	4088
3	245	3031.5	3732
4	327	2775.4	3375
5	409	2519.2	3019
6	476	2051.1	2501
7	544	1582.9	1983
8	611	1114.8	1465
9	679	646.6	947
10	746	178.5	428
11	782	0.0	428
KMW	10	ppg	
Initial TBG	4800	psi	Max.
Final TBG	550	psi	Max.

Remarks:
** Input cells are in light blue color.
** Input the planned kill speed and pump pressure in the pump data table.
** Dynamic CSG pressure should not exceed the above mentioned CSG dynamic schedule.
** Safety Margin is the Margin below the fracture pressure.

Well Type | Volumes | Input | Selector Tool

Figure 8: Bullhead calculations' output from the kill program selector

II. Results and Discussion

The program is applied on tow actual case to validate its results. The following are the results of these two cases studded by the program

Case Study 1

The first well was a vertical well with a total depth of 6,850 ft MD/TVD. The 9-5/8" casing was run and cemented at 3,250 ft MD/TVD. A leak-off test was conducted at 3,260 ft MD/TVD. The leak-off pressure was 1,235 psi with 9 ppg mud. The 8-½" hole was drilled with 10.4 ppg mud to 6,850 ft. A kick was observed during the drilling operation at 6,850 ft MD/TVD. The well has been shut-In and the surface pressures were recorded. No gas migration was detected. It was recorded from the offsets that there was no potential of H_2S gas during kill operation. The well conditions were inserted in the excel sheet program as shown in Figure 9.

Kill Method Selection Tool (Drilling Well)

Field Name		
Well Name		
Date	3/12/2021	
Formation Strength data		
LOT surface pressure	1235	psi
MW during test	9.00	ppg
MAMW	16.3	ppg
MAASP	998	psi
Pump Data		
Mud Pump Type	Triplex	
Liner Size	6	inch
Stroke Length	12	inch
Rod Diameter	4	inch
Pump Efficiency	97	%
Pump output	0.102	bbl/stk
Pump SCR	30	spm
Pump SCR pressure	220	psi
Shut In Data		
Intial SIDPP	400	psi
Initial SICP	600	psi
Pit Gain	14	bbl

Well Data		
Casing OD	9.625	inch
Casing ID	8.835	inch
Casing shoe MD	3250	ft
Casing shoe TVD	3250	ft
Hole size	8.5	inch
Hole MD	6850	ft
Hole TVD	6850	ft
Bit Size	8.5	inch
Bit MD	6850	ft
Bit TVD	6850	ft
Current MW	10.4	ppg
D/P OD	5	inch
D/P ID	4.276	inch
D/P length	5440	ft
HWDP OD	5	inch
HWDP ID	3	inch
HWDP length	810	ft
D/C OD	6.5	inch
D/C ID	2.5	inch
DC length	600	ft
Hole angle @ BTM	0	degree
Hole angle @ shoe	0	degree
KOP MD, ft		KOP TVD, ft
EOB MD, ft		EOB TVD, ft

Recorded Pressures during Shut-In Period			
Time	SIDPP	SICP	Migration
	400	600	Initial
	400	600	No
	400	600	No
			No
			No
			No
			No
			No
			No
			No
			No
			No
			No
			No
			No
			No
			No
			No
			No
			No
			No

Is the circulation valid through the kill string?	YES
Is the kick has a potential of H2S?	NO
Is the formation has good injectivity?	NO

Figure 9: Excel sheet input data for case study 1

From the program output kick tolerance calculations, the current kick size is within the kick tolerance volume as per Figure 10. The maximum allowable kick size before the casing shoe breakdown was 41 barrels and the kick size was 14 barrels. From the program selector tool, the system recommended to use the wait and weight method as shown in Figure 11 and this was shown in the graph that shows the highest Selection Index. Thus, the Wait and Weight method is the optimum kill method for this case.

Well Volumes				
Drill String Volume	107.35	bbl	1054.24	stks
Drill Pipe volume	96.63	bbl	948.92	stks
HWDP volume	7.08	bbl	69.55	stks
DC Volume	3.64	bbl	35.78	stks
Ann. Open Hole volume	155.19	bbl	1524.04	stks
Open hole	0.00	bbl	0.00	stks
D/C & OH	17.49	bbl	171.72	stks
HWDP & OH	37.18	bbl	365.12	stks
D/P & OH	100.52	bbl	987.19	stks
Ann. Cased Hole volume	167.51	bbl	1645.06	stks
Total Annulus volume	322.70	bbl	3169.10	stks
Total Well Volume	430.05	bbl	4223.34	stks

Kick Tolerance calculations			
Expected Influx grad.	0.124	psi/ft	
Pform	4104.48	psi	
Hmax	1437.32	ft	
Vinflux	41.89	bbl	at initial shut-in
Vinflux	44.30	bbl	Top of gas @ shoe
Kick Tolerance volume	**41.89**	bbl	
Kick intensity	**1.12**	ppg	

** in case of stripping, SIDPP should be Zero as KI should be 0 ppg.
** calculations should be checked.

Figure 10: Volumes and kick tolerance calculations for first well conditions

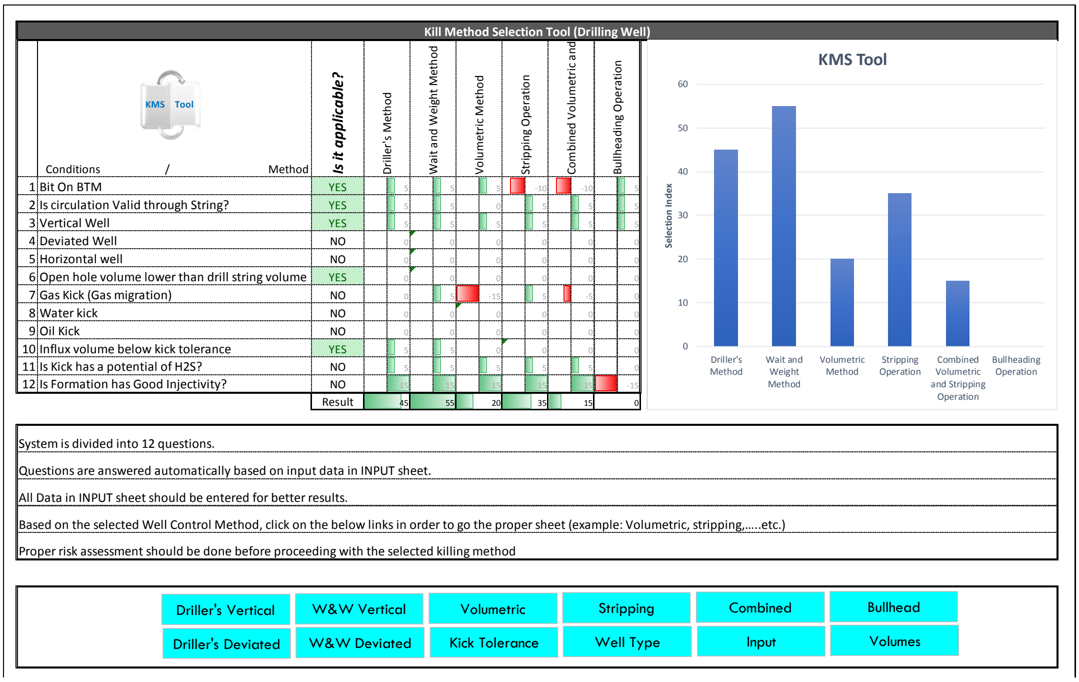


Figure 11: Program selector tool for case study 1

The kill sheet of the well is shown in Figure 12 where well data and well drawing, formation pressure strength, volumes, drill pipe schedule and pump strokes table are given on one sheet. These data were applied on the Drilling and Well Control simulator as shown in Figure 13 and Table 1. The well was killed safely without any complications.

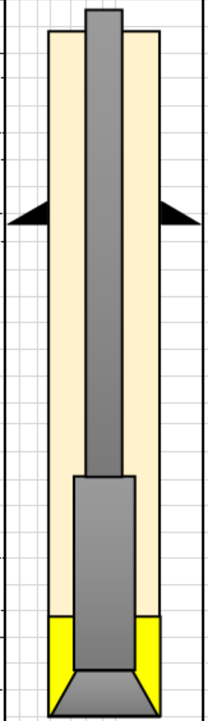
Well Name	0
Field Name	0
Date	1/0/1900

Initial Kick Data			Pump Data		
Kick Size	14	bbl	SCR	30	SPM
SIDPP	400	psi	Pressure	200	psi
SICP	600	psi	Output	0.1018	bps

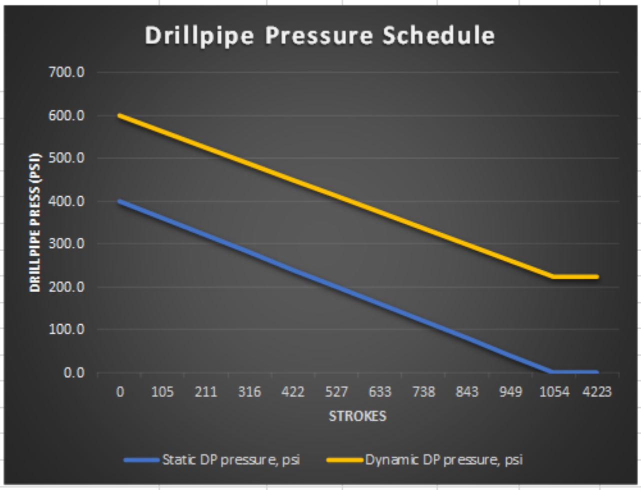
Formation Strength Data		
L.O.T Pressure	1235	psi
MW during Test	9.00	ppg
MAMW	16.3	ppg
MAASP	998	psi

Volumes	OD (inch)	ID (inch)	Length (ft)	Vol (bbl)	Strokes	Mins
Drill Pipe	5	4.276	5,440	96.63	949	31.6
HWDP	5	3	810	7.08	70	2.32
Drill Collar	6.5	2.5	600	3.64	36	1.19
String Volume				107.35	**1054**	35
DC / Open Hole	8.5	6.5	600	17.49	172	5.72
DP / Open Hole	8.5	5	3,000	137.70	1352	45.1
Open Hole Volume				155.19	**1524**	50.80
DP / Cased Hole	8.835	5	3250	167.51	**1645.1**	54.8
Total Annulus Vol				322.70	**3169**	106
Total Well Vol				430.05	**4223**	141

Well Data		
Drilling Mud Data:		
Mud Weight	10.4	ppg
Casing Data:		
Casing Size	9 5/8	inch
Casing ID	8.835	inch
Casing MD	3250	ft
Casing TVD	3250	ft
Hole Data:		
Bit MD	6850	ft
Bit TVD	6850	ft
Hole Size	8.5	inch
Hole MD	6,850	ft
Hole TVD	6850	ft



Chart



Calculations

Step #	Strokes	Static DP pressure, psi	Dynamic DP pressure, psi
0	0	400.0	600
1	105	360.0	562
2	211	320.0	525
3	316	280.0	487
4	422	240.0	449
5	527	200.0	411
6	633	160.0	374
7	738	120.0	336
8	843	80.0	298
9	949	40.0	260
10	1054	0.0	223
11	4223	0.0	223

KMW	11.6	ppg
ICP	600	psi
FCP	223	psi

Remarks:
** Input cells are in light blue color.
** Input the planned kill speed and pump pressure in the pump data table.
** Method will be applicable if the kick size is within the kick tolerance calculations.

Well Type | Volumes | Input | Kick Tolerance | Selector Tool

Figure 12: program calculations for selected W&W method (case study 1)

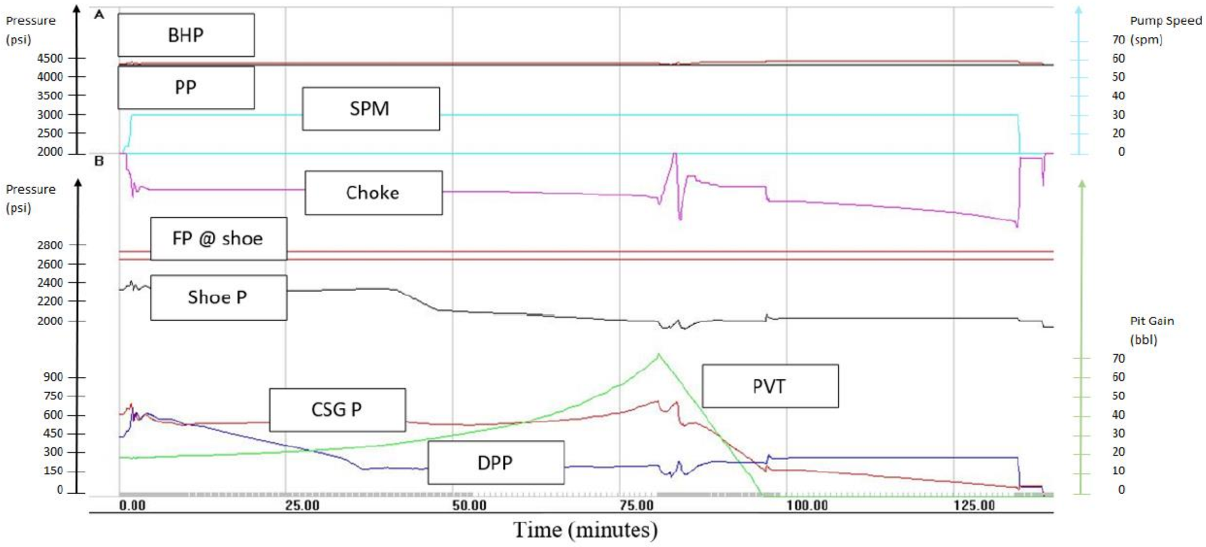


Figure 13: Pressure and Volume chart generated by the drilling and well control simulator of case study 1.

Table 1: Drill pipe pressure versus strokes pumped during the W&W method applied on the well control simulator (first case study).

STKs	DPP, psi
0	620
105	600
210	595
316	547
422	512
527	475
633	437
738	400
843	364
949	327
1054	250
4223	250-300

SIDPP = SICP = 75 psi after complete cycle.
Bleed pressures to Zero.
Check SIDPP = SICP = Zero
Well is killed.

Case study 2

The second well conditions were inserted in the program as shown in Figure 14. The well was drilled to 6,850 ft MD/TVD. The 9-5/8” casing was run and cemented at 3,250 ft MD/TVD. A kick was observed during the drilling 8-½” hole using 10.1 ppg mud. The well has been shut-In and the surface pressures were recorded. Gas migration was recorded. The well was vertical. It was recorded from the offsets that there was no potential of H_2S gas during kill operation.

Kill Method Selection Tool (Drilling Well)

Field Name		
Well Name		
Date	3/12/2021	
Formation Strength data		
LOT surface pressure	1235	psi
MW during test	9.00	ppg
MAMW	16.3	ppg
MAASP	1049	psi
Pump Data		
Mud Pump Type	Triplex	
Liner Size	6	inch
Stroke Length	12	inch
Rod Diameter	4	inch
Pump Efficiency	97	%
Pump output	0.102	bbl/stk
Pump SCR	30	spm
Pump SCR pressure	200	psi
Shut In Data		
Intial SIDPP	510	psi
Initial SICP	690	psi
Pit Gain	12	bbl

Well Data			
Casing OD		9.625	inch
Casing ID		8.835	inch
Casing shoe MD		3250	ft
Casing shoe TVD		3250	ft
Hole size		8.5	inch
Hole MD		6850	ft
Hole TVD		6850	ft
Bit Size		8.5	inch
Bit MD		6845	ft
Bit TVD		6845	ft
Current MW		10.1	ppg
D/P OD		5	inch
D/P ID		4.276	inch
D/P length		5435	ft
HWDP OD		5	inch
HWDP ID		3	inch
HWDP length		810	ft
D/C OD		6.5	inch
D/C ID		2.5	inch
DC length		600	ft
Hole angle @ BTM		0	degree
Hole angle @ shoe		0	degree
KOP MD, ft		KOP TVD, ft	
EOB MD, ft		EOB TVD, ft	

Recorded Pressures during Shut-In Period			
Time	SIDPP	SICP	Migration
	510	690	Initial
	530	710	yes
	550	730	yes
			No
			No
			No
			No
			No
			No
			No
			No
			No
			No
			No
			No
			No
			No
			No
			No
			No
			No
			No

Is the circulation valid through the kill string?	NO
Is the kick has a potential of H2S?	NO
Is the formation has good injectivity?	NO

Figure 14: Input data for case study 2

From the program kick tolerance calculations, the recorded kick size was within the kick tolerance volume as shown in Figure 15. The maximum allowable kick size before the casing shoe breakdown was 39 barrels and the kick size was 12 barrels. From the selector tool, the system recommended to use the volumetric method as shown in Figure 16 and this was shown in the graph that shows the highest Selection Index.

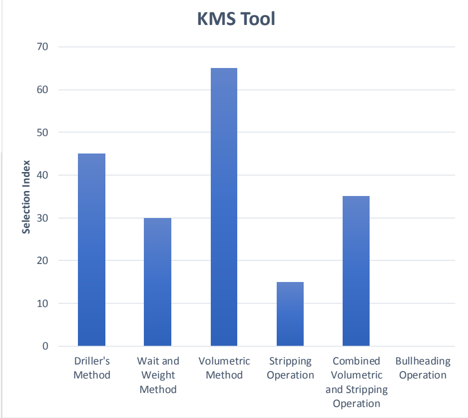
Well Volumes				
Drill String Volume	107.26	bbl	1053.37	stks
Drill Pipe volume	96.54	bbl	948.05	stks
HWDP volume	7.08	bbl	69.55	stks
DC Volume	3.64	bbl	35.78	stks
Ann. Open Hole volume	155.31	bbl	1525.23	stks
Open hole	0.35	bbl	3.45	stks
D/C & OH	17.49	bbl	171.72	stks
HWDP & OH	37.18	bbl	365.12	stks
D/P & OH	100.29	bbl	984.93	stks
Ann. Cased Hole volume	167.51	bbl	1645.06	stks
Total Annulus volume	322.82	bbl	3170.29	stks
Total Well Volume	430.08	bbl	4223.66	stks

Kick Tolerance calculations			
Expected Influx grad.	0.088	psi/ft	
Pform	4107.6	psi	
Hmax	1233.22	ft	
Vinflux	35.94	bbl	at initial shut-in
Vinflux	37.98	bbl	Top of gas @ shoe
Kick Tolerance volume	**35.94**	bbl	
Kick intensity	**1.43**	ppg	

Figure 15: Volumes and kick tolerance calculations for second case study

Kill Method Selection Tool (Drilling Well)

	Conditions / Method	Is it applicable?	Driller's Method	Wait and Weight Method	Volumetric Method	Stripping Operation	Combined Volumetric and	Bullheading Operation
1	Bit On BTM	YES	5	5	5	-10	-10	5
2	Is circulation Valid through String?	NO	-10	-10	15	0	0	5
3	Vertical Well	YES	5	5	5	5	5	5
4	Deviated Well	NO	0	0	0	0	0	0
5	Horizontal well	NO	0	0	0	0	0	0
6	Open hole volume lower than drill string volume	YES	0	0	0	0	0	0
7	Gas Kick (Gas migration)	YES	15	0	15	-5	15	0
8	Water kick	NO	0	0	0	0	0	0
9	Oil Kick	NO	0	0	0	0	0	0
10	Influx volume below kick tolerance	YES	5	5	0	0	0	0
11	Is Kick has a potential of H2S?	NO	5	5	5	5	5	0
12	Is Formation has Good Injectivity?	NO	15	15	15	15	15	-15
		Result	45	30	65	15	35	0



System is divided into 12 questions.

Questions are answered automatically based on input data in INPUT sheet.

All Data in INPUT sheet should be entered for better results.

Based on the selected Well Control Method, click on the below links in order to go the proper sheet (example: Volumetric, stripping,.....etc.)

Proper risk assessment should be done before proceeding with the selected killing method

Driller's Vertical	W&W Vertical	Volumetric	Stripping	Combined	Bullhead
Driller's Deviated	W&W Deviated	Kick Tolerance	Well Type	Input	Volumes

Figure 16: Program selector tool for case study 2

The output calculations of the kill sheet shown Figure 17, were applied during killing the well on the simulator as shown in Figure 18 and Table 2. A safety margin of 50 psi and a working pressure of 50 psi were used. The SICP was allowed to increase from 690 psi to 790 psi (SICP plus Safety margin and working pressure) by allowing the gas to migrate. The next step was to allow the gas to expand by bleeding a 4.9 bbl mud equivalent to 50 psi working pressure while maintaining the SICP pressure constant at 790 psi. The next step was to let the casing pressure to increase by working pressure then bled 4.9 bbl mud maintaining the casing pressure constant and continue with the same steps until the gas approached surface.

Well Name		
Field Name		
Date	3/12/2021	

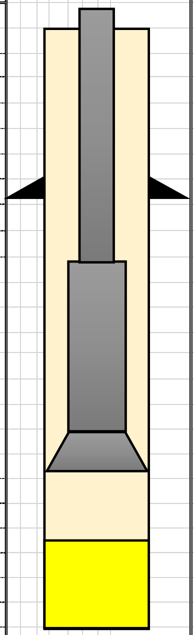
Initial Kick Data		
Kick Size	12	bbl
SIDPP	510	psi
SICP	690	psi

Pressure Assumptions		
Safety Margin	50	psi
Working Pressure	50	psi

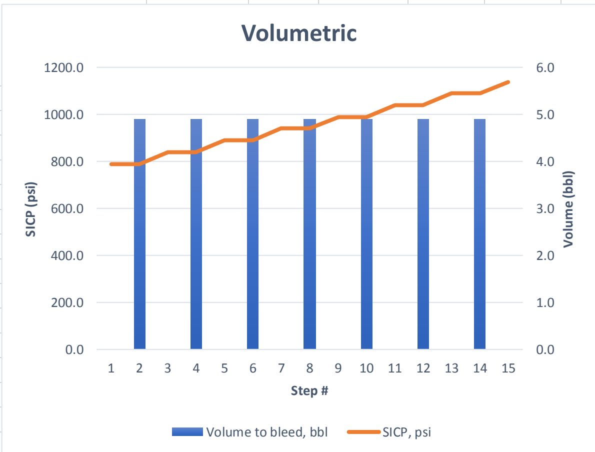
Volumes		
Drill Pipe OD	5	inch
Drill Pipe ID	4.276	inch
Avg. Stand length	93	ft
Closed End Disp.	0.02429	bpf
Drill Collar OD	6.5	inch
Drill Collar ID	2.5	inch
DP / CSG Capacity	0.05154	bpf
DP / OH Capacity	0.04590	bpf
DC / CSG Capacity	0.03478	bpf
DC / OH Capacity	0.02914	bpf

Well Data

Drilling Mud Data:		
Mud Weight	10.1	ppg
Casing Data:		
Casing OD	9 5/8	inch
Casing ID	8.835	inch
Casing MD	3250	ft
Casing TVD	3250	ft
Hole Data:		
Bit MD	6845	ft
Bit TVD	6845	ft
Hole Size	8.5	inch
Hole MD	6,850	ft
Hole TVD	6850	ft



Chart



Calculations

Step #	SICP, psi	Volume to bleed, bbl	Comment
1	790	0.0	Migration
2	790	4.9	Expansion
3	840	0.0	Migration
4	840	4.9	Expansion
5	890	0.0	Migration
6	890	4.9	Expansion
7	940	0.0	Migration
8	940	4.9	Expansion
9	990	0.0	Migration
10	990	4.9	Expansion
11	1040	0.0	Migration
12	1040	4.9	Expansion
13	1090	0.0	Migration
14	1090	4.9	Expansion
15	1140	0.0	Migration

Remarks:
** Input cells are in light blue color.
** Continue with the same sequence until all gas is at surface (as shown in calculations table).
** Consider increasing SICP with a value equivalent to the reduction in HP while gas starts to move around BHA.
** Number of steps will depend on depth, gas volume, gas expansion, Annular size, ….. Etc.
** Method will be applicable if the kick size is within the kick tolerance calculations.

Figure 17: Program calculations for volumetric method (case study 2)

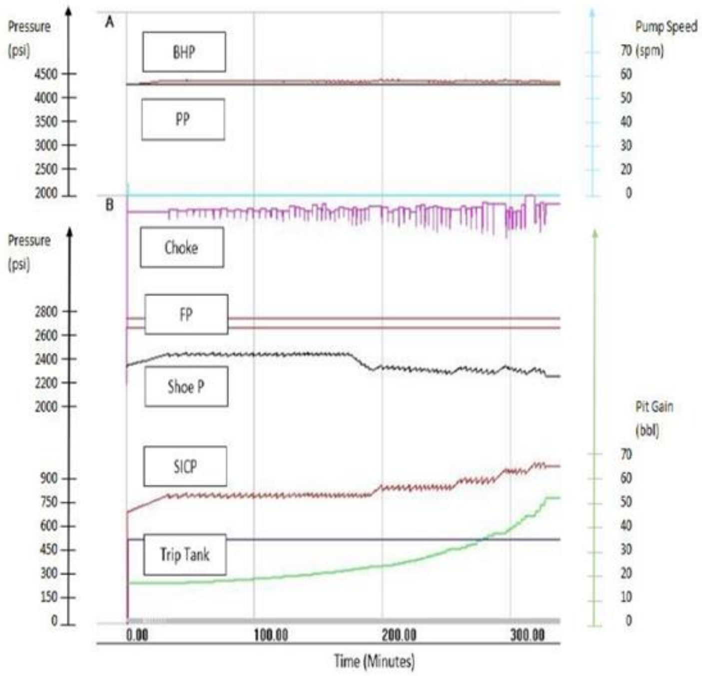


Figure 18: Pressure and Volume chart generated by the drilling and well control simulator of case study 2 while applying volumetric method.

Table 2: Casing pressure versus trip tank volume during the volumetric method applied on the well control simulator (second case study).

Volumetric Method Log Sheet

Kick Size	12	bbl
Mw	10.1	ppg
SICP	690	psi
SIDPP	510	psi

Step #1	SICP, psi	Tank Volume, bbl	Δ Volume, bbl	Remarks
1	690	323.2	0	Initial Condition
2	790	323.2	0	Migration "S.M and W.P"
3	790	328.1	4.9	Expansion "bleeding Mud"
4	840	328.1	0	Migration "W.P"
5	840	333	4.9	Expansion "bleeding Mud"
6	890	333	0	Migration "W.P"
7	890	337.9	4.9	Expansion "bleeding Mud"
8	940	337.9	0	Migration "W.P"
9	940	342.8	4.9	Expansion "bleeding Mud"
10	990	342.8	0	Migration "W.P"
11	990	347.7	4.9	Expansion "bleeding Mud"
12	975	347.7	0	Gas @ Surface

The gas is migrated and expanded safely to surface without any complications related the calculations as shown in the kill sheet. Since volumetric method allows gas kick to migrated and expanded under controlled condition to approach surface, lubricate and bleed method has to be used to replace the gas with mud. The program generates a kill sheet for lubricate and bleed method to replace the gas in the well with kill mud, Figure 19.

Well Name	KHRS-137		
Field Name	KHRS		
Date	3/12/2021		

Kick Data

Initial Kick Size	12	bbl	
SIDPP		psi	Gas @ surface after volumetric method
SICP	940	psi	Gas @ surface after volumetric method

Pressure Assumptions

Safety Margin	50	psi

Volumes

Drill Pipe OD	5	inch
Drill Pipe ID	4.276	inch
Avg. Stand length	93	ft
Closed End Disp.	0.02429	bpf
Drill Collar OD	6.5	inch
Drill Collar ID	2.5	inch
DP / CSG Capacity	0.05154	bpf
DP / OH Capacity	0.04590	bpf
DC / CSG Capacity	0.03478	bpf
DC / OH Capacity	0.02914	bpf

Well Data

Drilling Mud Data:

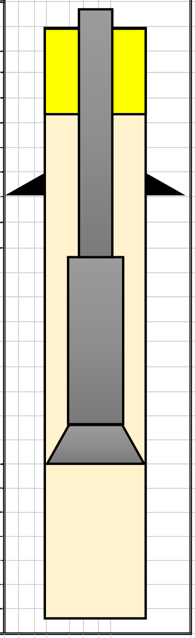
Mud Weight	10.1	ppg

Casing Data:

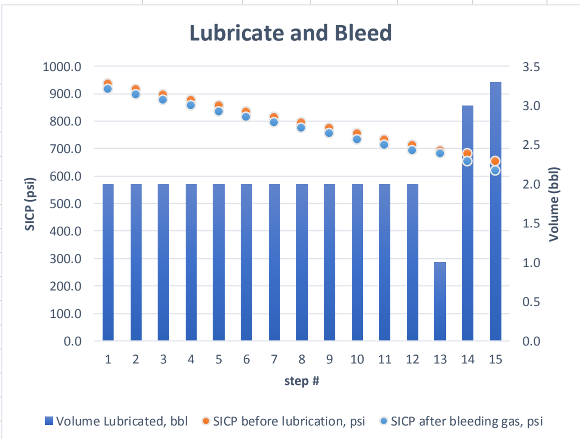
Casing OD	9 5/8	inch
Casing ID	8.835	inch
Casing MD	3250	ft
Casing TVD	3250	ft

Hole Data:

Bit MD	6845	ft
Bit TVD	6845	ft
Hole Size	8.5	inch
Hole MD	6,850	ft
Hole TVD	6850	ft



Chart



Calculations

Step #	SICP before lubrication, psi	Volume Lubricated, bbl	SICP after bleeding gas, psi	Comment
1	940	2.0	919.6	
2	919.6	2.0	899.2	
3	899.2	2.0	878.9	
4	878.9	2.0	858.5	
5	858.5	2.0	838.1	
6	838.1	2.0	817.7	
7	817.7	2.0	797.3	
8	797.3	2.0	777.0	
9	777.0	2.0	756.6	
10	756.6	2.0	736.2	
11	736.2	2.0	715.8	
12	715.8	2.0	695.4	
13	695.4	1.0	685.3	
14	685.3	3.0	654.7	
15	654.686	3.3	621.1	

Remarks:
** Input cells are in light blue color.
** Continue with the same sequence until all the gas is bled out of well (as shown in calculations table).
** Number of steps will depend on the gas volume, working pressure, ... Etc.
** Surface pressure during lubrication will be limited to the weekest point in the well (BOP/Wellhead WP, Fracture pressure, Burst pressure. Etc.)

Figure 19: Kill sheet calculations for lubricate & bleed method (case study 2)

The program is easy to work with and the results are generated quickly avoiding any unexpected improper decision of the team. The program can help the team to select the proper kill method and it will provide the team with the required kill sheets.

III. Conclusions

Based on the results obtained from the study the following conclusions are reached:

- Selection criteria for well control methods of drilling wells are justified based on 12 questions.
- Weighted average for each criteria is given based on 200 well data.
- Excel sheet program is built to select the optimum kill method for drilling or producing wells based on the answers to the selection criteria questions.
- Questions are set as well as input data are identified to be given in the program.

- Based on the input data and the answers, an excel sheet process the data and worked it out, then the optimum kill method is identified through a bar chart.
- Program output give a kill sheet and a kill data for the selected optimum kill method.
- Many runs for the program are processed for the selection of different kill methods.

Nomenclatures

$C_{DP\&OH}$	Annular capacity between drillpipe and open hole, bbl/ft
$C_{BHA\&OH}$	Annular capacity between BHA and open hole, bbl/ft
FCP	Final Circulation Pressure, psi
FG	Fracture Gradient, psi/ft
ICP	Initial Circulation Pressure, psi
IG	Influx gradient, psi/ft
K_g	Gas relative permeability, md
L_k	Kick length, ft
L_{max}	Maximum kick length, ft
MAMW	Maximum Allowable Mud Weight, ppg
MASP	Maximum Anticipated Surface Pressure, psi
MG	Mud Gradient, psi/ft
P_1	Formation breakdown pressure at shoe, psi
P_2	Formation pressure, psi
P_{SCR}	Dynamic pressure loss at slow circulation rate, psi
P_e	Pore pressure at the drainage radius, psi
P_P	Pore Pressure, psi
P_F	Fracture Pressure, psi
P_h	Hydrostatic Pressure, psi
P_{ch1}	Choke pressure, psi
P_{ann}	Annulus pressure, psi
P_W	Working pressure, psi
P_S	Safety margin, psi
P_s	Applied surface pressure during LOT, psi
P_{wf}	Pore Pressure at the wellbore, psi
P_{Shoe}	Casing shoe pressure, psi
q_{gsc}	Drilled gas entry rate, scf/min
R	Gas constant
r_e	Drainage radius, ft
r_w	Wellbore radius, ft
stk	Strokes
T_z	Bottomhole temperature, ˚F
V_1	Kick volume at casing shoe, bbl
V_2	Kick volume at initial shut in, bbl
V_k	Kick volume, bbl
Z	Gas compressibility factor
ΔP / 100 STK	Drill String pressure schedule, psi/100 stk
ρ_{influx}	Influx gradient, psi/ft
ρ_m	Mud gradient, psi/ft
μ_g	Gas viscosity, cp

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