

DEVELOPMENT OF A WELL INTEGRITY MANAGEMENT SYSTEM FOR DRILLING AND WELL CONTROL APPLICATIONS



Dissertation Presented to
Politecnico di Torino
Department of Environment, Land and Infrastructure Engineering

Supervisor:
Prof. Raffaele Romagnoli
Eng. Angelo Calderoni

Author:
Alcheikh Elia Abdo

October 2019

COPYRIGHT © 2019 BY ALCHEIKH ELIA ABDO



POLITECNICO
DI TORINO



DRILLMEC
DRILLING TECHNOLOGIES
Training & Well Control Center

DECLARATION

I declare that this project is my own work. It is being submitted for the degree of Master of Science in Petroleum Engineering in Politecnico di Torino, Italy. It has not been submitted for any degree or examination in any other university.

.....

(Signature of candidate)

.....day of..... year.....

DEDICATION AND ACKNOWLEDGEMENTS

I dedicate this work to my family and friends, for the love, support and the faith they always show in me.

I also present my thanks to professor Raffaele Romagnoli for his support and help during the project.

In addition, I would like to thank Eng. Angelo Calderoni, my agency advisor, for his faith in me.

Lastly, many thanks and appreciation to the team at Drillmec Spa, to Ali Talat Qushchi, Leonardo Bori, Vladimir Mitu and Francesco Vasta for their incredible support and encouragements, their expertise and professionalism. And special thanks to Mr. Francesco Curina who showed his faith in me and gave me this incredible chance to work on an important project like this one.

ABSTRACT

The continuing success of a drilling contractor depends on its ability to deliver completed wells at required deadlines with fully functioning barriers and to manage the integrity of these barriers in the most efficient manner. This will allow the contractor to adhere to its contract while maintaining the safety of its personnel, its assets, its reputation and the environment. Having a fully functioning WELL INTEGRITY MANAGEMENT SYSTEM, capable of efficiently managing the barriers of the wells being drilled is the main requirement to achieve this goal.

DRILLMEC SPA is a global leader in the manufacturing of advanced drilling rigs and a major provider of drilling services like HMIs and data acquisition systems, in addition to its world renowned training center. This places the company in a strategic position to implement a complete well integrity management system for its clients and provide the required personnel training to allow them to manage their wells in the safest and most efficient way.

This paper discusses the philosophy behind well integrity and the process that concluded in the development of the software that handles well integrity during the drilling and well control applications. This paper also describes how the information was gathered, analyzed and aggregated to develop the software and provide a summarized overview of well integrity and well barrier status for the drilling operations.

The software was developed following the guidelines of the NORSOK D-010 standards and the IWCF standard Well Control certification. The trials of the toolkit were conducted on the IWCF certified Well Control Simulator.

Table Of Contents

DECLARATION	2
DEDICATION AND ACKNOWLEDGEMENTS	3
ABSTRACT.....	4
List Of Figures	7
List Of Tables	8
List Of Equations	9
List Of Abbreviations	10
CHAPTER 1. INTRODUCTION	12
Introduction.....	13
Definition of Well Integrity	17
Design:	18
Drilling:.....	18
Operations:	19
Abandonment:	19
Introduction to WIMS.....	20
Objectives of a traditional Well Integrity Management System.....	21
Importance of WIMS	22
WIMS during drilling and well control.....	23
CHAPTER 2. EVALUATION OF ESSENTIAL ELEMENTS	26
Pressure Drop of a Plastic Drilling Fluid in Turbulent Flow:	27
Evaluation of the Rate of Penetration:	30
Effect of formation strength:	32
Effect of compaction:.....	32
Effect of pore pressure:	33
Effect of differential pressure:.....	33
Effect of drill bit diameter and WOB:	33
Effect of rotary speed:.....	34
Effect of drill bit tooth wear:	35
Effect of hydraulic:	35
Sustained Casing Pressure:	40
Definition	40
Causes	40
Standards and regulations	42
Monitoring	42
Acceptance criteria	44

SCP prevention through well design and operational considerations	45
Remediation	46
Recommendations	48
Integration with a Well Integrity Management Software Solution.....	49
Risk Assessment.....	52
Risk Methodology	52
Data Preparation	53
Failure modes	55
Assessment.....	56
CHAPTER 3. DEVELOPMENT OF THE WIMS TOOLKIT	59
Development of the WIMS toolkit	60
Choice of development platform	60
Choice of design parameters to be considered	61
Choice of monitored parameters to be considered.....	63
Development of the algorithms	64
Results and Discussion	86
Toolkit Interface	86
Presentation of the Theoretical Well used in Well Control operations.....	92
Results.....	97
CHAPTER 4. CONCLUSION	103
Final words and future prospects.....	104
References.....	108

List Of Figures

Figure 1. ROP function of WOB.....	34
Figure 2. ROP versus Rotary speed.....	35
Figure 3. Simulation results with originally suggested drillability coefficients and normalization values	37
Figure 4. Well Diagram subject of Risk Assessment	55
Figure 5. Hydraulic Algorithm in circular section and surface circuit	67
Figure 6. Hydraulic Algorithm for annular section	68
Figure 7. Standpipe Pressure Algorithm.....	69
Figure 8. Well Control Troubleshooting Algorithm.....	70
Figure 9. WOB Algorithm.....	71
Figure 10. Qualitative representation of a LOT	72
Figure 11. Algorithm for MAASP calculation.....	74
Figure 12. Algorithm for the evaluation of kick tolerance	77
Figure 13. Evaluation of the spread of the kick in the wellbore.....	78
Figure 14. Casing setting depths with and without consideration of kick tolerance	79
Figure 15. Algorithm for calculation of bottom hole pressure.....	80
Figure 16. Drilling break and kick evaluation.....	81
Figure 17. BOP failure monitoring.....	82
Figure 18. Annular pressure variations.....	83
Figure 19. Corrosion Control.....	84
Figure 20. Sour Service	84
Figure 21. Erosion Management	85
Figure 22. Screenshot from the WebApp Formation Data Page.....	87
Figure 23. Screenshot from the WebApp Drill String Program Page	87
Figure 24. Screenshot from the WebApp Drill Bit Data Page	88
Figure 25. Screenshot from the WebApp Mud System Properties Page	88
Figure 26. Screenshot from the WebApp Test Data Page	89
Figure 27. WIMS WebApp Python/Flask Code.....	90
Figure 28. Kick Tolerance Algorithm	91
Figure 29. Leak Off Test	96
Figure 30. Drilling Systems DrillSIM:20 simulator.....	96
Figure 31. Result Page of the fully operational well	98
Figure 32. Result Page when the primary barrier is lost.....	101

List Of Tables

Table 1. Normalized values	36
Table 2. Drillability Coefficients	36
Table 3. Risk Matrix.....	58
Table 4. Different categories of surface circuit dimensions	65
Table 5. Young modulus for the different categories	65
Table 6. Pore Pressure Gradient Distribution with Depth	93
Table 7. Drill String Composition and Parameters	94

List Of Equations

Equation 1. Shear Stresses for Bingham Plastics	27
Equation 2. Fanning friction factor iterative relationship	28
Equation 3. Fanning pressure drop due to friction	28
Equation 4. Reynolds number	28
Equation 5. Hedstrom number	28
Equation 6. Pressure drop in turbulent flow regime	28
Equation 7. ROP factor of eight parameters	32
Equation 8. Effect of formation strength	32
Equation 9. Effect of compaction.....	32
Equation 10. Effect of pore pressure	33
Equation 11. Effect of differential pressure	33
Equation 12. Effect of drill bit diameter and WOB.....	33
Equation 13. Effect of rotation speed	34
Equation 14. Effect of tooth wear	35
Equation 15. Effect of hydraulics.....	35
Equation 16. Hydraulic impact force.....	36
Equation 17. Relative mean error.....	37
Equation 18. Drilling Balance.....	76

List Of Abbreviations

ALARP	As Low As Reasonably Possible
ANN	Artificial Neural Network
API	American Petroleum Institute
BHP	Bottom Hole Pressure
BOP	Blow Out Preventer
DC	Drill Collar
DP	Drill Pipe
ECD	Equivalent Circulating Density
EPP	Equivalent Pore Pressure
Fj	Hydraulic Impact Force
HL	Hook Load
HMI	Human Machine Interface
HSE	Health, Safety and Environment
HWDP	Heavy Weight Drill Pipe
ID	Internal Diameter
LOP	Leak Off Point
LOT	Leak Off Test
LWD	Logging While Drilling
MAASP	Maximum Allowable Annular Surface Pressure
MMS	Minerals Management Service
MOC	Management Of Change
MOP	Maximum Operating Pressure
MWD	Measuring While Drilling

NCS	Norwegian Continental Shelf
NORSOK	Norsk Søkkelers Konkuranseposisjon
OD	Outside Diameter
OLF	Norwegian Oil Industry Association
PSA	Norwegian Petroleum Authority
ROP	Rate Of Penetration
RPM	Rotations Per Minute
SCP	Sustained Casing Pressure
SI	International System
SICP	Shut In Casing Pressure
SIDPP	Shut In Drill Pipe Pressure
SPM	Strokes Per Minute
SPOC	Single Point Of Contact
TDT	Thermal Decay Time
TVD	True Vertical Depth
UKCS	UK Continental Shelf
WOH	Weight On Hook
WIMS	Well Integrity Management System
WOB	Weight On Bit

CHAPTER 1. INTRODUCTION



POLITECNICO
DI TORINO



DRILLMEC
DRILLING TECHNOLOGIES
Training & Well Control Center

Introduction

The Norwegian Petroleum Authority (PSA) has conducted a wide and comprehensive survey of seven operating companies on the Norwegian Continental Shelf (NCS). The survey handled some pre-selected facilities to investigate the well integrity status of each well. This survey, conducted in 2006, found that about 18% of the production or injection wells were suffering from problems related to well integrity and that these problems were enough to impede the normal operations of the well (Corneliussen, Haga & Sorli, 2009). In addition, another survey conducted on the UK Continental Shelf (UKCS) between the years 2000 and 2005, found that 10% of the wells were shut-in due to problems also related to well integrity (Corneliussen et al., 2007).

These findings have prompted the PSA and other well integrity organizations to advise the operators, subjects of the surveys, to improve their focus on well integrity. The PSA recommended that companies “review their inhouse management systems for compliance with the requirements” of the international well integrity standards like the NORSOK D-010 standards and to decrease the possibility of incidents (Corneliussen, Haga & Sorli, 2009).

In addition to this, the PSA included a list of recommendations concluded from the analysis of the causes behind the failures (Corneliussen et al., 2007):

- Documentation of well integrity needs to be standardized.
- Well barriers and barrier envelopes are described in varying ways within the industry (even within a single company).
- Access to well integrity data is generally very complicated and needs to be more user-friendly.
- Documents handover process needs to be improved.

- There should be more attention and care when handling the verification and monitoring of well barriers and well integrity data.
- The technology used for handling well integrity data and monitoring well barriers must be improved with regards to systematic, preventive maintenance.
- There is an increased need to improve the training of personnel of the different companies working on the rig site like operators, contractors and service companies.
- Contribution to the standardization of well integrity procedures, measurements, data management and implementation must be encouraged.

Since these studies have been published, and especially following the devastating Macondo well blowout, attention and focus on well integrity has increased among operators, contractors and service companies alike.

The focus on well integrity is not only reflected in the internal work of companies but also in authorities and standardizing collaborations. All this means that companies with control of their well integrity have a competitive advantage with regards to safety and profitability (Corneliussen, Haga & Sorli, 2009). Indeed, well integrity has become one of the major selling points in the oil and gas industry and an important part of the oil company's business strategy.

However, even though the importance of well integrity has been recognized for over 15 years in the industry and significant improvements to design and operating procedures have been made, failures still occur and will probably continue to occur in the future. Today, most major incidents occurring in the petroleum field happen during the drilling and completion phase. This phase, in fact, is statistically the most dangerous one in all of the phases of a well's life cycle. This is due to the large number of different parameters that must all be controlled during the operation. Each of these parameters has many different failure modes and each failure mode can be sustained by

a multitude of causes. This renders the drilling operation a complex, delicate and stressful process.

Until now, all the work and development that has been made in the field of well integrity and well barrier maintenance has been focusing on the production, workover and abandonment stages of the well's life cycle. Very few advancements have been made with regards to drilling and completion. Of course, the set of rules and procedures detailing how exactly to perform a well control operation and maintain at least one barrier in place during all the processes have been around for some time. Organizations like the IADC and the IWCF have indeed standardized the way these operations must be carried out through their certificate system; for example, a driller must hold an IWCF Well Control Level 3 certificate and a Toolpusher must have the Level 4 certificate.

However, what these organizations fail to provide is correct mechanism to counter the most important factor of well control accidents: the human factor. A driller, even one who processes all the required certificates and training, will need a few minutes to register the occurrence of a kick. There are so many different parameters that he should check before he can officially declare that a kick occurred. In addition, there is the hierarchy of command. A driller might detect the kick fast enough, but he will have to wait until the Toolpusher gives the confirmation before he can start the well control operations. This is not the fault of the driller or any of the workers on the rig; this is just the maximum reaction time that a human can have.

This paper tries to mitigate the human factor by applying the concepts developed in the well integrity management systems monitoring and controlling the integrity of producing wells, to the drilling operations. In this paper, the methodology, organization and the tools needed to achieve full control of a well and maintain the integrity of all its barriers are detailed.

Finally, this paper will focus on the development, testing and implementation process of a software tool that has the objective of monitoring, evaluating and reporting well integrity issues during the drilling operations. The tool was called the My WIMS App and is intended to work as a sort of web app that performs all its objectives through the cloud. This choice has been made in order to allow the app to be available to as many employees as possible.

The tool has also the functionality of starting a DRILLMEC designed kick mitigation system that operates the well control procedures automatically. The tool was tested on a theoretical well provided by IWCF and implemented in the well control simulator designed by DRILLING SYSTEMS. The results showed great prospects for improved well control and integrity management of wells in the drilling phase as well as the ability to monitor rig equipment remotely.

Definition of Well Integrity

The Norsok D-010 standards provide the most widely accepted definition of Well Integrity; it's "the application of technical, operational and organizational solutions to reduce risk of uncontrolled release of formation fluids throughout the life cycle of the well".

Other definitions exist too. Most notably one might cite the ones provided by the Petroleum Exploration Society of Australia (PESA); "The instantaneous state of a well, irrespective of purpose, value or age, which ensures the veracity and reliability of the barriers necessary to safely contain and control the flow of all fluids within or connected to the well", and the ISO TS 16530-2 standard; "Containment and the prevention of the escape of fluids (i.e. liquids or gases) to subterranean formations or surface".

For this paper however, an independent definition shall be developed based simply on dividing the words that form the notion in question. First, let's start with the easiest of the two; "Well". Simply put, a well is a hole dug into the earth to allow bringing earth fluids from deep rock formations to the surface. A well is associated with equipment and structures that allow its normal functioning. Of these, the most important are the casing strings, the packers, the liners, the valves, the cement bonds and a slew of other equipment used either at surface or inside the borehole.

The second term to be defined is "Integrity". The word "Integrity" comes from the Latin word "Integer" which means to be whole or intact. This means that the integrity of a well is the condition of this well (along with all the equipment mentioned above) to be sound in construction and unified. All this simply means that the overarching objective of Well Integrity is to assure the sound functioning of the well and its subsequent elements throughout the well's life cycle.

This last part is very important. A well goes through many changes during its life. Some wells even change functions, that is they start as production wells and then are transformed into injection wells. Throughout these changes, a well can be at its most unstable state and thus maintaining sound functioning of its elements is of utmost importance. The well life cycle therefore is an important notion to define before progressing further in this paper.

The well life cycle is simply defined by its successive stages; Design, Drilling, Completion, Handover, Production, Workover then subsequent handover, second Production phase and finally Plug and Abandonment. For the sake of clearing the ambiguous, a specific focus will be maintained on the four main stages; Design, Drilling (and construction), Operations and Abandonment.

Design:

During the design stage, the primary consideration for Well Integrity is the reliability of the information provided for the subsurface pressure and heterogeneity. Foo & Stuart (2010) maintain that pore and fracture pressure predictions, in addition to borehole stability, formation lithology and fluid type, present a high level of uncertainty in most wells. The focus during the design phase is to reach the total required depth of casing under the provided conditions. Thus, the barriers selected might not necessarily be designed to sustain all the possible load scenarios that might occur during production and/or abandonment (Foo & Stuart, 2010).

Drilling:

In this phase, Key Performance Indicators (KPIs) are introduced and are mostly dominated by time constraints which usually act in an opposite way to Well Integrity. A time-depth curve will present an important visual indicator of success (Foo & Stuart, 2010). Quality and design verification, thus, takes a backseat in the success indicators' importance scheme.

Operations:

Fluids introduced during the production phase induce risks of corrosion, thermal and pressure loads that have yet to be experienced during drilling and completion (Foo & Stuart, 2010). Here, the importance of correct transfer of knowledge, data and records during handover is underlined.

Abandonment:

After the passing of the well through different operators and contractors and the different stages of its life cycle, it is fair to say that the last phase would be the most complex to manage operationally. Logistical issues, like information storage, record keeping, and data gaps only add to the complexity of the final stage. If a good management system is applied from the beginning all throughout the life cycle, however, this phase can be easily accomplished.

This, then, is the main objective of Well Integrity. But the trick is how to maintain Well Integrity in the way discussed above? The answer lies in a Well Integrity Management System.

Introduction to WIMS

In almost all the papers researched for this project, the main concept that the authors had developed was that the oil and gas industry had a previously established knowledge about well integrity during the design and construction phase and that the future needs of the industry should be focused on the production, intervention and abandonment phases.

While this is mostly true, and backed by extensive research, it was clear that very few companies have tried to automate the maintenance of well integrity during the construction phase like they did for the other phases. Problem detection has been always left to the driller and operator of the rig as they are the ones in direct contact with the equipment. A few years ago, this was the only option as there was no other way of detecting anomalies except by physical interaction with the rig and the monitoring of many parameters.

For example, a kick during the drilling operation can be detected by first an increase in ROP. If this happens, the driller should stop the operation and check for return flow rate from the well and pit volume increases. This all takes a few seconds to accomplish and usually by the time a kick is detected, and the well is closed, the volume of fluid that enters the well will surpass 1000 liters. In fact, with many trials on the DRILLING SYSTEMS simulator, using the IWCF standard exercise, an average influx volume would be around 2000 liters, with some cases reaching 3000 liters. That is considering that the people doing the simulation are experienced drillers having worked on a rig for more than 20 years.

An automatic detection of the influx of fluids would eliminate the human delay as all the different parameters can be monitored at the same time and down to 0.1 seconds of resolution. This will effectively reduce the latency time before the well can be closed and will reduce the influx volume to a minimum of 1000 liters.

To be exact, there are some software packages that use this algorithm to detect kicks in real time. These packages, usually called kick mitigation systems, are present in form of alarms. They can be set to specific ranges and whenever a value exceeds these ranges, the alarm goes off notifying the whole rig crew. However, these alarms are still monitoring independent parameters and cross correlation between the significance of different alarms has not been developed yet.

Objectives of a traditional Well Integrity Management System

A Well Integrity Management System (WIMS) is the name given to any methodology used to insure the flow of fluid through the designed pathway in a well. More importantly, a WIMS should prevent the flow of fluids through paths that were not designed for this purpose. A good WIMS software kit should provide an extensive data analysis package and adequate delivery mechanisms. A WIMS should provide a system of continuous management, assessment and verification of the different barriers put in place throughout the life cycle of a well. The WIMS should provide the five following objectives:

1. Definition and identification of well design and operation criteria.
2. Conduction of regular reviews to ensure integrity maintenance throughout the full lifecycle of the asset.
3. Complete compliance of all the assets of a company with international, regional or company standards.
4. Wide understanding of the defining rules and standards applied in each well between the employees belonging to different oil companies, drilling contractors or service companies.
5. Continuous and consistent monitoring of the assets grouped by location, type or size.

If the WIMS is designed, implemented and improved while keeping these objectives clear, it will help reduce the downtime and the costs of repair at the same time. In some cases, it can even help avoid catastrophic incidents like blowouts or major leaks. Abdel rady et al. (2010) indicate that a WIMS should be dynamic, not static, and open the doors for improvements in a continuous process. The required functions of a WIMS will be as follows:

1. Provide the operational status of a well.
2. Provide the integrity status of the well with adequate risk assessments in case the integrity status was found to be lacking.
3. Provide a clear Well Barrier Schematic that adheres to international regulations and explains the status of each Well Barrier Element. These include valves, casings, cement, formations or drilling fluids.
4. Provide an interactive way of producing standard reports and insuring the receipt of these reports by all the required personnel.
5. Define the responsibilities and roles of all the included personnel.

In the case of drilling or well control the job of a WIMS will be more complicated as the number of components and equipment used during these operations is higher than other stages of the well life cycle. In these phases the WIMS should also:

1. Provide surface equipment status through the measurements of different parameters.
2. Provide automatic detection of kick possibilities, with quick tips for decision making.

Importance of WIMS

A WIMS does not necessarily mean the use of advanced and expensive software solutions, even though these will help make the job easier and more accurate to a high degree. A

WIMS may be applied with minimal software use. It is enough to put together a set of standards that can be applied to all the wells in a given geological formation (reservoir).

However, very few drilling contractors and oil companies would choose a completely physical version of a WIMS. The implementation of a software solution for well integrity management is not so simple. The main challenges are related to the training of the workers and the transition management into the new system. A WIMS affects the way employees carry out their everyday jobs, that is why it's a high complexity tool according to Corneliussen et al. (2009). When enough research has been carried out and a good implementation plan put together a WIMS will be able to provide any company with the following benefits:

1. Improved safety of the company's assets (people and equipment).
2. Reduced downtime.
3. More homogenous working conditions and better understanding between the different levels of employees.
4. Faster response to emergencies and everyday inquiries.
5. Offsite monitoring and mitigation to specific issues.
6. Reduced accidents due to human error.
7. Easier transition of assets between different phases of a well lifecycle or between drilling contractors, service companies and oil companies.

WIMS during drilling and well control

The WIMS software that is being developed as the subject of this paper can be thought of as a mixture of different alarm systems working around the drilling rig. Their objective is to monitor different parameters regarding the drilling and well control operations. But in addition to simple monitoring the WIMS software will have the ability to correlate the different

measurements and calculations in order to provide a synchronized output in real time providing the driller and all other authorized personnel the same kind of data; the status of each well barrier, the problems that may occur and the cause of each problem. This can be provided as a form of table that identifies each well barrier and assigns a status for the given barrier. In addition, a well barrier schematic, specially customized for each well will be provided. In the results page, online links to the referenced standards can also be found.

The WIMS software will use the data indicated during the design phase in addition to measurements and any data variations that are taken during the construction phase. It will perform some advanced calculations and will cross correlate the results in order to decide the status of each barrier. These cross correlations will be the most difficult part to process and the software will need large amounts of processing power in order to be able to perform this operation in real time. The different inputs/outputs of the developed toolkit will be discussed in more detail in a later chapter along with the different algorithms that will lead to the results.

The toolkit will allow the well integrity engineering team to define the well type and design characteristics in addition to the development of its life cycle. It will also allow rig crew members to input measurements taken on the rig site to a variety of equipment regarding flow rates, pressures, temperatures and volumes. After doing the required processing, the toolkit will provide the authorized users with reports containing a specially designed well barrier schematic for each well being constructed, a complete identification of the barriers put in place in accordance with applied rules and standards (here the Norsok D-010 standards) and a list of their possible failure modes. The toolkit will also be able to identify the elements controlling each barrier (for example, for the drilling mud an element that may cause loss of the barrier might be the mud pumps).

Through the use of advanced calculation and synchronization algorithms, in addition to special intelligent programming of the different scenarios that may occur during drilling and well control operations, the toolkit will be able to predict the failure of each barrier element before it happens in the best case scenario and a fraction of a second after it happens in the worst case scenario. This functionality will be provided on a continuous basis and will be available to all authorized personnel on a global level. The only requirement will be the access to the worldwide web. The application will also provide online links to the specified standards and a standardized report formulation ready for print or email.

One missing feature that is still under development is the plug and play ability. This means that the only setup that the app will need is the initial induction of the application into the company workflow. At the moment the toolkit will need advanced setup to accommodate to changing well equipment and drilling fluid properties.

CHAPTER 2. EVALUATION OF ESSENTIAL ELEMENTS

Pressure Drop of a Plastic Drilling Fluid in Turbulent Flow:

The pressure drop is the energy needed to move a given fluid from one point to another. In the scope of the hydraulic circuit of the well the pressure loss is due to the friction of the fluid with the walls of the flow section. For the calculation of pressures and pressure drops in the hydraulic circuit, it is essential to have the ability to evaluate the pressure losses of a non-Newtonian fluid inside the drill string and in the annular section between the drill string and the bore hole or the casing. For the purpose of this paper, the non-Newtonian drilling fluid considered will be a plastic fluid, specifically a Bingham plastic.

Very few papers tackle the issue of pressure drop with Bingham plastics when this fluid is flowing in turbulent conditions, that is when the Reynold's number is above 2100. However, Lenschow (1992) developed a detailed process for calculating the previously mentioned pressure drop using the Fanning equation for pressure drop due to friction. Therefore, an explanation of the process he followed will be provided below with the resulting conclusions.

Lenschow (1992) explains that a fluid obeying the Bingham model will present a linear relationship between shear stress and shear rate. The equation between these is given as follows:

Equation 1. Shear Stresses for Bingham Plastics

$$\tau = \tau_o + \mu_p \times \gamma$$

Where τ is the shear stress in Pa, τ_o is the yield stress of Bingham plastics in Pa, μ_p is the plastic viscosity of Bingham plastics in Pa.s and γ is the shear rate in s^{-1} . From this equation one can infer the Buckingham-Reiner equation which this paper will not be addressing as it is specific to Laminar flow. However, with some assumptions as to the wall shear stresses, one can apply the concepts defined with this equation to develop the Fanning friction factor.

The Fanning friction factor f is related to the Reynolds number Re , and the Hedstrom number He . The friction factor is developed using an iterative process with two equations relating the factor to the pressure drop, the mud density and the flow rate.

Equation 2. Fanning friction factor iterative relationship

$$\frac{f}{16} = \left[\frac{1}{Re} + \frac{1}{6} \frac{He}{Re^2} - \frac{1}{3f} \frac{He^4}{Re^8} \right]$$

Equation 3. Fanning pressure drop due to friction

$$f = 25.83 \left(\frac{d\Delta p}{L\rho v^2} \right)$$

The Reynolds and Hedstrom numbers will be given by the following defining formulas, where 927.6 and 3.701×10^4 are consistency factors:

Equation 4. Reynolds number

$$Re = 927.6 \left(\frac{dv\rho}{\mu_p} \right)$$

Equation 5. Hedstrom number

$$He = 3.701 \times 10^4 \left(\frac{\tau_o d^2 \rho}{\mu_p^2} \right)$$

By combining the equations mentioned above, a final formula for the pressure loss can be applied for turbulent flow using Bingham fluids:

Equation 6. Pressure drop in turbulent flow regime

$$\Delta p = \frac{0.113 \rho^{0.8} q^{1.8} \mu_p^{0.2} L}{d^{4.8}}$$

The formula is expressed in SI meaning that the pressure drop will be given in Pa. For an annular section the equation remains the same with the diameter becoming $(ID_{\text{outer}} - OD_{\text{inner}})$ given in meters.

Lenschow (1992) found a relative error of around 20% when applying this formula for two types of fluids and a regression of 0.99, thus giving accuracy and veracity to the method applied.

This method, being studied thoroughly, was found accurate enough to be used in the code development for the Well Integrity Toolkit. However, it is important to note that the flexibility and customizability of this software tool renders it adaptable to any type of calculations. When implemented for a company, the tool can dynamically change the type of formulas used for different calculations and provide different methodologies to reach the same goals.

Evaluation of the Rate of Penetration:

In the oil and gas industry, it is common practice to calculate well depth using the nominal drill string length only when the bit is at the bottom (Kyllingstad & Thoresen, 2019).

This inherently brings a multitude of problems:

1. Uncertainty in the measured depth as elongations (dynamic and static) are not considered.
2. Increased response time for detecting drilling breaks or other sudden changes in downhole conditions.
3. Spiky and inaccurate ROP with very poor depth resolution.

This last point is of great importance for this paper, as the simulation model of the WIMS toolkit needs a reference value for the ROP to check the measurements against. In this chapter the methodology used for evaluating the ROP will be detailed.

First order of business is to define the ROP or rate of penetration. It is a measure of the speed of drilling, that is how fast does the bit go down through the formations. In field units it is given in feet per hour. As most of the price of an oil or gas well is taken by drilling, the ROP holds such an importance as to become directly proportional to the revenues; the higher the ROP, the higher the revenues.

This, however, is not technically true as a high ROP might sometimes mean bad events like drilling breaks and possibilities of a kick (influx of gas into the wellbore). Due to all this, it should be clear how important it is to evaluate the ROP of a drilling rig and to produce a very accurate and precise result. To do this, is not an easy job as there are many factors that come into play when evaluating the ROP. In fact, in this paper, eight parameters will be defined. Abdulazeez et al. (2019) have categorized these parameters in five different groups pertaining to the formation properties, the drilling fluid properties, the hydraulic parameters, the mechanical

parameters and the rig efficiency. These same categories are then classified into two types; those that are environmental and uncontrollable like the formation and mud properties (considering that mud properties are evaluated to meet the needs of well control before thinking about ROP), and those that are controllable such as RPM, WOB and the hydraulic properties. With this classification out of the way, it is possible to list the eight parameters as follows and in no particular order:

1. Effect of formation strength.
2. Effect of compaction.
3. Effect of pore pressure.
4. Effect of differential pressure.
5. Effect of drill bit diameter and WOB.
6. Effect of rotary speed.
7. Effect of drill bit tooth wear.
8. Effect of bit hydraulic (jet) impact force.

Someone with a keen eye might notice that 50% of these parameters are uncontrollable while the other 50% can be specified in the design stage and maintained or altered according to the needs of the situation during the operations phase. This was not by chance as Bourgoyne and Young proposed these factors back in 1972 in order to formulate an equation that may lead to the swift calculation of ROP in real-time. However, this would not be the case as any formula referencing eight factors at the same time with each factor allowing for a different range of applicable values is not easy to calculate instantaneously. The formula, thus, returns the ROP value as the product of all eight factors in the following manner:

Equation 7. ROP factor of eight parameters

$$ROP = f1 \times f2 \times f3 \times f4 \times f5 \times f6 \times f7 \times f8$$

Each of these factors will be given a personalized formula later with a use case and development explanation. But first, as with all engineers, one finds the need to explore other available equations in the hope of finding another -easier- way of reaching the same goal.

Kutas et al. (2015) provide a very concise resume of the different trials conducted in the last few decades to calculate the ROP. They indicate how the first models were based on the equilibrium between drilling-rate, weigh-on-bit and RPM equations. These relations, however, were only reliable when dealing with a perfectly cleaned hole. This left the Bourgoyne and Young model as the best choice for developing the required formulation. So, it is time for the factors that compose the formula to be evaluated.

Effect of formation strength:

This will be the only formula incorporating only one variable (a_1) that has a range designed to represent the effect of the formation strength along with the effects of drilled solids (cuttings). The ranges of all variables will be given in a table at the end of this section.

Equation 8. Effect of formation strength

$$f1 = e^{2.303a_1}$$

Effect of compaction:

This model assumes an exponential decrease of ROP with depth in a normally compacted formation. The N index in the formula refers to normal values which will be discussed afterwards.

Equation 9. Effect of compaction

$$f2 = e^{2.303a_2(TVD_N - TVD)}$$

Effect of pore pressure:

ROP is assumed to increase exponentially with pore pressure. A high ROP is mostly found in sandstones while a low ROP is found in shales and limestones. The low ROP is mainly caused by overburden stresses.

Equation 10. Effect of pore pressure

$$f3 = e^{2.303a3TVD^{0.69}(EPP-EPP_N)}$$

Effect of differential pressure:

The differential pressure is the difference between the hydrostatic pressure exerted by a drilling fluid of a given density at the bottom of the well and the pore pressure of the formation being drilled. Cuttings held at the bottom of the well can increase friction and bit tooth wear, while decreasing the hole cleaning efficiency. They can also affect the equivalent mud density by increasing it and thus impacting the differential pressure. This can badly impact the ROP.

Equation 11. Effect of differential pressure

$$f4 = e^{2.303a4TVD(EPP-ECD)}$$

Effect of drill bit diameter and WOB:

An exponential relationship exists between the rate of penetration and the weight on bit above a limit defined as the threshold weight needed to initiate the failure of the formation. According to Abdulazeez et al. (2019), in very soft, unconsolidated formations, the threshold can have a negative value. This means that the rig can have an ROP without applying WOB but by using the jetting function of the bit. There's also a high limit called the foundering point beyond which the WOB starts to negatively influence the ROP.

Equation 12. Effect of drill bit diameter and WOB

$$f5 = \left[\frac{WOB_s}{OD_{bit}} - \left(\frac{WOB_s}{OD_{bit}} \right)_t}{\left(\frac{WOB_s}{OD_{bit}} \right)_N - \left(\frac{WOB_s}{OD_{bit}} \right)_t} \right]^{a5}$$

Where WOB_s is the surface measured WOB and $\left(\frac{WOB_s}{OD_{bit}}\right)_t$ is the threshold value. The following graph presents the relationship between the rate of penetration and the bit weight to illustrate the lower threshold value and the flounder point.

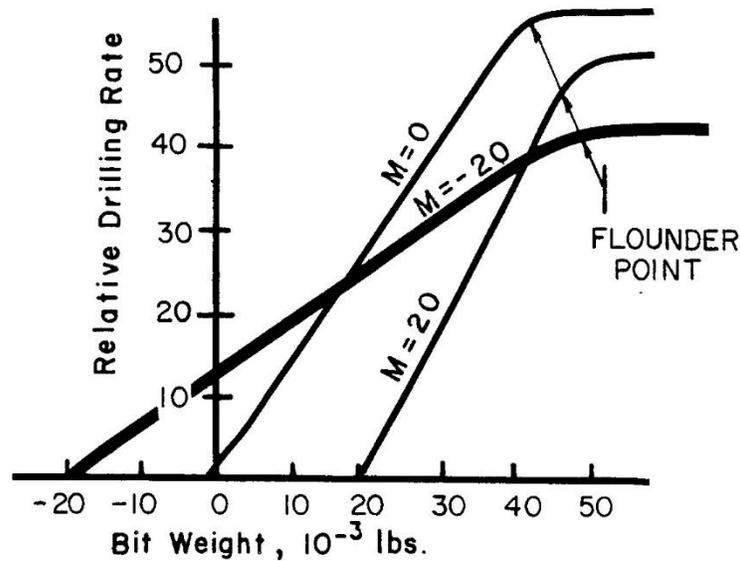


Figure 1. ROP function of WOB

Effect of rotary speed:

The ROP increases with increased RPM but with a negative derivative. This means that the increase in ROP is slower than the increase in RPM. This is due to a phenomenon called dwell time. Essentially, as the rotation speed increases, there will be less time for the WOB to be applied on each tooth. Thus, due to this incomplete application of weight the ROP will decrease.

Equation 13. Effect of rotation speed

$$f_6 = \left[\frac{RPM_s}{(RPM_s)_N} \right]^{a_6}$$

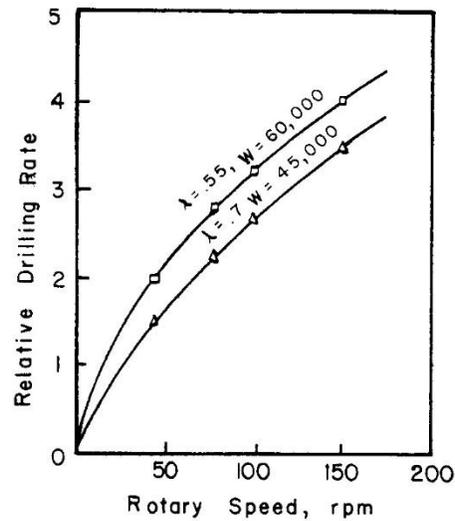


Figure 2. ROP versus Rotary speed

Effect of drill bit tooth wear:

This effect depends primarily on the bit type. With carbide insert bits, the ROP does vary greatly with tooth wear, while with milled tooth bits it has a much less significant decrease. Tooth wear is mainly affected by formation abrasiveness, tooth geometry, WOB, RPM and cleaning and cooling by the drilling mud.

Equation 14. Effect of tooth wear

$$f7 = e^{-a7h}$$

Where h is the dimensionless drill bit grading fractional tooth wear.

Effect of hydraulic:

Increased jet force implies better cleaning around bit teeth, easier avoidance of differential sticking and decrease of friction. This results in a higher ROP.

Equation 15. Effect of hydraulics

$$f8 = \left[\frac{Fj}{(Fj)_N} \right]^{a8}$$

Where F_j and $(F_j)_N$ are the hydraulic impact force and normalized hydraulic impact force applied beneath the drill bit respectively. F_j is given in lbf/nozzle as;

Equation 16. Hydraulic impact force

$$F_j = \frac{Q^2 \rho}{6023 \times A_n}$$

Where Q is the flow rate through one nozzle, ρ is the mud density and A_n is the area of one nozzle.

Below are listed the tables for the “a” factors and the Normalized values.

Table 1. Normalized values

Parameter	Value	Unit
(TVD)N	10000	ft
(EPP)N	9	ppg
(WOB/ODbit)N	4	klb/in
(F_j)N	1000	lbf
(RPMs)N	100	rpm

Table 2. Drillability Coefficients

Coefficient	Lower Boundary	Upper Boundary
A1	0.5	1.9
A2	0.000001	0.0005
A3	0.000001	0.0009
A4	0.000001	0.0001
A5	0.5	2
A6	0.4	1
A7	0.3	1.5

A8	0.3	0.6
----	-----	-----

The study performed by Kutas et al. (2015) was conducted on the Santos basin offshore Brazil. It's a pre-salt cluster structure in the middle of the Atlantic Ocean between South America and Africa. The predictive model used was the Oracle Crystal Ball Version 11.2.2 software that is an add-on to the Microsoft Excel 2010 spreadsheet software. The data set contained some 400 values of ROP surface measurements. A relative error of 0.457 was found using the following formula:

Equation 17. Relative mean error

$$Relative\ Error = \frac{\sum |(ROP_{field} - ROP_{calculated})|}{ROP_{field}}$$

The drillability coefficients used were as follows: a1=1.08355, a2=0.000001, a3=0.0009, a4=0.00001, a5=0.5, a6=0.651057, a7=0.3, a8=0.402447.

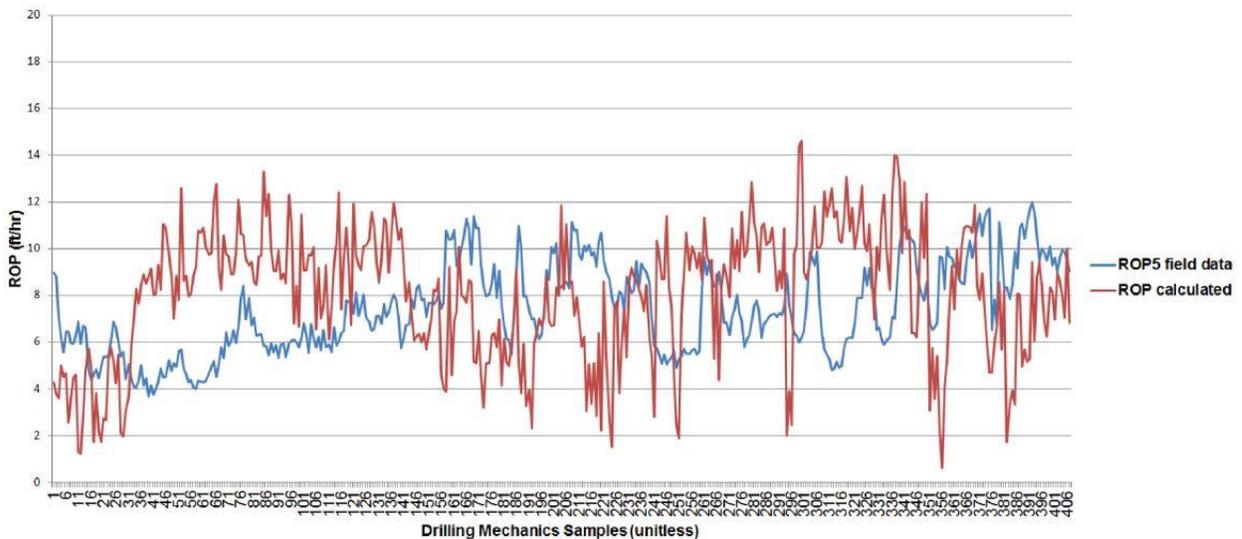


Figure 3. Simulation results with originally suggested drillability coefficients and normalization values

Having seen the results showed before, it was clear that a new methodology can be applied to acquire better results. Thus, an algorithm was developed in the aim of reaching the same objective - of evaluating an accurate value for ROP in real time - with a much-improved

accuracy. To achieve this objective a MATLAB code was developed that could make use of the Least Squares Method for regression and provide a new set of calculated drillability coefficients. For this to work, it was necessary to use the same set of normalized parameters and the same data set from the well. The set of 400 measurements was evaluated with an eleven points set for each of the coefficients. An error value of 0.048 was found with the drillability coefficients being as follows:

$$a1=1.9,$$

$$a2=0.000001,$$

$$a3=0.0009,$$

$$a4=0.0000505,$$

$$a5=0.5,$$

$$a6=1,$$

$$a7=0.3,$$

$$a8=0.6.$$

It is clear that with the use of sophisticated algorithms and regression techniques, along with improved computing power the results have improved by a significant margin. This was important for the scope of this paper as an accurate ROP is important for detecting an unwanted influx into the wellbore especially when the WIMS toolkit is dealing with theoretical situations and actual ROP values are not recorded on the field (as is the case here).

For the scope of this paper, this analysis covers all the interesting aspects of the problem of ROP evaluation. However, more research should be made to result in an even more accurate ROP. The research must include the effects of drill string elongations due to tensional stretching, WOB, flow induced hydraulic lift, ballooning, thermal expansion and some handful of other

parameters that affect the length of the drill string with varying degrees. As discussed before, the actual ROP measurements on field are taken as a function of drill string length, and when the expression of this last parameter is changing constantly, the expression of the ROP must be altered along with it. Normal regression and equation-based evaluations become inaccurate when these factors are put into play. To deal with this, most researchers in the field agree that the best way to deal with this issue is the use of state-of-the-art Artificial Neural Networks (ANN). Some ANN using Fuzzy Logic have achieved R^2 results of over 98% highlighting the degree of accuracy these methods have been able to accomplish. This, however, requires a lot more research and much more computing power than normal regression and is, therefore, not the objective of this paper.

Sustained Casing Pressure:

Definition

Ideally, a producing well should show pressure only in the production tubing. The gauges at the top of all other annular sections should show a value of zero. This is the case when the well is allowed to come to a steady state flowing condition and when the effect of pressurized fluids (due to heating by production fluids) is allowed to bleed off. If the bleed off valve is closed and the well is at the same steady state conditions, but the annular pressure is rising after a bleed off, then the casing is said to exhibit sustained casing pressure (SCP).

Therefore, an adequate definition of SCP would be given as per the Norwegian Oil and Gas Association: A pressure in any well annulus that is measurable at the wellhead and rebuilds when bled off, not caused solely by temperature fluctuations and not imposed by the operator. By the year 2011, SCP had been seen with 11,498 casing strings in over 8,122 wells as per the OLF. Around 90% of these cases are small enough to be completely contained by the casing strength. However, the remaining 10% can cause serious problems with respect to HSE as they present potential risks of losing hydrocarbon reserves and polluting aquifers and the environment. That is without mentioning the threat to human worker's life and the damage to the company's profit and reputation, should a major accident occur.

Causes

Whenever production rates in a well are significantly changed, a normal thermal expansion is expected to occur in the cement of the casing strings. These thermal effects can cause casing pressure increase which can be quickly bled to zero and will not persist once the production rate is returned to steady state. On the other hand, sustained casing pressure would most likely be attributed to one of the following three reasons: Tubing or casing leaks, poor primary cementing, damage to cement after setting.

Tubing and casing leaks

Such leaks can have a number of causes that may include poor thread connection, corrosion, erosion, thermal-stress cracking or mechanical ruptures. A quick method for identifying leaks is the application of a varying pressure in the inner string and monitoring of the pressure in the annular section. Should a similar trend be found in both media, a leak would make the most likely conclusion. In some special cases, a leak could be identified with routine production data.

Poor primary cementing

The most common problem faced during primary cementation is the invasion of fluids as the cement gels and loses its hydrostatic pressure. This kind of invasion can cause the formation of channels within the set cement. This influx of fluids can be a crossflow between two formations or a flow from a formation to the surface. The crossflow phenomenon increases greatly when the margin between pore pressure gradient and formation fracture gradient is allowed to decrease below 0.5 ppg according to the MMS (The US Minerals Management Services). In this case the well experiences loss of circulation which results in an influx of formation fluids. This is usually remediated on the spot with a squeeze cement at the casing seat and the liner top, but this remediation leaves the cement volume in between unrepaired. mud cake, that is not removed prior to cementing, in addition to borehole instability problems might cause the cement bond not to develop effectively and thus lead to a poor cement quality. These problems can be remediated by the use of appropriate cement composition and density.

Damage to primary cement

Mechanical impacts during tripping can shock the cement and cause the cement-casing bond to weaken. Changes in pressure and temperature which result in expansion and contraction of casing and cement can also weaken this bond, as the casing steel and the cement sheath are two different materials and thus react differently to changes in the environmental properties. In

addition, Portland cement is known to be brittle and susceptible to cracking when exposed to varying temperature and pressure loads.

Standards and regulations

US regulations

SCP is required to be eliminated completely according to the US Minerals Management Service (MMS). The MMS also grants “departures” from the normal regulations that permit the operation of wells with limited SCP problems. The company requesting a departure will have to present all the documents that attest to the need for operations with SCP along with diagnostic testing results. Only if these results were reviewed by the MMS and found compelling will the departure be granted. The MMS might also determine that immediate SCP removal is required or that it can be temporarily waived.

Norsok D-010

The Norwegian regulations specify min and max pressures for all annuli. Casing head pressures should be kept within these ranges to verify that the integrity of the well barriers is always kept. They also require continuous monitoring of the annuli and specify that if SCP is to be found, the only activity allowed on a given well is that which has the purpose of restoring its integrity.

Monitoring

The MMS specifies a series of diagnostic tests that have to be performed in order to detect SCP. These tests include fluid sample analysis, well logging, monitoring of fluid levels, pressure bleed-off performance, pressure testing, pressure build-up performance and wellhead maintenance. Each of these methods will be discussed below.

Fluid sampling and testing

The source of the influx can be deduced from the density of the given fluid. The density can be found by evaluating the weight and composition of the given fluid through a process of

sampling and testing. The process includes the matching of characteristics of known hydrocarbon formation fluids with those of the sampled fluid. A detailed gas composition or isomer analysis can then help determine whether the fluid is of deep or biogenic origin.

Well log analysis

Noise and temperature logs provide information as to the fluid entry and exit points behind the casing. Oxygen Activation logs are used to detect water channels. A cement bond log can evaluate the quality of the cement in eight directions with a very fine vertical resolution. It can also map gas channels. Thermal Decay Time (TDT) logs can detect gas accumulation in the annular space.

Fluid level monitoring

Using conventional acoustic tests, some operators reported success in accurately identifying fluid levels in the production casing. However, routine analysis of annular fluid levels may not be as simple due to gas cut fluids, the 90 degree turns in the wellhead and the geometry of the annular section itself. If possible, fluid level monitoring can help identify the presence and location of leaks in the tubing.

Pressure bleed-down performance

This operation is normally performed through a half inch needle valve. It can yield information about the annular volume, gas content and channel or micro-annulus flow capacity. The bleed-off flow rate can be measured and when matched to the time curve the total bled volume can be found. The casing pressure is also recorded (every hour as per MMS) and a data acquisition system or chart recorder can also be used. This will provide the maximum information required to identify communication between strings.

Pressure testing

It is usually performed after the SCP has been bled down. By knowing the first indication of surface pressure and the density of the fluid left in the annulus, the deeper zones contributing

to the SCP problem can be identified. This method assumes that all the fluid left in the annulus can be replaced by gas.

Pressure build-up performance

The rate of pressure build can provide information on the location of the leak too, but most importantly it can help identify the size of the leak. It is especially important when the SCP cannot be bled down to zero in a conventional method using a half inch needle valve. The pressures on all strings should be monitored and recorded.

Wellhead maintenance

Communication between casing strings can sometimes be through a point in the wellhead. In this case, periodic application of grease to the wellhead seals can potentially eliminate the problem.

Acceptance criteria

Leak rate criteria

The objective is to identify a rate below which a release will not result in unacceptable consequences and the probability of escalation is as low as reasonably possible (ALARP). API RP 14B indicates acceptance criteria of 15 scf/min (42 Sm³/min) for gas and 0.4 l/min for liquids. It may sometimes be possible to set criteria that exceed the ones resulting from the API RP 14B standards if it can be proven that no hydrocarbon is present in the source of influx.

Annulus pressure criteria

The objective is to determine a maximum allowable annular surface pressure or more commonly referred to as MAASP. It is a pressure at which the probability of failure is as low as practicable and normal operation of the wellhead is allowed. A maximum operational pressure (MOP) can also be indicated. This refers to a value lower than the MAASP that has the goal of reducing the probability of exceeding the MAASP and providing appropriate response time to

manage pressures approaching these values. The MOP also allows normal trouble-free operation of the well.

SCP prevention through well design and operational considerations

In general, when prevention of any problem is required the research starts with the original design of the system. This is also the case with sustained casing pressure, as the most effective way to prevent SCP is through the initial well construction process where the potential for SCP is identified and addressed. It is crucial that formations with potential for influx and annuli pressure buildup be identified and isolated. These also include permeable or fracture-prone formations. Such isolation can be achieved through the use of setting agents like cement or external packers.

Casing setting depths should be considered with regards to formation strength so it could withstand any influx from deeper formations during the life of the well. The potential loads and environments that the equipment will be exposed to during the working life cycle of the well should be identified. This applies to equipment installed during initial construction or later in the life of the well (saddles, patches, plugs...).

Parameters that are subsequent to well construction should be monitored and evaluated during operation to ensure the operation of the well within the limits of its design. Should the well be operated outside these limits, failures and degradations that lead to SCP and other undesired conditions will result. The relevant parameters that should be monitored and maintained include flow rates, pressures, temperatures, fluid compositions (especially water cut), solid content and content of corrosive compounds like H₂S, CO₂ and O₂. Appropriate alarm levels and stop criteria should be put in place to be able to detect and manage these parameters outside the design limits.

Special care should be given to degradation mechanisms such as corrosion and erosion. These can be monitored through the use of probes and downhole inspection calipers.

When considerable changes are made to the functionality of a well (for example when a well is transformed from production to injection), a full design review should be performed. The review should assess the suitability of the well for the new service. It should be proven that the well design is adequate to support the required pressure differential imposed by such a shift. In addition, equipment limitations should be identified along with strength of cap rock and formation and permeability of shallower formations that may be exposed to the new pressure. This should reduce the risk of out of zone injection which could later cause SCP not just in the injection well but also with other wells in the vicinity of the originally affected well.

Procedures should be developed to avoid unnecessary loading on the well in order to prevent degradation and failures resulting in SCP or other undesired conditions. Activities where these procedures are of importance are startup and shut in of the wells and situations where the well is exposed to significant changes in pressure and temperature over a relatively short period of time.

Remediation

A well workover is considered the main remediation method for SCP, as it is designed to block the leak path causing the problem. This can be simple in cases where the leak is in the tubing string, a down-hole packer, or in the wellhead. These workovers, however, can be extremely expensive and in some cases unjustified (for example if the well is nearing the end of its production life cycle). When the repairs have to be conducted outside of the production casing, the workover becomes technically difficult and expensive. For example, an operator spent 20 million USD over 13 months trying to eliminate SCP using block and circulation squeezes, and still some of the wells were reporting SCP at the surface.

Because of this high cost – low effectiveness duality, operators usually find themselves looking for other solutions to their SCP problems. Some of these solutions are:

1. Periodic bleeding of excessive pressure.
2. Partial bleeding followed by lubricating in a higher density fluid.
3. Insertion of a small diameter tubing into the annulus exhibiting SCP to allow shallow annular circulation.

It is important to note that some operators find the procedure of periodic bleed-off to worsen the sustained level of pressure. On the other hand, other operators indicate that periodic bleeding seems to temporarily limit the severity of the SCP problem.

Periodic bleed off

The bled fluid is usually either gas, foam or light liquid (<0.9 ppg). The removal of these fluids from the well can lead to reduced hydrostatic pressure and cause a new influx into the annulus. Some operators prefer bleeding to some pressure greater than atmospheric, in contrast to the MMS standard of bleeding to zero. If the wells are cemented to the surface, remediation methods are largely limited. The volume of accumulated fluid will be very small and the best method to mitigate the problem is by continuous bleed-off. If the high-pressure zone feeding the annulus is itself also small, this method will eventually lead to the elimination of SCP altogether.

Lubrication in weighted brine or mud

The main part of this method is to replace the bled gas or liquid with high density brine such as zinc bromide. The objective of this procedure is to provide hydrostatic pressure in the annulus and limit the influx of fluids. A stair-step replacement procedure is used where small volumes of fluid are bled and replaced by the zinc bromide brine. The results of this procedure are mixed at best: on the one hand, several operators have reported reduction of casing pressure while, on the other hand, it has been observed that pressures can also increase. It is also possible

to inject mud which will provide some added benefits since the solids in the mud can help plug the fractures present in the cement. Mud is also less corrosive and less toxic than the formulated brine. However, it is more difficult to inject.

Circulation of weighted mud or brine

When the well is not cemented to the surface, a small diameter flexible tubing can be inserted into the annulus to allow circulation up to 1000 ft of depth. This could allow the displacement of lighter fluids from the annulus and their replacement with heavier brine or mud.

Annular intervention

Internal casing patches can be used to repair a leak. In the past, operators used to inject cement or resin to plug the flow path to the surface. This approach may satisfy regulatory requirements by elimination of surface pressure but would definitely mask any increasing pressure below the plug.

Recommendations

All the previously mentioned methods can be used to varying degrees of success or failure and according to the specific circumstances of each scenario. Pumping operations can involve circulation, annular injection and pumping without annular injectivity. Such operations can involve placement of a setting agent and/or a heavy liquid in the annuli. In these applications the equipment, formation and overall well configuration located below the depth of the setting agent should be assessed to ensure that the source will be isolated properly over time and that a single failure will not lead to escalation and unacceptable consequences. Heavy liquids are used to hydrostatically control the source of the SCP by creating hydrostatic overbalance. Such applications are usually preferred when the source of the SCP is shallow permeable zones or when the leak resulting in SCP is one directional only. If such applications are used for permeable zones the placement of heavy liquid should be combined with placement of fluid loss

control material in front of the heavy liquid. Both differential pressure variations with time and with depth should be evaluated and appropriate pressure limits should be defined before the operation commences. The main well intervention methods currently in use can have some risks that include:

- Pressure control: working safely in the live annulus.
- Stuck pipe: often uncertain or unknown restrictions and clearance.
- Maximum operational depths: limited by restrictions, clearance and annulus configuration, risk of buckling and lockup.
- Pumping rates and pressures: low clearance necessitates small pipe, which results in high pressures and low rates for pumping operations.

Integration with a Well Integrity Management Software Solution

Ideally a WIMS (Well Integrity Management System) software solution should be able to provide clear and standardized classification of barrier status. This can be achieved only if the WIMS toolkit is combined with a practical application of international and local well integrity standards and procedures. Some of the key elements needed for achieving functional well integrity are:

1. Wells register: a single document listing all wells worldwide, regardless of location, function or status.
2. Well construction envelope: a standardized approach to determining operating limits.
3. Well failure matrix: pre-defined dispensation periods for the full range of failure scenarios.
4. Leak rate criteria: identification and adoption of robust leak acceptance standards based on industry best practices.

5. Well integrity software: selection of a software tool suitable for adoption and compatible with other company software solutions.

The key functions of a WIMS would be to:

1. Collect and analyze well production data and compare them with well construction data to confirm that from an operational standpoint, the well was working within its design characteristics.
2. Allow the standardization of valve acceptance testing criteria and test frequency. This would form part of a well failure matrix looking at different barrier components and the impact they might each have for well status.
3. Provide reference documents such as API guidelines that would be stored within the system.
4. Provide a simple but rugged paper trail to be used by well examiners in the annual audit process.

The main challenge of such a system would be to acquire a relevant database of well integrity failures. Once obtained, these failures can be reverse engineered to identify which barriers have had failures. Then, through rigorous analysis and application of acceptability norms a standard can be developed for use as a comparison tool to produce failure likelihood.

Once these systems are in place, a functional algorithm can be developed to analyze the status of each barrier in a well. The result would be an adequate well barrier schematic file providing the drawing representing the well in its current configuration along with all installed equipment and a clear delimitation of primary and secondary barriers. In addition, well information should be shown, and the integrity status of each barrier should be provided in a side table. The software can also provide map view of many wells in a given field (or global view) so

that failure patterns can be clearly identified. The program should also have the ability to provide qualitative risk analysis of the failures and a historical overview of past events.

Risk Assessment

Risk Methodology

A risk assessment that tackles aspects of well integrity will never be intended as a quantitative model that can produce a concrete numerical value for the risk level. It is a qualitative assessment methodology that evaluates the risk of well barrier failures. The unreliability of quantitative risk assessment is mostly due to the lack of historic data pertaining to the number and type of well barrier failures. Operators have seldom tried to record failure data and if they have, they would never accept to share such critical information. This is why, the application of a qualitative methodology, that relies on the past experiences and knowledge of the workers, is imperative in this case. However, for this assessment to be efficient and accurate, the participation of people with sufficient experience in different fields and disciplines and with varying background knowledge is essential.

Typically, the risk is evaluated using a risk matrix, with the severity of the risk being the product of the damage and the probability. Chastain & Dethlefs (2011), provide the main objectives of a qualitative risk analysis methodology for the well integrity field as the following:

- Follow a standard risk assessment method in the most consistent way to enable comparisons of risk levels between various failure modes.
- Assess well barrier failures in a qualitative way and provide a risk ranking for each well barrier failure mode in each type of well analyzed.
- Provide recommendations for mitigation scenarios for each well barrier failure mode that is considered unacceptable.
- Provide a full report that can be used as reference when managing well operations on a routine basis.

They also go on to provide a detailed step by step guide to performing the qualitative risk assessment as follows:

1. Establish the single point of contact (SPOC).
2. Establish the information to be gained such as number and types of wells and specific deliverables.
3. Confirm the methodology to be used and the data requirements.
4. Provide a description for each of the well types.
5. Define and list the well barrier failure modes to be evaluated.
6. Determine the likelihood and consequence of each well barrier failure mode scenario.
7. Record suggestions and recommendations for mitigating the risks.
8. Compute the risk ranking for each scenario.
9. Each failure mode must be evaluated completely before moving to the next one. The process must be repeated until all scenarios have been evaluated.
10. Compile the findings into a single document that can be used as reference for future work.

Data Preparation

- **Inventory of well types:** wells may have similar designs or similar services. These can be considered as one type of wells for easier evaluation. To group wells, consideration must be given to some different aspects of a well: location, process fluids, well construction, artificial lift methods, environmental sensitivity and others. Wells may also be categorized with respect to their design: number of casing strings. Wells can also be classified according to location: onshore, offshore, subsea, urban area. The well type categories can be as follows: free flowing producers, gas lifted producers, ESP producers,

gas injectors, water injectors, sour service. The goal is to enable the vast majority of wells to be captured in at least one of the categories.

- **Standard well:** the definition of a standard well for each category may not encompass all the wells within this category due to the wide variety of specifications for each considered parameter. This is why a conservative model would work best to showcase the worst-case scenario for each well type. Individual wells can later be compared to the standard well description and adjustments to the failure modes can be applied.
- **Well barrier schematics:** it is essential to provide a fully detailed well barrier schematic that is specific for each individual well to be considered in the assessment. A standard diagram may also be provided as a general rule for the category that may simplify complex diagrams. This is essential to help visualize potential failure paths and provide accurate and effective outcomes.
- **List of failure modes:** a comprehensive list of failure modes must be compiled for each well type.
- **Policies and operating procedures:** these are the documentations relating to the well operations that may include: valve testing, maintenance, diagnostics, corrosion, erosion, well testing and logistics management.
- **Regulations:** documentations that regulate different aspects of the well like testing, maintenance and other issues should be available.
- **List of definition and acronyms:** this provides all the workers that will handle the well data with the same level of understanding and knowledge about well specifics.

Failure modes

The failure mode is the description of a specific mechanical failure of a well barrier. Each failure mode will be evaluated for each well type, one at a time. Multiple failures at the same time are not considered as this would require a large number of permutations to evaluate. However, similar level failures can be grouped for analysis. The failure analysis follows the “what if?” methodology, meaning that the team analyzing the failure modes will have to ask the following question every time the consequences of a given failure mode are put in perspective: what if this barrier fails?

Most failure modes are universal for all wells in a given type. However, they will largely change in consequences and likelihoods which means in risk levels. Chastain & Dethlefs (2011), include the following example of well failures for the given diagram:

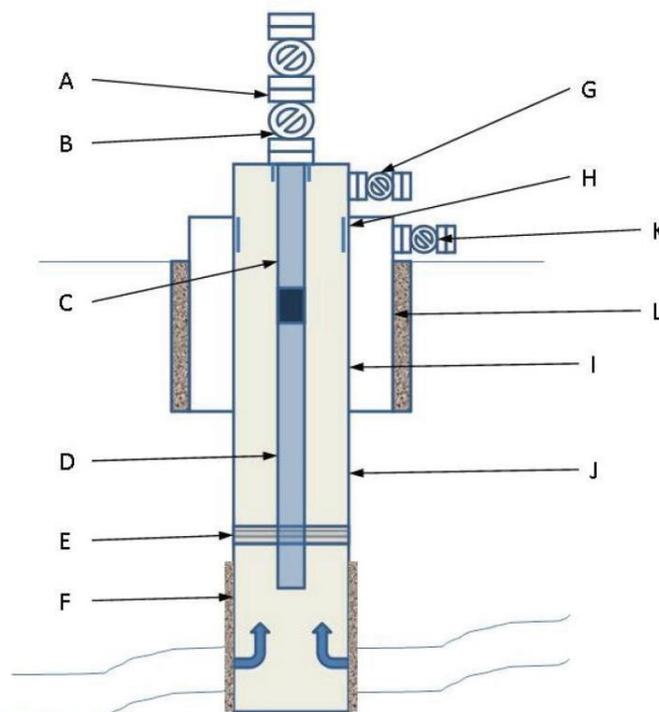


Figure 4. Well Diagram subject of Risk Assessment

Failure modes for the example include:

- A: external leak above the lower master valve
- B: external leak below the lower master valve
- C: tubing leak above the subsurface safety valve
- D: tubing leak below the subsurface safety valve
- E: packer leak
- F: production casing leak below packer
- G: annular valve leak
- H: production casing pack off leak
- I: production casing leak above surface casing shoe
- J: production casing leak below surface casing shoe
- K: B annulus valve leak
- L: surface casing leak

Assessment

After assembling a list of all possible well barrier failures, the assessment may begin using the risk matrix methodology. This can be done when the assessing team follows the given steps:

- Describe, in detail, the most likely cause for the given failure mode: details should be sufficient to allow any reader to understand the most likely reason for this failure. For example, if the failure mode is “tubing leak”, the failure cause would read: “tubing leak due to CO₂ internal corrosion”. This should also be backed by the statistics of each failure mode proving that this cause for failure is the most probable one.
- List the remaining functional well barriers and/or the administrative controls in place: to apply this step the assessing team must refer to the well barrier schematics, to determine

if there are any barriers remaining that may prevent a release. For example, for a tubing leak, the remaining barriers might be the Production Casing or the Surface Casing. On the other hand, for the failure mode “External Master Valve Leak”, there will be no more barriers available. The remaining barriers must be registered and documented.

- List the consequences of the single barrier failure: describe the outcome of each well barrier failure mode, under the assumption that all other well barriers are in place and functioning normally. The outcome should be realistic, plausible and credible. Active controls and safeguards like safety devices or devices intended to prevent the failure should not be considered when determining the final outcome. For example, a gas detection device used for shutting down a well must be considered as deactivated. The description should be clear enough to explain how the failure can impact each of the consequence categories used. For example, if the failure is tubing leak, the description would read: “release of fluids or pressure from tubing into annulus A. Production casing designed to contain fluids at maximum expected pressure and resist corrosion for 3 to 4 months”.
- Determine the likelihood and consequence severity of each failure: the severity of each consequence must be determined and given a rank from 1 (lowest) to 5 (highest) depending on the category that the consequence affects, safety, environment, asset damage, business interruption, public image and public notification). When determining the likelihood of each failure mode, the assessing team must consider all active or passive barriers to be present and fully functional. This means that the gas detection device mentioned previously, must be considered to be working properly. The likelihood is determined by using the previous experience and judgement of the engineers in question.

The likelihood decreases as the number and effectiveness of barriers increase. Likelihood is also ranked from 1 to 5 in the following manner; 1-improbable, 2-remote, 3-rare, 4-probable, 5-frequent.

- Determine the risk ranking of each category assessed, using the risk matrix: the risk matrix is formed by two axes; the horizontal one usually giving the consequence severity and the vertical one giving the likelihood of the failure. The risk ranking is given as the product of the consequence and likelihood. This means that the risk rank will be a given as a number between 1 and 25 and divided into the following categories; 1 to 4-low risk (no mitigation required), 5 to 10-medium risk (no mitigation required where controls can be verified as functional, ALARP should be evaluated), 11 to 16-significant (manage risk using prevention and mitigation with priority), 17 to 25-high (manage risk using prevention and mitigation with highest priority).

Table 3. Risk Matrix

		Consequence				
		1	2	3	4	5
Likelihood	5	5	10	15	20	25
	4	4	8	12	16	20
	3	3	6	9	12	15
	2	2	4	6	8	10
	1	1	2	3	4	5

CHAPTER 3. DEVELOPMENT OF THE WIMS TOOLKIT

Development of the WIMS toolkit

Choice of development platform

The objectives of the toolkit can be categorized in the following manner:

1. Provide accurate, complex and extensive calculations, estimations and cross-references with low error and latency in real time.
2. Be available for access instantaneously, at any location in the world and to different personnel at the same time.
3. Be easily configurable, and intuitive to accommodate for different levels of knowledge and professionalism.
4. Integrate well with already installed software solutions and measurement devices and procedures.

As this application would have to be written in code from the ground up, different coding languages and development environments were researched in order to find the most adequate solution to perform the operation. Of the considered options, Python was found to be the coding language best suited to be at the core of the application as it allowed flexibility both in transforming theoretical algorithms into code and in integrating well with online platforms, databases, excel spreadsheets and other tools that would have to be used.

To create the interface for the app, a mixture of HTML5 and Cascade Style Sheets coding was used and linked up with Python algorithms through the use of the FLASK web application development environment. For storage and database backup, the MICROSOFT SQL format was used. MATLAB was used for sensitivity analysis of different parameters during the development of the models used in the theoretical wells.

All in all, five different coding languages were used for the development of this project across four different platforms and countless functions and modules libraries.

Choice of design parameters to be considered

The design parameters are the ones that the drilling engineer specifies when doing his studies for the well. They are specified in the research and design phase and can be inserted directly into the WIMS toolkit during this stage (after creating a new well profile) or can be imported from other software solutions that the engineering team uses.

The engineer will be the only person allowed to change the design parameters for a well as this operation will require special access and will notify the operator to perform a Management Of Change (MOC) operation before the changes can take place. Other tools can be integrated to help with this last operation. The design parameters will include the following:

A. Formation data that include:

- a. A complete and detailed identification of the different layers that the well trajectory is expected to cross.
- b. The thickness of each layer.
- c. The type of rock of each layer.
- d. The bulk, effective and pore density of each layer.
- e. The fracture and pore gradients variations with depth in each rock layer.

B. Casing design program that includes:

- a. Number of casing strings.
- b. Dimensions of each casing string.
- c. Dry linear weight of each casing string.
- d. Shoe depth of each casing.
- e. Cement height at each casing shoe.

C. Drill String program that includes:

- a. Number of drill pipes, heavy weight drill pipes, drill collars and other components used.
 - b. Length and dimensions of each type of components used.
 - c. Dry linear weight of each type of component.
 - d. Grade of steel used.
 - e. Density of the used steel.
- D. Drill Bit data:
- a. Outside diameter
 - b. Nozzle number and sizes
 - c. Bit type and dullness factor.
- E. Drilling fluid program that includes:
- a. Drilling fluid type.
 - b. Drilling fluid rheology.
 - c. Drilling fluid parameters like plastic viscosity, yield point, Herschel-Buckley coefficients, the Young modulus.
 - d. Mud density programmed for each depth interval.

Some constraints will be added to the design factors before finalization, when the rig is up and running. These will be parameters like the air gap length, weight of the top drive system and traveling block used, the pump characteristics (SPM, piston stroke length and diameter), in addition to some constraints imposed by the driller or the supervisor that will be discussed and decided upon with the drilling engineer like the maximum Weight On Bit (WOB) and expected Rate of Penetration (ROP) for each formation type.

Choice of monitored parameters to be considered

The monitored parameters are the continuously changing values that must be monitored or measured at every interval of the drilling or well control operations. These can be measured pressures, loads or flow rates. In addition to these, the results of the different tests conducted must be included. Like before, these can also be pressures, loads and flow rates, but they can also be volumes, log data and other. Some parameters inputted as a result of performed tests are:

- A. Pressure of Leak off tests.
- B. Formation integrity test results.
- C. MWD, LWD test results.
- D. Inflow test results for different components.

The continuously measured parameters will be the following:

- A. Weight On Hook (WOH) or Hook Load (HL).
- B. Pressures at the casing head (SICP) and the tubing head (SIDPP).
- C. Pressure at the different hydraulic equipment at the surface (BOP accumulator, manifold and annular BOP pressures).
- D. Percentage of return flow at the flapper valve.
- E. Volume of mud in the tanks.

These parameters are the ones used in this version of the toolkit for the purpose of demonstrating its functionality. However, when deployed in a complete package and under the requirements of a customer, the toolkit can be configured to include any additional parameters the customer requires.

Development of the algorithms

As previously mentioned, the algorithms were coded in the Python language. This allows the toolkit to perform the same number of processes at the same level of complexity as other programs coded in other languages (like Java or C++), but in much shorter time. This is due to the simplicity and flexibility of the Python language. In addition, Python integrates extremely well with other languages and platforms such as HTML5, CSS and SQL Server in order to perform various operations like web application design and database backup.

The developed algorithms included different types of calculations, approximations and smart iterations in order to provide a resulting value that can be compared to a measured parameter or a design factor set a priori. Another type of algorithms, consists of just inputting data received from the different measurements and comparing this data to previously set limits (for example, the maximum working pressure at the manifold).

Mud properties and hydraulic program

The first and most essential algorithm to develop is the one controlling the variables of the hydraulic circuit. It is one of the longest algorithms especially that it's dependent on the dimensions of the drill string components and the shape of the flow cross section. This means that the formulas used should be varied for circular and annular sections. It also means that for each type of drill string component a different set of values should be calculated.

1. The first required step is to calculate the pump flow rate. The user will have a choice of two types of pumps; duplex and triplex. This refers to the number of piston/cylinder arrangements each pump has. For each option, the user will be able to input the characteristics of the pump; the liner inner diameter, the piston stroke length and the design working strokes per minute.

2. The second step is to calculate the pressure drop in the surface circuit using the mud density, viscosity and flow rate in addition to the Young Modulus (E) provided for different dimensions of surface pipelines in the following tables.

Table 4. Different categories of surface circuit dimensions

I	Stand Pipe	Length 40 ft	Internal Diameter 3"	III	Stand Pipe	Length 45 ft	Internal Diameter 4"
	Rotary Hose	Length 40 ft	Internal Diameter 2"		Rotary Hose	Length 55 ft	Internal Diameter 3"
	Swivel	Length 4 ft	Internal Diameter 2"		Swivel	Length 5 ft	Internal Diameter 2 1/2"
	Kelly	Length 40 ft	Internal Diameter 2 1/4"		Kelly	Length 40 ft	Internal Diameter 3 1/4"
II	Stand Pipe	Length 40 ft	Internal Diameter 3 1/2"	IV	Stand Pipe	Length 45 ft	Internal Diameter 4"
	Rotary Hose	Length 55 ft	Internal Diameter 2 1/2"		Rotary Hose	Length 55 ft	Internal Diameter 3"
	Swivel	Length 5 ft	Internal Diameter 2 1/2"		Swivel	Length 6 ft	Internal Diameter 3"
	Kelly	Length 40 ft	Internal Diameter 3 1/4"		Kelly	Length 40 ft	Internal Diameter 4"

Table 5. Young modulus for the different categories

Type of Surface Circuit	E value	
	Technical System	British System
I	8.790×10^{-6}	2.525×10^{-4}
II	3.298×10^{-6}	9.619×10^{-5}
III	1.829×10^{-6}	5.335×10^{-5}
IV	1.427×10^{-6}	4.163×10^{-5}

3. The third step is to calculate the flow cross section area. The user having inserted all the required types and dimensions of the drill string components and the casings, the algorithm will be able to calculate the given area for each cross section easily.
4. Once the area and the flow rate are known, the velocity can be easily obtained.
5. This step is a very delicate one. It involves the calculation of the different rheological parameters that govern the properties of the fluid used. The user will have a choice of three different types of drilling fluid rheology; Bingham plastic, Pseudo-plastic, Power Law and Newtonian fluid. These types are not used with the same frequency and the choice of which type to use is highly dependent on the drilling engineer's choices, the geology constraints and the company preferences. For the case study of this paper, a Bingham Plastic model was used. The calculation involves using the mud yield point, plastic viscosity, density, flow velocity and dimensions of the section in order to calculate the Bingham number (Bi), the Bingham function ($f(Bi)$) and the Reynolds number (Re).
6. At this point the first output can be given by the algorithm with regards to the flow regime in each section. The limit between laminar and turbulent flow is taken at $Re=2100$. As per common knowledge, it is preferable to have turbulent flow in the circular sections (inside the drill string) and laminar flow in the annular sections (between the drill string and open hole or casing). The turbulent flow in the inners is needed to provide enough velocity for the flow of the mud. The laminar flow is essential to protect the mud cake, to allow for more accurate measurements and logs and to decrease the pressure drop as much as possible. The algorithm will return a warning message in case an unwanted regime is established in a given section.

7. The algorithm will then be able to calculate the pressure drop in the given section, whether the flow regime is the adequate one or not.

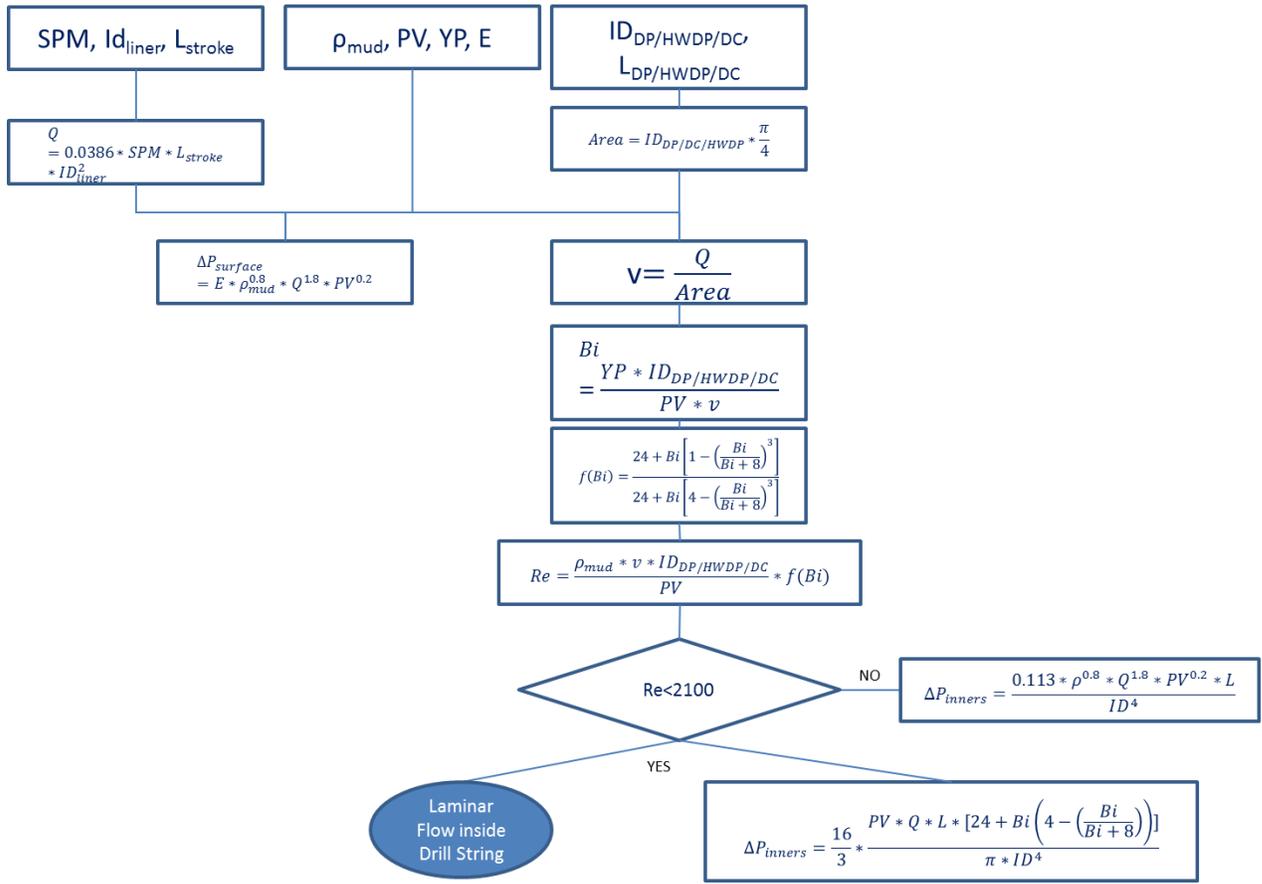


Figure 5. Hydraulic Algorithm in circular section and surface circuit

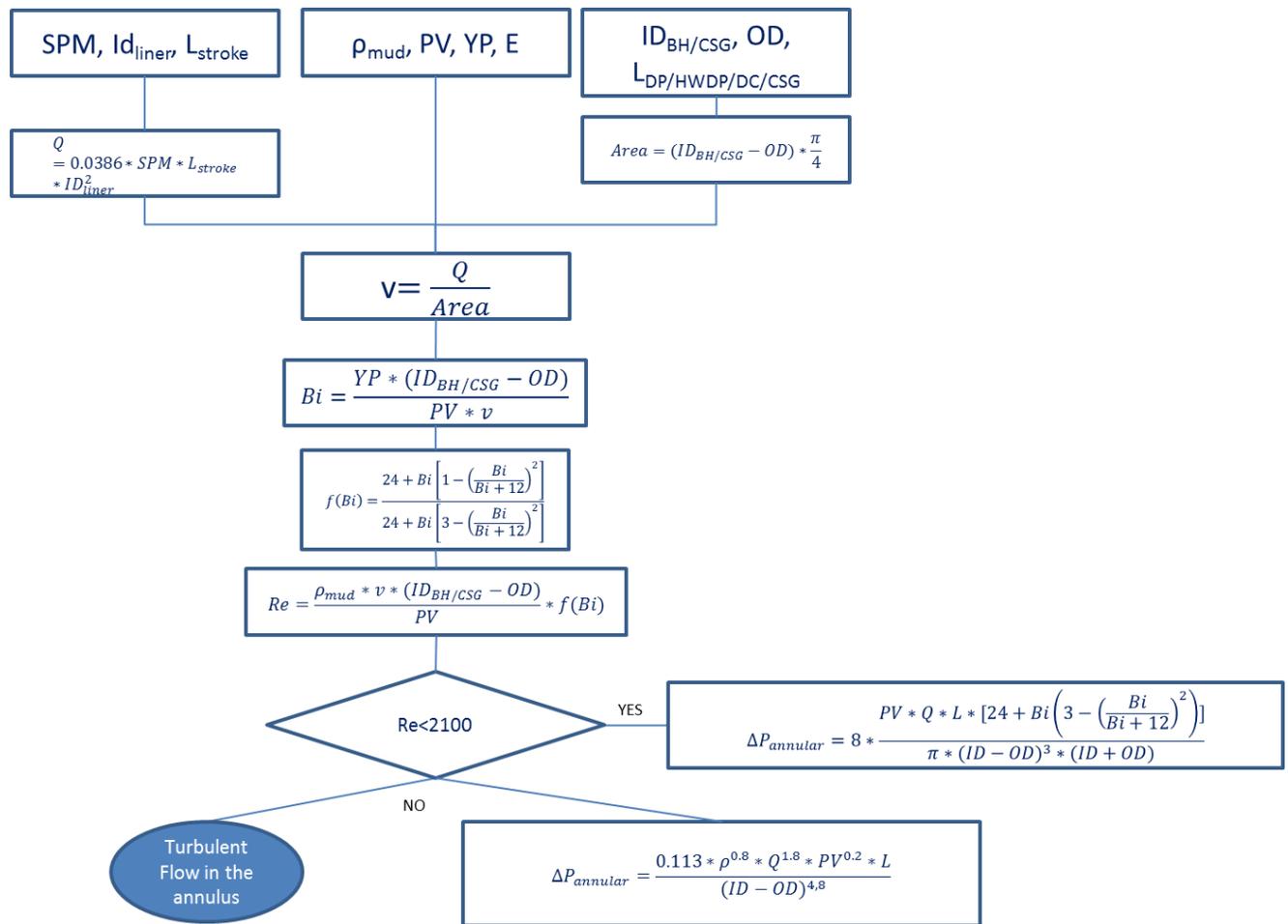


Figure 6. Hydraulic Algorithm for annular section

8. Then, it is important to calculate the pressure drop through the drilling bit. The user will be able to enter the diameter of each bit nozzle, for up to six nozzles. The total area of the bit outlet will be calculated and consequently, the flow velocity will be obtained. Once this is done the pressure drop can be calculated using the mud density, flow velocity, the WOB and the K1 and K2 factors which will be pre-specified for each bit. The WOB calculation will be tackled in the following sections.
9. The last step of the hydraulic algorithm is to calculate the stand pipe pressure, by adding all the previously calculated pressure drops.

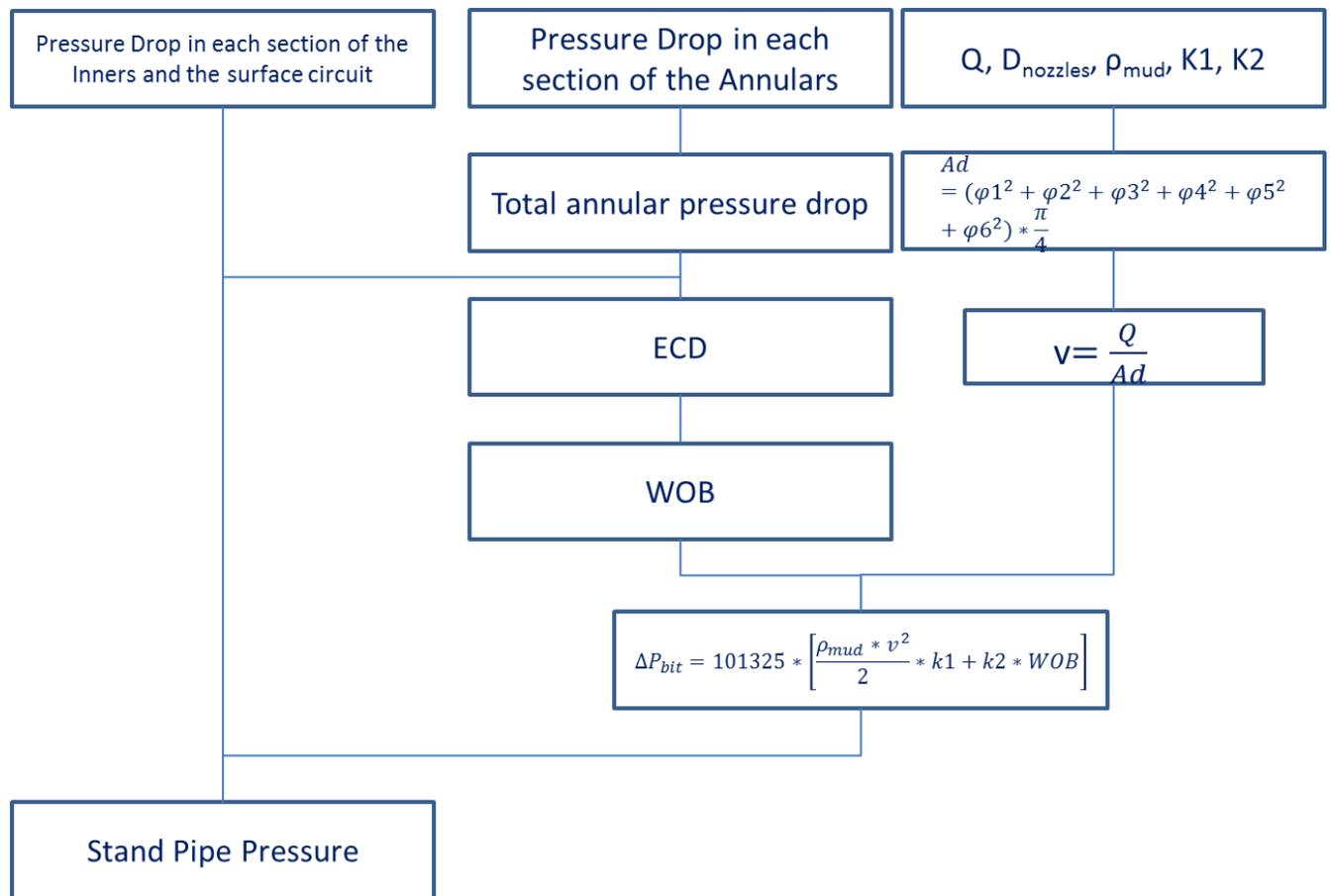


Figure 7. Standpipe Pressure Algorithm

10. Having calculated the Standpipe Pressure, many system checks can be conducted for well control operations. These are only activated in case the well is put under the condition of well control; meaning that a gas has entered the well bore, the well has been shut in and the procedures of removing the gas pillow have started. The different conditions are summarized in the following diagram. The measurement intervals can be tailored according to the user's needs. In this case they are fixed at 1 second between each two intervals, but since the algorithm is running on a web app, meaning the computation is done offsite, this time can be decreased to a few milliseconds.

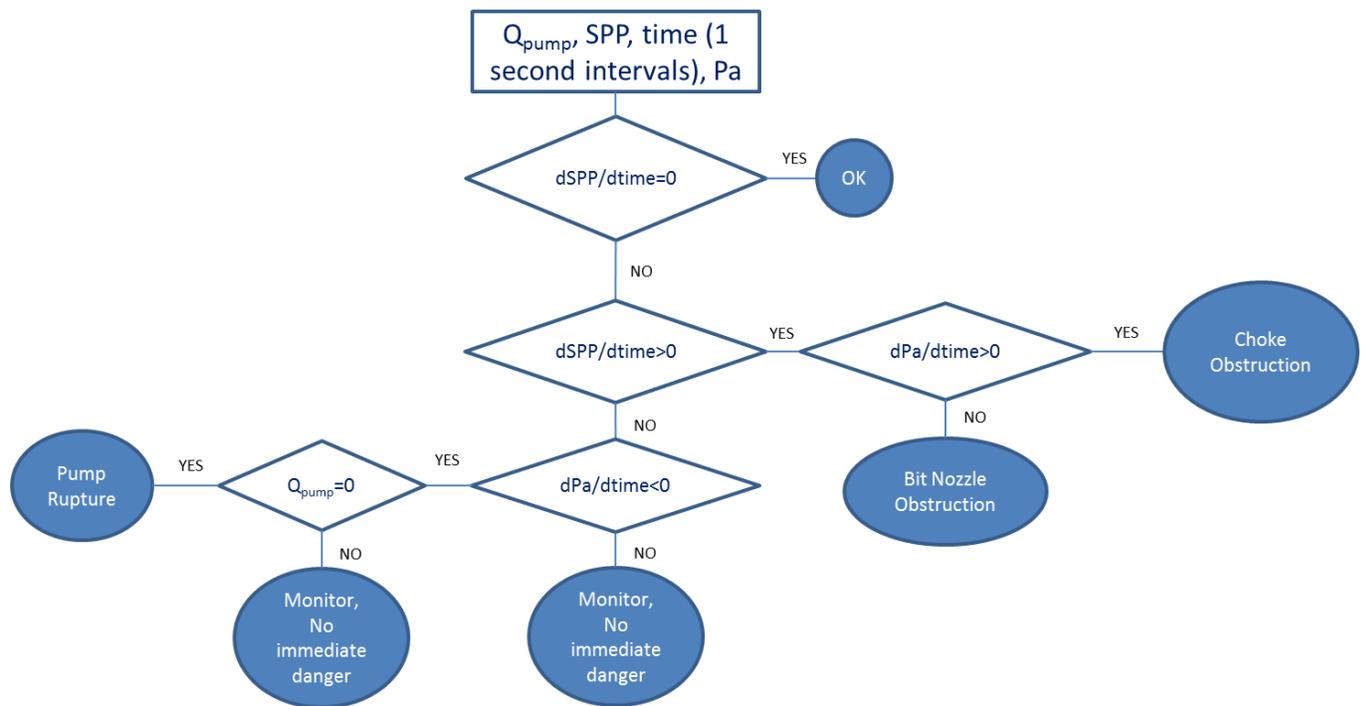


Figure 8. Well Control Troubleshooting Algorithm

Weight On Bit and Drill String design

The main target of the drill string program is to allow the bit to reach its final destination while maintaining the integrity of the drill string components. Since the drill pipes are the most fragile components of the drill string, their integrity is the main constraint that the drilling engineer will have to face when designing a drill string program and indicating a specific WOB. Essentially, the objective of the design is to provide a composition of the drill string that will allow it to reach the desired total depth and coupling this composition with an adequate WOB that will keep the drill pipes in tension. Should the drill pipes be put into compression many problems can occur; buckling of the drill string, breakage of the drill pipes and more. All of which will lead to a loss of well control.

The main target then is to keep the neutral point of the solicitation diagram in the bottom hole assembly; at the worst case, on the pin of the last drill pipe. This means roughly, that the WOB should be equal to or lower than the weight of the bottom hole assembly. If it is not the

case, the algorithm will provide a warning message telling the driller that the drill pipes are in compression.

The WOB cannot be measured directly. It is calculated by subtracting the Weight On Hook (WOH) or Hook Load (HL), which can be measured, from the drill string, top drive and drill string cumulative weights. Here, the buoyancy effects of the mud on the drill string are taken into consideration. The elongations of the drill string can also be added as constraints here, but this would make the calculations very complex for a relatively small change.

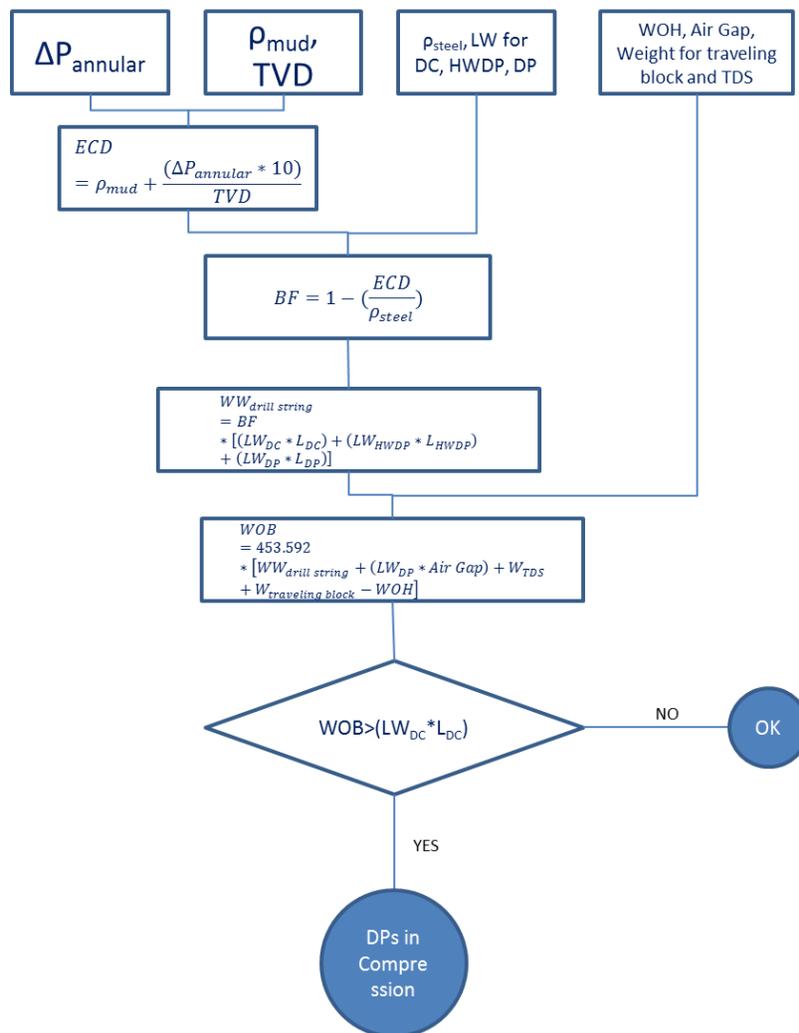


Figure 9. WOB Algorithm

Leak Off Test and MAASP

A leak off test (LOT) is essential in every well drilling operation. It is the most useful way for calculating the formation fracture gradient at the shoe of the last cemented casing. According to the Schlumberger oilfield glossary it is define as “a test to determine the strength or fracture pressure of the open formation, usually conducted immediately after drilling below a new casing shoe”. The procedure for performing a LOT is well known in the oilfield. It consists first of drilling through the shoe of the last cemented casing and drilling out the formation a few feet under the shoe. Then the drill string should be spaced out and the well should be shut in by closing the annular Blow Out Preventer. Then the test mud is gradually pumped through the choke line in small amounts. The drill pipe pressure and casing pressure are recorded for each volume of mud pumped. These pressures will increase with time. Below is a graph showing a qualitative LOT measurement.

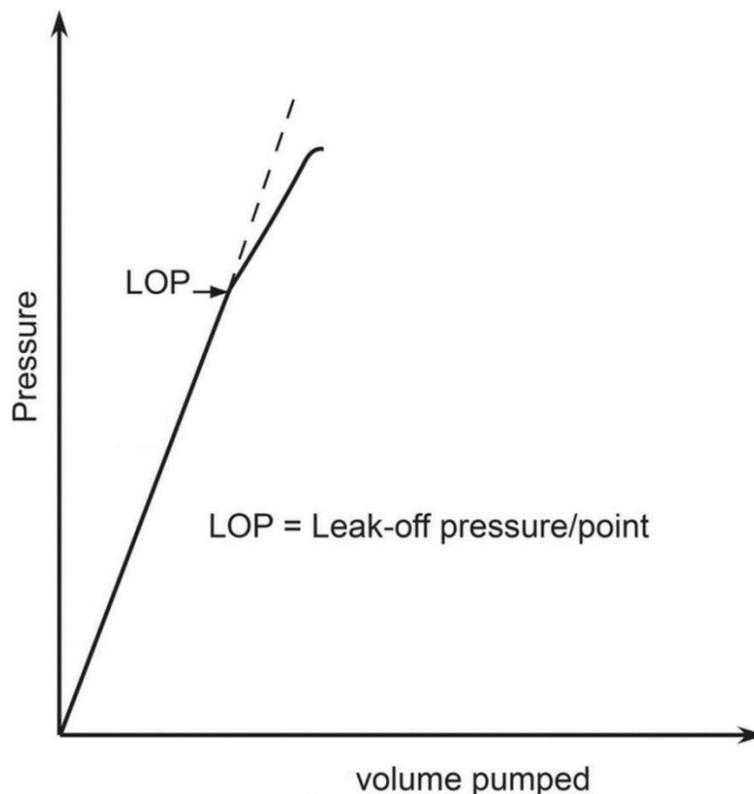


Figure 10. Qualitative representation of a LOT

The casing pressure should increase linearly with the pumped mud volume. Once the measurements leave the linear trend, the pressure will have exceeded the formation pressure and mud leak off into the formation occurs. The mud will move into the formation through permeable paths in the rock. The last pressure recorded just before the trend change is called the leak off pressure/point (LOP) and will be used in most of the following calculations.

The MAASP or Maximum Allowable Annular Surface Pressure or Pressure differential at the choke (ΔP_{ch}), is a safety margin used when designing the mud program. It allows to maintain the annular pressure at a value that will not cause the formation to fracture. This is very important during well control and the circulation of a kick out of the well since the pressure at the casing tends to increase during the migration of the gas upwards in the well. It is not advisable to calculate the dynamic MAASP since the equivalent mud density during circulation is always changing due to the presence of the gas, its migration and the expansion phenomenon that occurs as the gas migrates.

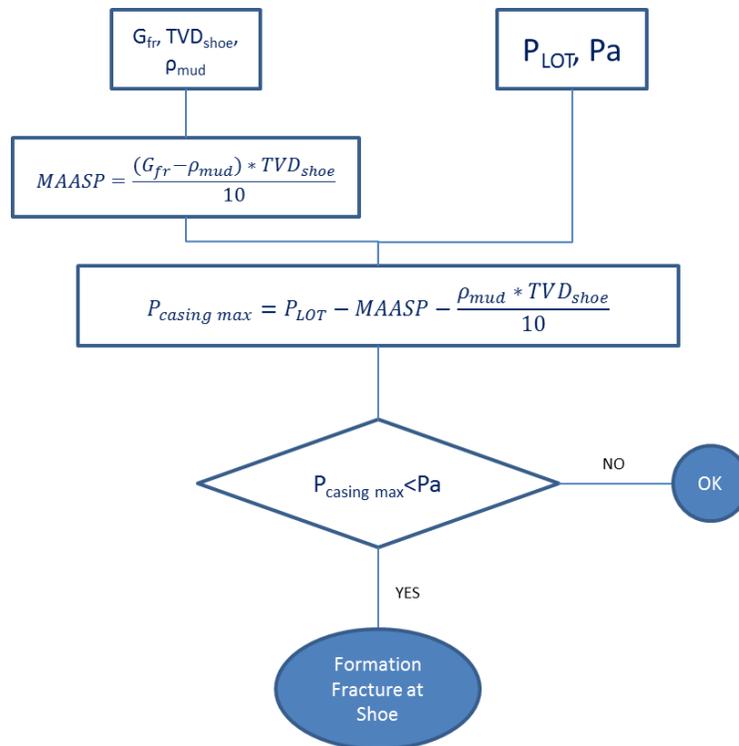


Figure 11. Algorithm for MAASP calculation

The MAASP is a very important parameter, often misinterpreted by the workers. During the Deepwater Horizon incident, it was proven that a misinterpretation of the LOT and therefore the MAASP has contributed in a large part to the catastrophic events that followed. As the algorithm diagram above shows, should the MAASP be exceeded the formation under the last cemented casing shoe will be fractured.

In some cases, when the annular pressure is increasing fast, the workers will tend to try to decrease the pressure with such a speed that the control of the gas is lost. In other cases, the MAASP is misinterpreted and the casing pressure is maintained at a lower value which will also cause the loss of well control and will allow for an additional kick into the well which will result in catastrophic consequences.

The use of such an algorithm will bypass the humane role in this specific situation and will allow more accurate measurements, predictions and interpretations during well control. It

will also significantly decrease the time needed for reacting to such an event. Finally, this will constitute a perfect tool for reviewing the causes of an accident should such a thing occur.

Kick Tolerance

Kick tolerance is an essential parameter that needs to be taken into consideration whenever designing a new well or whenever, during a drilling operation, there is an influx of fluid into the well bore and a well control process is required.

Often this parameter is skipped when preparing for well operations, which results in a large number of failures relating to well integrity. These failures do not just occur during the drilling operation but are also, in large part, a consequence of the drilling engineer's neglect of the importance of this parameter.

Engineers and drillers often choose to bypass the calculations relating to kick tolerance as this term is still mostly unclear to many workers in the industry. This is due to the wide variety of different definitions given to kick tolerance in different areas around the world or even different stages of the well life cycle. In fact, kick tolerance can be defined as a pressure, a gradient, a mud density increase or a volume. Each definition is, of course, better suited to a different phase of development or a different working environment. For the purpose of this paper, however, the best definition of kick tolerance would be to consider it a volume.

This means that kick tolerance can be defined as the maximum influx that can be circulated out from a wellbore with a constant bottom hole method, without fracturing the formation at its weakest point. The weakest point usually refers to the open hole section right under the last cemented casing shoe. In other words, the kick tolerance is capability of the wellbore to withstand the state of pressure generated during well control operations without fracturing the formation.

When kick tolerance is fully addressed, its inclusion in the design phase can have large impacts especially during the casing program design. Normally, to select the casing setting depths, a few parameters should be taken into consideration: lithology, over-pressurized formations, shallow gases, lost circulation and troublesome zones, directional well profile and regulations. If one is to address kick tolerance as well, it would mean that the drilling engineer would have to consider well control procedures when designing the casing setting depths as well.

There are two important parameters that should be calculated when designing a casing program including the kick tolerance; the MAASP which was already discussed in the previous section and the drilling balance. The drilling balance can be defined as the difference between the pressure due to the drilling mud and that of the formation at a given depth. It can give indications about the risks of kick occurrence and the effect of penetration rates and has the following formula:

Equation 18. Drilling Balance

$$\Delta P_{ab} = \frac{(\rho_{mud} - G_p) \times H}{10}$$

Where G_p (kg/l) is the pore gradient, H (m) is the true vertical depth at a given point and ρ_{mud} (kg/l) is the density of the drilling mud used. The MAASP and the drilling balance provide the maximum and minimum boundaries for the mud density while designing the hydraulic program. They also provide guidelines for casing design and setting depths.

This leads to the final evaluation of the kick tolerance, that should be calculated at every shoe cementation process and every time there is an influx of fluids into the wellbore and well control procedures need to be undertaken. The next algorithm provides the calculation steps used for the evaluation of kick tolerance.

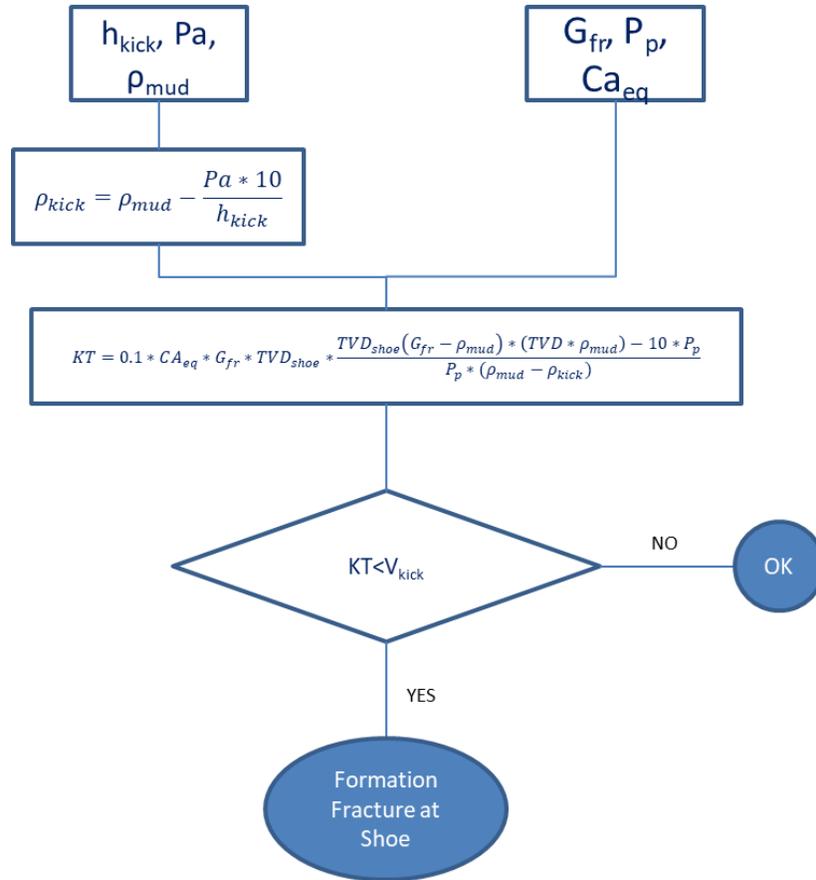


Figure 12. Algorithm for the evaluation of kick tolerance

This algorithm, however, must be accompanied by a system of iteration to identify the size and spread of the kick in the wellbore. Taking into consideration the different sizes, depths and shapes of each section of the wellbore, one can accurately identify the height and average cross section areas of the wellbore parts where the kick has spread.

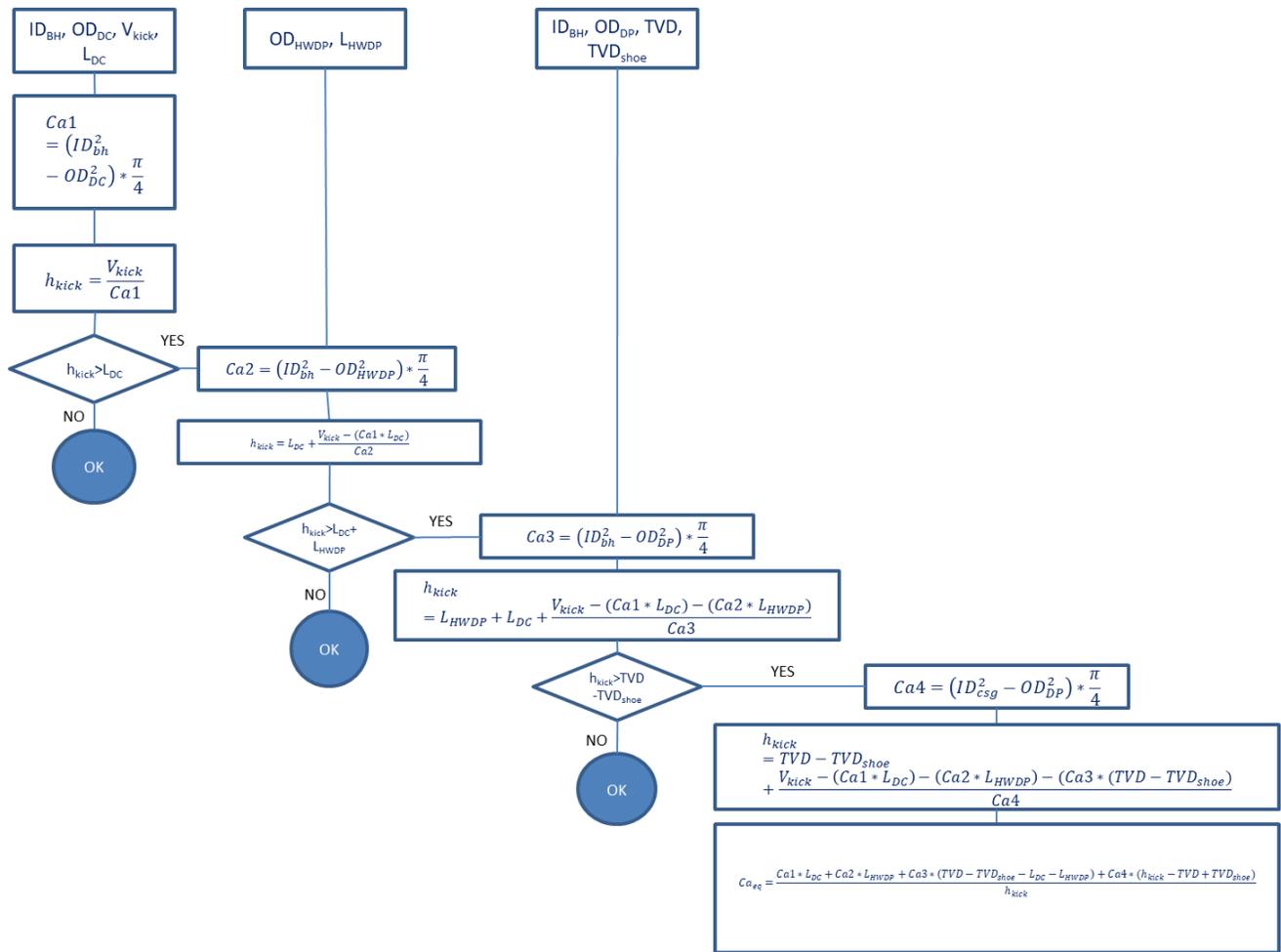


Figure 13. Evaluation of the spread of the kick in the wellbore

These two algorithms combined can indicate the to the driller instantaneously whether the volume of fluid that has entered the wellbore can be safely circulated outside using the traditional well control methods that maintain a constant bottom hole pressure. It can also indicate the height and position of the kick.

When used during the design phase the kick tolerance algorithm can provide the engineer designing the casing program with an additional safety margin that can be applied to the casing setting depths which will allow safe operations of the well in all major cases as the following graph shows.

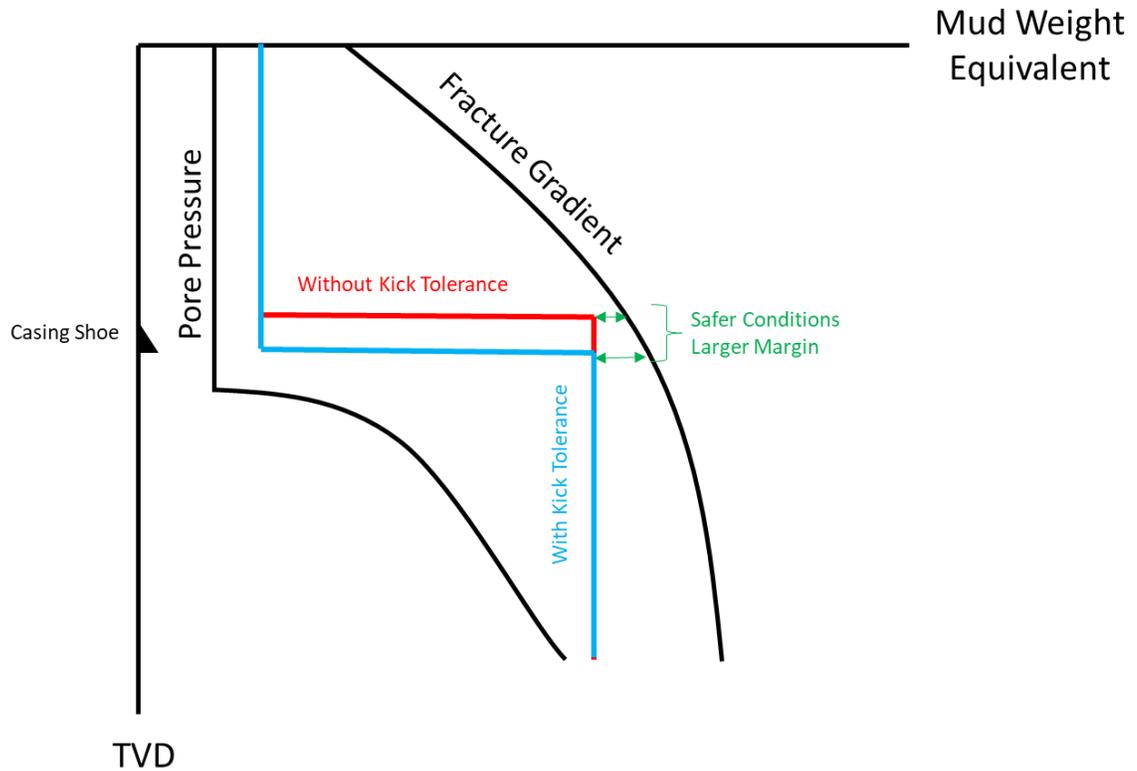


Figure 14. Casing setting depths with and without consideration of kick tolerance

Well Control Parameters

Well control is the collection of principles and procedures used by the drilling crew in order to maintain control over the well during normal operations and in case of formation fluid influx into the wellbore. The principles of well control require the application of the two barriers principle. During drilling operations, the barriers can be clearly identified, classified and maintained. The primary barrier to be considered is the mud column that provides the hydrostatic pressure that opposes the formation pressure.

This means that the main target of well control is to maintain this primary barrier, by maintaining a minimum value for the bottom hole pressure (BHP). The BHP is the sum of the hydrostatic pressure exerted by the drilling mud and the annular pressure drop caused by the

circulation of the mud in the hydraulic circuit. A simple Boolean operation can allow the identification of whether the primary barrier is lost or not.

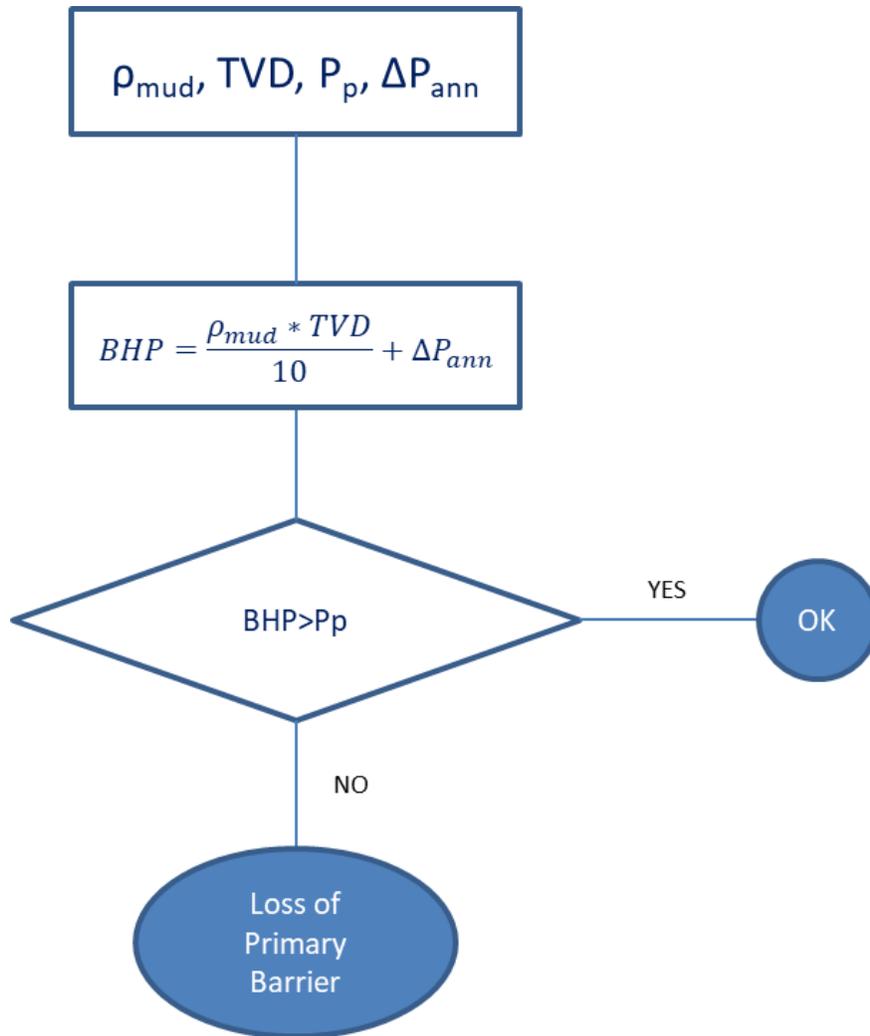


Figure 15. Algorithm for calculation of bottom hole pressure

The annular pressure losses are provided by the calculations previously discussed in the hydraulic program section.

Once the primary barrier is lost a kick may occur. The kick is identified by what is called a drilling break. The fastest way to identify a drilling break is by monitoring the ROP; should the rate of penetration be increasing with time when the driller has not intentionally proceeded to increasing it, this means there's a break of the drilling activity. The algorithm will then be able to

stop the drilling activity and shut down the mud pumps. After the circulation has been stopped, the return flows should also drop to zero, but if it doesn't, this verifies the possibility of a kick.

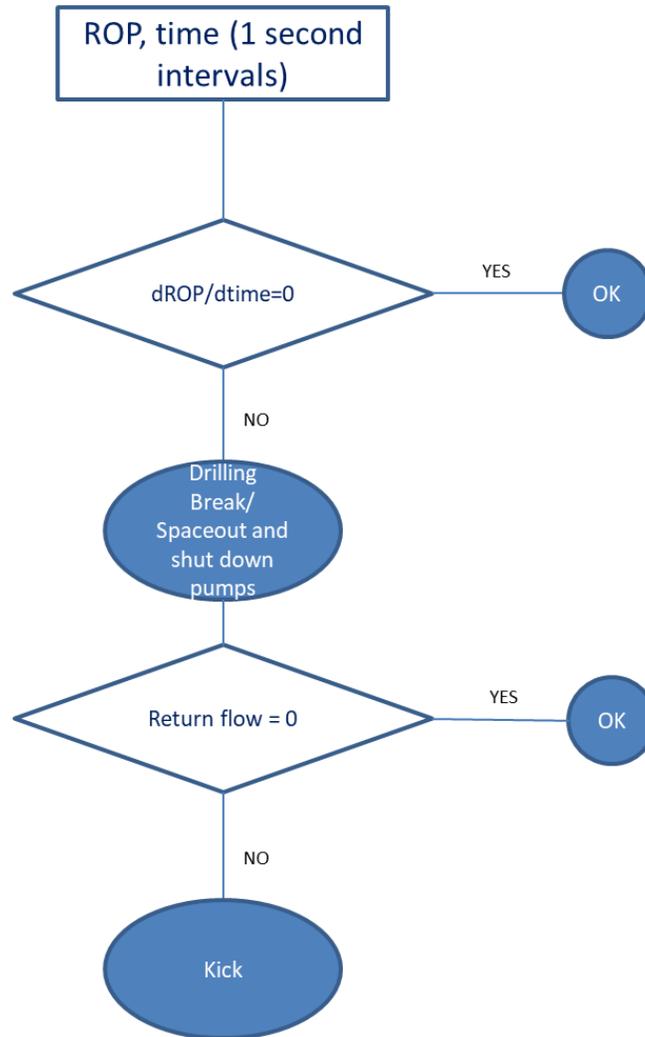


Figure 16. Drilling break and kick evaluation

In normal conditions, the driller would have to notice the increase in the rate of penetration on his own. An alarm can help, of course, but the driller will have to register the change, stop the operation and monitor the return flow rate. All this operation will require close to a minute according to the trials on the IWCF WELL CONTROL SIMULATOR. The algorithm will be able to evaluate the possibility of a kick in a faster way; in this case, a few

seconds. This has the benefit of shortening the time needed to shut in the well and starting the well control procedures, which in turn leads to a lower influx volume.

Once the kick occurs and the well control procedures are under way, the main barriers opposing the reservoir pressure are the secondary barriers. In the case of the drilling process, the most important secondary barrier is the BOP or Blow Out Preventer. Being a mechanical device, composed of many different elements that may all fail, it is essential to keep close control on all the different problems that may occur. A failure in the BOP will also mean there is no more barriers between the well and the outside and a blowout would be certain. The following algorithm monitors all the possible failures that may occur in the BOP column and its consequent equipment.

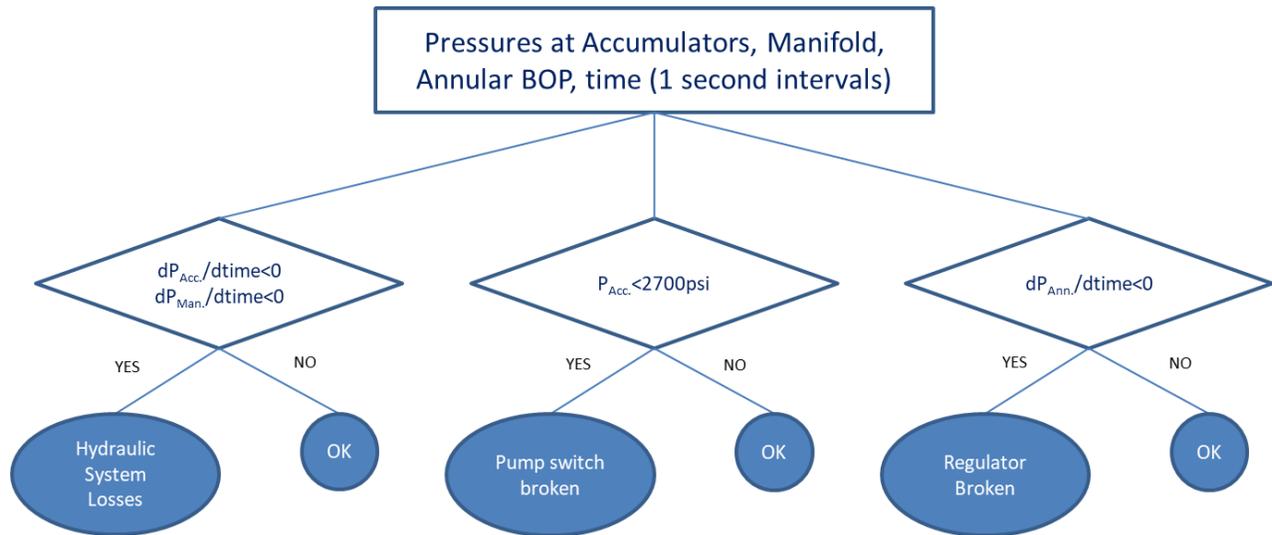


Figure 17. BOP failure monitoring

The very short time interval for measurement also provides fast response and lower possibility of major accidents.

Other problems

Problems may occur also in previously set casing strings. These usually require extensive repairs and the rig in question would probably be substituted for a workover rig. The following algorithms do not provide any calculations, but with special monitoring, some problems can be identified easily.

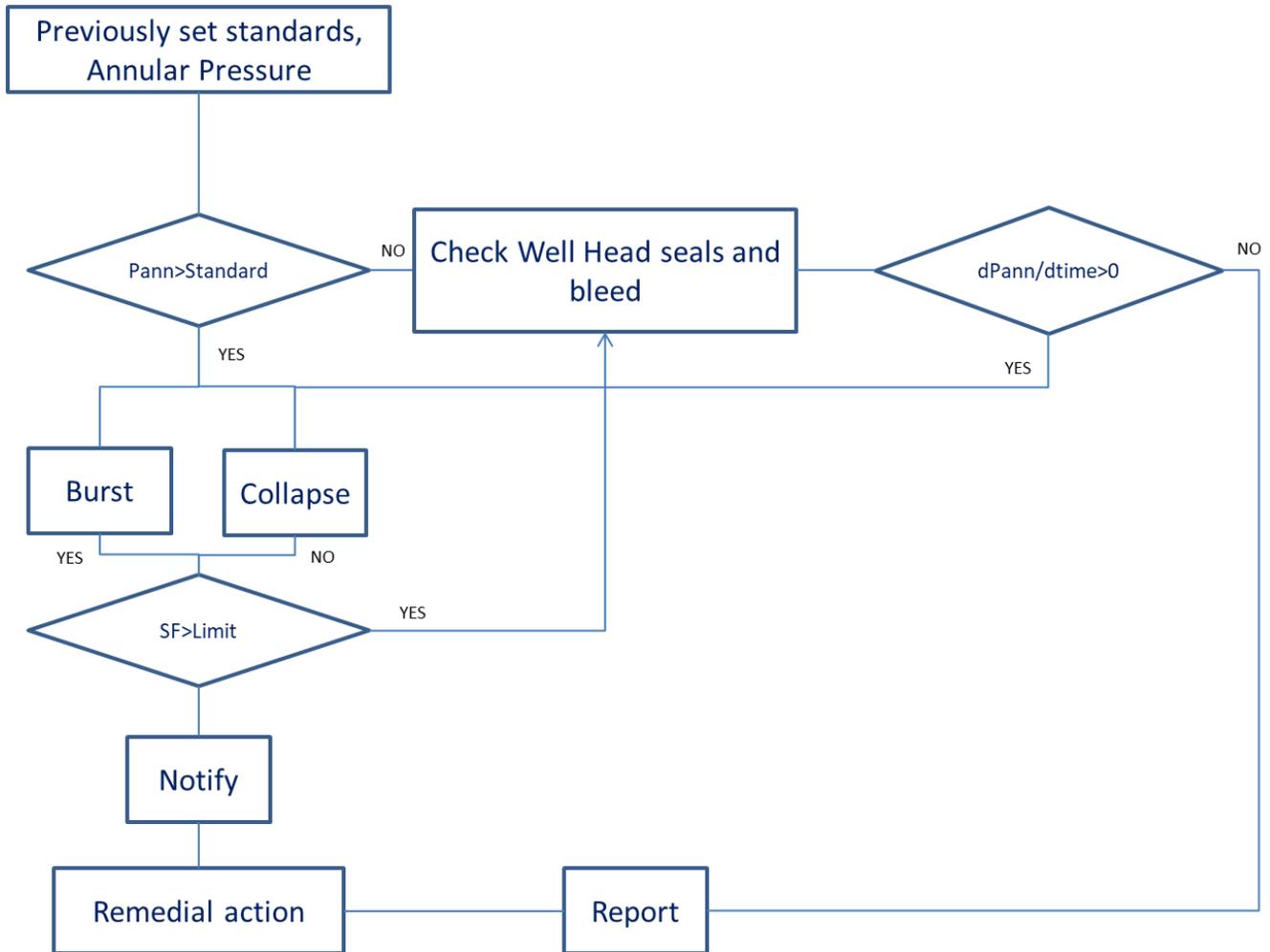


Figure 18. Annular pressure variations

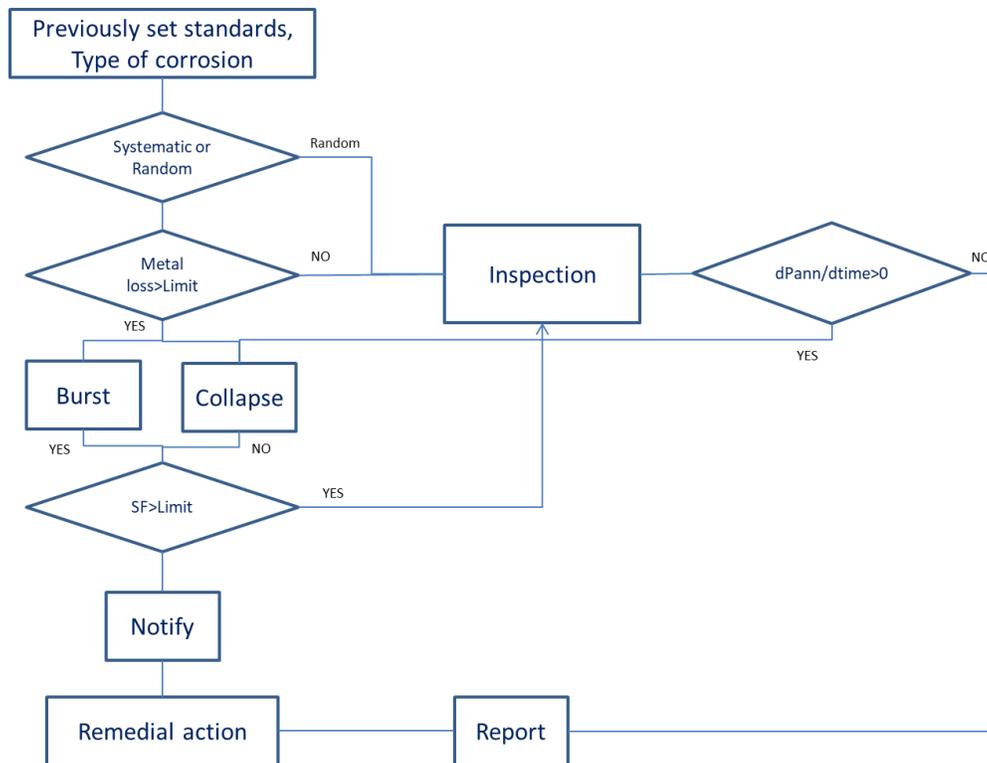


Figure 19. Corrosion Control

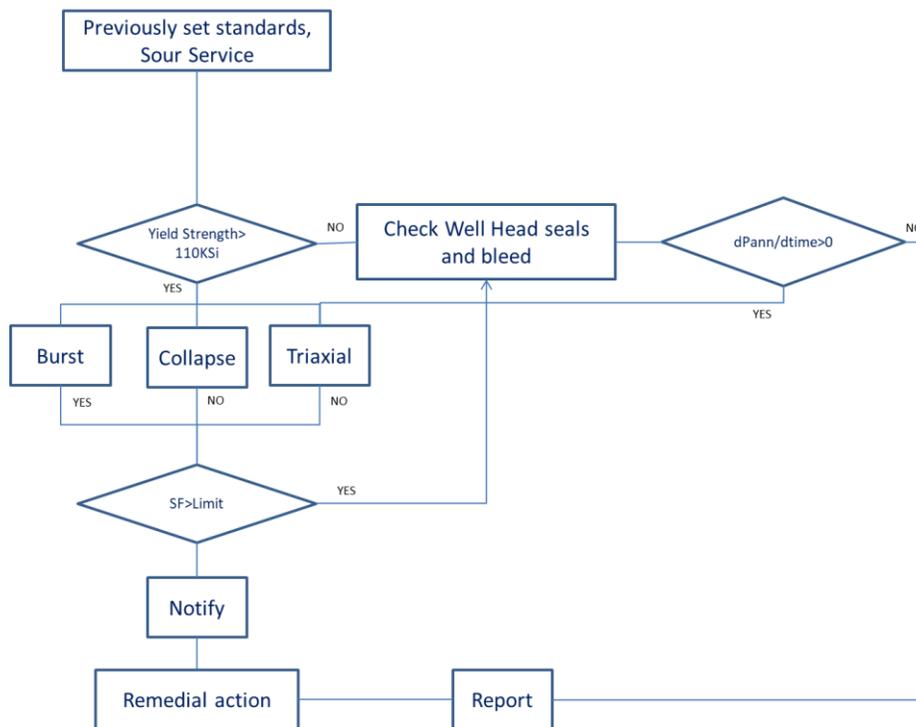


Figure 20. Sour Service

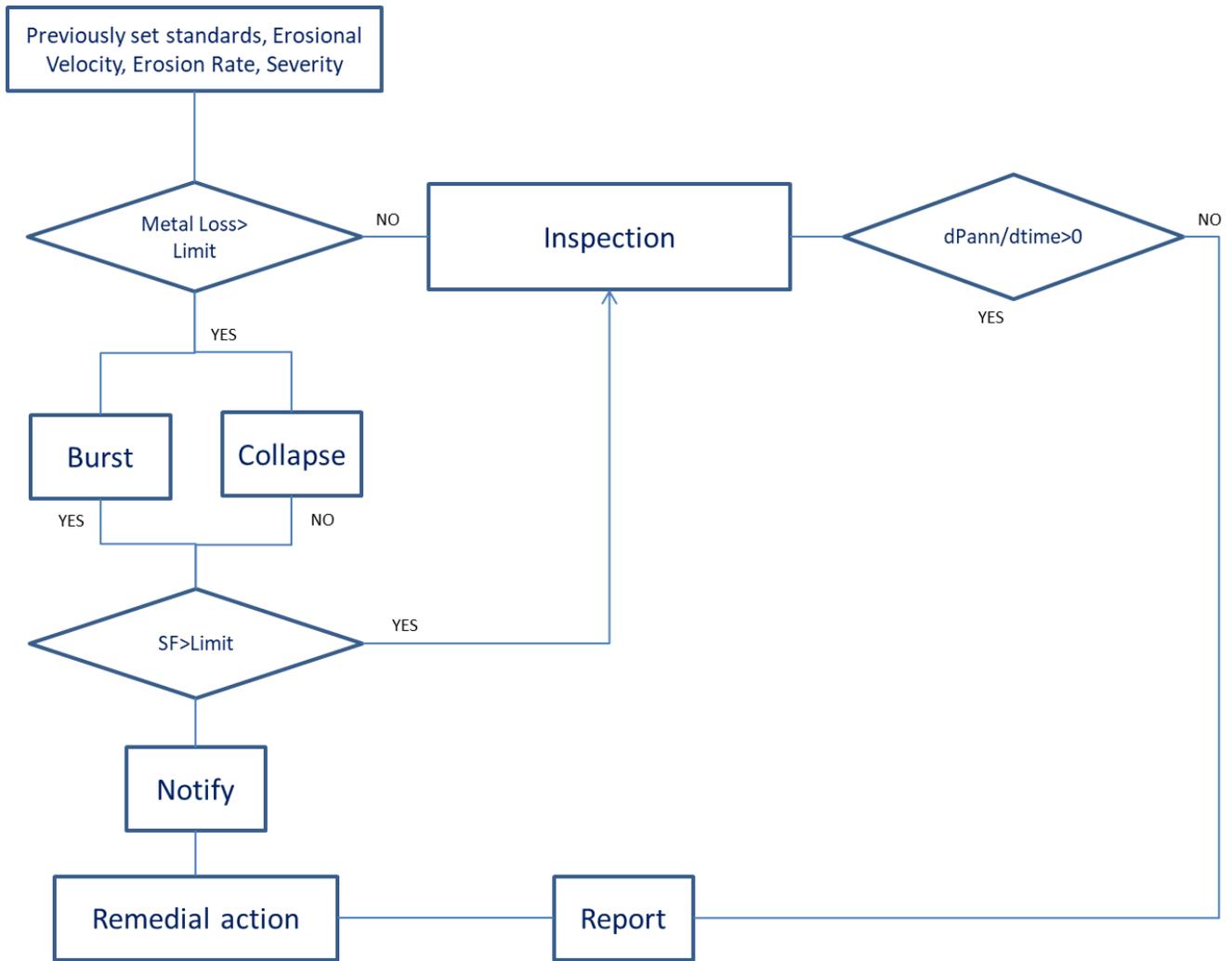


Figure 21. Erosion Management

Results and Discussion

Toolkit Interface

When designing an interface for such a tool that would have to be used by workers from a wide range of academic and professional levels and having different backgrounds, simplicity and intuitiveness are key elements. The tool is designed to process all the calculations, estimations and evaluations in the background. Only the engineer responsible will be able to access certain code features of the tool.

This leaves the interface with very few customizations possible. Most notably, the tool will need to provide an area where test results and daily observations are entered. For example, instead of allowing anyone to alter the pore gradient vs. depth curve, the tool will allow mid-level and field workers only to enter the formation gradient supposedly reached. It will allow field workers also to provide the composition and length of the drill string and drill bit that are being used in the current drilling stage. The following screenshots were taken from the actual interface provided with version 1.0 of the tool.

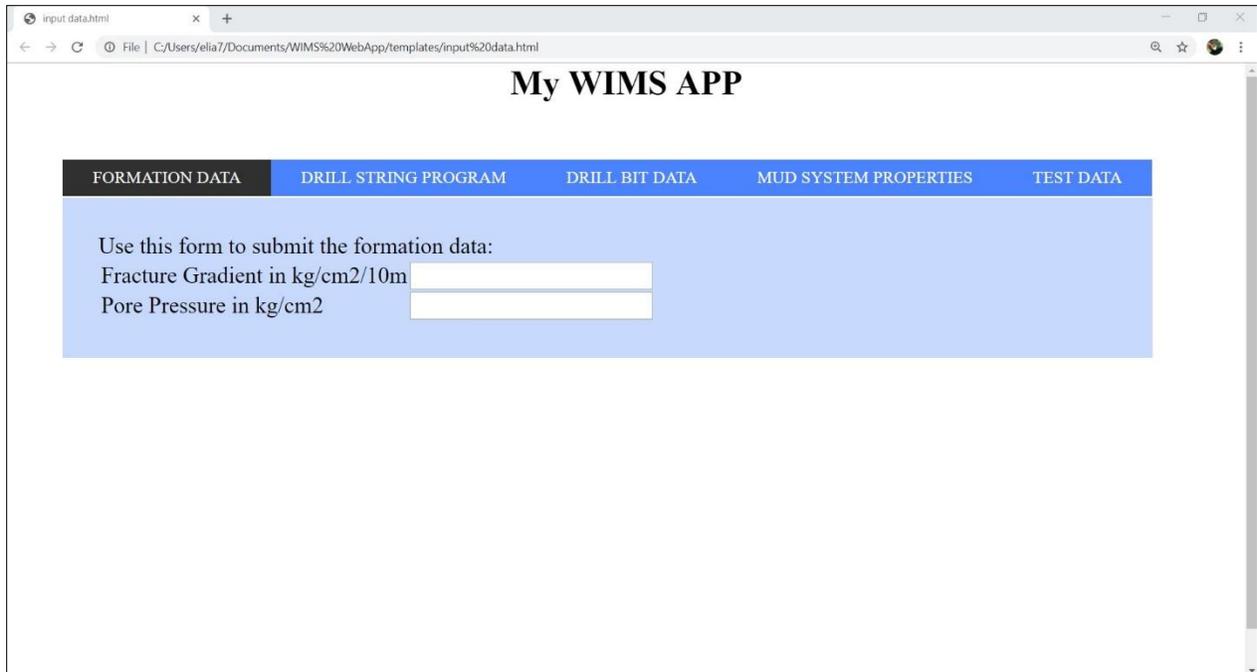


Figure 22. Screenshot from the WebApp Formation Data Page

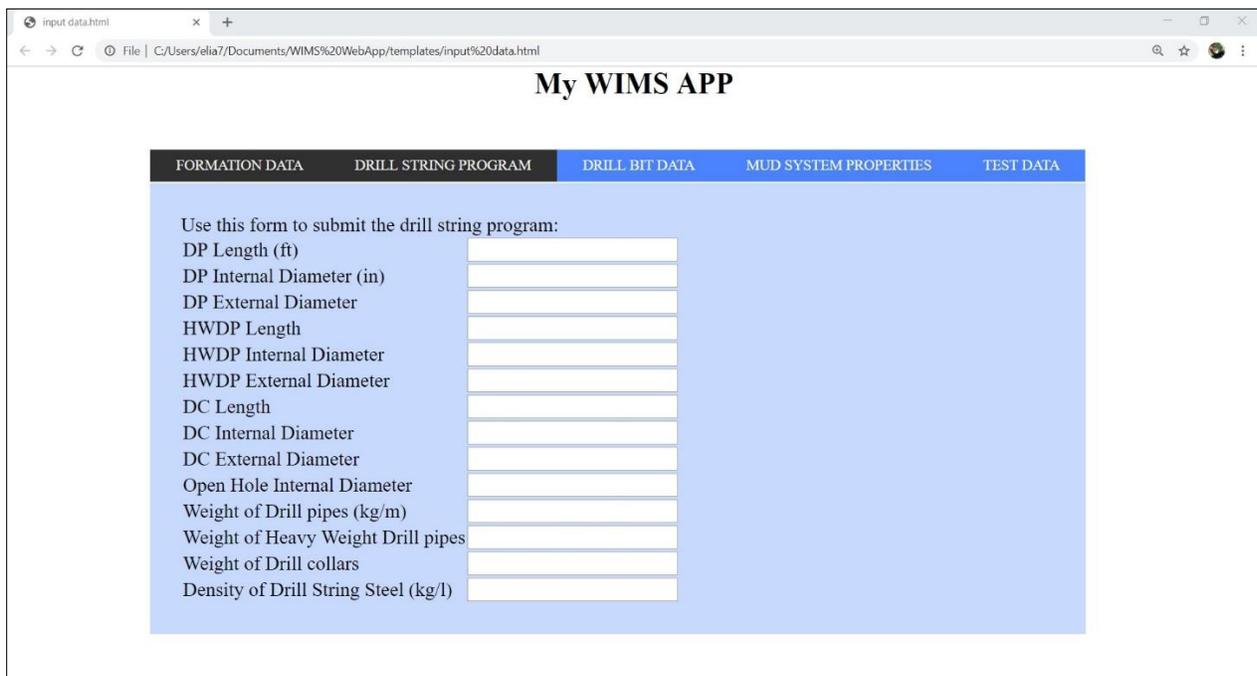


Figure 23. Screenshot from the WebApp Drill String Program Page

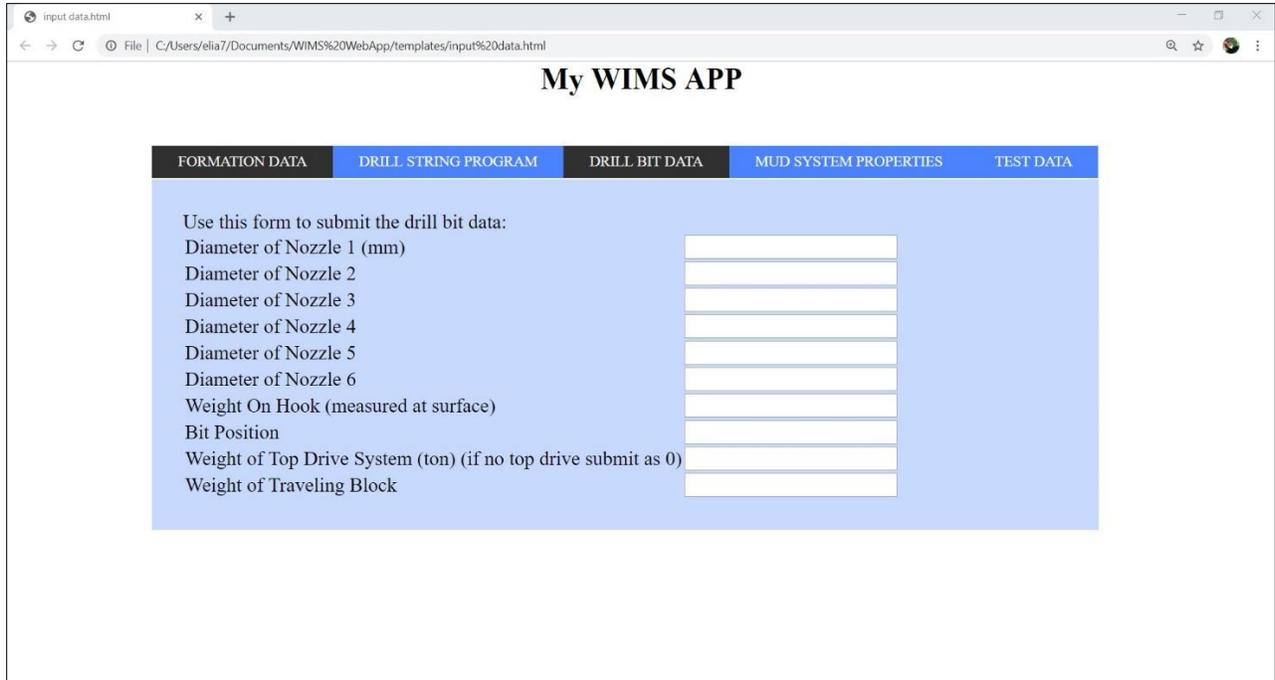


Figure 24. Screenshot from the WebApp Drill Bit Data Page

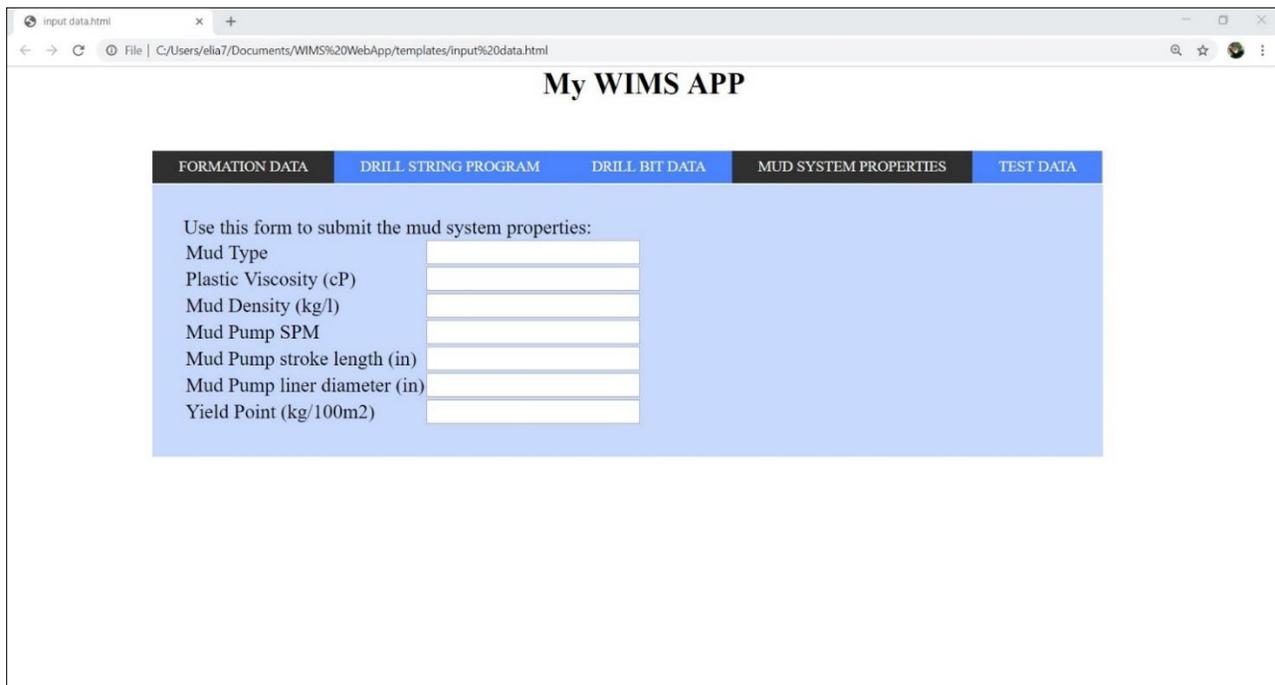


Figure 25. Screenshot from the WebApp Mud System Properties Page

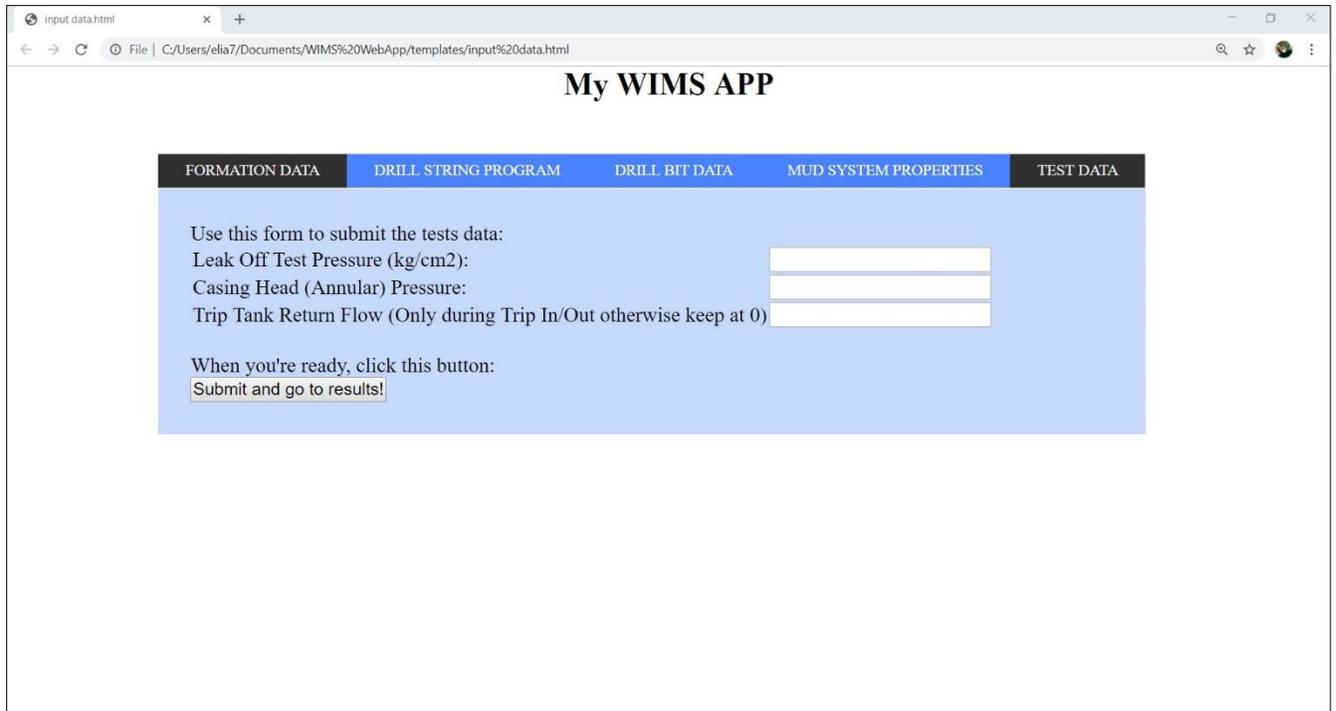


Figure 26. Screenshot from the WebApp Test Data Page

In the following paragraph, a sample code will be presented and will showcase the programming process of the toolkit. The code is written in Python and utilizes the Flask builder for the network functionality. A second paragraph will provide an example of a function that evaluates the height of the kick and the kick tolerance.

```

from flask import Flask, render_template, request, escape, make_response
from mywimsmodule import barrier_check
app=Flask(__name__)

def log_request(req:'flask_request')->None:
    with open('database.log', 'a') as welldatabase1:
        print(req.form, req.remote_addr, req.user_agent, file=welldatabase1, sep='|')

@app.route('/results', methods=['POST', 'GET'])
def dataentry_page() -> str:
    @app.route('/')
    @app.route('/entry')
    def entry_page() -> 'html':
        return render_template('input_data.html', the_title='Well Description!')

@app.route('/viewlog')
def view_the_log() ->'html':
    contents=[]
    with open('database.log') as welldatabase1:
        for line in welldatabase1:
            contents.append([])
            for item in line.split('|'):
                contents[-1].append(escape(item))
    titles=('Parameter', 'Remote_addr', 'user_agent')
    return render_template('viewlog.html', the_title='View Log', the_row_titles=titles,
the_data=contents,)

if __name__== '__main__':
    app.debug=True
    app.run()
    app.run(debug=True)

```

Figure 27. WIMS WebApp Python/Flask Code

```

def kick_tolerance_calc(id_bh, id_csg, od_dc, od_hwdp, od_dp, v_kick, dc_length,
hwdp_length, tvd, tvd_shoe, mud_density, annular_pressure, fr_gradient,
pore_pressure):
    """id in inches V kick in liters, length in ft, tvd in m, annular_pressure in kg/cm2,
    gradient in kg/l"""

    id_bh=id_bh*0.0254
    id_csg=id_csg*0.0254
    od_dc=od_dc*0.0254
    od_hwdp=od_hwdp*0.0254
    od_dp=od_dp*0.0254
    v_kick=v_kick/1000
    dc_length=dc_length*0.3048
    hwdp_length=hwdp_length*0.3048
    dp_length=dp_length*0.3048

    ca1=((id_bh**2)-(od_dc**2))*pi/4
    h_kick=v_kick/ca1
    if h_kick>dc_length:
        ca2=((id_bh**2)-(od_hwdp**2))*pi/4
        h_kick=dc_length+(v_kick-(ca1*dc_length))/ca2
        if h_kick>(dc_length+hwdp_length):
            ca3=((id_bh**2)-(od_dp**2))*pi/4
            h_kick=dc_length+hwdp_length+(v_kick-(ca1*dc_length)-(ca2*hwdp_length))/ca3
        if h_kick>(tvd-tvd_shoe):
            ca4=((id_csg**2)-(od_dp**2))*pi/4
            h_kick=tvd-tvd_shoe+(v_kick-(ca1*dc_length)-(ca2*hwdp_length)-(ca3*(tvd-
            tvd_shoe)))/ca4
        kick_density=mud_density-(annular_pressure*10)/h_kick
        caeq=((ca1*dc_length)+(ca2*hwdp_length)+(ca3*(tvd-tvd_shoe-dc_length-
        hwdp_length)))+(ca4*(h_kick-tvd+tvd_shoe))/h_kick
        kick_tolerance=0.000001*caeq*fr_gradient*tvd_shoe*(tvd_shoe*(fr_gradient-
        mud_density)*(tvd*mud_density)-(10*pore_pressure))/(pore_pressure*(mud_density-
        kick_density))
        if kick_tolerance<v_kick:
            warning='Warning! Danger of fracturing formation!!.'
        else:
            warning=''
    return(kick_tolerance, warning)

```

Figure 28. Kick Tolerance Algorithm

Presentation of the Theoretical Well used in Well Control operations

The well design used for the testing of the well integrity management toolkit is a theoretical one. It is the well typically used by the International Well Control Forum during the assessment process for Well Control certificates of the levels 3 and 4 meaning the assessment of Drillers and Toolpushers. The well design was originally inserted into the DRILLING SYSTEMS certified well control simulator and the kick and subsequent well control process have been simulated in order to provide a situation that is as close as possible to real life.

The well design chosen is a fairly simple one, though this does not mean that it isn't efficient in testing the effectiveness of the toolkit. A more complex well will not require a more complex software. It will only mean that the same software will have to do some extra evaluations in order to provide the complete analysis of the well.

The drilled formation is also theoretical and is simplified into seven measuring points that will give the pore pressure gradient. The first point is taken at surface, since the measurement is from the rotary table which is sitting above an air gap of 10.52m. The rest of the points are mostly following the normal compaction trend and have an average gradient of 0.1267 kg/cm²/m. The following table presents the different gradients measured at the seven points during the drilling operation, keeping in mind that no overpressure zone has been encountered and that the reservoir rock has not yet been reached.

Table 6. Pore Pressure Gradient Distribution with Depth

True Vertical Depth (m)	Pore Pressure Gradient (kg/cm ² /m)
10.52	0
1200.00	0.13
1699.87	0.13
1715.41	0.11
1724.23	0.11
1725.95	0.14
1731.26	0.14

The chosen well is an onshore production well with a single intermediate casing and a surface casing. The intermediate casing has a cemented shoe with a true vertical depth (TVDshoe) of 1203.96 m. It has an internal diameter (ID) of 8.68 inches. The steel used for the casing material has the following properties: collapse pressure= 327.9 kg/cm² and tensile strength= 89.88 metric tons.

The drill string used is composed of three types of elements; drill pipes (DP), heavy weight drill pipes (HWDP) and drill collars (DC). Each pipe is taken at an average 30 ft length. The DPs have a Dry Linear Weight of 29.02 kg/m, an internal diameter of 4.28 inches and an outside diameter of 5 inches. The DCs have a Dry Linear Weight of 130.37 kg/m, a 2.5 inches internal diameter and a 6.25 inches outside diameter. The HWDPs have a Dry Linear Weight of 73.37 kg/m, 3 inches of internal diameter and 5 inches for an external diameter. At the given

depth reached during testing a total number of 142 DPs were used in addition to 27 HWDPs and 20 DCs.

Table 7. Drill String Composition and Parameters

Component	Number	ID (in)	OD (in)	Dry Linear Weight (kg/m)
DP	142	4.28	5	29.02
HWDP	27	3	5	73.37
DC	20	2.5	6.25	130.37

The drill bit is a Tricone bit with an outside diameter of 8.5 inches and has three nozzles each of 12.7 mm size (diameter). This means that the uncased borehole inner diameter will also be 8.5 inches. The true vertical depth will be the same as the measured depth as the well is theoretical and taken at near perfect conditions. The true vertical depth is 1723.5m. The kick will be encountered at 1726.25m.

The choice of drilling fluid was the hardest as the properties affected by the mud are the ones that require the most detailed evaluation when dealing with well control processes. The Well Integrity Toolkit has the ability to perform operations on different kinds of mud. For the purpose of this paper, only the Bingham plastic rheology has been taken into consideration as this is the main mud rheology used during the IWCF Well Control certification process. When it would be commercially applied the toolkit will be customized to fit the needs of the company to which it is being developed. These needs might require the toolkit to adhere to international, local or company standards.

A mud with a Bingham plastic rheology is usually an oil-based mud and has three main parameters; the density, the yield point and the plastic viscosity. For this test, a standard mud density that is not variable with depth has been taken at 1.2 kg/l. This is to simplify the calculations and focus more on the functionality of the toolkit. In addition to the density, the yield point of the mud was taken at 97.65 kg/100m² and the plastic viscosity at 10 cP.

The mud pump is an essential element used when calculating the properties of the hydraulic program. Some parameters that may be changed, even in the same pump, must be specified prior to the start of any operations. These parameters are variable characteristics of each mud pump and are chosen by the pump mechanic in order to optimize the efficiency of the pumps. The parameters are the following; Piston Stroke Length at 12 inches, Liner Internal Diameter at 6 inches, Pump Output at 16.35 l/stroke and the efficiency at 98%. The pumps are run for this test at a speed of 90 SPM (strokes per minute). There are two pumps running at the same time each providing 45 SPM, but as they are identical, they can be substituted with a single pump running at 90 SPM for the sake of simplifying calculations.

The Top Drive System used has a weight of 22.68 metric tons and the traveling block sits at 15.88 metric tons. For these data at the given depth the hook load (HL) reads 67.53 metric tons.

Only one test has been performed at the given shoe depth which is a Leak Off Test. The test resulted in the following LOT pressure given as a gradient for more straightforward calculations:

0.19 kg/cm²/m.

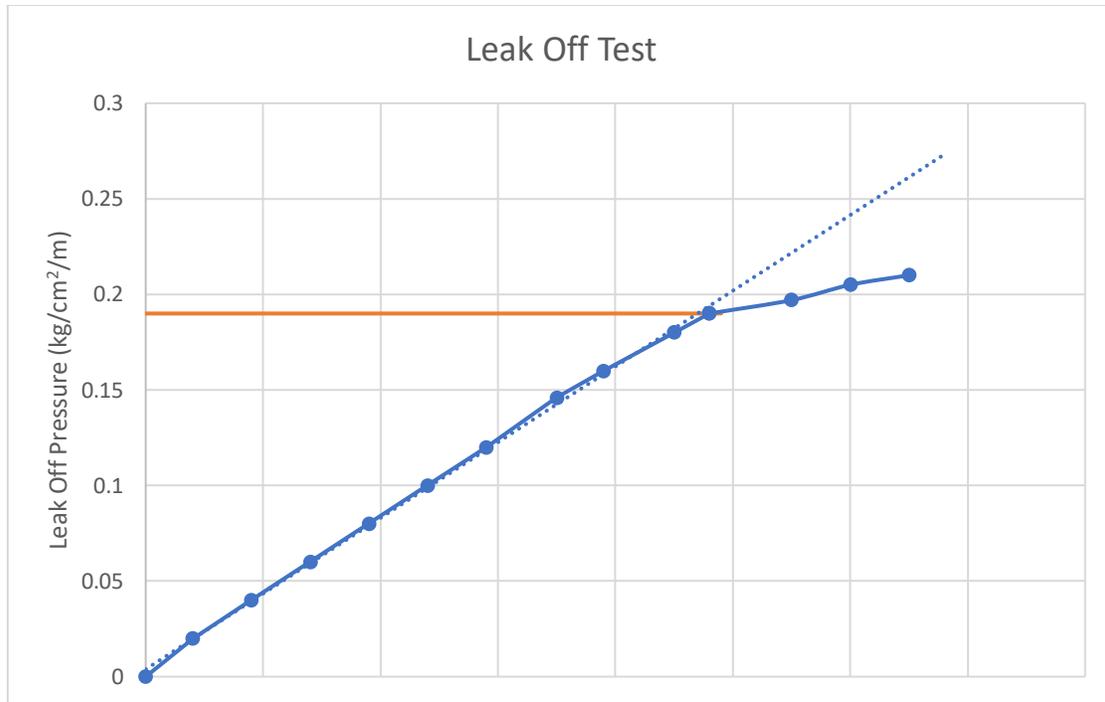


Figure 29. Leak Off Test

The DRILLING SYSTEMS DrillsIM:20 simulator is a portable real-time drilling and well control simulator. It can be used to develop exercises and tests that include oil-based mud, gas expansion and migration, dynamic pressures during well control, bottom hole effects – equivalent circulating density, choke washout and plugging, drilling and tripping and the IWCF required malfunctions. This makes it suitable to test the functionality of the toolkit and provide a key result; will the toolkit be able to interpret a kick faster than a human worker?



Figure 30. Drilling Systems DrillsIM:20 simulator

The previously detailed data was entered into the software and the simulation was run in order to test the time needed for a kick to develop. As the reaction times of different operators vary by a large amount, the parameter used to compare the effects of the Well Integrity Toolkit will be the volume of kick taken. This is possible since a faster reaction time means a smaller formation fluid influx into the well. The average volume of fluid that enters the well during normal well control operations with both a driller and a Toolpusher working is found to be 2343.41 liters. If the toolkit is effective, it would be able to provide an alarm for the kick and shut in the well automatically at a much lower influx volume.

Results

With all the data entered into the toolkit, a deep analysis of the properties and characteristics of the system is possible. The toolkit evaluates pressure drops in the hydraulic circuit, thus providing a final calculation of the bottom hole pressure. While this pressure is maintained at its design values, the toolkit will give a positive response for the barrier controlled by this pressure. This barrier is the primary barrier; the drilling fluid column.

As per the NORSOK D-010 standards, the optimal way to provide feedback about the different barriers established in the well is to show the user a page containing the Well Barrier Schematic of the well with the depth and size of the last casing reached clearly shown, a table providing information about the well and a table providing the names, monitoring methods and status of all barriers established in the well.

The following is the result page of the toolkit, while the well is functioning in the optimal way. The green color provided in the status column is an indication that any given barrier is functioning in the intended way. Should the barrier fail, the color would turn to red. The notes area will be used to add special measurement or values calculated by the algorithm when a barrier is lost.

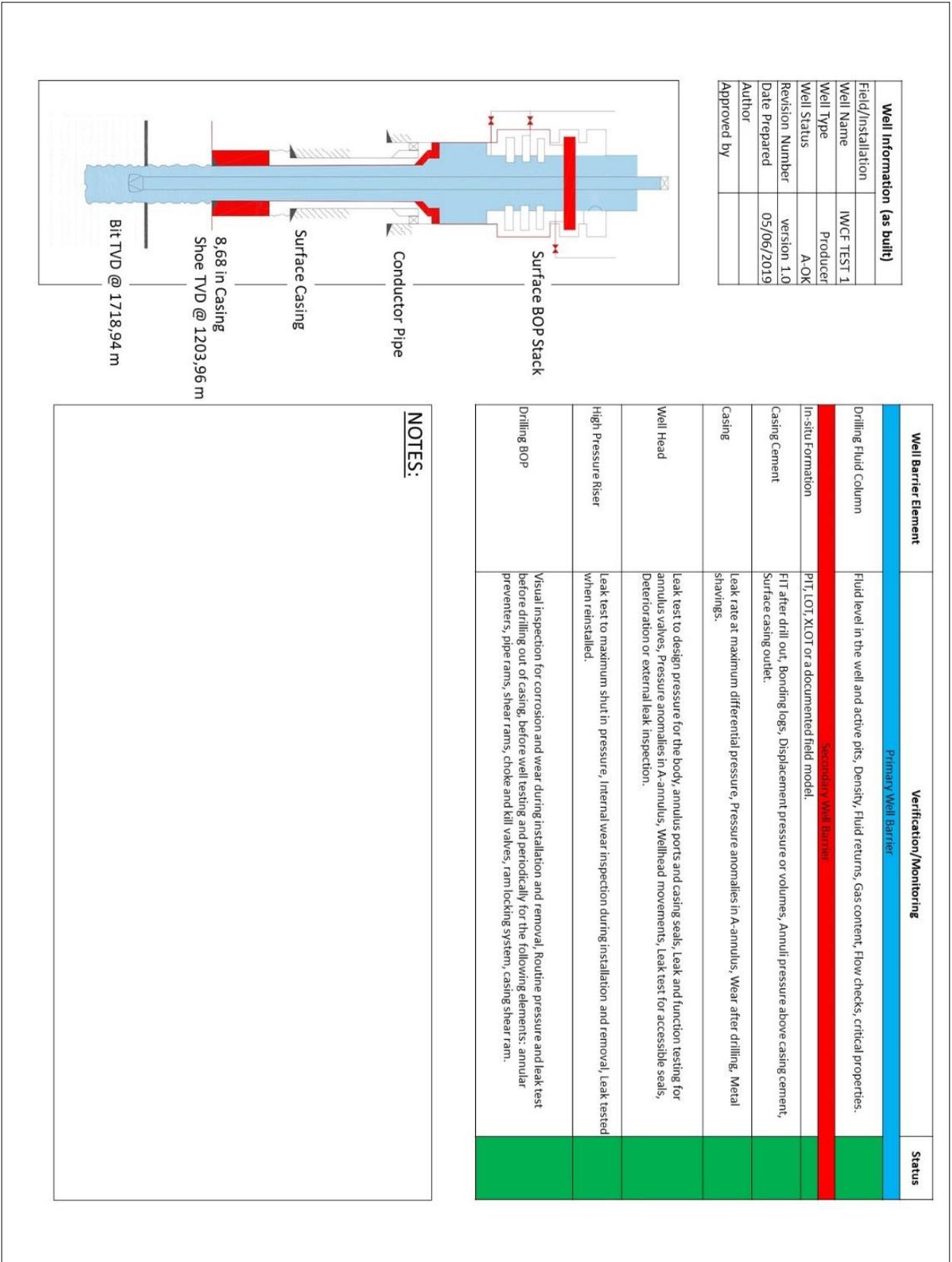


Figure 31. Result Page of the fully operational well

The failures of the different barriers can occur in the following manner:

- Primary Barrier:
 1. Drilling Fluid Column: when the bottom hole pressure (BHP) drops below the formation pore pressure, the primary well control is lost, and an influx may occur. If the return flow does not drop to zero after the well is shut in, the kick has certainly occurred. The wellbore contains formation fluids.
- Secondary Barriers:
 1. In-situ Formation: when the pressure at the last cemented casing shoe surpasses the MAASP or when the volume of kick that has entered the wellbore surpasses the kick tolerance, the formation at the shoe which is the weakest point is fractured.
 2. Casing Cement: if the pressure at the casing annulus surpasses the design pressure and does not go back to normal after bleed-off, the annulus is being invaded by fluids indicating cement or casing damage. Further tests must be conducted to identify.
 3. Casing: when casing pressure surpasses the designed casing collapse pressure, or the casing load surpasses the designed casing tensile strength.
 4. Wellhead: when the pressure at the top of the annulus exceeds wellhead design, or when leaks develop above the set criteria.
 5. High Pressure Riser: when the pressure exceeds wellhead design, or when leaks develop above the set criteria.
 6. Drilling BOP: when accumulator and manifold pressures drop with time, there are hydraulic system losses. When the accumulator pressure are

below 2700 psi, the pump switch is broken. When only the accumulator pressure is dropping with time, the regulator is broken. When the Stand Pipe Pressure and the annular pressure are increasing with time, there's an obstruction at the choke. When the Standpipe Pressure is decreasing and the pump flow is stopped, the pump is ruptured.

In the case of this theoretical well, only the loss of the primary barrier is simulated and the toolkit, thus, provides the following data while showing that the first barrier is not available anymore. The toolkit also sends an order to the rig control server to stop the drilling operation, perform the adequate space out and close the well using the method previously specified by the driller or the responsible Toolpusher.

The volume of the kick that entered the well was limited to around 1200 liters. This is because the kick was detected within one second which allowed the driller to close the well much faster than he would have if he was relying on his own analysis to detect the kick. The pressure exerted in all the sections of the well was decreased due to the lower volume of kick that entered the wellbore.

The software also provided a report of the barrier status of the well which is automatically sent to all authorized personnel. The kick is then known to all employees that are managing the drilling operation of this well.

CHAPTER 4. CONCLUSION



POLITECNICO
DI TORINO



DRILLMEC
DRILLING TECHNOLOGIES
Training & Well Control Center

Final words and future prospects

Sultan (2009) qualifies well integrity as a testimony to the well's capability of performing its functions while controlling the fluids flow through its barriers throughout its lifecycle. Managing well integrity starts with the design phase and continues through the multiple phases of the well's life cycle. Most professionals and academics focus on the long-term benefits of applying well integrity during the production, workover and later plug and abandonment of the well.

However, very few researchers are trying to improve the way well integrity is monitored and managed during the drilling phase. The drilling operation itself has been left to its old methods, while the other phases of a well life cycle have been improved and revolutionized by the introduction of new high-tech devices and state of the art computational power.

Drilling has always been a raw operation, basing on the strength and the experience of the workers and often relying on the rig crew to solve any problems manually. The tool discussed in this paper shows how much the oil and gas industry has to gain from applying the same concepts used in the later life of the well during the drilling and well control operation.

Present software tools fall well short of the widely accepted standards like the Norsok D-010. Most of these apply only to the operational phase of the well's life whereas the integrity management of the well should start with the design phase and must be monitored and maintained all throughout the well's life cycle. They rarely manage complex operations and suffice in measuring some basic parameters and providing their values for the driller or the Toolpusher who in turn is counted upon to make an informed decision on the state of integrity of the well and the procedures that need to be followed. With this respect, the drilling phase, which is the most critical phase of a well's life, is left to the better judgement of workers who, at the best-case scenario, might make a small mistake or overlook a unimportant parameter which

might cause a major incident. This is the case of the Macondo well blowout and the Piper Alpha incident as well as countless other accidents that have ruined the reputation of the oil and gas industry.

Through all these incidents, only one factor is constant, the human error. That is not to say that blowouts are purely the results of human mistakes, nor that to remove the human factor is to remove the weak point. This does not mean that the drilling operation can in any way be completed without the direct intervention of human workers. A machine will not be able to perform the same approximation that an experienced driller can make, and it will certainly not be able to avoid the risk of a kick.

However, it has been shown that the application of a well integrity management system during the drilling operation will produce less risk by detecting the presence of the kick faster than a human. The software does not only detect a kick, it also provides the same information at the same time for all the workers dedicated to a given well. It shortens the communication time, makes decision making easier, informs the driller or the engineer what is the problem exactly, shows the important parameters in logical sequence and takes the primary steps necessary to avoid accidents. In short, it organizes the work on the rig.

Borgersen et al. (2018) believe that any development to be made in the well integrity domain must be discussed according to the following categories; technology, methodology and organization, with technology and methodology gaining the first page importance.

With regards to organization, it is now clear, according to Borgersen et al. (2018) that well integrity is equivalent to regularity and standardization for the operator.

Methods and technologies introduced in the well integrity field pose a different subject and may allow for a quantum leap in the future. Daily well integrity work will be impacted by

the improvement of information flow and digitalization of the tasks and measurements (Borgersen et al., 2018). Improvements might include but are not confined to the following:

- More integration between standards.
- Software capacity for automatic drawings, procedures and interpretation of periodic testing.
- Proposed risk assessment following the well integrity status change.
- Integration of cement logs and cement data.
- Formation data: skin and permeability integration
- Testing history and database of all wells sharing similar design properties, geographic locations or formation types.
- Casing wear, strength, collapse and burst capacity logs.
- Corrosion and erosion modeling and prediction.
- Historic troubleshooting and barrier failure data.

In addition, the introduction of ANN to the drilling field in the area of drilling parameter predictions will make measurements and estimations much more accurate. It can also allow for a completely automated drilling and well control process. The emergency procedures would be carried out much faster and the well would be constructed much closer to the design expectations.

Finally, it is important to note the incredible work that can be done in the field of automation in the drilling and well control fields. And even though some complaints will arise with regards to substituting humans by machines, it is clear that the world has moved on from the traditional worker plan. The oil and gas industry must also move on if it is to survive the 21st century. Petroleum engineers must shift their skills from the basic abilities of calculation,

analysis and prediction, to the more advanced and more difficult path of teaching software and artificial intelligence machines to do their job for them.

References

Ahmed, S. F., Elkholy, M., Warnken, D., & Rocha, G. (2007, January 1). Design and Early Implementation of a Well Integrity Management System in an Offshore Brownfield Operation. International Petroleum Technology Conference. doi:10.2523/IPTC-11678-MS

Al-Ashhab, J., Afzal, M., & Emenike, C. O. (2004, January 1). Well Integrity Management System (WIMS). Society of Petroleum Engineers. doi:10.2118/88696-MS

Anders, J., Disbrow, J., Dube, A., & Hughes, A. (2015, March 3). Analytics Applied to Well Integrity. Society of Petroleum Engineers. doi:10.2118/173434-MS

Anders, J., Mofley, B., Nicol, S., Vo, N., Weiss, T., & Fjågesund, T. (2015, March 3). Implementation of Well Barrier Schematic Workflows. Society of Petroleum Engineers. doi:10.2118/173433-MS

Andreas Nascimento, David Tamas Kutas, Asad Elmgerbi, Gerhard Thonhauser, and Mauro Hugo Mathias, "Mathematical Modeling Applied to Drilling Engineering: An Application of Bourgoyne and Young ROP Model to a Presalt Case Study," *Mathematical Problems in Engineering*, vol. 2015, Article ID 631290, 9 pages, 2015. <https://doi.org/10.1155/2015/631290>

Annandale, A., & Copping, S. R. (2009, January 1). A Systematic Approach to Well Integrity Management. Society of Petroleum Engineers. doi:10.2118/123201-MS

Arnaout, A., O'Leary, P., Esmael, B., & Thonhauser, G. (2014). Distributed recognition system for drilling events detection and classification. *International Journal of Hybrid Intelligent Systems*, 11, 25-39. <https://doi.org/10.3233/HIS-130181>

Blick, E. F., & Shams, Q. (1989, January 1). Effect of Flow Properties on Drillpipe Neutral Point. Society of Petroleum Engineers. doi:10.2118/18694-MS

Brechan, B., Sangesland, S., & Naaden, C. (2018, January 29). Well Integrity - Next Developments. Society of Petroleum Engineers. doi:10.2118/189403-MS

Brodie, A. (2016, November 7). The Autonomous Management of Wells with Unplanned Sustained Casing Pressure. Society of Petroleum Engineers. doi:10.2118/183077-MS

Carpenter, C. (2015, January 1). Effective Well-Integrity Management in a Mature Sour-Oil Field. Society of Petroleum Engineers. doi:10.2118/0115-0093-JPT

Chitale, A. A., Blosser, W. R., & Arias, B. J. (2010, January 1). Use of Real-Time Data in Well Integrity Management. Society of Petroleum Engineers. doi:10.2118/128688-MS

Clark, P. E. (1995, January 1). Drilling Mud Rheology and the API Recommended Measurements. Society of Petroleum Engineers. doi:10.2118/29543-MS

Corneliussen, K., Sorli, F., Haga, H. B., Menezes, C. A., Tenold, E., Grimbert, B., & Owren, K. (2007, January 1). Well Integrity Management System (WIMS) - a systematic way of

describing the actual and historic integrity status of operational wells. Society of Petroleum Engineers. doi:10.2118/110347-MS

Daghmouni, H., El Mancini, M., Abdel Rady, S. A., & Shattawah, Y. (2010, January 1). Well Integrity Management System (WIMS) Development. Society of Petroleum Engineers. doi:10.2118/137966-MS

Denney, D. (2012, January 1). Kick-Tolerance Misconceptions and Consequences for Well Design. Society of Petroleum Engineers. doi:10.2118/0112-0085-JPT

Desouky, S. E. D. M., & Al-Saddique, M. A. (1999, December 1). Turbulent Pressure Loss of Yield-fluids In Pipes. Petroleum Society of Canada. doi:10.2118/99-13-09

Dethlefs, J., & Chastain, B. (2012, June 1). Assessing Well-Integrity Risk: A Qualitative Model. Society of Petroleum Engineers. doi:10.2118/142854-PA

Gouda, M. H., & Aslam, I. (2018, April 16). Well Integrity Life Cycle. Society of Petroleum Engineers. doi:10.2118/190504-MS

Haga, J., Corneliusson, K., & Sorli, F. B. M. B. (2009, January 1). Well Integrity Management in Talisman Energy Norway: A Systematic Way of Describing and Keeping Track of the Integrity Status for Wells in Operation. Society of Petroleum Engineers. doi:10.2118/120946-MS

Han, J., Sun, Y., & Zhang, S. (2019, March 22). A Data Driven Approach of ROP Prediction and Drilling Performance Estimation. International Petroleum Technology Conference. doi:10.2523/IPTC-19430-MS

Kairon, S. B., Lane, T. M., & Murrey, M. D. (2008, January 1). Optimizing Well Integrity Surveillance And Maintenance. International Petroleum Technology Conference. doi:10.2523/IPTC-12624-MS

Kazemi, M., & Wojtanowicz, A. K. (2014, October 27). Development of Improved Testing Procedure for Wells with Sustained Casing Pressure. Society of Petroleum Engineers. doi:10.2118/170693-MS

King, G. E., & King, D. E. (2013, November 1). Environmental Risk Arising From Well-Construction Failure--Differences Between Barrier and Well Failure, and Estimates of Failure Frequency Across Common Well Types, Locations, and Well Age. Society of Petroleum Engineers. doi:10.2118/166142-PA

Kopecki, D. S. (1989, January 1). Developing Complete Resistance to Stress Corrosion Cracking in Nonmagnetic Drilling Tools. Society of Petroleum Engineers. doi:10.2118/SPE-19548-MS

Kumar, A., Gillies, J., Mehra, R., Pardeshi, M., Wilke, A., & Li, J. (2017, March 14). Improved Primary Cement Jobs and Mitigation of Sustained Casing Pressure through the Use of Foamed Spacer Design Technology. Society of Petroleum Engineers. doi:10.2118/184605-MS

Kutas, D. T., Nascimento, A., Elmgerbi, A. M., Roohi, A., Prohaska, M., Thonhauser, G., & Mathias, M. H. (2015, December 6). A Study of the Applicability of Bourgoyne & Young ROP Model and Fitting Reliability through Regression. International Petroleum Technology Conference. doi:10.2523/IPTC-18521-MS

Kyllingstad, Å., & Thoresen, K. E. (2019, March 4). Improving Accuracy of Well Depth and ROP. Society of Petroleum Engineers. doi:10.2118/194098-MS

Ladley, R. S. (1961, January 1). Failure of High-strength Tubular Goods by Corrosion-cracking Mechanisms. American Petroleum Institute.

Lenschow, J. R. (1992, January 1). Pressure Drop Calculations For Drilling Fluids. Society of Petroleum Engineers.

Lind, Y. B., & Kabirova, A. R. (2014, October 14). Artificial Neural Networks in Drilling Troubles Prediction. Society of Petroleum Engineers. doi:10.2118/171274-MS

McLean, R. H. (1964, November 1). Crossflow and Impact Under Jet Bits. Society of Petroleum Engineers. doi:10.2118/889-PA

Mosti, I., Morrell, D., Anfinsen, B. T., Vielma, W. E. S., & Nergaard, K. (2017, March 14). Kick Tolerance and Frictional Pressure Losses, Added Safety or Added Risk? Society of Petroleum Engineers. doi:10.2118/184655-MS

Obodozie, I. E., Trahan, S. J., & Joppe, L. C. (2016, March 22). Eliminating Sustained Casing Pressure in Well Abandonment. Offshore Technology Conference. doi:10.4043/26432-MS

Rocha-Valadez, T., Hasan, A. R., Mannan, S., & Kabir, C. S. (2014, January 1). Assessing Wellbore Integrity in Sustained-Casing-Pressure Annulus. Society of Petroleum Engineers. doi:10.2118/169814-PA

Samad, S. A., Tarmoom, I. O., Binthabet, H. A., Chishti, K., Hussain, A., & Arafat, M. A. S. (2007, January 1). A Comprehensive Approach to Well Integrity Management. Society of Petroleum Engineers. doi:10.2118/105319-MS

Samuel, R. (2013, March 10). Well Integrity Management System (WIMS): Coupled Engineering Analysis. Society of Petroleum Engineers. doi:10.2118/164230-MS

Santos, O., Adasani, I., Azar, J. J., & Escorihuela, F. (1995, January 1). Determination of Casing Setting Depth Using Kick Tolerance Concept. Society of Petroleum Engineers. doi:10.2118/30220-MS

Singh, S. K., Subekti, H., Al-Asmakh, M., & Al-Samarraie, L. S. (2012, January 1). An Integrated Approach To Well Integrity Evaluation Via Reliability Assessment Of Well Integrity Tools And Methods: Results From Dukhan Field, Qatar. Society of Petroleum Engineers. doi:10.2118/156052-MS

Smith, L., & Milanovic, D. Z. (2008, January 1). The Total Control of Well Integrity Management. Society of Petroleum Engineers. doi:10.2118/117121-MS

Sparke, S. J., Conway, R., & Copping, S. (2011, January 1). The Seven Pillars of Well Integrity Management: The Design and Implementation of a Well Integrity Management System. Society of Petroleum Engineers. doi:10.2118/142449-MS

Stuart, C., & Foo, S. Z. C. (2010, January 1). Application of Intelligent Systems to Ensure Integrity Throughout Entire Well Life Cycle. Society of Petroleum Engineers. doi:10.2118/135907-MS

Sultan, A. A. (2009, January 1). Well Integrity Management Systems; Achievements Versus Expectations. International Petroleum Technology Conference. doi:10.2523/IPTC-13405-MS

Vignes, B., Tønning, S. A., & Aadnøy, B. (2008, January 1). Integrity issues in Norwegian Injection Wells. Society of Petroleum Engineers. doi:10.2118/118101-MS

Wakama, M., Eta, E., & Adeniyi, A. (2004, January 1). Well Integrity Management in Shell Nigeria. Society of Petroleum Engineers. doi:10.2118/88934-MS

Wescott, B. B., Dunlop, C. A., & Kemler, E. N. (1940, January 1). Setting Depths for Casing. American Petroleum Institute.

Wilson, A. (2018, December 1). Real-Time Data Analytics Allows for Bit-Wear Monitoring and Prediction. Society of Petroleum Engineers. doi:10.2118/1218-0067-JPT

Xu, R., & Wojtanowicz, A. K. (2001, January 1). Diagnosis of Sustained Casing Pressure from Bleed-off/Buildup Testing Patterns. Society of Petroleum Engineers. doi:10.2118/67194-MS

Yequan Jin, Cheng Li, Qian Wu, Methodology for kick tolerance calculation and well killing in Deepwater drilling, Natural Gas Industry B, Volume 3, Issue 5, 2016. Pages 472-478, ISSN 2352-8540, <https://doi.org/10.1016/j.ngib.2016.09.003>

Zhang, B., Guan, Z., Lu, N., Hasan, A. R., Xu, S., Zhang, Z., ... Xu, Y. (2018, March 20). Control and Analysis of Sustained Casing Pressure Caused by Cement Sealed Integrity Failure. Offshore Technology Conference. doi:10.4043/28500-MS

Zhang, Y., Brodie, A., McMahon, A., & Russell, L.-A. (2004, January 1). The Development and Application of a Novel Model for Tubular Corrosion Prediction. Society of Petroleum Engineers. doi:10.2118/87556-MS

Zhao, J., Shen, Y., Chen, W., Zhang, Z., & Johnston, S. (2017, October 4). Machine Learning & dash; Based Trigger Detection of Drilling Events Based on Drilling Data. Society of Petroleum Engineers. doi:10.2118/187512-MS