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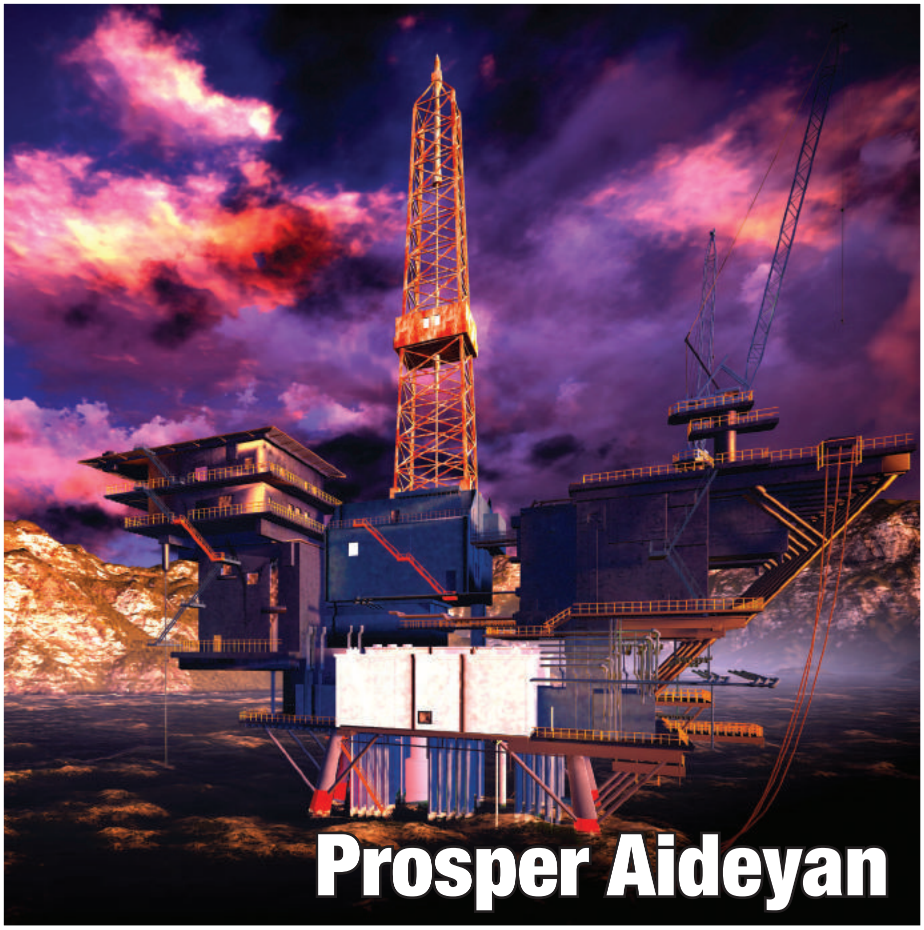
Drilling Operations:
Cost and Risk Management



Prosper Aideyan

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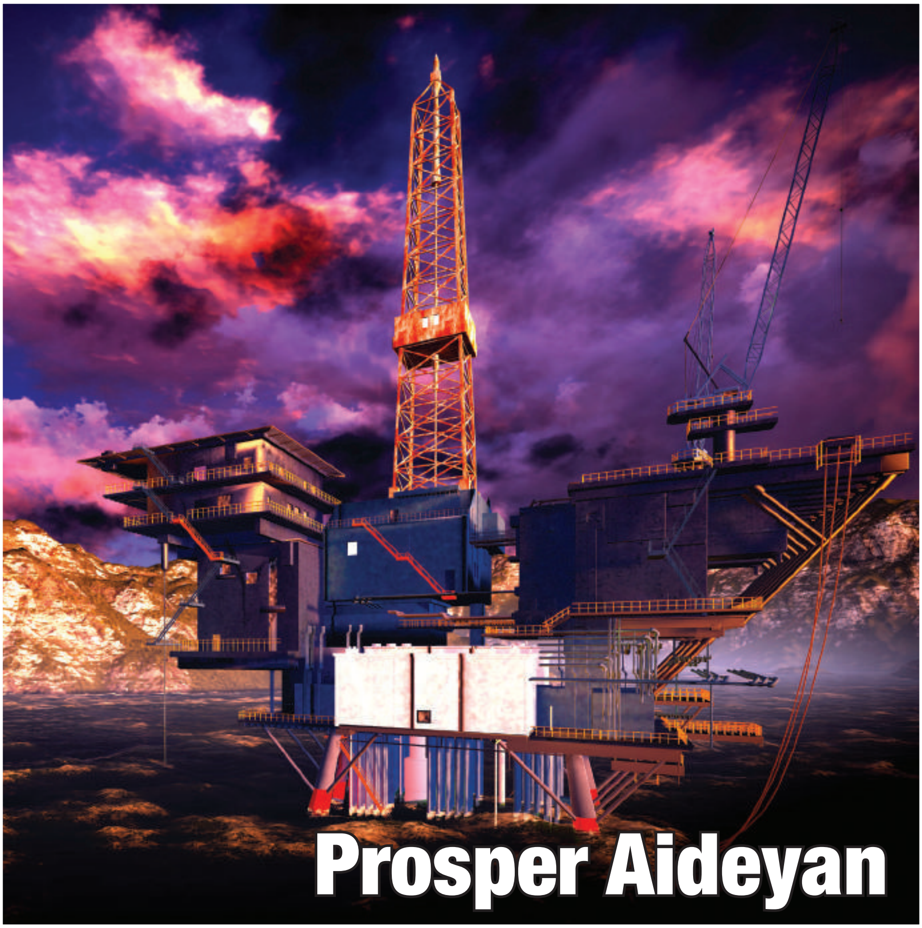

Prosper Aideyan

Drilling Operations
Cost and Risk
Management

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Drilling Operations: Cost and Risk Management

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HOUSTON, TX:
SigmaQuadrant.com
11306 Dawnheath Dr
Cypress, TX 77433

Director : **Dorothy Samuel**
Production Editor : **Hubert Daniel**
Senior Design Editor : **Balaji Srinivasan**
Copy Editor : **Sheena Reuben**

Includes bibliographical references and index.

ISBN-13: 978-0-990683629

10 9 8 7 6 5 4 3 2 1

1. Drilling Operations —Equipment and supplies. 2. Oil well drilling—Equipment and supplies. 3. Oil well drilling. 4. Gas well drilling. I. Title.

Printed in the United States of America
Printed on acid-free paper.

Text design and composition by: Kryon Publishing Services (P) Ltd., Chennai, India.
www.kryonpublishing.com

Drilling Operations Cost and Risk Management

Prosper Aideyan

σQuadrant
sigmaquadrant.com

A SigmaQuadrant Engineering Publication
Houston/Beijing/Chennai

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Acknowledgement

The author would like to thank his family, his friends, and colleagues in the course of his career whose valuable advices and experiences helped achieved the goal of writing this book.

Special thanks to Sheena Reuben who helped us with the copyediting and proof reading of this book.

The author dedicates this book to those who work together safely and efficiently to deliver energy to the world.

Preface

Often, drilling programs have documented risks and mitigations against the identified risks. Although preventative actions against the identified risks may be expressed within the program, the emphasis is usually on the mitigation barriers against the risks. Hence it is not uncommon to see the term "risks and mitigations" in a drilling program. This book was born out of the desire to deliver the same risk management concept applied in chemical plants and refineries into drilling planning and operations. Barriers to risk events should include preventative barriers and mitigation barriers. Mitigation barriers are reactive; the safety and cost of wells operations can be improved by creating preventative barriers to reduce the chance of the risk event occurring. Mitigation barriers improve the recovery time if a risk event should occur.

This book focuses on improving drilling operations by managing barriers (both preventative and mitigation) to risk events. In Chapter 1, the basic principles of risk management are described. The chapter talks about everything from identification of risks to creating barriers (people, process/procedures, and equipment) for identified risks as well as steps to help barrier creation. Chapter 2 describes the process of drilling optimization: reviewing non-productive events from offset wells or other drilling campaigns, categorizing non-productive time events into those that increase "drilling time" and those the extend "flat time" and barriers to be put in place to optimize drilling operations. Chapters 3 to 13 focus on common non-productive time events such as loss circulation, well control and so on that lead to down-time in drilling operations and barriers to the risk events as well as monitoring/control barrier (e.g., torque and drag). Useful drilling calculations are highlighted in Chapter 14. Chapter 15 focuses on other continuous improvement opportunities that are not covered in Chapters 2 through 13.

It is my desire that this book provides useful insight into drilling operations improvements in the area of cost and risks. It is a valuable resource for anyone involved in well planning and operations: engineers and technicians preparing risk assessments and risk workbooks, engineers involved in writing drilling procedures, engineers and managers reviewing and approving drilling programs, field engineers, supervisors and superintendents making decisions on the fly during drilling operations, and also students wishing to pursue careers in drilling engineering and operations.

Although significant effort has been made to avoid errors, they are sometimes inevitable. Suggestions towards the improvement of this book are welcome.

CHAPTER

1

Risk Management: Bow-ties and the "PPE" Concept

Every activity or operation in well construction has its own associated risk(s). The cost of running the operation will most certainly be impacted by the level of risk that can be taken for that particular operation. Typically, the running of an operation costs less if the level of risk associated with it is high, and it is higher if the level of risk is lower. However, any safety incidents arising out of high-risk operations could potentially lead to catastrophic damage, which in-turn may raise the overall cost of running the operation immensely. Therefore it is important to identify all risks associated with any operation during well construction and to determine what level of risk is acceptable and to what extent. Risk management is the economics of finding a suitable balance between running an operation by rejecting and

Table 1.1 Comparison of preventative and mitigation barriers.

	Preventative Barriers	Mitigation Barriers
1	Proactive	Reactive
2	Reduce the likelihood of an event occurring	Reduce the impact of an event
3	Involve elimination, prevention and control	Involve mitigation and a recovery plan
4	Usually engineering design (well trajectory design, BHA design, mud design), administrative actions (e.g., enforcement of buffer zones) and/or procedural (e.g., ensuring pipe movement to prevent differentially stuck pipe)	Personal and environmental protection, personal protective equipment (PPE) and Contingency plans/procedures. Can also be engineering actions (e.g., construction of berms for spill containment), or administrative actions (e.g., restricting access to only essential personnel during a well control event)

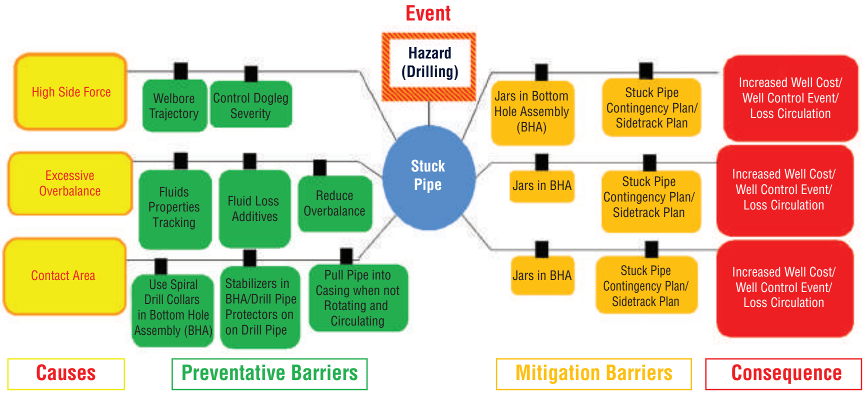


Figure 1.3: Bow-tie for stuck pipe.

adding fluid loss additive and filter cake reduction, and using spiral drill collars, stabilizers and drill pipe protectors to minimize contact area.

Control: Stuck pipe event can be controlled by creating a procedure that ensures pipe movement during repairs for surface and downhole failures when possible and also tracking fluid properties.

Drilling optimization can be broken down into the following:

- **Drilling time improvement:** Drilling time inefficiencies are factors that affect the rate of penetration. Examples are:
    - use of the wrong drill bit for formation drilled
    - poor mud motor/rotary steerable system tool selection
    - limitation of solid handling equipment
    - drill string vibration/buckling
    - pump limitation for hole cleaning
    - drill string size causing high pump pressure
    - unavailability or inadequate procedures for hole cleaning
    - data transfer limitation
- **Flat time reduction:** Flat time inefficiencies could be as a result of events that change drilling time to flat time or events that extend flat time. Examples of events that change drilling time to flat time are:
    - lost circulation
    - motor failure
    - MWD (measurement while drilling) failure
    - bit failure
    - drill string failure
    - stuck pipe
    - well control
    - wellbore instability
    - failure of surface and downhole equipment
    - casing wear

Examples of events that extend flat time are:

- suboptimal wellbore trajectory/hole tortuosity for casing running and logging – longer casing running/logging time
- swab/surge during casing running
- excessive breaking circulation/mud conditioning
- inefficiency breaking circulation while running casing/pipe leading to losses
- wellbore instability while drilling, logging/running casing
- excessive time to pull out of hole with drill string due to swab

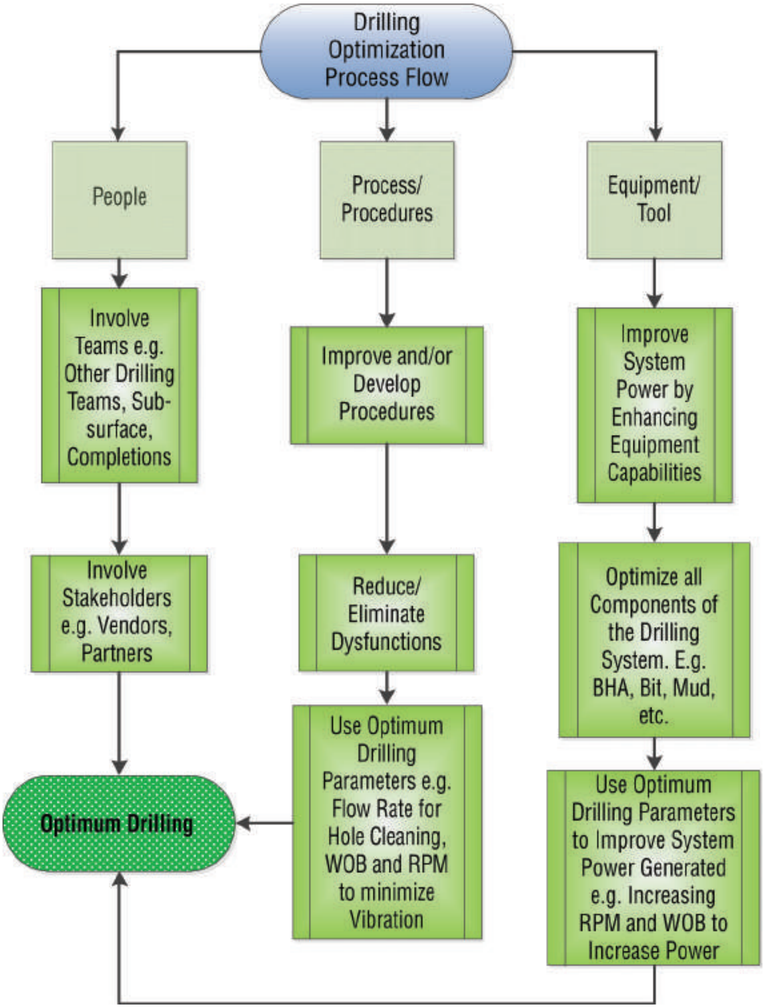


Figure 2.7: Drilling optimization process flow.

review offset risks and the result of the offset analysis should be incorporated into the new well design. The drilling engineer/team need to involve the stakeholders right from the beginning of the planning process. Drilling engineers should involve technical specialists, other teams/peers as needed. They should involve vendors and suppliers too, in order to utilize their specialized knowledge, new technology and database of offset wells since

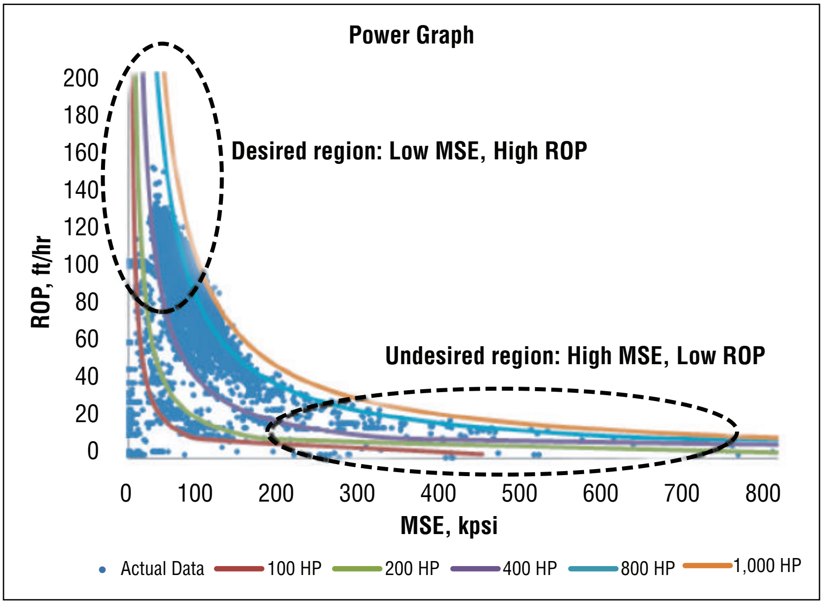


Figure 2.16: Power curve for a deep water well.

Note: Most data points fall in the desired region of high ROP, low MSE, and the transition zone. This is because ROP is not usually an issue because the rocks' compressive strengths are lower in deep water than onshore. For this particular well, pump relief valve set point as well as ECD limited the ability to increase the flow rate to clean the hole better to promote better transfer of energy to the bit (lower wellbore friction). With improved hole cleaning, if ECD and/or pump pressure do not limit flow rate, the data points in the transition zone could have moved to the desired zone on the plot. Real time vibration data did not suggest any issues due to vibration.

$$\text{Power}\left(HP\right) = 5.054\times10^{-7}\times E_m\times\left[\left(WOB\times ROP\right) + \left(377.14\times N_b\times T\right) + \left(\frac{6.765\times10^{-3}\times\rho\times Q^2\times D^2\times ROP}{d_e^4}\right)\right] \tag{2.3}$$

Where:

E_m = Mechanical efficiency ratio

MSE = Mechanical Specific Energy (psi)

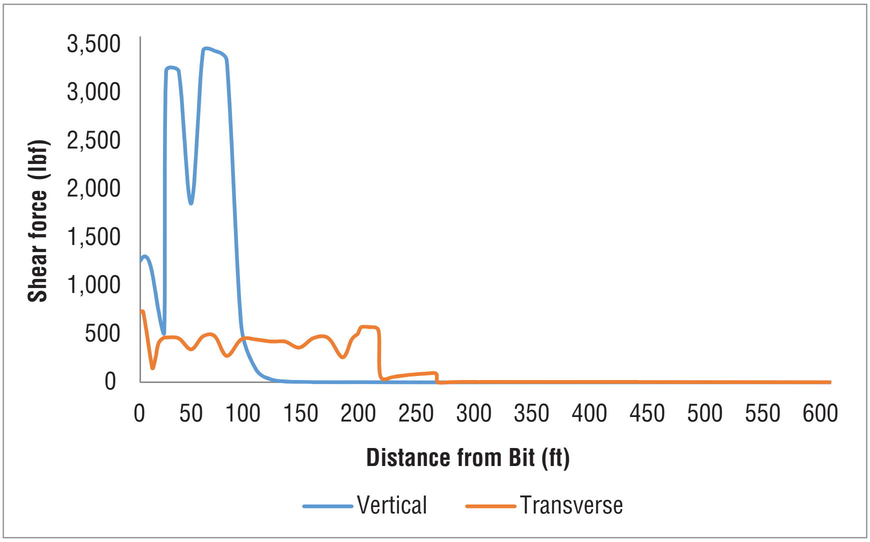


Figure 3.3: Shear force on drill string from critical speed analysis.

shear force. In this particular example, an MWD was placed at about 60 ft from the bit and it failed due to excessive vibration. This analysis was carried out after the failure but could have been really helpful and also saved a day of non-productive time if the analysis was done prior to designing the drill string as it would have helped with positioning the MWD away from the high stress zone.

In a major drilling program, it is recommended that vibration study should be undertaken in earlier wells to help determine ways to optimize ROP in subsequent wells. Downhole vibration tools should be run to understand the impact of drilling parameters and formation tendencies on vibration. Figure 3.4 is a typical output from a vibration recording downhole tool. When not financially constrained, it is good to test as many concepts as possible in earlier wells in order to capture as much learning as possible and then incorporate that into subsequent well plans.

Vibration could be axial, lateral, or torsional. See Figure 3.5. Axial vibration is the vibration along the longitudinal direction up and down the drill string. Lateral vibration occurs perpendicular to the length of the drill string. Axial and lateral vibrations occur because of insufficient downward force

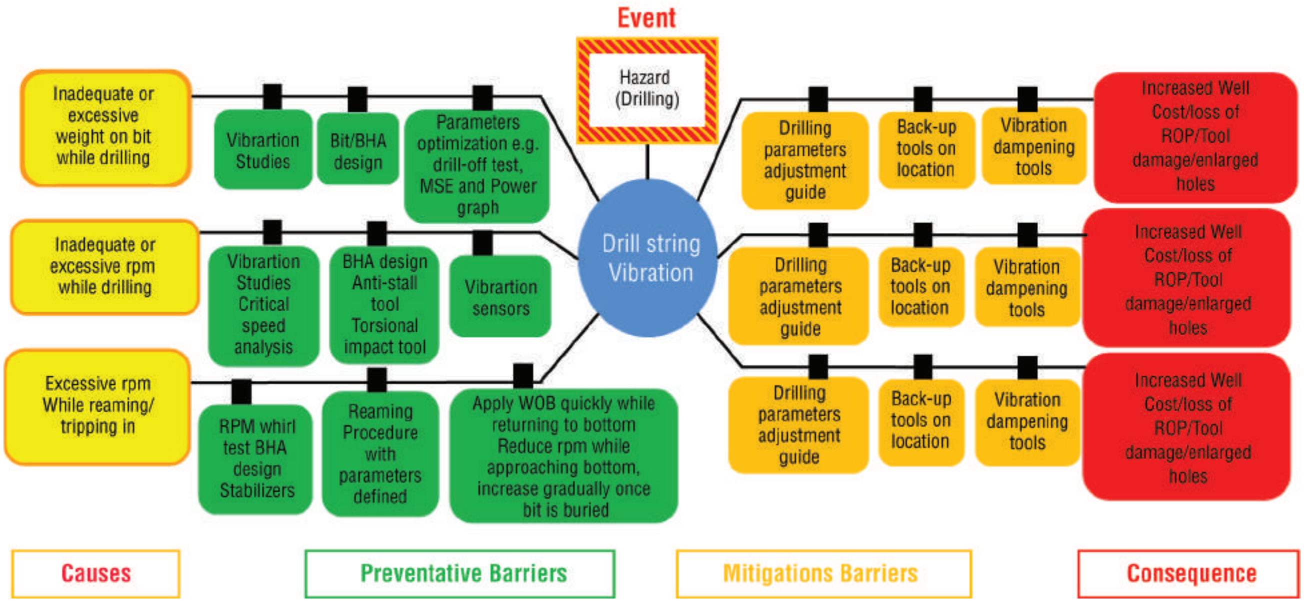


Figure 3.11: An example bow-tie for drill string vibration.

on the wellbore profile, critical RPM models may predict low drill string stress in RPM beyond the critical RPM range. In this case, the available RPM for hole cleaning is higher than the critical RPM.

Field experiments and laboratory studies suggest step increase in hole cleaning performance in high-angle wells at some RPM values. See Figures 4.3 and 4.4.

CUTTINGS CARRYING INDEX (CCI)

Cuttings carrying index provides a good idea on how good hole cleaning is. A CCI above 1.0 indicates good hole cleaning and a CCI below 0.5 is an indication of poor hole cleaning. See the following equations for CCI estimation.

$$CCI = \frac{K \times AV \times MW}{400,000 \times \left(1 + \sin\left(\theta\right)\right)}$$

where

K = Low shear rate viscosity/Power law constant

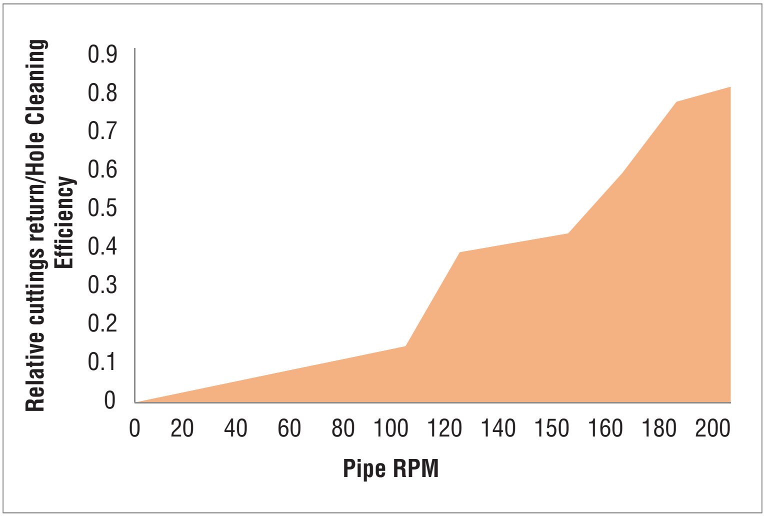


Figure 4.3: Cuttings return/hole cleaning variation with RPM. Larger step changes in cutting return volume occur at 100–120 RPM and at 150–180 RPM.

time, inefficient hole cleaning, high torque and drag, pack-off, lost circulation, stuck pipe, and potential loss of wellbore are examples of factors that result in non-productive time caused by a compromise in wellbore stability. Wellbore instability can result in reduction or enlargement of the wellbore. Hole reduction limits the size of pipe that can be run, affecting casing running operation, pack-off, or lost circulation due to pumping into packed-off annulus, and also high ECD while cementing casing. Hole enlargement causes inefficient hole cleaning and a bad cement job. The root cause of wellbore instability should be identified and barriers/actions generated to address the risk. Wellbore stability problems can be formation related, drilling practices related, and/or drill string design related. The most effective way to solve wellbore stability problems is to eliminate the root cause where possible. However if elimination of the root cause is cost prohibitive, it is good to use other preventative and control options including mitigation and having a contingency plan. See Table 7.1.

Table 7.1: Barriers for wellbore instability.

Elimination	• Identify fractures, weak/rubble zones and faults from seismic and modify well trajectory where possible. • Minimize wellbore inclination especially in formations prone to wellbore instability. • Drill in the direction of maximum horizontal stress if difference between minimum and maximum horizontal stresses is large.
Prevention	• If the root cause in offsets is formation or fluid related, proactively increase the mud weight and salinity to mud weight required per wellbore stability model prior to drilling the formation. Add fluid loss additives to control fluid loss. If losses are anticipated, proactively add lost circulation materials to the mud system. See the section on lost circulation. • Optimize trip speed to prevent swab and surge while pulling out of hole and running in hole with casing and drill pipe, increase the mud weight by trip margin prior to tripping or pumping while tripping pipe out of hole for ECD "pump out".
	• Use continuous circulation subs while making or breaking connections to enable continuous circulation

The equation for summing up an arithmetic series is given by

$$Sum = \frac{n}{2} \times \left[2a + \left(n - 1 \right) d \right] \tag{8.6}$$

where

n = Number of terms in the series – this is same as number of footage (pump and dump interval length-L)

a = First number in the series – this will be same as K

d = Common difference between two terms – this is also equal to K

Equation (8.6) can be written as:

$$V_{PAD} = \frac{L}{2} \left[2K + \left(L - 1 \right) K \right] = \frac{L}{2} \left[K + KL \right]$$

$$V_{PAD} = \frac{LK}{2} \left[1 + L \right] \tag{8.7}$$

$$V_{PAD} = \frac{L}{2} \times \frac{D_h^2}{1029.4} \left[1 + L \right] \tag{8.8}$$

$$V_{PAD} = \frac{L \times D_h^2}{2058.8} \left[1 + L \right] \tag{8.9a}$$

$$L \gg 1; \left[1 + L \cong L \right]$$

$$V_{PAD} = \frac{L^2 \times D_h^2}{2058.8} \tag{8.9b}$$

ESTIMATION OF DISCHARGE FLOW RATE DURING A WELL CONTROL EVENT

$$Q\left(bpm \right) = \frac{4.917 \times 10^{-6} kh \times \Delta P}{\beta\mu \times ln \left[\left(\frac{r_e}{r_w} \right) + s \right]} \tag{8.10}$$

$$M = \frac{4.917 \times 10^{-6} kh}{\beta\mu \times ln \left[\left(\frac{r_e}{r_w} \right) + s \right]} \tag{8.11}$$

Figure 12.4: Solid body centralizers with stop collars.

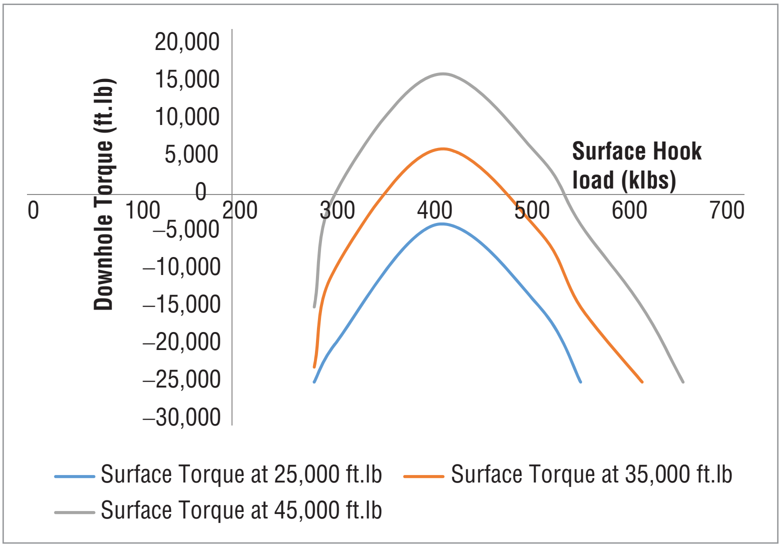


Figure 12.5: Plot of downhole torque at stuck point vs. Hook load. A combination of surface torque and hook load should be sufficient to deliver required torque at stuck point.

Geometrical sticking can be prevented by proper well design that has minimum tortuosity, no excessive dogleg and proper BHA selection that minimizes key seating (see Wellbore Trajectory Optimization in Chapter 15). Offset wells and experience in the area should provide useful information necessary to select BHA components. Mitigations

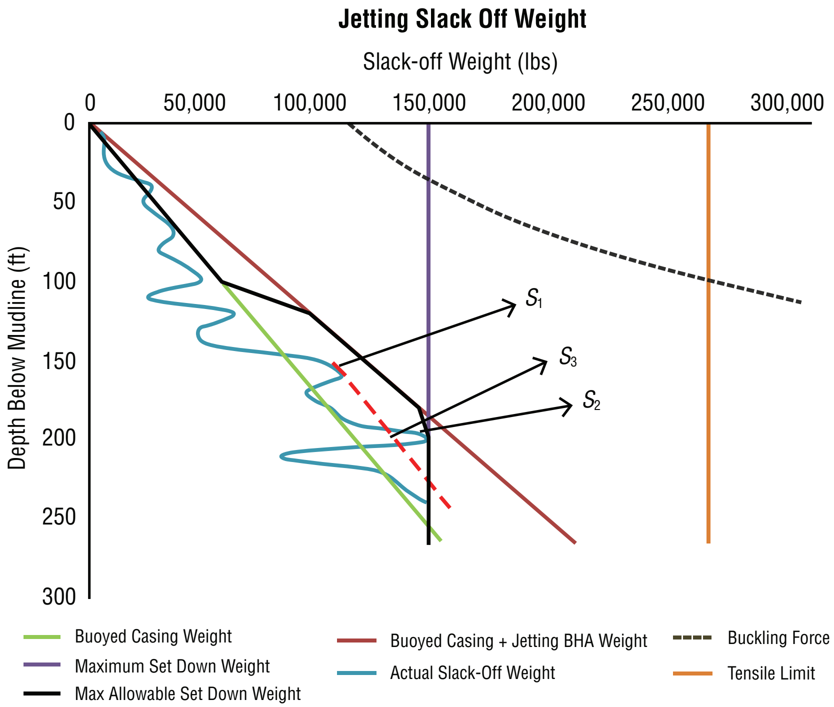


Figure 13.3: Determination of rate of strength development from plot of weight on bit while jetting.

2. Note the corresponding depths of the values above (L_2 for S_2 and L_1 for S_1).
3. Project a line from S_1 parallel to buoyed casing weight line to S_2. The point at which the depth corresponds to S_2 on the projected line is S_3.
4. Estimate the average ROP between the two points (ROP in ft/min).
5. Calculate time taken from L_1 to L_2 (T_{dr}) using

$$T_{\mathrm{dr}}\left(\mathrm{hr}\right) = \frac{L_2 - L_1}{\mathrm{ROP}_{\mathrm{ave}}\left(ft\,/\,min\right) \times 60}$$

6. Calculate the rate of change of slack-off value using

$$S_r = \frac{S_2 - S_3}{T_{dr}}$$

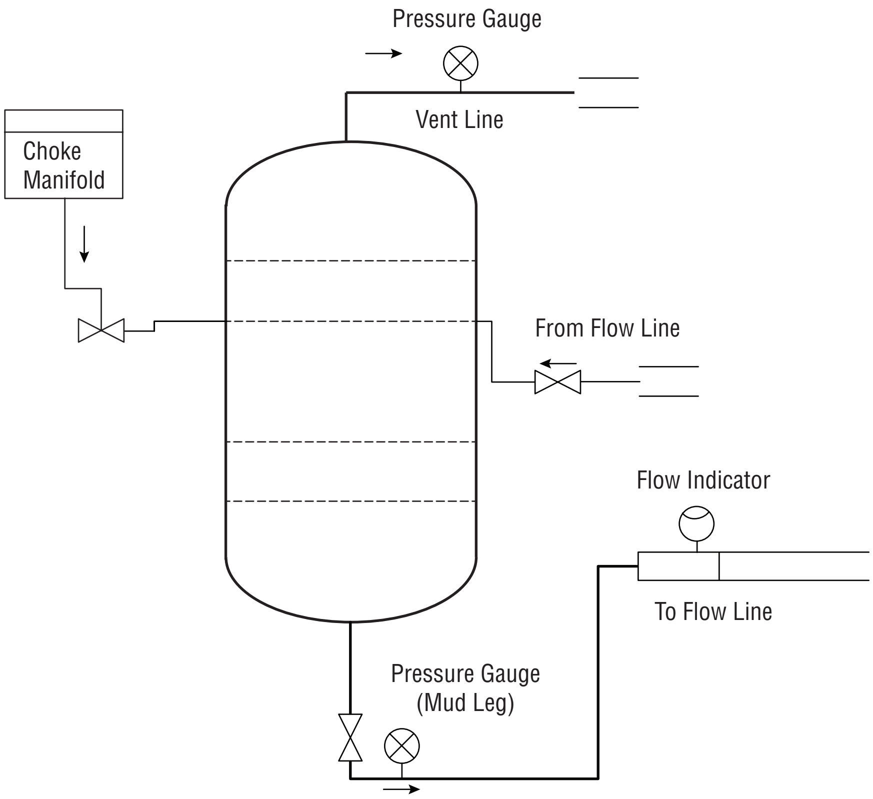


Figure 14.1: Mud gas separator.

$$Q_{\text{gas surface}}\left(\frac{\text{MMSCF}}{\text{day}}\right)=\sqrt{\frac{\Delta P_{ml}\times d_v^5}{4.39\times 10^4\times f\times \rho_g\times L_e}} \tag{14.3}$$

where

ΔP_{ml} = Pressure of mud leg (psi)

ρ_{mud} = Density of mud (ppg)

ρ_g = Density of gas (ppg)

f = Friction factor

d_v = Vent line diameter (in)

h_{ml} = Height of mud leg (ft)

L_e = Vent line equivalent length (ft)

Table 15.2: An example hole sizes optimization for all the hole sections in a well.

Hole Size	Capacity	Casing Size	Initial Clear-ance	New Hole Size	New Clear-ance	New Clearance with 70% Stand-off	BHA OD (40% flow area)	Maximum BHA OD (25% flow area)	Equiva-lent Hole Size(EHS)	EHS for Maximum BHA	EHS > Casing size	EHS Max BHA > Casing size
in	bbl/ft	in	in	in	in	in	in	in	in	in		
36.100	1.26599	36.00	0.050		Jetted							
32.500	1.02608	28.000	2.250	32.000	2.000	1.400	24.79	27.71	29.60	30.57	Yes	Yes
26.000	0.65669	22.000	2.000	24.000	1.000	0.700	18.59	20.78	22.20	22.93	Yes	Yes
22.000	0.47018	18.000	2.000	20.000	1.000	0.700	15.49	17.32	18.50	19.11	Yes	Yes
19.000	0.35069	16.000	1.500	18.000	1.000	0.700	13.94	15.59	16.65	17.20	Yes	Yes
17.000	0.28075	14.000	1.500	16.000	1.000	0.700	12.39	13.86	14.80	15.29	Yes	Yes
14.500	0.20425	11.875	1.313	14.000	1.063	0.744	10.84	12.12	12.95	13.37	Yes	Yes
12.250	0.14578	9.875	1.188	12.000	1.063	0.744	9.30	10.39	11.10	11.46	Yes	Yes
9.875	0.09473	7.750	1.063	9.875	1.063	0.744	7.65	8.55	9.13	9.43	Yes	Yes

For 10,000 ft of 14" casing run in singles, total connection time, T_s:

$$T_s = \left(\frac{10{,}000}{46} - 1\right) \times 0.048 = 10.39\,\text{hours}$$

For 10,000 ft of 14" casing run in triples, total connection time, T_t:

$$T_s = \left(\frac{10{,}000}{140} - 1\right) \times 0.048 = 5.16\,\text{hours}$$

For a rig with a spread rate of $1.2 million dollar per day, cost per hour is $50,000

Cost Savings = (10.39 – 5.16) × 50,000

= $261,000 less cost of bucking, storage and transportation

Figure 15.3 shows time savings as a function of number of joints per stand and slip to slip time for the example above.

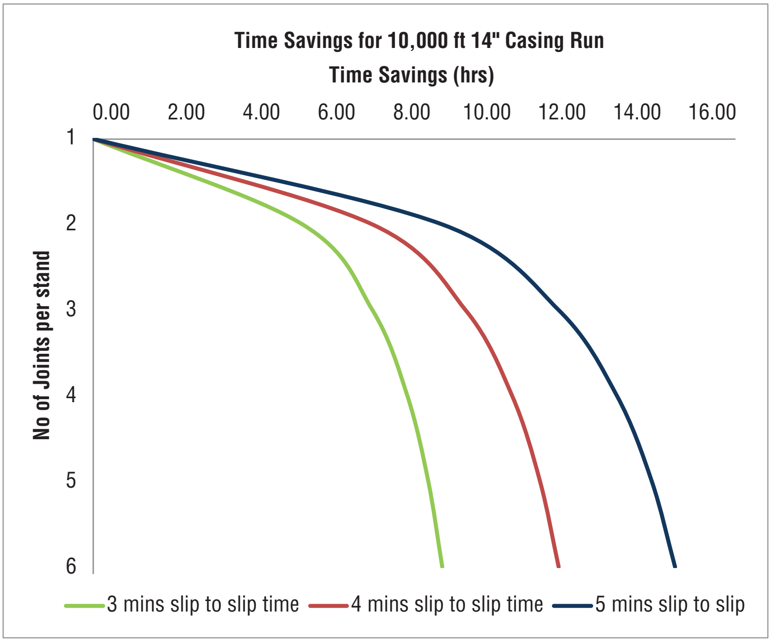


Figure 15.3: Example time savings for 10,000 ft of casing run for different slip to slip time.

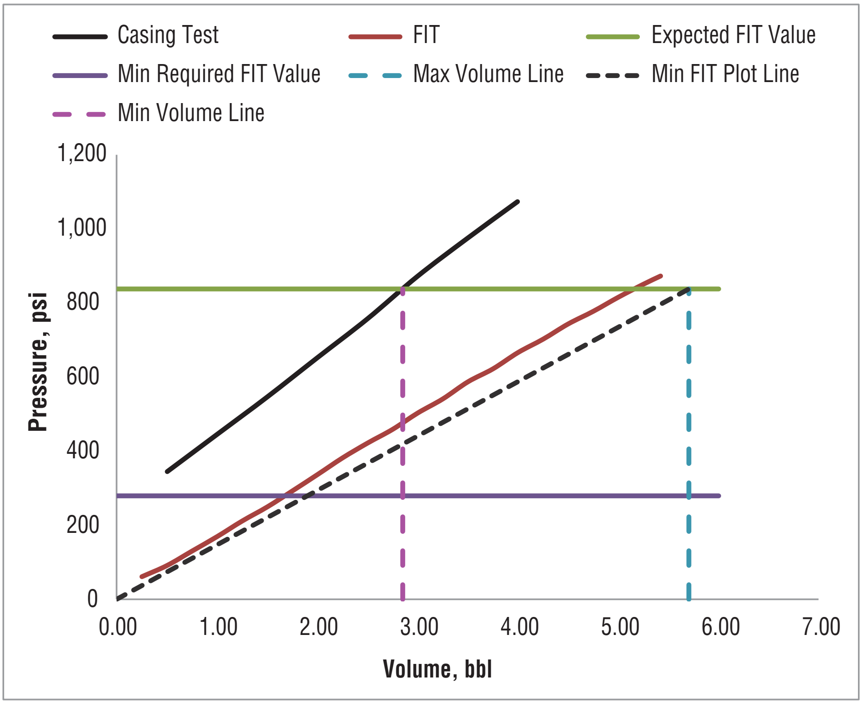


Figure 15.13: Determination of FIT pump rate from casing test and expected FIT value.

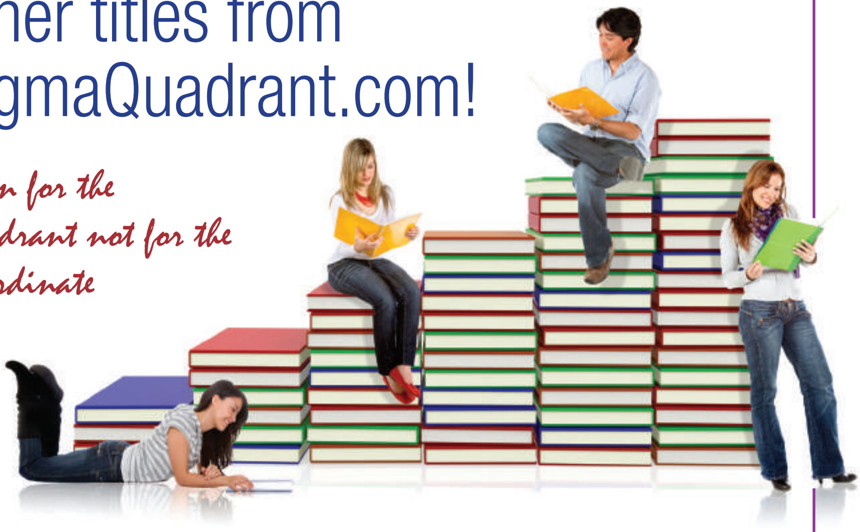
Minimum required FIT value in psi can be calculated from:

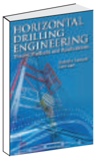
$$\text{Minimum Required FIT(psi)} = 0.052 \times \text{required drilling margin(ppg)} \times \text{Shoe TVD} \quad (15.28)$$

The required drilling margin is typically 0.5 ppg margin above the mud weight.

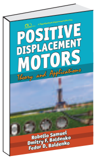
INNER STRING CEMENT JOB (CONSIDER FOR LARGE OD CASING CEMENT JOBS)

Use inner string cement job in all casing cemented prior to running BOP (riserless section). Inner string will help avoid problems in drilling wiper plug, plug spinning, and also to avoid contamination of casing ID,





HORIZONTAL DRILLING ENGINEERING



POSITIVE DISPLACEMENT MOTORS
Theory and Applications
Robello Samuel
Dmitry F. Baldenko
Fedor D. Baldenko

THIS BOOK is a practical guide to generate risk barriers required to manage risks and cost during well operations. Chapter 1 describes the basic principle of risk management (risk identification, risk assessment, risk barrier creation, and monitoring). This book covers drilling optimization and major drilling operations; non-productive time events such as hole cleaning, casing wear, lost circulation, wellbore stability, well control and so on; and providing barriers to the risk events. These barriers are sometimes presented in a table or "bow-tie" form for clarity. This book also covers useful drilling calculations during well planning and operations as well as continuous improvement opportunities for well cost management (e.g., wellbore trajectory optimization, hole size optimization, casing running optimization, optimization of time to break circulation, wellbore monitoring during flow check, after cementing and so on.

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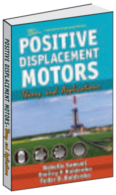

Positive Displacement Motors-*Theory and Applications*

by ***Robello Samuel***

Drilling Engineering Optimization

by ***Robello Samuel and J.J. Azar***

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Prosper Aideyan, P.E. holds a B.S. in Chemical Engineering from Louisiana Tech University and an M.Eng. in Petroleum Engineering from The University of Houston. He has over 10 years of multi-disciplinary experience in well planning and design, well operations, and process safety with major oil and gas companies.

He is very passionate about continuous improvement and optimization including but not limited to equipment design and re-design, process and procedural improvement, and process parameters optimization. His book on Drilling Operations: Cost and Risk Management is based on his experience from various successful drilling engineering and operations improvement projects he has worked on during the course of his career. Prosper Aideyan is a registered Professional Engineer in the State of Texas, USA.

σQuadrant
A SigmaQuadrant Engineering Publication
www.Sigmaquadrant.com

ISBN 978-0-9906836-2-9
9 780990 683629 >
ISBN: 978-0-9906836-2-9