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# Case-based drilling curricula using integrated HIL simulator and remote collaboration center

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# Case-based drilling curricula using integrated HIL simulator and remote collaboration center

**by**

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**Thesis**

Presented to the Faculty of the Graduate School of
The University of Texas at Austin
in Partial Fulfillment
of the Requirements
for the Degree of

**Master of Science in Engineering**

**The University of Texas at Austin**
**December 2016**

# Dedication

To *Mahyar* and *Shiva*. Still not sure if I should call you my parents or my friends. But I am sure that it was all because of you that I was able to get to where I am now. It was your sacrifices and guidance that brought me here. You provided so all I had to do was to follow my dreams. I hope this brings a smile to your face. Love you.

# Acknowledgements

On fall 2013 and in the process of applying to graduate schools, I watched a video on YouTube. In that video a charismatic man was talking about the opportunities for Mechanical & Aerospace engineers in Oil & Gas industry following by a demonstration of the drilling simulation laboratory. After googling his name and discovering his accomplishments, I was extremely interested to be part of his team. A year later I was sitting in the front row of the class that he taught. His enthusiasm for drilling and leadership skills were evident. After being persistent, he agreed to look at my résumé and gave me a chance to be part of his team. Dr. von Oort, I cannot express how grateful I am for the opportunity you gave me. It will be always my greatest accomplishment that I worked under supervision of such accomplished leader.

Dear Dr. Pryor, the first time that we met and I heard your perspective for this project, I thought it was not achievable. I realized how wrong I was when we ran the surge and swab laboratory for the first time. You taught me that no matter how unreachable my goals seem, I should not give up. Your positivity, support and patience were the main reasons to get to where we are now.

# Abstract

## Case-based drilling curricula using integrated HIL simulator and remote collaboration center

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The University of Texas at Austin, 2016

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The university educational system has raised many concerns in recent years regarding the effectiveness of its curricula and implementation. The focus on course-based training in engineering programs does not provide students sufficient opportunities to apply the attained knowledge and skills to demonstrate their competency. To address this deficiency of academia, industry spends millions of dollars building development programs and on-the-job training. This creates an opportunity for the universities to address this deficiency and increase their students' marketability, while also addressing problem solving in their curricula.

Inspired by a successful program developed and offered at Harvard Business School, the advantages and disadvantages of the case-based method was investigated. It was concluded that the students can benefit the most from a combination of existing educational and case-based curricula elements. Further research expressed the engineering students' interest and positive feedbacks towards utilization of this method supported by statistical analysis.

The aviation industry experienced a great training cost reduction and eliminated the on-the-training accidents after adopting simulators to train their workforce. This encouraged the Drilling & Automation team at University of Texas at Austin to develop the existing surface simulator further and utilize it as a tool to train the next generation of engineers to carry out the appropriate performance at the time of failure and emergencies.

By considering various effective skills development methods such as *Triadic method* and *Kolb's Four-Stage Learning Cycle,* ten case-based laboratories were designed and proposed. These open-ended student-led laboratories provide the opportunity for students to experience life-like challenges associated with drilling operations using a realistic up-to-date virtual drilling simulator. Students are divided in teams and assigned to different roles (drilling engineer, remote supervising engineer, etc.) where they are required to make decisions and communicate with one another. This creates a realistic work environment where depending on difficulty of each case, different amounts of stress are experienced.

To implement the proposed laboratories, down-hole physics models were identified and developed. These mathematical models were then simulated in MATLAB programing language and integrated with one another to form the down-hole simulator. An Application Program Interface, API, was developed to access the surface simulator data and to connect the surface and the down-hole simulators. The integrated developed simulator has potential for future research including automated rig design.

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# 1 Introduction

There have been many concerns over the past years regarding the university education system and the excessive focus on course-based training while demonstrating practical problem solving skills are ignored. To perform a certain task successfully and efficiently one needs knowledge, skills and opportunities to practice and apply the attained knowledge and skills. To address this deficiency, industry often spends millions of dollars building competency models, assessing skills, building development programs, and on-the-job training. According to Aggour, Donohue, and Donohue (2015), this creates great opportunities for universities to adopt the available competency models and implement them in their education system to make their program more effective at developing tomorrow's workforce to more effectively problem solving and apply their learned knowledge.

One of the biggest deficiencies in Petroleum Engineering programs and specifically in drilling engineering is lack of realistic simulators to train students. The existing simulators lack realistic interfaces to demonstrate various stages and challenges of drilling operations. They mainly focus on design aspects of the operation while other important aspects such as fast decision making, communication and etc. are ignored. This thesis presents the development process of a down-hole simulator as well as the process of integrating it with the existing state-of-the-art surface simulator which will be used as a tool to train engineers.

Based on the limitations associated with integration of the simulators, student-led case-based laboratories are proposed to be offered by the University of Texas at Austin Petroleum and Geoscience Engineering department. These laboratories are designed to address development of essential skills that are not gained through existing traditional educational system.

## 1.1 BACKGROUND

### 1.1.1 Motivation

The traditional engineering educational system focuses on teaching theories and examining students based on taught theories. The exams mainly require definitive answers while open-ended questions are uncommon. Due to this nature of engineering programs, the students lack critical thinking skills and thus are unable to relate their academic knowledge to their workplace and solve real-world, open-ended problems.

To address this deficiency a case-based teaching method is introduced. According to Berg (1990), case-based method allows students to experience the industrial setting without physical presence in the situation on a more convenient daily basis. Bilica (2004) asserts that utilization of open-ended cases develop students critical thinking skills in addition to their team work and communication skills.

Garcia et al (2012), Khan et al (2012) and Bozic (2014) conducted detailed studies on utilization of case-based studies in engineering curricula. The results of these studies agree upon effectiveness of the method to develop essential skills that are not addressed in traditional teaching method. They also express students' interest in learning through case-based method which can be used together with 3D virtualization to maximize students' enthusiasm for learning.

### 1.1.2 Case-based vs. Combination of case-based and traditional teaching methods

Harvard business school's MBA program is well known for its unique case-based teaching method. The MBA students at Harvard are evaluated solely based on their performance on over 500 business cases within the 2 years of the program. The cases simulate the problems that students might face in the future. To solve these cases, students must research the necessary theories and apply them in order to propose solutions.

Harvard MBA program has raised concerns regarding the effectiveness of the education that students get through this method. These concerns include the rapid change in companies' strategies to approach a problem, artificial nature of some cases and unrealistically providing too much information to the students. Critics believe that despite the benefits that one might obtain from these cases, solely relying on them while theories are not taught in classrooms, could negatively affect students in their future careers.

Considering both advantages and disadvantages of case-based learning method (discussed in more details in Chapter 2), this thesis proposes a combination of case-based and traditional teaching methods as a more effective tool to assist students in achieving higher competency levels for more in depth comprehension and better job marketability.

### 1.1.3 Drilling Simulators

Oil and gas industry adopted the developed technologies in aviation industry and implemented them to develop simulators. Similar to utilization of flight simulators for training purposes, the developed integrated drilling simulators (surface and down-hole) are used to train drillers, yet are not as common. There are many advantages associated with integrated drilling simulators. Offered trainings prepare drillers and engineers to react appropriately in emergency situations that cannot be experienced and taught in old-fashioned trainings.

According to Odegard et al (2013) utilization of integrated drilling simulators for students' education results in students' comprehension of their influence on wells and operations. Furthermore such simulators familiarize students with the state-of-the-art rig equipment. It is important to consider students' knowledge and capabilities while developing the down-hole part of the academia integrated simulators to prevent negative training.

The existing state-of-the-art NOV HIL Drilling Surface Simulator at the University of Texas at Austin has been utilized to demonstrate the components of a modern rig over the past years. This simulation environment includes two cyber-chairs which allow the operators to engage and move different components of the rig such as drawworks, top drive and etc. The presence of such surface simulator has offered the opportunity for the Rig Automation and Performance in Drilling (RAPID) consortium sponsored researchers at UT-Austin to develop a down-hole simulator and to integrate it with this surface simulator.

Figure 1-1 NOV HIL Drilling Surface Simulator

## 1.2 RESEARCH OBJECTIVES

The main goal of this thesis is to create drilling-related case-based laboratories based on real-life operation scenarios as complementary to traditional drilling classes offered at the University of Texas at Austin. The objectives to achieve this goal are as follow:

1. Design laboratories outlines to address the essential skills that are not gained through the traditional teaching method,

2. Adopt and utilize appropriate existing mathematical models from literature based on students' knowledge capabilities to develop a down-hole simulator,
3. Develop an Application Program Interface, API, to access the surface simulator's operation data and parameters,
4. Develop a platform to upload and execute the down-hole simulator models as a package in addition to feeding the accessed surface simulator's data into the down-hole models, and
5. To do design the system such that it is possible for future researchers to include more advanced models or develop new scenarios for teaching and/or research purposes.

## 1.3 APPROACH

The case-based laboratories are designed by considering various factors to maximize student learning outcomes. These factors include exposing students to "Kolb's Four Stage Learning Cycle" of concrete experience, reflective observation, abstract conceptualization and active experimentation. Additionally development of essential skills such as critical thinking, effective communication, decision making and etc. are addressed in these laboratories.

The laboratories are designed to engage students prior to execution of the cases. The students are asked to gather before each laboratory and review the necessary background knowledge and the operation procedure of the respective laboratory. They must discuss the possible containment actions and the countermeasures. This process navigates them through *Triadic Method* and ultimately develops their critical thinking ability.

After defining the laboratories outlines, the down-hole simulator is developed based on available mathematical models and is integrated with the existing surface simulator. The mathematical models are adopted complying with the undergraduate course (Drilling Engineering & Operations Management) that students must take prior/during these case-based laboratories.

The adopted mathematical models are implemented in MATLAB programming language. Each mathematical model is implemented in a separate function and the functions are combined to form the down-hole simulator. To increase the speed and efficiency of the down-hole simulator, discretization technique is utilized. This technique assumes constant properties along a predetermined length which for this thesis, the drill string and well are discretized into sections of one foot long. This technique allows modeling drill strings and well-bores with variable geometries as well as simulating multi-density mud in an efficient manner.

PLCs (Programmable Logic Controllers) are the computers where the surface simulator data are processed in the same way the data is processed on an actual rig; however, they generally do not have an interface for accessing the data. An Application Program Interface, API, is developed to access the PLCs data. The down-hole simulator is then integrated to the surface-simulator using a program written in Visual Basic IDE (Integrated Development Environment). This program serves as the bridge between the down-hole and surface simulators. It is capable of executing the API which is written in C++ as well as executing the MATLAB functions. It passes the surface simulator accessed data to MATLAB variables which are fed into the down-hole simulator. For each laboratory a Visual Studio Project file is created as a package consists of the API, the down-hole simulator functions and the connection interface between the two.

## 1.4 DELIVERABLES

This thesis delivers set of functions in MATLAB programming language that are combined with one another to form a down-hole simulator. It also delivers Visual Studio Project files that combine the necessary programs and functions to perform the proposed laboratories. It presents the laboratory handouts for students which provide them with the necessary knowledge, assignments, tasks and procedures to succeed in the laboratories. Below is the list of deliverable MATLAB functions that are developed to create the down-hole simulator:

- Initial Setting
- Bit Position
- Pipe Status
- Mud hydro-static head level
- Capacity
- Mud pumping
- Density discretization
- Diameter discretization
- Surge/swab pressure
- Frictional pressure loss and pump pressure
- Mud total pressure

- Axial force along the drill string
- Drill string buckling
- Rate of penetration
- Burst and collapse

The following is the list of deliverable laboratories packages (Visual Studio Project files and laboratories handouts):

- Introduction to drilling simulator
- Learning to trip in
- Learning to trip out
- Hydro-static pressure
- Surge & swab
- Learning to drill
- Buckling
- Rate of penetration
- Formation change
- Pipe burst

## 1.5 THESIS OUTLINE

This thesis is divided into 6 chapters. Chapter 1 discussed the motivation of this thesis and introduced the background knowledge, objectives and deliverables that understanding them is necessary in proceeding to next chapters. Chapter 2 introduces the competency models that can be used to boost the marketability of students. It goes over the advantages and disadvantages of case-based teaching method and proposes an effective teaching method. It then addresses the lack of essential skills development in engineering programs and offers a solution based on conducted experiences and applications of drilling simulators. Chapter 3 explains the lessons learned from the past experiences and important factors that must be taken into consideration to maximize student's learning outcomes. It proposes to integrate case-based laboratories into the existing curricula. It then illustrate the architecture and structure of proposed laboratories in addition to providing a list of them followed by justifications and detailed description of each. The mathematical models used to develop the down-hole simulator are discussed in Chapter 4. These models are adopted from the existing literature based on students' capabilities and the concepts covered in the prerequisite/corequisite course to minimize negative training. Chapter 5 explains the process of down-hole simulator development. It reviews the MATLAB functions that are developed based on the mathematical models following by functions developed to optimize the down-hole simulator. It describes the data acquisition, initialization, and synchronizing the behaviors of the developed codes, simulator hardware, and RTC visualizations. Chapter 6 provides the conclusions and lessons learned from this thesis in addition to recommendations for future work.

# 2 Literature Review

In this chapter, initially the importance of adopting competency models will be discussed following by investigating the effectiveness of case-based education in developing student competency. Specifically, the MBA program offered at Harvard Business School is studied to understand the advantages and disadvantages of case-based education. Next lack of opportunity to develop certain important skills such as communication and critical thinking skills in engineering programs are addressed.

A solution to assist engineering students to develop these necessary skills to succeed in their careers is proposed. The proposed solution suggests utilizing state-of-the-art drilling simulators to simulate real-life-like scenarios to test students' responses in critical events and to develop their competency. Next to support the effectiveness of the proposed solution, flight simulators and case-based studies in Aerospace Engineering are studied following by the development of drilling simulators and their applications in case-based studies.

## 2.1 COMPETENCY

Adopting the competency models allows skills development in addition to attaining theoretical knowledge through assessment. Learning and development programs can bridge the gap between the industry expectations and the universities outcomes. Aggour et al(2015) use the competency guideline (shown in table 2-1) alongside with SPE technical knowledge for graduating engineer matrix (Blasingame, 2010) and suggests an industry style competency model for universities consist of 4 levels of skills for any specific competency which benefits universities, students and the industry. The required competency levels for a certain job at different companies could vary and a certain job for a driller engineer might require different levels of different competencies, i.e. a desired job may require level 1 of drilling bits competency and level 2 of drilling fluids competency while another position may require level 2 for both competencies. Using the model, the students can bridge the gap between their skills and their desired job requirements contingent upon the availability of the training (Aggour et al., 2015). Achieving level 2 and beyond requires experimental education which is difficult in drilling engineering due to size and hazardous nature of the equipment; a similar problem that was previously faced by aviation industry until the utilization of the sophisticated flight simulators.

| **Level 1 Awareness** | **Level 2 Basic Application** | **Level 3 Skillful Application** | **Level 4 Mastery** |
|---|---|---|---|
| Understands basic principles | Has broad knowledge of principles and applications | Has detailed knowledge of principles and applications | Has full understanding of principles and practices |
| Has general awareness of the knowledge, skill, or procedures and its applications | Participates in routine applications | Stays current with new developments | Has detailed knowledge of industry trends, standards, and experiences |
|  | Participates in designing field applications | Understands and applies industry codes, standards, and regulations | Develops and transfers knowledge throughout the company |
|  |  | Participates in industry initiatives in subject area | Directs and supervises work |
|  |  | Shares information, best practices, and lessons learned | Develops company guidelines and strategies |
|  |  |  | Leads networks, mentors, and coaches |

Table 2-1 The Competency Levels(Jain & Ogle, 2015)

## 2.2 CASE-BASED STUDIES

Case-based educational system focuses on the students' decision making skills in diverse real life simulated problems that are created by the faculties. It requires students to learn the necessary theories on their own, get more engaged in discussion and defend their ideas as opposed to the traditional teaching methods which consist of lectures and traditional examination methods where the necessary theories to solve a problem is taught in classroom. The latter method could be accomplished by memorization of theories or by having an understanding of a simple procedure to approach a specific problem (Tucker, 2013).

According to Harvard Business School in the case-based learning method, a complete set of information necessary to approach a problem is given to the students. Similar to a real world problem, there is no definite solution and various approaches are taken to solve each case. A process that involves receiving different perspectives, debating, defending ideas and the skill of using experience and knowledge to analyze the issue and make the final decision under time constraints and stress ("The HBS Case Method - MBA - Harvard Business School," n.d.).

### 2.2.1 Harvard Business School

Harvard business school offers a MBA program in which the students are evaluated solely based on their performance on over 500 business cases within the 2 years of the program. Each case addresses a specific typical challenge relevant to the current business world. The cases are simulations of the problems that students may face in the future. Upon facing the problem, the students research the appropriate theories, analyze them, compare various approaches outcomes and come up with a set of recommendations. Once the students have their solution and before the final meeting with the professor, they gather and exchange their opinions in teams to “warm up”. In the class and under guidance of the professor over 90 students with different backgrounds discuss, debate and defend the solutions to suggest a final course of action. Almost 85 percent of the talking is done by the students which puts them in a situation very similar to what they will experience in their jobs (“The HBS Case Method - MBA - Harvard Business School,” n.d.).

The case-based system targets the development of skills essential in the business leadership. The students learn to build confidence and to defend their ideas against opponents using facts and analysis. Even though it requires more effort and time, it is more entertaining as students can sympathize and get emotionally involved, resulting in exhilarating feeling once the final solution is achieved. (Tucker, 2013)

Despite all the benefits that the case-based education provide, relying solely on case-based system arises some concerns regarding the education effectiveness. Wharton School of the University of Pennsylvania and Columbia University Business School are two of many institutes that are cautious to allow the case-based system to replace the traditional system due to effectiveness concerns. In modern day, the strategies used to approach a problem change rapidly making it difficult to keep the cases updated and relevant. Even if the cases and lessons are relevant to the current business climate, they might become irrelevant and outdated by the time the students begin to work; putting the emphasis on importance of learning the foundation before anything else. In addition some cases are made from simple concepts which make them artificial, time consuming and frustrating as compared to traditional learning methods. Critics believe providing all the necessary information to solve a case is unrealistic and unlikely to happen at students' jobs. Vice Dean Amir Ziv states *"most cases are, in a sense, too complete. You get a 30-page analysis – everything you need to know is there and is already presented in a structured way."* (Tucker, 2013)

According to the news organization of the Harvard Business School, The Harbus, some believe that due to the distinct characteristic of companies, the decision that is made in case-based education is unique and very specific to that company, thus making it impossible for students to learn the essentials to succeed through this method. Further concern arises from knowing the unknown in case based system which makes this method unrealistic since many information is gathered through trial and error in real world. This results in confusion and loss of confidence when a recent graduate experiences the situation. The mixture of the case based and traditional method exposes students to different situations with variable levels of provided information introducing them to different appropriate approaches including immediate decision making and decision making based on research (Harbus, 2011).

After giving full consideration to advantages and disadvantages of Harvard Business School case-based learning method, it is believed that a combination of case-based and traditional methods is more effective to assist students to achieve higher levels of competency outlined in table 2-1. The proposed method is to create the opportunity for students to have access to case-based drilling-related laboratories which are complementary to traditional drilling classes offered at the University of Texas at Austin.

### 2.2.2 Addressing Lack of Critical Thinking Skills in Engineering using Case-Based Studies

Ranky (2008) believes that the new generation of students differ from the past generations in many aspects. They are the video gaming generation who are extremely interested in virtual exploration. They are impatient with reading the static text books and are much more interested in real-world focused practical interactive learning methods. It is very beneficial to use this mentality in their favor and to make such learning methods more effective. Learning through exploration, trial & error, and without a fear of failure develops their problem-solving skills and makes them more self-critical. A cased-based learning method integrated with 3D virtualization can be utilized to maximize the students' interest in learning as well as their retention.

Depending on the objective of the instructor, different approaches can be taken to include cases in the teaching curriculum. Highly structured cases may be used to amplify the understanding of the theories while open ended cases have the potential to reinforce the importance of team work in addition to the critical thinking skills (Bilica, 2004).

Stanford University is a pioneer in integrating the case-based studies into the engineering field. Barrot (2001) enumerates the advantages of utilizing case-based system into the curriculum as four categories:

1. "Cases provide students with a link to the real world;

2. Cases develop students' critical thinking and problem solving skills;
3. Cases develop students' communication skills; and,
4. Cases involve students in a cooperative learning activity."

He expresses his concerns regarding the inability of the students to relate their academic knowledge to the workplace and solve real-world, open-ended problems. Various methods are utilized to bridge this gap including internships, seminars, workshops, projects and etc. The case-based system allows students to experience the industrial setting without physical presence in the situation on a more convenient daily basis (Berg, 1990).

In the real world, not all the necessary information to solve a case is known, therefore students utilize their critical thinking skills, problem-solving skills and logical reasoning to connect the dots. Due to the nature of engineering programs, the students lack critical thinking skills. This problem can be addressed by use of case-based teaching methods. The case-based method directs the students to develop their critical thinking skills by reasoning through presented data, figures, fact, theories and etc.

Two models are widely used in cased-base teaching method to develop students critical thinking and problem solving skills; teacher-led and student-led models. In the teacher-led model the professor controls the discussion and the students' participation is limited, while in the latter model the students direct the case to success and the professor interrupts when necessary. The students must get involved in the discussion, present their solutions effectively, defend them with logical reasoning, evaluate opposing alternatives based on the strengths and weaknesses and express their thoughts eloquently to come to a conclusion. In addition both models develops the students' communication skills to some extent. (Barrott, 2001).

*Triadic method* suggested by Friedman (1995) is one of many approaches to develop critical thinking skills through case analysis . In this method, students create contrary opinions and appraise them using the strengths and the weaknesses. This resolves the engineering students' inability to look for alternative solutions and forces them into logical reasoning skill development and critical thinking process.

The cooperative learning method is known as one of the most effective learning techniques where the essentials are learned through interactive discussions. Many researches have been devoted to discover the retention rates of the learner and the results all concur the previous statement (Stice, 1987).

| Learning Method | Retention By Learner |
|---|---|
| What They Read | 10% |
| What They Hear | 26% |
| What They See | 30% |
| What They See and Hear | 50% |
| What They Say | 70% |
| What They Say As They Do Something | 90% |

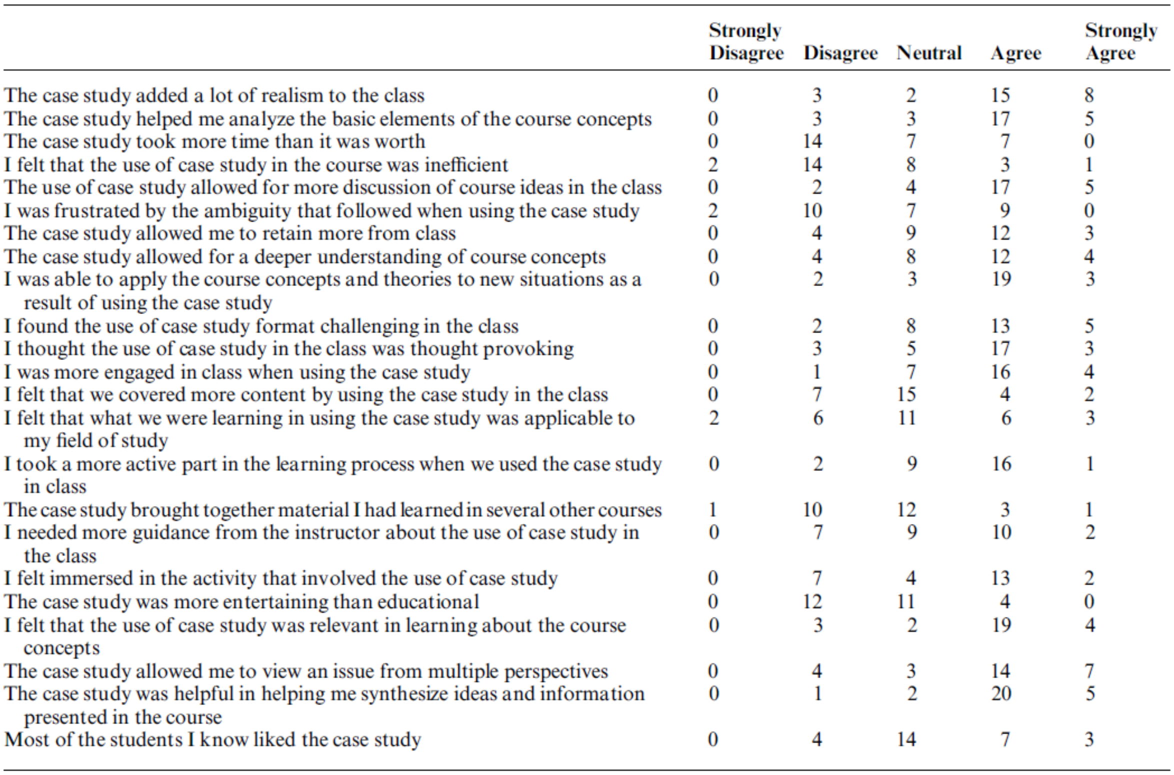
Table 2-2 Retention By Learner (Stice, 1987)

Kolb (1984) modeled the stages of learning, known as "Kolb's Four-Stage Learning Cycle", into four stages of: concrete experience, reflective observation, abstract conceptualization and active experimentation. The most effective learning is achieved by experiencing all the four stages of learning cycle. The process of solving a case-based scenario exposes the students to all the four stages resulting in significantly improved retention by the learner (Stice, 1987).

Paul Ranky (2008) with participation of over 250 partners from academia and industry has developed a 3D virtual case-based library to meet the desire for an interactive practical interface. This library demonstrates advanced industrial manufacturing facilities and techniques for the student using videos, images, panoramas and etc. The challenges regarding each case is presented in manner that engineers would face them at work environment. The customer requirements are taken into consideration first, then a solution is proposed based on the available machines and processes, following by a discussion opportunity.

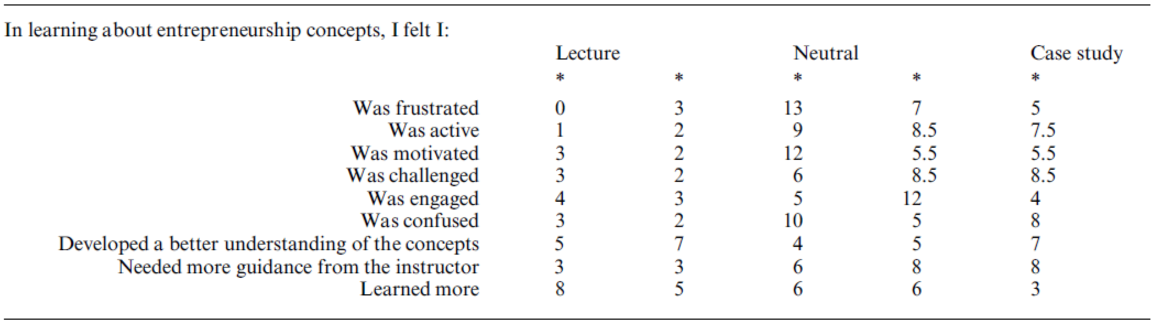
Bozic (2014) expresses her concerns regarding lack of innovation and idea generation skills development in the current undergraduate curriculum and proposes utilization of case-based instruction as a possible solution. Using instructor-led case-based discussion she examined 90 engineering students' attitude and interest toward the method for a specific case, disruptive innovation case study. The survey data was then collected to quantitatively determine the students' interest. 97.7% of the students believed that the case studies helped them to understand the theory and 80.2% agreed that it helped them to apply the theory.

Garcia et al (2012) conducted a detailed study on 28 engineering student's attitude on case-based exercise. The students were enrolled in a senior/graduate level course, Entrepreneurship and Business Strategy in Engineering, in Civil Engineering department of Purdue University. The subject was taught to the students in both lecture-based and case-based formats and focused on solving engineering related entrepreneurial cases. The students were then asked to participate in a Likert scale survey in order to measure their interest and engagement in the case study. Then they compared the experience gained from each method. From the survey results it was concluded that 81.5% of the students agreed on the ability of applying the theories to new situations as a result of the case study. 89.3% believed that the case study helped them to synthesize the information that was learnt in the class. 71.4% reported more engagement when case study was presented and 82.1% agreed on the effectiveness of case study on bridging the gap between the reality and the concepts learnt in the class. The results of the surveys are presented in the following tables:



| | Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree |
|---|---|---|---|---|---|
| The case study added a lot of realism to the class | 0 | 3 | 2 | 15 | 8 |
| The case study helped me analyze the basic elements of the course concepts | 0 | 3 | 3 | 17 | 5 |
| The case study took more time than it was worth | 0 | 14 | 7 | 7 | 0 |
| I felt that the use of case study in the course was inefficient | 2 | 14 | 8 | 3 | 1 |
| The use of case study allowed for more discussion of course ideas in the class | 0 | 2 | 4 | 17 | 5 |
| I was frustrated by the ambiguity that followed when using the case study | 2 | 10 | 7 | 9 | 0 |
| The case study allowed me to retain more from class | 0 | 4 | 9 | 12 | 3 |
| The case study allowed for a deeper understanding of course concepts | 0 | 4 | 8 | 12 | 4 |
| I was able to apply the course concepts and theories to new situations as a result of using the case study | 0 | 2 | 3 | 19 | 3 |
| I found the use of case study format challenging in the class | 0 | 2 | 8 | 13 | 5 |
| I thought the use of case study in the class was thought provoking | 0 | 3 | 5 | 17 | 3 |
| I was more engaged in class when using the case study | 0 | 1 | 7 | 16 | 4 |
| I felt that we covered more content by using the case study in the class | 0 | 7 | 15 | 4 | 2 |
| I felt that what we were learning in using the case study was applicable to my field of study | 2 | 6 | 11 | 6 | 3 |
| I took a more active part in the learning process when we used the case study in class | 0 | 2 | 9 | 16 | 1 |
| The case study brought together material I had learned in several other courses | 1 | 10 | 12 | 3 | 1 |
| I needed more guidance from the instructor about the use of case study in the class | 0 | 7 | 9 | 10 | 2 |
| I felt immersed in the activity that involved the use of case study | 0 | 7 | 4 | 13 | 2 |
| The case study was more entertaining than educational | 0 | 12 | 11 | 4 | 0 |
| I felt that the use of case study was relevant in learning about the course concepts | 0 | 3 | 2 | 19 | 4 |
| The case study allowed me to view an issue from multiple perspectives | 0 | 4 | 3 | 14 | 7 |
| The case study was helpful in helping me synthesize ideas and information presented in the course | 0 | 1 | 2 | 20 | 5 |
| Most of the students I know liked the case study | 0 | 4 | 14 | 7 | 3 |

Table 2-3 Student Responses to the Use(Garcia et al., 2012)



In learning about entrepreneurship concepts, I felt I:

| | Lecture | | Neutral | | Case study |
|---|---|---|---|---|---|
| | * | * | * | * | * |
| Was frustrated | 0 | 3 | 13 | 7 | 5 |
| Was active | 1 | 2 | 9 | 8.5 | 7.5 |
| Was motivated | 3 | 2 | 12 | 5.5 | 5.5 |
| Was challenged | 3 | 2 | 6 | 8.5 | 8.5 |
| Was engaged | 4 | 3 | 5 | 12 | 4 |
| Was confused | 3 | 2 | 10 | 5 | 8 |
| Developed a better understanding of the concepts | 5 | 7 | 4 | 5 | 7 |
| Needed more guidance from the instructor | 3 | 3 | 6 | 8 | 8 |
| Learned more | 8 | 5 | 6 | 6 | 3 |

Table 2-4 Comparison of Case-based and Lecture-based learning (Garcia et al., 2012)

## 2.3 FLIGHT SIMULATORS

### 2.3.1 Flight Simulators Evaluation

The history of the training using simulation dates back to over eighty years ago. In the 1960's the flight simulators were utilized in the commercial aviation and space programs due to many concerns including safety and training effectiveness. Without simulators it would not be possible to train the first astronauts to step on the moon (Page, 2000). In early 1900's flight simulation started with students learning to use the radar while taxiing using low powered machines, progressing to short hops and longer hops using the elevator controls and finally achieving flight (Turner, 1913). Then ground-based trainers were used to train the pilots where wind-facing airplanes were mounted to the ground. These methods were proven to be unsuccessful. The evolution of flight simulators progressed from utilization of analogue computers for instrument-system-Link trainers and visual-system-Link trainers to the current advanced state using digital computers (Page, 2000).

According to Page (2000) the aviation simulation industry faced many challenges in the process of developing the advanced simulators. These challenges include lack of required technology prior to the invention of digital computers as well as the computational challenges associated with them. The bad simulation resulted from inaccurate computation may result in negative training. Despite all those challenges there have many benefits for the aviation industry over the life of the flight simulators. The simulators, notwithstanding the inexactitude, were used during World War I for assessment of pilots' aptitude. During World War II, the need for large number of trained pilots was met by utilization of simulators (Notes on History of RAAF Training, 1939-44).

A historical point for the flight simulation industry was October 1973 when small number of airlines accepted the International Air Transport Association, IATA, offer to form a technical committee known as Flight Simulator Technical Sub-Committee, FSTSC, as a response to their unsuccessful earlier attempt in 1970 to regulate flight simulations. The formation of the IATA FSTSC committee resulted in common standards developed for both simulation industry and airframe/avionics suppliers. This effort gave credibility to flight simulation by both pilots and regulatory authorities. The aircrews are trained and licensed by using the flight simulators which results in great cost reduction as well as eliminating aircraft accidents while on training. It also makes it possible to learn what is impractical with real aircrafts including the aircrews training to carry out the appropriate performance at the time of failure and emergencies (Page, 2000).

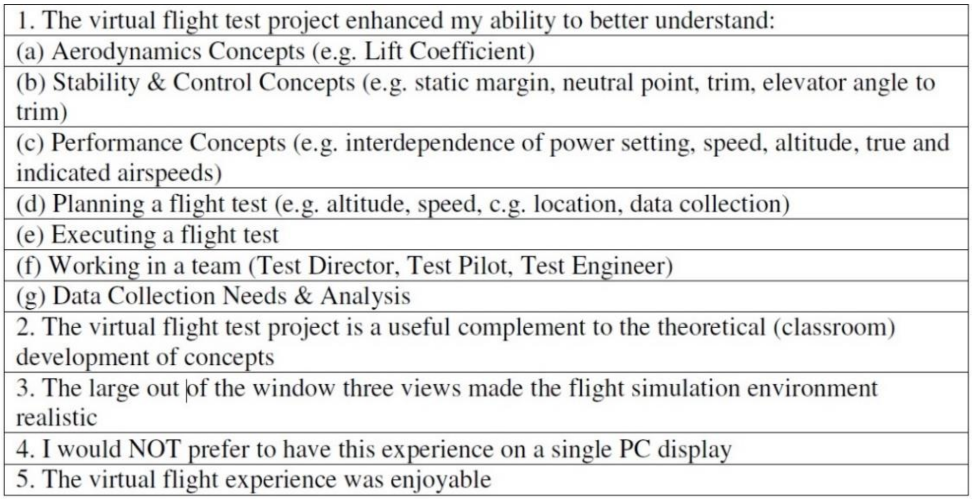
The oil and gas industry has the potential and a need to conform the aviation industry in forming a committee such as IATA FSTSC to standardize and enforce drilling training using simulators. Such act results in effective training that ultimately prepare drillers and engineers to react appropriately in emergency situations that cannot be experienced and taught in old-fashioned-trainings.

### 2.3.2 Case-Based Teaching in Aerospace Engineering

M. J Khan et al (2012) believe that incorporation of hands on experiences alongside with the learned theory would help students to have a better understanding of important concepts in Aerospace Engineering. This may be obtained by designing a small-scaled aircraft from scratch following by building and flying it. However their team has gone a step beyond that. They have built several realistic flight test scenarios and use them in Tuskegee University Aerospace Engineering curricula routinely. In their laboratory, they use Microsoft Flight Simulator FS2004 with three out-of-window views to provide a realistic feeling. The main objective of their laboratory is for groups of students to compare and relate the results obtained from the experiment to the theory and make decisions. I.e. finding the neutral point of an aircraft is one of the typical tests in their laboratory.

Each group consists of three students: flight test pilot, flight test engineer and flight test director. Prior to the laboratory, the students gather and plan the flight parameters including speed, altitude, loading, etc. that are relevant to the objective of the test. During the laboratory, the flight test pilot flies the aircraft, the flight test director is responsible to assure that the right data is recorded and the flight test director ensure that the fly is according to the flight plan.

The students participates in a 5-point Likert scale survey at the end of the course to evaluate the effectiveness of the laboratories. The survey questions and the results are shown in Table 2-5 and Figure 2-1 respectively.



1. The virtual flight test project enhanced my ability to better understand:
(a) Aerodynamics Concepts (e.g. Lift Coefficient)
(b) Stability & Control Concepts (e.g. static margin, neutral point, trim, elevator angle to trim)
(c) Performance Concepts (e.g. interdependence of power setting, speed, altitude, true and indicated airspeeds)
(d) Planning a flight test (e.g. altitude, speed, c.g. location, data collection)
(e) Executing a flight test
(f) Working in a team (Test Director, Test Pilot, Test Engineer)
(g) Data Collection Needs & Analysis
2. The virtual flight test project is a useful complement to the theoretical (classroom) development of concepts
3. The large out of the window three views made the flight simulation environment realistic
4. I would NOT prefer to have this experience on a single PC display
5. The virtual flight experience was enjoyable

Table 2-5 Student Survey Questions (M. J Khan et al 2012)

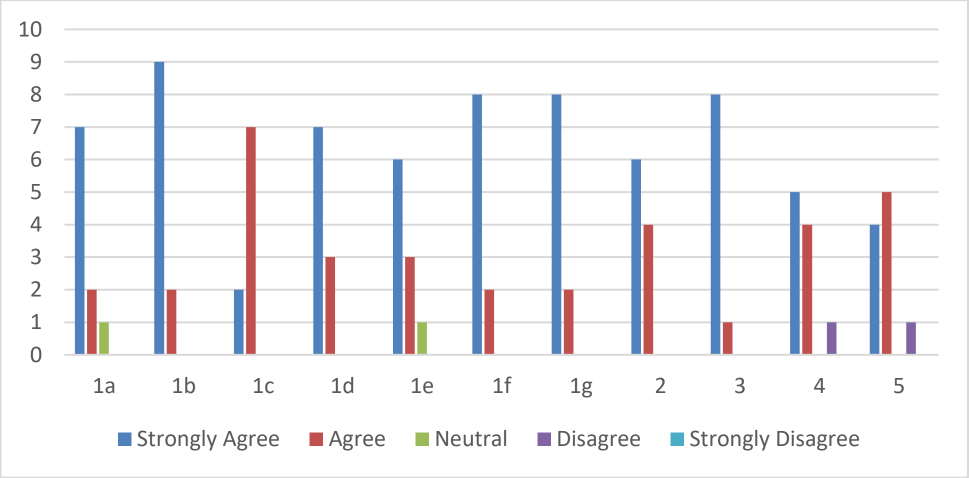


Figure 2-1 Survey Result (M. J Khan et al 2012)

Drilling industry and the aviation industry are similar in many aspects; drilling operations cost millions of dollars and its hazardous nature makes students hands-on training impossible. It is crucial to train engineers to have an in-depth understanding of concepts that are taught in the classrooms. Using realistic training methods creates the opportunity for students to test and observe the outcomes of their design in an operation i.e. design of the drill stand and its effects on surge/swab, maximum allowable tripping speed, maximum possible ROP and etc.

## 2.4 DRILLING SIMULATION ENVIRONMENTS AND CASE-BASED TRAINING

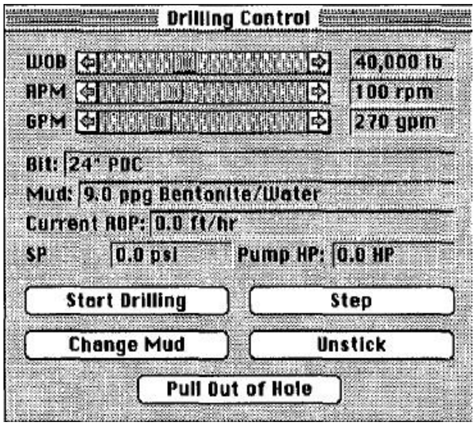
Oil and gas industry did not have to go through challenges that aviation industry faced over the past years to develop simulators and the developed technology was adopted. Many drilling simulators are developed and used to train drillers, yet the use of drilling simulators is not as common as the use of flight simulators, an issue that is addressed in this thesis. Furthermore, most drilling simulators are for procedural training. Physics-based simulators are significantly less common.

Traditionally the simulators are classified in two groups; first type focus on the design aspects of a well while second type have integrated the real drilling hardware to make it more realistic. The first type intention is to accurately calculate the effects of changing parameters for a specific well while the second type is mainly used to train drillers. The first type uses very complex models where a large number of inputs must be defined and due to the numerical calculation complexity it requires some time to perform the calculation and real time simulation is not achievable. On the other hand the second type uses bulky equipment which are usually very expensive (Cooper, Cooper, & Bihn, 1995).

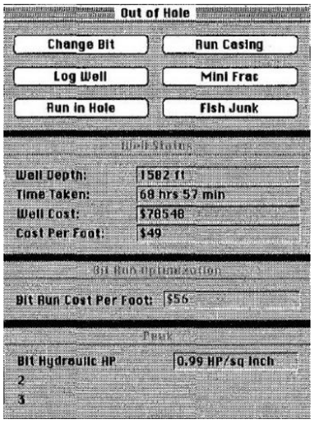
### 2.4.1 Cooper Drilling Simulator

George Cooper et al (1995) developed a drilling simulator with the purpose of drilling process optimization where their simulator was combination of the two mentioned types. Their simulator is simple and uses a realistic interface. In their simulator, the student/instructor chooses the subsurface lithology and the appropriate pore pressure, pressure gradient, bit type, etc. Once the initial parameters are defined, the operation begins and the driller is responsible to react to certain situations such as changing mud density to avoid fracturing or receiving kick. The simulator allows students to stop drilling, tripping out to change the bit or to run casing and trip in again to continue drilling. Figures 2-1 and 2-2 illustrates the parameters and functions that the operator has control over during tripping and drilling process.

The user is allowed to choose the operation complexity by selecting the parameters that affect the rate of penetration, i.e. considering bit wear or mud flow rate versus not considering them in ROP calculation. Based on the complexity level throughout the operation, the simulator checks for realistic possible failures such as an inadequate mud flow rate for cutting transport or exceeding the maximum pump pressure. Errors are then communicated to the operator who can address the issue.



WOB 40,000 lb
RPM 100 rpm
GPM 270 gpm
Bit: 24" PDC
Mud: 9.0 ppg Bentonite/Water
Current ROP: 0.0 ft/hr
SP 0.0 psi
Pump HP: 0.0 HP



Well Depth: 1582 ft
Time Taken: 68 hrs 57 min
Well Cost: $78548
Cost Per Foot: $49
Bit Run Cost Per Foot: $56
Bit Hydraulic HP 0.99 HP/sq inch
2
3

Figure 2-2 Drilling Control Panel
(Cooper et al., 1995)

Figure 2-3 Tripping Control Panel
(Cooper et al., 1995)

### 2.4.2 eDrilling Solutions Integrated Simulator

According to Odegard et al(2013), one of the most advanced drilling simulators of the second type is developed by their team. They integrated a surface simulator and a down-hole simulator. The down-hole simulator is developed using the most advanced models available in the literature.

These models take into account both transient and steady state conditions in order to be as accurate as possible. The down-hole simulator models includes pressure, flow, torque and drag, cutting status, pore pressure, rate of penetration, vibration, mechanical earth model and etc. The downhole pressure and flow model, one of many models used in the down-hole simulator development, is capable of calculating pressure, temperature and fluid volume during drilling, circulation and displacement. It calculates the dynamic effects of surge and swab as well as the transient pressure/flow while resuming circulation after static periods. The implemented torque and drag model takes into account the effects of string elasticity, buoyancy and etc. in order to calculate the correct bit depth. The advanced rate of penetration model allows realistic trend data modeling to be used in well control trainings such as drilling break and negative drilling break (Odegard et al., 2013; Rommetveit et al., 2007).

The surface simulator is developed based on a modern offshore rig and includes equipment such as drawworks, iron roughneck, mud pumps, trip tank, fingerboard and etc. It includes two cyber chairs as control system which are manufactured to be similar to those used in the drilling station (Odegard et al., 2013).

According to Odegard (2013) the main objective of utilizing this simulator is to have an early understanding of an actual well to be drilled and for the operators to be as prepared as possible for upcoming challenges and potential problems which results in safer and cheaper operations. Creating realistic scenarios by taking into account the dynamic effects, temperature effects, downhole pressure changes and etc. results in effective training of the operation team. The existing training scenarios that eDrilling Solutions offers includes:

- Drilling and tripping operations
- Stripping operations
- Connections
- Multi fluid operations
- Well control (kick and losses)
- Through Tubing Rotary Drilling
- Managed Pressure Drilling
- High Pressure High Temperature

- Extended Reach Drilling

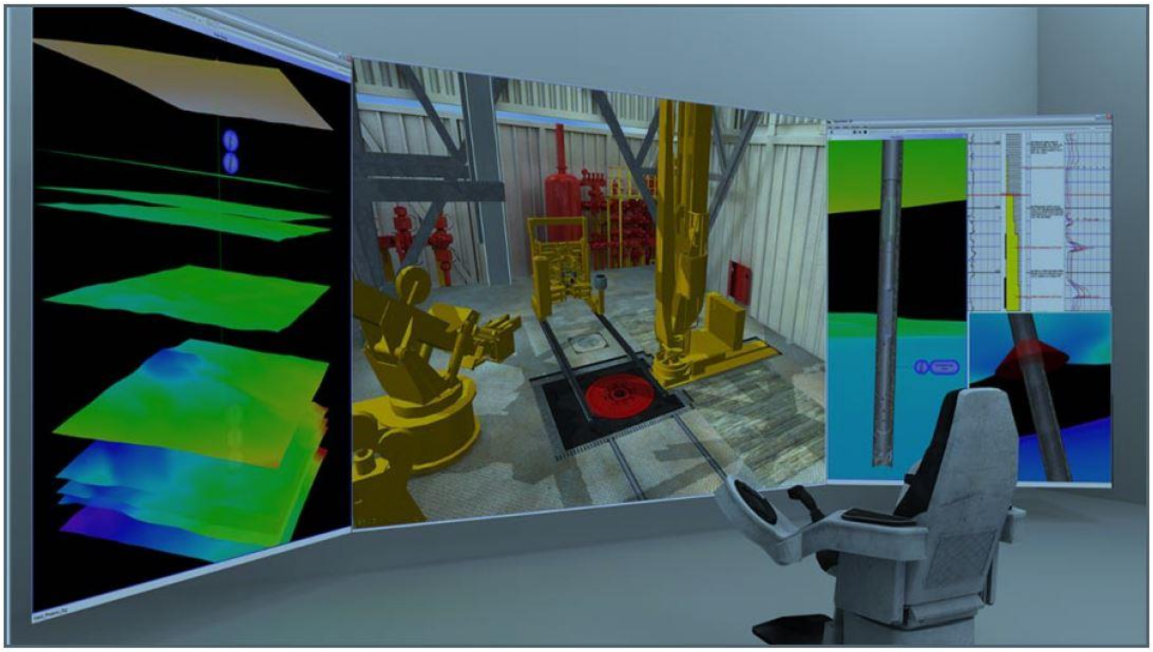


Figure 2-4 eDrilling Solution Simulator Setup (Odegard et al., 2013)

According to Odegard (2013) in order to achieve an effective training with the objectives of leadership skills development, risk handling and effective work process, the Compliance and Leadership model (Figure 2-5) must be applied to the training scenarios. The simulator models realistic scenarios and the teams are evaluated based on their ability and competence to plan and execute tasks to perform the safest and most efficient operation. Each team consists of a driller, a driller assistant, tool-pusher, drilling supervisor, drilling engineer and subcontractors.

- Communicate how we work when we execute tasks
- Be a role model in your interaction with others
- Train, observe, follow up and guide your group when using the model to ensure effective collaboration

Figure 2-5 Compliance and Leadership model (Odegard et al., 2013)

The training typically starts with a group discussion where the possible risks and challenges associated with the designed well are identified and evaluated. Then scenarios based on the operator needs and the simulator capacity are selected and loaded into the simulator. On the operation day, the team experiences three events which challenge their competency and reaction to live real-life-like incidents that are impractical to be learned through real operations. For instance some of high pressure high temperature, HPHT, training scenarios that eDrilling offers are drilling through a formation with narrow drilling margin, kick detection and handling, loss and ballooning identification and handling, drilling into a pore pressure ramp and etc. (Odegard et al., 2013).

During the simulated operation and after a certain time, “time-out is called” where the teams discuss the operation. During the time-out each team evaluates their performance and verifies the suggested procedure and makes necessary changes. This encourages individual understanding of the down-hole effects, the specific challenges associated with a field, the effects of different key drilling parameters and etc. However the main benefit of these time-outs is to reinforce the importance of the communication skills between the members (Odegard et al., 2013).

Odegard et al (2013) suggest utilization of an integrated simulator for students' education. They believe that the integrated simulator allows students to observe the influence of the surface simulator on wells in addition to familiarizing students with the state-of-the-art rig equipment. They also believe that the new drilling methods/concepts can be evaluated by developing and integrating the appropriate down-hole model to the surface simulator before applying them in real operations.

In May, 2016 eDrilling together with Maersk and Oiltec Solutions have signed a three years global contract with Statoil to train their employees utilizing their integrated simulator. The main goal is to reduce the offshore training time & cost and to increase the safety & efficiency. In addition this training put an emphasis on communication skills development in order to succeed the operation challenges ("Global Drilling Simulation Training Agreement with Statoil," 2016).

In addition to drilling training programs, Maersk Training offers a large variety of drilling-related-simulation trainings including Maritime, Crane operations, Freefall life boat and etc. ("Maersk Training," 2016). Other companies including Drilling STS, Drilling Systems and ARI Simulation offer drilling trainings using their own developed simulators. ("ARI SIMULATION," n.d., "Drilling STS," n.d., "Training Simulators," n.d.)

As suggested in the literature and to benefit students, the Drilling Automation team of UT-Austin developed down-hole models and integrated them with the available state-of-the-art surface drilling simulator.

### 2.4.3 NOV HIL Drilling Simulator at UT-Austin

The development in down-hole sensor technology and evolving substantial complexities in drilling wells in extreme conditions has compelled the industry to move towards employment of new generation of drilling rigs. The new generation of oil rigs utilizes the Drilling Control and Data Acquisition, DCDA, packages providing a safe and informed drilling process. This Human Machine Interface, HMI, system has many advantages comparing to the old-fashioned drilling and data acquisition including organized control systems across the driller's cabin as well as easing the accessibility of the information. In these rigs the monitors in front of the driller and the assistant driller display the real time and the historical information related to all digital and analogous sensors mounted on the drilling machinery. As opposed to the old fashioned drilling, utilizing the DCDA packages allows information distribution. Furthermore the drilling process of different rigs at different locations can be monitored and controlled within a single location such as a Real Time Operation Center or Remote Collaboration Center.

Once the operator sends a command from Cyber-base Chairs to the Machinery Control PLCs and I/O equipment, if an error is found by the PLC network, a feedback would be sent to the operator; else the PLC sends a feedback to the operator and a command to the machinery and instrumentation. In order to avoid dangerous movement of drilling machines these systems are equipped with anti-collision system. Anti-collision system is always active without any operator commands. Each drilling component sends its position to the anti-collision module and it decides if the components is about to enter a dangerous or collision-prone area. The anti-collision module then sends a normal signal to the component if it is not entering a dangerous zone. If a machine is entering the other machines area, machine will be stopped; a message will be given on the anti-collision display and appropriate light will be turned on.

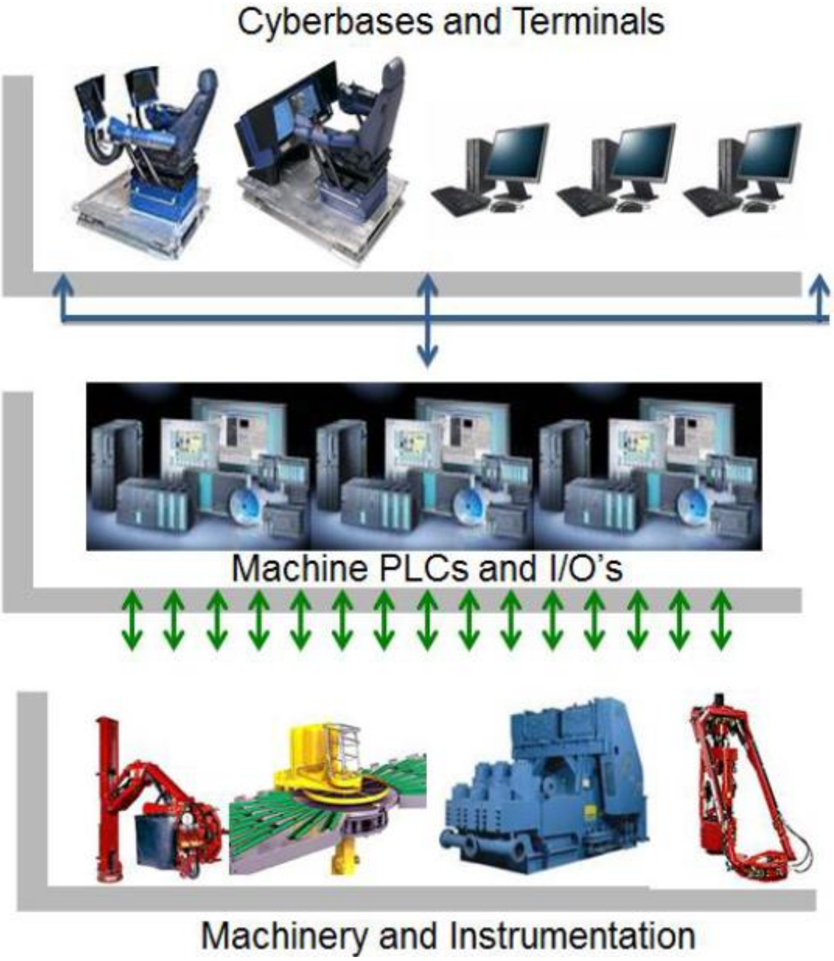


Figure 2-6 Signal Transfer

In 2014, National Oilwell Varco, NOV, made a generous donation by presenting "a first-of-its-kind drilling simulator" to the University of Texas at Austin Drilling Automation Lab ("National Oilwell Varco," n.d.). This Hardware-in-the-loop, HIL, drilling simulator is a HMI surface simulator based on a real offshore rig. This simulator consists of real-rig-like components including Top Drive, HydraTong, HydraRacker, Drawworks, Travelling Block, Catwalk machine and etc.

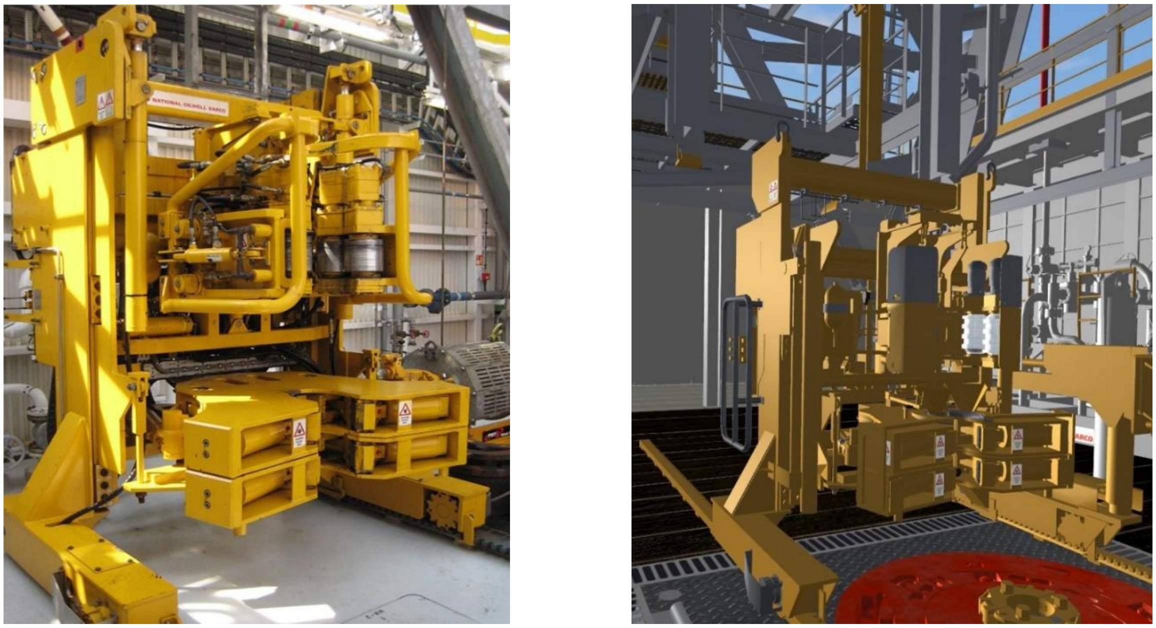


Figure 2-7 HydroTong on an offshore rig and it's 3D model on the simulator

The 3D model of the simulator components are designed using Autodesk Inventor 3D CAD software and then imported into 3D Studio Max in order to reduce the complexity of the models as well as linking the assemblies. The model is then exported into Ofusion in order to generate files for model and the Physics. These files are then used in the Object-

Oriented Graphics Rendering Engine, Ogre, and “Nvidia Physx” Physics engine. The simulation code is developed using different tools including Math lab/simulink, Simulation X and PLC code. The Math lab/Simulink are generated into dynamic-link libraries files,”.dll”, that are run on inter-process communications, IPCs, and is combined with PLC code (Berg 2011).

The existing surface drilling simulator at the University of Texas at Austin includes two Cyber-base Chairs as driller and assistant driller control systems. The driller and assistant driller are able to operate the rig equipment by using these chairs. Each chair consists two monitors which enables the operators to monitor and control various parameters including pump rates, WOB, torque and etc. In addition the operators can monitor each component from the cyber chairs using different cameras mounted on different parts of the rig in addition to the main dome display which grants a realistic 3D view of the rig.

As mentioned earlier the main objective of this thesis is to develop down-hole models, integrate them with the existing simulator, design real-life like scenarios and develop curricula to be taught to Petroleum Engineering students at the University of Texas at Austin. Several of the efforts reviewed above, show that – given an effective simulation environment – cased-based education can be effectively integrated into a more traditional academic curricula. It also determines that UT Austin is an ideal place to pursue such an endeavor thanks the presence of the NOV HIL Drilling Simulator if it is augmented with feasible down-hole models that support the fundamentals learned in the classroom and avoid the pitfalls of negative training.

# 3 Curricula Design

## 3.1 INITIAL CONSIDERATIONS

The main objective of this project is to create opportunity for Petroleum Engineering students at University of Texas at Austin to have access to a state-of-the-art laboratory where they can experience real-life drilling incidents. However, the ultimate goal of this project goes further by systemizing these laboratories to boost the students' comprehensions of the underlying science as well as increasing their competency level to solve problems within the oil industry by applying fundamental domain knowledge.

Several case-based teaching methods and their effects on students' learnings were studied in Chapter 2. As the result of this investigation, combination of case-based laboratories and traditional teaching methods is selected for our curricula design. It is recommended that PGE students take the "Drilling Engineering & Operations Management" course prior to or during taking the "case-based laboratories" course. This is to ensure that students learn the fundamentals and theories to have the necessary knowledge while attending student-led laboratories.

The case-based teaching method supports the development of the essential skills necessary for the students to succeed. Skills such as confidence which are gained inside a classroom are developed more along with other essential skills (i.e. commutations skills) throughout this course. The key elements to be considered for this curricula design based on previous experiences are listed here:

1. Cases must be realistic and relate theories to real-world problems

2. Cases must be entertaining to stimulate student interest
3. Cases must utilize realistic up-to-date virtual exploration
4. Cases must expose students to “Kolb’s Four Stage Learning Cycle”
5. Cases must develop and emphasize effective communication
6. Cases must be well designed but open-ended to reinforce student’s knowledge and to develop their critical thinking ability respectively
7. Cases must encourage cooperative learning to familiarize students to real-world work environment
8. Cases should avoid or minimize the impact of “negative simulation” so students do not have to be re-trained by future industry employers

The proposed case-based curricula consists of ten separate laboratories which are built upon each other. Students participate in one laboratory per week. A typical long semester is about 15 weeks. Thus 10 lessons provides some flexibility to avoid lesson in the first and last week as well as weeks where there may be examinations in the course. These laboratories focus on real-world incidents and challenge students abilities to relate and utilize the theories that they learn in class to solve these incidents.

## 3.2 LABORATORY DESIGN

### 3.2.1 Laboratory Architecture

To support the case-based curricula development, the existing state-of-the-art surface simulator at UT-Austin is utilized as the proper tool to satisfy the virtual exploration need where accessing real oil field is not practical. The dome display of this drilling simulator grants a realistic feeling to the students as opposed to old-fashioned-2D training simulators.

Communication skills development and cooperative learning are two of the main objectives considered in the case-based curricula design. To achieve these objectives, and similar to Tuskegee University flight simulator laboratory and eDrilling training classes, the students in our proposed laboratories are grouped into teams. Each team consists of driller, assistant driller and two engineers. The driller and the assistant driller operate the rig using the cyber-chairs while the engineers monitor the operation to ensure the safety and efficiency.

The students in the engineer role are in a separate room referred to as Remote Collaboration Center, RCC, where they have access to data and trends. These data and trends are updated based on the operational parameters (WOB, tripping speed and etc.) that the students in the operator role choose while operating the rig. Based on these trends, the engineers perform the necessary calculations, if needed, and make decisions to adjust the operational parameters. These decisions must be in line with achieving the safest and most efficient performance. They communicate these recommendations to the operators and monitor the trends to assure the desired impact.

The operators and engineers go through a rotation after each laboratory where they change their roles. This exposure assures good understanding of each role and responsibilities associated with them. On the laboratory day a certain task is given to each team where they get evaluated based on the completion time as well as how efficient and safe they perform the task. To monitor their performance, the instructor has access to trends and data that are distributed from the down-hole simulator.

To implement these laboratories, a down-hole simulator must be developed and integrated with the existing surface simulator. The down-hole simulator must collect the operational parameters from the surface simulator. It must then take initial conditions & parameters into consideration and calculates the variables that are essential to check for possible failures. For instance the mud pressure variable must be calculated to check for failures such as pipe burst/collapse or fracturing formation. The down-hole simulator development will be discussed explicitly in Chapter 4 & 5.

The down-hole simulator generated data are available to both students and the instructor. The instructor has access to a complete set of these calculated variables that the students' performance are reflected on. Unlike the instructor, students have access to limited set of these data including bit position, bit velocity, mud level and etc. The data that are accessed by the students do not indicate any information regarding the down-hole condition, yet are essential for further calculations that must be done by the students. Using these data the engineers perform calculations and make suggestions. In order for students to be as prepared as possible they are notified about the upcoming scenario prior to each laboratory.

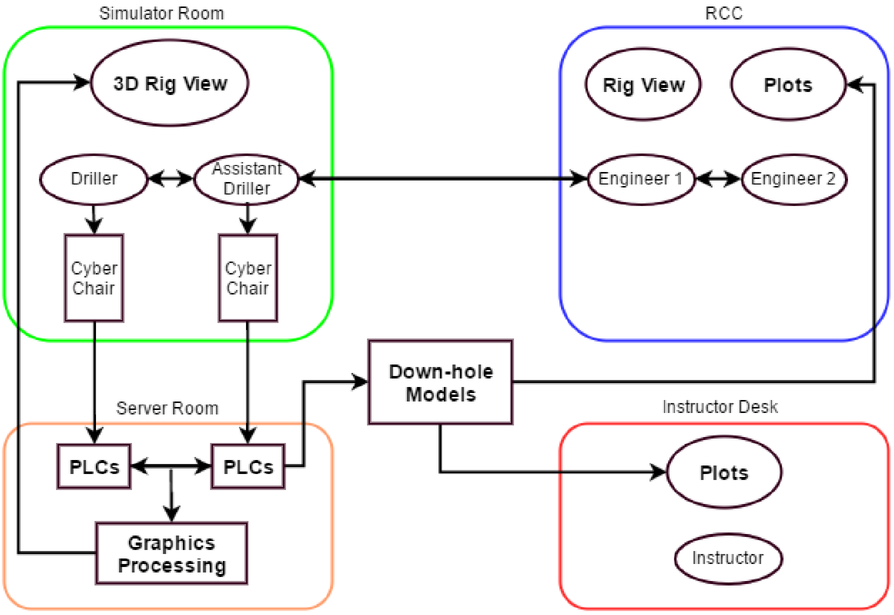


Figure 3-1 The Laboratory Architecture

### 3.2.2 Students Role Prior to the Laboratories

A week prior to each laboratory, the laboratories handouts are given to the teams. These handouts include necessary background knowledge, procedure, preparation requirements and the corresponding scenario for the operation. Within the given week, students must gather to discuss possible incidents, containment actions and the countermeasures. This encourages students to use *Triadic Method* and ultimately develops their critical thinking ability.

The majority of proposed laboratories require team members to develop MATLAB codes. These codes are the means for the necessary calculations during the laboratories where back-of-the-envelope calculation is neither sufficient nor fast enough. Students must gather information from various resources to consider every possibility in their code development. The time-consuming nature of information-collection and code-development enforces students to work efficiently by distributing work among members as well as working in team. Once each induvial collects the necessary information, they gather to combine and utilized these information to develop the corresponding laboratory MATLAB code. During this process they start evaluating ideas by utilizing logical reasoning which assists their critical thinking skill development.

### 3.3 LABORATORIES OUTLINE

After fully considering the course syllabus for Drilling Engineering & Operations Management (co-requisite course) in addition to the limitations dictated by the available tools, the proposed laboratories are listed below followed by justification and detailed descriptions.

1. Introduction to drilling simulator
2. Learning to trip in
3. Learning to trip out
4. Hydro-static pressure
5. Surge & swab
6. Learning to drill
7. Buckling
8. Rate of penetration
9. Formation change
10. Pipe burst

### 3.3.1 Lab 1 - Introduction to drilling simulator

*Objective:* Getting familiar with the new generation of drilling rigs that use Drilling Control and Data Acquisition (DCDA)

*Description:* Students get introduced to the Human Machine Interfaces (HMI) and the advantages associated with them comparing to the old-fashioned drilling and data acquisition systems. These systems will replace the old-fashioned data acquisition systems in the near future. Therefore, it is important for the next generation of petroleum engineers to have a good understanding of these systems and to know how to operate them.

In the first part of this laboratory, the instructor introduces and presents different components of a modern offshore rig to the students. This virtual exploration allows students to relate what they studied in the class room to a real-world-like oil rig. Additionally it assists them to have a better understanding of different components location on an oil rig.

In the next part of the first laboratory, students learn about the cyber-base drilling control systems and how to operate them. They get familiar with the cyber-chairs components and their functions including functional keyboard, joystick, throttle wheels, etc. Then they learn how various oil-rig components including drawworks, elevator, top drive, hydraracker, etc. are operated from these cyber-chairs.

As part of their laboratory assignment, they utilize the cyber-chair controls to interact with the major rig components. These in-laboratory assignments provide them with the necessary skills to proceed to next laboratories. The basic layout and purpose of each of these components has already been discussed in the Drilling Engineering & Operations

Management course (assuming it is happening concurrently to the lab). These assignments include but are not limited to:

1. Send command and control the drawworks, hydraracker and etc.
2. Change between different monitoring windows to read top drive height, weight on bit, etc.
3. Change between different cameras to access multiple viewing perspectives of selected tool(s)
4. Get access to fingerboard and pipe stands information

*Student Learning Outcomes:*

- Recognize the advantages of Drilling Control and Data Acquisition (DCDA) and compare it to existing old-fashioned drilling and data acquisition
- Identify the virtual state-of-the-art oil rig components
- Operate the cyber-base drilling control system to get control of rig components

### 3.3.2 Lab 2 - Learning to trip in

*Objective:* Learning to trip and successfully tripping in a pipe stand

*Description:* The second laboratory is the foundation of the following laboratories. Since the students go through assignment rotations in following laboratories (performing as operator vs. engineer), it is required for all four of them to know how to operate the cyber-chairs to trip in the drill string. Therefore in this laboratory they all go through a rotation in the simulator room as driller and assistant driller. They follow a provided step-by-step procedure on how to trip in.

To familiarize themselves with design and planning process, the students must perform very simple calculations related to the amount of pipe in the hole. Thus the students in the control room can calculate and monitor progress while the students in the cyber-chairs can focus on learning the mechanics of tripping.

*Student Learning Outcomes:*

- Review the process of getting control over rig components/monitoring cameras
- Operate the cyber-base drilling control system to make connections and to trip in
- Practice necessary communication skills between driller and assistant driller to avoid rig's components collision
- Practice planning and communication between the remote collaboration center and the drillers.

### 3.3.3 Lab 3 - Learning to trip out

*Objective:* Tripping out while monitoring the bit position in Remote Collaboration Center and locate the bit at a desired depth

*Description:* In this laboratory students are divided into two groups of operators and engineers. This laboratory is designed for students to practice the previous laboratory and be as prepared as possible for the next laboratories where the objectives are beyond solely operating the system. Even though this laboratory assignment is to trip out a few stands of pipe, the process is similar to the previous laboratory with some minor changes in the procedure. While the operators practice the tripping process, the engineers in RCC monitor the trends in order to meet the laboratory objective.

In this specific laboratory students are asked to trip and locate the bit at a specific depth. The students (Engineers) in the RCC have access to bit position, bit velocity and well depth information. They make operation-related decisions based on the trends shown in the RCC. The Engineers then communicate these decisions with the operators to adjust the tripping velocity and to stop the process when the bit is at the desired depth.

*Student Learning Outcomes:*

- Review the process learned in previous laboratory to get control of oil rig components and to make connections
- Operate the cyber-base drilling control system to trip out
- Monitor data trends in RCC
- Practice communication skills (between operators and engineers in RCC) to successfully complete the tasks

Figure 3-2 Operation Room

Figure 3-3 Remote Collaboration Center

### 3.3.4 Lab 4 - Hydro-static pressure

*Objective:* Detecting the bit condition (closed vs. open) in addition to tripping out a few stands of pipe in the shortest possible time while staying within the drilling window with the minimum numbers of annulus fillings

*Description:* This laboratory is the first one that requires students to develop their codes and to use them during the operation. The students develop two codes prior to this laboratory; one to detect the bit condition and the other to calculate the mud hydro-static pressure. The drop in mud level resulting from the tripping out process is shown in the RCC. Engineers determine the bit condition by considering the length and geometry of the drill string that is tripped out and the given drop in mud level.

Students then calculate the mud hydro-static pressure and compare it to the given pore pressure. If the mud pressure falls below a certain value, engineers are required to communicate with the operators to stop the process and fill the annulus. The operators fill the annulus by starting the mud pump. While mud is pumped in the annulus, engineers must monitor the mud level trend and instruct the operators to stop the pump and resume the operation once the annulus is filled.

In this laboratory the algorithm for one of the required codes (detecting bit condition) is given to students to familiarize them with the code-development process. Note that students are allowed and encouraged to use other methods to develop their code.

*Student Learning Outcomes:*

- Operate the cyber-base drilling control system to trip out

- Apply theories learned in class to detect the bit condition and to calculate the mud static pressure based on data shown in the RCC while operating
- Monitor the trends in the RCC to stay within the drilling margin and practice communication skills
- Plan the tripping out process accordingly with minimum possible time to be spent on annulus filling
- Review and improve IADC guideline efficiency for annulus filling

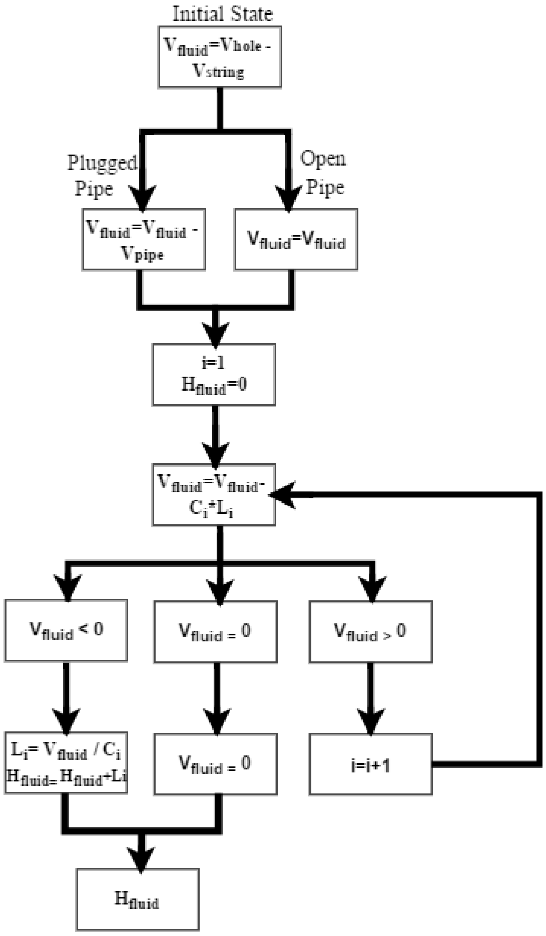


Figure 3-6 Fluid Level Algorithm for Bit Condition Detection

### 3.3.5 Lab 5 - Surge & swab

*Objective:* Tripping in a few stands of drill string while maintaining the pressure within the drilling window (considering the dynamic effects of mud in addition to static effects on mud pressure calculation)

*Description:* The students are required to trip in a few stands of pipe in the shortest possible time without fracturing the formation. In the first step, engineers execute their MATLAB code (pre-laboratory assignment) to calculate the fracture gradient based on the given pore pressure and available correlation between the two. In the next step - and to calculate the induced surge pressure accurately - they detect the bit condition using what they learned in the previous laboratory.

Having determined the fracture pressure, mud hydro-static pressure and the bit condition, the engineers then calculate the maximum allowable tripping speed. Students calculate this speed by executing their MATLAB code (pre-laboratory assignment) which is developed based on the theories that are learned in the class. Accordingly, engineers make decision to adjust the operation tripping speed. They communicate this decision with the operators and inform them to increase/decrease the tripping velocity. The tripping speed must be monitored from the bit velocity trend in the RCC to assure that the desired tripping speed is achieved.

The mud total pressure - combination of induced surge pressure and the mud hydro-static pressure - must stay below the fracture pressure throughout the entire operation. The maximum allowable speed depends on various factors including fracture gradient, length & geometry of the drill string, wellbore geometry and etc. Therefore it is essential to calculate the maximum allowable tripping speed continuously. This laboratory assists students to understand the importance of actively calculating the operational parameters for highest efficiency.

*Student Learning Outcomes:*

- Operate the cyber-base drilling control system to trip in/out
- Apply theories learned in class to calculate the fracture gradient in addition to considering dynamic effects on mud pressure calculation
- Monitor the trends in RCC to stay within the drilling margin and actively suggest maximum safe tripping speed based on the detected bit condition and on-site calculations
- Practice decision making and communication skills in fast paced operation and under stress
- Analyze the effects of drill string and well-bore geometry on induced surge/swab pressure

### 3.3.6 Lab 6 - Learning to drill

*Objective:* Learning to engage top drive and successfully drilling a few feet

*Description:* Prior to the sixth laboratory students learned about tripping process and challenges associated with it. From this laboratory they start to investigate the challenges of drilling process. The structure of the sixth laboratory is similar to the second one. All four members of each team go through a rotation in the simulator room as driller and assistant driller. They follow a step-by-step procedure on how to operate the cyber chairs to connect the drill string to the top drive and to drill.

*Student Learning Outcomes:*

- Operate the cyber-base drilling control system to get control of the top drive and to drill into the formation
- Practice necessary communication skills between driller and assistant driller to avoid rig's components collision

### 3.3.7 Lab 7 - Buckling

*Objective:* Drilling a few feet while considering the effects of weight on bit on rate of penetration and on drill string failure

*Description:* Students apply what they learned in the previous laboratory to drill a few feet into the formation in the shortest possible time. They are required to monitor and adjust the WOB to maximize the rate of penetration without buckling the drill string. In this particular laboratory and to demonstrate the effects of WOB with respect to the ROP, it is assumed that WOB is the only varying operational parameter.

The students use their developed code (pre-laboratory assignment) to calculate the axial force/stress along the drill string given the weight on bit, drill string weight & geometry, mud density, bit condition (open vs. closed), etc. Then they are required to detect the sections in compression and calculate the maximum allowable weight on bit that does not cause the drill string to buckle. The engineers then communicate this information to the driller to increase/decrease the WOB accordingly as well as monitoring the WOB trends to assure that the desired value is achieved.

This laboratory emphasizes that due to limitations dictated by the drill string, formation hardness and etc. it is not always possible to achieve the maximum possible rate of penetration.

*Student Learning Outcomes:*

- Practice previous laboratories calculations (detecting bit condition and BHP)
- Apply theories learned in the class to actively calculate axial stress along the drill string and to calculate the maximum allowable WOB
- Monitor data trends in RCC to ensure safety and quality of the operation
- Analyze the trade-off between the WOB and drill string materials on ROP

### 3.3.8 Lab 8 - Rate of penetration

*Objective:* Controlling the weight on bit and rotary speed to achieve the most efficient rate of penetration (time and cost consideration)

*Description:* In this laboratory students investigate the combined effects of torque and WOB on ROP in addition to the operation cost for drilling into a given formation. They perform the break-even analysis and study the relation between bit wear, ROP and cost of operation.  During the operation, the operators must trip out a few feet to detect the bit condition. Then similar to the previous laboratory, the engineers calculate the maximum allowable weight on bit which does not cause the drill string to buckle.

Following calculating the maximum allowable WOB, engineers must execute their new developed code to calculate the optimum weight on bit and rotary speed for a specific formation. The main objective of this calculation is to improve the drilling performance and to minimize the drilling cost. Students are required to consider maximum allowable WOB, bit & rig operation costs, round trip and connection time, tooth-wear parameters and etc. in the optimum operation parameters calculation.

Once the optimum parameters are calculated, engineers communicate with operators to adjust the WOB and rotary speed to these values accordingly. After drilling a few feet by applying the optimum values, each team is required to drill with different WOB and rotary speed values. The main objective of this process is to demonstrate the advantages and disadvantages of deviating from the optimum values.

*Student Learning Outcomes:*

- Practice previous laboratories calculations (detecting bit condition and BHP)
- Apply theories learned in the class to calculate the optimum WOB and rotary speed based on formation and operation parameters (mud density, drill string weigh, etc.)
- Monitor data trend in RCC to ensure safety and quality of the operation
- Analyze the trade-off between the WOB & rotary speed on ROP and efficiency based on break-even analysis

### 3.3.9 Lab 9 - Formation change

*Objective:* Detecting the lithology of an unknown formation while drilling in it as well as adjusting the operational parameters to achieve the fastest and most efficient rate of penetration

*Description:* The ninth laboratory is a combination of the previous two laboratories where several formations are drilled into as oppose to one particular formation. Students drill in two to three very thin formations which the lithology changes must be detected. The lithology is determined based on the WOB, rotary speed and the given rate of penetration.

Once the lithology of the formation is detected, engineers execute their developed code to calculate the optimum WOB and rotary speed for that particular formation. The operators then adjust the WOB and rotary speed based on the calculated values and as advised by the engineers. Engineers must actively monitor the rate of penetration trend to detect the formation changes. Once the formation is changed, they must respond quickly to detect the formation and to change the operational parameters in order to minimize the total cost.

*Student Learning Outcomes:*

- Practice previous laboratories calculations (detecting bit condition and BHP)
- Apply theories learned in the class to detect the formation that is being drilled based on the operational data in RCC
- Apply theories learned in the class to calculate optimum WOB and rotary speed for detected formations

- Practice decision making and communication skills in fast paced operation and under stress
- Analyze the relation between WOB & rotary speed on ROP for different formations

### 3.3.10 Lab 10 - Pipe burst

*Objective:* Demonstrating the effects of bit balling on pump pressure and drill string failure in addition to understanding frictional pressure drop across the drill string, bit and annulus.

*Description:* During the operation and while drilling, gradual bit balling happens which causes the mud pump pressure to increase. Engineers must detect this pressure increase from the trends shown in the RCC and advise operators to adjust the mud flow rate to prevent pump and drill string failure. In order to do so, engineers execute their pre-laboratory developed code which calculates the frictional pressure drops inside the drill string and the annulus as well as the pressure drop across the bit. For accurate calculation this code must take the drill string & well geometry as well as the mud flow rate into consideration to determine the flow regimes and calculate the pressure losses.

Once the pressure losses are known, engineers execute their previous codes to calculate the hydro-static and induced surge/swab pressures. Engineers then combine these pressures and losses to obtain the mud total pressures inside the drill string and the annulus. They must consider pump pressure, pressure losses, mud hydro-static pressure and induced surge/swab pressure in their calculations. Based on the calculated mud pressures across the pipe and by considering the drill string strength, thickness, burst & collapse regions and etc., engineers must verify that their suggested flow rate does not cause the pipe to burst.

*Student Learning Outcomes:*

- Apply theories learned in class to calculate the frictional pressure losses and combine them with mud hydro-static and surge/swab pressures for mud total pressure calculation
- Monitor the data trends in RCC and detect abnormalities in pump pressure trend
- Apply theories learned in class to investigate the mud pressures across the drill string and the possibility of drill string failure due to pump pressure increase
- Practice decision making and communication skills in fast paced operation and under stress
- Analyze the relation between flow rate, bit's nozzles area and pump pressure

Table 3-1 represents the summary of the proposed laboratories. The "Instructor" column represents the plots and data that the instructor has access to. The engineers have access to a limited set of data comparing to the instructor. They must develop MATLAB codes as part of their "pre-laboratory assignments" to perform necessary calculations and generate the missing plots and data based on the given set. These calculations and the generated results assist teams to make decisions during the operation and complete the assigned tasks successfully.

| | Instructor | Engineers | Students Codes |
|---|---|---|---|
| Laboratory 3 – Tripping out | 1. Bit Position<br>2. Bit Velocity<br>3. Well Depth | 1. Bit Position<br>2. Bit Velocity<br>3. Well Depth | Not Required |
| Laboratory 4 Hydrostatic Pressure | 1. Bit Position<br>2. Bit Velocity<br>3. Well Depth<br>4. Mud Head Drop<br>5. Drilling Window<br>6. Mud Pressure | 1. Bit Position<br>2. Bit Velocity<br>3. Well Depth<br>4. Mud Head Drop<br>5. Pore Pressure | 1. Detect Bit Condition<br>2. Calculate hydrostatic mud Pressure |
| Laboratory 5 Surge & Swab | 1. Bit Position<br>2. Bit Velocity<br>3. Well Depth<br>4. Mud Head Drop<br>5. Drilling Window<br>6. Mud Pressure | 1. Bit Position<br>2. Bit Velocity<br>3. Well Depth<br>4. Mud Head Drop<br>5. Pore Pressure | 1. Detect Bit Condition<br>2. Calculate hydrostatic mud Pressure<br>3. Calculate Surge/Swab<br>4. Calculate mud total pressure<br>5. Calculate Fracture Pressure |
| Laboratory 7 Buckling | 1. Bit Position<br>2. Bit Velocity<br>3. Well Depth<br>4. Mud Head Drop<br>5. Drilling Window<br>6. Mud Pressure<br>7.WOB<br>8.Rate of Penetration | 1. Bit Position<br>2. Bit Velocity<br>3. Well Depth<br>4. Mud Head Drop<br>5. Pore Pressure<br>6. WOB<br>7. Rate of Penetration | 1. Detect Bit Condition<br>2. Calculate axial stress along the drill string<br>3. Calculate maximum allowable WOB |
| Laboratory 8 Rate of Penetration | 1. Bit Position<br>2. Bit Velocity<br>3. Well Depth<br>4. Mud Head Drop<br>5. Drilling Window<br>6. Mud Pressure<br>7.WOB<br>8.Rate of Penetration | 1. Bit Position<br>2. Bit Velocity<br>3. Well Depth<br>4. Mud Head Drop<br>5. Pore Pressure<br>6. WOB<br>7. Rate of Penetration | 1. Detect Bit Condition<br>2. Calculate axial stress along the drill string<br>3. Calculate maximum allowable WOB<br>4. Calculate optimum WOB and rotary speed |
| Laboratory 9 Formation Change | 1. Bit Position<br>2. Bit Velocity<br>3. Well Depth<br>4. Mud Head Drop<br>5. Drilling Window<br>6. Mud Pressure<br>7.WOB<br>8.Rate of Penetration | 1. Bit Position<br>2. Bit Velocity<br>3. Well Depth<br>4. Mud Head Drop<br>5. Pore Pressure<br>6. WOB<br>7. Rate of Penetration | 1. Detect Bit Condition<br>2. Calculate axial stress along the drill string<br>3. Calculate maximum allowable WOB<br>4. Calculate optimum WOB and rotary speed |
| Laboratory 10 Pipe Burst | 1. Bit Position<br>2. Bit Velocity<br>3. Well Depth<br>4. Mud Head Drop<br>5. Drilling Window<br>6. Mud Pressure<br>7.WOB<br>8.Rate of Penetration<br>9. Pump pressure<br>10. Pipe Internal/External pressure | 1. Bit Position<br>2. Bit Velocity<br>3. Well Depth<br>4. Mud Head Drop<br>5. Pore Pressure<br>6. WOB<br>7. Rate of Penetration<br>8. Pump pressure | 1. Detect Bit Condition<br>2. Calculate axial stress along the drill string<br>3. Calculate maximum allowable WOB<br>4. Calculate optimum WOB and rotary speed<br>5. Calculate frictional pressure loss and pressure loss across the bit<br>6. Calculate mud total pressure<br>7. Calculate maximum allowable pump pressure to avoid pipe burst |

Table 3-1 Laboratories Data Summary

## 3.4 CURRICULA DESIGN SUMMARY

This chapter detailed the objectives and outcomes of the proposed laboratories. These case-based laboratories are developed to expand students' critical thinking ability as well as other essential skills that are not developed using traditional teaching methods. The laboratory and team structures are designed to enhance students' communication skills under fast-paced, high-stressed environment. The implementation of these laboratories are contingent upon developing the down-hole simulator and integrating it with the existing surface-simulator. The down-hole simulator development is subjected to limitations dictated by the available tools as well as the students' capabilities. The subsequent two chapters discuss the mathematical model selection and implementation process to develop the integrated drilling simulator.

# 4 Model and Tool development

## 4.1 MODELS OUTLINE

In Chapter 3, a list of proposed laboratories followed by justification and detailed description of each was presented. In order to construct the proposed laboratories, models have to be identified and/or developed and then implemented in MATLAB programming language as “major” functions. Additionally “subsidiary” functions are developed to facilitate the major functions of the down-hole simulator. Some of these subsidiary functions – including a discretization function - improve the calculation speed from a few seconds to one hundredth of a second. Other subsidiary functions such as “bit position” are necessary to accordingly execute the major functions (will be discussed in great details in Chapter 5). In order to understand, visualize a student that intends to trip out a stand of 45 feet and consider the following two scenarios:

1. Tripping out 25 feet, filling the annulus and tripping out the remaining
2. Tripping out 25 feet, filling the annulus, tripping in 5 feet and tripping out the remaining

While the final outcomes of the two scenarios seem identical, the final mud volume and hydro-static head drop of the two are not the same. The details on different functions and their tasks in the down-hole simulator will be discussed in Chapter 5.

In this chapter the mathematical models used in the major functions development are discussed. These models are taught to the students prior to the laboratories and the students in the remote collaboration center, RCC, will use them in order to make decisions.

The models are chosen to provide the best combination of accuracy and simplicity to develop students' competency. The following is the list of models that are used in the major functions of the down-hole simulator development following by more details in section 4.2:

- Fracture pressure predication
- Hydro-static head drop and mud static pressure
- Pump flow rate
- Frictional pressure loss and pump pressure
- Surge & Swab induced pressure
- Drill string buckling
- Rate of penetration
- Burst & Collapse

## 4.2 MATHEMATICAL MODELS

The mathematical models that are used in down-hole simulator development are collected, unless stated otherwise, from the available literature and represented in "Fundamental of Drilling Engineering" book by Robert F. Mitchell and Stefan Z. Miska.

### 4.2.1 Units

The International System of Units, SI, and the US Customary Units, USCU are two examples of widely used unit systems. However for many years, oil and gas industry has been using set of units referred to as field units. The main reason for utilization of this set of units is the convenience associated with it, i.e. due to large area of a reservoir it is more convenient to measure it's area in acre as oppose to US Customary unit of $ft^2$. For the majority of the equations used in down-hole simulator development, field units are utilized. However in some cases different units are used, i.e. $in^2$ is used instead of acre for bit's nozzle area. The following table summarizes the units used in this project and their respective counterparts in oil field units. Field units were also selected to reinforce the necessary attendance all engineers in the oil industry must maintain given the international and legacy of the variety of equipment and standards in the industry.

| | **Units in This Project** | **Field Units** |
|---|---|---|
| **Area** | $\text{in}^2$ | acres |
| **Density** | ppg | ppg |
| **Flow rate-liquids** | gpm | $\frac{\text{bbl}}{\text{D}}$ |
| **Length** | in and ft | ft |
| **Pressure** | psi | psi |
| **Pressure gradient** | $\frac{\text{psi}}{\text{ft}}$ | $\frac{\text{psi}}{\text{ft}}$ |
| **Rotary speed** | spm | rpm |
| **Unit Weight** | $\frac{\text{lbf}}{\text{ft}}$ | $\frac{\text{lbf}}{\text{ft}}$ |
| **Velocity** | $\frac{\text{ft}}{\text{s}}$ | $\frac{\text{ft}}{\text{s}}$ |
| **Viscosity** | cP | cP |
| **Volume** | bbl | bbl |
| **WOB** | lbf | lbf |

Table 4-1 Units

### 4.2.2 Fracture pressure predication

In this project the initial settings and known parameters are entered in an excel file prior to each laboratory (discussed in Chapter 5). The pore pressure information is one of many knowns that are provided to the students prior to execution of the laboratories. The pore pressure information is used to calculate the fracture pressure using the existing correlations and to generate the drilling window plot shown in Figure 4-3. Hubbert & Willis, Mathew & Kelly and Ben Eaton correlations are the most applicable and widely used of all. The Hubbert & Willis correlation (Hubbert & Willis, 1957) used in the down-hole model development is as follow:

$$F_{min} = \frac{1}{3}(1 + 2 * \frac{\mathrm{P}}{\mathrm{D}}) \qquad \text{Equation 4-1}$$

$$F_{max} = \frac{1}{2}(1 + \frac{\mathrm{P}}{\mathrm{D}}) \qquad \text{Equation 4-2}$$

where F and $\frac{\mathrm{P}}{\mathrm{D}}$ are the fracture and pore pressure gradients in $\frac{psi}{ft}$.

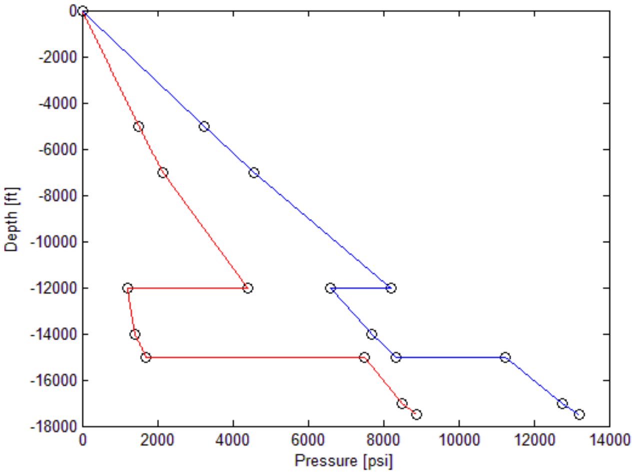


Figure 4-1 Generated Drilling Window

### 4.2.3 Hydro-static head drop and mud static pressure

The hydro-static head level of the mud is used to calculate the mud static pressure. The mud level in the drill string/annulus is subjected to change under different scenarios and must be updated according to the drill string length that is tripped in/out. The initial mud volume must be known prior to any change in order to calculate and update the mud head level. The mud volume is calculated based on the initial information entered in the spreadsheet and based on the conservation of volume:

$$V_{total} = V_{hole} = V_{string} + V_{fluid}$$ Equation 4-3

where:

$$V_{hole} = \frac{D^2{}_{hole}}{1029.4} \cdot Length_{hole}$$ Equation 4-4

$$V_{string} = \frac{OD^2{}_{pipe} - ID^2{}_{pipe}}{1029.4} \cdot Length_{pipe}$$ Equation 4-5

Thus for drill string and well with complex geometry:

$$V_{fluid} = \sum_{i=1}^{n} \frac{D^2{}_{hole}}{1029.4} \cdot Length_{hole} - \sum_{i=1}^{n} \frac{OD^2{}_{pipe} - ID^2{}_{pipe}}{1029.4} \cdot Length_{pipe}$$ Equation 4-6

where $V_{hole}$, $V_{string}$ and $V_{fluid}$ are open hole, drill string and mud volumes in bbl respectively. $D_{hole}$ is the diameter of the open hole, OD and ID are the outer and inner diameters in inches and Length is in ft.

The calculated mud volume is settled within the available spaces inside the pipe and the annulus. These spaces are referred to as *capacity* and they represent the volume available for mud per foot of drill pipe/annulus. The capacities actively change as the drill string is tripped in/out due to complex geometries of the drill string and the wellbore. The capacities in different sections of the pipe/well are calculated from the following equations:

$$C_{Open-Hole} = \frac{D^2{}_{hole}}{1029.4} \left[\frac{bbl}{ft}\right] \qquad \text{Equation 4-7}$$

$$C_{annulus} = \frac{D^2{}_{hole} - OD^2{}_{pipe}}{1029.4} \left[\frac{bbl}{ft}\right] \qquad \text{Equation 4-8}$$

$$C_{pipe} = \frac{ID^2{}_{pipe}}{1029.4} \left[\frac{bbl}{ft}\right] \qquad \text{Equation 4-9}$$

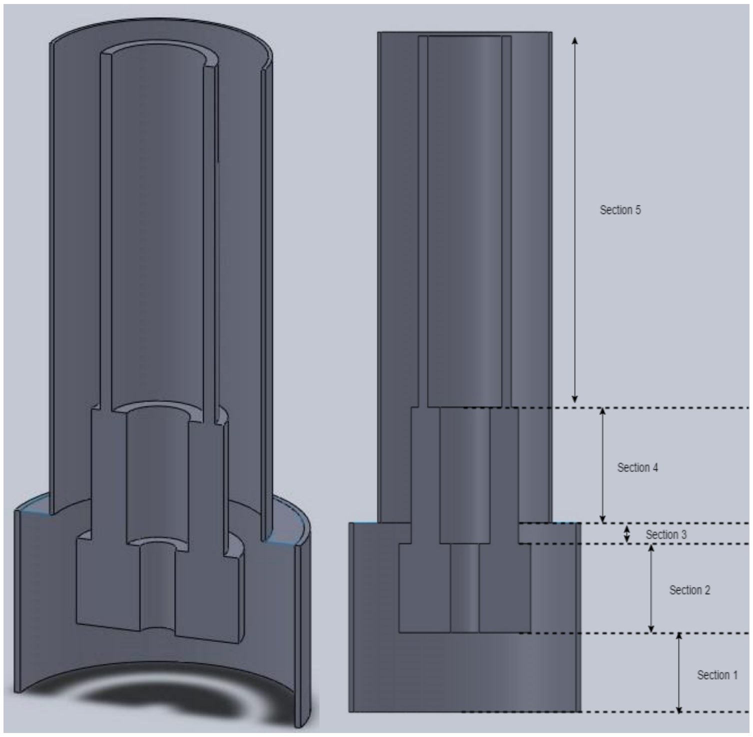


Figure 4-2 Variable drill string and well geometry and available capacities

In order to calculate the mud level, the available volume of each section, product of capacity and length, must be subtracted from the mud volume. This process starts from the bottom-most section and resumes until they balance the mud volume. The summation of sections lengths represents the mud level.

### 4.2.4 Pump flow rate

As mentioned in "Laboratories Outline" section of Chapter 3, the mud pressure must be maintained above the pore pressure while tripping out. When the mud static pressure drops close to the pore pressure, students are advised to stop the operation, fill the annulus using pumps and resume the process. The pump flow rate is calculated based on the pump information (liner diameter and etc.) entered in the spreadsheet as well as the pump speed which students control from the cyber-chairs:

$$Q_{total} = 0.0102\, \eta \cdot {D_{liner}}^2 \cdot L_{stroke} \cdot N \qquad \text{Equation 4-10}$$

Where $Q_{total}$ is in gallon per minute, gpm, $D_{liner}$ and $L_{stroke}$ are the pump liner diameter and piston stroke length respectively in inches and N is the pumping speed in stroke per minute, spm.

### 4.2.5 Frictional pressure loss and pump pressure

In addition to the mud static pressure, the dynamic (section 4.2.5) and frictional effects must be taken into mud total pressure calculation. The shear force between the flowing mud and pipe/well surfaces in the drill string/annulus creates frictional losses. The frictional pressure loss is affected by many factors including mud viscosity, the flow path geometry, the flow regime and the mud rheology. This project assumes non-Newtonian Bingham plastic rheology for mud and subsequently the appropriate frictional loss and dynamic pressure models are utilized.

Similar to Newtonian fluids, the shear stress and the shear rate of Bingham plastic fluids demonstrate linear relationship with each other. However the correlation in the Bingham plastic is offset by a constant value indicating that fluid does not flow at low stresses and makes this model appropriate to be used for drilling mud rheology. Figures 4-3 and 4-4 represent the Newtonian and Bingham plastic rheological models following by their mathematical correlations.

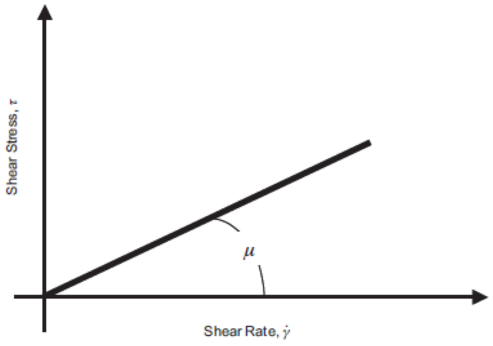


Figure 4-3 Newtonian Fluid (Bourgoyne1991)

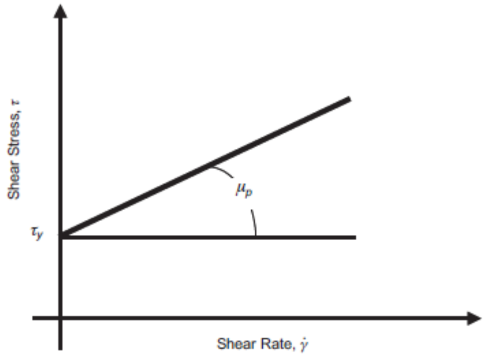


Figure 4-4 Bingham Plastic (Bourgoyne1991)

$$\tau = \mu\bar{\Upsilon} \qquad \text{Equation 4-11}$$

$$\tau = \mu_p\bar{\Upsilon} + \tau_0 \qquad \text{Equation 4-12}$$

Where $\tau$ and $\tau_0$ are the shear stress and yield point in $\frac{lb}{100\,ft^2}$, $\mu$ and $\mu_p$ are viscosity and plastic viscosity in cP and $\bar{\Upsilon}$ is the shear rate in $s^{-1}$.

In order to apply the appropriate mathematical models of the selected mud rheology, the flow velocities inside the pipe and the annulus are calculated. The velocity calculation is based on the pump flow rate and the drill-string/wellbore geometry and is as follow:

$$v_{drill\ string} = \frac{Q}{2.448\ {D_0}^2} \qquad \text{Equation 4-13}$$

$$v_{annulus} = \frac{Q}{2.448\ ({D_2}^2 - {D_1}^2)} \qquad \text{Equation 4-14}$$

Where $v$ is the fluid velocity in $\frac{ft}{s}$, Q is the pump flow rate in gpm, $D_0$, $D_1$ and $D_2$ are the pipe inner, pipe outer and wellbore diameters in inches respectively.

Next the apparent viscosity and the Reynolds number for both inside the drill string and the annulus are calculated. A Reynolds number of less than 2100 and above 4000 indicates laminar and turbulent flow respectively. Based on the calculated Reynolds number the appropriate equations for frictional pressure calculation are applied:

**Inside drill string:**

$$\mu_a = \mu_{p+} \frac{6.66\ \tau_0\ D_0}{v_{drill\,string}} \qquad \text{Equation 4-15}$$

$$Re_{drill\ string} = \frac{\rho\ v_{drill\,string}\ D_0}{\mu_a} \qquad \text{Equation 4-16}$$

*Laminar:*

$$\Delta P_{friction\_drill\,string} = \left(\frac{\mu_p\, v_{drill\,string}}{1500\, {D_0}^2} + \frac{\tau_0}{225 D_0}\right) \Delta L \qquad \text{Equation 4-17}$$

*Turbulent:*

$$\Delta P_{friction\_pipe} = \left(\frac{\rho^{0.75} {v_{drill\,string}}^{1.75} {\mu_p}^{\ 0.25}}{1800\, {D_0}^{1.25}}\right) \Delta L \qquad \text{Equation 4-18}$$

**Annulus:**

$$\mu_a = \mu_{p+} \frac{5\, \tau_0 (D_2 - D_1)}{v_{annulus}} \qquad \text{Equation 4-19}$$

$$Re_{pipe} = 757 \times \frac{\rho\, v_{annulus}\, (D_2 - D_1)}{\mu_a} \qquad \text{Equation 4-20}$$

*Laminar:*

$$\Delta P_{friction\_annulus} = \left(\frac{\mu_p\, v_{annulus}}{1000\, (D_2 - D_1)^2} + \frac{\tau_0}{200 (D_2 - D_1)}\right) \Delta L \qquad \text{Equation 4-21}$$

*Turbulent:*

$$\Delta P_{friction\_annulus} = \left(\frac{\rho^{0.75} {v_{annulus}}^{1.75} {\mu_p}^{\ 0.25}}{1396\, (D_2 - D_1)^{1.25}}\right) \Delta L \qquad \text{Equation 4-22}$$

where $\mu_a$ and $\mu_p$ are apparent and plastic viscosities in cP, $\tau_0$ is the yield point in $\frac{lb}{100\, ft^2}$ and $D_0$, $D_1$ and $D_2$ are the pipe inner, pipe outer and wellbore diameters in inches respectively. $\upsilon$ is the fluid velocity in $\frac{ft}{s}$, $\rho$ is the fluid density in ppg, $\Delta P$ is the frictional pressure loss in psi and $\Delta L$ is the length in ft.

As the next step to obtain the pump pressure, the pressure loss across the drill bit must be determined. The equation for bit pressure loss is derived from the energy balance equation alongside with the Bernoulli's equation. This model assumes frictionless flow in the bit nozzles and is presented below:

$$\Delta P_{bit} = \frac{8.311 \times 10^{-5} \rho Q^2}{{C_d}^2 {A_{total}}^2} \qquad \text{Equation 4-23}$$

where $\Delta P_{bit}$is the pressure loss across the bit in psi, $\rho$ is the mud density in ppg, Q is the pump flow rate in gpm, $C_d$ is the dimensionless discharge coefficient and $A_{total}$ is the total area of the nozzles in $in^2$.

Finally the pump pressure is calculated based on the frictional pressure losses in the drill string/annulus and across the bit as follow:

$$P_{pump} = \Delta P_{drill\ string} + \Delta P_{annulus} + \Delta P_{Bit} + \Delta P_{surface} \qquad \text{Equation 4-24}$$

### 4.2.6 Surge & Swab induced pressure

In addition to the mud static pressure, the dynamic and frictional effects must be taken into mud pressure calculation. The surge and swab pressures are induced due to drilling fluid movement in opposite direction of the drill string movement. These pressures depend on the direction of the movement as well as the tripping speed, drilling fluid density, viscosity and most importantly the wellbore and drill string geometry.

Two dynamic and steady-state approaches are widely used to determine the surge and swab pressures. The dynamic model takes acceleration, change in tripping velocity, pressure generated by breaking the mud gel, inertia and the viscous drag of the mud column into consideration. While the steady-state approach ignores the acceleration and change in tripping velocity.

The steady-state approach known as Burkhardt prediction model for Bingham Plastic is utilized for the down-hole simulator development of this project. The very first step in Burkhardt's surge & swab pressures calculation is to find the mud velocity. Once the bit condition is known, the mud velocity is calculated as follow:

$$\mathrm{V}_m = -\mathrm{V}_p * \left(\frac{\mathrm{D}_p{}^2}{\mathrm{D}_h{}^2 - \mathrm{D}_p{}^2}\right) \qquad \text{Closed ended pipe} \qquad \text{Equation 4-25}$$

$$\mathrm{V}_m = -\mathrm{V}_p * \left(\frac{4\mathrm{D}_p{}^2 * (\mathrm{D}_h - \mathrm{D}_p)^2 - 3\mathrm{D}_p{}^4}{4\mathrm{D}_p{}^2 * (\mathrm{D}_h - \mathrm{D}_p)^2 * (\mathrm{D}_h{}^2 - \mathrm{D}_p{}^2) + 6\mathrm{D}_p{}^4}\right) \qquad \text{Open ended pipe} \qquad \text{Equation 4-26}$$

where $\mathrm{V}_m$ and $\mathrm{V}_p$ are mud and pipe velocities in $\frac{\mathrm{ft}}{\mathrm{s}}$ respectively, $\mathrm{D}_h$ and $\mathrm{D}_p$ are the well diameter and the pipe outer diameter in inches.

Next in order to calculate the effective annular velocity, the type of the flow must be determined. The Reynolds number and the apparent viscosity in field units are calculated from the following equations:

$$\mu_{apparent} = \mu_p + \frac{5\tau_0(D_2 - D_1)}{V} \qquad \text{Equation 4-27}$$

$$N_{RE} = 757 \times \frac{\rho v(D_2 - D_1)}{\mu_{apparent}} \qquad \text{Equation 4-28}$$

where $\mu_p$ and $\mu_{apparent}$ are the plastic and apparent viscosity in cP, $\tau_0$ is the yield point in $\frac{\text{lb}}{100ft^2}$, $D_2 and\ D_1$ are the well diameter and the outer pipe diameter respectively, $\rho$ is the density in ppg and v is the mud velocity in $\frac{ft}{s}$.

Again, the region with a Reynolds number below 2100 or above 4000 indicates laminar or turbulent flows respectively and those with Reynolds number in between indicate transitional flow. Based on the calculated Reynolds numbers, the effective annular velocity is calculated from the following equation:

$$V_e = V_m \times \kappa V_p \qquad \text{Equation 4-29}$$

Where $\kappa$ is the mud clinging constant and is calculated according to the flow characteristic using Guo and Liu (2011) correlations:

$$\kappa = 0.275\ (\frac{D_p}{D_h}) + 0.25 \qquad \text{for laminar flow} \qquad \text{Equation 4-30}$$

$$\kappa = 0.1\ (\frac{D_p}{D_h}) + 0.41 \qquad \text{for turbulent flow} \qquad \text{Equation 4-31}$$

Finally the surge/swab pressure is calculated from:

$$\Delta P\ = \pm[\frac{\mu_p * |v_e|}{1000(D2-D1)^2} + \frac{\tau_0}{200(D2-D1)}]\ \Delta \text{L} \qquad \text{for laminar flow} \qquad \text{Equation 4-32}$$

$$\Delta P = \pm \frac{\rho^{0.75} * v_e{}^{2} * \mu_p{}^{0.25}}{1396(D2-D1)^{1.25}} \Delta \mathrm{L} \qquad \text{for turbulent flow} \qquad \text{Equation 4-33}$$

Figure 4-5 illustrate the algorithm for the surge/swab calculation.

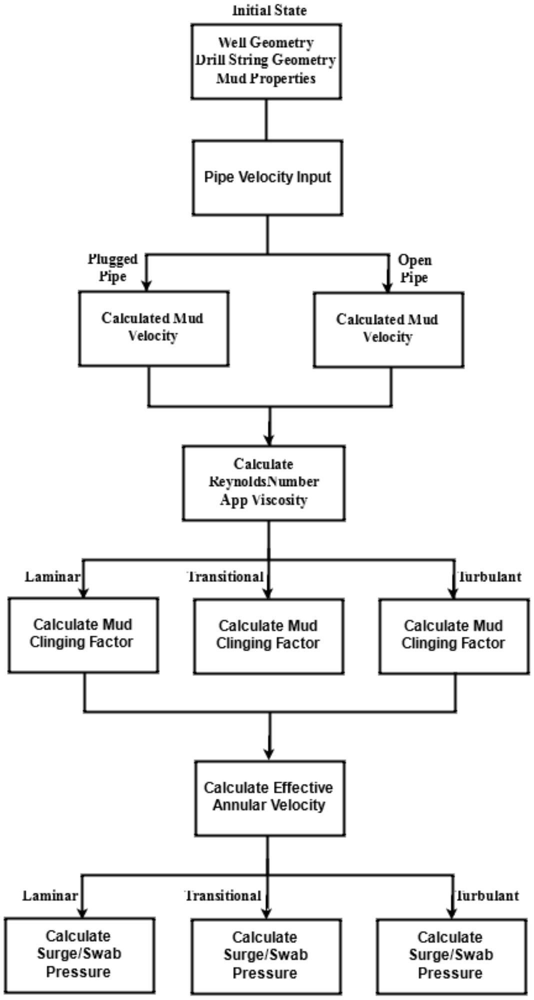


Figure 4-5 Surge/Swab calculation algorithm

### 4.2.7 Drill string buckling

One out of many roles of the drill string is to provide the necessary Weight On Bit (WOB) for drilling. The weight of the drill string is supported by the drilling hook and the rig. To achieve a certain WOB, the hook is loosen and the drill string weight is used to provide the desirable WOB. However there are limitations and excessive WOB can damage and buckle the drill string.

In order to calculate the maximum allowable WOB to prevent buckling, the axial force along the drill string must be known. The axial force along the drill string depends on many factors including drill string density, drill string geometry, drilling fluid density and the buoyant force, weight on bit and etc. This project considers vertical well models with complex geometry.

An upward force acts on an immersed-in-mud drill string due to a greater hydraulic pressure at its bottom comparing to the pressure at the top. This upward force is referred to as buoyancy force and has the magnitude of the displaced fluid weight that would have occupied the space of the inserted drill string. In order to take this effect into account, a term known as buoyancy factor is defined as follow:

$$K_b = \frac{\gamma_m}{\gamma_{ds}} \qquad \text{Equation 4-34}$$

where $K_b$ is the buoyancy factor, $\gamma_m$ and $\gamma_{ds}$ are the drilling fluid and the drill string specific gravity respectively.

The axial force at a given points along a drill string is calculated using the free body diagram and the static equilibrium concept. Figure 4-6 represents the free body diagram of a portion of a drill string. The axial force at point *i-1* is calculated from the following equation, where downward force is considered as positive:

$$F = \sum_{i+1}^{i-1} w_{u_i} + P_i(A_i - A_{i-1}) - WOB$$

Equation 4-35

where $w_u$ is the unit weight of drill string in $\frac{lbf}{ft}$, $P_i$ in psi is the hydraulic pressure at the point where the cross-sectional area changes, A is the cross-sectional area in $in^2$ and WOB is the weight on bit in lbf.

Following calculating the axial force, it is observed that for none-zero WOB values, some sections of the drill string are in compression and the rest are in tension. Figure 4-7 illustrate tension and compression along a drill string resulted from different WOBs.

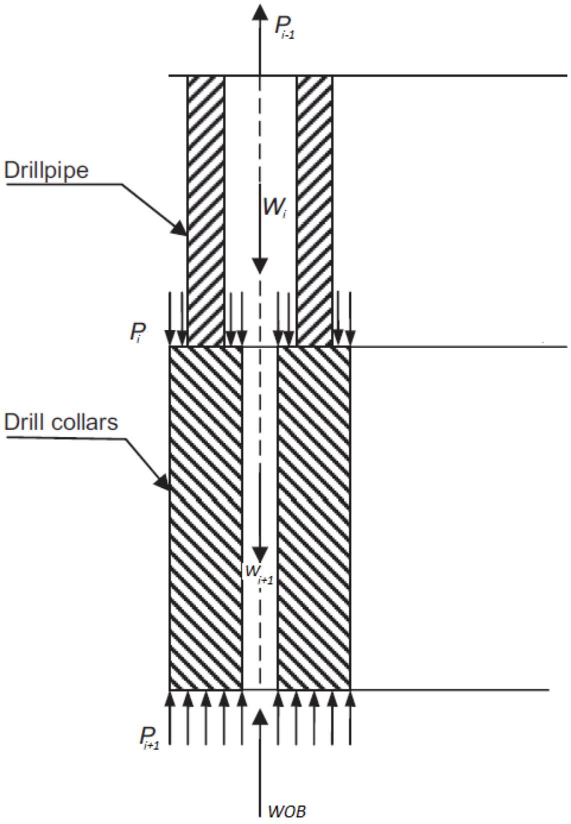


Figure 4-6 Drill String Free Body Diagram (Miska 2011)

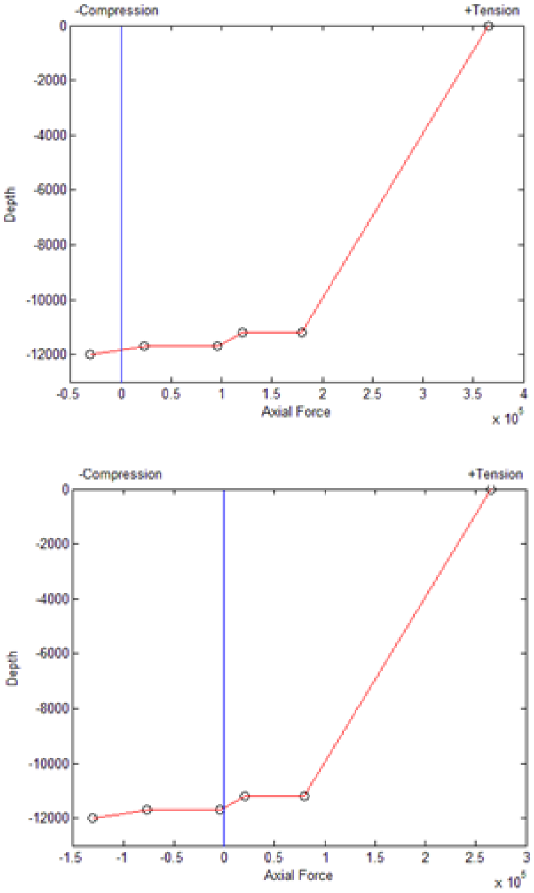


Figure 4-7 Axial Force along a Drill String

Different materials are capable of withstanding a certain compressive stress referred to as ultimate compressive stress. Once the compressive stress acting on the drill string is higher than its materials ultimate stress, the drill string undergoes a sideways failure known as buckling. The drill string sideways movement is restricted by the well, therefore the drill string would not fracture and it may only contacts the borehole. The deviated drill string causes the drill bit to drill an inclined hole.

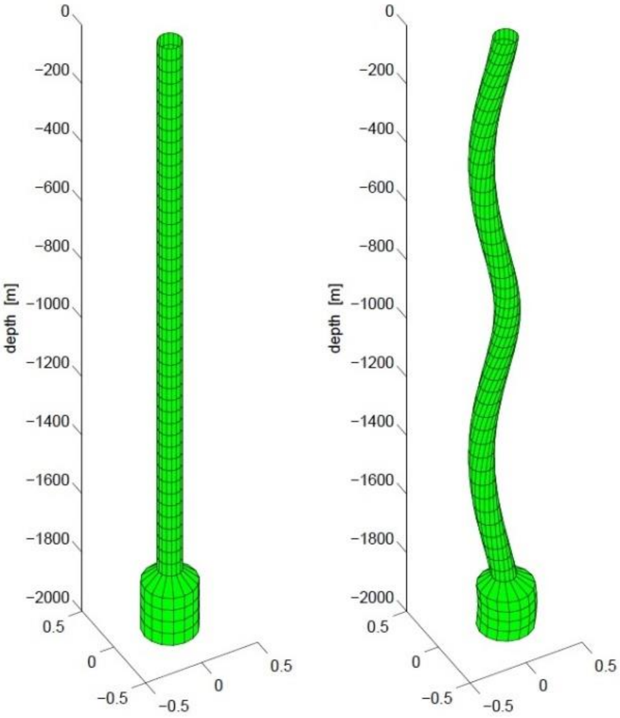


Figure 4-8 Drill String Buckling (“Drill-String Dynamics | School of Engineering | The University of Aberdeen,” n.d.)

Determined by the magnitude of the WOB, two types of buckling are possible; first order buckling where the first buckle contacts the wall and the second order buckling where the second buckle contacts the wall. The theoretical maximum weight on bit value that the drill string can withstand without buckling is modeled by Lubinski. Lubinski theory assumes frictionless system and the critical weight on bits are calculated as follow:

$$W_{cr1} = 1.94 w_{bp} m \qquad \text{Equation 4-36}$$

$$W_{cr2} = 3.75 w_{bp} m \qquad \text{Equation 4-37}$$

where $W_{cr1}$ and $W_{cr2}$ are the critical weight on bits in lbf that cause first order and second order buckling respectively, $w_{bp}$ is the unit weight of a specific section of the drill string in drilling fluid with $\frac{lbf}{ft}$ unit and m is a scaling factor. The latter two are calculated as follow:

$$m = \sqrt[3]{\frac{EI}{w_{bp}}} \qquad \text{Equation 4-38}$$

$$w_{bp} = w_u \,(1 - K_b) \qquad \text{Equation 4-39}$$

where $w_u$ the unit weight, $K_b$ is the buoyancy factor, E is the modulus of elasticity and I is the moment of inertia. The combined EI term is referred to as bending stiffness of the drill string. The moment of inertia for a circular cross section is calculated as below:

$$I = \frac{1}{64}\pi(OD^4 - ID^4) \qquad \text{Equation 4-40}$$

where OD and ID are the outer and inner diameter of the pipe respectively.

### 4.2.8 Rate of penetration

The Rate of Penetration model is used to accurately calculate the ROP according to formation lithology as well as the bit properties. The rate of penetration depends on many parameters including but not limited to bit type, formation characteristics, bit tooth wear, rotary speed and weight on bit. Many of these variables and how they affect ROP are partially understood. Additionally the developed models for ROP calculation assume that the variables affecting ROP are all independent of one another. For laboratories outcomes purposes, the rate of penetration model for roller-cone bits is used. Equation 4-41 represents one of many available rate of penetration models proposed by Bourgoyne and Young that is used in this thesis.

$$\mathrm{ROP} = (f_1)(f_2)(f_3)(f_4)(f_5)(f_6)(f_7)(f_8) \qquad \text{Equation 4-41}$$

Where $f_1$through $f_8$ are functional relations between drilling variables and the rate of penetration. These functional relations are empirical correlations that are observed based on experimental data and are as follow:

$$(f_1) = e^{2.303a_1}=K_s \qquad \text{Equation 4-42}$$

where $f_1$ is the drillability of the formation and represents the effects of bit type and formation strength.

$$(f_2) = e^{2.303a_2(10000-D)} \qquad \text{Equation 4-43}$$

$$(f_3) = e^{2.303a_3D^{0.69}(g_p-9)} \qquad \text{Equation 4-44}$$

$f_2$ and where $f_3$ are the effects of compaction on penetration rate and they both increase the rock strength. $f_2$ considers the rock compaction due to depth and $f_3$takes into account the compaction resulted from an abnormally pressured formation. D is the true vertical depth in ft and $g_p$ is the pore pressure gradient in ppg.

$$(f_4) = e^{2.303 a_4 D (g_p - \rho_c)} \tag*{Equation 4-45}$$

$f_4$ considers the effects of overbalance on rate of penetration and $\rho_c$ is the equivalent circulating density in ppg.

$$(f_5) = \left[ \frac{\left(\frac{W}{d_b}\right) - \left(\frac{W}{d_b}\right)_t}{4 - \left(\frac{W}{d_b}\right)_t} \right]^{a_5} \tag*{Equation 4-46}$$

$f_5$ demonstrates the effects of weight on bit on rate of penetration. In Equation 4-46, W represents the WOB in klbf and $d_b$ is the drill bit diameter in inches. The subscript t indicates the threshold values which are very small and usually neglected for soft formations. However for harder formations they can be estimated from the drill-off tests at very low WOB. $a_5$ is a formation dependent coefficient that varies from 0.5 to 2 depending on the formation lithology.

$$(f_6) = \left(\frac{N}{60}\right)^{a_6} \tag*{Equation 4-47}$$

The effects of rotary speed on rate of penetration are considered in $f_6$ where N is the rotary speed in rev/min and $a_6$ is a coefficient similar to $a_5$ which varies from 0.4 to 1.

$$(f_7) = e^{-a_7 h} \quad \text{Equation 4-48}$$

$f_7$ models the effects of tooth wear where h is the fractional tooth wear. The coefficient $a_7$ is calculated from the rate of penetration under similar operating conditions and different bit conditions. This value for milled-tooth bits varies from 0.3 to 1.5.

$$(f_8) = \left(\frac{F_j}{1000}\right)^{a_8} \quad \text{Equation 4-49}$$

$f_8$ represents the effects of hydraulics where $F_j$ is the jet-impact force beneath the bit in lbf where the coefficient $a_8$ varies from 0.3 to 0.6.

### 4.2.9 Burst & Collapse

In the last proposed laboratory, students investigate the effects of bit balling on pump pressure (section 4.2.4) and the change in the drill string internal pressure. The increase in the internal pressure due to bit balling and the difference in the internal and external pressures may result in the drill string to burst. In addition in cases that the external pressure is significantly higher than the internal pressure such as cases where a gas kick is received, the pipe might collapse.

Many mathematical models are developed to estimate the critical differential pressure between the external and internal pressures to prevent the pipe burst/collapse. These models include Barlow uniaxial burst equation, uniaxial collapse, biaxial collapse and triaxial yield (von Mises). Some of these models are over conservative while others are simplified, therefore selecting the appropriate model is of high importance. Figure 4-9 illustrates a combination of burst/collapse models.

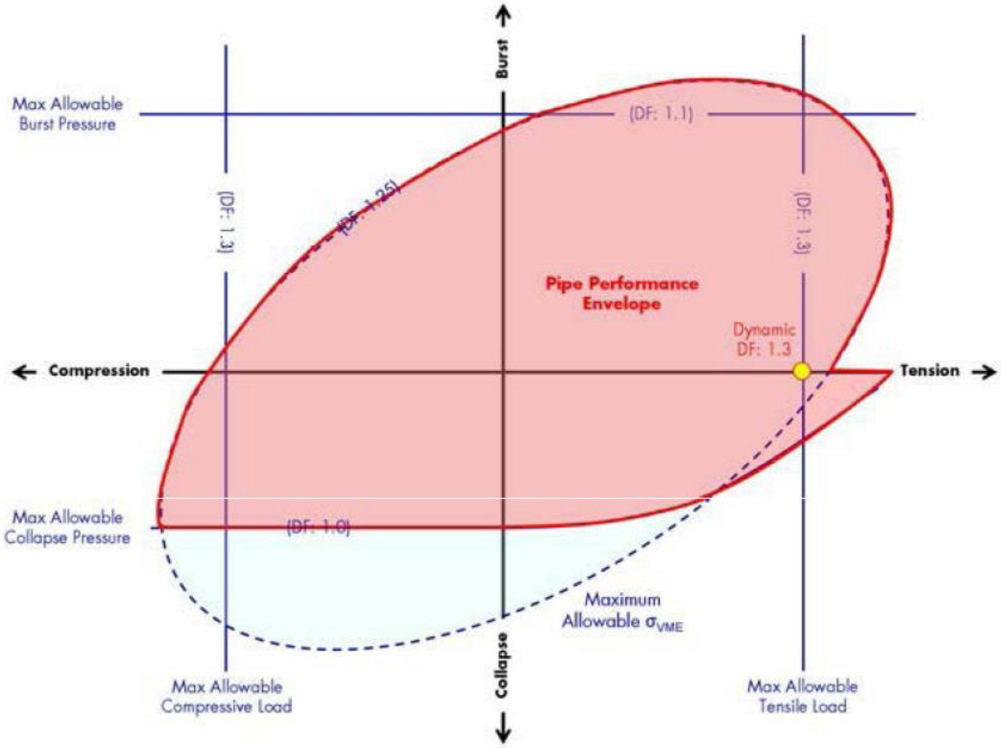


Figure 4-9 Uniaxial/Biaxial vs Triaxial Envelopes (Drilling Engineering & Operations Management Lecture Notes)

In Figure 4-9 the “Max Allowable Burst Pressure” line refers to the Barlow uniaxial burst model and the “Max Allowable Collapse pressure” refers to biaxial collapse model while the ellipse represents the von Mises’s yield model. The first quadrant illustrates the burst prediction for a pipe that undergoes tension. According to von Mises’ model combination of the tensile and burst load increases the pipe performance while combination of compressive and burst loads reduces the pipe performance. These combination effects are ignored in Barlow's burst prediction which makes von Mises's yield model a more reliable approach for burst prediction. On the other hand and for collapse loads, von Mises's model only considers yield strength of the materials while the biaxial model takes yield, plastic, transitional and elastic failures into consideration. This results in false collapse prediction by von Mises's model and the biaxial collapse model must be applied. The shaded envelope of Figure 4-9 illustrates the appropriate models for burst and collapse prediction.

To predict the burst load using von Mises's triaxial model, the axial, radial and tangential stresses on the pipe must be determined. The axial stress is calculate as described in section 4.2.6. The radial and tangential stresses are calculated using the Lamé equations:

$$\sigma_t = \frac{P_i A_i - P_o A_o}{(A_o - A_i)} + \frac{(P_i - P_o) A_i A_o}{(A_o - A_i) A} \qquad \text{Equation 4-50}$$

$$\sigma_r = \frac{P_i A_i - P_o A_o}{(A_o - A_i)} - \frac{(P_i - P_o) A_i A_o}{(A_o - A_i) A} \qquad \text{Equation 4-51}$$

Where $P_i$ and $P_o$ are the internal and external pressures in psi,$A_i$ , $A_o$ and A are the cross-sectional areas at inner diameter, outer diameter and the point of interest in $in^2$respectively.

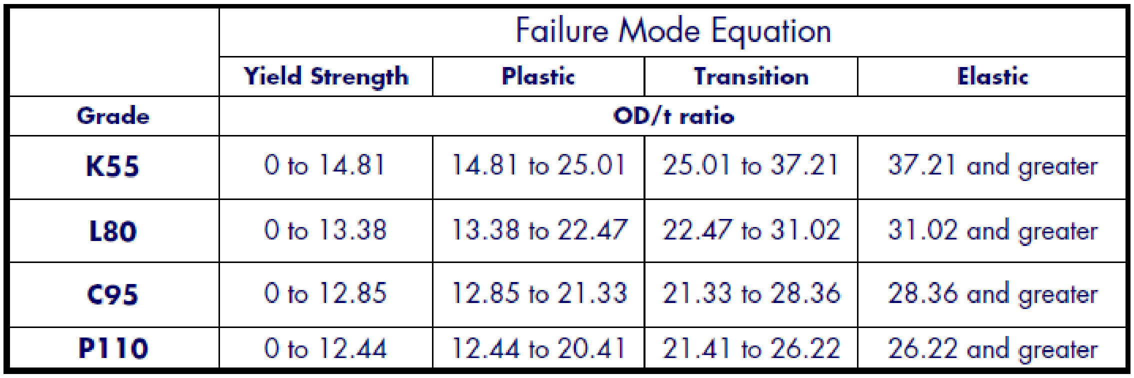
Knowing the axial, radial and tangential stresses, the critical yield stress by von Mises's model is calculated as follow where the pipe bursts if this value exceeds the materials yield stress.

$$\sigma_{VME} = \sqrt{(\sigma_a - \sigma_t)^2 + (\sigma_t - \sigma_r)^2 + (\sigma_r - \sigma_a)^2 + 6\tau^2} \qquad \text{Equation 4-52}$$

The pipe collapse is a much more complex phenomenon comparing to pipe burst due to instability type of failure. Pipe collapse is affected by many factors including ovality, diameter to thickness ratio, yield strength, type of heat treatment and etc. Collapse is categorized into the following four different modes based on the yield stress and diameter to thickness ratio of the pipe:

- Yield-strength collapse
- Plastic collapse
- Transition collapse
- Elastic collapse

The following table illustrate categorization of different pipes based on their yield strengths and the diameter to thickness ratios:



| | Failure Mode Equation | | | |
|---|---|---|---|---|
| | **Yield Strength** | **Plastic** | **Transition** | **Elastic** |
| **Grade** | **OD/t ratio** | | | |
| **K55** | 0 to 14.81 | 14.81 to 25.01 | 25.01 to 37.21 | 37.21 and greater |
| **L80** | 0 to 13.38 | 13.38 to 22.47 | 22.47 to 31.02 | 31.02 and greater |
| **C95** | 0 to 12.85 | 12.85 to 21.33 | 21.33 to 28.36 | 28.36 and greater |
| **P110** | 0 to 12.44 | 12.44 to 20.41 | 21.41 to 26.22 | 26.22 and greater |

Table 4-2 Collapse Modes (API Bulletin 5C3)

The critical collapse pressure is calculated according to the failure mode and by applying the appropriate equation of each mode. The five F factors are used in collapse pressure failure prediction. These factors are calculated according to the pipe materials yield stress and are as follow:

$$F_1 = c_0 + c_1\sigma_{yield} + c_2{\sigma_{yield}}^2 + c_3{\sigma_{yield}}^3 \quad \text{Equation 4-53}$$

$$F_2 = c_4 + c_5\sigma_{yield} \quad \text{Equation 4-54}$$

$$F_3 = c_6 + c_7\sigma_{yield} + c_8{\sigma_{yield}}^2 + c_9{\sigma_{yield}}^3 \quad \text{Equation 4-55}$$

$$F_4 = \frac{\left[\frac{3R_F}{(2+R_F)}\right]^3}{\sigma_{yield}\left[\frac{3R_F}{(2+R_F)}-R_F\right]\left[1-\frac{3R_F}{(2+R_F)}\right]^2} \quad \text{Equation 4-56}$$

$$F_5 = F_4R_F \quad \text{Equation 4-57}$$

where

$c_0 = 2.8762$

$c_1 = 0.10679 \times 10^{-5}$

$c_2 = 0.21302 \times 10^{-10}$

$c_3 = -0.53132 \times 10^{-16}$

$c_4 = 0.026233$

$c_5 = 0.50609 \times 10^{-6}$

$c_6 = -465.93$

$c_7 = 0.030867$

$c_8 = -0.10483 \times 10^{-7}$

$c_9 = 0.36989 \times 10^{-13}$

$c_{10} = 46.95 \times 10^6$

$R_F = \frac{F_2}{F_1}$

The critical collapse pressure calculation for the four mentioned collapse modes is as follow:

- Yield Strength Collapse:

$$P_{cr} = 2\sigma_{yield}\left(\frac{\left(\frac{D}{t}\right)-1}{\left(\frac{D}{t}\right)^2}\right) \quad \text{Equation 4-58}$$

Where D is the pipe outer diameter, t is the pipe thickness and $\sigma_{yield}$ is the pipe material yield stress.

- Plastic Collapse

$$P_{cr} = \sigma_{yield} \times \left( \frac{F_1}{\left(\frac{D}{t}\right)} - F_2 \right) - F_3 \qquad \text{Equation 4-59}$$

- Transitional Collapse

$$P_{cr} = \sigma_{yield} \times \left( \frac{F_4}{\left(\frac{D}{t}\right)} - F_5 \right) \qquad \text{Equation 4-60}$$

- Elastic Collapse

$$P_{cr} = \frac{46.95 \times 10^6}{\left(\frac{D}{t}\right) \times \left[\left(\frac{D}{t}\right) - 1\right]^2} \qquad \text{Equation 4-61}$$

The above equations are used to calculate the uniaxial critical collapse pressure. For cases where collapse load is combined with tensile load, the actual critical collapse pressure is lower than these calculated critical pressures. To consider the effects of tension, yield stress ($\sigma_{yield}$) used in the above equations must be modified. This modification is done based on von Mises theory and by applying the following equation:

$$\sigma_{pa} = \left[ \sqrt{1 - 0.75 \left( \frac{\sigma_a}{\sigma_{yield}} \right)^2} - 0.5 \left( \frac{\sigma_a}{\sigma_{yield}} \right) \right] \sigma_{yield} \qquad \text{Equation 4-62}$$

The bi-axial critical collapse pressure is determined by substituting the yield stress ($\sigma_{yield}$) with the equivalent yield stress ($\sigma_{pa}$) in Equations 6-58 through 6-61. The bi-axial critical collapse pressure must then be compared to the external pressure equivalent to determine the pipe collapse failure status. The external pressure equivalent is calculated as follow

$$P_{eq} = P_e - \left[1 - \frac{2}{\left(\frac{D}{t}\right)}\right] P_i \qquad \text{Equation 4-63}$$

where $P_e$ and $P_i$ are the external and internal pressures, $\frac{D}{t}$ is the outer diameter to thickness ratio of the pipe and $P_{eq}$ exceeding $P_{cr}$ indicates collapse failure.

## 4.3 MODEL AND TOOL DEVELOPMENT SUMMARY

The mathematical models that were discussed in this chapter are chosen as the basis of the down-hole simulator development. As mentioned they are chosen due to many factors including simplicity, available system limitations, fast processing time, and consistency with the co-requisite course and assumed capabilities of the students. In the next chapter the implementation of these models and numerical approaches to develop the down-hole simulator in MATLAB programming environment is discussed.

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# 5 Implementation

This chapter details the development of the down-hole simulator and presents the steps that were taken to implement the mathematical models (introduced in Chapter 4) into the simulator. It should be noted the primary goal is to use this package as a tool to obtain the laboratories presented in Chapter 3 and a long-term goal to perform research and extend to include improved downhole models. As discussed in previous chapters, each mathematical model is simulated in MATLAB and integrated with one another to form the down-hole simulator. Down-hole simulator consists of primary and subsidiary functions. Utilization of subsidiary functions facilitates the numerical calculations to model complex cases. For instance, diameter discretization, a subsidiary function, enhances the calculation time of modeling a complex case like variable drill string geometry.

MATLAB is used as the primary programming language for simulating the models. This is mainly due to the familiarity of students with this software, its capability of MATLAB in creating high quality graphics, and compatibility with longer terms goals. In the current version of the laboratories, students will use MATLAB as the primary tool to complete their assignment tasks. The current version of the down-hole simulator allows the students to use MATLAB for calculation purposes only. However, the future plan is to expand the package further by adding a feature which will enable the students to interact directly with simulator by integrating their codes within the simulator.

The current chapter illustrates the approaches taken to translate the mathematical models into algorithms and ultimately into MATLAB functions. As previously stated, API

(Application Program Interface) extracts the data from the surface simulator and inputs them into the down-hole simulator. The details of integrating API into the package is also presented in this chapter.

The primary and subsidiaries functions, which are developed into the down-hole simulator, are listed in Table 5-1 following by detailed discussion on development process of each.

| **Down-Hole Simulator Functions** | |
|---|---|
| Axial force along the drill string | Initial Setting |
| Bit Position | Mud hydro-static head level |
| Burst and collapse | Mud pumping |
| Capacity | Mud total pressure |
| Density discretization | Pipe Status |
| Diameter discretization | Rate of penetration |
| Drill string buckling | Surge/swab pressure |
| Frictional pressure loss and pump pressure | |

Table 5-1 Down-Hole Simulator Functions

## 5.1 READING DATA FROM THE SURFACE SIMULATOR

The operational parameters of mathematical models are physical variables such as bit weight, rotary speed, tripping velocity, pump speed and etc. The operators (students) control these parameters from the cyber-chairs of the surface-simulator. These parameters must be accessed through the API and fed into the developed down-hole simulator.

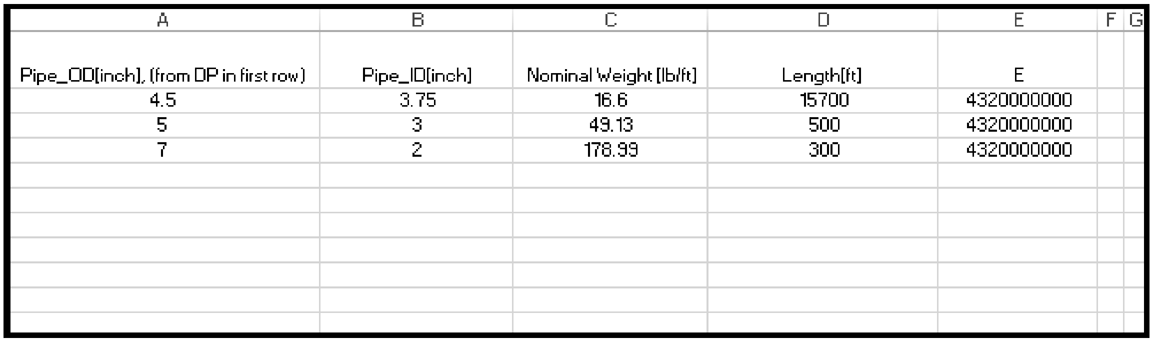
Once the operators change a parameter, a command is sent from the cyber-chairs to the PLCs where the necessary calculations to simulate the surface are done. Then the outputs are sent to the graphic processors and back to the cyber-chairs. PLC's output cannot be directly sent to the down-hole simulator since it lacks a standard API. In order to solve this issue, NOV developed a source code written in C# language to work as an API. This code has been translated to C++ by the previous graduate student working on this project. As a result, Visual Studio IDE is used to execute the C++ API as well as a platform to integrate and execute the down-hole simulators functions.

The visual studio file performs two major tasks: accessing the PLC's output and executing MATLAB functions of down-hole simulator. Once the API is executed, the streamed data from the PLCs are accessed in a predetermined time steps. The time steps to access data are defined within the body of the API code and can be modified to any desired rate. With the current set-up, the data can be accessed at rates up 1,000 Hz. But due to latency in the modelling algorithms data was typically accessed asynchronously and using a computation single thread that includes the modeling algorithms. This approach is more pragmatic and a multi-threaded architecture is left as an activity for future work. For instance, let's assume that the first set of data is accessed at time zero and fed into the down-hole simulator. If the processing time of the down-hole simulator for this set is fifty milliseconds, the next set of data which is fed into the simulator are those accessed at fifty milliseconds. Any data that are accessed between times zero and fifty milliseconds at 1,000 HZ rate (predetermined rate) are simply ignored. In the real world, such data could be used to mitigate sensor noise, but this problem does not exist in the current set up and there are no near-term plans to utilize hardware as part of the lesson plans.

In addition to accessing the PLCs' data, the developed API is also used as a platform to connect the surface and the down-hole simulators. As stated earlier, the down-hole simulator is developed in MATLAB while the operational data variables extracted from the surface simulator through API are in C++ format. Therefore, all the developed codes in this project are run in Visual Studio IDE due to the capability of this environment to connect the C++ and MATLAB variables. In other words, the down-hole simulator (packaged of MATLAB codes) is opened in Visual Studio IDE. The operational data variables (in C++ format) are passed into MATLAB variables using pointers and byte addresses. These operational data along with the initial conditions (defined in Section 5.2) form the necessary set of inputs to run the down-hole simulator.

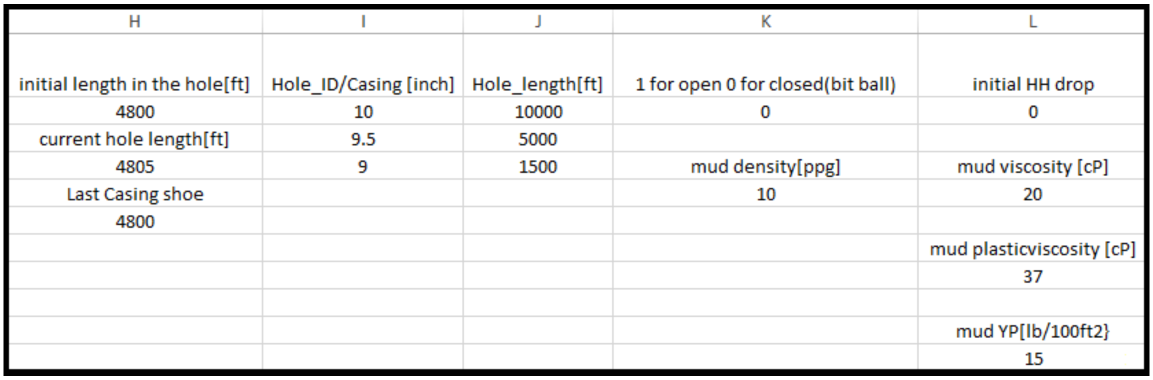
## 5.2 INITIAL SETTINGS AND PARAMETERS

Prior to running each laboratory, the initial settings of the operation must be specified. Initial condition and parameters are defined manually in a spreadsheet for every laboratory. The initial conditions are divided into two categories on separate spreadsheet pages: “General setting” and “P0_PF”. The “General setting” section includes operation-related parameters, such as drill string design, wellbore design, bit diameter and etc. Information regarding the current status of operation such as length of the drill string in the well, length of the drilled well and mud density are also included in this section. The “P0_PF” section contains the necessary information to define the formation. The pore pressure, height of each formation and empirical coefficients to be used in the rate of penetration correlations are defined in this section. Figure 5-1 and 5-2 illustrate a completed spreadsheet.



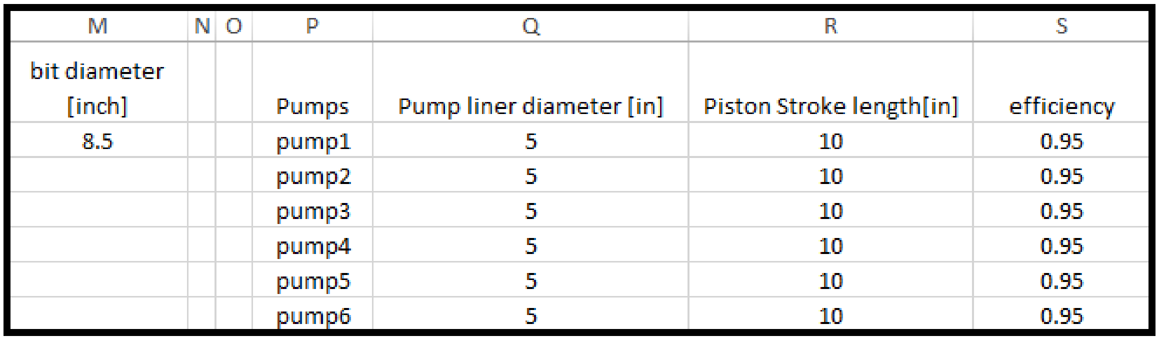
| A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|
| Pipe_OD[inch], (from DP in first row) | Pipe_ID[inch] | Nominal Weight [lb/ft] | Length[ft] | E | | |
| 4.5 | 3.75 | 16.6 | 15700 | 4320000000 | | |
| 5 | 3 | 49.13 | 500 | 4320000000 | | |
| 7 | 2 | 178.99 | 300 | 4320000000 | | |

Figure 5-1a "General setting" tab



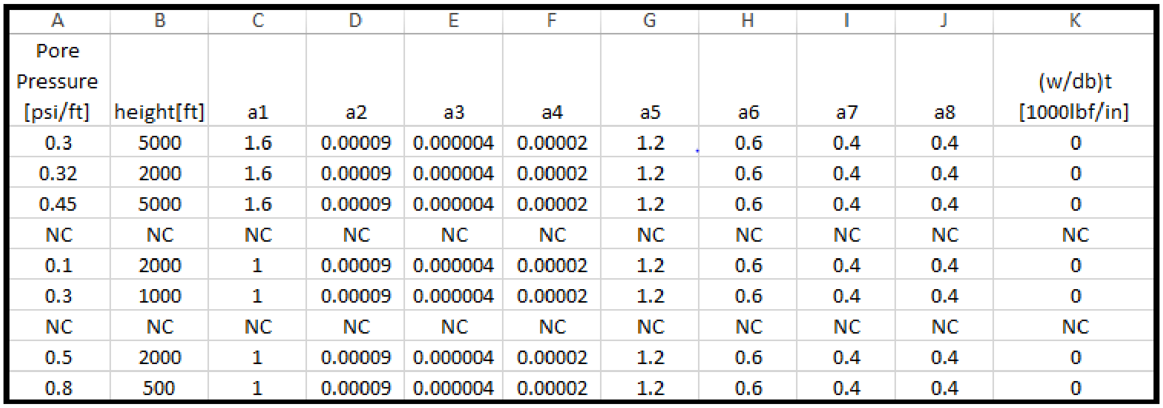
| H | I | J | K | L |
|---|---|---|---|---|
| initial length in the hole[ft] | Hole_ID/Casing [inch] | Hole_length[ft] | 1 for open 0 for closed(bit ball) | initial HH drop |
| 4800 | 10 | 10000 | 0 | 0 |
| current hole length[ft] | 9.5 | 5000 | | |
| 4805 | 9 | 1500 | mud density[ppg] | mud viscosity [cP] |
| Last Casing shoe | | | 10 | 20 |
| 4800 | | | | |
| | | | | mud plasticviscosity [cP] |
| | | | | 37 |
| | | | | |
| | | | | mud YP[lb/100ft2} |
| | | | | 15 |

Figure 5-1b "General setting" tab



| M | N | O | P | Q | R | S |
|---|---|---|---|---|---|---|
| bit diameter [inch] | | | Pumps | Pump liner diameter [in] | Piston Stroke length[in] | efficiency |
| 8.5 | | | pump1 | 5 | 10 | 0.95 |
| | | | pump2 | 5 | 10 | 0.95 |
| | | | pump3 | 5 | 10 | 0.95 |
| | | | pump4 | 5 | 10 | 0.95 |
| | | | pump5 | 5 | 10 | 0.95 |
| | | | pump6 | 5 | 10 | 0.95 |

Figure 5-1c "General setting" tab



| A | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|
| Pore Pressure [psi/ft] | height[ft] | a1 | a2 | a3 | a4 | a5 | a6 | a7 | a8 | (w/db)t [1000lbf/in] |
| 0.3 | 5000 | 1.6 | 0.00009 | 0.000004 | 0.00002 | 1.2 | 0.6 | 0.4 | 0.4 | 0 |
| 0.32 | 2000 | 1.6 | 0.00009 | 0.000004 | 0.00002 | 1.2 | 0.6 | 0.4 | 0.4 | 0 |
| 0.45 | 5000 | 1.6 | 0.00009 | 0.000004 | 0.00002 | 1.2 | 0.6 | 0.4 | 0.4 | 0 |
| NC | NC | NC | NC | NC | NC | NC | NC | NC | NC | NC |
| 0.1 | 2000 | 1 | 0.00009 | 0.000004 | 0.00002 | 1.2 | 0.6 | 0.4 | 0.4 | 0 |
| 0.3 | 1000 | 1 | 0.00009 | 0.000004 | 0.00002 | 1.2 | 0.6 | 0.4 | 0.4 | 0 |
| NC | NC | NC | NC | NC | NC | NC | NC | NC | NC | NC |
| 0.5 | 2000 | 1 | 0.00009 | 0.000004 | 0.00002 | 1.2 | 0.6 | 0.4 | 0.4 | 0 |
| 0.8 | 500 | 1 | 0.00009 | 0.000004 | 0.00002 | 1.2 | 0.6 | 0.4 | 0.4 | 0 |

Figure 5-2 "P0_PF" tab

In order to interconnect all these variables together, the initial-setting function is developed. Once the main file in Visual Studio (referred to as “project” file) is executed, MATLAB environment will become available and the initial-setting function is executed. It should be noted that a naming convention is followed to generate a title for every initial setting function of each laboratory. Each name consists of “`initial_setting`” and the laboratory name. For instance, the function “`rate_of_penetration_initial_setting`” defines the global initial variables of the rate of penetration laboratory.

The following command is used (in Visual Studio) to call this function:

*engEvalString(Engine_ptr, "rate_of_penetration_initial_setting;")*

After executing this command, the initial parameters, stored in the spreadsheet, are assigned to their global variables in the MATLAB environment. Some adjustments on the entered values are required in order to obtain the current status of the operation. These calculations and adjustments are done within the initial setting function. For instance, the designed drill string is defined in columns A though E of the “General_setting” spreadsheet page. An example is shown in Figure 5-1a. The information for designed drill pipe, heavy-wall drill pipe and drill collar are defined in separate rows and from top to bottom respectively. Column H of Figure 5-1b represents the current length of the drill string in the wellbore. For this particular example, 4800 feet is assigned to this length. With some minor modifications, the current lengths for each section of drill string is calculated without overriding the designed values.

Additionally the initial mud volumes in the annulus and the drill string are calculated within the initial setting function. The mud volumes are calculated based on the drill string and wellbore geometry as well as the initial mud head drop specified in the excel file. The calculated mud volume is constant throughout the operation and is only subjected to change under two separate scenarios; pumping mud in the annulus or tripping in to the point where mud starts to pour out of the well (will be discussed in Section 5.3.2). This calculated mud volume is used to determine the mud head level after the drill string is tripped in/out. Furthermore the mud hydro-static pressure is actively calculated based on the mud head level.

As mentioned before subsidiary functions are developed and used to reduce the down-hole simulator processing time. In order to reduce the processing time within milliseconds, all the operational parameters including drill string lengths, mud properties and etc. are discretized into increments of one foot using subsidiary functions. I.e. 100 feet of mud with density of 10 ppg is discretized into 100 one foot increments of the same density.

Utilization of this method expresses the assumption that the properties are constant within every one foot.

The initial setting function employs subsidiary functions to discretize the mud as well as the formation information. The formation information including the pore pressure are specified in the “P0_PF” section of the initial setting spreadsheet. The discretized pore pressure is used to calculate the fracture pressure using the Hubbert & Willis correlations (Figure 4-1).

## 5.3 MATLAB FUNCTIONS

As discussed earlier, the initial parameters are allocated as global MATLAB variables. Global variables can be retrieved at any time by other functions as inputs. This section discusses the function development process and details how the operational and initial parameters are handled. These functions form the basis of the down-hole simulator.

### 5.3.1 Bit Position

The main objective of the “`bit_position`” function is to update the bit position, drill string length and the well depth in addition to calculating the bit velocity. The main inputs of this function are:

- top drive position
- pipe in elevator status (will be discussed in Section 5.3.1.1)
- current drill string
- well lengths and diameters
- designed drill string and well plan
- formation coefficients

- WOB and rotary speed

Top drive position data are available on the PLCs and can be transferred through an Ethernet cable to the computer that is running the down-hole simulator. Based on the top drive position changes, drill string and well information are updated. Top drive position is a function of the length of the wire that the drawworks drum releases/retracts. For the case where bit reaches the bottom of the well, releasing more wire is only reflected on the top drive data accessed through the PLCs. The data indicates change in top drive position while the top drive in the surface simulator display is static. Therefore determining the bit position solely based on the top drive position should not be the prime method. While developing the bit position function, all these parameters need to be considered to reduce this wrong signal.

There are two possibilities for the bit position; off-bottom and on-bottom. There are two subsequent possibilities of upward and downward movement associated with each. When the bit moves upward from the mentioned positions, the drill string information will be updated according to the top drive position while the well information remains unchanged.

When the bit moves downward from an off-bottom position, the drill string length will be updated based on the change in the top drive position. This is followed by comparing the bit position to the well depth. The moment the bit reaches the bottom of the well a “dummy” variable is switched indicating that the status has changed from tripping to drilling for the next time the function is called.

In the event that the bit is moving downward from an on bottom position, a corrective approach is used to calculate the rate of penetration (in contrary to all other cases where the drive position was used to update the drill string and well information). It should be noted that the rate of penetration is acquired by calling a function with the same name. Subsequently, the rate of penetration is converted to the drilled length based on the used time step. The drill string and the well information are updated at last. The material properties, pipe inner and outer diameters and well diameter of the added section are updated based on initial drill string and well plan that were assigned in the spreadsheet.

#### *5.3.1.1 Pipe status*

The pipe status in the elevator/top drive is determined by the "`check_pipe_in`" function. When there is no engagement between the pipe and top drive, the top drive position change does not cause any changes in the drill string and well information. Figures 5-3 and 5-4 show the bit position and bit velocity versus time. The black section in the graphs presents the time period that the drill string and well information remain constant while an empty elevator/top drive position changes.

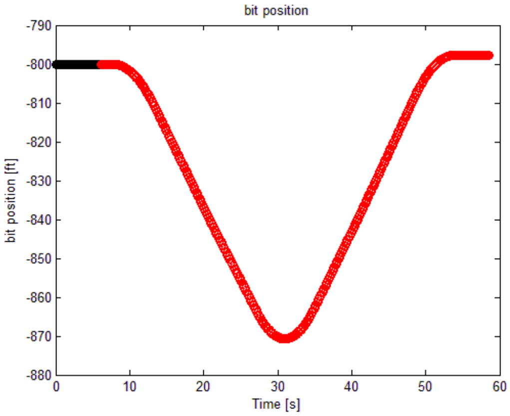


Figure 5-3 Bit position

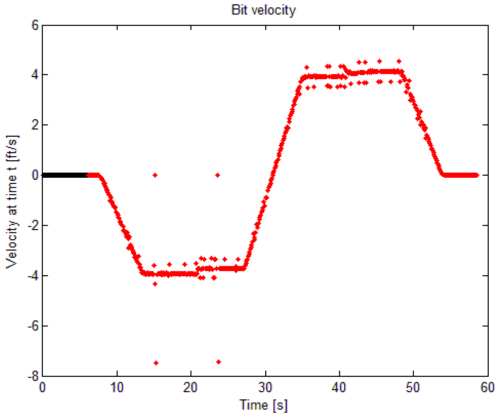


Figure 5-4 Bit Velocity

### 5.3.2. Mud hydro-static head

The "`hydraulic_head_drop`" function is developed to calculate the mud hydro-static head. As mentioned, the initial mud volume is calculated within the initial setting function and is assigned to a global variable. The mud volume gets updated by either this or the "filling annulus" function (Section 5.3.2.1). The mud volume stays constant for the cases where the bit is tripped out without circulation. It decreases when the bit is tripped in while the mud level has reached the surface (pouring out) and it only increases when mud is pumped in.

In order to enhance the down-hole simulator processing time, this function only updates the mud head level for every one foot change in the drill string length. Selecting a smaller value generates more accurate results but reduces the calculation speed. Additionally to boost the down-hole simulator performance, the "`capacity`" subsidiary function is developed and executed within the "`hydraulic_head_drop`" function.

The “`capacity`” function receives the drill string and well information as inputs and retunes the discretized drill pipe and annulus capacity matrices. The length of each matrix is equal to the length of the wellbore and the entries are calculated conforming to the assumption that the properties are constant for every one foot (Section 5.2). Therefore each entry of the capacity matrix represents the volume available for mud per one foot of drill pipe/annulus at the depth equal to its respective index. For instance, if the 1000th entry of the capacity matrix is 0.05, it indicates that the capacity from 1000 to 1001 feet below the surface is 0.05.

For cases where the drill string is off-bottom, the number of non-zero entries of the drill string capacity matrix are equal to the length of the drill string and the remaining entries of the matrix are zero. To clarify further, the capacity matrix for 1000 feet of a drill string in a 1200 feet well have 1000 non-zero entries in the top portion of the matrix and 200 zero entries in the bottom portion. These zero entries indicate that there is no space for mud to settle inside the drill string and it only settles in the annulus. The capacity matrices for the drill string and the well with complex geometries are shown in Figure 5-5.

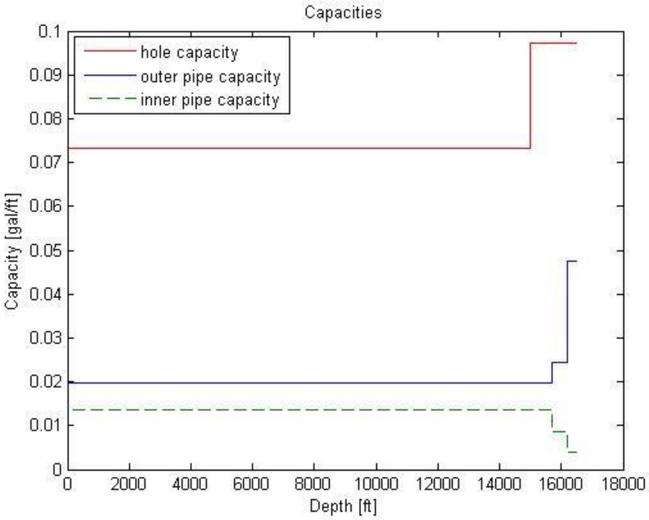


Figure 5-5 Capacity calculation for variable drill string and well geometry

After determining the capacity matrices, the "`hydraulic_head_drop`" function subtracts these entries from the mud volume orderly from the last entry to the top (mud fills the bottom section of well/drill string first). This process continues up to the point where there is no mud volume left to fill the available spaces in drill string/annulus. Since the capacities are discretized in one foot increments, the index of the last entry that was subtracted from the mud volume represents the depth that the mud has reached. I.e. if the 50th entry of the capacity matrix of a 1000 foot drill string/well is the last entry that was subtracted from the mud volume before it reaches zero, the mud has reached to 50 feet below the surface and has filled 950 feet of drill string/annulus. Figure 5-6 represents the mud level calculation algorithm.

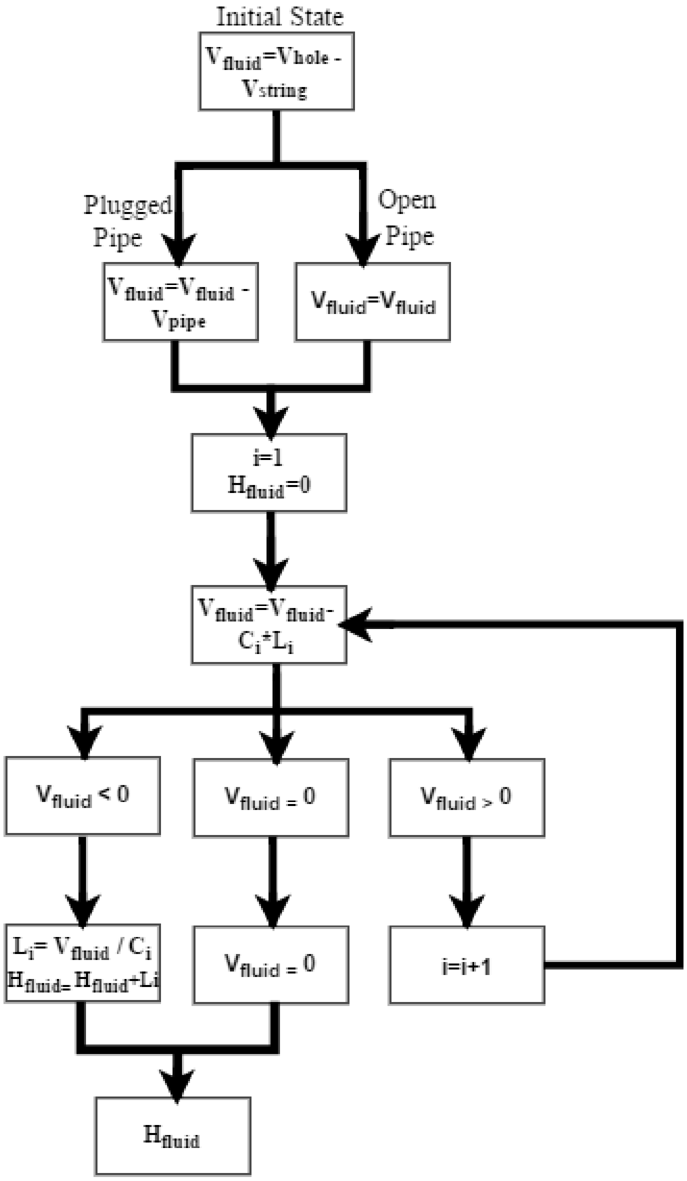


Figure 5-6 Mud head calculation

Once the mud level in the annulus is calculated, it is subtracted from the well depth to determine the annulus mud level drop. Figure 5-7 represents the mud level drop resulted from tripping 90 feet of a complex geometry drill string from a vertical well.

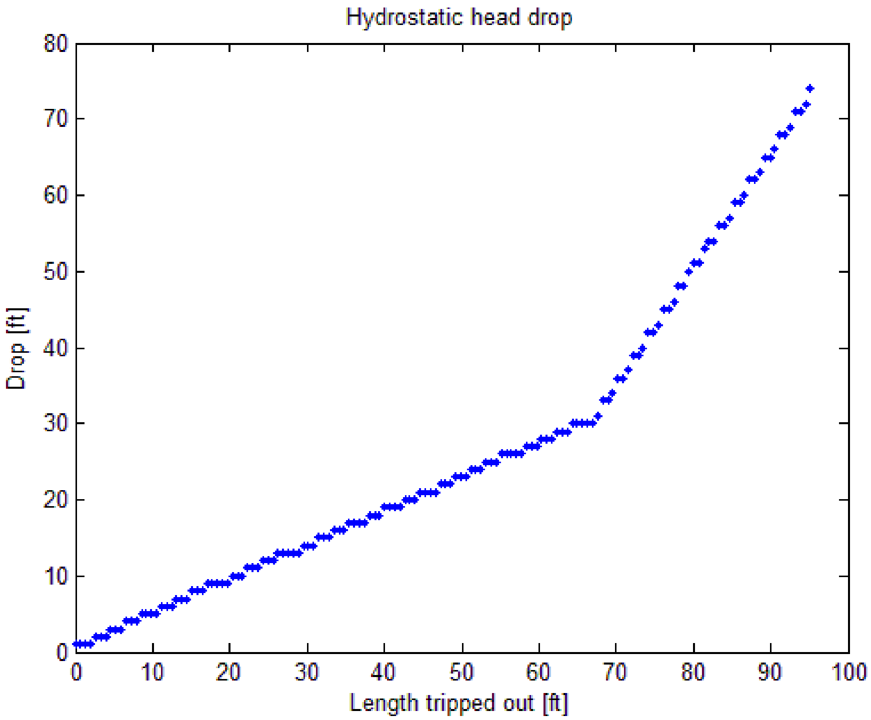


Figure 5-7 Hydro-static head drop

#### *5.3.2.1 Pumping mud in the annulus*

In some of the laboratories, students are required to start pumping mud into the drill string/annulus. After starting the pump, the streamed pump-speed data is collected from the PLCs and passed into the “`filling_annulus`” function. The role of this function is to calculate the pumped mud volume flow rate by using the pumping speed and the pump characteristic parameters. These characteristic parameters were defined in the spreadsheet prior to the operation (Figure 5-1c). The equations used to determine these parameters are discussed in Section 4.2.4.

The mud volume pumped into the annulus is then added to the previously calculated initial mud volume. The engineers can monitor the mud volume from the trends shown in RCC. Once the pump is started, the “hydro-static head drop” graph (Figure 5-7) disappears and the required volume to fill the annulus is shown (Figure 5-8). It continues to the point where annulus is filled followed by a completion message which appears on the same plot (Figure 5-9).

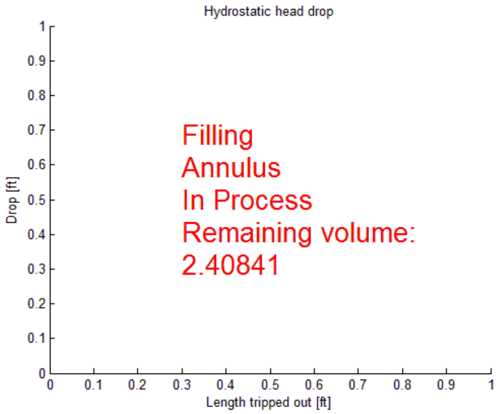


Figure 5-8 Filling annulus in process

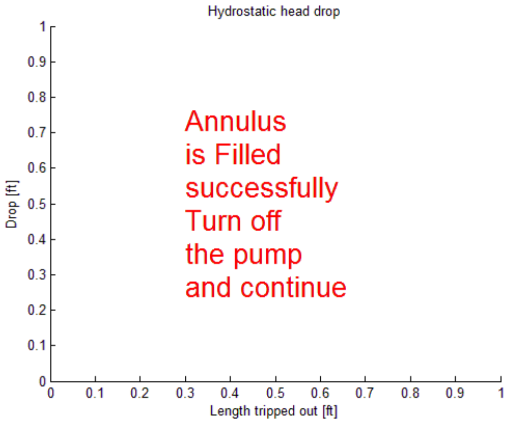


Figure 5-9 Completion message

### 5.3.3. Density Discretization

Due to the complexity of the mud density profile, the “`multi_density_rho`” subsidiary function is developed to discretize the mud density in both annulus and drill string. The discretized mud density matrix is obtained using the following parameters: various mud densities and their respective volumes in the drill pipe/annulus, drill string and the wellbore geometry. The final matrix contains the mud density discretized into increments of one foot. This discretized matrix is used to calculate the mud pressure and to investigate the loss circulation, formation fracturing, burst and collapse possibilities.

Once this function is executed two global mud density matrices for drill string and annulus are defined and values are assigned to them. The lengths of these matrices are determined by the length of the drill string in the well and wellbore depth respectively. In cases where the mud level is below the surface, a zero entry is added on the top of the mud density matrix for every foot of difference between mud head and surface.

### 5.3.4. Surge/Swab Pressure

To increase the accuracy of the down-hole simulator in mud pressure calculation, the dynamic and frictional effects must be taken into account in addition to the mud static pressure. An important factor to calculate the surge/swab pressure is to determine in which regions the flow is laminar and in which regions the flow is turbulent. For the annulus this highly depends on the clearance between the drill string and the wellbore and on their geometries. The smaller annular clearance increases the Reynolds number resulting in a higher induced surge/swab pressure.

After executing the "`surge_swab`" function, the drill string and the wellbore are discretized into smaller sections of 1 foot length to determine the Reynolds number at different depths. To facilitate this, the "`diameter_discretization`" subsidiary function is developed. By calling this function three discretized matrices of wellbore diameter, pipe inner and pipe outer diameters are defined and values are assigned to them. I.e. the 10th entry of each matrix represents the wellbore, drill string inner and outer diameters at 10 feet depth. Since the drill string length cannot exceed the wellbore depth the length of each matrix is defined to be equal to the wellbore depth. For sections with no drill string in the hole, the inner and outer diameters matrices entries are assigned to be zero.

Bit condition is another important factor which is considered in the surge/swab pressure calculation. Closed bits tend to generate more pressure comparing to open bits. This is due to higher volume of fluid which must be displaced to balance the volume after the drill string is tripped in/out. Considering the bit condition and the discretized geometry of the drill pipe (defined after calling "`diameter_discretization`" function), the discretized mud velocity matrix is calculated. Each entry of the obtained matrix represents the mud velocity along a one foot section of the drill string. Then the apparent viscosity and Reynolds number matrices are obtained similarly with their entries calculated based on the equations presented in Section 4.2.6.

Once the Reynolds number matrix is calculated, the entries that their values indicate laminar flow are segregated from those indicating turbulent flow. Following this, the clinging constant, the effective mud velocity and the surge/swab pressure matrices are calculated by applying the appropriate equations presented in Section 4.2.6. The entries of the calculated surge/swab pressure matrix represent the induced pressures for one foot sections regardless of the effects of sections above or below. Therefore to calculate the total induced pressure the cumulative summation of this matrix is computed.

Each entry of the cumulative summation matrix represents the total induced pressure at a depth equal to the matrix index. I.e. the 10th entry of the cumulative summation matrix represents the total surge/swab pressure at ten feet below the surface. Figures 5-10

– 5-12 represent the Burkhardt experimental data and the predicted induced pressure. The simulated results of this project are shown in Figure 5-14 using the same parameters and velocity (Figures 5-13).

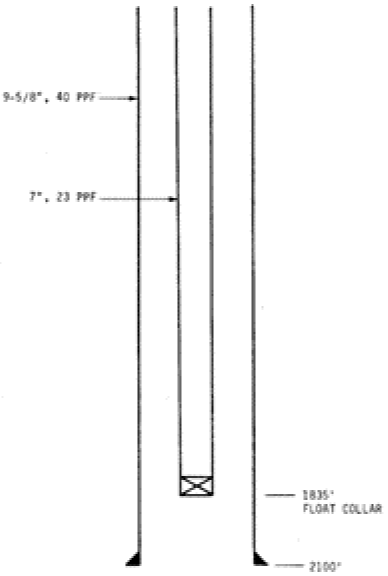


Figure 5-10 Burkhardt Wellbore/Drill String Geometry

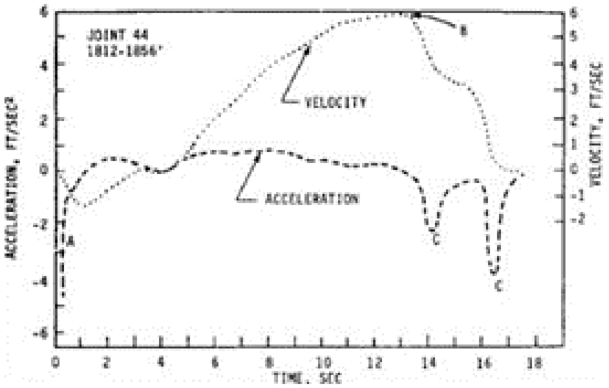


Figure 5-11 Burkhardt experiment Velocity Profile

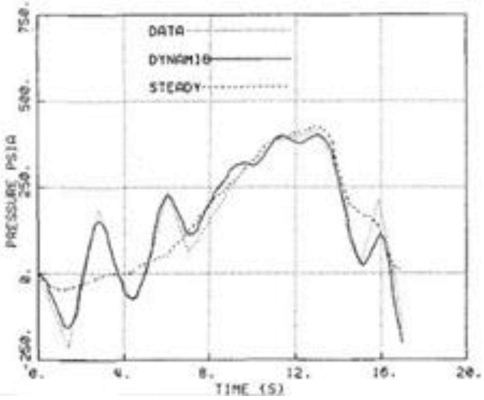


Figure 5-12 Burkhardt Pressure Prediction

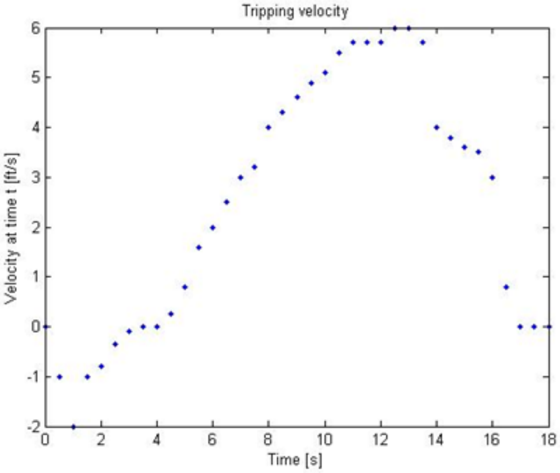


Figure 5- 13 Model Velocity Input

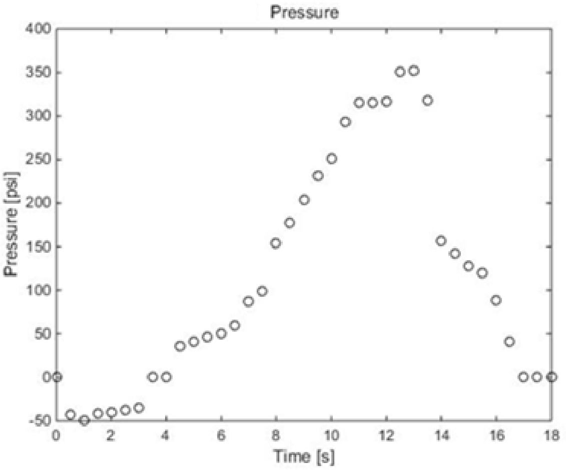


Figure 5-14 Developed Model Pressure Prediction

### 5.3.5. Frictional pressure losses and pump pressure

The frictional pressure losses must be considered in mud total pressure calculations to provide precise mud pressure. A similar approach, explained in the previous section, is taken to calculate the frictional losses inside the drill string and the annulus. Upon executing "`pump_pressure`" function, the mud properties, drill bit characteristic, drill string and well bore geometries information are passed into this function as inputs. These inputs are defined in the initial setting function according to respective values entered in the spreadsheet.

In the next step of the "`pump_pressure`" function the drill string and the well-bore geometrical information are discretized using the "`diameter_discretization`" subsidiary function. Once wellbore, drill string inner and outer diameter matrices are defined, the pump flow rate is calculated based on the pump speed accessed from the PLCs. Then the appropriate equations presented in Section 4.2.5 are utilized to generate the mud velocity matrices in both drill string and annulus. It should be noted that the annulus mud velocity for sections without the drill string is assumed to be zero. Based on this assumption, the lengths of both matrices are equal to the drill string length where each entry represents a constant velocity in every one foot section.

Similar to mud density discretization (Section 5.3.3), other mud properties are also discretized. The apparent viscosity and Reynolds number matrices for both drill string and annulus are then calculated. According to the obtained Reynolds number matrices, the sections with turbulent flow characteristics are segregated from laminar sections. The appropriate equations discussed in Section 4.2.5 are utilized and the frictional pressure losses for every one foot section is calculated. In the last step and similar to "*`surge_swab`*" function the cumulative summation of the matrices are computed to obtain the total frictional losses from the surface to a certain point.

The obtained frictional losses matrices for drill string and annulus are utilized in pump pressure calculation in addition to the mud total pressure computation (Section 5.3.6). Figure 5-15 illustrates the total frictional losses along the drill string and the annulus. Figure 5-16 represents the calculated pump pressure using equations of Section 4.2.5 for a case where the bit nozzles get plugged with time.

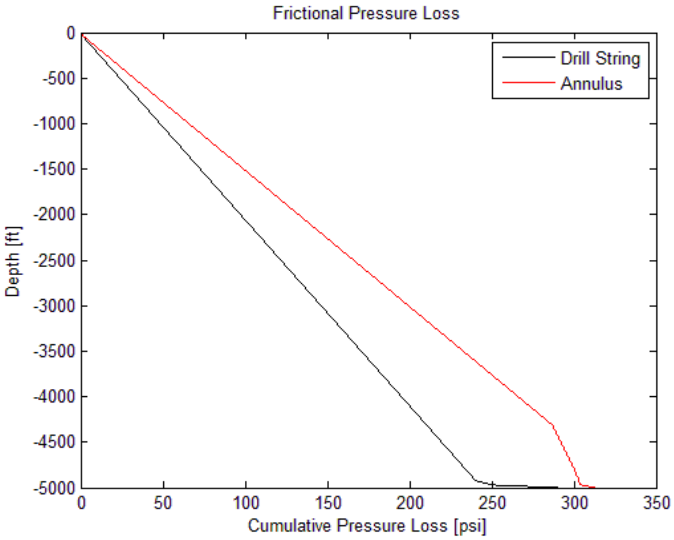


Figure 5-15 Frictional pressure Losses

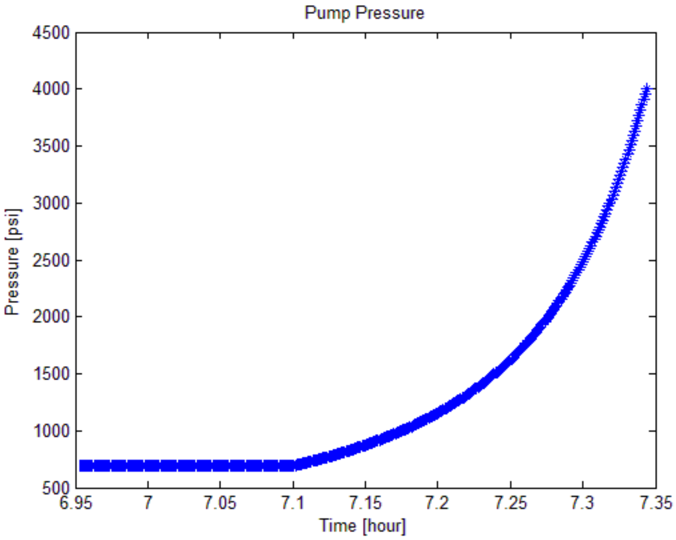


Figure 5-16 Pump Pressure increase due to bit balling

### 5.3.6. Mud Total Pressure

The "`mud_pressure`" function calculates the mud total pressure by integrating the mud pressure related parameters including mud hydro-static pressure, induced surge/swab pressure, pump pressure and frictional losses. The annulus and drill string discretized mud density matrices are used to calculate the hydro-static pressures. For this purpose, the following equation is utilized where the hydro-static pressure at each depth is the product of cumulative summation of densities and gravitational constant.

$$\left[P_{i\_static}\right] = g \cdot \sum_{1}^{i} [\rho]_i \qquad \text{Equation 4-1}$$

where $P_{i\_static}$ is the hydro-static pressure matrix, $\rho$ is the density and "i" is the matrix index. The index can be any value between 1 and the well-bore depth in increments of one foot (the density was discretized into increments of one foot).

The calculated surge/swab pressure (Section 5.3.4) and the frictional pressure losses (Section 5.3.5) are then integrated with the hydro-static pressure to obtain the mud total pressure. The total pressure matrices for both annulus and the drill string are calculated as follow:

$$[P_{annulus}] = \left[P_{static\_annulus}\right] + \left[P_{surge/swab}\right] + \left[P_{frictional\_annulus}\right] \qquad \text{Equation 4-2}$$

$$\left[P_{drillstring}\right] = P_{pump} + \left[P_{static\_drillstring}\right] - \left[P_{frictional\_drillstring}\right] \qquad \text{Equation 4-3}$$

Once the mud total pressure matrices are computed, the entries of $P_{annulus}$ matrix are compared to the entries of the pore pressure and fracture pressure matrices with the same indexes (same index represent same depth). For the cases where the total pressure falls out of the drilling window, a message appears on the screen which indicates that the mud pressure is above/below the fracture/pore pressure. Figure 5-17 represents the mud total pressure with and without considering the dynamic surge/swab effect.

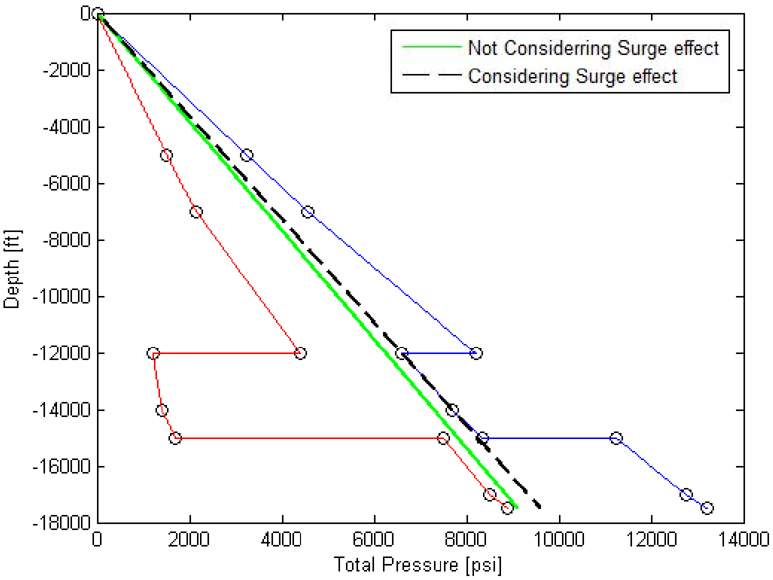


Figure 5-17 Drilling Window and Mud Total Pressure

### 5.3.7. Drill string buckling

The “`buckling`” function is developed to check for pipe failure (buckling) while the operator is drilling and WOB is applied. Once this function is executed, the drill string and wellbore information, the mud level, the discretized mud total pressure matrices inside the drill string and the annulus are accessed as inputs.

Within this function the “axial” function is called which returns a discretized matrix with entries equal to axial force along the drill string in one foot increment. As a result of this discretization approach, the axial force matrix length is equal to the length of the drill string. The axial force function is capable of processing variable mud densities as well as complex drill string & wellbore geometries in buoyancy and axial forces calculations. Following the axial force calculation, the index of the neutral point on the drill string is determined.

In the next step and within the buckling function the discretized matrices for drill string cross sectional area, drill string density, buoyancy factor, drill string unit weight and scaling factor are defined and respective values are assigned to them. Based on these matrices the critical weight on bit matrices for both first order and second order buckling are calculated. The minimum values of these two matrices are then compared to the operational WOB that is accessed through the PLCs. For the cases where the operational WOB exceeds the calculate critical values, a message appears on the axial force plot and indicates the type of buckling. Figure 5-18 and Figure 5-19 illustrate axial forces along the same drill string resulted from different WOBs and the messages that appear due to drill string buckling.

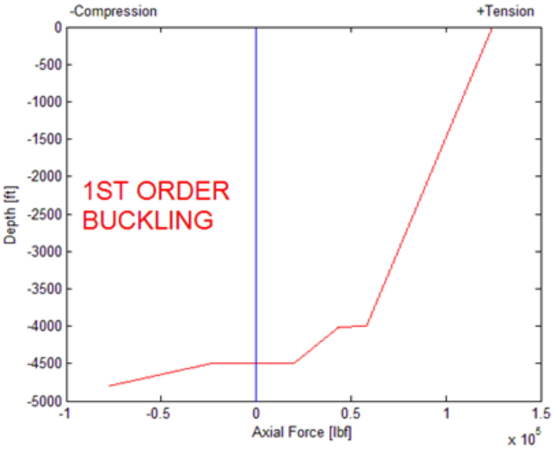


Figure 5-18 Firs-Order Buckling

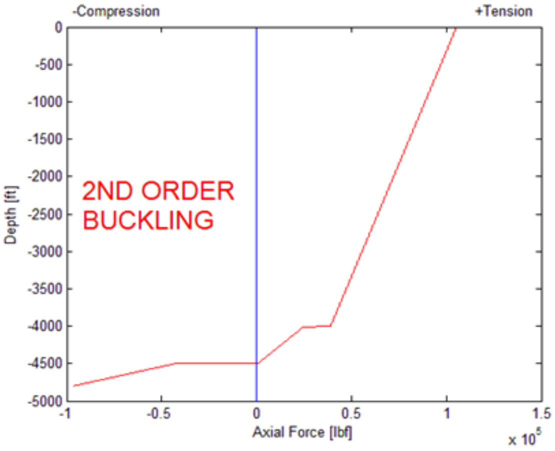


Figure 5-29 Second-Order Buckling

### 5.3.8. Rate of Penetration

Recalling from Section 5.3.1 the drill string and well information are updated based on the changes in top drive position that is accessed through the PLCs. The surface simulator computes the top drive position based on length of the drawworks wire that is released or retracted. It was mentioned that once the bit reaches bottom of the well, there is a contrast between the top drive position shown in the surface simulator display and the top drive position data accessed thought the PLCs. This indicates incapability of the surface simulator to distinguish between off-bottom and on-bottom bit positions. In order to resolve this issue, the "*`bit_position`*" function is utilized to consider various bit positions and movements possibilities.

One of these possibilities is the downward movement of an on bottom bit (drilling). In this event a corrective approach is used to calculate the rate of penetration. Once the "*`bit_position`*" function detects this situation, it ignores the topdrive position data accessed from the PLCs and call the "*`rate_of_penetration`*" function. This function calculates the rate of penetration based on the equations presented in Section 4.2.8.

In the next step, the calculated ROP is converted to the drilled length by according to the predetermined time step. Then the drill string and wellbore information (diameter, materials and etc.) are updated by according to the drilled length and the designed plans entered in the excel file.

As discussed in Section 4.2.8 various variables control the rate of penetration calculation. However for simplicity and purposes of the laboratories, the coefficients of these variables are selected such that only WOB, rotary speed and formation drillability control the ROP. The WOB and rotary speed data are accessed through the PLCs once the "`rate_of_penetration`" function is called and the drillability of the formation is predetermined in "P0_PF" section of the excel file.

### 5.3.9. Burst & Collapse

The "`burst_collapse`" function is the last function added to the down-hole simulator. This function is developed to check for pipe failures due to difference between mud total pressure in the drill string and the annulus (it is also capable of checking for casing failure). It performs the necessary calculations to check for the drill string collapse failure caused from a higher external pressure comparing to the internal pressure such as an event where gas kick is received as well as the burst failure caused from a higher internal pressure.

This function takes the drill string information, calculated axial force along the drill string, the mud densities in drill sting and annulus as inputs. These discretized matrices were defined in previous functions and are passed into the "`burst_collapse`" function upon executing. To avoid repetitious calculation and to boost this function performance, the diameter to thickness ratios discretized matrix and five F factors (section 4.2.9) were calculated in the initial setting function and their values are passed into this function.

Within this function and based on the difference between the internal and external pressures, the depths that the pipe is at risk of burst are recognized and segregated from those at risk of collapse. Once these depths are known (which are equal to the indexes of discretized matrices), all other discretized matrices are also separated.

For the sections that the pipe is at risk of burst, the discretized axial, tangential and radial stresses and the von Mises's yield matrices are computed using equations provided in Section 4.2.9. The internal pressure is then subtracted from the external pressure and the resulted matrix is compared with the von Mises's yield matrix and for the events where the pipe bursts, a message ("Pipe Burst") appears on the instructor screen. It should be noted that since the matrices indexes indicate different depths, only entries with same index are compared against each other.

The collapse failure type for different sections of the drill string are determined based on the discretized diameter to thickness ratio and yield point matrices for the sections at risk of collapse failure. The "discretized collapse type" matrix is defined and the values are assigned to it. Based on this matrix, the indexes for each collapse type (types 1, 2, 3 and 4) are distinguished. Based on these indexes, sections at risk of different collapse failure types are segregated from one another. Next the appropriate equations (Section 4.2.9) are used to calculate the critical pressures for each collapse type. Finally these four different critical pressure matrices are combined into one discretized matrix.

In the next step the effective pressure discretized matrix is calculated to take the axial stress effect into consideration. Then entries with same indexes of this matrix and the critical pressure matrix are compared with each other to determine if collapse happened. Similar to the case where pipe bursts, a message appears on the screen indicating that the pipe has collapsed.

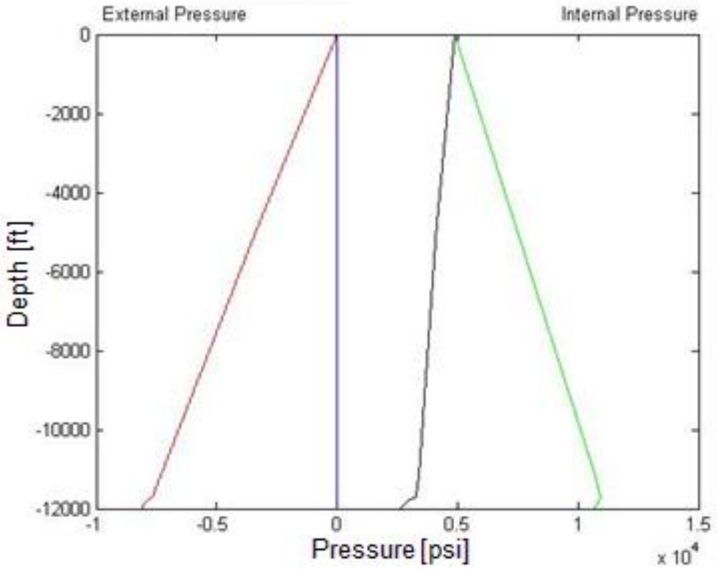


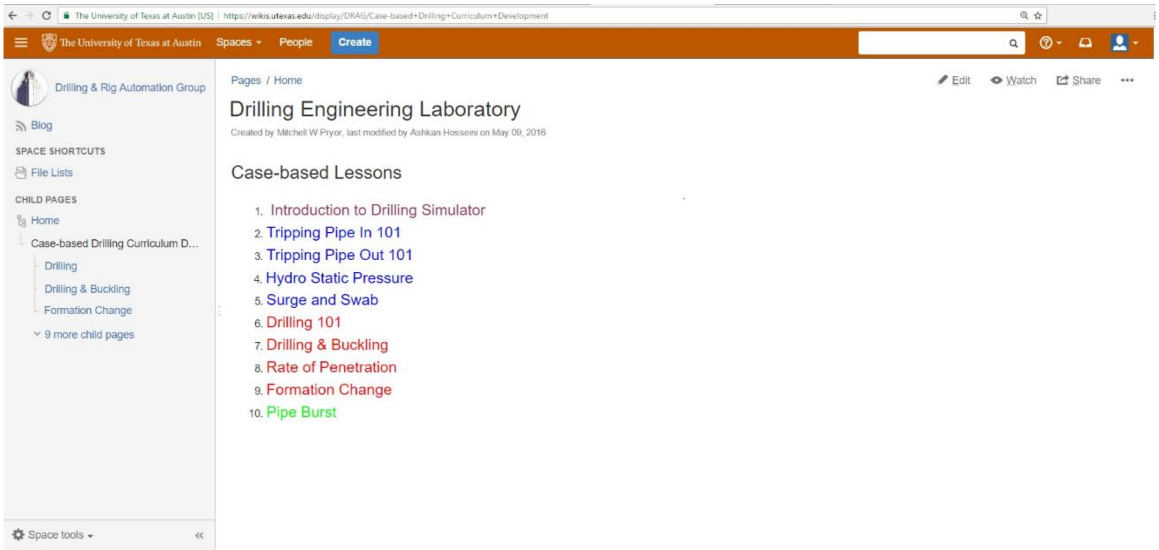
Figure 5-20 Mud Total Pressure across the Drill String

## 5.4 UNIVERSITY WIKI SERVICE

The University of Texas at Austin provides online spaces for university-affiliated groups and project. These spaces are accessible through World Wide Web address of "*https://wikis.utexas.edu*" where accessing a certain space requires authorization from the owner of the space. The Drilling & Rig Automation team has been using the university wiki service for sharing information with its members.

The proposed laboratories handouts that provide the necessary information and instruction to successfully perform the operations are uploaded to this online space. A major advantage of this information sharing media is that it allows students to observe changes made to these notes simultaneously as oppose to traditional method where the instructor had to remove the uploaded Microsoft Words/PDF file, apply changes and re-upload the file.

Once the authorization is granted to the students, they can go to the web address and log in using their "UT EID" and password. After finding the designated space for the drilling laboratory course, they will be able to observe the list of laboratories. Each of these laboratories (shown in figure 5-20) are linked to the respective laboratory handout where students have access to prior, during and after laboratories.



Drilling Engineering Laboratory

Created by Mitchell W Pryor, last modified by Ashkan Hosseini on May 09, 2016

Case-based Lessons

1. Introduction to Drilling Simulator
2. Tripping Pipe In 101
3. Tripping Pipe Out 101
4. Hydro Static Pressure
5. Surge and Swab
6. Drilling 101
7. Drilling & Buckling
8. Rate of Penetration
9. Formation Change
10. Pipe Burst

Figure 5-31 University Wiki Website Snapshot

## 5.5 IMPLEMENTATION SUMMARY

This chapter summarized the implementation details for the models described in Chapter 4 and utilized in the lessons designed in Chapter 3. Beyond the details of programming languages and development platforms, this chapter described how the functions handle nonlinear boundary conditions, data acquisition, initialization, and synchronizing behaviors, interfacing with the existing simulator hardware, and RTC visualizations. Visualizations examples were given for each developed function.

By using the simulator, some aspects of the problem that would exist in the real world (asynchronous sensor/controller actions, signal noise, etc.) were ignored, which kept the scope of implementation within the abilities of a PGE student with some but limited programming experience. However, other data sources that would be trivial to acquire with a simple sensor where more complex to simulate. Future work could include integration of more realistic data management or code optimization to minimize the model processing times.

# 6 Conclusion and Recommendations for Future Work

## OVERVIEW

This projected was initiated to develop drilling-related laboratories based on real-life drilling operations to train next generation of Petroleum Engineers. The ultimate goal of the project was to boost the students' comprehensions of the underlying science in addition to increasing their competency level to join the industry using a combination of traditional and case-based teaching methods. This was achieved through fulfilling the following objectives:

1. Designing laboratories outlines to develop the essential skills which are not gained through the traditional teaching method
2. Adopting and utilizing the appropriate mathematical models from the existing literature based on system limitations, fast processing time and students capabilities to develop a down-hole simulator
3. Development of an Application Program Interface, API, to access the surface simulator's operational data and parameters through the PLCs to generate trends and monitor the operation in the Remote Collaboration Center ,RCC,
4. Development of a platform to integrate the surface and down-hole simulators

## 6.1 SUMMARY OF WORK

To address the general deficiency of academia and to increase students' competency level, the Drilling and Automation team at the University of Texas at Austin initiated to develop a series of student-led laboratories to expose students to a realistic work environment. The motivation to develop these laborites was initially raised from the MBA program offered at Harvard Business School where the students are evaluated solely based on their performance on over 500 business cases.

This motivation was enhanced after investigating the aviation industry accomplishment where a great cost reduction in training was achieved in addition to eliminating the on-the-training accidents. The aviation industry adopted and enforced training through simulators where their workforce have the chance to experience what is impractical to learn with real aircraft. They are trained to carry out the appropriate performance at the time of failure and emergencies. Due to similar nature of the Aviation and Oil & Gas and industry, it was realized that the latter has the potential of adopting this training method.

After fully investigating the advantages and disadvantages of case-based learning method in addition to various effective skills development methods and competency models, a series of case-based student-led laboratories were proposed. To offer a combination of traditional and case-based methods, these laboratories are proposed as complementary to the traditional drilling classes offered at the University of Texas at Austin. Students are required to attend "Drilling Engineering & Operations Management" class prior or during attending these laboratories to ensure that students learn the fundamentals and theories and have the necessary knowledge.

The architecture of the laboratories were designed to enhance development of skills which are neglected in the traditional teaching method. In the laboratories design, realistic and up-to-date systems were utilized to assure effectiveness of the training. Similar to real-world work environment, students are assigned to different roles. They are grouped in teams consist of operators and engineers. The operators (driller and the assistant driller) operate the 3D-virtual rig using the cyber-chairs while engineers are located in a separate location referred to as Remote Collaboration Center, RCC. The engineers are responsible to monitor the operation to ensure the safety and efficiency. They have access to the operational data and trends and are responsible to perform calculations, make decisions and to communicate these decisions with the operators.

Based on the designed structure and by considering the desired learning outcomes, ten separate laboratories were proposed. With implementation of the proposed laboratories, Petroleum Engineering students at University of Texas at Austin has the opportunity to experience real-life like challenges associated with drilling operations using a realistic up-to-date virtual drilling simulator. Utilization of the proposed laboratories navigates students through all four stages of Kolb’s four-stage learning cycle where the most effective learning is achieved.

The open-ended nature of the laboratories as well as the structure of the cases are such that students must actively perform calculations to take the most updated operational parameters into consideration to make the right decision. In addition during the operation and based on their previous decisions, students get exposed to certain consequences. This exposes them to different possibilities and outcomes which enhances their critical thinking skill development.

Furthermore, based on the difficulty of each laboratory, different amounts of stress are experienced. Like a real operation, engineers must communicate with the operators during an incident. The fast paced nature of the laboratories and the fact that engineers must perform necessary calculations and make decisions in a short time, creates a realistic work environment and engages students emotionally in the operation.

These proposed laboratories were subjected to implementation complications. The most important one of many was the accuracy of down-hole simulator's calculation. False calculations could result in negative training. Since the students are asked to make decisions based on their calculations, inconsistency between their calculations and false down-hole simulator calculations could results in negative training and undermining their confidence. Another implementation challenge was the processing time of the down-hole simulator. A long delay between the time that operators change a parameter or send a command to the simulator and the time that results are shown in the RCC, could arise confusing and ultimately lead to negative training.

By considering the mentioned implementation challenges and to minimize the negative training, appropriate mathematical models were identified. The majority of these models and their respective theories are taught in the "Drilling Engineering & Operations Management" class. These models were then simulated in MATLAB programming language as functions and the main building blocks of the down-hole simulator.

Additionally the laboratories are designed such that the students in the engineer role must use these models for calculations and decision making. This consistency ensures that the effects of negative training are negligible.

The first development phase of the integrated simulator started with developing an interface to access the surface simulator data. PLCs are the computes where the surface simulator data are processed, however they generally do not have an interface for accessing the data. An Application Program Interface, API, was developed to access the PLCs data. This program was initially written in C# and was translated to C++.

The second development phase of the integrated simulator was to develop the down-hole simulator. As mentioned the adopted mathematical models were the building blocks of the down-hole simulator. However developing the down-hole simulator goes beyond simply implementing these models in MATLAB. Other factors such as handling initial & boundary conditions, the processing time optimization and etc. were also considered.

The down-hole simulator was designed such that it required the user to enter the initial settings in an excel file prior to the operations. These initial settings include the designed drill string & well information, the last known length of each, pore pressure, pump characteristic parameters and etc. These initial settings are passed into the down-hole simulator once the simulator is executed and are used in the mathematical models in addition to the operational parameters.

To boost the down-hole simulator processing time, discretization method was utilized. For this purpose, subsidiary functions were developed to boost the processing time and facilitate the major functions (the implemented mathematical models). The main task of the subsidiary functions are to discretize operational parameters such as mud density and velocity in addition to drill string and wellbore geometry. These discretized parameters are stored in form of matrices which allows the models to handle complex cases such as multi-density mud in drill string/annulus and as well as complex drill string/well geometry.

In the process of developing the down-hole simulator, an inconsistency between the graphical display and the streamed PLCs data of the surface simulator was noticed. In some cases, the PLCs data represented change in top drive position while the top drive was static in the simulator graphical display. After further investigation it was understood that the surface simulator computes the top drive position based on length of the drawworks wire that is released/retracted. This resulted in incapability of the surface simulator to distinguish between off-bottom and on-bottom bit positions and in some cases a rate of penetration as high as tripping speed was observed. This problem was addressed by developing a function to handle different events accordingly.

After developing the down-hole simulator, a platform was designed and developed to integrate the down-hole simulator functions as well integrating the surface and down-hole simulators. The down-hole simulator was developed in MATLAB while the API, which allows accessing surface simulator data, was developed in C++. In order to connect the two, Visual Basic IDE was utilized. This Visual Studio platform allowed us to execute the MATLAB engine and pass the accessed surface simulator data to global variables in MATLAB using pointers and byte addresses.

Following the development of the integration platform, a Visual Basic Project file was created for each laboratory. The appropriate models were uploaded on these files according to the laboratory purpose. Execution of each file is sufficient to initiate the respective laboratory and to generate the trends shown in RCC.

## 6.2 EXECUTION & PRELIMINARY FEEDBACK

Integration of the surface and down-hole simulators created the opportunity to execute the proposed laboratories. The laboratories objectives vary from following and understanding a step-by-step procedure to making decisions based on calculations and trends. In the process of developing the down-hole simulator, some of the laboratories were tested to ensure their effectiveness in meeting the objectives.

The second laboratory (learning to trip in) was executed during spring semester 2016. Over twenty undergraduate students of the University of Texas at Austin participated in this laboratory. The step-by-step procedure to operate the cyber-chairs to trip a few stands of pipe was given to the students. The students went through a rotation as driller and assistant driller where they experienced different responsibilities of each role. After executing the laboratory it was brought into attention that a single laboratory on learning to trip was not sufficient for students to learn to operate the cyber-chairs without using the provided step-by-step procedure. Therefore it was decided to add a similar laboratory to the proposed curricula to allow students to get more familiar with the process of operating the cyber-chairs.

The surge & swab laboratory was executed by graduate students and presented to the Rig Automation and Performance in Drilling (RAPID) consortium members. Two graduate students in the Remote Collaboration Center, RCC, monitored the data & trends and were responsible to make decisions. Based on the shown trends, they actively performed necessary calculations and obtained the most efficient tripping velocity while the mud pressure stayed within the drilling margin. They communicated with the operators using a cellphone and advised them to modify the tripping velocity accordingly. The results of this test was promising and both students and the consortium members expressed their interests in the executed laboratory.

## 6.3 FUTURE WORK

In addition to the proposed laboratories, there were others that due to implementation complications and possibility of negative training were not proposed in this project. For instance following the tenth laboratory where students decrease the mud flow rate to reduce pump pressure after bit balling is detected, another laboratory was initially in mind. The objective of that laboratory was to investigate the effects of low flow rate on cuttings transport. In a more complex laboratory comparing to the tenth one, once bit balling was detected students were supposed to reduce the flow rate to avoid pipe burst and trip out the pipe. Reducing the flow rate below a certain rate results in a stock pipe due to cuttings settlement. However in such case due to our limitations, it was not possible to communicate with the surface simulator to barricade top drive movement and ignore the sent command from the cyber-chairs. Such events, diminish the realism of the laboratory and are postponed to future where more access to interact with surface simulator is granted by NOV.

As mentioned, the mathematical models that are used in this project were chosen based on various factors including the assumed capabilities of students and the fast processing time of the models. Additionally the down-hole simulator and the integration platform were designed and developed from scratch where substantial amount of time was spent on. The future work could include adopting and optimizing the most advanced and complex existing models and integrating them with the down-hole simulator. This creates the opportunity to practice rig automation on the existing virtual oil rig prior to implementation of automation on the actual rigs.

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