MANAGED PRESSURE DRILLING CANDIDATE SELECTION

A Dissertation

by

ANANTHA SARAT SAGAR NAUDURI

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

May 2009

Major Subject: Petroleum Engineering

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ABSTRACT

Managed Pressure Drilling Candidate Selection. (May 2009)

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Managed Pressure Drilling now at the pinnacle of the 'Oil Well Drilling' evolution tree, has itself been coined in 2003. It is an umbrella term for a few new drilling techniques and some preexisting drilling techniques, all of them aiming to solve several drilling problems, including non-productive time and/or drilling flat time issues. These techniques, now sub-classifications of Managed Pressure Drilling, are referred to as 'Variations' and 'Methods' of Managed Pressure Drilling.

Although using Managed Pressure Drilling for drilling wells has several benefits, not all wells that seem a potential candidate for Managed Pressure Drilling, need Managed Pressure Drilling. The drilling industry has numerous simulators and software models to perform drilling hydraulics calculations and simulations. Most of them are designed for conventional well hydraulics, while some can perform Underbalanced Drilling calculations, and a select few can perform Managed Pressure Drilling calculations.

Most of the few available Managed Pressure Drilling models are modified Underbalanced Drilling versions that fit Managed Pressure Drilling needs. However, none of them focus on Managed Pressure Drilling and its candidate selection alone.

An ‘Managed Pressure Drilling Candidate Selection Model and software’ that can act as a preliminary screen to determine the utility of Managed Pressure Drilling for potential candidate wells are developed as a part of this research dissertation.

The model and a flow diagram identify the key steps in candidate selection. The software performs the basic hydraulic calculations and provides useful results in the form of tables, plots and graphs that would help in making better engineering decisions. An additional Managed Pressure Drilling worldwide wells database with basic information on a few Managed Pressure Drilling projects has also been compiled that can act as a basic guide on the Managed Pressure Drilling variation and project frequencies and aid in Managed Pressure Drilling candidate selection.

DEDICATION

I dedicate this dissertation to my grandparents, Mrs. Nauduri Laxmi Kantham and Mr. Nauduri Peri Sastry, and Mrs. Gorthi Malathi and Mr. Gorthi Venkata Sanyasi Rao for their unflinching faith in me, love and affection;

To Mr. Ravi Sri Krishna Moorthy, for being a great influence in my life;

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To Dr. Teodoriu, my graduate committee member, for his interest and presence at my defense through internet from Germany; and to Dr. Jochens, my graduate committee member, for her interest and help with my understanding of the Managed Pressure Drilling (MPD) regulations;

To George Medley, my external committee member, a very knowledgeable yet unassuming person, who was my mentor at SIGNA Engineering and a great friend, for teaching me the basics of MPD and guiding me through my research;

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To the MPD wells dataset providers – SIGNA Engineering Corporation of Houston for helping me first with a detailed set of MPD wells data on all four of the MPD variations; AtBalance with Smith of Houston for providing me second detailed MPD wells dataset, which helped me in expanding my database; and Secure Drilling for providing me with third set of MPD wells database;

To SIGNA Engineering, AtBalance with Smith, Secure Drilling, Tesco Corp, and Dual Gradient Systems LLC, for providing prompt and detailed information on their work, MPD projects, and systems and technology, whenever I approached them; and to AGR Subsea AS and Halliburton, for their help related to their technologies and services;

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To my family, for their confidence in me, encouragement, support and love;

And to all those people whom I failed to mention, but without whose help this work would have never been possible.

I thank you all, for your time, help, encouragement and for making these four years a memorable experience.

NOMENCLATURE

AFP	Annular Friction Pressure
ABP	Application of Backpressure
API RP	American Petroleum Institute Recommended Practices
BHA	Bottomhole Assembly
BP	Backpressure
BOP	Blowout Preventer
BHP	Bottomhole Pressure
CSM	Candidate Selection Model
CTD	Coiled Tube Drilling
CBHP	Constant Bottomhole Pressure
CCC	Continuous Circulation Coupler
CCS	Continuous Circulation System
DD	Directional Drilling
DwC	Drilling with Casing
DGD	Dual Gradient Drilling
ECD	Equivalent Circulation Density
EMW	Equivalent Mudweight
ERD	Extended Reach Drilling
ft	Feet/Foot

Fp	Fracture-Pressure
GOM	Gulf of Mexico
HazID	Hazard Identification
HazOP	Hazardous Operations
HSE	Health, Safety & Environment
HD	Horizontal Drilling
ID	Inner Diameter
IADC	International Association of Drilling Contractors
JIP	Joint Industrial Project
LRRS	Low Riser Return System
MPD	Managed Pressure Drilling
NOC	National Oil Company
NPT	Non Productive Time
NTL	Notice to Lessees and Operators
OD	Outer Diameter
PoCP	Point of Constant Pressure
Pp	Pore-Pressure
Ppg	Pounds Per Gallon
PMCD	Pressurized Mud Cap Drilling
Psi	Pounds Per Square Inch

RCD	Rotating Control Device
ROP	Rate of Penetration
SPE	Society of Petroleum Engineers
SMD	Subsea Mudlift Drilling
TLP	Tension Let Platform
TVD	True Vertical Depth
UBD	Underbalanced Drilling
UBO	Underbalanced Operations
WBP	Wellbore Pressure
WBS	Wellbore Stability

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1. INTRODUCTION

Drilling technology has made tremendous progress from the initial water and brine wells drilled in ancient China; kanats and quanats constructed in Persia and Mesopotamia; ‘Joseph’s Well,’ an ancient water well of Cairo, Egypt; and several other primitive wells drilled for water, brine, oil and gas in prehistoric times (Brantly 1971; Short 1993).

Many great people took drilling technology forward by leaps and bounds to the place where it is today. Leonardo Da Vinci the great architect, inventor and engineer, left behind several ideas, still used in most of the industrial equipment, including oil well drilling. Georgious Agricola, a geologist and mining expert, in his treatise, ‘De Re Metallica’ at the beginning of the Renaissance, said a lot about digging holes in the earth for ores. David Ruffner and Joseph Ruffner ‘drilled’ the first brine well as opposed to ‘dug’ and later developed the early ‘well drilling tools and practices’.

Edwin L Drake drilled the first purposeful well for oil in United States. Rodolphe Leschot invented and patented the earliest form of diamond core drills. T. F. Rowland patented an ‘offshore rotary drilling rig’. Captain Lucas, with his Spindletop field wells, Earle Halliburton with his cementing service company, inventors of derricks, rigs, drill pipe, casing, and downhole equipment, all took drilling engineering giant strides forward (Brantly 1971).

This dissertation follows the style of *SPE Drilling & Completion.*

Moving on to modern times, in the last few decades, technologies like ‘Horizontal Drilling’ (HD), ‘Directional Drilling’ (DD), ‘Extended Reach Drilling’ (ERD), ‘Casing Drilling’ / ‘Drilling with Casing’ (DwC), ‘Coiled Tube Drilling’ (CTD), Underbalanced Drilling (UBD) , and Managed Pressure Drilling (MPD), have made it possible to drill wells that could not otherwise be drilled, and made huge contributions to meet the global oil demand and production.

This dissertation is about one of these latest technologies, ‘MPD’, its subcategories referred to as ‘Variations’ and ‘Methods’ of MPD, and its ‘Candidate Selection’.

1.1. MPD: Brief Intro

MPD is one of the latest drilling technologies that is being increasingly used to drill wells that cannot be drilled using conventional drilling techniques because of problems like deeper target depths, reservoir depletion, narrow pore pressure and fracture pressure windows and other drilling problems associated with non-productive time (NPT) or drilling flat time (Hannegan 2005; Stephenson et al. 2005; Saponja et al. 2006; Beltran et al. 2006; Mawford et al. 2006; Rehman 2006; Nauduri et al. 2009; Malloy et al. 2009).

MPD has a very wide range of applications (Hannegan et al. 2004; Nauduri et al. 2009) and is the next step in the evolution of drilling techniques following the UBD technology (Hannegan and Wanzer 2003; Hannegan 2005; Nauduri and Medley 2008).

1.2. Nature of the Problem

With growing drilling problems and increasingly complicated drilling undertakings, many projects seem to be potential applications/candidates for MPD (Hannegan 2005). Although MPD fits many of these scenarios, not all of these projects require MPD. Hence, candidate selection of MPD is recommended before deciding ‘TO USE’ or ‘NOT TO USE’ MPD for a given project.

Many computer simulators and software models are available in the drilling industry to perform drilling hydraulics calculations and simulations. Many of these models can do conventional hydraulics; some carry out UBD calculations and a very few deal with MPD hydraulic calculations. A select few of the MPD models are designed only for MPD; many of them are modified versions of UBD models that fit MPD needs. Some of them perform MPD candidate selection. However, none of them concentrate specifically on MPD and its candidate selection.

1.3. Proposed Solution

To develop ‘Candidate Selection Model and Software’, as a part of research that can perform the basic candidate selection of MPD, acting as a preliminary screen to determine the utility of a candidate well for the application of MPD. To develop an MPD worldwide wells database that acts as an accessory to the MPD candidate selection.

1.4. Objectives

- To Study the available MPD techniques, variations, and methods used in the drilling industry. To understand the engineering considerations, constraints, and rationale behind such MPD applications.
- To develop an MPD Candidate Selection Model (CSM): To Understand/Identify the steps involved in the candidate selection process and to develop a 'Flow Diagram' to decide the utility of MPD for a given candidate well or a project.
- To develop a Candidate Selection Software, that can act as 'a Preliminary Screening Tool', capable of running under multiple scenarios, outputting information on MPD hydraulics, equipment and procedures.
- To develop a Worldwide MPD wells database with information such as Variation/Method used, Equipment, Location, Date, and other available data that can act as a basic guide on the MPD variation and project frequencies, that can aid in MPD candidate selection.

1.5. Review of Available Hydraulic Software Models

Among the several software models available in the drilling industry, very few are pertinent to MPD hydraulics and calculations. The operator(s) of the prospects, the oil Majors, National Oil Companies (NOCs), or independent oil companies, generally rely on the service companies and consultants for their software needs for projects like MPD.

Software that includes the temperature effects and compressibility factors are believed to give results that are close to the values measured in the real well conditions. Some of the service companies and consultants develop and maintain software related to MPD, UBD, etc., since they work on those specific areas and deal with such operations frequently.

A few of these companies involved in MPD projects alphabetically are: ‘AGR Subsea AS’, ‘AtBalance with Smith’, ‘Baker Hughes’, ‘Blade Energy’, ‘Dual Gradient Systems LLC’, ‘Halliburton’, ‘MI Swaco’, ‘National Oilwell Varco’, ‘Secure Drilling’, ‘Smith Services’, ‘SIGNA Engineering Corp’, and ‘Weatherford’.

1.5.1. Service Providers and Consultants

Offsite hydraulics flow modeling is used by operators during the planning process of the project and is generally required for procuring permits to drill from the regulatory agencies, like the Minerals Management Service, Health and Safety Executive etc. These hydraulic models are used to plan the fluids programs[*] and to some extent, the equipment arrangements[**]. The service companies like Halliburton and Weatherford, consultants like Blade Energy and SIGNA Engineering Corp., and mud companies like Baker Hughes, etc. together provide some of these capabilities.

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[*] Personal Communication with D. Hannegan. 2009. Fort Smith, AR: Weatherford

[**] Personal Communication with G. Medley. 2009. Houston: SIGNA Engineering Corporation

While drilling onsite, an MPD software that can use real time input data such as the pump rates, standpipe pressure, casing pressure, choke manifold pressure, etc., is required. Such software can provide early kick/loss detection, send/receive signals to/from automatic and semi-automatic chokes, and in the process provide lead time to increase/decrease mud-weight and circulation rate without any interruption to ‘drilling ahead’. The companies like Secure Drilling and AtBalance provide such services [*].

A few of these companies provided information on their MPD function and activities; the software they use during MPD design and execution phases, and its capabilities; and information on the candidate selection models they use (if they use) and their features.

AtBalance: This service company uses ‘EZClean’ software for real time operations to integrate their MPD equipment with the rig equipment[**]. ‘EZClean’ is modified version of Shell’s proprietary single phase steady state model. For their calculations during ‘Design/Engineering Phase’ they use ‘Presmod’ software to do transient modeling and ‘KICK’ software for multiphase modeling, both developed by ‘SPT Group’.

Blade Energy: Little information is available about this service company related to MPD through the company website. This company did not respond to any of the several emails sent and calls given to them. This company does some work related to UBD.

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[*] Personal Communication with D. Hannegan. 2009. Fort Smith, AR: Weatherford

[**] Personal Communication with D. Reisthma. 2009. Houston: AtBalance with Smith

Halliburton: This service company uses the GeoBalance^{TM} for MPD services. It also provides several software services for several other drilling related operations[*].

Secure Drilling: This service company uses an in-house software called 'TDHysim', for performing MPD hydraulic calculations[**]. TDHysim uses proprietary mathematical models that include the effects of temperature and pressure, and the same software is used for field operations and during the engineering planning and design phase.

SIGNA Engineering: This service company uses two separate software modules 'HUBS' and 'ERDS', for their hydraulic calculations, engineering design and planning[†]. 'HUBS' is primarily developed for handling and solving problems associated with Underbalanced Operations (UBO). ERDS is designed for MPD operations. It uses the fluid compressibility and the temperature effects in its calculations.

Weatherford: Weatherford uses SURE software for the MPD candidate selection, which is a modified version of the UBD candidate section model (Weatherford 2009a). For other hydraulic calculations they use proprietary software available to Weatherford personnel alone. SURE is available for their general public through their website[‡].

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[*] Personal Communication with S. Shayegi. 2009. Houston: Halliburton

[**] Personal Communication with H. Santos. 2009. Houston: Secure Drilling

[†] Personal Communication with G. Medley. 2009. Houston: SIGNA Engineering Corporation

[‡] Personal Communication with D. Hannegan. 2009. Fort Smith, AR: Weatherford

2. EVOLUTION OF THE DRILLING TECHNOLOGY

There are many stages in the evolution of drilling technology. The first stage is the ancient water and brine wells drilled from the prehistoric eras to not so modern times. The second stage is the drilling of the earliest oil wells, and development of basic derricks, rigs, and cable tool rigs. The third stage is the development of rotary hoists and machines, drilling shafts and drill bits, casing, drilling fluids and mud circulating systems, formation and well testing, cementing, and all those other systems, equipment and procedures that are now considered as an integral part of ‘Conventional Drilling’.

The final stage in the evolution is the development of the specialized techniques like CTD, ERD, Casing Drilling or DwC, UBD, and MPD. Some of these technologies, based on their relevance to MPD, are briefly discussed in this section.

2.1. Conventional Drilling

‘Conventional Drilling’ is a generic term used to describe a typical onshore or offshore drilling operation that involves use of equipment, procedures and personnel that would be required to drill any other oil well. Usually in such an operation, a rig consisting of a top drive and a rotary table that rotates a kelly is used. The kelly in turn rotates the drillpipe and drill bit. There is a system to circulate drilling mud or drilling fluids in and out of the borehole and a place to hold these drilling fluids called the ‘Mud Pits’.

The drilling crew is trained and/or is experienced in handling basic drilling operations such as, making and breaking connections, casing, cementing, logging, and well control operations. Generally, specialized equipment and permitting is not required for conventional drilling operations; however, there might be a few exceptions.

The advantages of conventional drilling are:

- The wells are comparatively inexpensive,
- The equipment and drilling crew are generally available,
- The well design and planning operations are uncomplicated, and
- The regulatory permitting issues are less stringent.

The disadvantages of conventional drilling are:

- The drilling crew might run into a few drilling problems that could result in loss of time and money, and
- In very rare cases lack of advanced equipment and drilling experts might cause blowouts, Health, Safety and Environment (HSE) issues and/or fatalities.

However, it is important to remember that drilling problems can still occur and mishaps can still happen, even after the use of the additional drilling equipment and presence of the drilling experts on the rig. Periodic training of the crew, proper and regular maintenance of the equipment, and following set procedures are a few of the several key steps that are still very important for safe and trouble free drilling environment.

2.1.1. High Dynamic Overbalance in Conventional Drilling and its Effects

In conventional drilling, in order to stay between the pore pressure (Pp) or wellbore stability (WBS) limit and fracture pressure (Fp) limit, a mud weight that is higher than the Pp/WBS and lower than the Fp is used in static condition. In dynamic condition, additional energy is required to overcome the pipe and annular frictional pressure (AFP).

This implies that additional pressure equal to the AFP is applied (or required) at the bottom of the hole. Hence, the bottomhole pressure (BHP) or the wellbore overbalance increases by the value of AFP in dynamic circulation conditions. This increase in overbalance can cause some drilling-related problems and make drilling difficult.

Some of the effects of high overbalance are:

- Reduced rate of penetration
- Differential sticking
- Kick-loss cycles
- Surge and swab effects

The annular pressure profile, referred to as the wellbore pressure (WBP) is sometimes represented as equivalent mudweight (EMW). The relation between BHP or WBP and the EMW is given by the **Eq 1.1.** Observe that the units of WBP are pounds per square inch (psi), while the units for EMW are pounds per gallon (ppg).

$$EquivalentMudWeight_{AtDepth'D'}(EMW) = \frac{Wellbore\,\mathrm{Pr}\,essure(WBP)}{0.052 \times Depth(D)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 1.1$$

In this dissertation, the term WBP is used whenever referring to the annular pressure profile, to avoid confusion that can be created by change of units.

2.2. Underbalanced Drilling

'UBD' or 'Underbalanced Drilling' is a key step in the evolution of the drilling technology and is the predecessor to the MPD technology. Typical reasons for using UBD for a project are generally faster rate of penetration (ROP), and/or reduced formation damage or wellbore skin. The basic principle of UBD is to keep the WBP below the formation pore pressure and deliberately invite influx.

UBD techniques have been around for a long time. All the primitive drilling operations like the wells drilled in China were, in a way, UBO (Brantly 1971). One of the first references to UBD documented is a patent to P. Sweeney on January 2, 1866 for a process using compressed air to clean cuttings out of the hole (SIGNA 2000).

UBD has been used in Oklahoma, California, Utah, New Mexico, Texas, and other states; and internationally at least in Canada, Mexico, Brazil, Argentina, Colombia, Australia, Russia, Africa, Middle and Far East (SIGNA 2000).

2.2.1. What is UBD?

UBD , sometimes also referred to as UBO, refers to all those deliberately undertaken drilling operations and techniques, which have WBP less than the formation fluid pressure at least in one point of the open wellbore. Note that another part of the open wellbore can be at balance or overbalanced in an UBO. The operation is called an UBO if the wellbore is underbalanced even at a single point.

2.2.2. Utility of UBD

Drilling underbalanced results in several benefits like – faster penetration of the drill bit, increased drill bit life, instantaneous openhole testing of reservoirs, reduced skin damage or formation damage, lesser drilling problems associated with kick-loss cycles, surge and swab effects and differential sticking. UBD along with other technologies like HD, CwD, CTD, and advanced pressure detection and sensing tools became a very successful tool for the drilling industry.

2.2.3. UBD and Conventional Drilling

The primary difference between UBD/UBO and conventional drilling is the value of pressure at which the BHP (or the WBP at a different 'given depth') will be held in comparison to the Pp, at the bottom of the hole (or at that different 'given depth').

For conventional drilling, the BHP/WBP is held above the Pp to prevent the well from kicking in static condition. This requires overcoming the annular friction component in dynamic circulation conditions, which results in an increase in the BHP/WBP or the overbalance pressure. This high overbalance increases the infusion of fluids into the formation, reduces the ROP, and causes other drilling related problems.

On the contrary, in UBO the BHP/WBP is below the Pp at least in a part of the wellbore, reducing/limiting the overbalance and eliminating some of the problems associated with this additional overbalance in the conventional drilling methods.

All the processes like casing, cementing, logging, DD, etc. that are done on a regular well are also required for UBO. However, special procedures, training and expertise are required to handle all these operations. Additional equipment is also required for UBO on top of equipment used for conventional drilling. Permitting and approvals from regulatory agencies are also very different for UBO.

2.2.4. Equipment

UBD/UBO requires specialized equipment since there is a continuous, though controlled, flow of fluids to the surface. The key elements of a typical UBO are included in this section. Additional equipment is chosen based on the project objectives, requirements, and availability. More UBO/MPD equipment is shown in Appendix A.

2.2.4.1.Rotating Control Device (RCD)

There are two designs of RCDs: active seal design and passive seal design. Companies like Smith Services, Weatherford, etc. supply the passive seal RCDs (**Figs. 2.1a and 2.1b).** The only active seal design in the market is Shaffer's PCWD (Pressure Control While Drilling). A few earlier versions of active seal RCD designs, like the 'RBOP®' manufactured by Precision Drilling (Canada) and 'RPM 3000' manufactured by Alpine (Canada) are commercially not available in the market anymore.

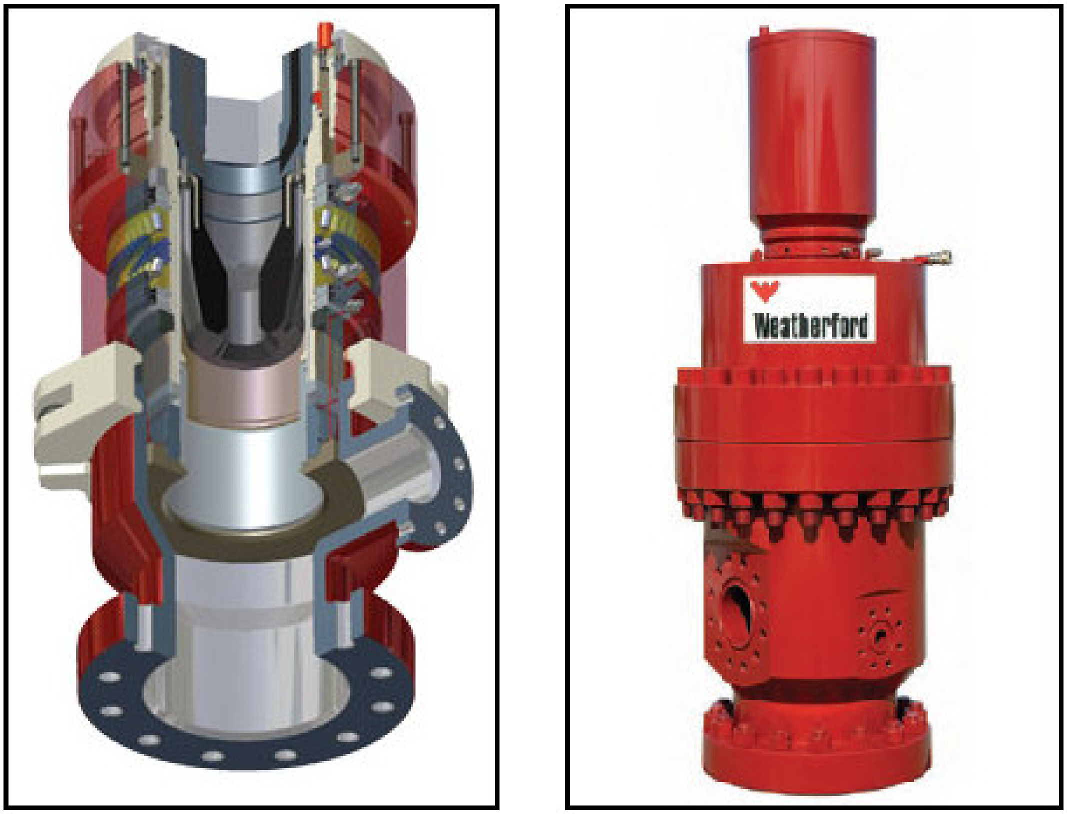

Fig 2.1 a

Fig 2.1 b

Fig. 2.1–Rotating Control Devices. Fig. 2.1(a) – Shows HOLD^{TM} 2500, a Smith Services RCD (Smith 2009g) and Fig. 2.1(b) – Shows Weatherford-Williams® M7800 RCD (Weatherford 2009a).

2.2.4.2.Choke Manifolds

The management of the BHP is very important for operations like UBD and MPD. Chokes are devices that restrict or slow down the flow of fluids. They can be used to shut the well in, interrupting the circulation, and maintaining a required pressure at the wellhead, thereby, maintaining the required BHP.

For UBD and MPD operations, additional chokes are placed in the fluids' return path to give better control over the BHP by applying backpressure (BP). Three major types of chokes available in the drilling industry are: fully automatic chokes, semi-automatic chokes and manual chokes. **Fig. 2.2** shows an Auto Choke.

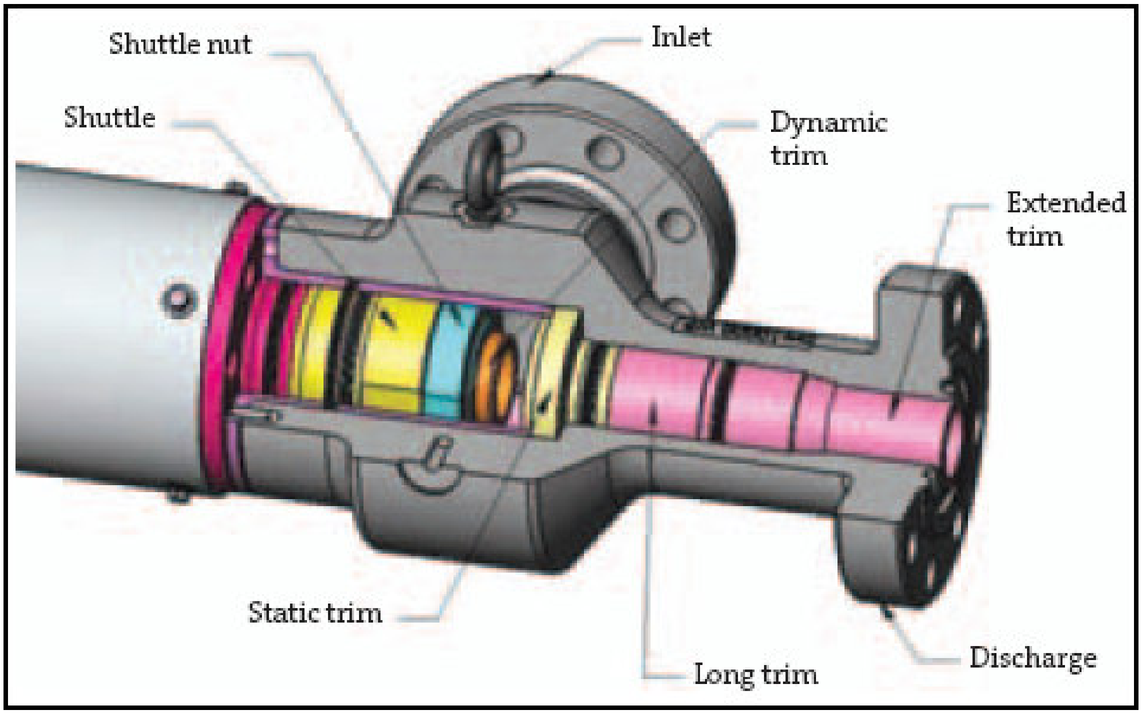

Fig. 2.2 – Auto Choke. This Figure shows the cross section of an Auto Choke and nomenclature of its parts. (MI Swaco 2009c).

2.3. Other Drilling Technologies of Last Few Decades

DD, HD, Casing Drilling, Expandable Casing, and Performance Drilling are important landmarks in the evolution of drilling technology. Many of these technologies are used simultaneously to drill a well depending on the objectives and constraints of the project. Some of these techniques have been used in past and current UBD and MPD projects to drill very complex wells.

2.3.1. Directional Drilling

DD evolved from the need to drill in a direction other than vertical. It is conventionally defined as a procedure to drill a non-vertical hole in the earth (Short 1993). Typically, wells with angles ≤ 60° are considered as directions wells. The earliest needs for DD were to sidetrack from a fish or a caved hole, or to correct crooked hole problems. Its first prominent application was to contain a blowout in South-East Texas in mid 1930's (Short 1993). The whipstock was the earliest DD tool. Over the years, several special tools and equipment have been developed for DD.

DD is used for several reasons. For example 1) to access reserves below inaccessible regions: forests, swamps, marshes, hills, and mounds, 2) to avoid populated areas: cities and towns, 3) to drill in/around water bodies: lakes, ponds, and oceans. DD allows drilling multiple wells from the same surface location and reduces the cost and time.

2.3.2. Horizontal Drilling

HD, is a technology used to drill wells close to horizontal or at 90° angle from the vertical axis. Most of the wells drilled at angles >60° have similar problems, and are considered horizontal or close to horizontal (Short 1993). A generally accepted inclination for horizontal wells however, ranges between 75° and 100° from the vertical axis. HD had been tested in several countries by 1950; however, high cost, lack of demand and lack of advanced equipment hampered its progress.

There are three patterns for drilling horizontal wells: Short, Medium and Long radius wells (Aguilera et al. 1991). Short radius wells have build rates between 1.5° to 3°/ft (or 150° to 300°/100ft), reach horizontal within 20 to 60 feet from kickoff and have horizontal sections 300 to 400 ft long. Medium radius wells have build rates between 8° to 20°/100 ft and have horizontal sections 1500 to 5000 ft long. Long radius wells have radius between 2° and 6°/100 ft and have horizontal sections 2000 to 8000 ft long. The modern ‘Extended Reach’ wells may have even longer horizontal sections, in excess of 20000 ft. A few wells have horizontal sections as long as 35,000 ft.

The important benefits of horizontal wells are: 1) improved productivity of oil and gas from both very permeable and impermeable formations, 2) increased connectivity of vertical fractures, and producing zones in a heterogeneous reservoir, resulting in higher productivity, 3) reduced sand production, and 4) reduced gas and water coning.

A few difficulties in HD are: 1) improper hole cleaning, 2) high levels of torque and drag, 3) problems in holding angle, and 4) problems with high build rates (Aguilera et al. 1991; Short 1993).

2.3.3. Casing While Drilling

‘Casing While Drilling’ technology, is related to drilling using ‘Casing’ instead of ‘Drill Pipe’. The casing transmits the required mechanical cutting forces and the hydraulic energy to the rock, while simultaneously casing the wellbore. The earliest know instance of casing drilling was in Russia in the 1930’s.[*]

DwC as an UBO was applied first to slimhole reentry wells in 1995 in the mature low permeability Vicksburg sands of South Texas (Gordon et al. 2003; Strickler 2006). In 2001, after completion of 10 reentry wells in this field, UBD DwC gained commercial acceptance. According to Tesco Corp, over 1000 sections and 3 million feet have been drilled with casing by Dec 2008.[**] There are two techniques available in the drilling industry for casing while drilling.

2.3.3.1.Casing Drilling

The first method is ‘Casing Drilling ™’. The patents and Intellectual Property rights for this technology are under dispute. This method allows: 1) use of multiple bit runs per

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[*] Personal Communication with M. Montgomery. 2009. Houston: Tesco Corporation

[**] Personal Communication with M. Montgomery. 2009. Houston: Tesco Corporation

hole section, 2) use of higher bit speeds and, 3) drilling directionally (SIGNA 2006). In this method, conventional bits and reamers are used, and the bottomhole assembly (BHA) is run/ retrieved using a wire line. Either a fit-for-purpose rig is built or the rig itself is modified, to house the required additional equipment. A heavy duty wireline unit and an operator are typically required for this technique.

2.3.3.2.'Drilling with Casing'

The Second method is Weatherford's 'Drilling with Casing'. This method is relatively simpler and does not require any modifications to the rig. It uses specially designed and constructed drillable bits, made up directly on the bottom of the casing. The casing BHA and the bit are not retrievable and are left in the ground, which can be drilled through for drilling the next hole section. Disadvantages of this method are: 1) each hole section has to be drilled with one drillbit and 2) drilling directional holes is difficult (SIGNA 2006; Weatherford 2009).

2.3.3.3.Advantages of Casing While Drilling

- This process reduces a number of trips, and the associated drilling flat time/NPT.
- It gets casing to design depth through problem formations.
- It reduces drilling problems associated with surge and swab, lost circulation, and differential sticking.
- It improves kick control and allows using high-density mud.

3. MPD BASICS

MPD is one of the latest drilling techniques that is being increasingly used to drill wells that cannot be drilled using conventional drilling techniques. MPD is a collective name for a group of Old, Modified, and New Drilling Techniques, referred to as ‘Variations’ and ‘Methods’ of MPD. Each of these Variations/Methods can Achieve a definite Purpose or Solve a particular Drilling Problem or Meet a specific project Constraint (Nauduri and Medley 2008).

‘Managed Pressure Drilling’ and the acronym ‘MPD’ were first coined in 2003 (Hannegan and Wanzer 2003). The IADC UBO Committee Meeting, held at Amsterdam, (17–18 Feb 03), made an initial move towards a formal definition of MPD. The first industry definition, authored by Olli Coker, Rick Stone, and Don Hannegan, was published in the abstract of ‘The MPD Forum’, organized by PennWell magazine publishers, at Galveston, Texas. In 2004, IADC added MPD to the UBO Committee's initiatives and changed the name of the committee to MPD & UBO, and the MPD first sub-committee adopted the definition drafted for the PennWell MPD Forum[*].

Even though the concept of MPD was developed early in this decade, many of the techniques have been developed and successfully tested quite a long time ago. Some of these techniques can be dated back to as early as 18th and 19th centuries.

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[*] Personal Communication with D. Hannegan. 2009. Fort Smith, AR: Weatherford

MPD has inherited many of its traits from its precursor UBD. Even though these two techniques are very different, it is not difficult to observe similarities in: 1) the type of equipment used, 2) the drilling, casing, cementing, and well control procedures, 3) the planning, executing, and training, and 4) the objectives and deliverables of the project.

3.1. IADC Definition

The IADC UBO MPD committee made modifications to the MPD definition in Jan 2008 after the IADC MPD first sub-committee adopted the Penn Well draft in 2004.

3.1.1. Definition – Feb 2004 to Jan 2008 (IADC 2008a; IADC 2008b)

- "MPD is an adaptive drilling process used to more precisely control the annular pressure profile throughout the wellbore."
- "The objectives are to ascertain the downhole pressure environment limits and to manage the annular hydraulic pressure profile accordingly."

3.1.2. Appended Line to Above Definition in Jan 2008

- "MPD is intended to avoid continuous influx of formation fluids to the surface. Any flow incidental to the operation will be safely contained using an appropriate process."

3.2. Proactive and Reactive MPD Classification

Depending upon the stage where MPD is chosen to be used, all MPD activities can be broadly classified as Proactive MPD or Reactive MPD.

3.2.1. Proactive MPD

All MPD activities where the use of MPD is considered beforehand are proactive MPD activities. All the associated steps like well planning, equipment procurement, approvals from regulatory agencies, written procedures for all the drilling activities, training of drilling crew and associated personnel, HAZID & HAZOP, contingency plans and sequence of MPD execution are established and put in place beforehand.

The IADC definition of proactive MPD is, “Using MPD methods and/or equipment to actively control the pressure profile throughout the exposed wellbore” (IADC 2008a).

3.2.2. Reactive MPD

All MPD activities, where the use of MPD was never considered at any stage before in the project (or was considered and ruled out), and when it became very difficult for the project to move forward without the use of MPD, and only then MPD equipment is rigged and MPD used, are referred to as ‘reactive MPD activities’.

Reactive MPD projects are not always last minute decisions. The scale and nature of a few small projects is such that, either MPD might not be required to finish them, or there is little economic loss in stopping in the middle of the project and rigging up for reactive MPD. For such projects, the additional hassle of getting proactive MPD in place is futile.

The IADC definition of reactive MPD is, "Using MPD methods and/or equipment as a contingency to mitigate drilling problems as they arise" (IADC 2008a).

3.3. Constant BHP/Variable BHP Classification (SIGNA 2000)

Another way of classifying MPD techniques is based on the BHP being 'Variable' or 'Constant' during the MPD process. The 'Constant BHP' techniques focus on maintaining the same WBP in static and dynamic circulations conditions at some point in the hole. On the other hand, the Variable 'BHP' techniques focus on maintaining WBP within the pressure window, but do not require the WBP to remain same in static and dynamic condition.

The subcategories of Variable BHP method in this classification are:

- Intermittent UBD
- Varying Overbalance BHP
- Pressurized Mudcap Drilling (PMCD)

The subcategories of Constant BHP method in this classification are:

- Riserless Drilling
- Dual Gradient Drilling (DGD)
- Continuous Circulation System (CCS)
- Using BP Pump: More Accurate Control
- Using Automatic/Semi-Automatic/Manual Chokes: Less Accurate Control

In this classification, it may be observed that a few UBD techniques are also considered part of MPD. This classification is NOT consistent with the IADC definition of MPD.

3.4. 'Variations and Methods' Classification of MPD (Hannegan 2005)

This is another common classification of MPD that is described in detail in section 4.1. In this classification the subsections of MPD are classified into more than two categories unlike the 'Proactive and Reactive Classification' described in section 3.2 or the 'Constant/Variable BHP Classification' described in section 3.3.

The big sub classification of MPD is referred to as 'Variations'. Four major variations of MPD are so far identified and referred to in the MPD literature. They are: Constant Bottomhole Pressure (CBHP), PMCD, DGD and HSE (Hannegan 2005; Hannegan and Fisher 2005; Hannegan 2006). These variations are further divided into 'Methods'. Some variations have many different methods to attain MPD, while some have just one.

A detailed list of methods and variation is given below:

- CBHP
    - CCS
    - Application of Backpressure (ABP)
        - Using BP Pump
        - Using Chokes: Automatic/Semi-Automatic/Manual
        - Point of Constant Pressure (PoCP) (Stone and Tian 2008)
- PMCD
- DGD
    - Mud Dilution
    - Riserless Mud Recovery
    - Subsea Mudlift Drilling (SMD)
    - Using Special Purpose Tools
    - Injection of Incompressible Light Solids/Liquids (Under Research)
- HSE or Closed System

In this dissertation, CCS is considered as a subcategory of CBHP variation, even though it is classified as a separate variation by some experts. Formalistically PoCP is not a CBHP variation. On the contrary CBHP is a sub classification of PoCP with the bit as the point of constant pressure. However, in this case the classification pattern of the drilling industry is followed. Observe that BP can be applied using a BP pump/choke. At places where greater control of the BHP is required, use of BP pump is recommended.

3.5. MPD: Why? What? Which? Where? When? How?

3.5.1. Why Use MPD?

MPD is probably the only solution to many of the otherwise conventionally 'Undrillable' prospects. It reduces several drilling problems that cost time and money. MPD reduces risk and increases safety of drilling operations. MPD is an engineering and scientific way to drill the current Complex, Extended Reach, difficult Multilateral wells.

3.5.2. What Can MPD Do?

A Well planned and executed application of MPD can help mitigate drilling related problems and cut costs. Properly planned MPD projects can

- Minimize kick-loss cycles
- Lessen stuck pipe problems
- Help reach the target depth
- Provide better borehole stability
- Reduce the downtime / NPT issues
- Reduce the number of casings required
- Help early kick detection and reduce the kick volume
- Minimize the number of mud changes to the target depth
- Lessen the ballooning/breathing issues, surge and swab issues

3.5.3. Which Variations or Method to Choose

The table 3.1, shown below, provides a simplified guide for choosing MPD variations and methods for given 'pressure conditions' and 'equipment limits'. It may be noted with caution that the table below broadly serves as a guide for selecting an MPD method or variation, under different observed conditions. Differences in rig space, equipment setup and availability, conditions and objectives of operation, and other considerations sometimes require a different variation or method from the options shown below.

Table 3.1 Observed Conditions and the Corresponding Selection of an MPD Variation and/or Method

Observed Conditions	Variation	Method
Narrow Pressure window – LP equipment at the surface	CBHP	CCS
Narrow Pressure window – HP OK at surface		ABP
Severe lost circulation zones. No possibility for CBHP	PMCD	PMCD
LP & HP zones. Zone not too deep for the subsea pump.	DGD	SMD
LP & HP zones. Enough rig space for 2 muds & separation		Mud Dilution
LP Zones		LRRS
Special needs requiring a closed system.	HSE	HSE
Threat to Health, Safety and Environment		HSE

(After Nauduri and Medley 2009)

After choosing the MPD variation and method, performing a detailed candidate selection process is recommended. This helps in understanding the utility of MPD for a given project and assists the operator in making a better judgment. Some of these methods are discussed in detail in section 4.1 of the dissertation.

3.5.4. Where Has MPD Been Used? Who Used It?

MPD has been used in all the populated continents of the world and in both onshore and offshore locations. MPD projects, including single and multiple operators, are done by majors, independents and NOC's. In offshore locations MPD has been used on Jack-Ups, Production Platforms, Moored Semi-Submersibles, and on Drill Ships[*]. The applications of MPD have been rising in the past few years. More details about worldwide MPD projects are given in section 4.3.

3.5.5. When to Say Yes to MPD? Or Which Wells are Candidates for MPD?

A few rules of thumb to identify an MPD candidate well are (SIGNA 2006):

- Drilling problem(s) that cannot be solved with other techniques are making it impossible to drill:
  - cyclic problems like kicks and losses
  - surge and swab effects
  - narrow pressure windows
- Probably UBD is also a solution; however, regulatory rules do not allow UBD
- High drilling flat time or non-productive drilling time
- When there are HSE concerns
- Running out of casing sizes before reaching TD

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[*] Personal Communication with D. Hannegan. 2009. Fort Smith, AR: Weatherford

3.5.6. How Is MPD Different From UBD & Conventional Drilling?

MPD aims at staying between the Pp and Fp window similar to the conventional method of drilling. However, MPD uses an additional array of equipment that gives better control of the WBP and provides better information of downhole conditions. This info and control of WBP, helps in making better decisions and in navigating through tougher pressure conditions. MPD is a better way using physics to meet the desired ends.

The UBD and MPD operations have a fundamental difference, the same difference that UBD and conventional operations have. The WBP is deliberately maintained less than the Pp at least at one point of the open wellbore for UBO, encouraging an ‘influx’ of fluids in to the wellbore. This controlled influx of underground fluids is not considered as a ‘kick’. The containment of these fluids is only at the surface in the form of flaring the gases and/or diverting the fluids into a pit.

For conventional and MPD operations, the objective is to stay above the Pp, at any point of the open wellbore, during the entire drilling operation. Any influx that occurs if the WBP drops below the Pp is termed as ‘kick’, even if it can be contained quickly and safely. Uncontainable influxes/kicks may result in dire consequences like blowouts.

With the additional array of equipment in MPD operations, it is easier and safer to perform a few drilling operations that cannot be performed with conventional drilling.

3.5.7. How Can MPD Reduce NPT or Drilling Flat Time?

‘NPT’ or ‘non-productive time’, refers to the rig time lost in solving the drilling and wellcontrol problems. Most of the operations performed focus on regaining control of the well. ‘Drilling flat time’ refers to all the time when no progress in hole is made. The operations such as well logging, cementing, and casing operations are all considered as part of drilling flat time.

MPD can solve several drilling problems as described in section 3.5.2. Many of the conventional drilling operations face these NPT issues and are forced to use MPD in the middle of the projects.

In zones that have narrow pressure windows or have concerns because of the surge and swab problems, it is very difficult to run casing or perform well logging operations. MPD can help case such formations and help log those formation safely and quickly, saving time and money.

4. MPD IN DETAIL

This section gives more information about the MPD and its operations. Topics discussed in this section are: the detailed classification of ‘Variations and Methods’ used in the dissertation, different MPD application types, industrial experience of MPD, and different MPD equipment.

4.1. Variations and Methods

MPD operations are classified into ‘Variations’ of MPD and each variation is attained/ executed by one of its ‘Methods’. A few variations and methods of MPD have been identified and referred to, over the past few years in MPD literature. Several methods for attaining MPD, some of them very old techniques, some new and some under research are all described in some detail in this subsection.

The ‘Constant BHP / Variable BHP’ Classification discussed in section 3.3, includes the intermittent UBO as part of MPD. In this dissertation UBO is not considered as a subcategory of MPD, consistent with the IADC definition. The ‘Variations & Methods’ classification of MPD is used in this dissertation, since it doesn’t consider UBO as subcategory of MPD. A detailed list of different ‘Variations and Methods’ of MPD is given in section 3.4. The table 3.1 shows some of the subcategories of this MPD classification and the scenarios where they might be used/recommended.

4.1.1. Constant Bottomhole Pressure

CBHP MPD variation is one of the most widely used MPD variations, which helps in maintaining the BHP (or WBP at a given depth or WBP in the entire wellbore) within a given range under both static and dynamic mud circulation conditions. Having WBP constant helps in 1) avoiding drilling problems associated with frequent changes of mud weight, 2) drilling through tight windows, and 3) reaching target safely and reduce NPT.

Two different methods are identified so far for the CBHP variation: BP application (or ABP) and continuous circulation of mud (or CCS). The ABP method uses equipment like BP pump and chokes, which that help in holding some BP while making connection, in order to keep the WBP above the Pp. The CCS system uses a Continuous Circulation Coupler (CCC) that helps in circulating drilling mud even when making/breaking connections. Hence, the wellbore is always under a circulating condition.

4.1.1.1.CBHP MPD: ABP Using BP Pumps

In this method of MPD, a BP pump is connected to the drilling fluids return line, say at point ‘A’ as shown in **Fig. 4.1**. Where such a pump is not available, a third rig pump or a cement pump can be used. Let us assume that the pressure at this point ‘A’ is ‘X psi’ when the BP pump is NOT switched on. Now when the pump is switched ON, let us assume that the mud is circulated through the point ‘A’ at ‘Y psi’. Observe that if ‘Y’ is less than ‘X’ then the BP pump cannot circulate mud through the returns line.

Further assume that the bit is at point ‘B’, and the BHP when the pump is switched OFF is BHP-1 and when the pump is switched ON is BHP-2. Remember that if we move towards point ‘B’ in the returns line, the pressure would always increase independent of BP pump’s being switched OFF or ON. Hence, the BHP-2 will always be greater than the BHP-1 if ‘Y’ is greater than ‘X’ or if the mud is getting circulated by the BP pump.

Also observe that the increase in pressure at point ‘A’ when the pump is switched on is ‘Y – X psi’ which is also called the BP. Now the same amount of increase in pressure will be felt all along the returns line from point ‘A’ to point ‘B’, as no other parameters are being changed. Hence, the BP applied at the bit when the BP pump is switched ON is ‘Y – X psi’. Typically the amount of BP held is approximately equal to the AFP drop.

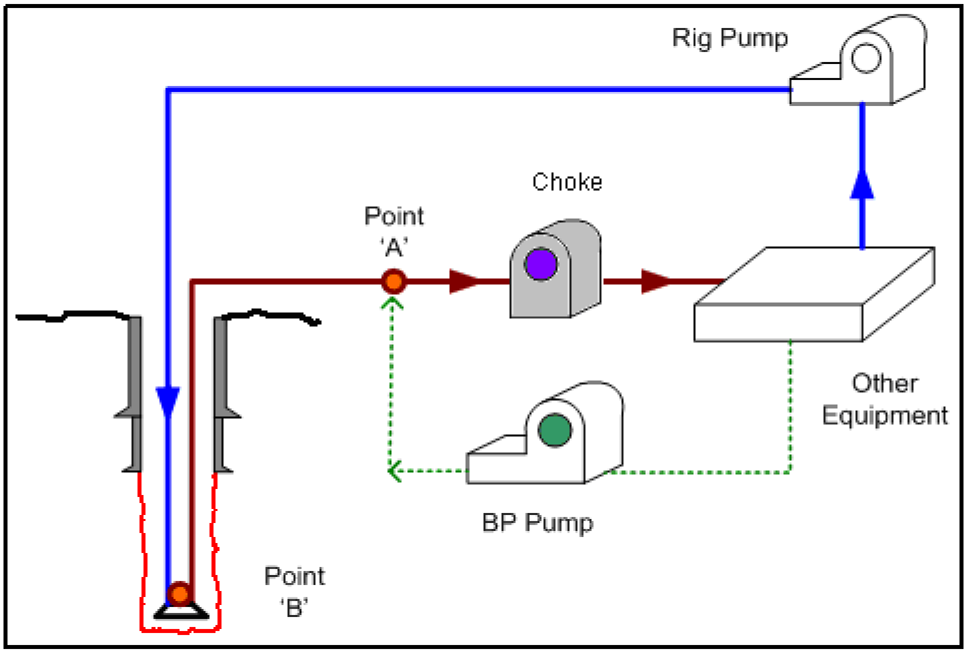


Fig. – 4.1 Equipment setup showing BP pump and choke. Blue path shows mud supply to the bit, brown path shows mud returns and green path shows BP circuit.

The applied BP can be adjusted very accurately by changing a few parameters of the BP pump like the circulation rate. This gives a better control of the BHP and helps in performing CBHP very accurately. This system is recommended when dealing with a very narrow pressure window that does not give a big room for error.

4.1.1.2.CBHP MPD: ABP Using Chokes

An automatic/semi-automatic/manual choke is used in some MPD operations, without including the BP pump in the MPD equipment setup. The effect of using a choke is the same as that of BP pump. However, automatic chokes **(Fig 4.2)** are more accurate and can hold BP similar to the automatic BP pumps. Semi-automatic and manual chokes are less accurate and should be used when the pressure window is sufficiently wide. For example if the window is 20 psi, use BP pump or an automatic choke that is capable of holding BP within this window; if it is 200 psi a manual choke would suffice.

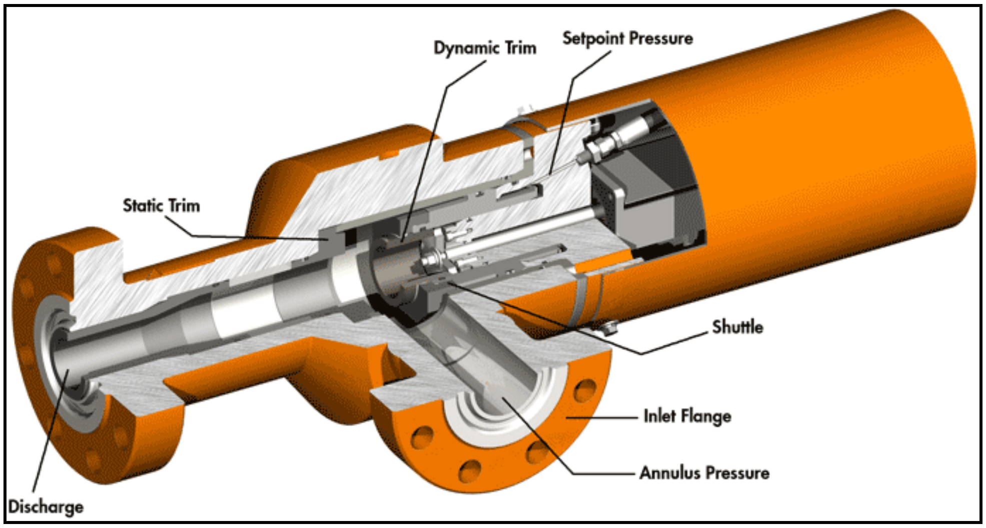


Fig. – 4.2 Cut section of a Super Auto Choke (MI SWACO 2009).

4.1.1.3.Point of Constant Pressure

PoCP, an advanced CBHP variation, was coined in 2008 (Stone and Tian 2008). This MPD method allows having the static and dynamic WBPs equal (or within a given range) at any point/depth of the open wellbore, not just at the bottom of the hole. The trick in PoCP lies in identifying the choke point of the given pressure window. PoCP can be used to drill extremely narrow pressure windows **(Fig. 4.3).**

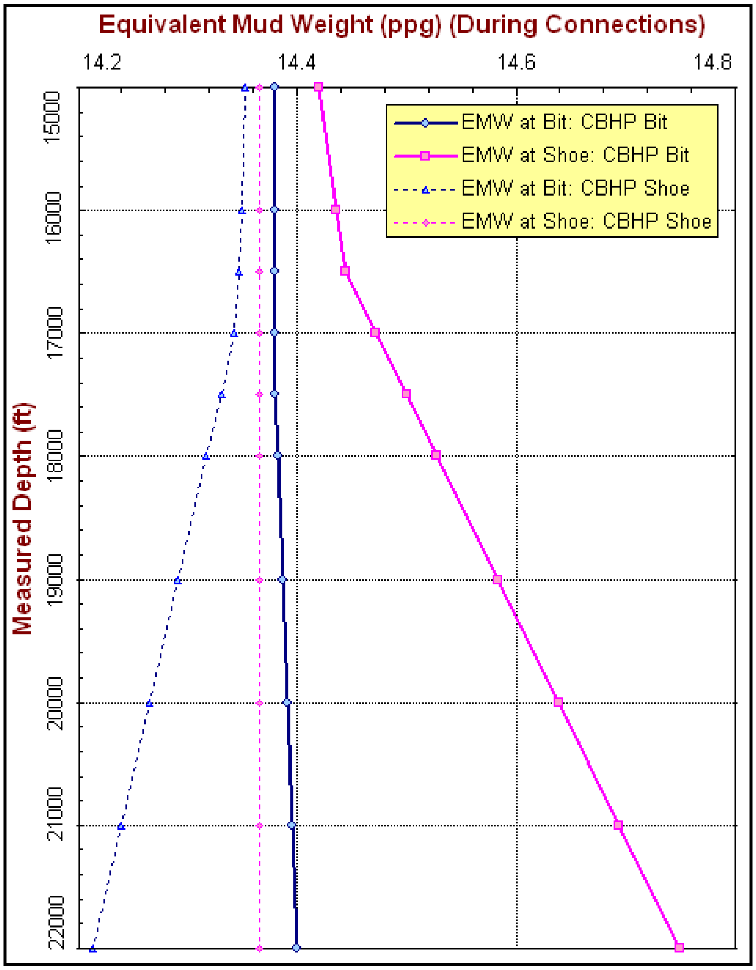


Fig. 4.3 – PoCP pressure plots. PoCP (at shoe) can be used to drill comparatively smaller window (14.2 ppg to 14.4 ppg) compared to regular CBHP that would require a bigger window (14.4 ppg to 14.8 ppg) (Nauduri and Medley 2009).

4.1.1.4. Continuous Circulation System

CCS, now owned and marketed by National Oilwell Varco, was developed as a part of a Joint Industry Project (JIP), in which several oil majors like Shell, BP, Statoil, BG, Total, and ENI participated (Jenner et al. 2004). The CCS system uses a CCC, shown in **Fig. 4.4.** CCS helps in continuous circulation of mud, even when making/breaking connections (or tripping pipe), unlike the conventional drilling operations, where the mud circulation has to be stopped while tripping pipe.

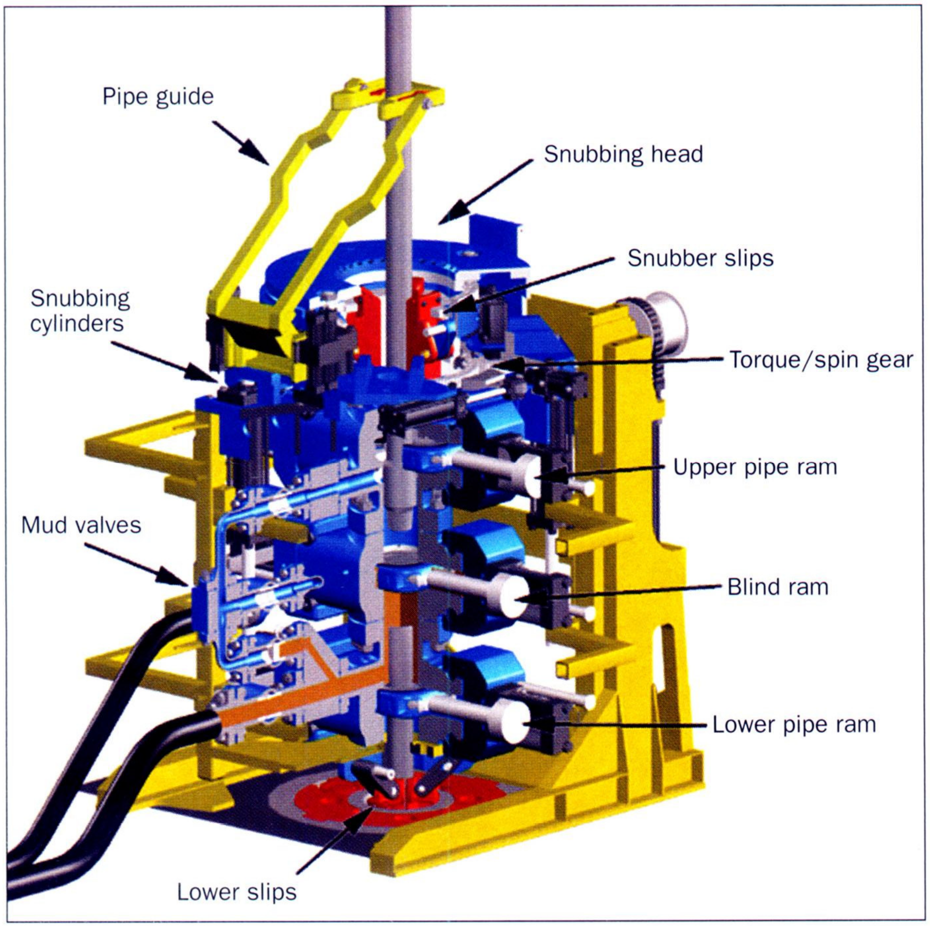


Fig. 4.4 – CCC with detailed description of its parts. CCC has a foot print of 5ft x 6ft and is 8 feet high, expandable to 12ft. (Flatern 2003).

Using CCS helps in preventing most of the drilling problems that are caused due to frequent starting and stopping of the mud circulation (Calderoni et al. 2006). Note that when the bit is not in the open hole section, the driller switches to conventional tripping procedures, since continuous circulation of mud is not required in the cased hole section.

The CCS system consists of three important parts: the Coupler, a mud flow diverter manifold, and a hydraulic power unit. The CCC is made up of three blowout preventer (BOP) bodies (upper pipe rams, middle blind rams and lower pipe rams), an iron roughneck/snubbing device on top, and retractable drill pipe slips attached to the bottom, as shown in the Fig. 4.4. This entire setup is contained in a protective steel casing.

Making a connection: The CCC is closed around the drillpipe. The upper and lower pipe rams closed with the tool joint between them, creating an isolated enclosure as shown in step 1 in **Fig. 4.5.** This chamber is pressurized with drilling mud to the circulating pressure and the drillpipe connection is broken using the snubber at the top of CCC (Step 2 in Fig. 4.5). This snubber can restrain and control the upward movement of the disconnected tool joint against the upward force exerted by the mud in the chamber. Now there are two mud circulation paths – one through the stand pipe, top drive, kelly, and the other through the side of CCS. Then the middle blind rams are closed as shown in step 3 of Fig. 4.4. Then the mud in the isolated upper chamber is removed as shown in step 4 of Fig. 4.4. Then the kelly pipe is removed as shown in the step 5. Now the new pipe stand is added to the kelly and the reverse order shown in Fig. 4.5 is followed.

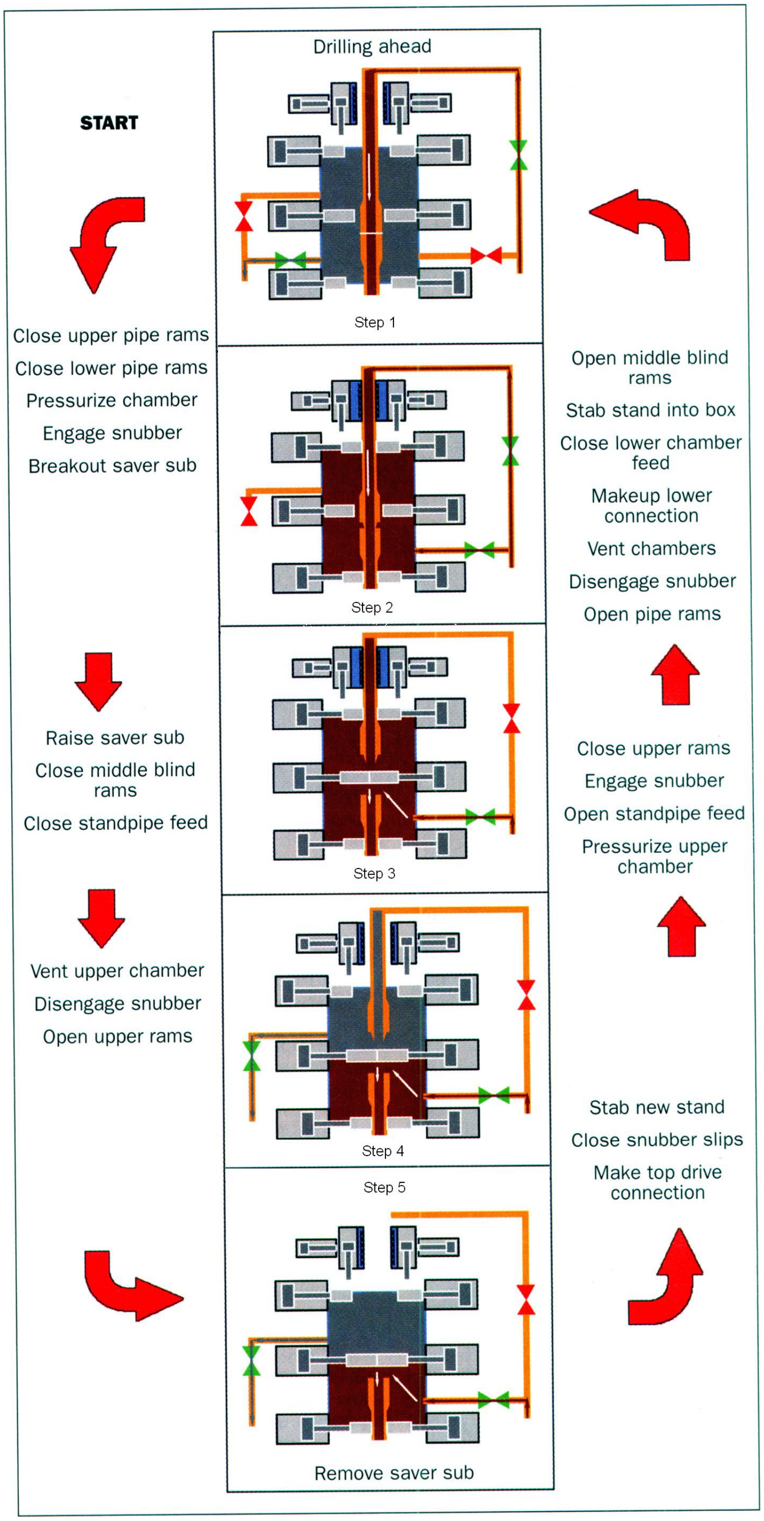


Fig. 4.5 – CCS stages in making and breaking a connection. Steps 1 to 5 showing the making/breaking of connection using a CCS (Flatern 2003).

4.1.2. Pressurized Mudcap Drilling

PMCD, also known as ‘light annular mud cap’ or ‘closed-hole circulation drilling’, (Moore 2008) is the most frequently used variation of MPD, which helps in drilling through highly fractured formations and zones with severe lost circulation problems.

PMCD is developed from an earlier technique called ‘mudcap drilling’ that has been used in the drilling industry for a very long time, to drill fields like the Austin chalk, Texas. ‘Floating mudcap’, is the oldest and simplest form of mudcap drilling (Moore 2008). In PMCD, a combination of two drilling fluids, a low density low-cost sacrificial fluid and a high density pressured mud column, helps drill through these formations.

An inexpensive sacrificial fluid that is readily available at most of the drilling locations, like seawater in offshore locations, is pumped through the drillstring and the drill bit. This fluid carries away the rock chips and cuttings into the fractured zone, as shown in **Fig. 4.6.** A heavier density fluid, referred as the mudcap, is present in the annulus above this trouble zone. The hydrostatic head of this mudcap fluid helps in maintaining the required BHP and prevent the well from kicking.

The annular pressure is monitored throughout the PMCD operation and whenever this pressure increases, indicating migration into the annulus of hydrocarbons, more mud is pumped into the annulus to restore the original BP, and preventing a kick.

Some advantages of using PMCD MPD variation are: 1) it helps drill the troubled zone that cannot be otherwise safely drilled, 2) it helps in cutting costs as significant amount of expensive drilling mud is saved that would have been otherwise lost, 3) it improves ROP as a lower density mud is used, 4) and it reduces a lot of NPT that would otherwise be a big concern with zones having troubles with kick loss cycles, lost circulation, etc.

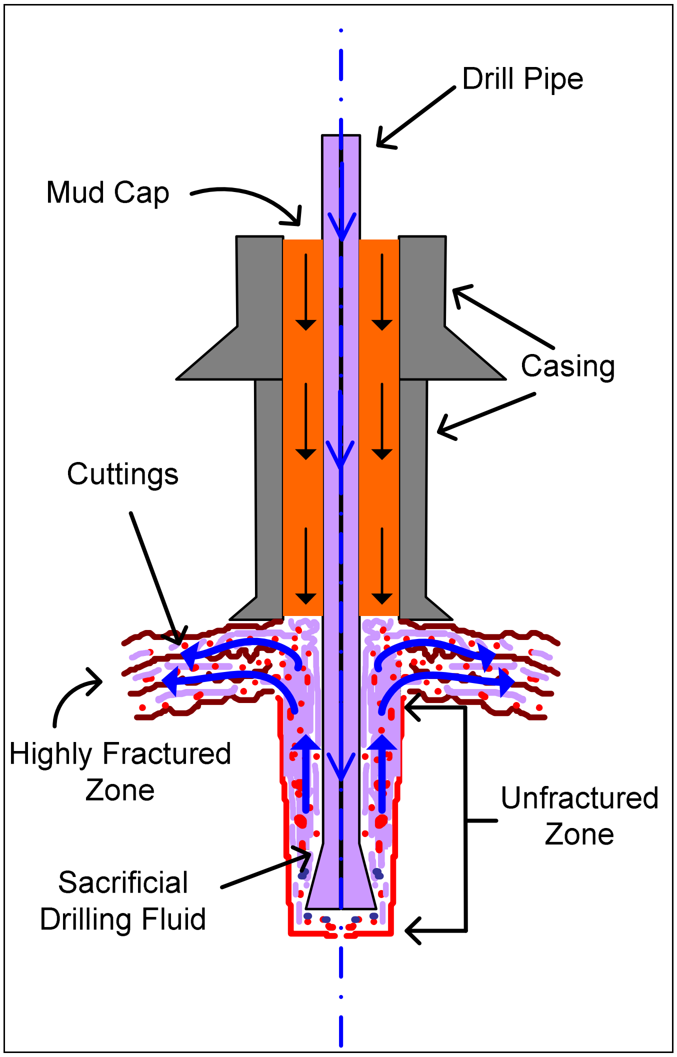


Fig. 4.6 – Pressurized Mudcap operations. The Figure shows the sacrificial drilling fluid taking away cuttings into the fractured formation and the pressurized mud cap present in the annulus, preventing a kick.

Some of the sour formations (fields containing H_2S) like Tengiz field, Kazakhstan, were safely and successfully drilled for the first time using PMCD (Sweep et al. 2003). It is important to use fluid that is readily available in large quantities as the sacrificial fluid. Equipment used/recommended for PMCD operations consists of a RCD, choke manifold, BOP, downhole deployment valve, and a mud gas separator (Moore 2008; Colbert and Medley 2002).

4.1.2.1.PMCD Drilling

In PMCD, a mud that is slightly lower in density than required to keep the well balanced is used. This requires a positive BP or casing pressure to be maintained at the surface, which helps in monitoring the bottomhole conditions better. If the casing pressure increases, which implies the wellbore is becoming underbalanced, more mudcap fluid is pumped (or bull-headed) into the annulus. Drilling continues with the sacrificial fluid, which takes the cuttings into the formation (Moore 2008).

4.1.2.2.PMCD Tripping

During the tripping operation, the volume of ‘annular mud’ or ‘higher density mud acting as the mudcap’, equal to the volume of pulled drillpipe, is pumped through the kill line. The excess mud is lost into the formation if more volume of mud is pumped. The WBP can fall below Pp probably resulting in a kick and increasing the casing pressure, if less volume of mud is pumped. Then more mudcap fluid is bullheaded into the annulus to balance the wellbore and formation pressures, and reduce the casing pressure.

4.1.3. Dual Gradient Drilling (DGD)

DGD, has two gradients in the WBP profile that help reach the target depth in extended reach wells, deepwater wells and wells with similar drilling problems. The initial impetus for this technology was to primarily address the problems associated with the offshore conventional riser drilling operations (Gault 1996; Choe and Juvkam-Wold 1997a, 1997b, 1998; Peterman 1998; Choe 1999; Schubert 1999; Forrest et al. 2001; Choe et al. 2004; Schubert et al. 2006). Using various tools and methods described in this section, DGD can also be used to address drilling problems on onshore wells.

A few DGD techniques include: using subsea annulus returns pumps, riserless mud recovery, mud dilution, injecting light liquids and solids through concentric casing and/or parasite strings and using the tools like Equivalent Circulation Density (ECD)-Reduction Tool. A few of these methods are discussed in this section.

4.1.3.1.Riserless Mud Return System (Cohen et al. 2008)

Riserless Mud Return (RMR^{TM}) system, described in section 4.7, uses an automatic subsea pump to perform DGD. This subsea pump, forces returns to the surface through a returns conduit. A computer control system and additional monitoring equipment helps in maintaining the required BHP, by changing the speed of this pump, to match a preset point at the wellhead. In case of a kick, the pump rate is modified to match the preset point at the surface. This system is available with the company called AGR Subsea AS.

4.1.3.2.SMD

SMD is a JIP, in which companies like BP, Conoco, Chevron, Texaco, Schlumberger, and Hydril participated. It is a DGD variation, which uses equipment such as: Sea water driven mud lift pump, subsea rotating diverter, cuttings processer etc. (Cohen et al. 2008). A detailed equipment diagram is shown in **Fig. 4.7.**

The mud returns, carrying the cuttings from the drillbit, are diverted by a subsea rotating diverter to a cuttings processer, which pulverizes the cuttings. The crushed returns are then pumped to the surface with the help of the subsea pump, through a return line, without casing problems by clogging the pipes and equipment.

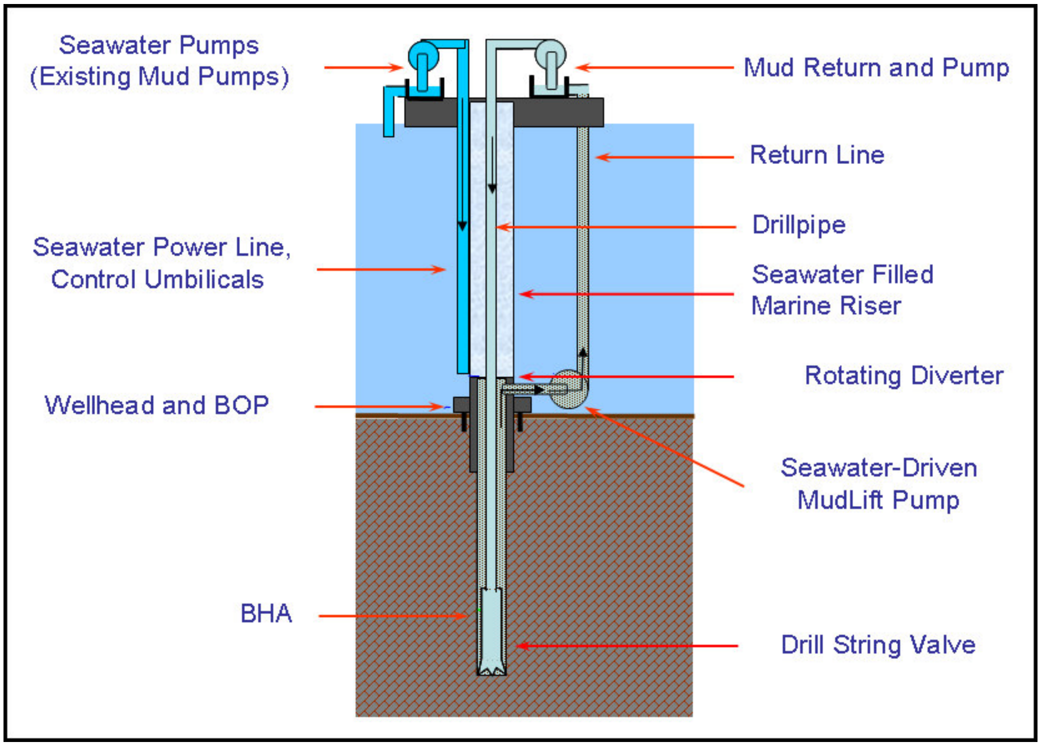


Fig. 4.7 – Equipment diagram for SMD DGD variation (Cohen et al. 2008).

The circulating pressure profile for SMD operation is shown in **Fig. 4.8**. The line AB is the pressure profile in the drillpipe before mud reaches the drill-bit. The line BC indicates the bit pressure drop and CD is the pressure profile in the annulus before it reaches the mudline. The line DE represents the energy added by the subsea pump to the mud pressure circuit and EF is the pressure profile in the mud returns line.

Observe that the point 'D' is usually at the seawater hydrostatic. Hence the reminder of the pressure circuit is designed by fixing this point at the mudline and seawater gradient intersection. The density of the drilling fluid used is higher than the seawater density. This helps in drilling formations that have the Pp and the Fp gradients very close, with lesser number of casing strings **(Figs. 4.9a and 4.9b).**

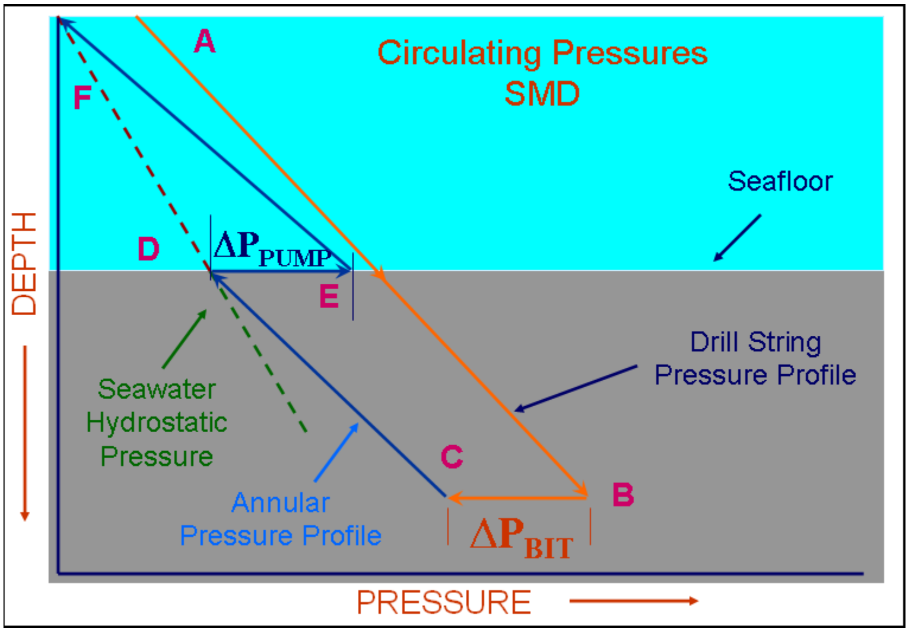


Fig. 4.8 – Various stages in the circulating pressure profile in SMD (after Juvkam-Wold 2007).

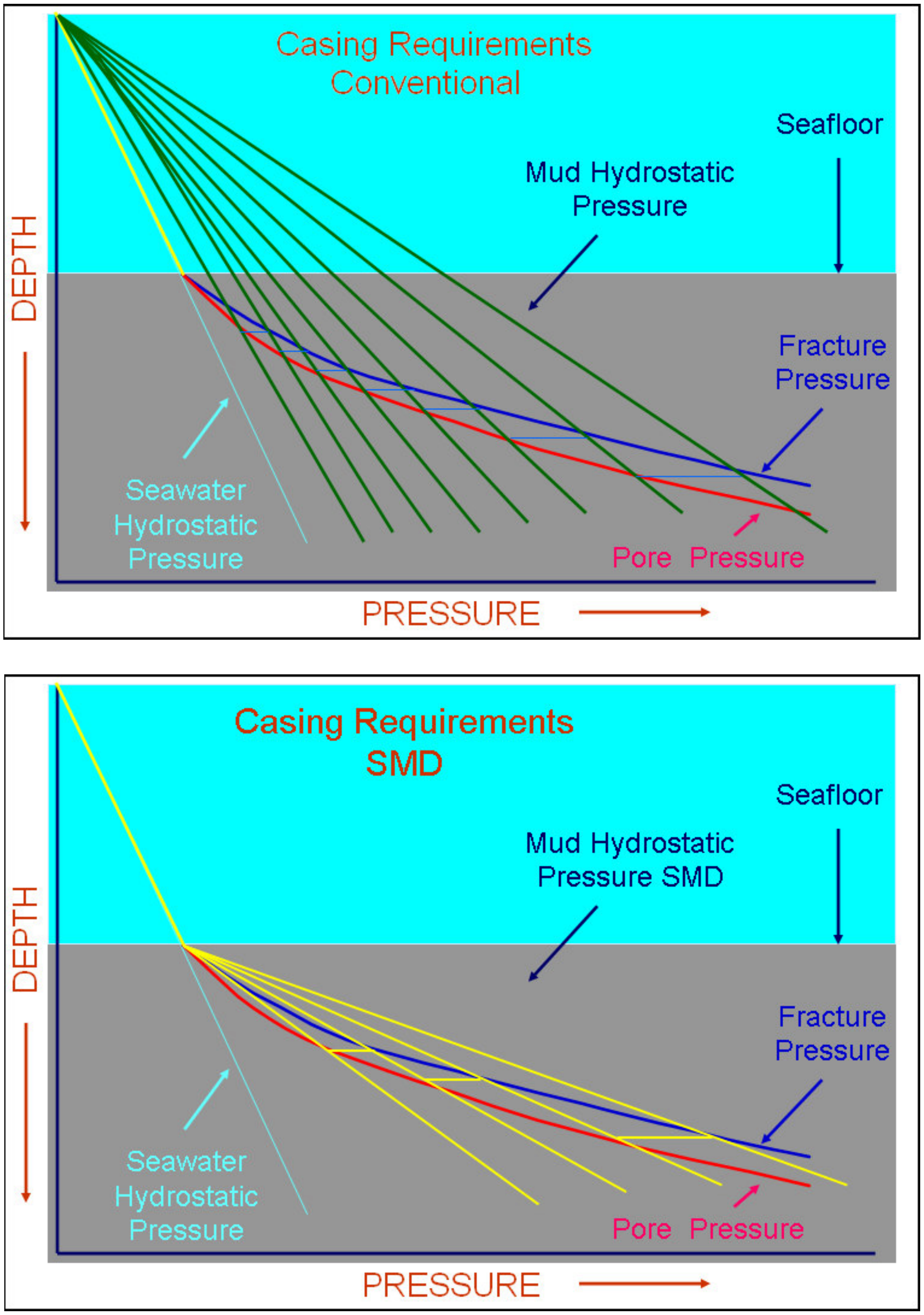


Fig. 4.9 – SMD and Conventional Casing Requirements. Fig. 4.9(a) – shows the Casing Requirements for a conventional drilling operation. The casing seats are very near because of the high overburden of the seawater column in deep water wells, which causes the Pp and the Fp curves to stay very close or flatten. Hence, more casing strings are required to case the hole. Fig. 4.9(b) – Shows the Casing Requirements for SMD operation. The number of casing strings required is reduced considerably in SMD (after Juvkam-Wold 2007).

4.1.3.3.Mud Dilution

Dilution of drilling mud is a newer method of DGD, developed and patented by Luc deBoer who also founded the ‘Dual Gradient Systems LLC’ in 2000. In this method, a high density mud is used to drill the well that is pumped through the drillpipe, the bit and the annulus. A lower density mud is introduced in the annulus at a point very close to the mudline, diluting the returns, and bringing the second pressure gradient in the wellbore pressure profile **(Fig. 4.10)** (De Boer and Boudreau).

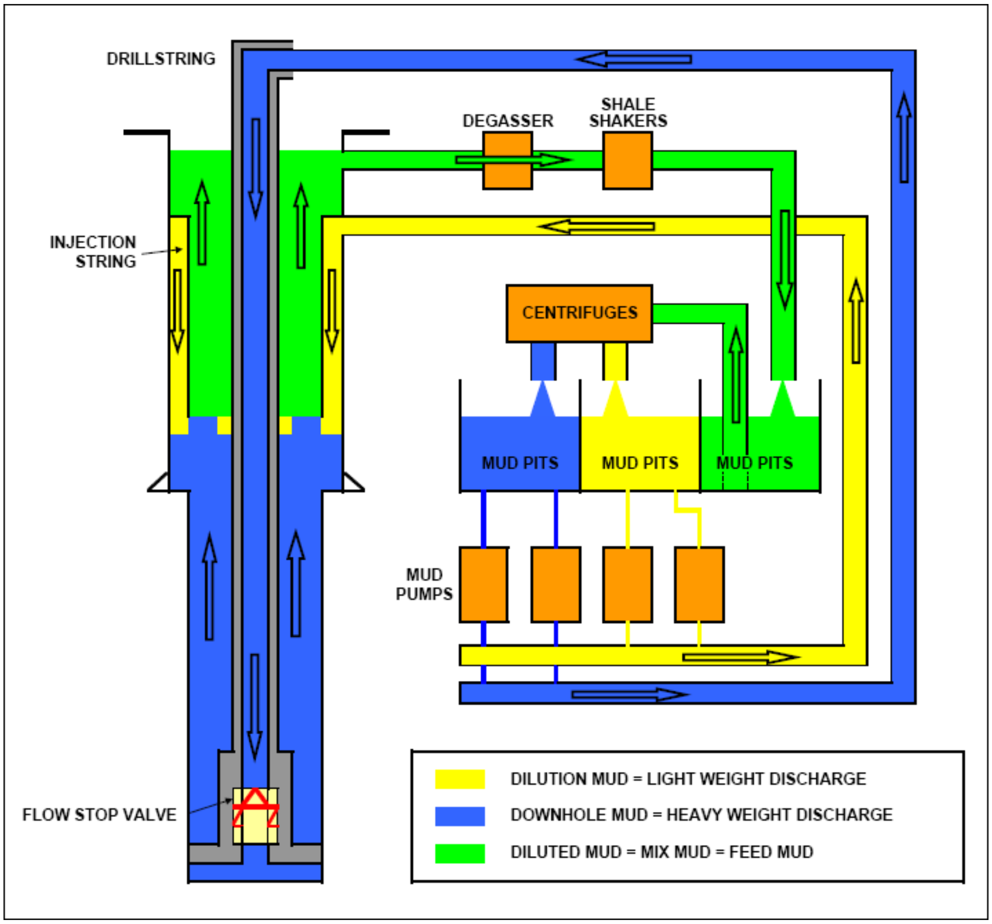


Fig. 4.10 – Mud Dilution circulation system. This Figure uses a surface BOP stack. (De Boer and Boudreau).

The green fluid path represents the diluted mud return that passes through the degasser and a shale shaker for removal of dissolved gas and cuttings respectively. Then a set of centrifuges divides this mud into heavier and lighter muds. The heavy density mud (blue path) is diluted by the lighter density mud (yellow path) resulting in the mud dilution.

The advantages of this system are: 1) this method can be used on most of the offshore projects, and 2) most of the equipment used has been in use in drilling industry for a long time, so lesser training and understanding issues are present. The disadvantage is: requirement of a large rig space and additional centrifuges to maintain drilling muds with two densities apart from space for the mud returns.

4.1.3.4.Incompressible Light Solids & Fluids and Special Tools

Injection of materials with lower densities in returns line, would decrease the overall density of the returns/mud and thereby reduce the hydrostatic head above the point of injection. The mud dilution method of DGD is based on the same working principle. The injected materials could be incompressible solids (Medley et al. 1995) or liquids (mud dilution) or gases (similar to gas lift). Some of these ideas are still under research phase, while a few like ‘mud dilution’ and ‘gas lift’ are commercially available.

Special tools such as the ECD reduction tool, shown in Appendix A, help in reduction of the AFP, which in turn helps in reducing the BHP (Bern et al. 2004). Such tools create a variation in the pressure profile that is theoretically two gradients in the wellbore.

4.1.4. Health, Safety and Environment (HSE)

‘Return flow control’ or ‘closed loop system’ or ‘HSE’, all represent the same MPD variation. This variation is predominantly used for closing the mud return system under the rig floor for HSE reasons, which also includes providing a positive diversion of unexpected kicks away from the rig floor.

This variation addresses the newly appended part of the IADC MPD definition, section 3.1.2: the safe containment of the incidental formation fluids in case of an influx. The equipment used for a HSE variation essentially consists of a RCD, a dedicated MPD choke and a drillstring float. Typical MPD equipment rig up is shown in **Fig. 4.11.**

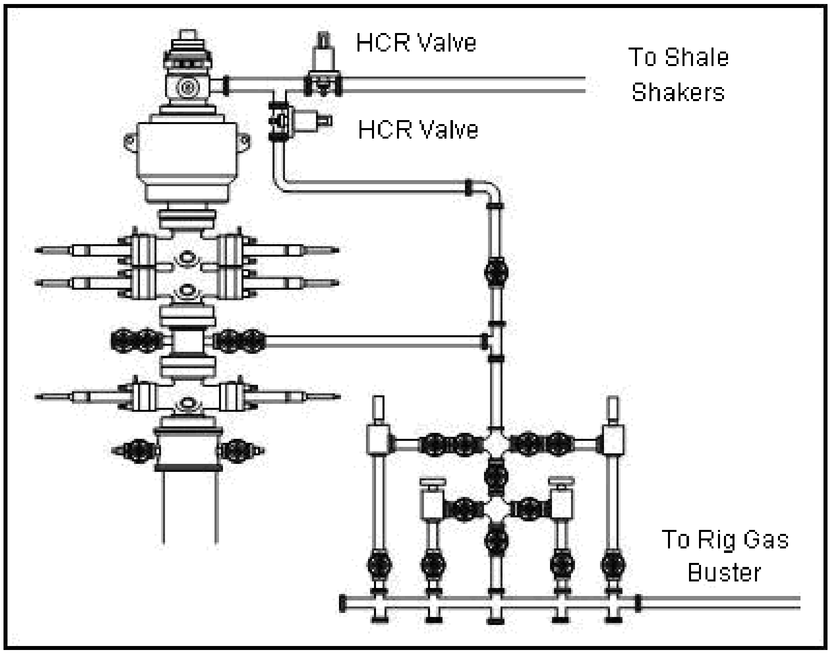


Fig. 4.11 – MPD equipment rig up for returns flow control (Nas et al. 2009).

4.2. Types of MPD Applications

Several MPD wells are drilled worldwide so far and the range of application of MPD has increased enormously over the past few years. Starting from its traditional applications in the past few decades, even before MPD itself was coined and each variation was being individually developed and tested, to current modern applications that serve very complex objectives, MPD has grown rapidly.

Three distinct divisions of MPD applications can be observed by looking back at the history of MPD applications. The first level related to the earliest MPD applications deals with the 'Traditional MPD Applications'. With innovation, advancement in equipment, and improved understanding and knowledge of WBP regimes, applications of MPD have reached level 2, 'Advanced Applications'. With the current complex objectives and constraints of projects that are very different from the traditional objectives, MPD's application is realizing an 'Expanded' function.

4.2.1. Traditional Applications

Earliest MPD application was to solve problems associated with 'tight pressure margins' or 'narrow pressure windows', i.e., staying between both Pp/FS and Fp gradients. Typically a CBHP variation with surface BP helps to drill through tight zones and to drill infill wells in normally or severely depleted reservoirs. (Nauduri et al. 2009).

PMCD has been a solution to drill highly fractured or cavernous formations that experience total or near-total mud losses and where no other drilling method could be used to safely reach the target. In offshore locations where reaching target depth without running out of casing sizes is a problem, DGD has potential as a solution. HSE, being a closed loop system, has an application whenever there is a concern for HSE; or when the regulatory agencies require containment of the mud and drilled contents (e.g., safely containing H_2S when drilling through such zones).

4.2.2. Advanced Applications

PoCP, a modification of CBHP, helps drill through very narrow pressure windows that would be undrillable even with the use of CBHP. In PoCP, the depth where the static and dynamic WBPs are equated is not the bottom of the hole. This helps is reducing the operations window and helps drill through very narrow pressure windows. PoCP is explained in more detail in section 3.4 and section 4.1.13.

Drilling through many depleted and over pressured zones, in a single hole section using CBHP or PoCP is also an advanced use of MPD. Such processes require better planning, accurate equipment and a very systematic execution, as there is very little room for error. Using combinations of two variations for the same hole section is another advanced MPD application. For some wells, PMCD and HSE were used on same/different zones to drill through a cavernous formation and zone that required drilling fluids containment.

4.2.3. Expanded Applications

MPD is now being used for objectives like advanced kick/loss detection, validation of Pp, improvement of ROP, mitigation of formation invasion, and several other applications that do not have the constraints of narrow windows or problems with reaching the target. For the earlier MPD/UBD projects these were just useful by-products. However, for the current projects, these benefits have become so critical that they have become objectives in themselves.

ROP improvement: Even though there is some disagreement with this theory, a reduction in the dynamic overbalance reduces the differential pressure at the rock-bit interface, which in turn reduces the force with which a broken chip or piece of rock is held in its place. Hence, lesser force and time are required to displace the broken chip from its former position in the rock. Therefore, the rate at which the cuttings are removed from the rock or hole increases, which in turn increases the ROP of the drill bit or the rate at which new hole is created. Improved ROP is a direct benefit of reduction in the overbalance pressure.

In one North Sea project, MPD was used to obtain better ROP and to stay close to the formation pressure. Many UBD projects are designed wholly to obtain better ROP. However, achievement of this benefit with MPD is preferred since it is accompanied by fewer issues or concerns with safety compared to UBD.

Validation of pressure: Validation of pressure is a classic application of “Walk the Line” MPD. Reducing the ECD and lowering the dynamic BHP to as close as possible to the Pp, has evolved into an accepted technique for validating or determining the pressure regime. At least one major operator has utilized MPD to ‘find’ the pore pressure in an exploration well where the pressure profile was not well defined. There were more than one predicted Pp gradients for this onshore well and the various potential pressure profiles developed from the offset wells and other available geological data were inconsistent.

The operator decided to use CBHP MPD variation to stay close to an agreeable pressure profile using surface BP and was able to successfully validate or establish a definite Pp regime for the field. This technique is closely related to the enhanced kick and loss detection category of MPD, discussed below.

Formation invasion mitigation: Mitigating formation invasion is another advantage of lower overbalance and has been another important objective for UBD projects. Higher overbalance increases the pressure differential across the openhole between the formation fluids and the wellbore fluids, forcing drilling mud or filtrate into the formation. Since MPD can help maintain a lower overall BHP and reduce the quantity of fluid invading into the formation, a reduction in the formation invasion is typically witnessed in CBHP and DGD projects.

Enhanced kick and loss detection: MPD requires additional equipment to obtain better control of the WBP profile for monitoring and detecting variations in the fluid flow and volume. This also enables a very early detection of an influx from the formation or loss of fluids into the formation. Early detection of kicks and losses can reduce NPT and prevent undetected kicks and blowouts. With the increasing depth and complexity of offshore and onshore wells throughout the world, kick-loss cycles have become a very difficult drilling menace. MPD has proven invaluable in such critical wells.

4.3. MPD Equipment (SIGNA 2006)

List of MPD equipment used in MPD operations:

- Surface and subsea RCD
- Manual, semiautomatic, and process-controlled choke manifolds
- Wireline-retrievable drillstring floats
- Casing isolation valves and/or downhole deployment valve
- ECD reduction tools
- Nitrogen production units
- Subsea mud-return pumps
- Surface mud logging equipment
- Real-time pressure and flow-rate monitoring equipment
- Continuous circulating systems
- Pressure while drilling equipment or ‘PWD’

Note that only some of the above mentioned equipment would be required for a given MPD job depending on the method/variation of MPD used, location, availability of alternate equipment, regulatory requirements etc. More details about the MPD/UBD equipment and figures are provided in Appendix A.

4.4. MPD Experience of Drilling Industry

Several MPD wells have been drilled worldwide in both onshore and offshore locations. MPD has been used in USA, Canada, Mexico, South America, North-Sea, Europe, Africa, Middle-east, Australia, South-East Asia, China, India and several other parts of the world. According to some accounts and information available in the public domain more than 350 MPD wells have been drilled offshore by the end of 2008 (Hannegan 2009).

Both oil majors like BP, Shell, ConocoPhillips, Chevron, Total, and Statoil, and relatively smaller companies with lesser range of operations like Cheyenne Petroleum, Cypress E&P (both Onshore Texas), Pioneer (Alaska), Sinopec (China), E&I Libya, etc., have some experience in MPD operations.

Typically these companies have assistance from the service providers at various stages of the MPD projects like well planning, hydraulics, equipment selection, permitting, MPD procedures etc.

4.4.1. *Operators: Majors/NOCs/Independents*

CHEVRON: This operator has some experience with MPD operations. Both Chevron and Texaco (now part of Chevron) were member of the JIP that developed the SMD. Several PMCD wells were drilled in Tengiz field in Central Asia to mitigate H_2S problems and lost circulation problems. Unocal (now Chevron) drilled 3 CBHP wells from a platform. There are some MPD projects done in Angola and Africa, and a few more CBHP/DGD are being planned in offshore Gulf of Mexico (GOM).

SHELL: This major oil company has drilled several MPD wells. There are some CBHP applications in the Mars TLP and Auger TLP in deepwater GOM (Reitsma and Riet 2005; Roes et al. 2006; Chustz et al. 2007; Chustz et al. 2008). There are also a few PMCD applications in Asia and South America. Shell also participated in the JIP that developed the CCS.

BP: This major oil company has great MPD experience. It participated in the CCS and SMD JIPs. It has drilled several CBHP wells in GOM and DGD wells in Asia. It has also drilled PMCD wells at different locations around the world.

TOTAL: This operator is gaining MPD experience very quickly. Some CBHP wells are being drilled in the North Sea. There are a few applications in Africa and more wells are planned in Africa and South East Asia.

ConocoPhillips: This operator has participated in the SMD JIP and has been active from the initial phases of MPD development. It has experience in drilling CBHP, PMCD and HSE wells in various locations around the world.

Several other oil companies have drilled wells world over. Some of them are included in the MPD wells database shown in Appendix B.

5. CANDIDATE SELECTION – LONG AND SHORT OF IT

The worst reason to use a technology is that it is new. Any technology for that matter, new or old, should not be applied without careful understanding and evaluation of the entire process. A technology used for wrong reasons is bound to give wrong, sometimes even catastrophic, results.

5.1. Candidate Selection/Feasibility Study

The MPD candidate selection process and MPD feasibility study are very similar screening processes with very slight distinction, which finally determine the utility of MPD for a given project (Nauduri and Medley 2008).

In Candidate Selection a given well/section is analyzed to see if it fits the application of MPD. Those profiles that cannot be drilled using MPD or that do not need MPD are discarded. Here MPD is the focus of analysis. Other drilling methods are irrelevant.

In a MPD feasibility study, MPD is generally one of the many options considered or evaluated for the project. Other drilling options considered include the Drilling While Casing, CTD, UBD etc. The Project and its objectives have higher precedence over the type of process that will be selected. MPD is selected or discarded at the end of the study. The reservoirs, wells, or the field are the focus of analysis here.

5.1.1. Definition of Candidate Selection

MPD Candidate Selection Process can be defined as: A process that understands and/ or establishes the purpose of the project, procures the required data and investigates the data by performing hydraulics analysis, identifies a suitable MPD variation, suggests all the methods to achieve it, determines the viability of such methods or their alternatives, and optionally looks at the required equipment, their availability and the procedures involved in executing MPD (Nauduri and Medley 2008).

5.1.2. Aspects of Candidate Selection

There are three important aspects to consider before deciding 'to use' or 'not to use' MPD. The first aspect is to identify the possible serious drilling problems for the given prospect, to understand the effects of those problems and determine the possible loss of time and money if conventional methods are used to drill the prospect. The second aspect is to understand the different MPD variations and the possible utility of MPD in mitigating those problems and realizing the objectives of the project.

The final aspect is the additional cost associated with the MPD equipment, training, writing and developing drilling and tripping procedures, availability of MPD experts and safe execution of these set operation guidelines and procedures of MPD. The operator(s) of the project should carefully consider these aspects while making their decision.

5.2. Important Steps of Candidate Selection

A few important steps in the candidate selection and MPD execution are listed below.

- Defining/ Identifying/ Establishing the purpose
    - Define the Objectives
    - Identify the drivers for the project
- Procuring Information/Understanding
    - Procuring Information – offset wells data, geological data
    - Understanding the prospect and the drilling problem
    - Understand the MPD variations and variation/method selection
- Evaluation/Analysis
    - Conventional Hydraulics
    - MPD hydraulics
    - Determination of critical parameters
- Results

5.2.1. Defining/ Identifying/ Establishing the Purpose

The first step the operator generally does/should do is to establish the rationale behind the study. This helps in identifying and establishing the key driving factors, and thus aids in defining the project objectives. Hence, this should be the first step in any screening process; and when this is done right, it will set a right stage for the rest of the process.

5.2.2. MPD Application Drivers

For any MPD project, it is very important to identify the reason for using MPD. After the objectives of the project are identified, the operator(s) of the field should identify, understand, and quantify the project's driving factors. This is an initial step in problem identification. The method selection is done after gathering information in the next step. A few MPD driving factors are:

- Minimize overbalance using CBHP to
    - Increase ROP
    - Avoid differential sticking
    - Prevent lost returns
    - Reduce formation damage
- Extend the depth between casing setting points using CBHP and DGD to
    - Avoid kick/loss cycles
    - Reach target depth
    - Drill through narrow kick tolerances/ pressure windows
    - Drill through depleted tight gas zones containing nuisance gas
- Use PMCD to
    - Drill through huge caverns and lost circulation zones
- Use HSE to
    - Drill in the regions that have Health, Safety and Environment concerns
    - Drill whenever a closed cycle is required/recommended

5.2.3. Information Procurement/Understanding

Once the objectives are defined, and the drivers identified, the next step is to procure any relevant well data and understand the chosen MPD option well. The relevant well/field/prospect data is available from regulatory agencies, several offset wells drilled in the adjacent locations, and the geological logs and interpretations.

Understanding of the prospect and the drilling problem, with good knowledge of the pressure regimes, is very important in method selection and to perform subsequent hydraulic analysis. The quality of this information helps in making better engineering decisions at a later stage, and quantifies the project drivers.

The crucial step, sometimes overlooked, is the understating of the selected MPD process, its abilities and its limitations. MPD used for the wrong purposes or used beyond what it can perform might lead to catastrophic consequences.

5.2.4. Evaluation

The next step is the hydraulic evaluation and analysis. This is done in two phases and the second phase is performed according to the requirement. The first phase is conventional hydraulics, where BHP management is done using a few steps suggested in section 5.2.5 ‘Management of Pressure’.

Several ‘conventional pressure management’ parameters like the fluid rheology, mud-weight, circulation rate etc. are varied in order to meet the project objectives, until there is no further room for parameter change. If the project objectives are not met and further parameter modification is not possible, then MPD hydraulic analysis is performed.

For some variations like DGD and PMCD, performing conventional hydraulic analysis is futile and the MPD hydraulic analysis is performed directly. The MPD hydraulic analysis varies for each MPD method (Tian et al. 2007). Apart from optimizing the ‘conventional pressure management’ parameters, a few additional parameters are also calculated for the different methods and variations of MPD.

The additional parameter optimized for the all the methods of CBHP variation is the BP. For the PoCP method, the depth of constant pressure is also determined. For the CCS method, there is no additional parameter.

For PMCD variation, the BP at the surface, the height, density and rheology of the pressurized mud column along with the properties of the sacrificial fluid are determined.

For the mud dilution method of DGD variation the additional parameter is the second mud-weight or the diluted mud’s density. For the subsea mud lift method, the BP and rate of circulation for the subsea pump are determined. For the LRRS, the depth of the mud column in the riser is calculated.

For the HSE variation, no additional parameters are required to be calculated. However, the key considerations would be to identify: ‘weight-up/use conventional well control’.

5.2.5. How to Manage Pressure

The pressure profile in the wellbore can be managed by several techniques. For convenience we can divide this section into two stages: 1) varying the ‘Conventional Pressure Management’ parameters and 2) managing/optimizing the MPD parameters.

Stage 1: Conventional Pressure Management Parameters

- Rheology
- Mud weight
- Solids content
- Circulation rate
- Cuttings concentration

Stage 2: MPD Pressure Management Parameters

- Back pressure – CBHP, DGD and PMCD
- Height of the fluid column – DGD
- Parameters of secondary fluid/mud column/sacrificial fluid – DGD and PMCD
- Design/location of tools/valves and surface equipment – all variations

5.2.6. Pressure-Management Effects

By changing the mud rheology, the properties like the mud viscosity, yield point etc. are changed that change the frictional pressure drop parameter, which in turn changes the BHP. Hence, by changing the fluid rheology, we get better control of the BHP.

By changing mud weight, solids content, and cuttings concentration, the density parameter is changed in the **Eq 5.1.** Since, the BHP is directly proportional to the density (from Eq 5.1); by changing the density we change the BHP.

$$BHP = 0.052 \times TVD \times MW \quad \text{........} \quad 5.1$$

Altering the fluid column in the hole changes the TVD parameter in the Eq 5.1. Since, BHP is proportional to the height of the fluid column, varying the height varies the BHP.

The relation between the Pressure drop (ΔP) and the Circulation rate (Q) can be determined using the American Petroleum Institute Recommended Practices 13D (API RP 13 D) equations, given in Appendix C. The Pressure drop (ΔP) is directly proportional to the Circulation rate (Q) **(Eq 5.2)** in laminar conditions.

$$\Delta p \propto Q \quad \text{........} \quad 5.2$$

The Pressure drop (ΔP) is directly proportional to square of the Circulation rate (Q) **(Eq 5.3)** in turbulent conditions.

$$\Delta p \propto Q^2 \quad \text{.......} \quad 5.3$$

Hence, any changes in the circulation rate would vary the pressure drop in the annulus and thus vary the BHP. Therefore altering the rate of circulation of the drilling fluid is another method of changing the BHP.

Using MPD can change the Eq 5.1 by: 1) introducing additional terms and/or 2) including additional factors that change the MW and TVD parameters, and hence providing better control of BHP as shown in **Eq 5.4.**

$$BHP = 0.052 \times TVD \times MW + BP \quad \text{.......} \quad 5.4$$

Application of surface or subsea BP can be represented as shown in Eq 5.4**.** The several DGD variations change the density and TVD parameters. The effects of the individual parameter can be easily understood by writing the BHP term for each density or depth and then adding the individual effects **(Eq 5.5).** When $TVD_2 > TVD_1$,

$$BHP \begin{array}{l} = Hydrostatic_1 + Hydrostatic_2 + BP \\ = 0.052 \times [TVD_1 \times MW_1 + (TVD_2 - TVD_1) \times MW_2] + BP \end{array} \quad \text{.......} \quad 5.5$$

5.2.7. Results

The possible options for the candidate selection are – 1) MPD is not required, 2) MPD is required and is possible, and 3) MPD is required however, no MPD option exists.

The important result of the candidate selection is one of the above options. If MPD is not required or if MPD is not possible then the process stops. However, if there is a possibility for MPD and there is a method available to perform it, then the process continues until MPD is executed safely.

5.3. Important Steps of MPD Project Preparation and Execution

After the decision to use MPD on a potential candidate is made, the follow steps are generally followed to finish the project safely

- Procurement/People
    - Equipment available/procurement
    - Availability of experts
- Preparation
    - HazID and HazOP
    - Procedures
    - Training
- Execution

6. MPD CSM – RESULTS AND DISCUSSION

To use a technology like MPD, without knowing or determining its utility for the project at hand is imprudent. It is equally thoughtless not to use such technology that could solve several drilling problems and save time and money, without doing a systematic engineering analysis or a detailed MPD candidate selection.

MPD Candidate selection has become ever more important, complex and challenging for several reasons such as: 1) Increased complexity of planned wells, 2) several drilling problems that need to be properly addressed, 3) HSE, insurance and permitting issues, 4) the kind of solutions MPD is providing with its traditional, advanced and expanded applications, and 5) performing MPD itself: planning, training, and execution.

6.1. Problem Identification and Definition of Project Scope

The summary of the problem is: Whether to ‘choose MPD’ or ‘not to choose MPD’

- Drillers always need ‘ANSWERS TO’: a) challenging drilling problems, b) complex project objectives, and c) quality, time and regulatory constraints.
- MPD is ‘A SOLUTION’: MPD with its variations and several methods, and range of applicants (traditional, advanced and expanded) is a solution.
- MPD is NOT always ‘THE SOLUTION’: Not all wells that are potential MPD candidates need MPD. Simple parameter changes and alternatives might exist.

Project Scope:

This research project on MPD and its candidate selection tries to answer the question whether to ‘choose MPD’ or ‘not to choose MPD’, in the following few steps.

- Develop a candidate selection process for MPD
    - Develop a flow diagram identifying the key steps for candidate selection
    - Develop the CSM based on this flow diagram
- Develop a candidate selection software
    - Perform basic hydraulic calculations with given input
    - Perform utility analysis for chosen MPD methods
    - Report results in the form of graphs and tables
    - Provide flexibility on input parameters/scenarios
- Develop an MPD worldwide wells database
    - Compile a MPD database with basic MPD information
    - Provide frequencies based on variations, locations etc.

6.2. Candidate Selection Process

To determine if MPD is ‘required’ or ‘not required’, we have to ensure no other option is a possibility. Like what Sir Arthur Conan Doyle's famous character Sherlock Holmes has said, “When you have eliminated all which is impossible, then whatever remains, however improbable, must be the truth”. We assume that MPD is not necessary and check for other available options. When nothing else works, MPD is the solution.

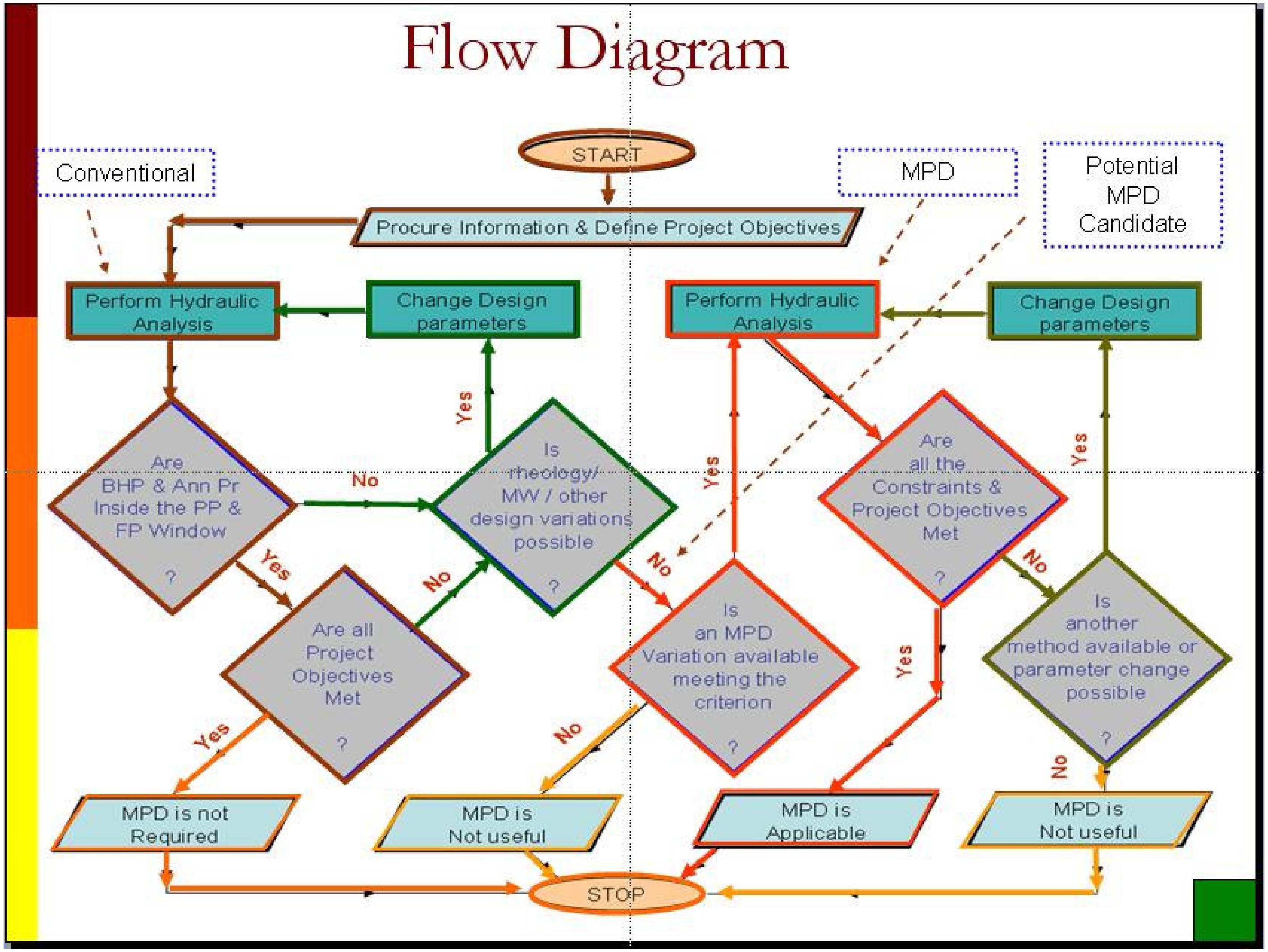
6.2.1. CSM Flow Diagram

The flow diagram is the first step in the MPD CSM research. The steps suggested in section 5.2.5 ‘How to manage pressure’ are performed to check for the possibility of non-MPD options. When they fail MPD options are checked to arrive at a possible solution. There are three possible solutions for this analysis:

- MPD is not required:
    - Not all the wells that are considered require MPD.
    - Changing the rheology or other design parameters is all that is required.
- MPD is not useful:
    - The given well is a potential candidate for MPD.
    - However, MPD is not the solution.
- MPD is applicable:
    - The given well is a potential candidate for MPD.
    - There is a MPD variation or solution available to suit the given scenario.

6.2.1.1.Explanation of the Steps in the Flow Diagram

This flow diagram **(Fig. 6.1),** which closely follows the section 5.2 ‘Important Steps of candidate selection’, can be divided into different paths, based on the function performed in that part of the flow diagram. For ease of understanding, each of these parts are designated a different color code. A list of color codes, and the functions that are performed in that part of the flow diagram, are discussed in the subsection 6.2.1.2.



Flow Diagram

Fig. 6.1 – MPD Process flow diagram.

6.2.1.2.List of Color Codes Used in the Flow Diagram and the Functions Performed

Brown Path: This path shows the conventional/non-MPD hydraulic analysis done after defining the project objectives and procurement of all relevant information. If all the project objectives are met, then the orange path is chosen since 'MPD IS NOT NECESSARY'; otherwise the dark green path is chosen.

Dark Green Path: This path shows the parameter adjustment suggested in section 5.2.5 'How to manage pressure'. The process of adjusting the parameters is performed until – a) the project objectives are all met, or b) there is no further room for parameter change.

Orange Path: If the project objectives are met by parameter adjustment, then the orange path is taken as MPD is not required for this candidate. However, if the project objectives are not met and there is no further room for parameter adjustment, then we take the most important path of the flow diagram, which indicates that this well is a 'Potential MPD Candidate'.

Red Path: This path begins when we know that there is a 'Potential MPD Candidate' as indicated in the Fig. 6.1. The first question answered in this part is whether there is an MPD variation available meeting the given criteria. If the answer is 'NO' the yellow path indicating that 'MPD IS NOT USEFUL' is taken. If the answer is 'YES' the red path continues further.

The next step in the red path is performing the MPD hydraulics. If all the project constraints and the project objectives are met, then ‘MPD IS APPLICABLE’ is the result of this candidate selection process. However, if we know that there is an MPD method available that can address the problem at hand and all project objectives are not met, then the light green path is followed.

The Light Green Path: The light green path includes the MPD parameter changes and loops back into the red path. The red path and light green path are taken several times until we conclude that: a) project objectives cannot be met with any of the available MPD methods and variations or b) until an MPD solution is found.

Another Yellow Path: For the case ‘a’ indicated above, either change of the project objectives is recommended or an alternative drilling technique is suggested that can help solve the problem. The result of the candidate selection then would be ‘MPD NOT USEFUL’, which means that this is a potential candidate for MPD; however MPD cannot solve this problem. Yellow path is used since MPD is not useful.

For the case ‘b’ the detailed MPD solution is provided by following ‘Red Path’.

The MPD CSM flow diagram is just a guide for the candidate selection. Deviations to the above mentioned model are possible in some cases.

6.3. Online Database

The idea behind collecting the worldwide MPD wells database is to provide an accessory to the candidate selection process. This is the second step of the MPD CSM research. Three MPD well datasets have been provided so far for the purpose of this research project. These databases provide information on some of the aspects of the MPD wells drilled so far. Information on some of the wells is available in the public domain. However, information on few other wells included in the database is not yet released to the public. Hence, some details of those wells are left blank.

The first database, with name DB-1 included in Appendix B is provided by SIGNA Engineering Corp, Houston. It contains information about the country and region of the MPD well, type of MPD variation used, location (onshore or offshore), type of BOP used (surface or subsea), MPD category (proactive or reactive MPD), and the month and year it was drilled. In this database, there are instances where more than one MPD variation was used on the same well.

The second database, with name DB-2 also included in Appendix B is provided by AtBalance with Smith. It contains details such as the location of the MPD well, the year, name of the company (left blank for confidential wells), type of rig used, and if it is onshore or offshore. All the wells listed here are drilled using the CBHP variation of MPD using surface BP pump.

The third database, DB-3, provided by Secure Drilling, is also included in Appendix B. It consists of information about the location of the MPD well, type of rig used, type of drilling mud used, project type (exploratory or development well), and the month and year it was drilled.

More details about the MPD wells databases can be obtained by contacting the database providing companies. The results from all the databases are given in the form of pie and bar charts in the next subsection.

6.3.1. SIGNA Engineering Database

The distribution of the several variations of MPD based on SIGNA Engineering Database is provided in the **Fig. 6.2.** This is the only database that provides information on all four MPD variations. The remaining two datasets provide data points for the CBHP MPD variation alone, with the exception of one PMCD data point in the Secure Drilling database.

From the Fig. 6.2, it can be observed that CBHP and the PMCD variations are used very frequently, consistent with the earlier description of the MPD variations. The term 'MPCD', stands for 'MPD Casing Drilling'. One instance of using MPCD is recorded in this database. Three DGD data points are also included in this dataset. The total number of data points in this dataset is 82.

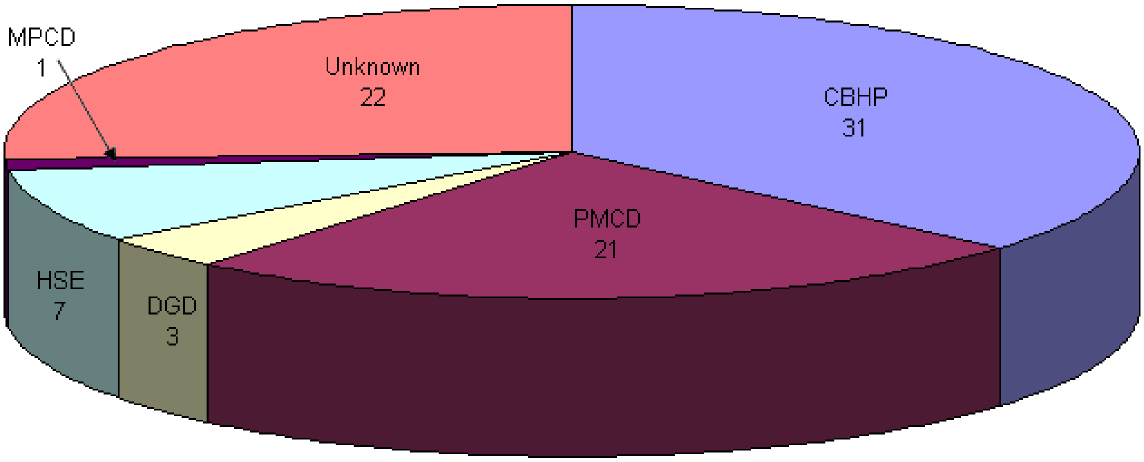


Fig. 6.2 – Pie chart showing the distribution of MPD Variations. The SIGNA Engineering Database is used for this Figure.

6.3.2. AtBalance with Smith Database

Fig. 6.3 gives the distribution of the MPD wells based on the type of rig used and **Fig. 6.4** shows the increase in the application of MPD in the past few years. Fig. 6.3 and 6.4 are based on AtBalance database.

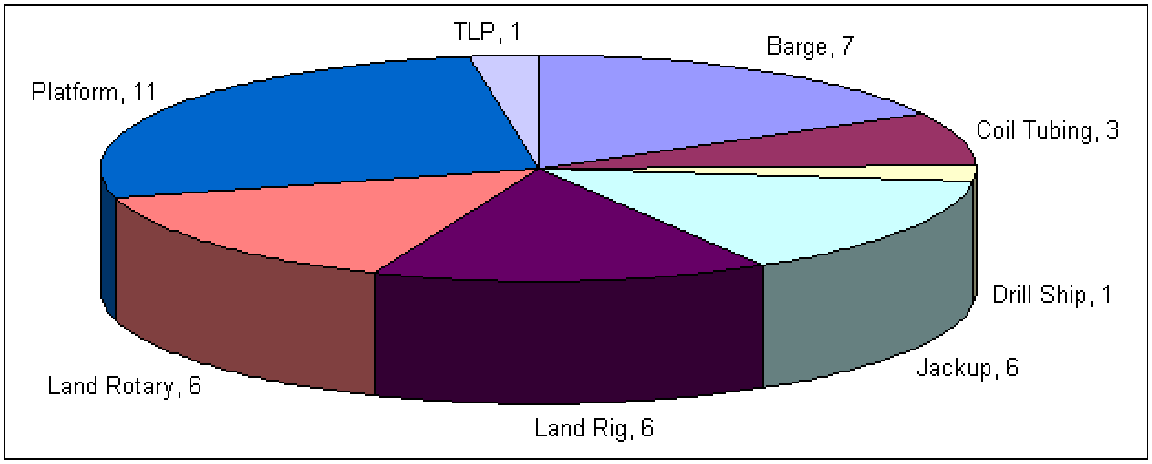


Fig. 6.3 – Pie Diagram showing the distribution of MPD wells based on the Rig Type used based on Atbalance Database.

In the Fig. 6.3, 'TLP' stands for 'Tension Leg Platform'. The frequency of each piece of pie is shown next to the name of the division in Fig 6.3. The expansions of all the abbreviations used in these figures can be found in the nomenclature. The total number of data points in the AtBalance dataset is 41.

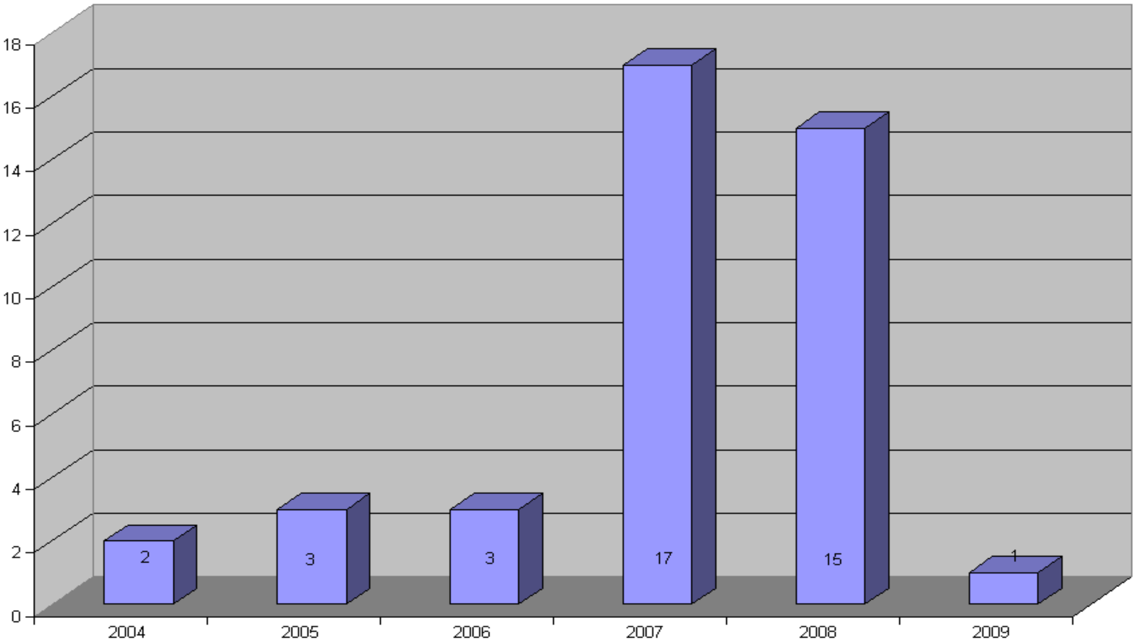


Fig. 6.4 – The number of CBHP MPD operations done each year since 2004 based on AtBalance database.

6.3.3. Secure Drilling Database

The **Fig. 6.5** shows the distribution of the MPD wells based the drilling rig type used to drill the wells. The Secure drilling data is used in this figure. The total number of data points in this dataset is 25.

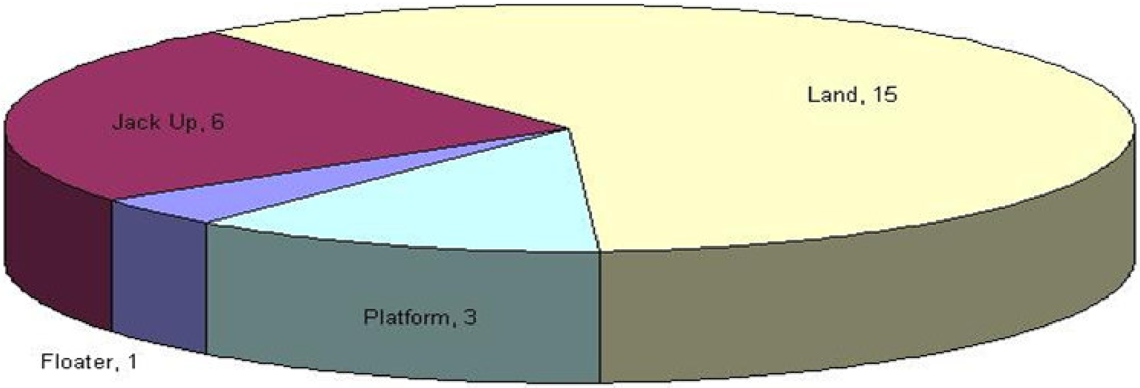


Fig. 6.5 – The Distribution of MPD wells based on the 'Rig Type' used based on the Secure Drilling Database.

6.3.4. Comments on All Three Databases

The cumulative MPD wells database has about 148 MPD well data points. This is close to 42% of the actual number of MPD wells known to have been drilled so far. However, information about the same well might be included in more than one datasets.

6.4. MPD CSM Software

Software that can perform the candidate selection based on the developed CSM and flow diagram is discussed in this subsection. The Microsoft's 'Visualbasic.net' is used to develop the MPD CSM software. The software is named 'DZxION'. A few additional software tools available in the computing industry are also used along with VB.net. A detailed explanation of several features, functions, input and output options of the 'DZxION' MPD CSM software is also provided in this section.

6.4.1. DZxION Software Description

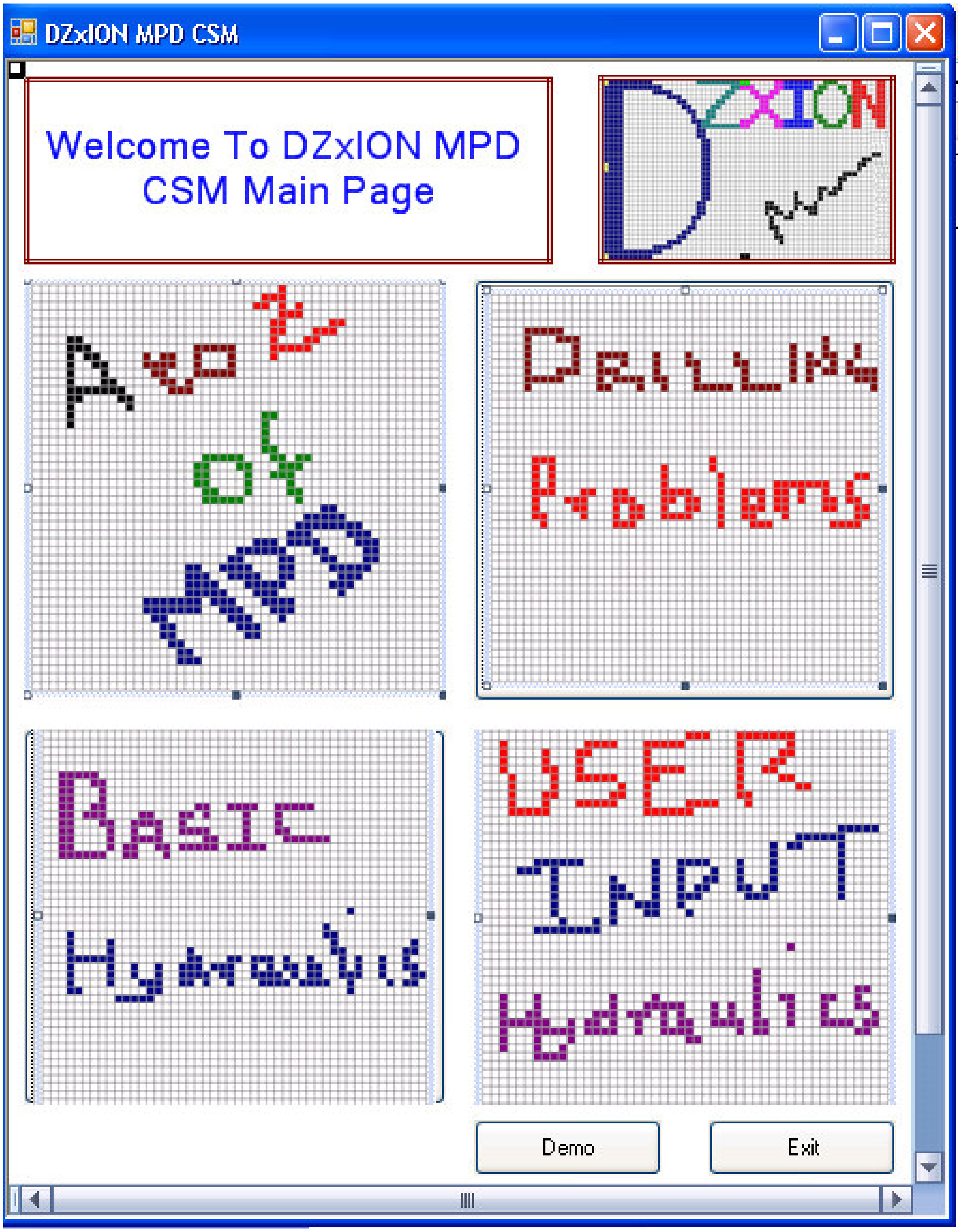
This subsection provides the several aspects of the DZxION MPD CSM software. The 'main screen' or 'main menu' or 'main page' of DZxION **(Fig. 6.6)** will be loaded at the beginning, when the software is run. The top two cells have the welcome screen and the 'DZxION' Icon. The two bottom cells are 'Help' and 'Exit' buttons. The remaining big buttons represent the four different input types.

Clicking the 'Help' button will load the detailed help file. It will include explanation of the different input and output buttons, the essential input parameters required to run the CSM features, and ways to look at the output. The 'Exit' will close the program.

6.4.1.1.Input Features

There are three different input features available for the candidate selection software: 1) Elementary Input, 2) General Engineering Input and 3) External Hydraulics Input. There is a fourth 'Method Selection Option' that helps with MPD method selection based on the MPD drilling problems and the associated drilling expenses.

Selecting 'A to Z MPD' loads the Elementary Input mode, selecting the 'Method Selection' button loads the method selection mode, selecting the 'Basic Hydraulics' button loads the General Input mode, and the 'User Input Hydraulics' button loads the External Hydraulics Input mode.



DZxION MPD CSM

Welcome To DZxION MPD CSM Main Page

Fig. 6.6 DZxION MPD CSM Main Screen. The figure shows all the options available on the starting screen of the MPD CSM software. The 'A to Z' MPD option loads the Elementary Input mode discussed in the section 6.4.1.2. The Method selection options are discussed in the section 6.4.1.3. The Basic Hydraulics Button loads the General Input Option discussed in the section 6.4.1.4. The 'User Input Hydraulics' button loads the External Hydraulics Input mode discussed in 6.4.1.5.

6.4.1.2.‘Elementary Input / No Input’ or ‘A to Z of MPD Option’

This part is referred as the ‘A to Z MPD’ option in the CSM software. The user can look at the different variations and methods of MPD – their description, how they work etc. When the user clicks on the ‘A to Z MPD’ option ‘Select an MPD Variation’ form **(Fig 6.7)** is loaded. The user can choose one of the four MPD variations and find further information on that variation and the methods available to achieve that MPD variation.

The user can also choose to look at example wells for each MPD variation. The Pp and Fp data is generated using equations that are available in the literature. This input mode is specifically developed for educational purposes of MPD. The user can choose to vary a few input parameters – like changing the pressure regime ranges, drilling problems at the location, etc. The output is available in the form of plots, tables and explanation of the MPD method or variation suitable for the given conditions.

6.4.1.3.Method Selection

This mode helps in identifying a suitable method for the given set of drilling problems and constraints. The user can input the kind of drilling problem associated with the well and information on the costs for with combating those problems. The output for this mode is an MPD method/variation that fits the given scenario.

It is recommended to run the ‘General Engineering Input’ mode or the ‘External Hydraulics Input’ mode after performing the MPD method selection.

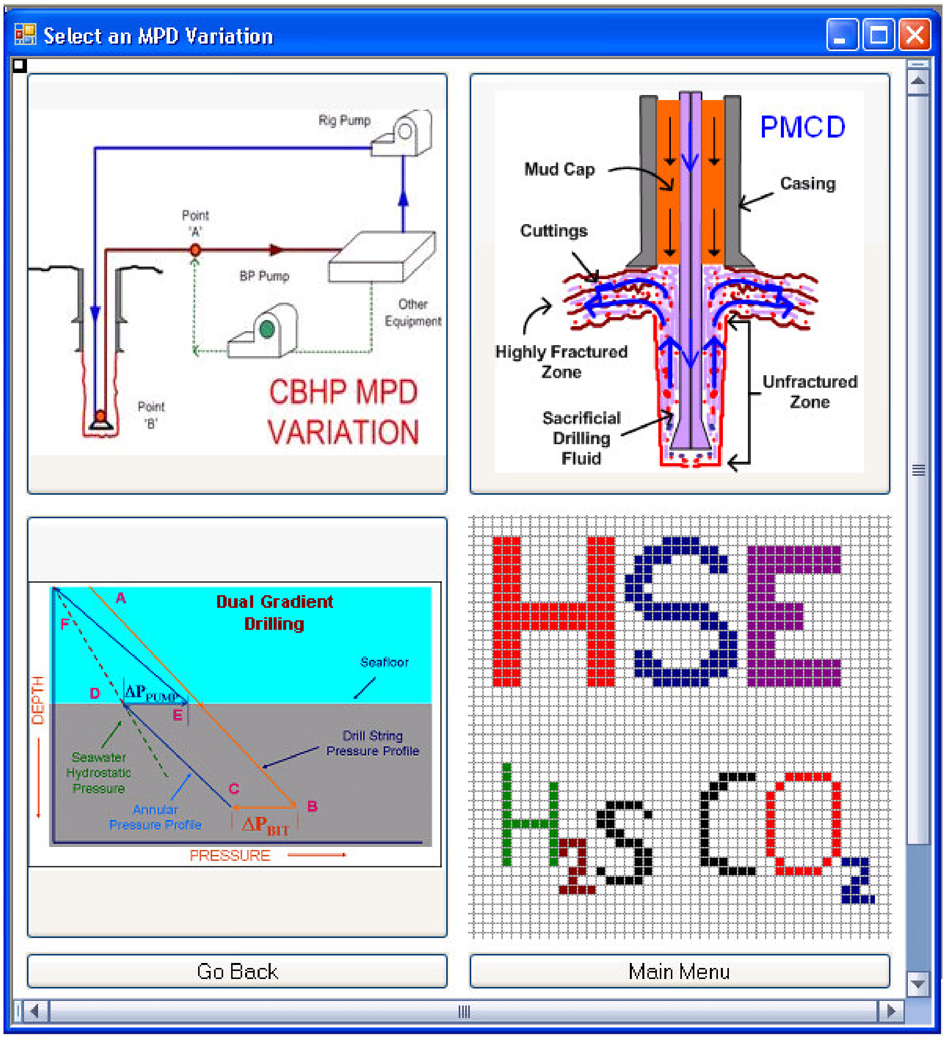


Fig. 6.7 The Select Variation Form. This form is loaded after choosing the 'A to Z MPD' option in the DZxION main page (Fig. 6.6).

6.4.1.4. 'General Engineering Input' or 'Basic Hydraulics Mode'

This input mode is built for the complete candidate selection using all the required input information. This mode is activated when the user clicks the 'Basic Hydraulics' option from the DZxION main screen. For calculating the annular pressure drop, DZxION uses the API RP 13D equations shown in Appendix C. This software does not include the effects of compressibility and temperature while performing the hydraulic calculations.

Clicking the 'Basic Hydraulics' option on the DZxION main page, will load the 'Basic Hydraulics Control Panel' form **(Fig 6.8).** There are four options available on the DZxION Basic Hydraulics Control Panel. The first option is 'Load Input Data'. The user can load the required input parameters like the mud rheology, circulation rate, casing and wellbore details, etc.

The second option is 'Provide Additional Method Details'. This option helps the user to enter additional details about the chosen MPD variation or method. The third option is 'Calculate and Show Results'. Once all the required input parameters are loaded into the software, the user can click this option to perform the hydraulic calculations and see the results. The fourth option takes the user back to the 'Main Page' of the simulator.

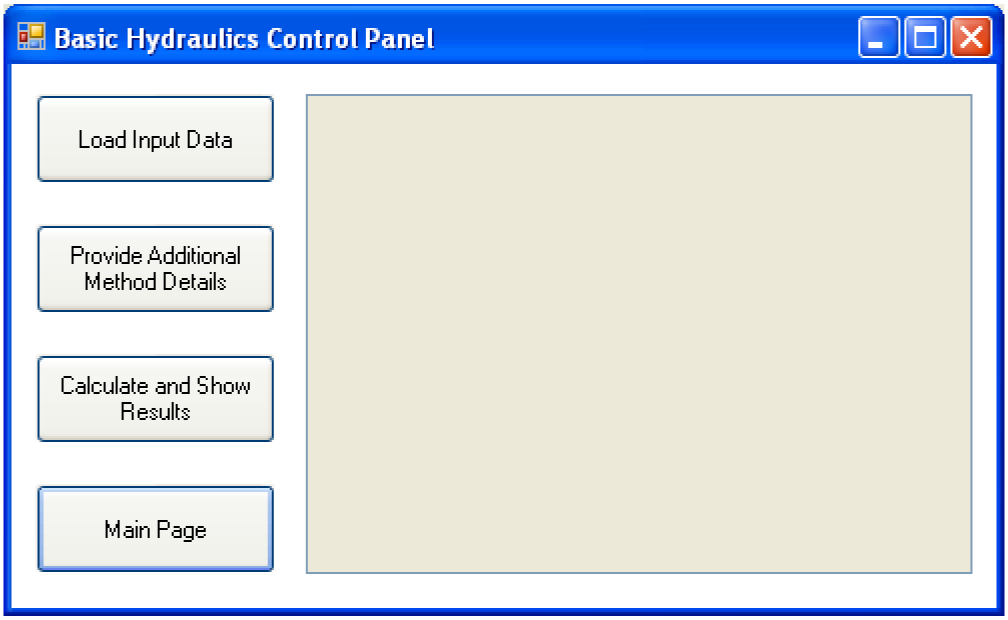


Fig. 6.8 DZxION Basic Hydraulics Control Panel. This forms loads when the user clicks the 'Basic Hydraulics from the DZxION Main Page.

Clicking the ‘Load Input Data’ option in the Basic Hydraulics Control Panel (Fig. 6.8) will open the DZxION Basic Hydraulics Input Module **(Fig 6.9).**

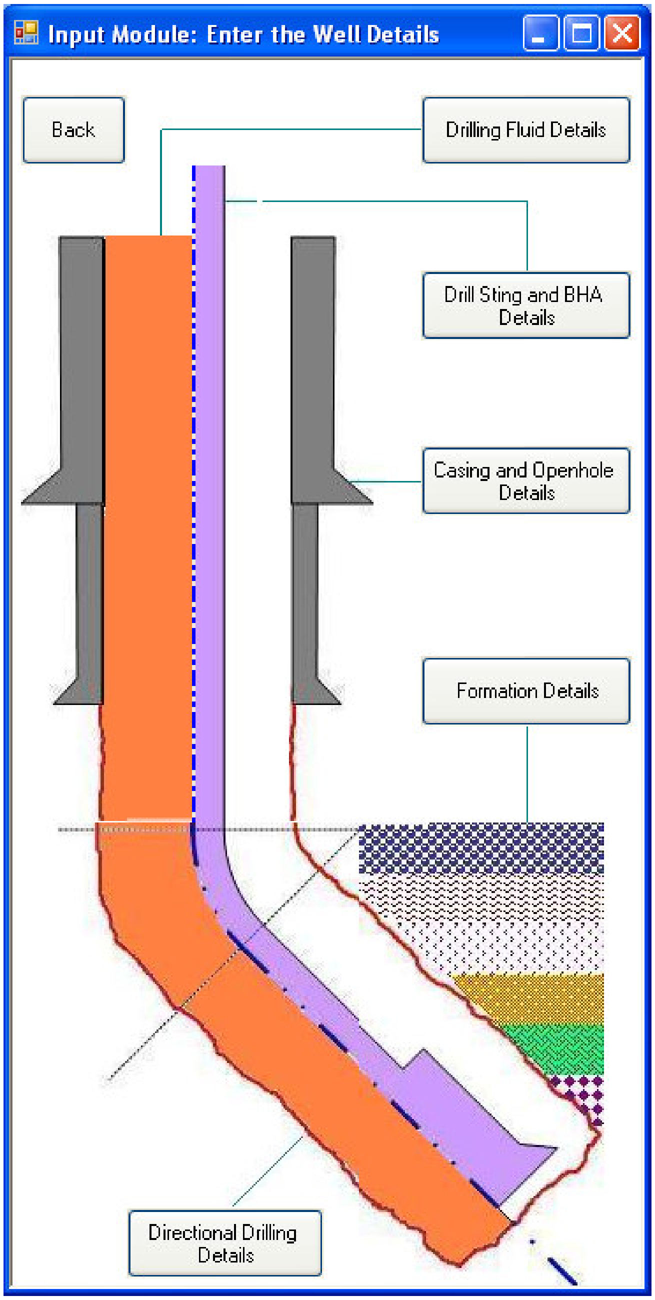
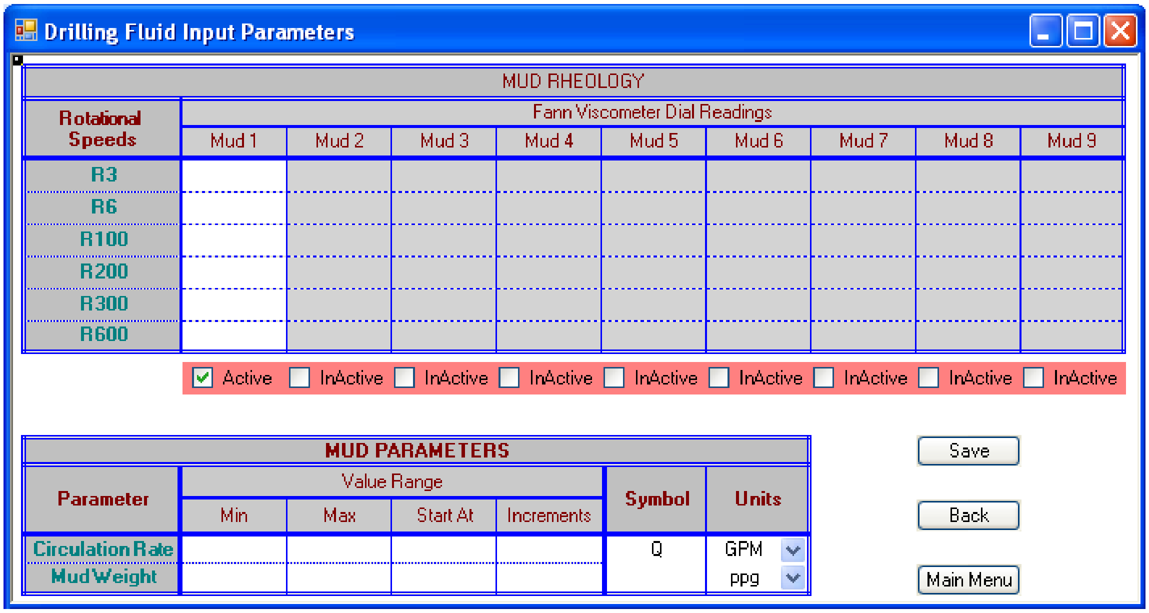


Fig. 6.9 DZxION Basic Hydraulics Input Module. This form helps the user to load the required input details for performing the hydraulic calculations.

Clicking the ‘Drilling Fluid Details’ option in the Basic Hydraulics Input Module (Fig. 6.9) will open the Drilling Fluid Input Parameters Form **(Fig 6.10).** The user can input upto nine different mud rheology values in the Mud Rheology table and choose to activate the mud rheology values that he wants to use in the calculations. The inactive rheology values will be saved on the form and can be activated when required. Until then those values will not be available for performing the hydraulic calculations.

The user can input the minimum and maximum values of the circulation rate and mud weight for the hydraulic calculations on this form. The user can also provide the start-at value and the increments they want to use. Therefore, this software performs hydraulic calculates for a range of ‘circulation rates’ and ‘mud weights’ for a given mud rheology.



MUD RHEOLOGY

Rotational Speeds	Fann Viscometer Dial Readings								
	Mud 1	Mud 2	Mud 3	Mud 4	Mud 5	Mud 6	Mud 7	Mud 8	Mud 9
R3									
R6									
R100									
R200									
R300									
R600									
	☑ Active	☐ InActive	☐ InActive	☐ InActive	☐ InActive	☐ InActive	☐ InActive	☐ InActive	☐ InActive

MUD PARAMETERS

Parameter	Value Range				Symbol	Units
	Min	Max	Start At	Increments		
Circulation Rate					Q	GPM
Mud Weight						ppg

Fig. 6.10 Drilling Fluid Input Parameters Form. The user can input upto nine different mud rheologies and choose the one rheology from the active mud rheologies to perform the hydraulic calculations.

The user can load the drillstring and BHA, casing, formation, and the directional drilling details by choosing the corresponding tabs in the Basic Hydraulics Input Module (Fig. 6.9). A list of essential and optional input parameters for the DZxION software is given below:

- Pressure Regimes Information
    - Pp and Fp data
    - FS limits (Optional. Required if FS > Pp)
    - Desired operating or Working limits (if different from Pp and Pf, and FS)
- Drill String and BHA Details:
    - All the details of the drillstring and BHA – Ids (Optional), ODs, lengths
- Drill-Bit Details: Nozzle Sizes / Pressure Drop Across the Bit (Optional)
- Drilling Fluid
    - Rheology (Required, at least one set of data)
    - Mudweight, circulation rate
- Wellbore Geometry
    - Wellbore profile – the directional drilling info
    - Casing details & Openhole details: Ids (required), ODs (Optional)

The software has default values for all the parameters and the user can choose to load some of those parameters according to their requirement. The hydraulic calculations cannot be performed without the required input parameters mentioned above.

Clicking the ‘Provide Additional Method Details’ option in the Basic Hydraulics Control Panel (Fig. 6.8) will open the ‘Provide Additional Method Details’ Form **(Fig 6.11).** This form can be used to provide the details about the individual MPD variations and additional details relevant to the hydraulic calculations.

The ‘Max Allowed Back Pressure’ option for the CBHP or DGD variations makes the software to set the upper limit for performing the MPD calculations.

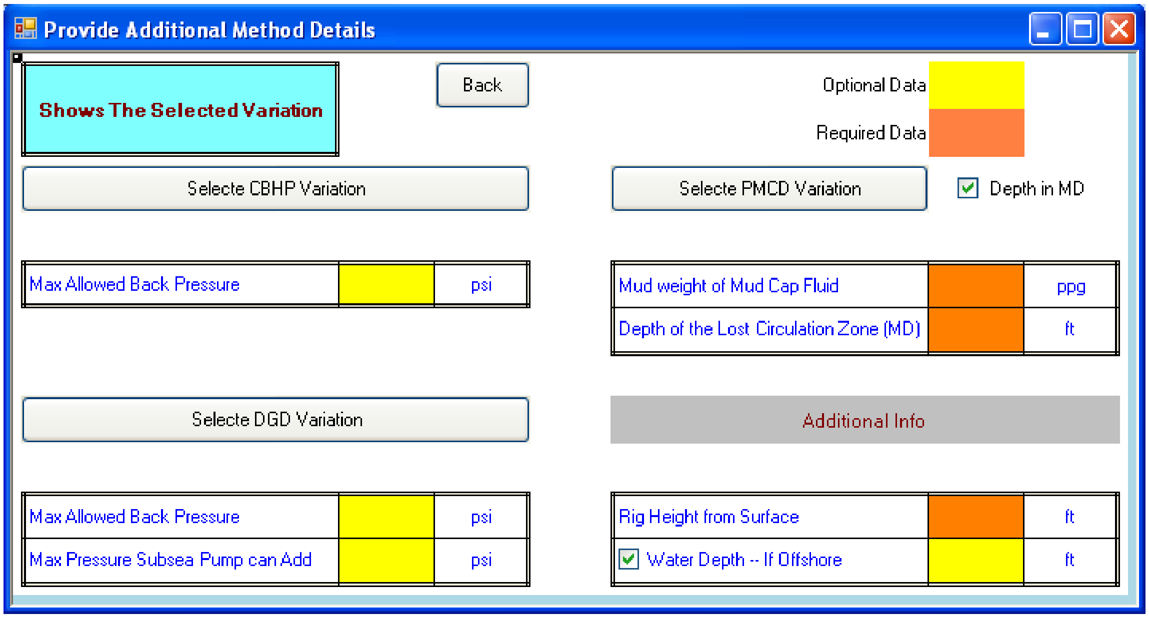
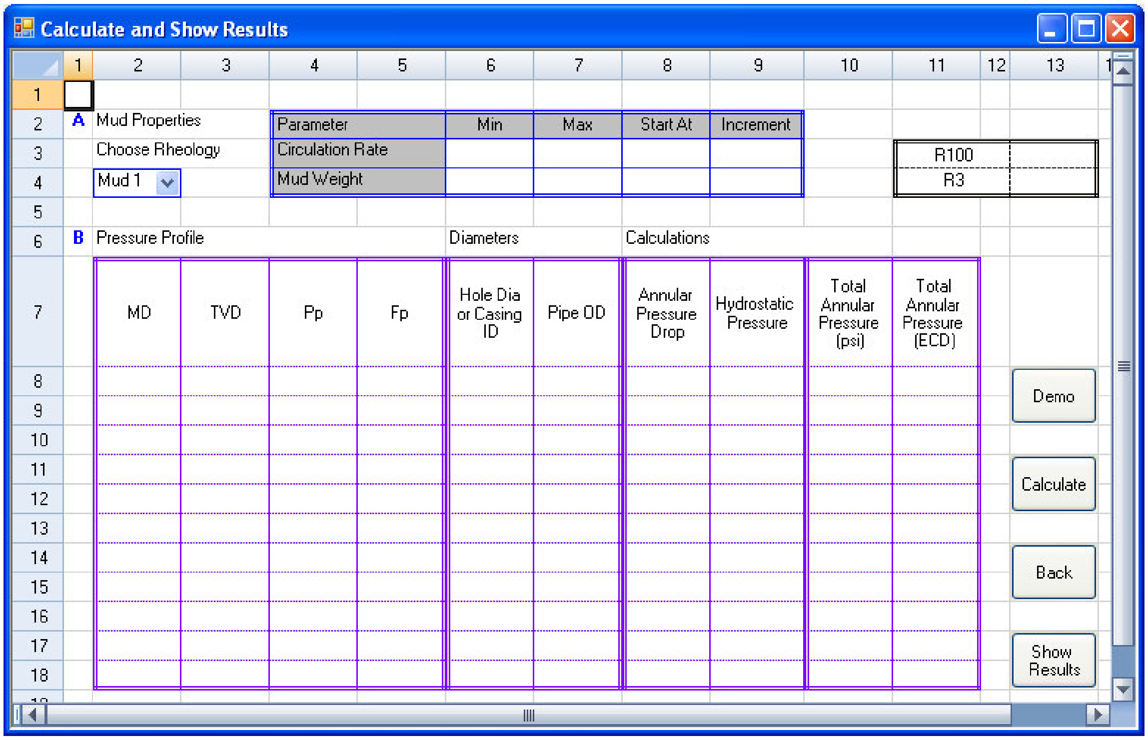


Fig. 6.11 Provide Additional Method Details.

Clicking the ‘Calculate and Show Results’ option in the Basic Hydraulics Control Panel (Fig. 6.8) will open the Calculate and Show Results Module **(Fig 6.12).** The user can load the required mud rheology. All the other input data will be automatically loaded into this form. Clicking the ‘Show Results’ button provides the results (Section 6.4.2).



Parameter	Min	Max	Start At	Increment
Circulation Rate				
Mud Weight				

MD	TVD	Pp	Fp	Hole Dia or Casing ID	Pipe OD	Annular Pressure Drop	Hydrostatic Pressure	Total Annular Pressure (psi)	Total Annular Pressure (ECD)

Fig. 6.12 Calculate and Show Results Module.

6.4.1.5.'External Hydraulics Input' or 'User Input Hydraulics'

This input mode is built for users who want to input the hydraulic pressure calculations from different software that might include the temperate and compressibility effects. The user can choose this mode by clicking the 'User Input Hydraulics' option in the DZxION main page. The user can then load the formation data and the hydraulic simulation results from the external software at the chosen circulation rate, mud weight, and the corresponding MPD parameters.

The DZxION output for this option is provided in the form of tables and plots similar to the 'Basic Hydraulics' mode described earlier.

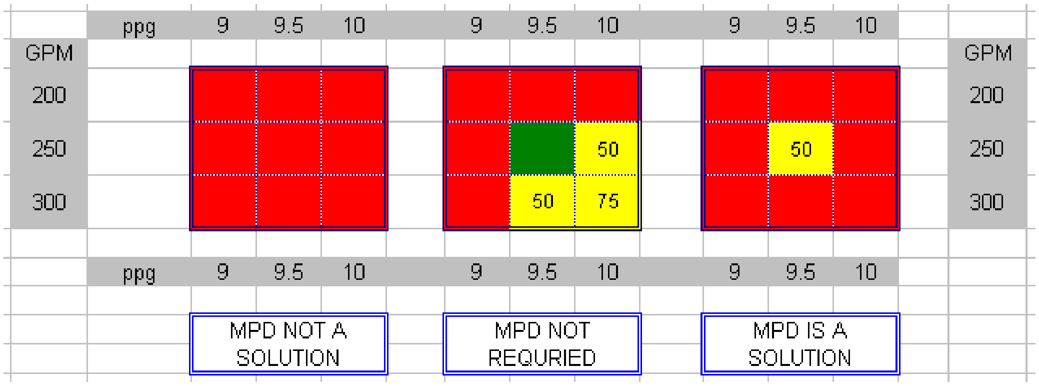
6.4.2. Explanation of DZxION Software Results

The results are displayed in the form of color code described below. The conventional hydraulic calculations are performed using the given input data (Fig. 6.12). The user chooses the required mud rheology and clicks ‘Show Results’ button.

6.4.2.1.Introduction to Results: Color Coding

Green Square: If the WBP is within the Pp/FS and Fp window, then the result for that mud weight and circulation rate is represented as a green square **(Fig. 6.13)**. Therefore, the well can be drilled for the given input information and for the given rheology, at the indicated circulation rate and mud weight, using conventional drilling techniques.

Yellow Square: If the WBP falls out of the pressure window, MPD calculations are performed. If the well can be drilled using MPD, then the result is represented by a yellow square. The Arabic numerals in the yellow square represent the required BP



	ppg	9	9.5	10	9	9.5	10	9	9.5	10	
GPM											GPM
200		🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	200
250		🟥	🟥	🟥	🟥	🟩	🟨 50	🟥	🟨 50	🟥	250
300		🟥	🟥	🟥	🟥	🟨 50	🟨 75	🟥	🟥	🟥	300
	ppg	9	9.5	10	9	9.5	10	9	9.5	10	
		MPD NOT A SOLUTION			MPD NOT REQURIED			MPD IS A SOLUTION			

Fig. 6.13 Sample Possible Results for CBHP MPD variation.

Note that the yellow squares have additional information about the MPD variation/method parameters. This results table is developed for the CBHP MPD variation. Hence, ‘the required BP’ is shown in the yellow squares.

Red Square: If both conventional and MPD techniques do not work for the given circulation rate and mud weight, then the result is represented as a red square.

6.4.2.2.Classification of Results

The Fig. 6.13 shows the possible three different types of results for the software output.

All Red Squares: The first option shows that for the given rheology, circulation rate range, and mud weight range, the well cannot be drilled using the conventional and MPD drilling techniques. The point to be noted here is that there is a potential MPD candidate, but the hydraulic calculations say, ‘MPD cannot drill the well’.

At Least One Green Square: The well can be drilled conventionally.

At Least One Yellow Square: The well can be drilled using MPD techniques.

Yellow and Green Squares: MPD is a solution, but is not required for the given candidate well, since it can be drilled using conventional drilling methods.

7. CONCLUSIONS

The conclusions of the project are divided into four sections – conclusions of the MPD study, conclusions of the CSM Flow Diagram, conclusions of the CSM Software, and the conclusions of MPD Worldwide Database.

7.1. Conclusions of MPD Study

- MPD is at the top of the drilling technology evolution tree, and with its ‘Conventional’, ‘Advanced’ and ‘Expanded’ applications, it can solve several drilling problems and has filled the ‘Technology Not Available’ gap.
- There are several classifications of MPD. However, the classification scheme of ‘Variations and Methods’, helps in better understanding of all the available MPD categories and subcategories.
- The four prominent variations are: CBHP, PMCD, DGD, and HSE.

7.2. Conclusions of MPD CSM Flow Diagram

- The MPD ‘Flow Diagram’ identifies the several critical steps involved in MPD candidate selection.
- The ‘Flow Diagram’ differentiates the results into ‘MPD not required’, ‘MPD cannot help’ and ‘MPD is a solution’ classes.

7.3. Conclusions of MPD CSM Software

- The MPD CSM software can act as a preliminary screen to determine the utility of MPD for the potential MPD candidate wells. It can perform preliminary screening for most of the currently available MPD methods and variations.
- The three input modes: ‘Elementary Input’, ‘General Engineering Input’ and ‘External Hydraulics Input’, provide flexibility to the users.
- The software follows API RP 13 D guidelines for calculating the annular and pipe pressure drops.
- The software performs the basic hydraulic analysis and calculations that would help the user to make a better engineering decision in deciding whether ‘TO USE’ or ‘NOT TO USE MPD’ for the given prospect.

7.4. Conclusions of MPD Worldwide Database

- The database can help as a basic guide to the worldwide distribution of drilled MPD wells giving information such as the frequency of MPD variations for a given location and in a given period of time.
- The database so far contains limited amount of data because of the confidential nature of the data and limited sources available to procure it.
- The cumulative database shows that the CBHP and PMCD variations are very widely used variations of MPD.

8. SUGGESTED TOPICS FOR FUTURE WORK

There are two important suggestions that can improve the CSM and software and keep it up-to-date.

- Using the ‘Temperature effects’ and the ‘Compressibility effects’ while calculating the hydraulic pressure calculations.
- Database: expanding the database and making it up-to-date as far as possible.

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APPENDIX A

MPD EQUIPMENT

This section provides information on commonly used MPD equipment. Section 4.4 in the dissertation provides a list of equipment and Appendix D providers more information on the MPD equipment providers.

A–1 RCDs Weatherford:

Fig. A–1 Williams® Weatherford M7800 RCD (Weatherford 2009).

- Williams® M7800 RCD: drill strings diameter ≤ 6⅝ inches; 2500 psi dynamic/5000 psi static; dual element design, no top flange; for rigs with surface BOP's onshore and offshore. This RCD is shown in **Fig. A–1** and Fig. 2.1a.

- Williams® M7875 RCD Docking Station: drill strings diameter ≤ 6⅝ inches; 500 psi@200 rpm, 700 psi@150 rpm, 1000psi@100 rpm, 1500psi@50 rpm, and 2000psi static; with top flange; most suitable for offshore rigs where there is a need to switch from conventional to MPD quickly, and vice versa.
- Williams® Marine Diverter Insert RCD: converts rigs marine diverter to function as a rotating marine diverter; pressure capability same as the diverter's, 500 psi.
- Others in development: Low Profile RCD (<20 inches tall); M7900 RCD (21¼ inches diameter), and Drilling with Casing RCD (≤ 13⅝ inches).

A–2 RCDs Smith Services:

- Hold™ 2500: rotating 2500 psi / static 5000 psi, max rpm 150, max pass through bearing assembly is 12¼ inches (**Fig. A–2a).** (Smith Services 2009f, 2009g).
- DHS 1400: rotating 600 psi/static 1000 psi, max rpm 150, max pass through bearing assembly is 14 inches (**Fig. A–2b).** (Smith Services 2009a).
- Model 7068: rotating 250 psi / static 750 psi, max rpm 150, max pass through bearing assembly is 13¾ inches. (Smith Services 2009c).
- Model 8068–G: static 750 psi, max rpm 150, max pass through bearing assembly is 13¾ inches(**Fig. A–2c).** (Smith Services 2009b, 2009e).
- Model 7368: rotating 250 psi / static 750 psi, max rpm 150, max pass through bearing assembly is 7 $^{1}/_{16}$ inches(**Fig. A–2d).** (Smith Services 2009d, 2009h).
- Other available models are: Model 8068, RDH 2500®, and RDH 500®.

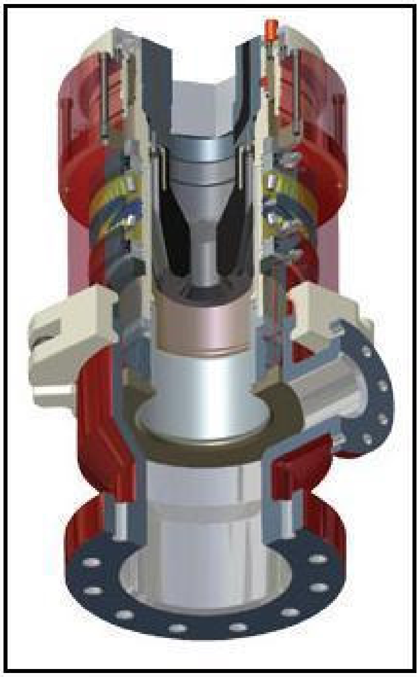


Fig A-2a

Fig A-2b

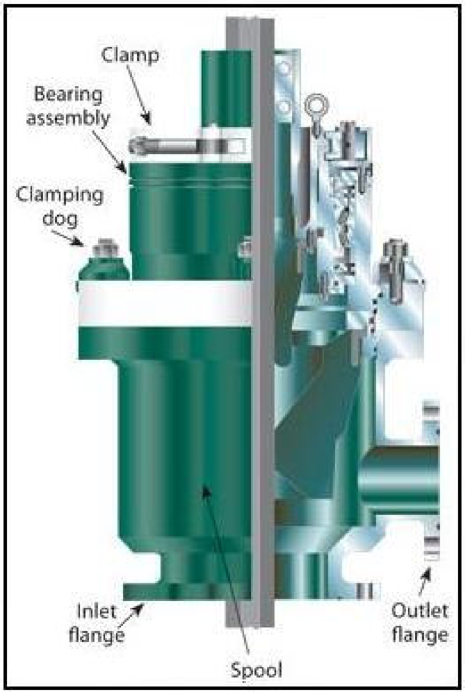


Fig A-2c

Fig A-2d

Fig. A–2 RCDs Smith Services. Fig. A–2a is HoldTM 2500, Fig. A–2b is DHS 1400, Fig. A–2c is Model 8068-G, and Fig. A–2d is Model 7368.

A–3 Chokes: MI SWACO

- 10K SUPER CHOKE: max pressure 10,000 psi, rig air activation/operation, also manual activation. **(Fig. A–3a).** (MI SWACO 2009).
- 15K CHOKE: max pressure 15,000 psi, rig air activation/operation, also manual activation. (MI SWACO 2009).
- 20K ULTRA CHOKE: max pressure 20,000 psi, rig air activation/operation, also manual activation. (MI SWACO 2009).
- ECHOKE SYSTEM: tested upto 10,000 psi, 15 ksi and 20 ksi also possible; variable-speed drive; Ethernet communication possible. **(Fig. A–3b).** (MI SWACO 2009).

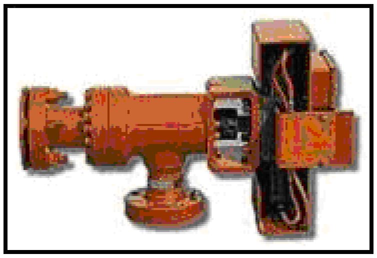


Fig A–3a

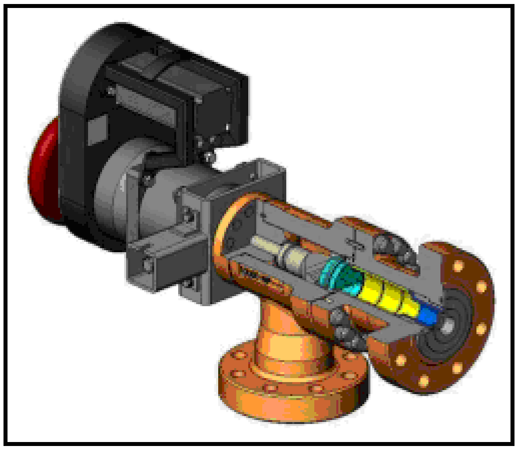


Fig A–3b

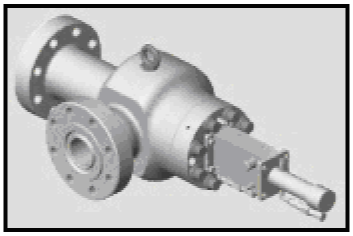


Fig A–3c

Fig. A–3 Chokes MI SWACO. Fig. A–3a 10 ksi Choke, Fig. A–3b EChoke System, and Fig. A–3c Super Auto Choke (MI SWACO 2009).

- SUPER AUTOCHOKE: max pressure of operation 10,000 psi, automatic pressure regulation; H_2S service, and no leak shut in. **(Fig. A–3c).** (MI SWACO 2009).

A–4 Drill String Valve

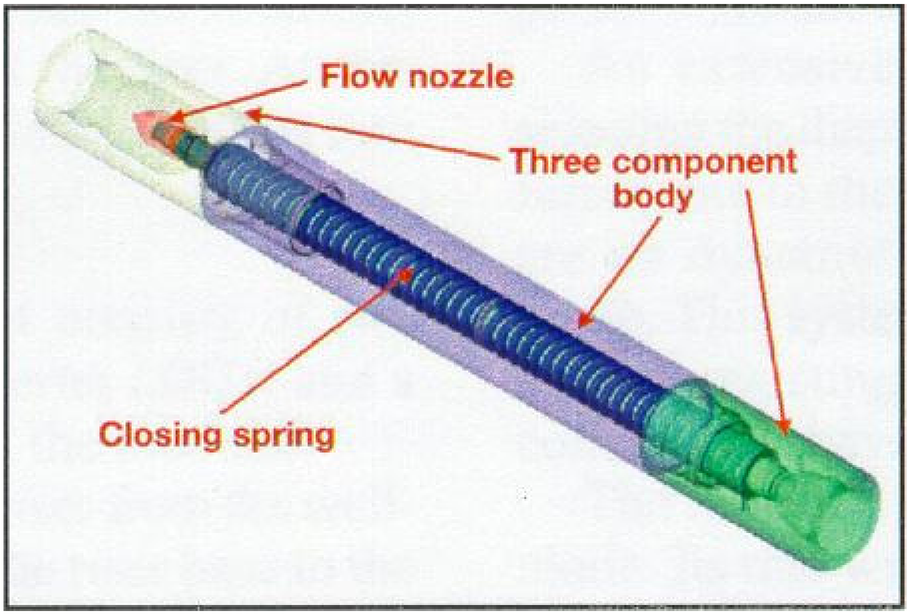


Fig. A–4 Drill String Valve (DSV) (Juvkam-Wold 2007).

APPENDIX B

MPD WELLS DATABASES

As mentioned earlier in the section 6.2, three companies provided the MPD wells data bases. SIGNA Engineering provided the DB–1, AtBalance with smith provided DB–2, and Secure Drilling provides DB–3. In the ‘Category’ column of the DB–1, ‘P’ represents ‘Proactive MPD wells’ and ‘R’ represents ‘Reactive MPD wells’.

Table B–1: MPD Wells Database–1 (DB–1): SIGNA Engineering Corp.

Sl No	Country	Region	Offshore	BOP	Variation	Category	Year	Month
1	USA	GoM	Yes			P	2005	Jul
2	USA	GoM	Yes	Surface	CBHP	P	2005	Mar
3	USA	GoM	Yes	Surface	CBHP	P	2006	Sep
4	Malaysia	East Sarawak	Yes	Subsea	PMCD	P	2003, 2004	
5	USA	GoM	Yes	Subsea	CBHP		2005, 2006	
6	Norway	North Sea	Yes		CBHP			
7	USA	South Texas	No	Surface	MPCD	P	2003, 2004	
8	Algeria							
9	USA	South Texas	No	Surface	HSE	P		
10	Kazakhstan	Kashagan	Yes	Surface	PMCD	P		
11	Argentina			Surface				
12	Kazakhstan		No	Surface	PMCD	P	2001	
13	USA	South Texas	No	Surface	PMCD	P	2000	
14	Venezuela	Lake Maracaibo	Yes	Surface	PMCD	P		
15	Colombia			Surface	Gas Injection			
16	Venezuela	Lake Maracaibo	Yes	Surface	PMCD	P		
17	Africa		Yes	Surface	PMCD	P		
18	Indonesia		Yes	Surface	PMCD, CBHP	P		
19	Vietnam	South China Sea	Yes	Surface	HSE	P		

Table B–1 Continued

Sl No	Country	Region	Offshore	BOP	Variation	Category	Year	Month
20			Yes	Surface	HSE	P		
21	Norway		Yes	Surface	HSE	P		
22	USA	GoM	Yes	Surface	CBHP	P		
23	USA	Texas	No	Surface	CBHP	P	2007	
24	Angola	Offshore	Yes		CBHP	P		
25		Bay of Bengal	Yes		PMCD, CBHP	P		
26	USA	GoM	Yes	Surface	CBHP	P	2004	Dec
27	USA	GoM	Yes	Surface	CBHP	P	2005	Jan
28	USA	GoM	Yes	Surface	CBHP	P	2005	Feb
29	USA	GoM	Yes	Surface	CBHP	P	2007	Mar
30	USA	GoM	Yes	Surface	CBHP	P	2007	Feb
31	Norway	North Sea	Yes	Surface	CBHP	P		
32	Kazakhstan	Caspian Sea	Yes	Surface	PMCD	P	2006	Aug
33	USA	Fort Bend County, Texas	No	Surface	CBHP	P	2006	Jun
34	USA	Polk County, Texas	No	Surface	PMCD (Contingency)	P	2006	Apr
35	Africa	Angola	Yes	Surface	CBHP; PMCD Contingency	P	2006	
36	USA		Yes	Surface	CBHP	P		
37	USA	GoM	Yes	SubSea	CBHP	P		
38	Venezuela	eastern Venezuela						
39	China	Southern China	No			P	2006	Mar
40	Vietnam	Offshore Vietnam	Yes		HSE	P		
41	Vietnam	Offshore Vietnam	Yes		HSE	P		
42	Malaysia	East Sarawak	Yes		PMCD	P		
43	Malaysia	East Sarawak	Yes		PMCD	P		
44	Malaysia	East Sarawak	Yes		PMCD	P		
45			Yes		HSE	P		
46			Yes		CBHP	P		
47	Indonesia		Yes		PMCD	P		
48	Indonesia		Yes		PMCD	P		
49	Indonesia		Yes		PMCD	P		
50	Mexico	Veracruz	Yes		CBHP	P		
51					CBHP, DAPC			
52	USA	Wharton County, Texas	No	Surface	CBHP	P	2007	May
53	Kazakhstan	Caspian Sea	Yes	Surface	PMCD	P	2004	Jul

Table B–1 Continued

Sl No	Country	Region	Offshore	BOP	Variation	Category	Year	Month
54	USA	GoM	Yes		PMCD	P	2005	Aug
55	Norway	North Sea	Yes	Surface	CBHP	P	2007	Aug
56	USA	GoM	Yes				2008	Jun
57	Australia	South Australia	No		CBHP		2008	Jun
58	South America	Falkland Islands	Yes				2008	May
59	USA	GoM				P	2008	May
60	United Kingdom	North Sea	Yes					
61	USA	Texas	No				2008	Aug
62	USA	North Dakota	No					
63	USA	Alaska					2008	Jun
64	USA	GoM	Yes				2008	Jun
65	USA	GoM	Yes				2008	Jun
66	USA	GoM	Yes				2008	Apr
67	USA	GoM	Yes				2008	Jul
68	USA	GoM	Yes				2008	Apr
69	Canada	Alberta	No				2008	Aug
70	Norway	North Sea	Yes			P	2005	Jun
71	Norway	North Sea	Yes			P	2006	Feb
72		Caspian Sea	Yes	Subsea	Riserless Dual Gradient	P		
73	Russia	Shakalan	Yes	Subsea	Riserless Dual Gradient	P		
74		Mediterranean	Yes	Surface		P		
75		West Nile Delta	Yes	Surface		P		
76	Brazil		Yes		CBHP	P	2006	Aug
77	Brazil		No		CBHP	P	2006	Aug
78		Mediterranean	Yes		CBHP	P	2007	
79	Mexico	GoM (Bay of Campeche)	Yes		CBHP	P		
80	Canada	North-east British Columbia	No		CBHP	P		
81	Canada		No	Surface	CBHP	P		
82	Sumatra		No	Surface	PMCD	P		

Some of the information has been removed from the DB–1 for the reasons of confidentiality. In some places the information is not available. More information on the DB–1 can be obtained from the SIGNA Engineering Corporation.

In the DB–2, the confidential information is deleted as well. This database consists of all CBHP MPD wells. Further information on this database can be obtained from AtBalance with Smith.

Table B–2: MPD Wells Database–2 (DB–2): AtBalance with Smith

Sl No	Company	Location	Year	Onshore /Offshore	Rig Type
1	Shell NAM	Holland	2004	Onshore	Land
2	Geodynamics	Cooper Basin, Australia	2004	Onshore	Land
3	Shell E&P Co	Mississippi Canyon, GOM 806	2005	Offshore	TLP
4	Shell UK	UK NS	2005	Offshore	Coil Tubing
5	Shell E&P Co	Wyoming	2005	Onshore	Coil Tubing
6	Shell UK	UK NS	2006	Offshore	Coil Tubing
7	Shell E&P Co	Garden Banks, GOM 426	2006	Offshore	Platform
8	Petronas Carigali	Myanmar	2006	Offshore	Drill Ship
9	Lavon Evans	Wharton Co,	2007	Onshore	Land
10	Confidential	Coastal USA	2007	Offshore	Barge
11	Shell E&P Co.	Garden Banks, GOM 426	2007	Offshore	Platform
12	Confidential	Coastal USA	2007	Offshore	Barge
13	Confidential	Coastal USA	2007	Offshore	Barge
14	Shell E&P Co	Garden Banks, GOM 426	2007	Offshore	Platform
15	Shell E&P Co	McAllen Pharr field, South TX	2007	Onshore	Land
16	Shell E&P Co	Garden Banks, GOM 426	2007	Offshore	Platform
17	Talisman	Malaysia	2007	Offshore	Jackup
18	Confidential	Coastal USA	2007	Offshore	Barge
19	Talisman	Malaysia	2007	Offshore	Jackup

Table B–2 Continued

Sl No	**Company**	**Location**	**Year**	**Onshore /Offshore**	**Rig Type**
20	Talisman	Malaysia	2007	Offshore	Jackup
21	Geodynamics	Cooper Basin Australia	2007	Onshore	Land
22	Confidential	Coastal USA	2007	Offshore	Barge
23	Confidential	Coastal USA	2007	Offshore	Barge
24	Shell E&P Co	Hidalgo County, TX	2007	Onshore	Land Rotary
25	Confidential	Coastal USA	2007	Offshore	Barge
26	Geodynamics	Australia	2008	Onshore	Land Rotary
27	Confidential	UK North	2008	Offshore	Platform
28	Confidential	UK North	2008	Offshore	Jackup
29	Confidential	N. Africa	2008	Onshore	Platform
30	IPM - Pemex	Villahermosa, Mexico	2008	Onshore	Land Rotary
31	Shell - Mars	GOM	2008	Offshore	Platform
32	Shell-Auger	GOM	2008	Offshore	Platform
33	Geodynamics	Australia	2008	Onshore	Land Rotary
34	Shell-Auger	GOM	2008	Offshore	Platform
35	Confidential	Canada, Foothills	2008	Onshore	Land Rotary
36	Confidential	Canada, Foothills	2008	Onshore	Land Rotary
37	Shell - South Texas	McAllen Pharr field, South TX	2008	Onshore	Land
38	Shell - Mars	GOM	2008	Offshore	Platform
39	British Petroleum	GOM	2008	Offshore	Jackup
40	Talisman	Asia	2008	Offshore	Jackup
41	Confidential	GOM	2009	Offshore	Platform

The DB–3 also consists of all CBHP wells, except for one PMCD well. More information related to the database can be obtained from Secure Drilling.

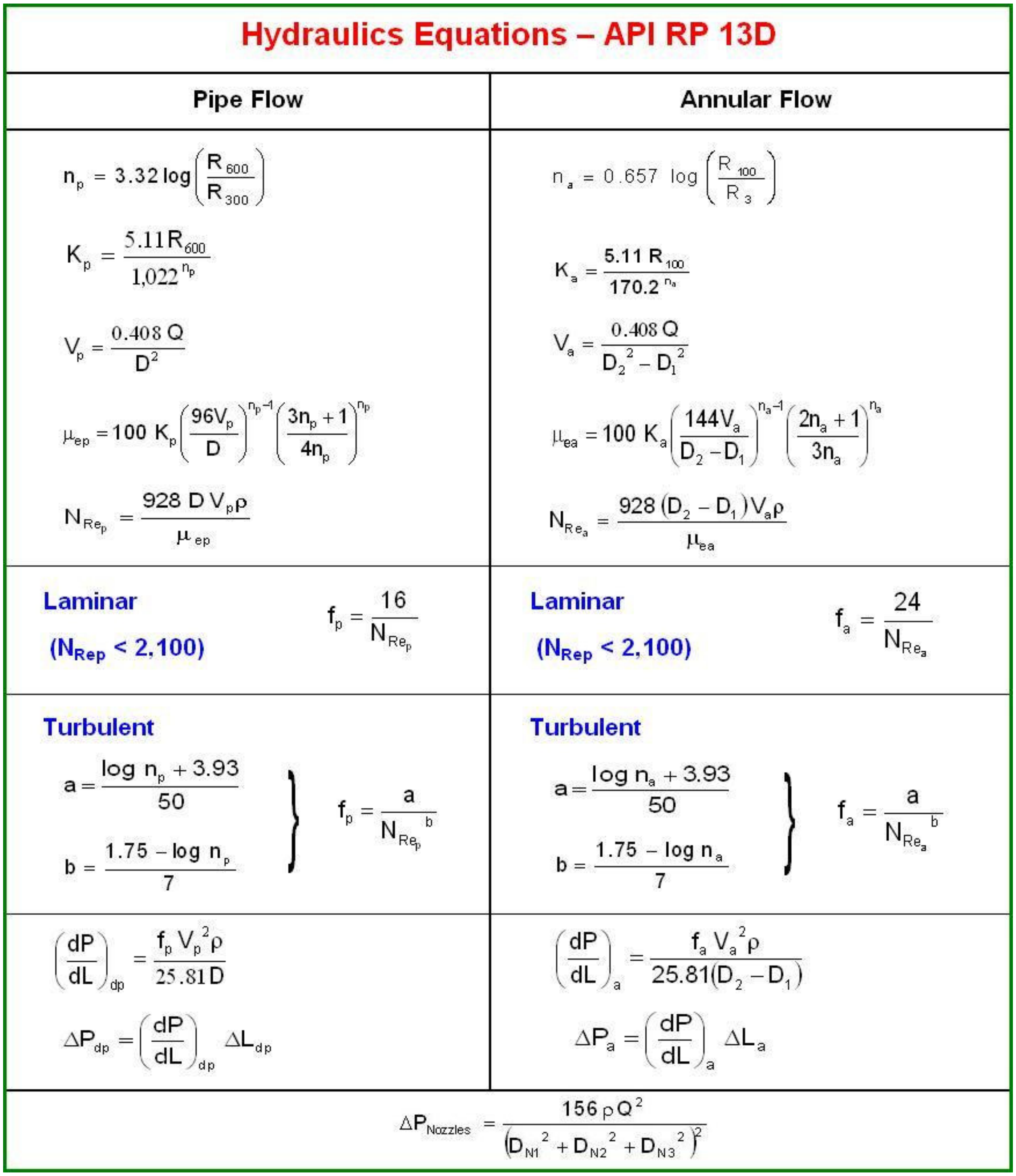
Table B–3: MPD Wells Database–3 (DB–3): Secure Drilling

Sl No	Location	Rig Type	Project type	Month & Year	Mud Type
1	Brazil	Land	Exploration	Jul-06	WBM
2	USA, S.Texas	Land	Development	Aug-06	OBM
3	Angola	Jack Up	Exploration	Jul-06	WBM
4	Brazil	Land	Development	Oct-06	WBM
5	Norway	Platform	HPHT	Mar-07	SBM
6	Texas	Land	Exploration	Feb-07	OBM
7	Brazil	Land	Exploration	Apr-07	WBM, OBM
8	Texas	Land	Exploration	May-07	OBM
9	Norway	Platform	HPHT	Sep-07	SBM
10	Egypt	Jack Up	Exploration	Aug-07	WBM
11	Cameroon	Jack Up	Exploration	Mar-08	OBM
12	Mexico	Land	Exploration	May-08	OBM
13	Texas	Land	Exploration	Jul-08	OBM
14	Texas	Land	Exploration	Jul-08	OBM
15	Venezuela	Land	Development	Sep-08	WBM
16	Texas	Land	HP	Oct-08	OBM
17	Norway	Platform	HPHT	Jul-08	Formate
18	Tunisia	Jack Up	PMCD		
19	Libya	Floater	HPHT, Exploration	Oct-08	WB
20	USA	Land	HP Development	Oct-08	OBM
21	UK	Jack Up	HPHT		
22	Brazil	Jack Up	Exploratory	Aug-08	SBM
23	Venezuela	Land	HP, Development		OBM
24	USA	Land	HP, Development	Dec-08	OBM
25	USA	Land	Exploratory	Jan-09	OBM

OBM stands for oil based mud, SBM stands for synthetic based mud and WB stands for water based mud.

APPENDIX C

API RD 13D EQUATIONS



Hydraulics Equations – API RP 13D

Pipe Flow	Annular Flow
$n_p = 3.32 \log\left(\frac{R_{600}}{R_{300}}\right)$ $K_p = \frac{5.11 R_{600}}{1{,}022^{n_p}}$ $V_p = \frac{0.408\,Q}{D^2}$ $\mu_{ep} = 100\,K_p\left(\frac{96V_p}{D}\right)^{n_p-1}\left(\frac{3n_p+1}{4n_p}\right)^{n_p}$ $N_{Re_p} = \frac{928\,D\,V_p\rho}{\mu_{ep}}$	$n_a = 0.657\,\log\left(\frac{R_{100}}{R_3}\right)$ $K_a = \frac{5.11\,R_{100}}{170.2^{n_a}}$ $V_a = \frac{0.408\,Q}{D_2^2 - D_1^2}$ $\mu_{ea} = 100\,K_a\left(\frac{144V_a}{D_2-D_1}\right)^{n_a-1}\left(\frac{2n_a+1}{3n_a}\right)^{n_a}$ $N_{Re_a} = \frac{928\,(D_2-D_1)V_a\rho}{\mu_{ea}}$
Laminar **(N_{Rep} < 2,100)** $f_p = \frac{16}{N_{Re_p}}$	**Laminar** **(N_{Rep} < 2,100)** $f_a = \frac{24}{N_{Re_a}}$
Turbulent $a = \frac{\log n_p + 3.93}{50}$ $b = \frac{1.75 - \log n_p}{7}$ $f_p = \frac{a}{N_{Re_p}^{\,b}}$	**Turbulent** $a = \frac{\log n_a + 3.93}{50}$ $b = \frac{1.75 - \log n_a}{7}$ $f_a = \frac{a}{N_{Re_a}^{\,b}}$
$\left(\frac{dP}{dL}\right)_{dp} = \frac{f_p V_p^2 \rho}{25.81\,D}$ $\Delta P_{dp} = \left(\frac{dP}{dL}\right)_{dp} \Delta L_{dp}$	$\left(\frac{dP}{dL}\right)_a = \frac{f_a V_a^2 \rho}{25.81(D_2 - D_1)}$ $\Delta P_a = \left(\frac{dP}{dL}\right)_a \Delta L_a$

$$\Delta P_{Nozzles} = \frac{156\,\rho Q^2}{\left(D_{N1}^{\,2} + D_{N2}^{\,2} + D_{N3}^{\,2}\right)^2}$$

APPENDIX D

MPD SERVICE COMPANIES AND CONSULTANTS

AGR Subsea AS: This company provides DGD equipment and services (AGR 2009) for the MPD projects. It uses a DGD system ROR^{EM} (Cohen et al. 2008), which can be used before setting surface casing, unlike other DGD methods. This RMR^{TM} system **(Fig. D–1)** uses an automatic subsea pump that pumps the returns from the mudline to the rig floor, a returns conduit, a suction module attached to the wellhead that is also attached to the returns conduit, and a control module.

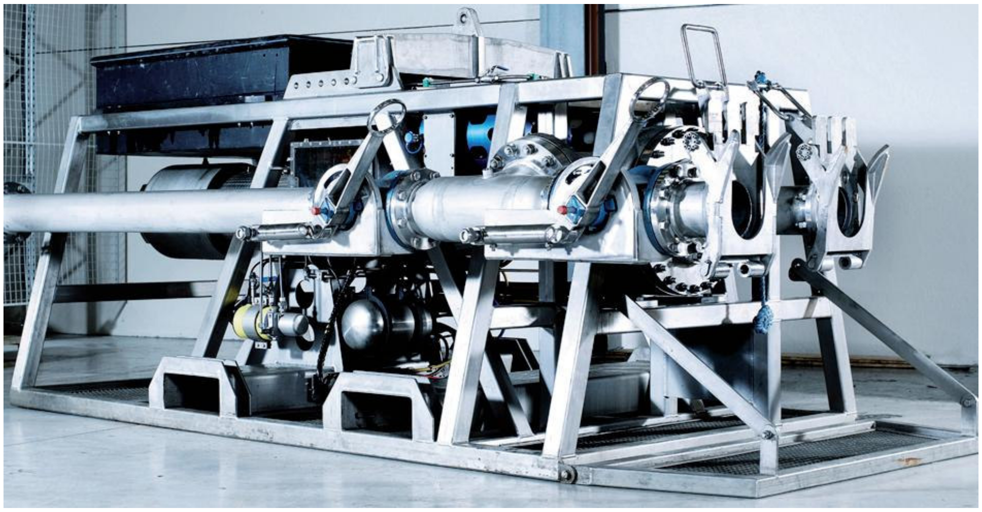


Fig. D–1 AGR's RMR Equipment (AGR 2009).

AGR also provides a few other operations related to well services, trenching and excavating, subsea operations. More information about this system can be obtained from the AGR website http://www.agr.com.

AtBalance: This service company provides CBHP services with their Dynamic Annular Pressure Control^{TM} (DAPC^{TM}) system. DAPC^{TM} consists of the following equipment: a fully automated choke, a BP pump, a Coriolis flow meter, and an Integrated Pressure Manager (AtBalance 2009). A piping and instrumentation drawing (P&ID) for the DAPC system used by AtBalance service company is shown in the **Fig. D–2**.

This service company provides the equipment and the expertise for their DAPC CBHP variation. The additional material required might/would consist of a RCD, additional chokes, and pressure measurement equipment. AtBalance filed software analyzes the real time data obtained by the PWD equipment /other sources and the DPAC choke **(Fig. D–3)** makes the required adjustments like holding BP to maintain the required BHP. This system has been used for more than 40 projects (Database-2). More information can be obtained from their website http://www.atbalance.com/index.html.

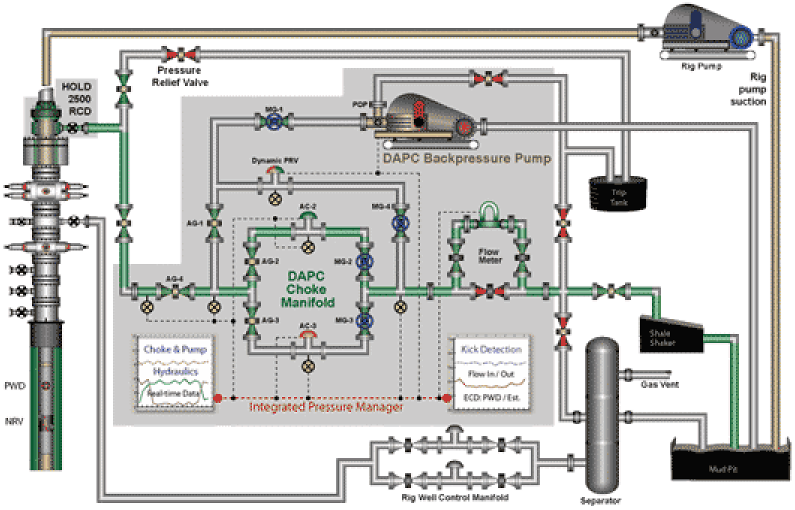


Fig. D–2 P&ID of a DAPC System (AtBalance 2009).

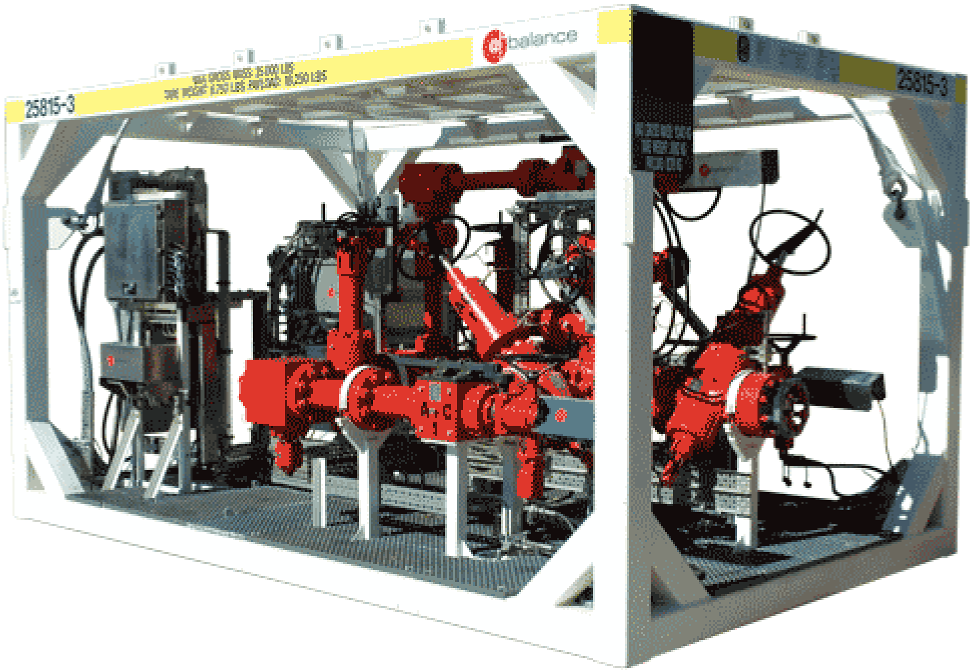


Fig. D–3 AtBalance's DAPC Choke Manifold.

Baker Hughers: Baker provides several drilling services. The significant MPD service is providing different kinds of drilling muds, such as: emulsions, oil based muds and water based muds. Since, all MPD operations are pressure sensitive, designer muds are very useful for MPD operations. More info can be found at www.bakerhughesdirect.com.

Dual Gradient Systems LLC: They provide the expertise and support related to the mud dilution method of DGD variation of MPD. The additional equipment required for this operation consists of degassers and centrifuges with sufficiently larger capacities. Luc deBoer developed and patented this system. Further info can be found at their soon to be launched website www.dgdrilling.com.

Halliburton: This service company provides an array of MPD equipment: Three and Four phase separators, compressors, boosters, flare stacks, Nitrogen Membranes, choke manifolds, RCDs, QTV (Quick Trip Valves) or downhole valves, NRV (Non Return Valves), and flow meters. They also provide additional services such as sample catching and analysis, erosion monitoring, providing chemicals/additives, and general drilling equipment and software. Their website, http://www.halliburton.com, provides more info.

MI Swaco: They provide a key MPD equipment element, chokes (Figs. 2.2 and A–3). The automatic chokes and BP pumps play a key role is many MPD operations. The EChoke has Ethernet communication capability that is very useful for MPD operations. The Super Auto Choke can be used on wells that have H_2S concerns, which makes it very useful for HSE MPD operations. They also provide several other drilling services such as drilling fluid system and software, drilling rig equipment and instrumentation, range of production and reservoir solutions. More information about MI Swaco can be found at their website http://www.miswaco.com.

National Oilwell Varco (NOV): They provide the CCC for the CCS DGD MPD variation (Fig. 4.4) and the expertise and support for this operation (Calderoni et al. 2006). Other equipment and services provided by NOV consists: hoisting, motion compensation and power systems; drillbits, top drives, mud pumps, rigs and structures, and waste management. More info can be found in section 4.1.1.4 of the dissertation and at NOV website http://www.nov.com.

Secure Drilling: This service company also provides CBHP MPD services. The Secure Drilling^{TM} is based on the closed loop micro-flux control method, which can identify small influxes or losses. Proprietary software calculates the adjustments required for the applied surface BP based on this information. This system can also be used for purposes like to predict the pressure profiles and to identify problems like wellbore ballooning. It has been used on more than 30 MPD projects.

The Secure Drilling^{TM} consists: a fully automated choke manifold **(Fig. D–4),** a mass flow meter, a pressure sensing equipment, a hydraulic power unit, a control until and a panel. Additional equipment required for the MPD operation consists of an RCD and depending on the need, a choke, a gas separator and additional chokes (Santos et al. 2005). More information can be obtained from their website http://www.impact-os.com/secure_drilling.htm.

Fig. D–4 Secure Drilling Choke Manifold (Nogueira et al. 2006).

SIGNA: This consultant company provides several MPD services such as MPD feasibility studies, preparation of MPD Procedures, Training, HAZOP/HAZID, and provides MPD experts who help in project execution. SIGNA has helped to drill over 80 MPD projects world over. It also provides additional services for UBD operations, casing drilling, project management, and software design.

Smith Services: This Company provides another key element for MPD operations, RCDs (Figs. 2.1, A–1, and A–2). It also provides several drilling services such as: bits, reamers, hole expanders and other BHA equipment; surface and rig equipment; tubular products and services; fishing and remedial operations equipment etc. More information about Smith Services can be found at http://www.siismithservices.com/index.asp.

Weatherford: This service company provides a range of MPD equipment and services. In the equipment section, it provides the RCDs, NRVs, Chokes, flow meters, logging while drilling tools (LWD) and pressure while drilling (PWD) etc. In MPD services, it provides the MPD feasibility studies. Weatherford also provides additional drilling services such as Drilling with Casing, direction drilling, solid Expandables, cementing services etc. More information can be found at http://www.weatherford.com/index.asp.

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