MAJOR PROJECT REPORT

SUBMISSION ON

Analysis of Drilling Mud Hydraulics involved in Hole cleaning process

SUBMITTED BY

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PREFACE

This report intends to serve as a reference and a guide to the students of petroleum engineering who wish to enhance their knowledge in drilling fluid hydraulics. This report contains all basic materials, techniques and algorithm for the understanding of the topic immensely.

Each chapter will be focused on the specific elements that revolve around the Drilling Mud Hydraulics. The chapters are compiled in such a way that it starts from the basics and in the end, the reader will be aware of the issues concerning hole cleaning, and their remedial measures using Drilling Mud Hydraulics.

Drilling Mud Hydraulics involves the study of rheological mud properties, pressure loss analysis near various components of the circulation system and their effects on equivalent circulating density of mud.

Our goal is to make the reader understand the drilling fluids usage in the hole cleaning process, how important is the DMH study related to the hole cleaning, and the properties considered and their calculations in order to arrive at the concluded parameters for the efficient hole cleaning.

This report is different from the views of the textbook by providing the practical field calculations wherein the industrial usage will be understood by the reader and gets an insight to relate the textbook aspects in real world applications.

Thanks and Regards,

Parvez Nophel, Pradeep Kumar and Tanmay Patel.

CERTIFICATE

This is to certify that this project report entitled **"Analysis of Drilling Mud Hydraulics involved in Hole cleaning process"** submitted to **University of Petroleum and Energy Studies, Dehradun** is a bonafide record work done by **Mr. Parvez Nophel, Mr. Pradeep Kumar** and **Mr. Tanmay Patel** under my supervision from **September 2014 to April 2015**.

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DECLARATION BY AUTHORS

This is to declare that this report has been written by us. No part of the report is plagiarized from other sources. All the information included from the other sources has been duly acknowledged. We aver that if any part of the report is found to be plagiarized, we shall take full responsibility for it.

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Regards,
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ABSTRACT

Drilling Mud Hydraulics has a profound impact on various functions that are necessary to be done effectively as well as efficiently. This project is on the analytical study of the hydraulics of the drilling mud, clarifying the aspects required to be analyzed.

In the recent years, the directional drilling is widely used due to the complex geology to drill the extended reach wells and horizontal wells. There are increased well bore problems while drilling. Efficient way of handling those problems without any Non Production Time (NPT), is to use the components already present in the operations and this has been done for the past century with various advancement. The problems related will be discussed in the coming chapters.

In this project, a detailed study will be done the on the drilling fluids properties which are required for the well bore cleaning. Parameters set for the drilling fluids will be calculated based on algorithm framed from the practical formulae in use. Based on the calculated results the optimized parameters will be discussed for the efficient hole cleaning.

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1 BASIC MUD

Drill Mud: Any of a number of liquid and gaseous fluids and mixtures of fluids and solids (as solid suspensions, mixtures and emulsions of liquids, gases and solids) used in operations to drill boreholes into the earth

1.1 Functions of Drilling Mud

Major functions of drilling fluids are:

1. Remove Cuttings from the Well

Cuttings removal, termed as hole cleaning is a function of cutting's shape, size and density together combined with Rate of Penetration, drillstring rotation and the viscosity, density and annular velocity of the drilling fluid.

a. Viscosity:

- Cuttings settle rapidly in low viscosity fluids (e.g. Water) and are difficult to circulate out of well. Increased viscosity of drilling fluids improves cuttings transport.
- Muds are mostly thixotropic, i.e. they gel under static condition.
- Fluids that are shear thinning and have elevated viscosities at low annular velocities are best for efficient hole cleaning

b. Velocity:

- Higher annular velocity improves cuttings removal
- With thinner drilling fluid, high velocities may cause turbulent flow, which helps clean the hole but may cause drilling or wellbore problems.
- The rate at which cuttings settle in a fluid is called the slip velocity.
- Slip velocity: Function of cutting's density, shape and size and drilling mud's viscosity, density and velocity.
- Cuttings are transported to the surface if Annular Velocity > Slip Velocity
- The net velocity at which the cuttings move to the surface is called transport velocity.
- In a vertical Well,
  Transport velocity = Annular Velocity – Slip Velocity
- The transport velocity as defined for vertical wells is not relevant for the deviated or horizontal wells, since cuttings settle down to the low side of the hole across the fluids flow path.
- Cuttings beds are formed at the bottom side of the wellbore, restricts flow, increase torque and are difficult to remove.

- Two different approaches used for the difficult hole cleaning situations in high angle and horizontal wellbores:
  a. Use of shear thinning thixotropic fluids with high low shear rate viscosity (LSRV) and laminar flow conditions
        - E.g. Biopolymer Systems
          Flocculated Bentonite Slurries- like Mixed Metal Hydroxide (MMH)
     - Such drilling fluid system provides a high viscosity with relatively flat annular velocity profile, cleaning a large portion of the wellbore cross section. Tend to suspend cuttings from settling to the low side of the hole.
  b. The use of a high flow rate and thin fluid to achieve turbulent flow
     - Turbulent flow will provide good hole cleaning and prevent cuttings from settling while circulating, but cuttings will settle quickly when circulation is stopped.
     - It's effectiveness is limited to;
     1. Large hole Size
     2. Low Pump Capacity
     3. Increased Depth
     4. Insufficient Formation Integrity
     5. Use of mud motors and DHT's that restrict flow rate
  c. **Density:**
  - Increased density fluids aid hole cleaning by increasing the buoyancy forces acting on the cuttings.
  - High density fluids can clean the whole adequately at even lower annular velocities and lower rheological properties.
  - Mud weight in excess of what is needed to balance the pressure has a negative impact on the drilling operation, therefore it should never be increased for hole cleaning.

  d. **Drillstring Rotation :**
  - High rotary speeds also aid to hole cleaning by providing circular component to annular flow path, this helical flow around the drillstring causes drill cuttings near the wall of the hole where poor hole cleaning conditions exist to be moved back into the higher transport regions of the annulus.

2. Controlling Formation Pressure:

- Typically as formation pressure increases, drilling fluid density is increased with barite to balance pressures and maintain wellbore stability. This keeps formation fluids from flowing into the wellbore and prevents pressured formation fluids from causing blowout.
- In static conditions, pressure exerted by the drilling fluid column is equal to the hydrostatic pressure and is a function of mud density and TVD.
- Hydrostatic pressure also controls stress regimes in formations other than those exerted by formation fluids.

  E.g. in case of geologically active regions, tectonic forces impose stress and make wellbore instable. Also orientation of the wellbore in high angle and horizontal wells can cause decreased wellbore stability and can be controlled with hydrostatic pressure.

  Mud Window Limitation: the mud weight is needed to control the formation pressure and the maximum mud weight that will not fracture the formation.

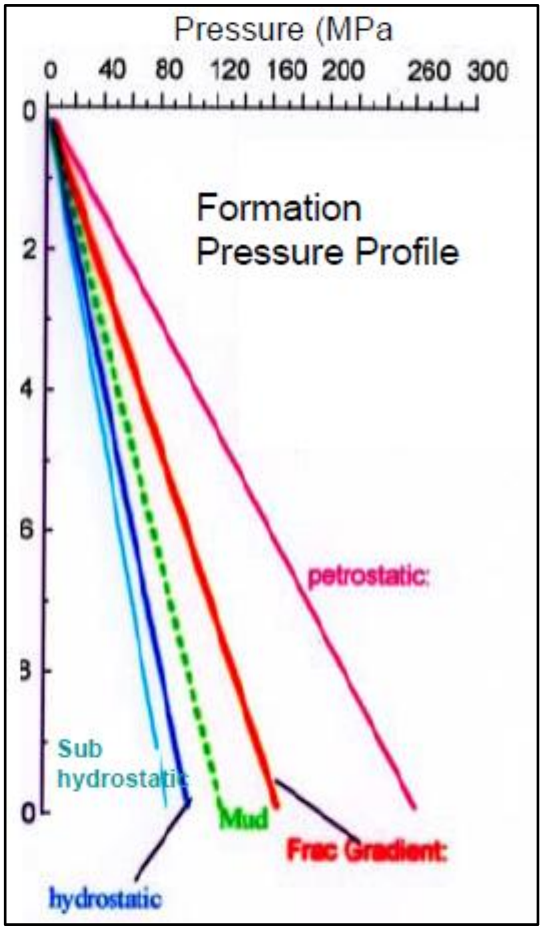


Fig1: Formation Pressure Profile

3. **Suspend & Release Cuttings**
    - Drill cuttings that settle during static conditions can cause bridges and fill, which can cause stuck pipe or lost circulation.
    - Weight material which settles is called as sag and causes a wide variation in the density of the drilling fluid.
    - Sag occurs most often under dynamic condition in high angle wells, at low annular velocities.
    - Drilling fluid properties that suspend cuttings must be balanced with those that aid in cuttings removal by solids- control equipment.
    - Cuttings suspension requires :
        - High viscosity
        - Shear thinning thixotropic properties
    - One easy way to determine whether drill solids are being removed is to compare the sand content of the mud at the flow line and at the suction pit.

4. **Seal Permeable Formations**
    - When mud column pressure is more than formation pressure mud will invade in the formation and a mud filter cake of mud solids will be deposited on the wall of the wellbore.
    - Drilling fluid systems should be designed to deposit a thin, low permeable filter cake on the formation to limit the invasion of mud filtrate.
    - Problems related to thick mud filter cakes and excessive filtration includes;
        a. Tight hole conditions
        b. Poor log quality
        c. High torque and drag
        d. Stuck pipe
        e. Lost circulation
        f. Formation damage
    - In case of high permeable formation with large pore throats, whole mud may invade in the formation depending on the size of the mud solids. For such situation bridging agents must be used to block large openings so that mud solids form a seal.
    - Bridging agent includes calcium carbonate, ground cellulose, seepage loss and fine LCM
    - Additives can be applied to improve filter cake, like bentonite, natural and synthetic polymers, organic deflocculating additives, asphalt, gilsonite etc.

5. **Maintain Wellbore Stability**
    - Complex balance of mechanical (Pressure and Stress) and chemical factors.

- Chemical composition and mud properties must combine to provide a stable well bore until casing can be run and cemented.
- The weight of the mud must be within necessary range to balance the mechanical forces acting on the wellbore, i.e. formation pressure and wellbore stress related to orientation and tectonics.
- Wellbore instability is greatest when hole maintain its original shape and size, once its enlarged or eroded it becomes weaker and more difficult to stabilize leading to;
  a. Low annular velocity
  b. Poor hole cleaning
  c. Increased solids loading
  d. Fill
  e. High treating cost
  f. Poor formation evaluation
- Hole enlargement through sand and sandstone formation is due largely to mechanical actions;
  a. Erosion caused by hydraulic forces
  b. Excessive bit nozzle velocities
- More conservative hydraulic program, particularly with regard to impact force and nozzle velocities must be carried.
- Poor consolidated sands require overbalance to limit the wellbore enlargement and a good quality filter cake containing bentonite .
- In shales, with WBM, chemical differences cause interactions between the drilling fluid and shale that leads to swelling or softening.
- Highly fractured, dry and brittle shales with high dip can be extremely unstable when drilled. (failure mainly due to mechanical instability)
- Chemical inhibitors are added to help control mud/shale interactions.
- System with high calcium, potassium and other chemical inhibitors are best for drilling in water sensitive formations.
- Salts, polymers, glycols, oils, asphaltic materials, surfactants are used in WBM to inhibit shale swelling.
- OBM or SOBM are used to drill the most water sensitive shale areas with difficult drilling conditions.
- Emulsified brine reduces water activity and creates osmotic forces that prevent adsorption of water by shales.

6. Minimize Formation Damage

(Any reduction in a producing formation’s natural porosity and permeability)

- Can happen as a result of plugging of mud or drill solids or through chemical (mud) and mechanical (drilling assembly) interaction with the formation.

- Reported as skin damage value or by amount of pressure drop that occurs while the well is producing.
- Example:
  a. When a hole is cased, cemented and perforated, perforation depth allows efficient production, even if near wellbore damage exists.
  b. When horizontal well is completed with one of the open hole techniques, a ‘reservoir drill- in’ fluid specially designed to minimize damage is required.
- Most common mechanism for formation damage are:
  a. Mud or drill solids invading formation matrix and plugging pores.
  b. Precipitation of mud filtrate and formation fluids being incompatible.
  c. Precipitation of solids from the mud filtrates with other fluids, such as brines or acids during completion or stimulation procedures.
  d. Swelling of formation clays within the reservoir, reducing permeability.
  e. Mud filtrate and formation fluid forming and emulsion restricting permeability.

7. Cool, Lubricate and Support the Bit and Drilling Assembly

- Circulation of drilling fluids cools the bit and drilling assembly, transferring the heat away from the source, distributing it throughout the well
- Drilling fluids cools the drillstring to temperature lower than bottom hole temperature.
- Drilling fluids lubricates the drillstring further reducing frictional heat.
- The lubricity of any fluid is a measure of its coefficient of friction (COF)
- OBM and SOBM lubricate better than WBM, but lubricants can also be added to WBM
- Amount of lubrication provided depends on ;
  a. Types and quantity of drill solids
  b. Weight material
  c. Chemical composition; pH, salinity and hardness
- Drilling fluids help to support portion of the drillstring or casing string weight through buoyancy.
- If a drillstring , liner or casing string is suspended in the drilling fluid, it is buoyed by a force equivalent to the weight of the mud displaced, thereby displacing hook load on the derrick.

8. Transmit Hydraulics Energy to Tools and Bit

- Hydraulic energy can be used to maximize ROP by improving cuttings removal at the bit.
- Also provides power for mud motors to rotate the bit and for LWD and MWD tools

- Hydraulics program are based on ;

  Sizing the bit nozzles property to use available mud pump horse power to generate maximized pressure drop at the bit or optimize jet impact force on the bottom of the well.
- Drill string pressure losses are higher in the fluids with high density, plastic viscosity and solids.
- Use of small ID drill pipe or tool joints, mud motors and MWD/LWD tools all reduce the amount of pressure available for use at the bit.
- Low solids, shear thinning DF or those that have drag reducing characteristics, such as polymer fluids, are most efficient at transmitting hydraulic energy to drilling bit and tools.

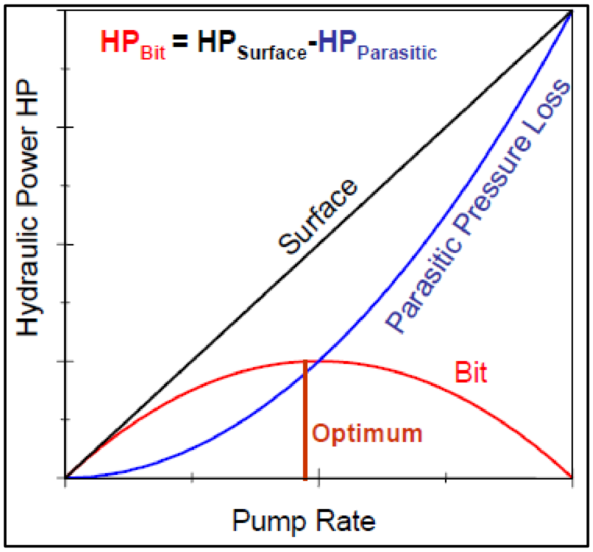


Fig2: Bit hydraulics curve

9. Ensure Adequate Formation Evaluation

- Chemical and physical properties of mud affect formation evaluation.
- During drilling the circulation of mud and cuttings is monitored for signs of O&G by technicians called mud loggers.
- They examine cuttings for mineral composition, paleontology and visual signs of HC.
- Potentially productive zones are isolated and evaluated by performing Formation Testing (FT) or Drill Stem Testing (DST) to obtain pressure and fluid samples.
- Importance of mud in Formation Evaluation:
  a. If cuttings disperse in mud there will be nothing for the mud logger to evaluate at the surface.
  b. If cuttings transport is poor it will be difficult for the mud logger to determine the depth at which cuttings originated.

   c. Certain electric logs works in conductive fluids while others in non conductive. DF properties affect the measurement of rock properties by electrical wireline tools.
   d. Excessive mud filtrate can flush O&G samples from near the wellbore region, adversely affecting logs, FT and DST samples.
   e. Mud containing high potassium interfere logging of natural formations radioactivity.
   f. For optimum wireline logging mud must not be too thick.
- Mud for drilling cores is selected based on type of evaluation to be performed;
  a. Mineral Analysis: mud type is not a concern
  b. Water Flood/Water Wettability Studies: a “bland” neutral pH WBM without surfactants or thinners is needed.
  c. Measuring Sw: Bland oil mud with minimal surfactant and no water or salt is recommended.

10. Control Corrosion

- Dissolved gases like oxygen, carbon dioxide, hydrogen sulfide can cause corrosion problems.
- Low pH aggravates corrosion
- DF should not damage rubber or elastomer goods
- Corrosion coupons are used to measure corrosion types and rates

11. Facilitate Cementing and Completion

- During casing run, the mud must remain fluid and minimize pressure surges so that fracture induced lost circulation do not occur.
- No cavings, cuttings and bridging.
- Thin, slick filter cake
- Effective mud displacement requires;
  a. hole to be near gauge
  b. low viscosity mud
  c. non- progressive gel strength

12. Minimize Impact on Environment

- Different environmental considerations ;
  a. Population density
  b. Geographic situation (Offshore/Onshore)
  c. Rainfall
  d. Proximity to disposal site
  e. UG water table

1.2 COMPOSITION OF DRILLING FLUIDS

a. Continuous Phase – Liquid/gas
b. Dissolved/ Dispersed Chemicals/Suspended Particles

1.3 CLASSIFICATION OF DRILLING FLUIDS

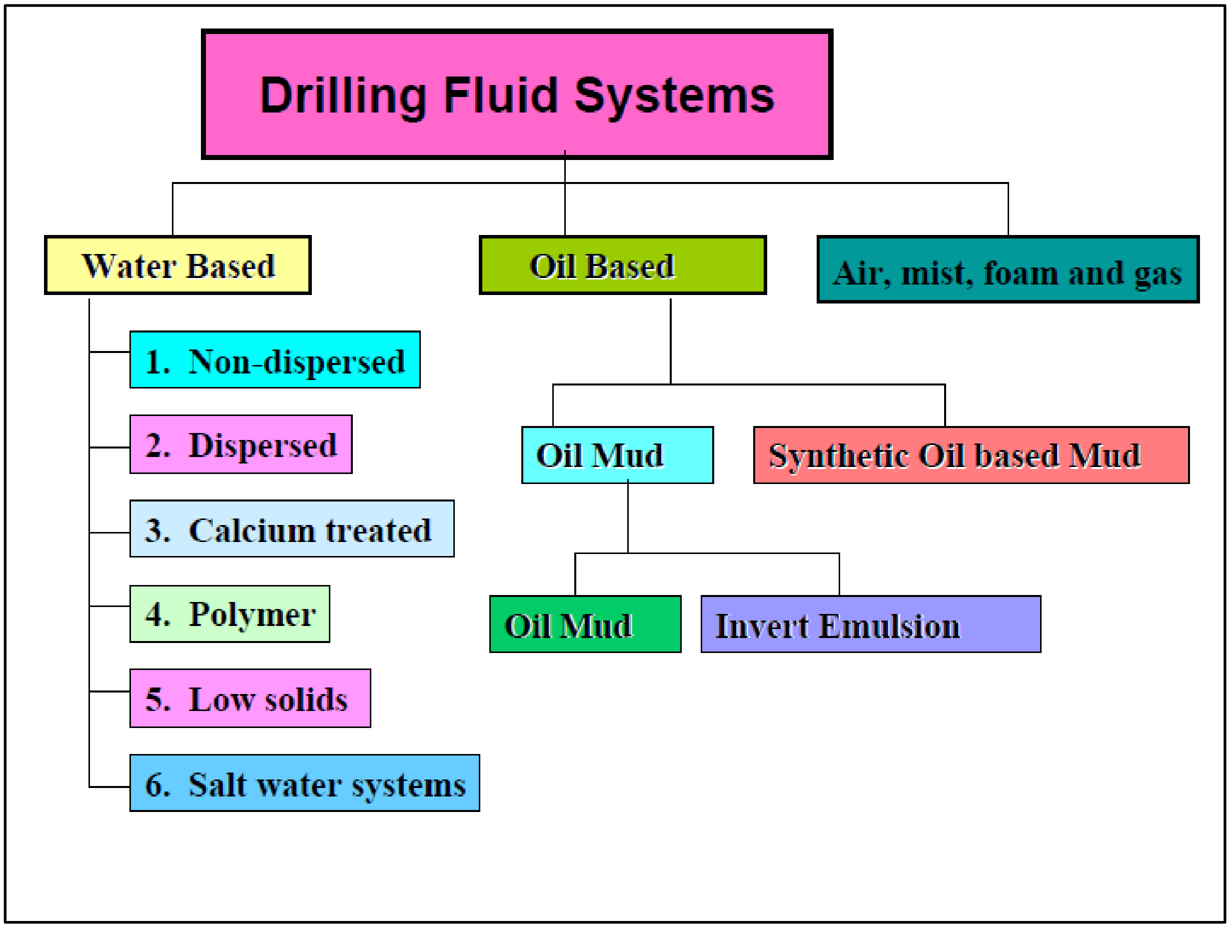


Fig3: Classification of DF System

1.3.1 Water Base Fluids (WBM)

Polymer Fluids:

- Muds incorporating long chain, high molecular weight polymers are utilized to either encapsulate drill solids to prevent dispersion and coat shales for inhibition.
- Various types of polymers are available,
  a. Acrylamide
  b. Cellulose
  c. Natural gum based products
- Frequently inhibiting salts such as KCl or NaCl used for greater stability
- Minimum amount of bentonite
- Temp. limits < 150deg. C

Low Solid Fluids:

- Amount (volume) and type of solids are controlled
- Total solids should not range higher than about 6% to 10% by volume.
- Polymer additive used as viscosifier or bentonite extender
- Improves ROP

1.3.2 Oil Base Fluids (OBM)

- Used for applications where fluid stability and inhibition are necessary such as;
  a. High temperature Wells
  b. Deep holes
  c. Slicking and hole stabilizing problems
- **OBM**: formulated with oil as continuous phase and often used as coring fluids
- No additional water or brine is added
- Special OBM additives includes;
  a. Emulsifiers and wetting agents (fatty acids and amine derivatives)
  b. High molecular wt. soaps
  c. Surfactants
  d. Amine treated OM
  e. Organic clays
- **Inver Emulsion Muds**: water in oil emulsions typically with calcium chloride brine as the emulsified phase and oil as continuous phase

  Synthetic Oil Based Muds (SOBM)
- Designed to mirror OBM performance without environmental hazards
- Primarily esters, ethers, poly alpha olefins, isomerised alpha olefins
- Environmental friendly, canbe discharged offshore , non sheening and biodegradable

1.4 AIR, MIST, FOAM, GAS SYSTEM

(Reduced DF weight category)

- **Dry Air Drilling:** injecting dry air or gas into wellbore at rates capable of achieving annular velocities that will remove cutting
- **Mist Drilling:** injecting foaming agent into the air stream which mixes with produced water and coats the cutting which prevents mud rings allowing drill solids to be removed
- **Foam:** uses surfactants and possibly clays or polymers to form a high carrying capacity foam
- **Aerated Fluids:** mud with injected air (reduces hydrostatic head) to remove drilled solids from wellbore.

1.5 MONITORING OF DRILLING FLUIDS

1. **Specific Gravity**: using mud balance
2. **Viscosity**: Plastic Viscosity (PV) – frictional resistance in fluid in motion
   Yield Point (YP)- electrical resistance in the fluid motion
   Measured by marsh funnel and Fann VG meter)

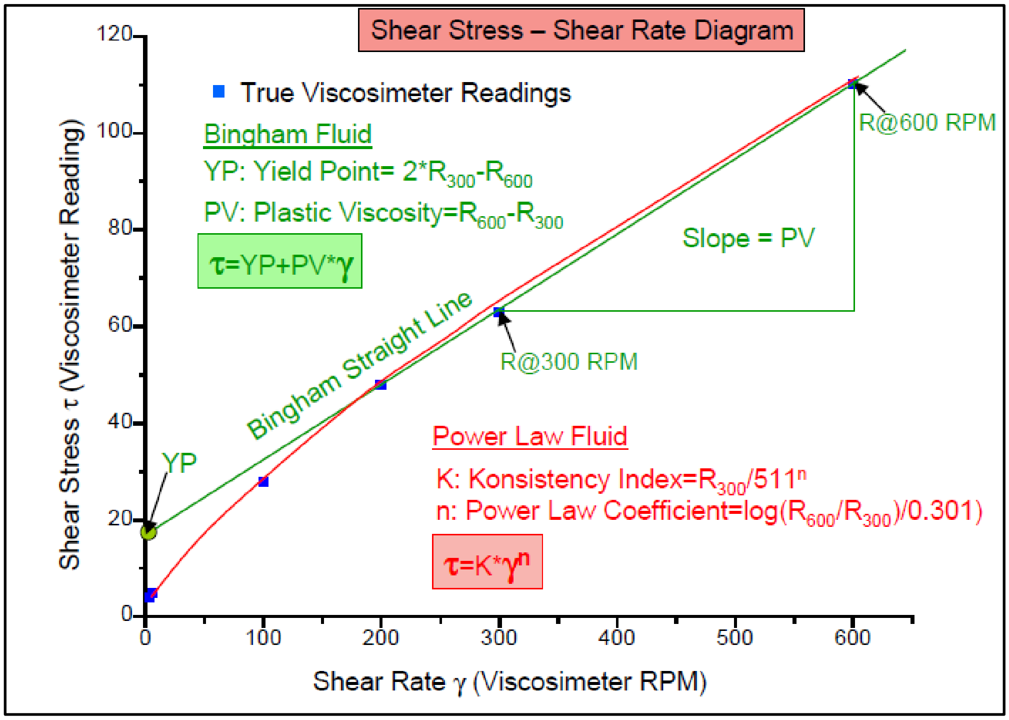


Fig4: Shear Stress Vs Shear Rate Curve

3. **Sand Content:**
    a. Abrasive and harmful to equipments
    b. High sand content contributes to undesired thick filter cake; raise unwanted sp. Gravity, lost circulation, formation invasion etc.

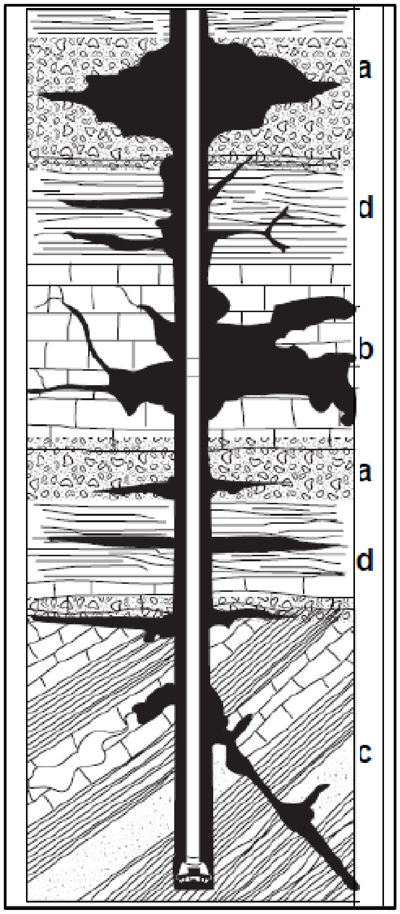


Fig5: Lost Circulation

4. **Solid Contents** : Removal equipments;
    a. Shale Shaker
    b. D-Sander
    c. D-Silter
    d. Mud Cleaners
    e. Centrifuge

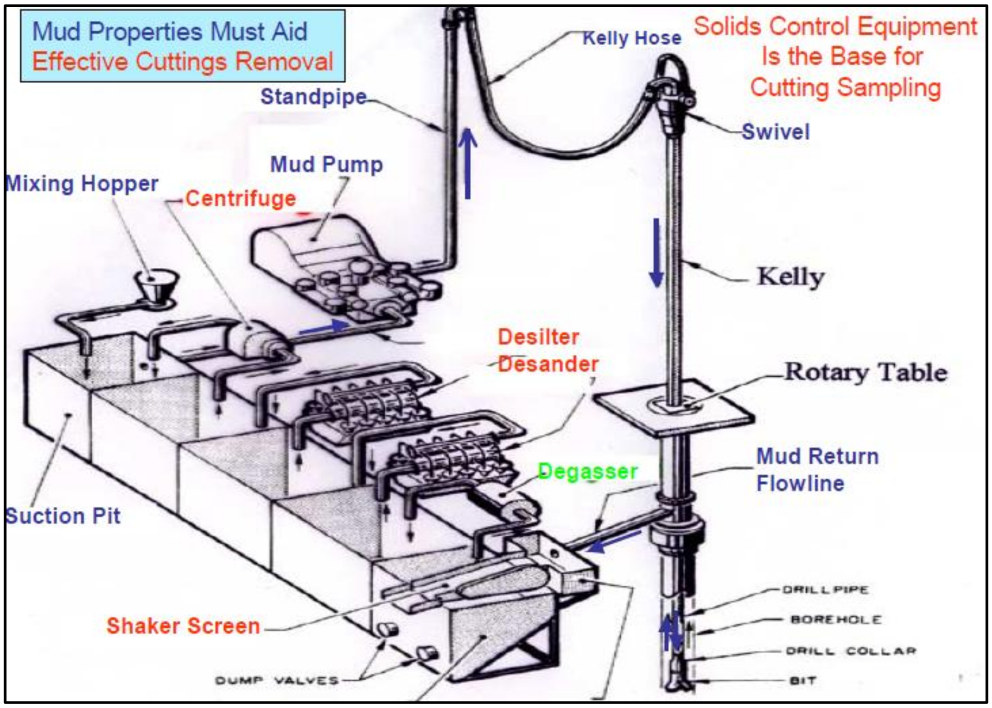


Fig6: Solid Control

5. **Salinity** (Potassium Ion/ PHPA Estimation)
    - Precipitate method – filtrate
    - Salinity- Potassium chromate and silver nitrate
    - Potassium Ion- sodium perchlorate
    - PHPA- stannin chloride

1.6 MUD CHEMICALS

1. **Water :**
   - Highest surface tension, dielectric constant , heat of fusion , heat of vaporization
   - Dissociation of salts , acids and bases in water
   - Reaction between water and clay surfaces and the effect of electrolytes dissolved in water on the clay-water interactions are responsible for drilling mud properties

2. **Aluminium Stearate:**
   - White powder
   - Used in de-foamer i.e. reduces foaming action
   - Insoluble in water
   - Partially soluble in diesel and hence treated by making solution in diesel (2.5%)

3. **Bactericide:**
   - Controls bio degradation of natural organic additives in polymer mud

4. **Bentonite:**
   - Minimum 85% montmorillonite
   - Sp. Gravity 2.45-2.55
   - Sodium Bentonite or Calcium Bentonite depending on dominant exchangeable cation
   - High yield and low yield bentonite
   - Functions of bentonite in DF :
     a. Reduce water seepage or filtration in to permeable formation
     b. Increase hole cleaning capacity
     c. Forms thin filter cake of low permeability
     d. Promotes hole stability
     e. Avoid loss of circulation

5. **Barite:**
    - Grey powder
    - Sp. Gravity 4.2-4.25
    - Virtually insoluble in water and does not react with other mud component
    - $CaSO_4$ (gypsum) present as impurity causes contamination in fresh water muds
    - Used to increase sp. Gravity of mud to control formation pressure
    - Other weighing material are hematite and galena

6. **Caustic Soda (NaOH)**
    - Increase pH of mud
    - Sp. Gravity 2.13
    - Added to mud slowly to avoid sudden increase in pH that results in decomposition of polymers and unwanted sudden rise of viscosity in bentonite mud.

7. **Caustic Potash (KOH)**
    - Increase pH of Potassium treated mud and stabilizes lignite
    - Sp. Gravity 2.04

8. **Sodium Carboxymethyl Cellulose (CMC)**
    - Most widely used organic polymers are semi synthetic produced by chemical modification of cellulose
    - Water dispersible, colorless, odorless, non-toxic
    - CMC- LVG
      CMC-HVG
    - Isotropic polymer adsorbed on clays
    - Increases viscosity and reduce filtration loss
    - Thermal degradation starts as temp. approaches 150deg. C

9. **Common Sall**
    - Used to prepare brine during activation of well
    - Used for inhibition
    - Sp. Gravity- 1.20

10. Corrosion Inhibitor

- KCl mud and brines

11. Calcium Carbonate (MCC)

- Fine powdered, practically insoluble in water
- Sp. Gravity 2.6-2.8
- Used as bridging agent and weighing material in NDDF

12. Drilling Detergent

- To clean bit / stabilizers/ tool joints during drilling of clay and increase ROP

13. E P LUBE

- Used as lubricant at deeper depth
- Vegetable oil based lubricant
- Makes a very high slim strength between formation and string surface thus reduces friction

14. Lignite

- Mild dispersant
- Acts as thinner
- Increased temperature stability (upto 260deg C)
- Deflocculant: reduces attraction between clay and particles

15. Limestone

- Weighing material
- Sp. Gravity 2.65

16. Linseed Oil

- Vegetable oil used as lubricant
- Creates film between formation and string

17. Mica

- Loss Circulation material
- Form of flakes which plugs the large gaps in the formation in case of mud loss

18. Poly Anionic Cellulose (PAC)

- Limitation of CMC in salt solution led to development of PAC polymer
- Sp. Gravity 1.5-1.6
- Thickens salt solution, environmentally acceptable polymer
- Shale inhibitor
- Two forms are available;
  a. PAC (LVG) – viscosifier anf filtration control
  b. PAC(RG)- viscosifier, filtration control, has long chain than PAC(LVG)

19. PHPA

- Shale stabilization and inhibition by encapsulation of cutting in mud
- Long chain polymer

20. POLYOL (Poly glycol)

- Shale stabilization and lubrication
- Clouding at temperature higher than 78deg C
- Plugs formation pores and prevent invasion and imparts BHS

21. Potassium Chloride:

- Shale stabilization and brine preparation
- Replaces Na ion in bentonite with Potassium ion thus preventing swelling of clays

22. Resinated Lignite

- Dispersant and used for filtration control and temperature stabilization of rheology
- Stable upto 160deg C

23. **Sulphonated Asphalt**
    - Shale stabilizers
    - Used in WBM for hole stabilization
    - Adsorbed on shale to plug microfractures

24. **Soda Ash**
    - Removal of calcium from muds and make up water
    - Sp. Gravity 2.53
    - Increase pH in mud

25. **Spotting Fluid** : for freeing stuck pipe by reducing IFT between filter cake and string eventually cracking the cake

2 RHEOLOGY

RHEOLOGY:

- It is the study of how matter deforms and flows
- It is possible to determine how a fluid will flow under conditions, including ;
  a. Temperature
  b. Pressure
  c. Shear Rate
- Viscosity: Substance resistance to flow

  Viscosity= Shear Stress/ Shear Rate
  - Dependent on the average velocity of the fluid in the geometries it is flowing. Shear rate is more in small geometries (inside drill string) and lower in larger geometries (casing and riser annuli)
  - Higher shear rate causes a greater resistive force of shear stress
  - Relation between shear stress and shear rate describes how a fluid flows
  - **Shear Rate = V2-V1/d**

    Where; V2= Velocity of layer B
    V1= Velocity of layer A
    D= distance between the layers

CONVERSION FACTOR:

Shear Rate = RPM * 1.703

- **Shear Stress**: Force required to sustain shear rate

CONVERSION FACTOR:

Shear Stress = VG Reading * 1.0678

It is stated in types;

1. **Funnel Viscosity :**
   a. Measured using a Marsh Funnel
   b. Used to detect the relative changes in the fluid's properties
2. **Apparent Viscosity**
   a. Mud viscometer reading at 300 RPM or half of meter reading at 600 RPM
   b. AV = 300*ϴ/ω
3. **Effective Viscosity**

   a. It is the fluid’s viscosity under specific conditions that includes shear rate, pressure and temperature.

4. **Plastic Viscosity**
   a. PV= ϴ600-ϴ300
   b. Part of resistance to flow caused by mechanical friction
   c. Affected by ; solids concentration, size and shape of solids, viscosity of fluid phase, presence of long chain polymers
   d. Changes in PV can cause change in the pump pressure
   e. Lower PV should be kept because;
      1. Greater energy at the bit
      2. Greater flow in the annulus for hole cleaning
      3. Less wear and tear on equipment
5. **Yield Point**
   a. YP= ϴ300- PV
   b. Measurement of electro-chemical or attractive forces, result of opposite charges in the fluids
   c. Dependent upon;
      1. Surface properties of the fluid solids
      2. Volume concentration of the solids
      3. Electrical environment of these solids (ions)
6. **Low Shear Rate Viscosity (LSRV)**
   a. Critical for solid suspension and hole cleaning in horizontal and high angled wells.
   b. Measured using a Brookfield viscometer at a shear rate of 0.3 RPM.
7. **Gel Strength**
   a. Gel strength readings taken at 10-sec and 10-min intervals, and in critical situations at 30-min intervals, on the Fann VG meter provide a measure of the degree of thixotropy present in the fluid.
   b. The strength of the gel formed is a function of the amount and type of solids in suspension, time, temperature and chemical treatment.
   c. Excessive gel strengths can cause complications, such as the following:

      1. Entrapment of air or gas in the fluid.
      2. Excessive pressures when breaking circulation after a trip.
      3. Reduction in the efficiency of solids-removal equipment.
      4. Excessive swabbing while tripping out of the hole.
      5. Excessive pressure surges while tripping in the hole.
      6. Inability to get logging tools to the bottom.

d. The initial gel strength measures the static attractive forces, while the yield point measures the dynamic attractive forces.

2.1 Importance of Rheology

Rheology has a significant influence in controlling the following cardinal factors:

1. **Hole Cleaning** : Controlled by rheological parameters like;
    - Density of mud
    - Viscosity of mud

2. **Suspension of Solids** : Controlled by parameters like;
    - Slip Velocity
    - Annular Velocity (AV increases with decrease in hole size)
    - Viscosity (Buoyancy of mud is affected)

3. **Wellbore Stability**: Achieved by following parameters;
    - Hydrostatic head
    - Hole Cleaning
    - Proper inhibition to shale
    - Rock Matrix Analysis
    - Shale Analysis (XRD,XRF)
    - Shale Reactivity (Capillary Suction Timer (CST))
      Less CST, less will be the reactivity and vice-versa
    - Fluid Filtration: Lesser the fluid loss, better the quality of filter cake which increases well bore stability

4. **Equivalent Circulation Density (ECD)**
    - Equivalent circulating density is the effective density of the circulating fluid in the wellbore resulting from the sum of the hydrostatic pressure imposed by the static fluid column and the friction pressure.
    - It is calculated as;
      ECD= MW+ Pa/ (0.052*D) in lb/gal
    - ECD should not go beyond LOT value
    - In offshore operations maintaining ECD is very crucial because a slight increase in ECD value can cause loss of ~1000gal of mud.

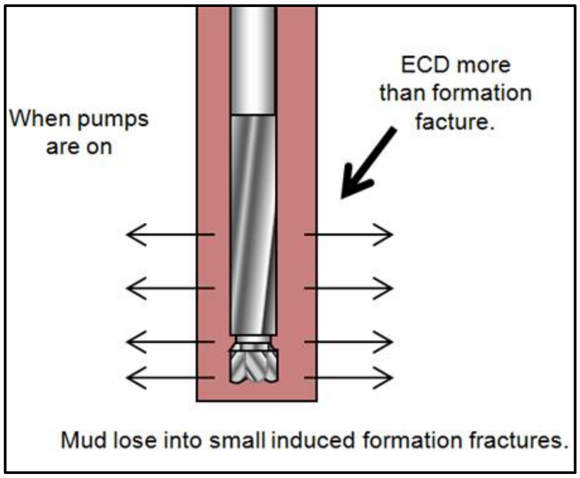


Fig7: Impact of increased ECD

5. **Swab and Surge Pressure** : Rheological parameters affecting Swabbing and Surging are;
    - Gel Value : If gel becomes progressive then swabbing and surging occurs and leads to increase in ECD
    - Increase in temperature causes increase in gels values.

2.2 FLUID FLOW MODELS:

- **Bingham Plastic Model**
- **Power Law Model**
- **Herschel- Buckley Model (Modified Power Law)**
- **Casson Robertson –Shift Model**

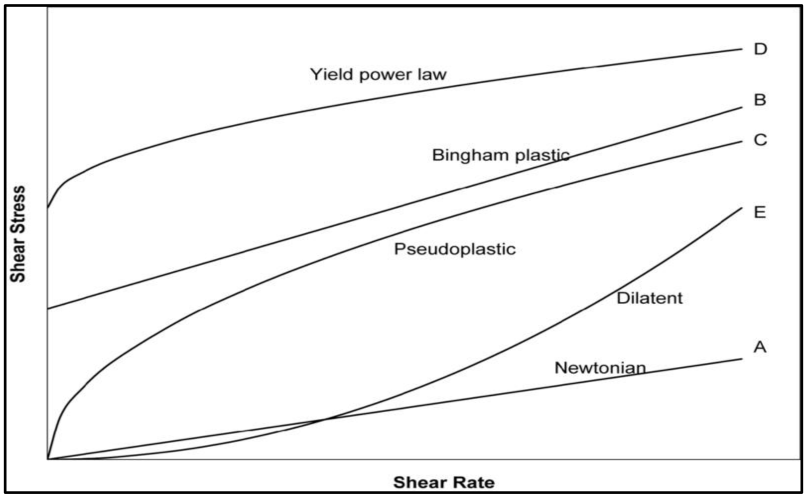


Fig8: Fluid Flow Model

2.2.1 BINGHAM PLASTIC MODEL

These fluids require a finite shear stress, τ_y; below that, they will not flow. Above this finite shear stress, referred to as yield point, the shear rate is linear with shear stress, just like a Newtonian fluid. Bingham fluids behave like a solid until the applied pressure is high enough to break the sheer stress.

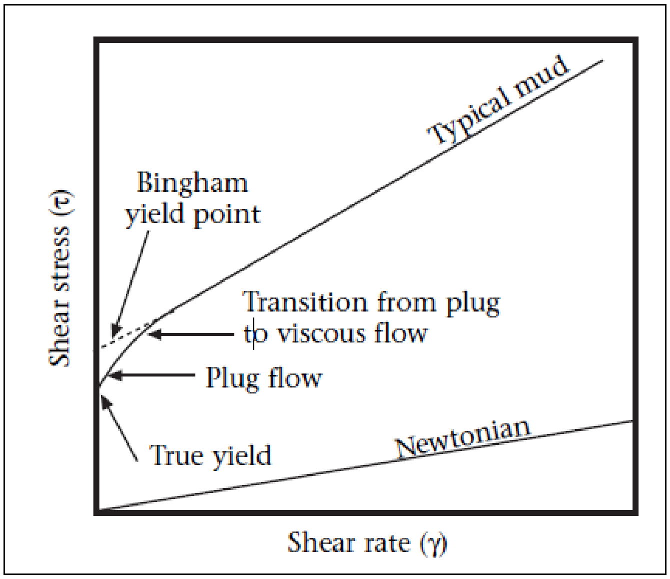


Fig 9: Illustration of Bingham Plastic Model

Mathematical Expression:

- **F= YP+PV(R/300)**
  Where;
  F= dial radius at speed R
- **PV = $R_{600} - R_{300}$**
- Mud additives count to Plastic Viscosity especially wetting agents.
- Lesser the size, more will be surface area, more will be the friction
- Increase in PV, leads to increase in Mud weight, causing differential sticking
- Sand control equipments , like centrifuge cuts around half the value of PV
- Factors affecting Yield Point (YP);
  a. Type of formation (carbonates, formation salts)
  b. Reactions of clay (clay carry residual charges that affects YP)
  c. Overtreatment of mud chemicals
  d. Contaminants like acid gases such as H_2S, CO_2 etc.
- Yield Point can be treated by addition of chemicals; more clay leads to more YP
  a. Dilution Method
  b. Addition of dispersants or thinners
- YP increases, Gel value increases

2.2.2 POWER LAW MODEL

These fluids exhibit a linear relationship between shear stress and shear rate when plotted on a log-log paper.

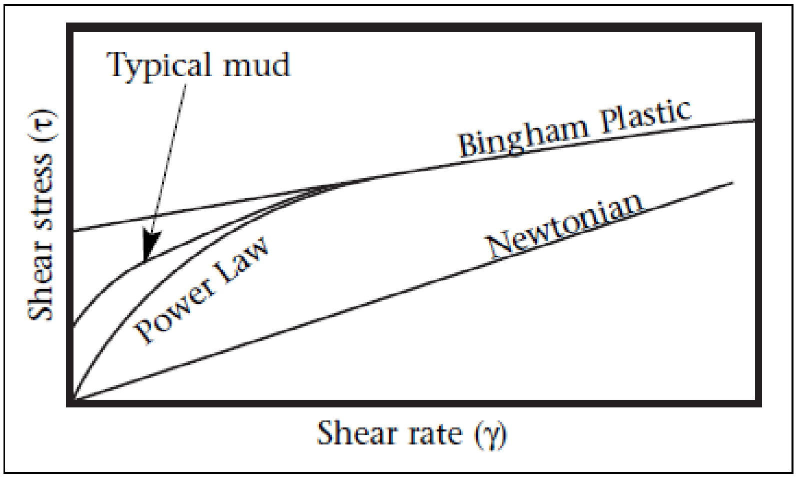


Fig 10: Illustration of Power Law Model

Mathematical Expression:

Shear Rate = K (Shear Stress) $^{\mathbf{n}}$

Where; K= Consistency Factor

n= Fluid Flow Index

Depending on the value of "n," three different types of flow profiles and fluid behavior exist: 1. n < 1: The fluid is shear-thinning, non-Newtonian.

2. n = 1: The fluid is Newtonian.

3. n > 1: The fluid is dilatants, shear thickening (drilling fluids are not in this category).

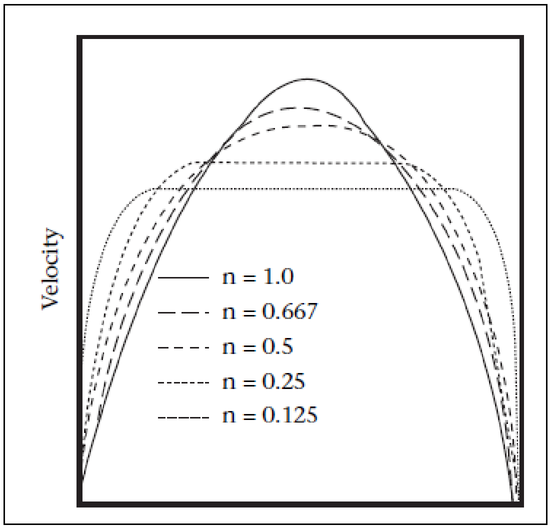


Fig 11: Velocity Profile depending on "n" value

A fluid's hole-cleaning and suspension effectiveness can be improved by increasing the "K" value**.**

$\mathbf{V_{G\ (Reading)} * 1.0678 = K\ (V_{G\ (RPM)} * 1.703)^{n}}$
n= shear thinning ability of mud (thixotropic property of fluid)

- n_a (annulus) / n_p (pipe)
- $n_p = 3.321 \log Ø_{600} / \log Ø_{300}$
- $n_a = 0.657 * \log Ø_{100} / Ø_6$
- more the value of n, more will be shear thinning, more will be k
- $K_p = 5.11 * R_{600} / 1022^{np}$
- $K_a = 5.11 * R_3 / 511^{na}$
- $n<1$ (always)

2.2.3 MODIFIED POWER LAW

Also known as Herschel-Buckley fluids, these fluids require a finite shear stress, τ_y, below which they will not flow. Above this finite shear stress, referred to as yield point, the shear rate is related to the shear stress through a power-law type relationship.

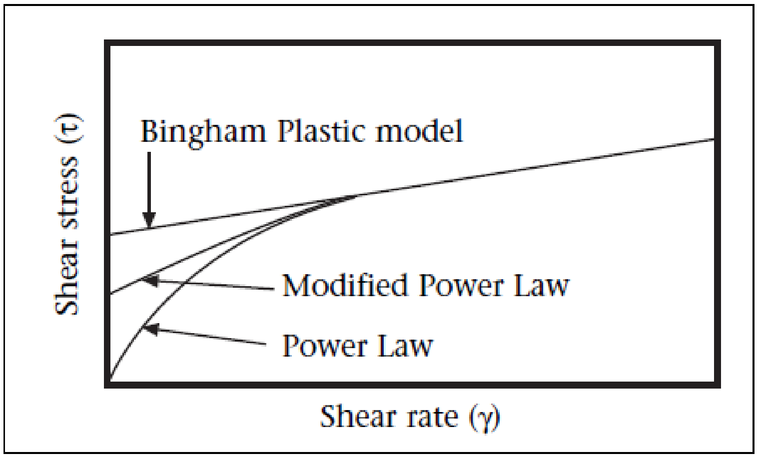


Fig12 : Illustration of Modified Power law

Mathematical Expression:

Shear Rate = Yield Stress + K (Shear Stress) ^{n}
Where Yield Stress is the R3 Reading

- The yield stress has been accepted to be the value for the 3-RPM reading or initial gel on the VG meter.
- Converting the equations to accept VG meter data gives the equations for “n” and “K.”

$$n= \log (\Theta_2- \Theta_0) - \log (\Theta_1- \Theta_0)/ \log \omega_2- \log \omega_1$$

$$k= \Theta_1- \Theta_0/\omega_1^{n}$$

Where:
n = Power Law index or exponent
K = Power Law consistency index or fluid index (dyne sec–n/cm2)
Q1 = Mud viscometer reading at lower shear rate
Q2 = Mud viscometer reading at higher shear rate
Q0 = Zero gel or 3-RPM reading
w1 = Mud viscometer (RPM) at lower shear rate
w2 = Mud viscometer

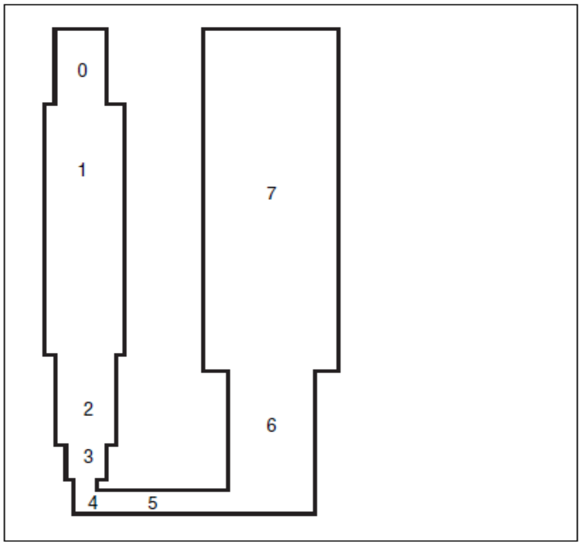
3 HYDRAULICS

HYDRAULICS

- In accord with drilling fluids, hydraulics refers to the operations where the drilling fluid is used to transfer pressure from the surface to the bit where the pressure drop across the bit is used to enhance the Rate of Penetration.
- Part of the fluid's energy is expended in sweeping the area ahead of the bit free of generated cuttings and preventing the stacking of cutting on the bit face and body.
- For the fluid to perform some of its other functions (e.g. Carrying cuttings to the surface), the fluid pump must be capable of overcoming the accumulated pressure losses associated with the surface equipment, the drill string, the bit and the annulus.
- Also, the pump must be capable of providing flow rate to remove the cuttings out of the well bore.
- These pressure losses also affect the total pressure exerted by the fluid column on the;

1. Wellbore
2. potentially raising lost circulation
3. kick control
4. well bore stability

- The rheology of the drilling fluid directly affect the circulating system pressure losses, the more accurately the rheological models used to describe the drilling fluid represent the fluid, the more precise the hydraulics analysis can be.



0	**Standpipe/top drive/ Kelly**
1	**Inside Drill Pipe**
2	**Inside Drill Collars**
3	**Inside Downhole Tools**
4	**Bit Nozzle**
5	**Annulus open hole/Drillstring**
6	**Annulus Liner/ Drillstring**
7	**Annulus Casing or Riser/ Drillstring**

Fig13: Simplified Circulating System

3.1 HYDRAULICS ANALYSIS

The following parameters are evaluated in the analysis:

Parameters:

1. Determining annular pressure losses to establish ***equivalent circulating density*** **(ECD)**. ECD is important for prevention of loss of circulation and preserving casing shoe integrity.
2. Assessing the effects of fluid changes on the system's hydraulic performance.
3. Optimizing hydraulics for enhanced drilling performance (e.g., increased ROP).
4. Ensuring good hole cleaning (cuttings transport and concentration in the annulus).
5. Preventing borehole erosion from turbulent flow in the annulus.
6. Preventing borehole instability and pressure control problems from pulling pipe too fast (swabbing).
7. Preventing loss of circulation from running pipe too fast (surging).

3.1.1 ANNULAR PRESSURE LOSS AND ECD CALCULATION

1. Draw hole geometry showing all casing IDs, hole size, and drill string IDs and ODs.

2. Calculate the fluid velocity for the first geometry interval, where;
Va = annular fluid velocity for the interval (ft/sec),
Q = volumetric flow (pump) rate (gal/min),
D2 = hole diameter (in.),
D1 = outside diameter of the drill pipe (in.).

3. A. Calculate the n value (flow behaviour index) for the interval, where;
na = annular flow behaviour index (dimensionless),
Ø300 = V-G meter, 300-rpm dial reading,
Ø 3 = V-G meter, 3-rpm dial reading

B. Calculate the K value (consistency factor) for the annular interval, where;
Ka = annular consistency factor (poise),
Ø 600 = V-G meter, 600-rpm dial reading.

4. Calculate the effective viscosity me in the annulus, where;
μe_a = annular effective viscosity (cp)

5. Calculate the Reynolds (Re) for the annular interval, where;
Re_a = Annular Reynolds number (dimensionless),
ρ = fluid density (lbs/gal)

6. A. Calculate the Reynolds number for the change from laminar to transitional flow for the interval, where;
$\mathbf{Re_L}$ = the laminar to transitional flow Reynolds number (dimensionless)

6. B. Calculate the Reynolds number for the change from transitional to turbulent flow for the interval, where;
$\mathbf{Re_T}$ = the transitional to turbulent flow Reynolds number (dimensionless)

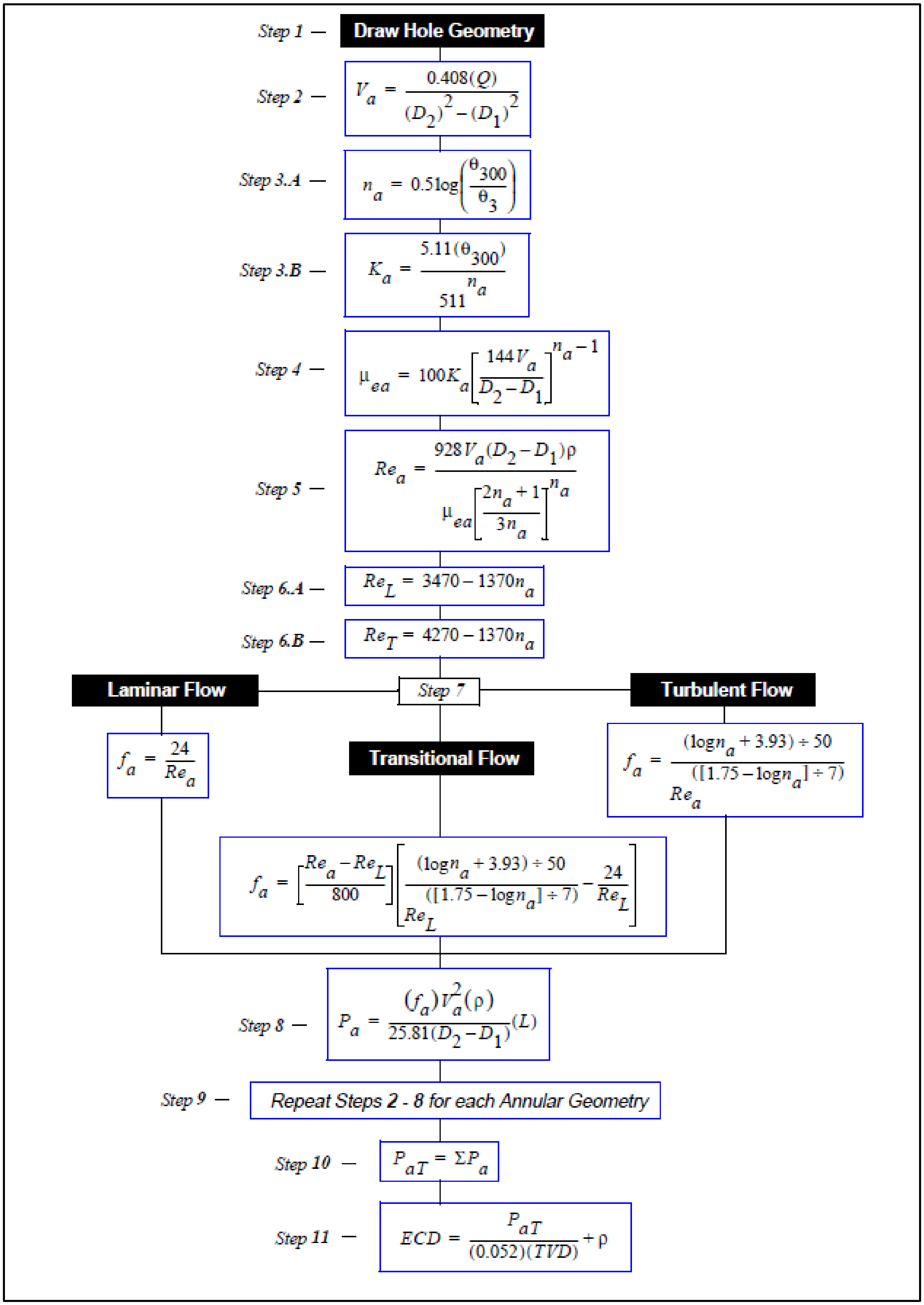
7. If $\mathbf{Re_a > Re}$, use the laminar flow equation to calculate the friction factor

- If $\mathbf{Re_a > Re_T}$, use the turbulent flow equation to calculate the friction factor
- If $\mathbf{Re_L < Re_a < Re_T}$, use the transitional flow equation to calculate the friction factor, where
  $\mathbf{f_a}$ = the annular Fanning Friction Factor (dimensionless)

8. Calculate the pressure drop (P) for the interval, where;
Pa = the interval pressure drop (psi),
L = the length of the interval (feet)
9. Steps 2 through 8 must be repeated for different annular geometry.

10. Calculate the total annular pressure loss (**PaT**) in psi by summing the individual pressure drops calculated for each interval.

11. Convert the total annular pressure loss to equivalent circulating density (ECD), where;
ECD = equivalent circulating density (lbs/gal)



Step 1 — **Draw Hole Geometry**

Step 2 — $$V_a = \frac{0.408(Q)}{(D_2)^2 - (D_1)^2}$$

Step 3.A — $$n_a = 0.5\log\left(\frac{\theta_{300}}{\theta_3}\right)$$

Step 3.B — $$K_a = \frac{5.11(\theta_{300})}{511^{n_a}}$$

Step 4 — $$\mu_{ea} = 100K_a\left[\frac{144V_a}{D_2 - D_1}\right]^{n_a - 1}$$

Step 5 — $$Re_a = \frac{928V_a(D_2 - D_1)\rho}{\mu_{ea}\left[\frac{2n_a + 1}{3n_a}\right]^{n_a}}$$

Step 6.A — $$Re_L = 3470 - 1370n_a$$

Step 6.B — $$Re_T = 4270 - 1370n_a$$

Step 7

Laminar Flow

$$f_a = \frac{24}{Re_a}$$

Turbulent Flow

$$f_a = \frac{(\log n_a + 3.93) \div 50}{Re_a^{([1.75 - \log n_a] \div 7)}}$$

Transitional Flow

$$f_a = \left[\frac{Re_a - Re_L}{800}\right]\left[\frac{(\log n_a + 3.93) \div 50}{Re_L^{([1.75 - \log n_a] \div 7)}} - \frac{24}{Re_L}\right]$$

Step 8 — $$P_a = \frac{(f_a)V_a^2(\rho)}{25.81(D_2 - D_1)}(L)$$

Step 9 — *Repeat Steps 2 - 8 for each Annular Geometry*

Step 10 — $$P_{aT} = \Sigma P_a$$

Step 11 — $$ECD = \frac{P_{aT}}{(0.052)(TVD)} + \rho$$

3.1.2 DRILLSTRING PRESSURE DROP

1. Calculate the fluid velocity in the drill pipe, where;
Vp = pipe fluid velocity (ft/sec),
Q = volumetric flow (pump) rate (gal/min),
D = pipe inside diameter (I.D.) (in.)

2. A. Calculate the n value (flow behavior index) for the interval, where
np = pipe flow behavior index (dimensionless),
Ø600 = V-G meter, 600-rpm dial reading,
Ø300 = V-G meter, 300-rpm dial reading

B. Calculate the K value (consistency factor) for the annular interval, where
Kp = pipe consistency factor (poise),
Ø600 = V-G meter, 600-rpm dial reading.

3. Calculate the effective viscosity (me) in the pipe, where
μe_p = pipe effective viscosity (cp).

4. Calculate the Reynolds (Re) for the pipe interval, where
Re_p = pipe Reynolds number (dimensionless),
ρ = fluid density, lbs/gal.

5. A. Calculate the Reynolds number for the change from laminar to transitional flow for the interval, where;
Re_L = the laminar to transitional flow Reynolds number (dimensionless)

B. Calculate the Reynolds number for the change from transitional to turbulent flow for the interval, where;
Re_T = the laminar to transitional flow Reynolds number (dimensionless)

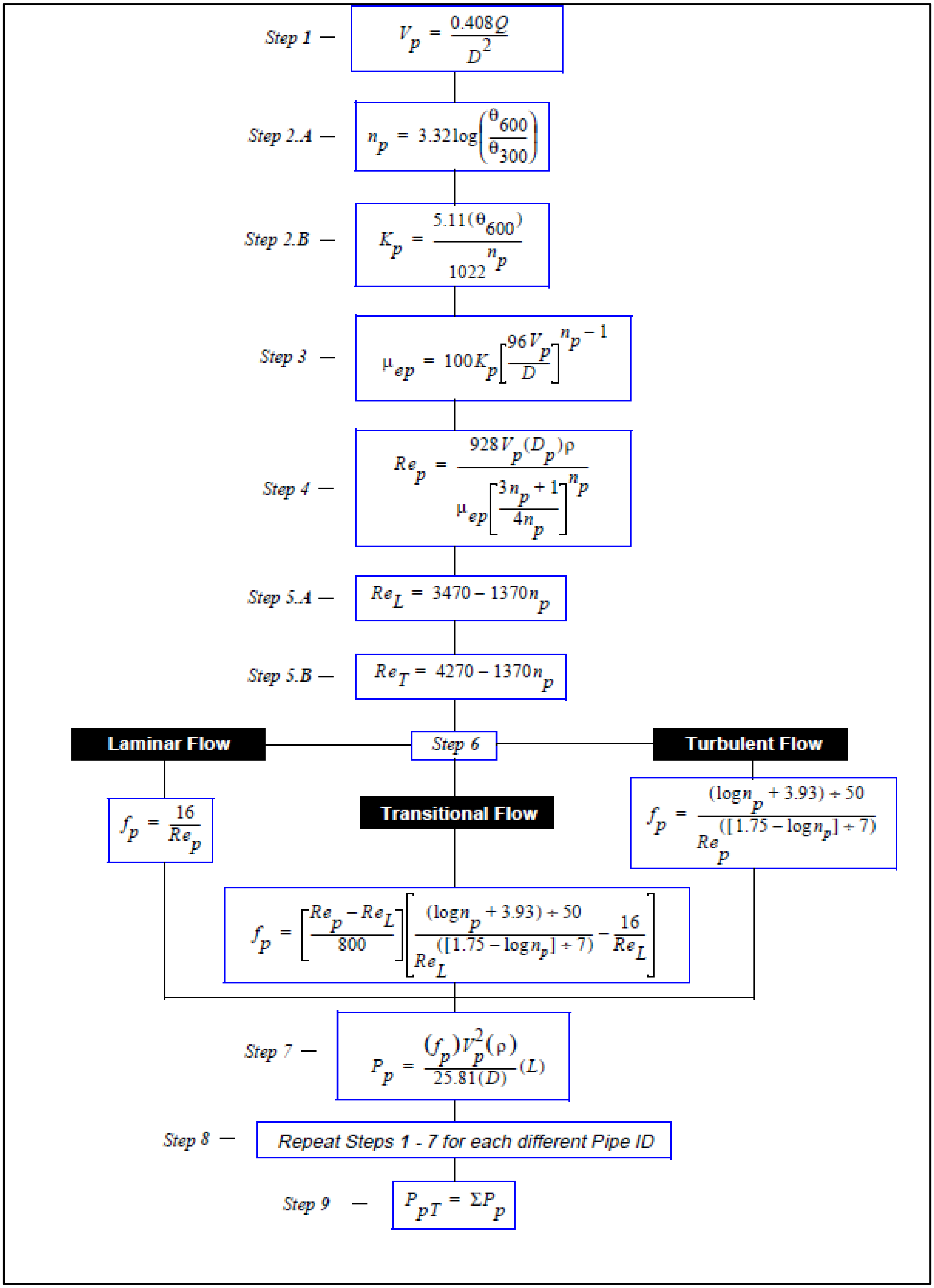
6. If $Re_P > Re_L$, use the laminar flow equation to calculate the friction factor;
- If $Re_P > Re_T$, use the turbulent flow equation to calculate the friction factor
- If $Re_L < Re_P < Re_T$, use the transitional flow equation to calculate the friction factor, where

fp = the pipe Fanning Friction Factor (dimensionless)

7. Calculate the pressure drop (P) for the interval, where;
Pp = the pipe pressure drop (psi),
L = the length of the pipe section (feet)

8. Steps 2 through 8 must be repeated for each different pipe internal diameter (I.D.)

9. Calculate the total pipe pressure loss (PpT) in psi by summing the individual pressure drops calculated for each pipe I.D



Step 1 — $$V_p = \frac{0.408Q}{D^2}$$

Step 2.A — $$n_p = 3.32\log\left(\frac{\theta_{600}}{\theta_{300}}\right)$$

Step 2.B — $$K_p = \frac{5.11(\theta_{600})}{1022^{n_p}}$$

Step 3 — $$\mu_{ep} = 100K_p\left[\frac{96V_p}{D}\right]^{n_p-1}$$

Step 4 — $$Re_p = \frac{928V_p(D_p)\rho}{\mu_{ep}\left[\frac{3n_p+1}{4n_p}\right]^{n_p}}$$

Step 5.A — $$Re_L = 3470 - 1370n_p$$

Step 5.B — $$Re_T = 4270 - 1370n_p$$

Step 6

Laminar Flow

$$f_p = \frac{16}{Re_p}$$

Transitional Flow

$$f_p = \left[\frac{Re_p - Re_L}{800}\right]\left[\frac{(\log n_p + 3.93) \div 50}{Re_L^{([1.75 - \log n_p] \div 7)}} - \frac{16}{Re_L}\right]$$

Turbulent Flow

$$f_p = \frac{(\log n_p + 3.93) \div 50}{Re_p^{([1.75 - \log n_p] \div 7)}}$$

Step 7 — $$P_p = \frac{(f_p)V_p^2(\rho)}{25.81(D)}(L)$$

Step 8 — *Repeat Steps 1 - 7 for each different Pipe ID*

Step 9 — $$P_{pT} = \Sigma P_p$$

3.1.3 SWAB AND SURGE PRESSURES

- When the drillstring is run into the hole, the friction of the drilling fluid moving against the pipe causes the bottom of the hole to experience pressure increase. This increase in pressure is termed as Surge Pressure.

- Conversely, when the pipe is tripped out of the hole, there will be a decrease in the total pressure that the borehole experiences. The decrease is termed as the Swab Pressure.

- Running the pipe into hole too fast may lead to fracturing the wellbore and loss of circulation, while tripping out too rapidly may lead to the influx of the formation fluids (kicks), excessive fill on trips, and other wellbore stability problems.

Calculation:

1. Determine the average speed of pipe movement (Vpm). Either of two methods can be used;

Method 1
• **Vpm** = average pipe movement speed, ft/min
• **Ls** = stand length, feet
• **t** = time from slips to slips, seconds

Method 2
• **Lj** = joint length, feet
• **t** = joint time through rotary table, seconds

2. Calculate the equivalent fluid velocity in the annulus (Vm) for the first geometry interval, where;

Vm = equivalent fluid velocity for the interval (ft/min),
D2 = hole diameter (in.),
D1 = outside diameter of the drill pipe (in.)

3. A. If the drilling fluid’s rheological properties have changed since the last annular hydraulics analysis, calculate a new annular n value (flow behaviour index) for the interval, where;

na = annular flow behavior index (dimensionless),
Ø300 = V-G meter, 300-rpm dial reading,
Ø3 = V-G meter, 3-rpm dial reading

.

B. If the drilling fluid’s rheological properties have changed since the last annular hydraulics analysis, calculate a new annular K value (consistency factor) for the annular interval, where;

Ka = annular consistency factor (poise),
Ø600 = V-G meter, 600-rpm dial reading

Note: *If the fluid's properties have not changed, use the n and K values previously calculated. Go to Step 4*

4. Calculate the new effective viscosity (μ_e) in the annulus, using Vm, where;

μe_a = annular effective viscosity (cp).

5. Calculate the Reynolds (Re) for the annular interval using the new μe_a and Vm , where;

Re_a = Annular Reynolds number (dimensionless),
ρ= fluid density (lbs/gal)

6. A. If the fluid's rheological properties have changed since the last hydraulics analysis, calculate the Reynolds number for the change from laminar to transitional flow for the interval, where;

Re_L = the laminar to transitional flow Reynolds number (dimensionless)

B. Calculate the Reynolds number for the change from transitional to turbulent flow for the interval, where;

Re_T = the transitional to turbulent flow Reynolds number (dimensionless)

If the fluid's properties have not changed, use the previously calculated values and proceed with Step 7

7. If $Re_a > Re_L$, use the laminar flow equation to calculate the friction factor.
• **If $Re_a > Re_L$**, use the turbulent flow equation to calculate the friction factor.
• **If $Re_L < Re_a < Re_T$**, use the transitional flow equation to calculate the friction factor, where fa = the annular Fanning Friction Factor (dimensionless)

8. Calculate the pressure drop (P) for the interval, where;

Pa = the interval pressure drop (psi),
L = the length of the interval (feet)

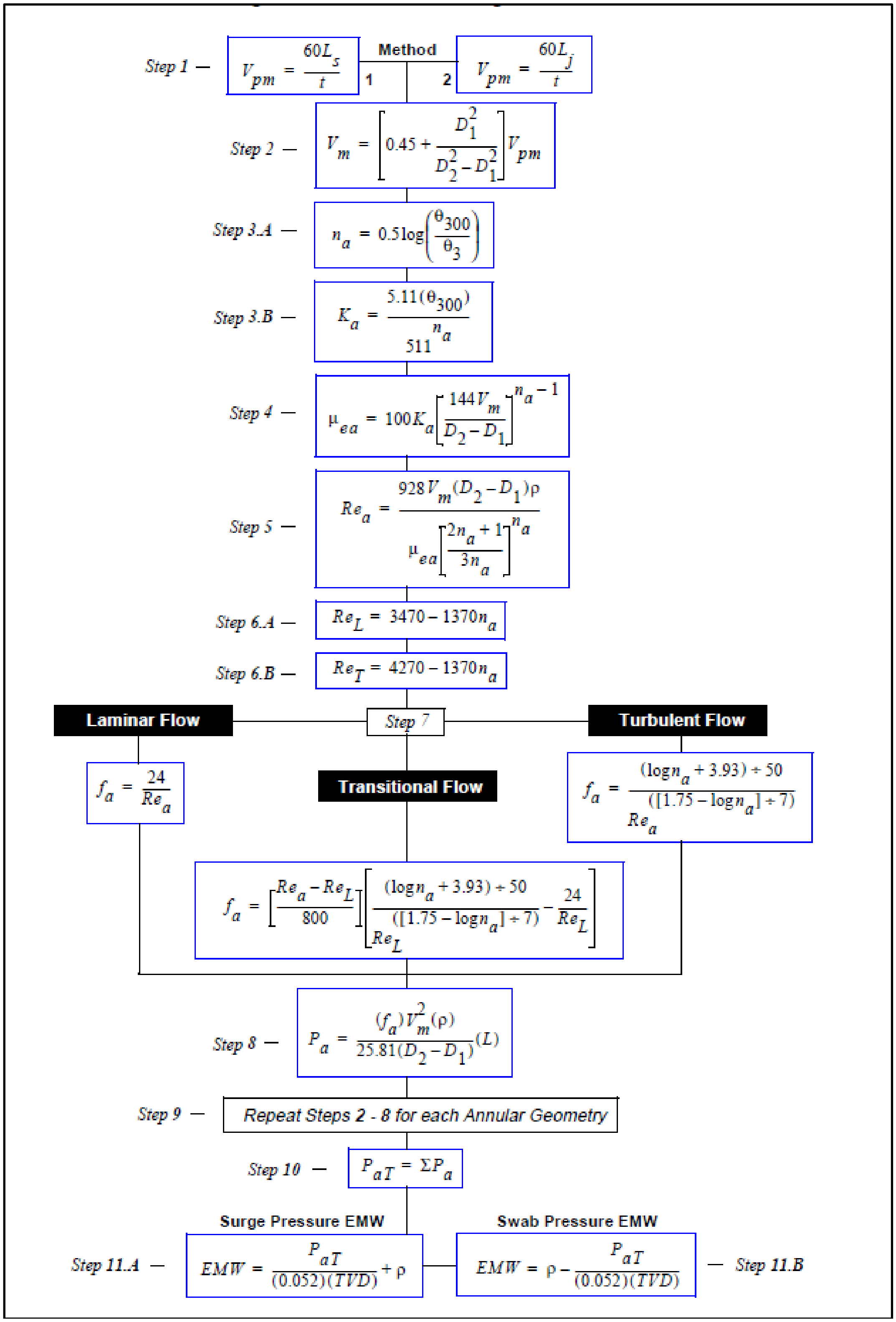
9. Steps 2 through 8 must be repeated for different annular geometry.

10. Calculate the total annular pressure loss (PaT) in psi by summing the individual pressure drops calculated for each interval.

11. A. If running into the hole, calculate the equivalent fluid density due to the surge pressure by adding the total annular pressure loss density equivalent to the fluid density, where;

EMW = equivalent fluid density (lbs/gal).

B. If pulling out of the hole, calculate the equivalent fluid density due to the surge pressure by subtracting the total annular pressure drop density equivalent from the fluid density.



3.1.4 SLIP VELOCITY AND HOLE CLEANING

- Major function of the drilling fluid is to transport drill cuttings from the bottom of the hole to the surface where they can be removed. Poor hole cleaning can result in severe operational problems including:
  a. High Torque and Drag
  b. Reduced ROP
  c. Stuck Pipe
  d. Difficulty in running casing
  e. Primary cementing failures
- The ability of the fluid to clean the hole depends on :
  a. Rheology and density of fluid
  b. Flow rate
  c. Size of the cuttings
- The settling rate is termed as the Slip Velocity.

CALCULATIONS:

1: From the annular hydraulics analysis for each interval, determine if the fluid is in laminar or turbulent flow. If the fluid is in laminar flow, continue with Step 2 to calculate the slip velocity. If the fluid is in turbulent flow, skip to Step 7.

2: Calculate the boundary layer shear rate (ϒB), where;

ϒB = boundary layer shear rate (sec-1),
Dc = particle diameter (in.),
ρ = fluid density (lb/gal)

3: Calculate the shear stress (τp) developed by the particle, where;

τp = particle shear stress (lb/100 ft2),
T = particle thickness (in.)

4: Calculate the shear rate developed by the particle (ϒp) using tp and the low shear rate n and K values for the drilling fluid, where;

ϒp = the particle shear rate (sec-1),
na = the low shear rate annular behaviour index
K = the annular consistency factor

5: Compare ϒp to ϒB to determine which equation to use to calculate the slip velocity.

6: Calculate the slip velocity and skip to Step 9.

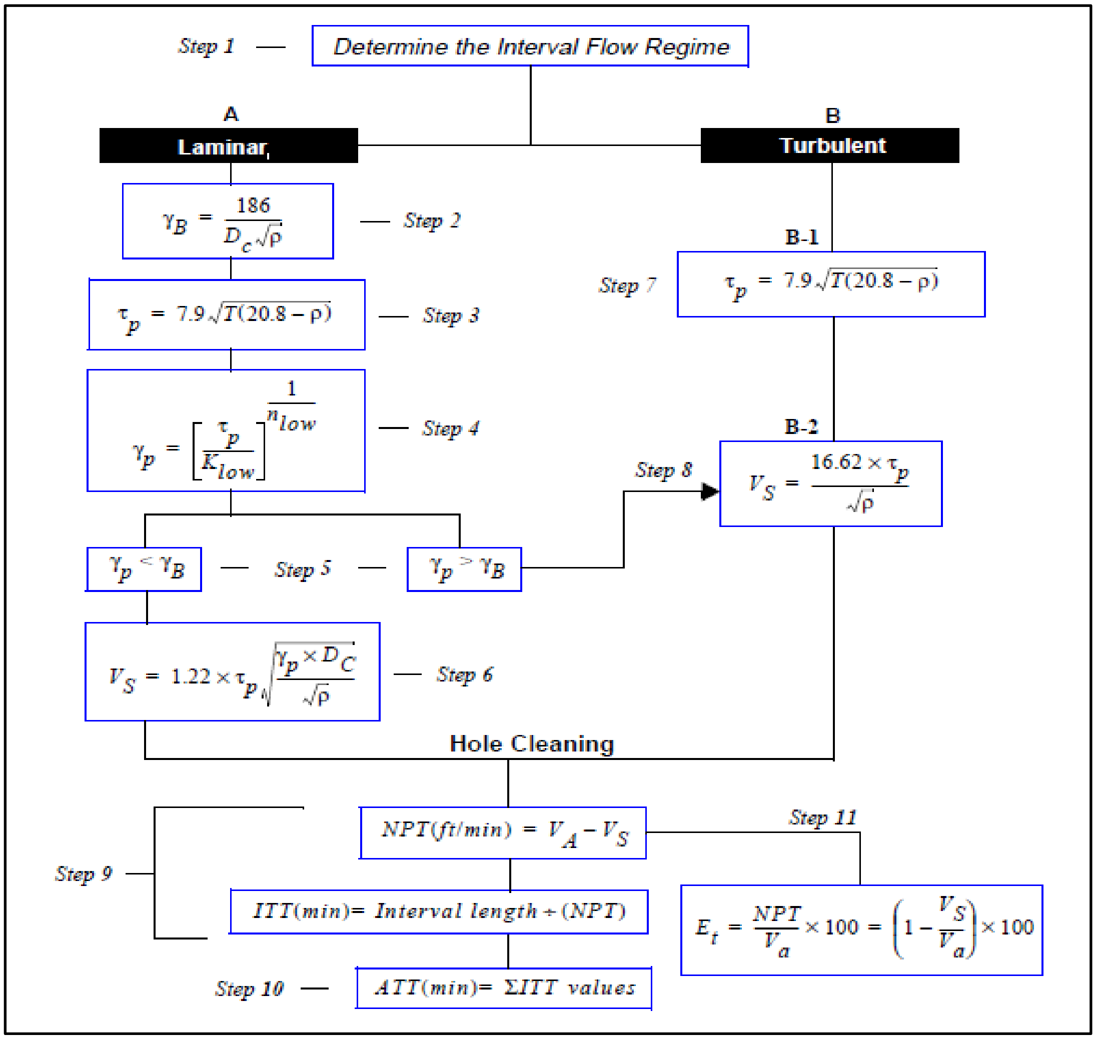
7: For any interval in turbulent flow, use equation B-1, to calculate the shear stress developed by the particle.

8: Use equation B-2, to calculate the slip velocity
9: Calculate the NPT and ITT, where;

NPT = net particle transport (ft/min),
VA = the interval annular velocity (ft/min) (= Va multiplied by 60 sec/min)

10: Calculate the ATT by summing the individual ITT values.

11: Calculate the transport efficiency (Et) in per cent for any interval by dividing the NPT by the interval's annular velocity and multiplying the quotient by 100%. The higher the transport efficiency, the higher the fluid's carrying capacity and the faster the cuttings are removed from the wellbore.



3.1.5 CUTTINGS CONCENTRATION

- The concentration of cuttings (Ca) in the fluid in any annular interval can be calculated by using the following equations. Depending upon the formations drilled, a Ca > 6% to 8% volumes can result in hole cleaning problems such as mud rings and pack-off.

CALCULATIONS:

1. For cuttings concentration (vol %), calculate

$$\boxed{C_{a} = ((ROP)\ D^{2}/14.71*E_{t}*Q)*100}$$

Where;

C_a = cuttings concentration (vol %),
D = hole diameter (in.),
E_t = interval transport efficiency expressed as a decimal fraction
Q = flow rate (gal/min),
ROP = rate of penetration (ft/hr)

2. The effective fluid weight (lbm/gal) resulting from the accumulation of cuttings in the annulus can be calculated by

$$\boxed{\rho_{e}=(S.G._{c})*(8.34)*(C_{a}/100)+\rho(1-C_{a}/100)}$$

Where;

ρe = effective fluid weight due to cuttings concentration (lbm/gal),
$S.G._c$ = specific gravity of the cuttings,
C_a= cuttings concentration (vol %),
ρ= fluid density (lbm/gal).

3.1.6 BIT HYDRAULIS ANALYSIS

1. **ΔPb** *(Pressure Loss at Bit)*: This equation gives that amount of the total circulating pressure that is consumed at the bit.

2. **HHPb** *(Hydraulic Horsepower at the Bit)*: Calculates the total hydraulic horsepower available across the face of the bit. Hydraulic horsepower is a measure of work done by moving fluid.

3. **HHPb/in2** *(Hydraulic Horsepower per Square Inch of the Bit Area)*: Converts the total Hydraulic Horsepower at the bit to that available per square inch of the bit face area.
   RULE: A general range of HHPb/in2 for optimized drilling is 2.5 to 5.0.4.

4. **Vn** *(Bit Nozzle Velocity)*: Calculates the velocity with which the fluid moves through the bit nozzles at the current flow rate. **RULE**: The nozzle velocity ranges between 250 to 450 ft/sec for most drilling operations.

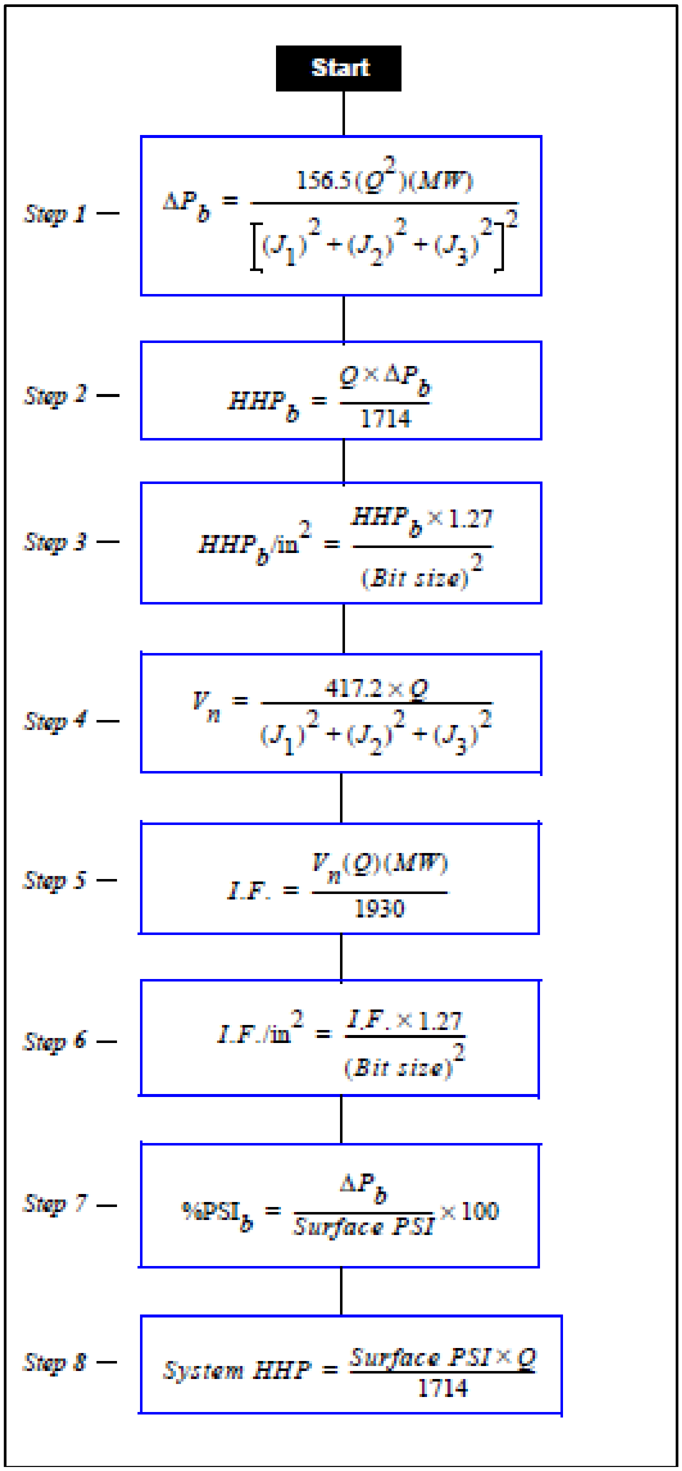
5. **I.F.** *(Impact Force)*: Gives the total lbs force exerted at the formation face by the fluid flowing through the bit nozzles.

6. **I.F. /In2** *(Impact Force per Square Inch of the Bit Area)*: Converts the total Impact Force to that available per square inch of bit face area.

7. **%PSI$_b$** *(Percent of Pressure Lost at Bit)*: Gives the percentage of total surface pressure that is expended at the bit. This is the complementary parameter of DPb in Step 1.

8. **System HHP** *(Total Hydraulic Horsepower of the Circulating System)*: Calculates the total hydraulic horsepower expended throughout the entire circulating system. Used as a benchmark of the efficiency of the hydraulics program.

   Note: *The % of Hydraulic Horsepower at the bit is equal to the % pressure loss at the bit.*



Step 1 —

$$\Delta P_b = \frac{156.5\,(Q^2)(MW)}{\left[(J_1)^2 + (J_2)^2 + (J_3)^2\right]^2}$$

Step 2 —

$$HHP_b = \frac{Q \times \Delta P_b}{1714}$$

Step 3 —

$$HHP_b/\text{in}^2 = \frac{HHP_b \times 1.27}{(Bit\ size)^2}$$

Step 4 —

$$V_n = \frac{417.2 \times Q}{(J_1)^2 + (J_2)^2 + (J_3)^2}$$

Step 5 —

$$I.F. = \frac{V_n(Q)(MW)}{1930}$$

Step 6 —

$$I.F./\text{in}^2 = \frac{I.F. \times 1.27}{(Bit\ size)^2}$$

Step 7 —

$$\%\text{PSI}_b = \frac{\Delta P_b}{Surface\ PSI} \times 100$$

Step 8 —

$$System\ HHP = \frac{Surface\ PSI \times Q}{1714}$$

4 WELL COMPLICATIONS

4.1 LOST CIRCULATION:

The losses of mud to the subsurface formation are called lost circulation. It is one of the primary reasons for high mud cost in most of the cases. The other problems like wellbore instability, stuck pipe, inadequate hole cleaning, improper filtration control are some of the factors that can induce lost circulation.

Lost circulation can be broadly classified in to two major categories:

- **Natural:** these occur when formations have very large pores or contain natural fractures or voids.
- **Induced:** these occur when a fracture created in the well due to hydraulic forces in the wellbore exceeding the formation strength.

Natural losses:

1. high matrix permeability formations such as gravels coarse sands
2. Cavernous or vuggy formations.
3. Formations with natural conductive fractures or fault.

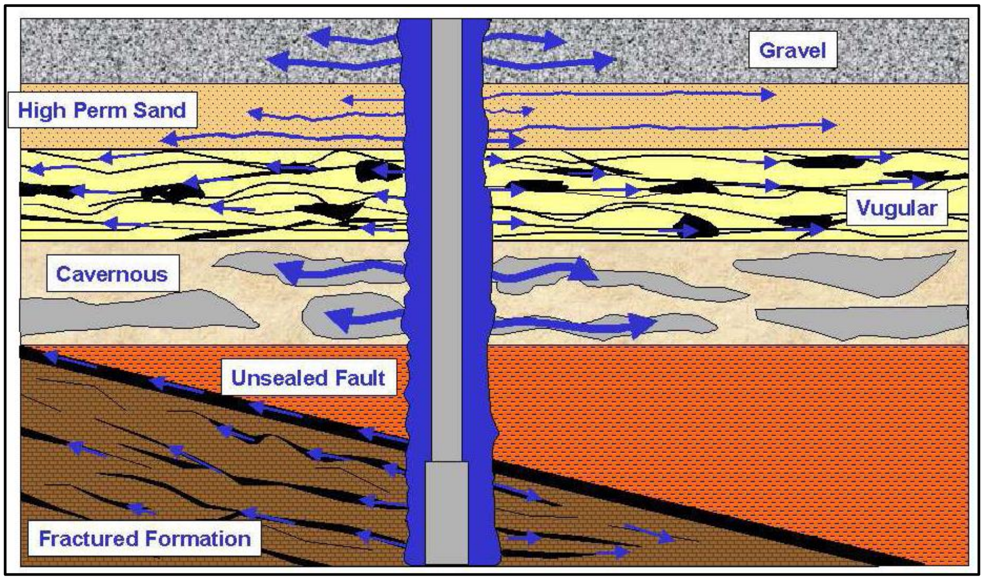


Fig14: Natural Lost Circulation

Induced losses:

1. high mud weight and hence high ECD
2. Tripping in tight hole resulting in swabbing and surging.
3. Very tight filtration rate.
4. Inadequate hole cleaning results in reduction in annular clearance.
5. Wellbore instability.
6. High ROP during drilling.
7. High flow rate.

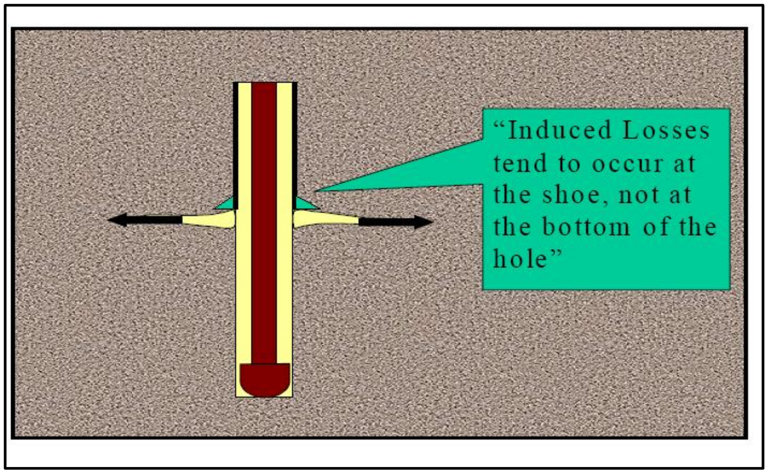


Fig15: Induced Lost Circulation

4.1.1 IDENTIFICATION AND PREVENTION

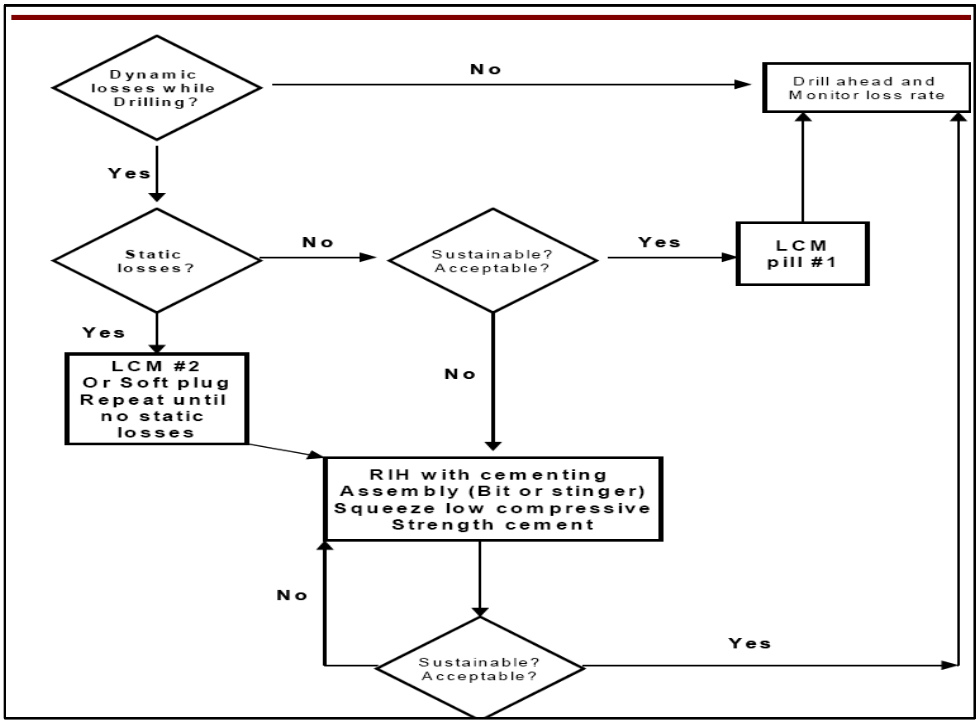


Fig16: Lost Circulation Identification and Prevention Workflow

Loss rate definition:

Loss Severity	Loss Rate (bbl/hr)	Loss Rate (m^3/hr)
Seepage	<10	<1.6
Partial	10 - 30	1.6 – 4.8
Severe	30 – 100	4.8 – 16
Total	>100	>16

Fig17: Loss Rate Definition

Graphical representation of loss rate definition:

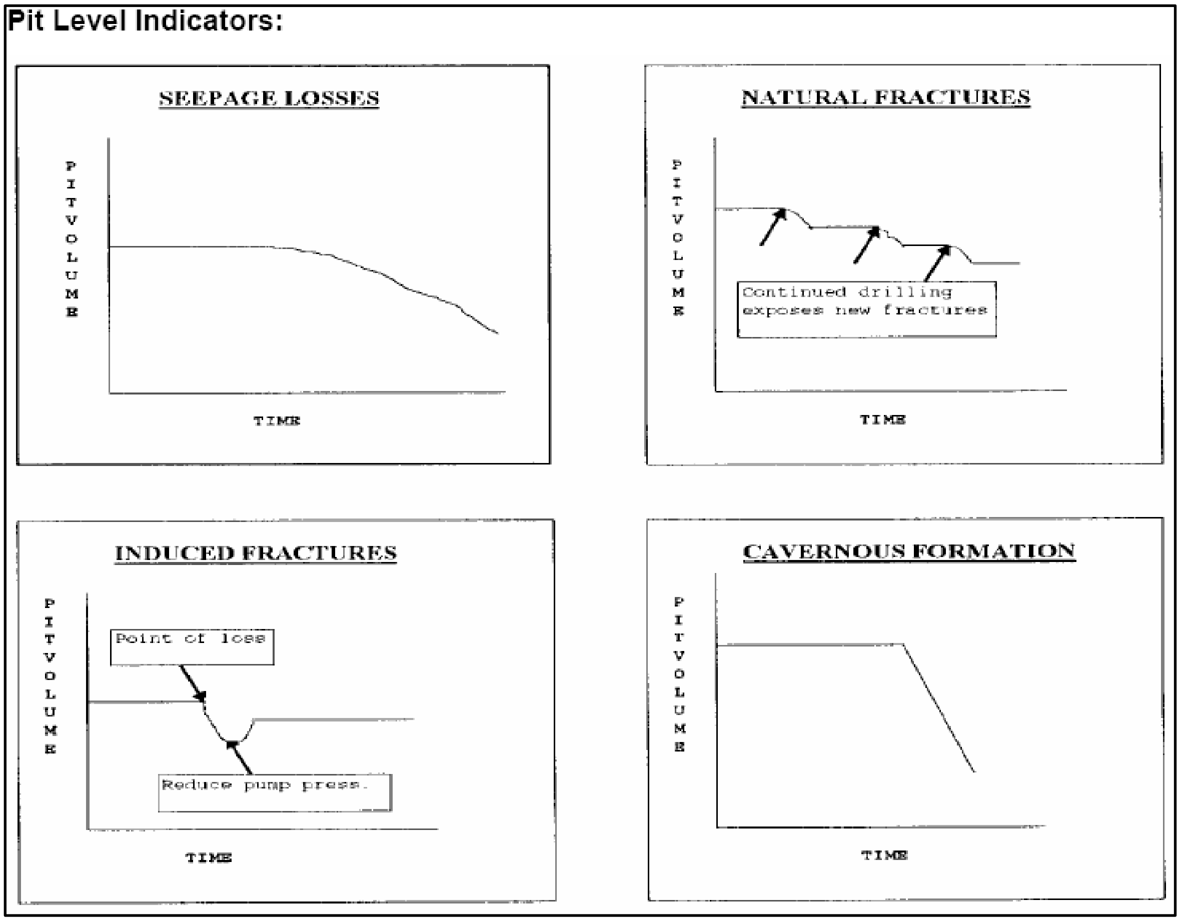


Fig18: Pit Level Indicators for Lost Circulation

4.1.2 PREVENTION

Preventive Products:

Types of products	*Name of products*
Fibrous	**MIX-II, MI ceder fiber, sawdust, drilling paper and magma fiber.**
Granular	**Nut plug (C / M / F), calcium carbonate (C/M/F), G-Seal (coarse graphite)**
Blends	**Kwick Seal (C/M/F), MI Seal**
Flakes	**Flakes (cellophane), Mica(C/M/F), phenoseal.**

LCM PILL CONCENTRATION:

1. ***For seepage losses (<10bbls/hr)***

   Calcium carbonate (fine) = 15ppb.

   Calcium carbonate (medium) = 10ppb.

   Kwick seal (medium) = 10ppb

   Kwick seal (fine) = 10ppb.

2. ***For partial losses (10-30 bbls/hr):***

   Calcium carbonate (coarse) = 10ppb.

   Calcium carbonate (medium) = 10ppb.

   Calcium carbonate (fine) = 20ppb.

   Kwick seal (medium) = 10ppb.

3. ***For severe losses (30-100 bbls/hr):***

   Calcium carbonate (coarse) = 35ppb.

   Calcium carbonate (medium) = 20ppb.

   Kwick seal (medium) = 15ppb

   Kwick seal (coarse) = 15ppb.

4.2 STUCK PIPE

- Drilling a well requires a drill string (pipe & collars) to transmit the torque provided at the surface to rotate the bit, and to transmit the weight necessary to drill the formation. The driller and the directional driller steer the well by adjusting the torque, pulling and rotating the drill string.
- When the drill string is no longer free to move up, down, or rotate as the driller wants it to, the drill pipe is stuck. Sticking can occur while drilling, making a connection, logging, testing, or during any kind of operation which involves leaving the equipment in the hole.

- The drill string is stuck if **BF + FBHA > MO**
  Where,

  MO, maximum overpull: the maximum force that the derrick, hoisting system, or drill pipe can stand, choosing the smallest one

  BF, background friction: the amount of friction force created by the side force in the well

  FBHA: The force exerted by the sticking mechanism on the BHA (Bottom Hole Assembly)

4.3 MECHANISMS OF STUCK PIPE

DIFFERENTIAL STICKING

- Differential sticking happen when the drill collar rests against the borehole wall, sinking into the mudcake.
- The area of the drill collar that is embedded into the mudcake has a pressure equal to the formation pressure acting on it.
- The area of the drill collar that is not embedded has pressure acting on it that is equal to the hydrostatic pressure in the drilling mud.
- When the hydrostatic pressure (*Ph*) in the well bore is higher than the formation pressure (*Pf*) there will be a net force pushing the collar towards the borehole wall.

  Mathematical Expression:

- Overpull due to differential pressure sticking can be calculated from the product of the differential pressure force times the friction factor :

  Overpull = Fdp f……………………………………………………………………. (1)

  Where *Fdp* = differential pressure force [psi/in2] and f = friction factor.

- The differential pressure force is defined:

$$Fdp = (144\ in^2 / ft^2) Amc\ (Ph - Pf) \ldots\ldots (2)$$

Where Fdp = differential pressure force [lbf],

Amc = cross section embedded in mud cake [ft2],

Ph = hydrostatic pressure [psi], and Pf = formation pressure [psi].

- The friction factor depends on the formation and the drill collar surface. It varies from 0.15 to 0.50.
- The hydrostatic pressure is defined:

$$Ph = TVD \times \Upsilon = TVD \times \rho \times 0.433\ psi / ft / 8.33 ppg \ldots\ldots (3)$$

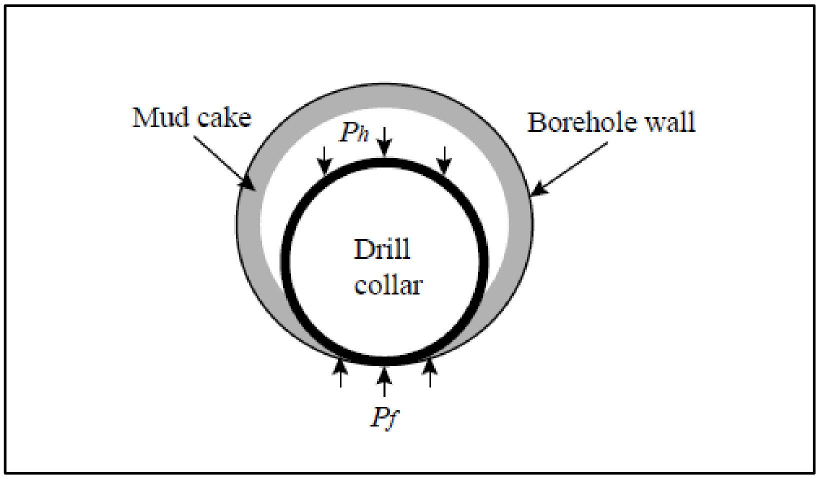


Fig19: Differential Sticking

- The thickness of the filter cake is critical in differential sticking. The thicker the filter cake the bigger is the cross sectional area that the formation pressure acts on. Thus, the differential sticking force is higher when the mud cake is thicker.

4.3.1 IDENTIFICATION AND PREVENTION

- **Warning Signs**
  - **a.** Increasing overpull in long connections.
  - **b.** Overpull and torque increases when drillstring is stationary for some time.
  - **c.** Overpull decreases after reaming.

- **Identification**
  - **a.** The pipe was stationary before it got stuck.

b. Full circulation is possible.
c. BHA adjacent to thick sand.
d. Hydrostatic pressure overbalance.

- **Preventive Action**
  a. Keep track of differential pressure in sands if possible.
  b. Don't stop too long for a survey. If necessary continue drilling after the precursor comes up.
  c. Keep the mud weight under control.
  d. Use a short BHA.
  e. Make frequent wiper trips.

4.4 INADEQUATE HOLE CLEANING

- If the cuttings are not removed from the well properly, they will settle around the drillstring, usually the BHA, causing the drill collars to become stuck.
- The problem is worse in overgauge hole sections where the annular velocity is lower. Cuttings will build up and eventually slump in the hole.
- The cuttings are scraped by the stabilizers and the bit when the BHA is moved up the hole at a connection or a trip out. The cuttings accumulate in front of the bit and stabilizers. The overpull will increase until the cuttings will stick the BHA.

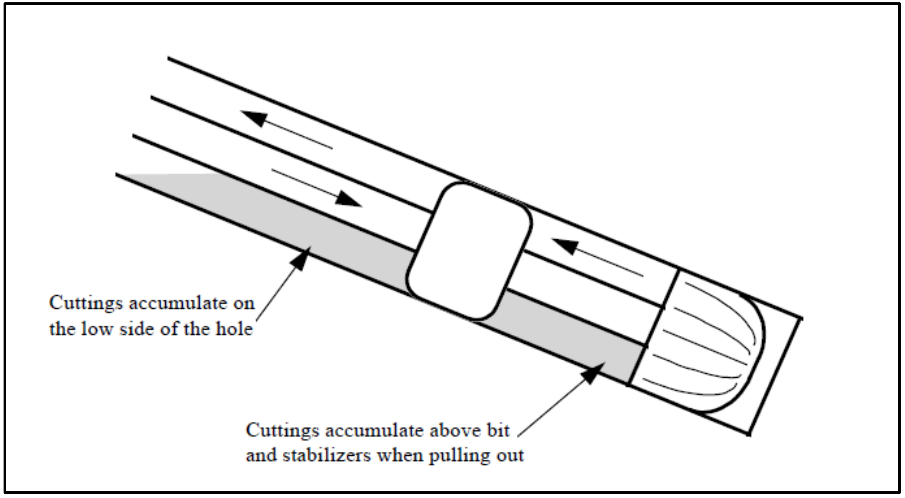


Fig20: Cuttings accumulate around BHA to cause increase in overpull

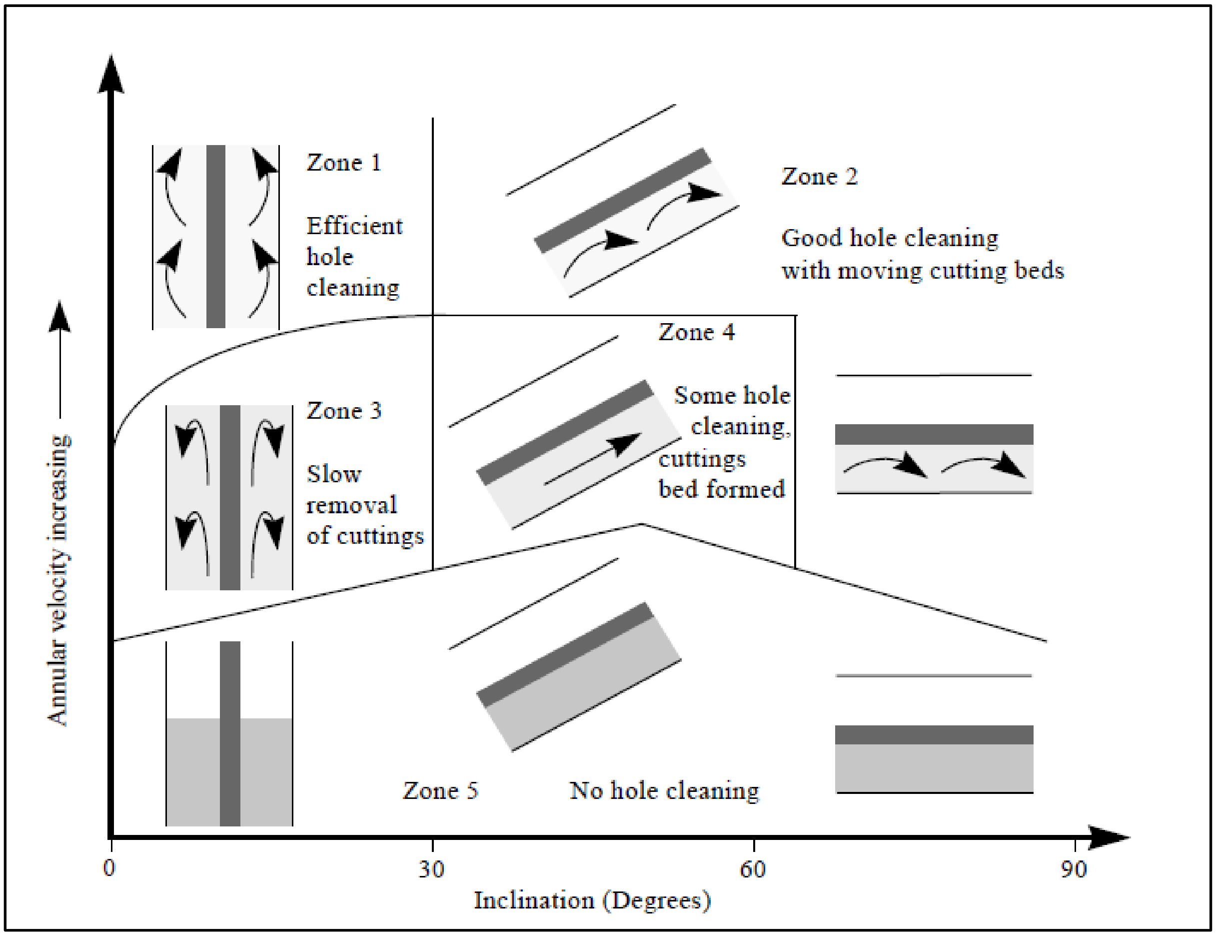


Fig21: Flow pattern of Cuttings in Deviated Well

4.4.1 IDENTIFICATION AND PREVENTION:

- **Warning Signs**
  - **a.** Insufficient cuttings on shaker.
  - **b.** Excessive overpull at connections and trips.
  - **c.** Reduced overpull when pumping.
  - **d.** Increase in pump pressure and pressure spikes when hole momentarily plugs up.
  - **e.** Pump pressure much higher than predicted using hydraulics program.

- **Identification**
  - **a.** Stuck shortly after pumps are shut off.
  - **b.** Circulation lost.

- **Preventive action**
  - **a.** Circulate all cuttings out before tripping out.
  - **b.** If motor is used, rotate before tripping out of hole.
  - **c.** Keep the pumps running.
  - **d.** The ROP can be lowered to reduce the amount of cuttings.
  - **e.** Check shale shakers to see if the cuttings are being removed.

4.5 CHEMICALLY ACTIVE FORMATIONS

- Different formations have a different degree of absorbing water. Some high clay content rocks absorb water and swell.
- The amount of swelling varies from highly reactive “gumbo” (fast absorption rate) to shales, which absorb water very slowly.
- When drilling with water based mud, the water is absorbed into these types of formations (commonly shales), causing them to swell and weaken.
- As a result, chunks of shale will break-off and fall into the borehole. The water-absorbed (hydrated) shale tends to stick to the drill string and accumulate in sufficient quantities to fill the entire annulus around the BHA, causing it to become stuck.

4.5.1 IDENTIFICATION AND PREVENTION

- **Warning Signs**
  a. Large clumps of hydrated shale (gumbo) coming out of the hole.
  b. Drilling rate is slower as less weight gets to the bit.
  c. BHA packed off with gumbo (inspected at trips).
  d. Increase in pump pressure.
  e. Increase in torque as the hole size is reduced due to swelling.

- **Identification**
  a. Cannot circulate mud.
  b. Sticking can occur during any operation while in open hole.

- **Preventive Action**
  a. Minimize time in open hole.
  b. Maintain mud inhibitors at high enough levels.
  c. Minimize length of BHA and open hole sections.
  d. Avoid additional open hole operation such as wireline logging, survey runs, etc.

4.6 MECHANICAL STABILITY

- Before the drill bit enters a section of the hole, the rock supports three unequal stresses in four different directions. These are:

  1. **Vertical Stresses**: At depths greater than 1,500 feet, the largest stress on a rock formation is usually the stress imposed on it from the weight of all material above it, which acts in the vertical direction.

  2. **Side Stresses**: The side stresses which act in the horizontal component in both directions. A typical value of these stresses is 0.75 psi/ft.

- The drilling process effectively replaces the cylinder of rock with mud. Usually, the mud weight is balanced to the pore pressure of the formation, however in some instances the mud weight cannot totally support the borehole pressure.
- The rock around the borehole is forced to act as extra support. If the formation is strong, then there will be no problem. However, in younger formations, where the rock is not strong, the rock will not be able to support this extra stress.
- The rock will deform and the wellbore will begin to contract in a small amount.

4.6.1 IDENTIFICATION AND PREVENTION:

- **Warning Signs**

  a. Large cuttings, low shale strength.
  b. Tight hole over long sections during trip.
  c. Large overpulls due to cavings.
  d. Increase in pump pressure due to cavings in borehole.
  e. Slower drilling rate

- **Identification**
  a. Circulation restricted or impossible.
  b. Sticking can occur during any operation while in open hole.

- **Preventive Action**
  a. Gradually increase mud weight.
  b. Follow hole cleaning procedures.
  c. Complete each hole section fast, therefore minimize time in hole.

4.7 FRACTURED/FAULTED FORMATIONS:

- Rock near faults can be broken into large or small pieces. If they are loose they can fall into the well bore and jam the string in the hole. Even if the pieces are bonded together, impacts from the BHA due to drill string vibration can cause the formation to fall into the well bore. This type of sticking is particularly unusual in that stuck pipe can occur while drilling.

Fig22: Fractured Formation

4.7.1 IDENTIFICATION AND PREVENTIONS:

- **Warning Signs**
  a. Hole fill on connections.
  b. Possible losses or gains.
  c. Fault damaged cavings at shakers.
  d. Increase in pump pressure.

- **Identification**
  - **a.** Sticking can be instantaneous.
  - **b.** Circulation restricted or impossible.

- **Preventative Action**
  - **a.** Minimise drill string vibration.
  - **b.** Choose an alternative RPM or change the BHAconfiguration if high shock vibrations are observed.
  - **c.** Slow the trip speed before the BHA enters a suspected fractured/faulted area.
  - **d.** Generally, fractured formations require time to stabilise. Be prepared to spend time when initially drilling and reaming prior to making significant further progress.
  - **e.** Circulate the hole clean before drilling ahead
  - **f.** Start/stop the drill string slowly to avoid pressure surges to the well bore.

  Anticipate reaming during trips. Ream fractured zones cautiously.

4.8 OVERPRESSURED FORMATIONS

- An additional stress is applied to the rock if the hydrostatic pressure is less than the formation pore pressure. The formation in this case will tend to “pop” or “heave” into the wellbore.
- The shale pieces can sufficiently accumulate to pack off the BHA and cause sticking. The heaving shale condition occurs only when no permeable sand is present, since permeable sand with a higher pore pressure than mud pressure would cause a kick.

4.8.1 IDENTIFICATION AND PREVENTION:

- **Warning Signs**
  - **a.** Large, brittle, concave shaped carvings.
  - **b.** Recently crossed a fault.
  - **c.** Absence of permeable formations.
  - **d.** Large overpulls at connections.
  - **e.** Restricted circulation due to cavings loading the annulus.
  - **f.** Torque may increase.

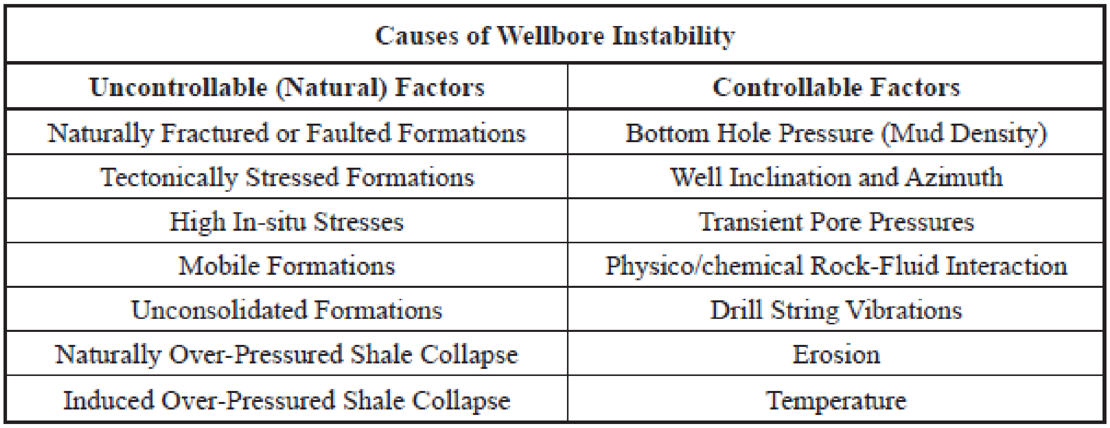
- **Identification**
  - **a.** Circulation restricted or impossible.
  - **b.** Stuck shortly after pumps off.

- **Preventative Action**
  - **a.** Monitor all cuttings; be on a lookout for large concave shale pieces.
  - **b.** Monitor Rate of Penetration (ROP - Drilling Rate).
  - **c.** Follow hole cleaning procedures

4.9 OTHER FACTORS:

a. Unconsolidated Formations
b. High Dip Sloughing
c. Mobile Formations
d. Under gauge Hole
e. Collapsed Casing etc.

WELLBORE INSTABILITY



Causes of Wellbore Instability	
Uncontrollable (Natural) Factors	**Controllable Factors**
Naturally Fractured or Faulted Formations	Bottom Hole Pressure (Mud Density)
Tectonically Stressed Formations	Well Inclination and Azimuth
High In-situ Stresses	Transient Pore Pressures
Mobile Formations	Physico/chemical Rock-Fluid Interaction
Unconsolidated Formations	Drill String Vibrations
Naturally Over-Pressured Shale Collapse	Erosion
Induced Over-Pressured Shale Collapse	Temperature

Fig23: Causes of Wellbore Instability

CONTROLLABLE FACTORS:

a. Mud Density

- Depending upon the application, either the bottom hole pressure, the mud density or the equivalent circulating density (ECD), is usually the most important determinant of whether an open wellbore is stable.

b. Well Inclination and Azimuth:

- Inclination and azimuthal orientation of a well with respect to the principal in-situ stresses can be an important factor affecting the risk of collapse and/or fracture breakdown occurring.

c. Transient Wellbore Pressures:

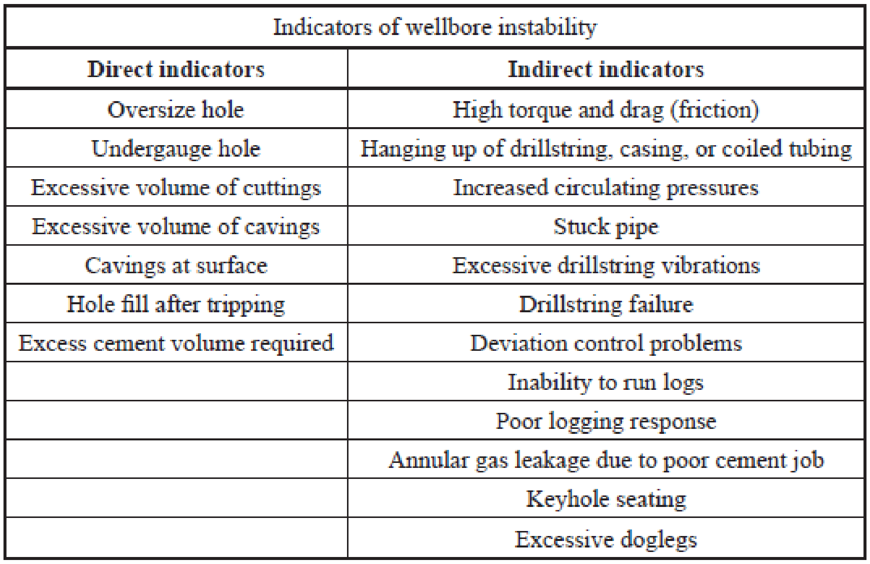
- Transient wellbore pressures, such as swab and surge effects during drilling, may cause wellbore enlargement.
- Surge pressures can also cause rapid pore pressures increases in the near-wellbore area sometimes causing an immediate loss in rock strength which may ultimately lead to collapse.

d. Physical/Chemical Fluid Rock Interaction

- There are many physical/chemical fluid-rock interaction phenomena which modify the near-wellbore rock strength or stress.
- These include hydration, osmotic pressures, swelling, rock softening and strength changes, and dispersion.

e. Drillstring Vibrations:

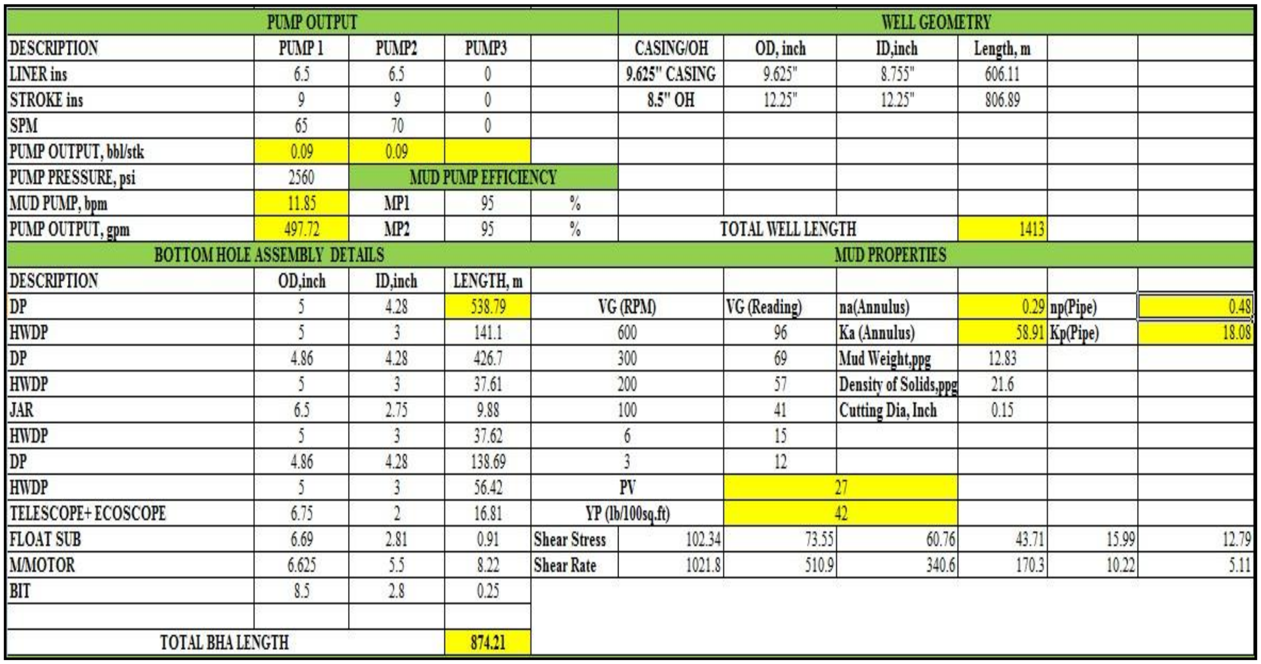
- Drillstring vibrations can enlarge holes in some circumstances. Optimal bottomhole assembly (BHA) design with respect to the hole geometry, inclination, and formations to be drilled can sometimes eliminate this potential contribution to wellbore collapse.



Indicators of wellbore instability	
Direct indicators	**Indirect indicators**
Oversize hole	High torque and drag (friction)
Undergauge hole	Hanging up of drillstring, casing, or coiled tubing
Excessive volume of cuttings	Increased circulating pressures
Excessive volume of cavings	Stuck pipe
Cavings at surface	Excessive drillstring vibrations
Hole fill after tripping	Drillstring failure
Excess cement volume required	Deviation control problems
	Inability to run logs
	Poor logging response
	Annular gas leakage due to poor cement job
	Keyhole seating
	Excessive doglegs

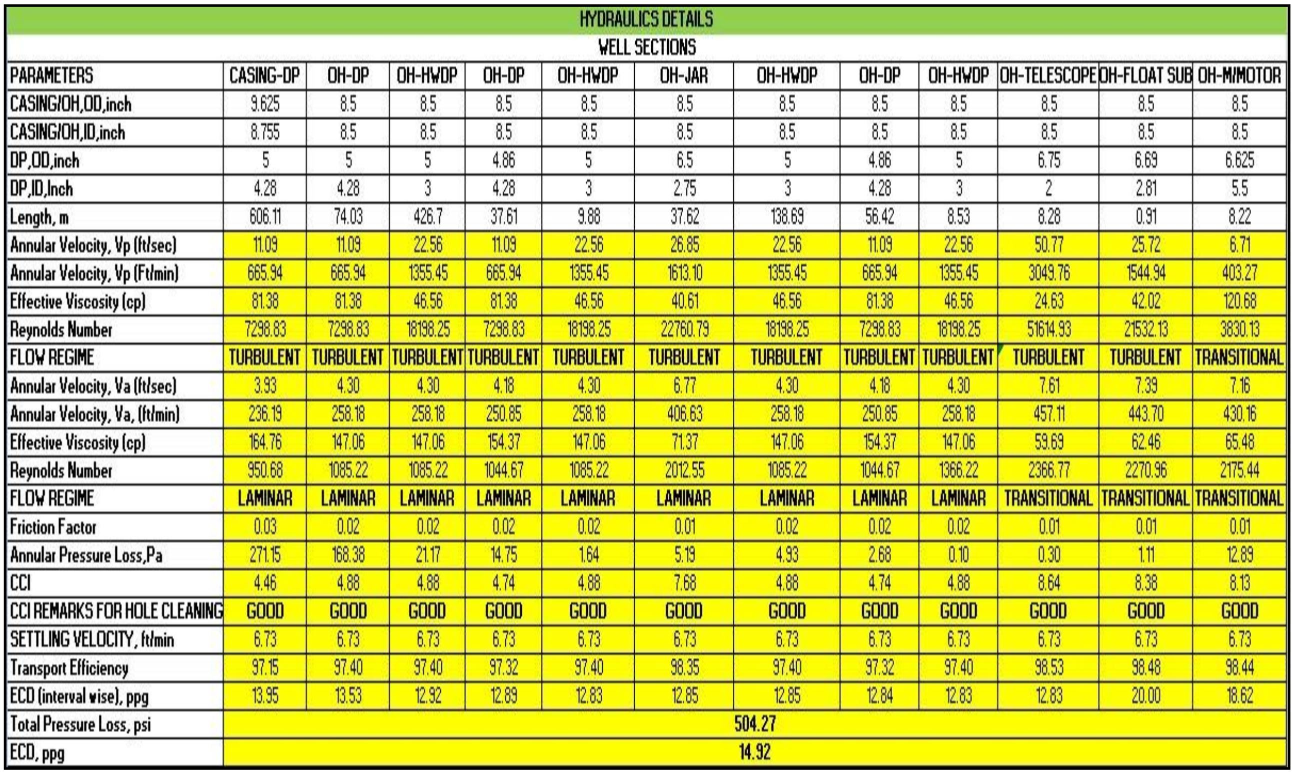
Fig24: Indicators of Wellbore Instabilit

5 EXCEL Sheet Formulation of Mud Hydraulics.



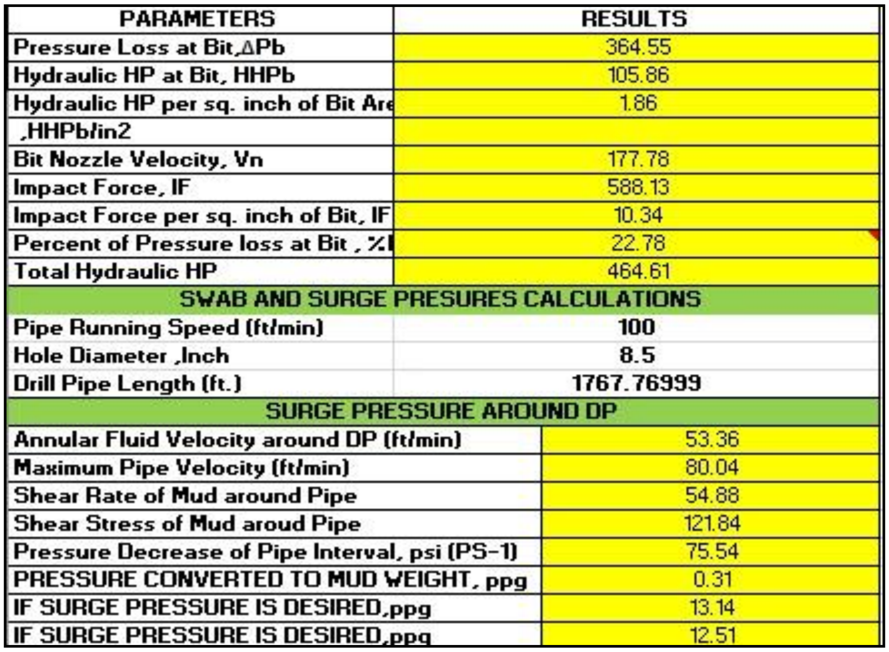
PUMP OUTPUT					WELL GEOMETRY					
DESCRIPTION	PUMP 1	PUMP2	PUMP3		CASING/OH	OD, inch	ID,inch	Length, m		
LINER ins	6.5	6.5	0		9.625" CASING	9.625"	8.755"	606.11		
STROKE ins	9	9	0		8.5" OH	12.25"	12.25"	806.89		
SPM	65	70	0							
PUMP OUTPUT, bbl/stk	0.09	0.09								
PUMP PRESSURE, psi	2560	MUD PUMP EFFICIENCY								
MUD PUMP, bpm	11.85	MP1	95	%						
PUMP OUTPUT, gpm	497.72	MP2	95	%	TOTAL WELL LENGTH			1413		
BOTTOM HOLE ASSEMBLY DETAILS				MUD PROPERTIES						
DESCRIPTION	OD,inch	ID,inch	LENGTH, m							
DP	5	4.28	538.79	VG (RPM)		VG (Reading)	na(Annulus)	0.29	np(Pipe)	0.48
HWDP	5	3	141.1	600		96	Ka (Annulus)	58.91	Kp(Pipe)	18.08
DP	4.86	4.28	426.7	300		69	Mud Weight,ppg	12.83		
HWDP	5	3	37.61	200		57	Density of Solids,ppg	21.6		
JAR	6.5	2.75	9.88	100		41	Cutting Dia, Inch	0.15		
HWDP	5	3	37.62	6		15				
DP	4.86	4.28	138.69	3		12				
HWDP	5	3	56.42	PV		27				
TELESCOPE+ ECOSCOPE	6.75	2	16.81	YP (lb/100sq.ft)		42				
FLOAT SUB	6.69	2.81	0.91	Shear Stress	102.34	73.55	60.76	43.71	15.99	12.79
M/MOTOR	6.625	5.5	8.22	Shear Rate	1021.8	510.9	340.6	170.3	10.22	5.11
BIT	8.5	2.8	0.25							
TOTAL BHA LENGTH			874.21							

Fig25: Well Data



HYDRAULICS DETAILS												
WELL SECTIONS												
PARAMETERS	CASING-DP	OH-DP	OH-HWDP	OH-DP	OH-HWDP	OH-JAR	OH-HWDP	OH-DP	OH-HWDP	OH-TELESCOPE	OH-FLOAT SUB	OH-M/MOTOR
CASING/OH,OD,inch	9.625	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
CASING/OH,ID,inch	8.755	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
DP,OD,inch	5	5	5	4.86	5	6.5	5	4.86	5	6.75	6.69	6.625
DP,ID,Inch	4.28	4.28	3	4.28	3	2.75	3	4.28	3	2	2.81	5.5
Length, m	606.11	74.03	426.7	37.61	9.88	37.62	138.69	56.42	8.53	8.28	0.91	8.22
Annular Velocity, Vp (ft/sec)	11.09	11.09	22.56	11.09	22.56	26.85	22.56	11.09	22.56	50.77	25.72	6.71
Annular Velocity, Vp (Ft/min)	665.94	665.94	1355.45	665.94	1355.45	1613.10	1355.45	665.94	1355.45	3049.76	1544.94	403.27
Effective Viscosity (cp)	81.38	81.38	46.56	81.38	46.56	40.61	46.56	81.38	46.56	24.63	42.02	120.68
Reynolds Number	7298.83	7298.83	18198.25	7298.83	18198.25	22760.79	18198.25	7298.83	18198.25	51614.93	21532.13	3830.13
FLOW REGIME	TURBULENT	TURBULENT	TURBULENT	TURBULENT	TURBULENT	TURBULENT	TURBULENT	TURBULENT	TURBULENT	TURBULENT	TURBULENT	TRANSITIONAL
Annular Velocity, Va (ft/sec)	3.93	4.30	4.30	4.18	4.30	6.77	4.30	4.18	4.30	7.61	7.39	7.16
Annular Velocity, Va, (ft/min)	236.19	258.18	258.18	250.85	258.18	406.63	258.18	250.85	258.18	457.11	443.70	430.16
Effective Viscosity (cp)	164.76	147.06	147.06	154.37	147.06	71.37	147.06	154.37	147.06	59.69	62.46	65.48
Reynolds Number	950.68	1085.22	1085.22	1044.67	1085.22	2012.55	1085.22	1044.67	1366.22	2366.77	2270.96	2175.44
FLOW REGIME	LAMINAR	LAMINAR	LAMINAR	LAMINAR	LAMINAR	LAMINAR	LAMINAR	LAMINAR	LAMINAR	TRANSITIONAL	TRANSITIONAL	TRANSITIONAL
Friction Factor	0.03	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.01	0.01	0.01
Annular Pressure Loss,Pa	271.15	168.38	21.17	14.75	1.64	5.19	4.93	2.68	0.10	0.30	1.11	12.89
CCI	4.46	4.88	4.88	4.74	4.88	7.68	4.88	4.74	4.88	8.64	8.38	8.13
CCI REMARKS FOR HOLE CLEANING	GOOD	GOOD	GOOD	GOOD	GOOD	GOOD	GOOD	GOOD	GOOD	GOOD	GOOD	GOOD
SETTLING VELOCITY, ft/min	6.73	6.73	6.73	6.73	6.73	6.73	6.73	6.73	6.73	6.73	6.73	6.73
Transport Efficiency	97.15	97.40	97.40	97.32	97.40	98.35	97.40	97.32	97.40	98.53	98.48	98.44
ECD (interval wise), ppg	13.95	13.53	12.92	12.89	12.83	12.85	12.85	12.84	12.83	12.83	20.00	18.62
Total Pressure Loss, psi	504.27											
ECD, ppg	14.92											

Fig26: Hydraulic Details section wise



PARAMETERS	RESULTS
Pressure Loss at Bit,ΔPb	364.55
Hydraulic HP at Bit, HHPb	105.86
Hydraulic HP per sq. inch of Bit Are	1.86
,HHPb/in2	
Bit Nozzle Velocity, Vn	177.78
Impact Force, IF	588.13
Impact Force per sq. inch of Bit, IF	10.34
Percent of Pressure loss at Bit , %I	22.78
Total Hydraulic HP	464.61
SWAB AND SURGE PRESURES CALCULATIONS	
Pipe Running Speed (ft/min)	100
Hole Diameter ,Inch	8.5
Drill Pipe Length (ft.)	1767.76999
SURGE PRESSURE AROUND DP	
Annular Fluid Velocity around DP (ft/min)	53.36
Maximum Pipe Velocity (ft/min)	80.04
Shear Rate of Mud around Pipe	54.88
Shear Stress of Mud aroud Pipe	121.84
Pressure Decrease of Pipe Interval, psi (PS-1)	75.54
PRESSURE CONVERTED TO MUD WEIGHT, ppg	0.31
IF SURGE PRESSURE IS DESIRED,ppg	13.14
IF SURGE PRESSURE IS DESIRED,ppg	12.51

Fig 27: Results

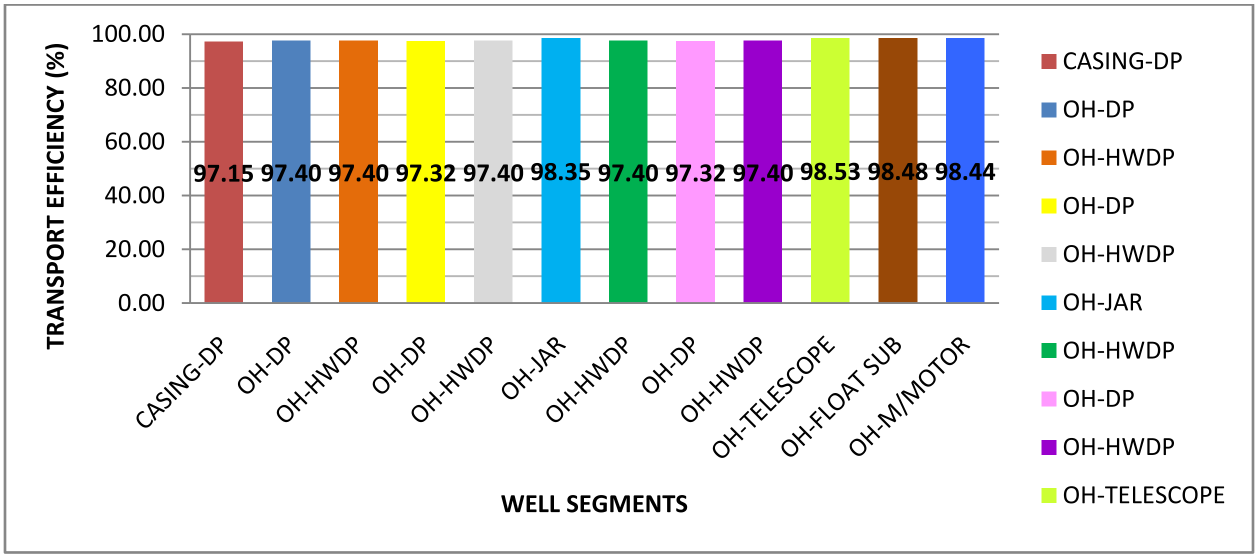
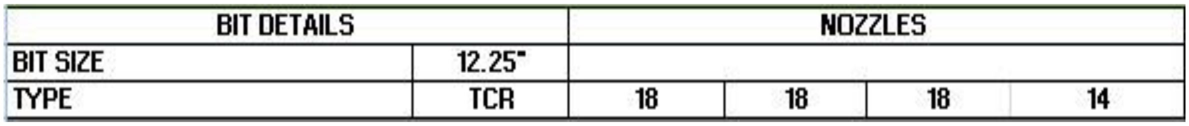


Fig 28: Transport Efficiency



BIT DETAILS		NOZZLES			
BIT SIZE	12.25"				
TYPE	TCR	18	18	18	14

Fig 29: Bit details

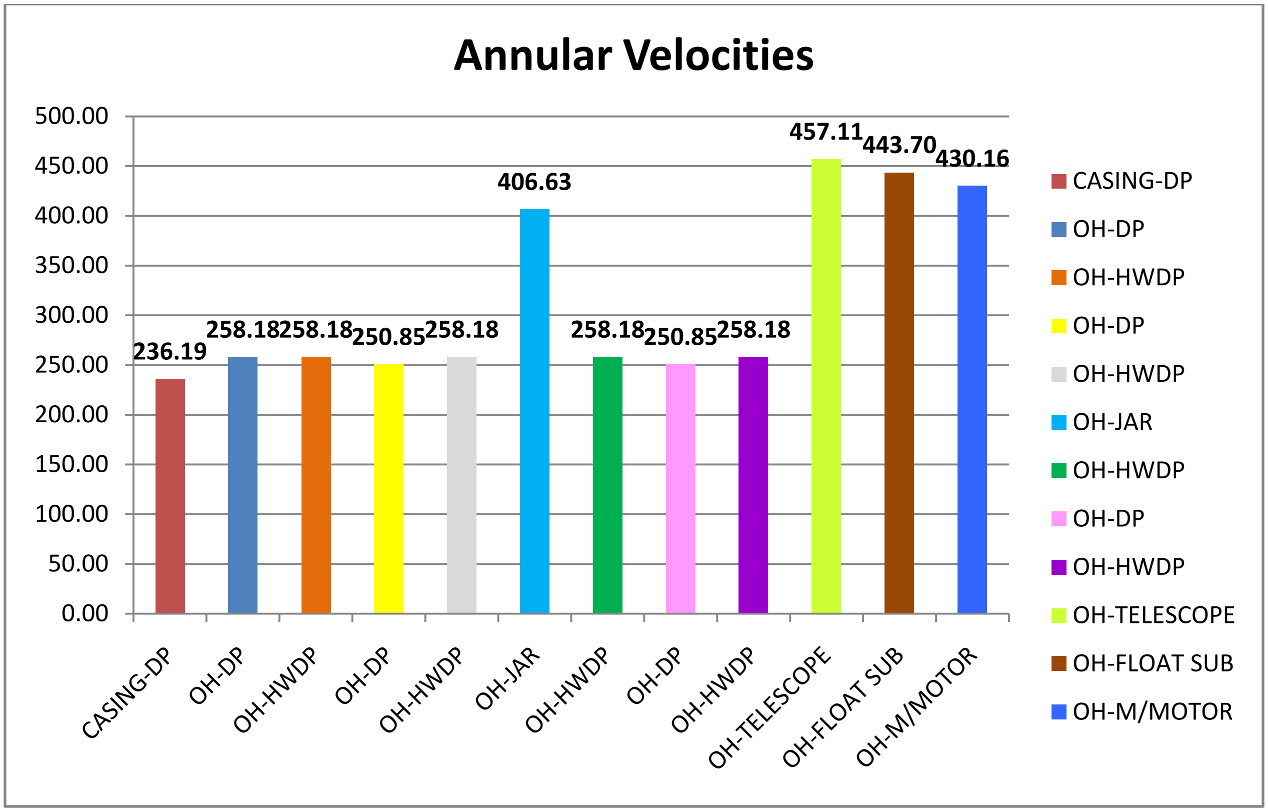


Fig 30: Annular velocities

6 CONCLUSIONS

The properties of the drilling mud to be set for a better hole cleaning has been the fore most importance of this project. The calculative procedures discussed in this report are in progressive manner allows the mud engineer to select the parameters required.

The hydraulics analysis calculations done based on an example datasets for different well sections, confirms that rheological properties such as effective viscosity, gel strength are to be maintained with due care to suffice the cutting carrying capacity. Cutting concentration increases in the open hole section which can be maintained by using viscous thin fluids with higher velocities and viscous fluids with moderate velocities.

Other parameters such as drillstring rotation, washout prevention are some of the supporting aspects with drilling practices along with planning a good mud program.

A good mud program is essential for the better drilling performance. Around 80 – 90 % of drilling problems are handled using the mud itself, thus the mud engineer plays crucial role during the entire drilling operation.

7 REFERENCES

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