

## MUD ENGINEERING

### **This chapter covers the following items**

- Function of drilling mud
- Drilling mud
- Types of drilling mud
  - Water base mud
  - Oil base mud
  - Emulsion mud
- Fundamental properties of mud
- Mud calculations
- Mud contaminant
- Mud conditioning equipment

### **Function of drilling mud**

#### **Cool bit and its teeth**

- Drilling action requires mechanical energy in form of weight on bit, rotation and hydraulic energy
- Large part of energy dissipated as heat
- Heat must be removed to allow drilling
- Mud helps remove heat
- Mud helps remove cutting between the teeth and prevent bit balling

#### **Cool and lubricate drill string**

- Rotating drill string generates heat
- Mud help dissipate heat from hole
- Mud absorbs heat by convection and release it by radiation
- Mud lubricate drill string and reduce friction

#### **Control formation pressure**

- For safe drilling, high formation pressures must be contained within the hole to prevent damage and injury
- This achieved by hydrostatic pressure of mud
- Mud pressure should be higher than formation pressure

- An overbalance of 100-200 psi is used
- Pressure overbalance is referred as chip hold down pressure (CHDP)
- Penetration rate decreases as CHDP increases
- For abnormal pressure CHDP becomes negative and kick will happen

### **Carry cutting to surface**

- Cutting generated by the bit must be removed
- Drilling mud carries cutting from bottom to surface
- Carrying capacity depends on annular velocity, plastic viscosity and yield point of mud and slip velocity of generated cutting
- For power law fluid, slip velocity is:

$$V_s = \frac{175 D_p (\rho_p - \rho_m)^{0.667}}{\rho_m^{0.333} \mu_e^{0.333}} \text{ ft/min}$$

$$V_s = \frac{15.23 D_p (\rho_p - \rho_m)^{0.667}}{\rho_m^{0.333} \mu_e^{0.333}} \text{ m/s}$$

$D_p$  = Particle diameter, in or mm

$\rho_p$  = Particle density, ppg, g/l

$\rho_m$  = Mud density, ppg, g/l

$\mu_e$  = Effective viscosity, cp

- Annular velocity  $V_r$  is the flow rate divided by the annular area
- Lift velocity  $V = V_r - V_s$
- The mud also must suspend cutting when drilling stops

### **Stabilize the wellbore**

- Good mud cake stabilizes the hole
- Differential pressure between mud and formation keeps hole stable
- Reduce drilling time also helps keep hole stable

### **Help in evaluation and interpretation of well logs**

- During logging mud fill the hole
- Logs used to detect hydrocarbon, measure porosity, formation pressure
- Mud should possess properties that help evaluate these properties

### **Drilling mud**

- Fresh water gives a pressure gradient of 0.433 psi/ft
- Normal formation pressure gradient is 0.465 psi/ft
- Fresh water can not control formation pressure
- Solids are added to increase water density to control pressure

### **Types of drilling mud**

#### **Water base mud**

- Consists of:
  - Liquid water, continuous phase
  - Reactive solids, for viscosity and yield point
  - Inert solids, for density
  - Chemical additives, to control properties

#### **Reactive solids**

- Clays are added to provide viscosity and yield strength
- Mechanism is very complex
- Internal structure of clay particles and electrostatic forces develop viscosity
- Two types of clay are available
- Bentonite clay, montmorillonite (smectite) group used with fresh water
- Attapulgite clay, salt gel (playgorskite) group of clay used in fresh and salt water

#### **Nature of clay**

- Defines as natural, earthy, fine-grained material that develop plasticity when wet
- Form from chemical weathering of igneous and metamorphic rocks
- Mainly form from volcanic ash

- Wyoming bentonite is the famous one
- Atoms from layers
- There are three atomic layers: tetrahedral layer, octahedral layer, and exchangeable layer
- Tetrahedra made up of flat honeycomb sheet made up of silicon atom surrounded by four oxygen
- Tetrahedra are linked to form sheet by sharing three of their oxygen atoms
- Octahedral layer are sheets composed of linked octahedra, each made up of an aluminium and magnesium atom surrounded by six oxygen
- They linked through oxygen making three octahedra
- Exchangeable layers of atoms or molecules bound loosely into the structure giving the clay its physical properties
- The nature of these layers are stacked together on top of one another define the type of clay
- The sandwiches of tetrahedral and octahedral layers are joined with exchangeable layer
- Distance between layers are 9-15 Angstrom units (0.9-1.5 nm)
- In some clays, the exchangeable layer is relatively tightly bound in the structure
- Cation exchange capacity (CEC) measures how readily exchange take place
- CEC measured by dispersing a known amount of clay in a solution of magnesium chloride to replace as much as possible the exchangeable layer with magnesium
- It then transferred to a solution of potassium or calcium chloride
- The amount of potassium or calcium absorbed by clay is measured
- The amount is expressed in milliequivalents per 100 gm of dry clay and called (CEC)
- Typical values of bentonite are 70-130 and for attapulgite 5-99
- CEC used as a guide to the quality of clay

### **Hydration of clay**

- Clays with high CEC exchange large amount of water into the exchangeable layer and adsorb water onto the outer surface of plates
- This effect gives high viscosity and high yield point

- Adsorption of water causes a very sticking expansion of clay
- For sodium bentonite, the distance between layers increased from 9.8 to 40 Angstrom
- For calcium bentonite from 12.1 to 17 A
- Overall hydration transform clay from dry power to plastic slurry
- The effectiveness is measured by yield of clay
- Yield of clay is defined as the number of barrels of 15 CP mud obtained from 1 ton (2000 lb) of dry clay
- Clay yield depends on: purity, nature of atoms in exchangeable layers and salinity of water

### **Bentonite or attapulgite**

- Bentonite consists primarily of montmorillonite
- Came from French town Montmorillon, where first mined 1874
- Basic structure is close to pyrophyllite.
- There are a small number of exchangeable ions, sodium calcium and magnesium
- Most common bentonite are those with sodium and calcium as exchangeable ions
- Attapulgite belongs to a different family of clay minerals
- Instead crystallizing as platy crystals, it forms needle like crystals
- Have excellent viscosity and yield strength when mixed with salt water
- Disadvantage is suffering high water loss and poor sealing properties
- Dispersion, flocculation and deflocculation
- Agitating of clay suspension in water gives three modes: edge to edge; face to edge; and face to face
- Dispersion occurs with no face or edge association
- It results in increase in viscosity and gel strength
- Aggregate occurs with face to face association
- Aggregate results in a decrease in viscosity and gel strength
- Flocculation occurs with face to edge association
- It causes excessive gelation
- Flocculation can be broken by chemical thinners
- The resulting suspension is called deflocculated

## **Inert solids**

- Include low gravity and high gravity
- Low gravity include sand and chert
- High gravity are added to increase mud weight or density
- Referred to as weighting materials
- Mud named as weighted mud, they are:

**Barite** (barium sulphate,  $\text{BaSO}_4$ ) sp.gr. 4.2

- Used to prepare mud in excess of 10 ppg
- Referred to as weighting agent for low cost and high purity

**Lead sulphides** (galena) sp.gr. 6.5-7.0

- Allowing mud weight up to 35 ppg

**Iron ores**, sp. gr. 5+

- More erosive
- Contain toxic materials

## **Chemical Additives**

- Used to control mud properties
- Divided into thinners and thickeners

## **Mud thinners**

- Reduce viscosity by breaking attachment of plate through edge or face by attaching the clay plates
- **Phosphates:** sodium tertaphosphates ( $\text{Na}_4\text{P}_3\text{O}_7$ ) and sodium acid pyrophosphated ( $\text{Ba}_2\text{H}_2\text{P}_3\text{O}_7$ ), Suitable for any pH value, Limited to 175 F (70 C)
- **Chrome lignosulphonate:** Decomposes at 300 F (149 C), deflocculate and disperses clay, Reduce viscosity, yield strength and water loss, chrome lignosulphonate attaches to broken edges of clay reduces the attractive forces,
- **Lignite:** Decompose at 350 F (177 C), can be used as water loss agent

- **Surfactants** (surface tension reducing agent): Reduce water loss, Used as emulsifiers in oil base mud

### **Mud thickeners**

- **Lime or cement:** Increase viscosity by flocculation resulting from replacement of  $\text{Na}^+$  cations by  $\text{Ca}^{++}$  cations
- **Polymers :**
  - Large molecules made up of many repeated small units called monomers
  - Used for filtration control, viscosity modification, flocculation and shale stabilization
  - Cause little change in solid contents of mud
  - Polymer mud have high shear-thinning ability at high shear rate
  - This reduces viscosity and in turn frictional pressure loss
  - Hydraulic bit horse power increases and in turn penetration rates
  - Three types are available:
    - **Extenders:** sodium polyacrylate, increases viscosity by flocculating bentonite
    - **Colloidal polymer:** CMC, HEC and starch
      - **CMC:** an ionic polymer produced by treating cellulose with caustic soda and monochloro acetate, molecular weight ranges between 50,000 and 400,000
      - **HEC:** similar to CMC but hydrate in all types of salt waters
      - **Starch:** produced from corn or potatoes, molecular weight up to 100,000, used to develop viscosity and act as filtration control agent
      - Control filtration by forming sponge like bags wedges into the opening of the filter cake, disadvantage is that it is amenable to bacterial attack at low pH
    - **Large chain polymer:** include xanthenes gum
      - It is water soluble
      - Produced by the action of bacteria on carbohydrates

- Molecular weight 5,000,000
- Amenable of bacterial attack at temperature above 300 F
- Build viscosity in all types of water
- More expensive
- Limited with 13 ppg mud

## Types of water base mud

### Clear water

- Fresh or saturated brine water can be used to drill hard, compacted and near-normally pressured formation

### Native mud

- Water pumped down letting it react with formation containing clay or shale
- Water dissolves clay and return to surface as mud
- Characterize by high solid content and high filter loss resulting in thick filter cake

### Calcium mud

- Reduce clay and shale swelling
- Superior to fresh water mud for drilling gypsum and anhydrite
- Compared to sodium, calcium cations strongly attaches to clay sheets
- The sheets tend to be pulled together and aggregated
- Calcium reduces clay swelling by 50% with 150 ppm concentration, therefore clay cuttings will be reduced
- Can tolerate high concentration of drilled solids with viscosity increase
- Two types are available: Lime mud and gyp mud
  
- **Lime mud:** up to 120 ppm soluble calcium
  - Prepared by mixing bentonite, lime ( $\text{Ca}(\text{OH})_2$ ), thinner, caustic soda and an organic filtration control agent
  - Lime provide the inhibiting ion ( $\text{Ca}^{++}$ )
  
- **Gyp mud:** up to 1200 ppm soluble calcium
  - Similar to lime except that lime is replaced by gyp
  - Has greater stability than lime



### **Lignosulphonate mud**

- Suitable for high density, > 14 ppg
- Work under high temperature 250-300 F (121-149 C)
- High tolerance for contamination of drilled solids, salt anhydrite, cement
- Low filter loss
- Consists of: Fresh or sea water, bentonite, chrome or ferrochrome lignosulphonate, caustic soda CMC or stabilized starch
- Optional materials such as lignite, oil, lubricants, surfactants
- Suitable for drilling shale
- Disadvantage; cause damage to reservoir permeability
- Now seldom used

### **KCl/Polymer muds**

- Consists of: fresh or sea water; KCl; inhibiting polymer; viscosity building polymer (xanthenes); CMC or stabilized starch; caustic soda or caustic potash, and lubricants
- Suitable for drilling shale because it prevents shale sloughing
- Used to drill pay zone due to its low solid contents
- Known as low solid or nondispersed mud
- Low tolerance to solids; need efficient desanders and desilters
- Have many advantages:
  - High shear thinning allow solids removal
  - High true yield strength
  - Improve bore hole stability
  - Good bit hydraulics
- Disadvantage is instability at temperature above 250 F (121 C)

### **Salt-saturated mud**

- Water is saturated with sodium chloride; 315,000 ppm
- Drills salt domes and salt sections, prevent hole washout
- Used with polymer to inhibit the swelling of bentonitic shale
- Consists of: fresh, brine or sea water; common salt; encapsulating polymer, and CMC or starch
- Low tolerance to solids
- Need high filter loss additives

## **Oil base mud**

- Water in oil emulsion
- Diesel or crude oil forms its continuous phase
- Sometimes called invert emulsion
- Water droplets are emulsified in oil
- Water is used for gel strength and barite content
- Soaps are used as emulsifiers
- Soaps are made from monovalent ion ( $\text{Na}^+$ ) or divalent ion ( $\text{Ca}^{++}$ )
- The soap molecule bridge together oil and water interfaces
- Agitation is required to break the water into small droplets
- Oil/water ratio determine the final properties
- Higher oil water increases resistance to contamination and temperature stability
- Used to drill hole with severe stability
- More stable at high temperature
- An excellent to drill pay zone; reduce formation damage and preserve original permeability
- Disadvantages:
  - Contaminate the environment
  - Flammability hazards
  - Difficult removal of drilled solids due to high plastic PV
  - Difficult electric logging

## **Emulsion mud**

- Water is a continuous (normal oil 5-10% by volume)
- Formulated by using sodium soap as emulsifier
- Oil is added to increase penetration rate, reduce filter loss, improve lubricity, reduce lost circulation and reduce torque and drag in directional well

## **Properties of mud**

- Include weigh or density, rheological properties, filtrate and mud cake, and pH value

## **Mud weight or density**

- Weight or mass per unit volume
- Depend on solids in the liquid, either in solution or suspended

- Calculated by sum of weighs over sum of volumes
- Increases by adding solid materials
- Decreased by adding water or oil or aerating the liquid
- Measured by mud balance: a steel cup filled with freshly mud sample and balanced on a knife edge
- Expressed in ppg, pcf or  $\text{kg/m}^3$

### **Rheological properties**

- They are plastic viscosity, yield point and gel strength

### **Plastic Viscosity (PV)**

- Control the magnitude of shear stress develops as one layer of fluid slides over another
- Measure of friction between layers
- Provides a scale of the fluid thickness
- Decreases with increasing temperature; with liquids; the reverse with gasses
- Effective viscosity depends on fluid velocity flow pattern, difficult to measure, but calculated
- For Bingham plastic

- $$\mu_e = PV + \frac{300}{V_a} (D_h - D_p) YP$$

- For power law

- $$\mu_e = \left[ \frac{2.4V_a (2n+1)}{(D_h - D_p) 3n} \right]^n 200K \left( \frac{D_h - D_p}{V_a} \right)$$

- Plastic viscosity and yield point are measured by Viscometer
- Six readings are available at six rpm (3, 6, 100, 200, 300, 600)
- PV is the difference between reading sat 600 and that at 300
- YP is the difference between readings at 300 and PV
- March funnel is used to viscosity
- Measurement shows thickness or thinning of fluid
- Mud with poured in 1500 cc funnel with orifice at the end
- Time to collect 946 cc (one quart) is measured
- Time for water about 26 sec
- Time for the rest indicate the gel strength

### **Yield point**

- A measure of the attractive forces between particles due to positive and negative charges
- Measure the forces causes mud to gel in case of motionless
- Shows a minimum level of stress must be provided before mud flow
- Expressed in  $\text{lb}/100\text{ft}^2$

### **Gel strength**

- Ability of mud to develop gel structure
- Defines the ability of mud to held solids and measure thixotropy
- Determined using viscometer
- The sample stirred at high speed and the allowed to rest for 10 sec or 10 min
- The torque readings at 3 rpm is taken as gel strength at specified time
- Expressed in  $\text{lb}/100 \text{ft}^2$
- Converted to metric by multiplying by 0.478

### **Filtration and filter cake**

- Fluid loss against porous and permeable rock is called filter loss
- A layer of solids deposited on the rock is described as filter cake
- Loss occur when mud pressure is higher than formation pressure
- Quantity of mud loss depends on volume of filtrate and thickness and strength of filter cake, and differential pressure
- Can be determined by filter press, called API filter press
- Consists of a cylinder with 3 in diameter and 2,5 in length with fine screen at the base
- Pressure applied on the sample, 100 05 500 psi and 60 F
- HPHT filter press measure at bottom hole pressure and temperature
- The volume collected in cc per 30 min, API filter loss
- The thickness of mud cake in  $1/32$  in express the mud cake thickness
- Betonite, emulsified oil, dispersant, CMC and starch used to reduce filter loss, starch is used with  $\text{pH} > 11.5$
- Ideal mud gives small filter loss and thin and tough mud cake

### **pH of mud**

- Describe the acidity or alkalinity of mud

- Defined as the negative logarithm of the hydrogen ion (H<sup>+</sup>)
- Measured by pH meter or strips
- The following table shows the pH value and the description of the fluid

H <sup>+</sup>	OH <sup>-</sup>	pH=-log H <sup>+</sup>	Description
10 <sup>0</sup>	10 <sup>-14</sup>	0	Acidic
10 <sup>-7</sup>	10 <sup>-7</sup>	7	Neutral
10 <sup>-10</sup>	10 <sup>-4</sup>	10	Basic
10 <sup>-17</sup>	10 <sup>0</sup>	14	Basic

The following table shows the pH value of some solutions

Solution	pH
Distilled water	7
Bentonite suspension	8
Caustic soda, 10% concentration	
Lignite, 10%	5
Sodium acid phosphate	3.09-4.2

- Play a major role in controlling calcium stability
- Starch is used to increase pH to 11.5, but with bactericide
- Optimum pH between 8 and 11
- Minimum value of 7 should be maintained to control corrosion

### Mud calculations

#### Mud weight increase

- Amount of barite
- $$M = 1491 \frac{(\rho_{m1} - \rho_{m2})}{(35.5 - \rho_{m2})} \quad \text{Lbs}$$
- Number of sacks

$$\triangleright S = 15.9 \frac{(\rho_{m2} - \rho_{m1})}{(35.5 - \rho_{m2})} \text{ Sacks}$$

➤ Mud volume increase due to adding barite

$$\triangleright V = \frac{42(\rho_{m2} - \rho_{m1})}{(35.5 - \rho_{m2})} \text{ Bbl}$$

### To reduce mud weight by adding oil or water

$$\triangleright V_{o,w} = V_{m1} \frac{(\rho_{m2} - \rho_{m1})}{(\rho_{o,w} - \rho_{m2})}$$

### Final mud density

$$\triangleright \rho_{m3} = \rho_{m1} - \left( \frac{V_{m2}}{(V_{m1} + V_{m2})} \right) (\rho_{m1} - \rho_{m2})$$

➤ Or

$$\triangleright \rho_{m3} = \rho_{m1} - \left( \frac{V_{m2}}{(V_{m1} + V_{m2})} \right) (\rho_{m1} - \rho_{m2})$$

### In metric system

#### Mud weight increase

➤ Amount of barite

$$\triangleright M = 42500 \frac{(\rho_{m1} - \rho_{m2})}{(4250 - \rho_{m2})} \text{ Kg}$$

➤ Number of sacks

$$\text{➤ } S = 996.7 \frac{(\rho_{m2} - \rho_{m1})}{(4250 - \rho_{m2})} \text{ Sacks}$$

➤ Mud volume increase due to adding barite

$$\text{➤ } V = \frac{10(\rho_{m2} - \rho_{m1})}{(4250 - \rho_{m2})} \text{ m}^3$$

### To reduce mud weight by adding oil or water

$$\text{➤ } V_{o,w} = V_{m1} \frac{(\rho_{m2} - \rho_{m1})}{(\rho_{o,w} - \rho_{m2})}$$

### Final mud density

$$\text{➤ } \rho_{m3} = \rho_{m1} - \left( \frac{V_{m2}}{(V_{m1} + V_{m2})} \right) (\rho_{m1} - \rho_{m2})$$

➤ Or

$$\text{➤ } \rho_{m3} = \rho_{m1} - \left( \frac{V_{m2}}{(V_{m1} + V_{m2})} \right) (\rho_{m1} - \rho_{m2})$$

### Mud contaminants

#### Sodium chloride

- Enters mud during drilling salt domes, rock salt beds, evaporites or any bed containing salt water
- Increase viscosity, yield strength and gel strength of bentonite mud due to flocculation
- Salt decreases pH value
- Salt solution cause hole enlargement, so salt saturated mud is recommended

- Routine measurements of mud chloride content are used to monitor the change in mud salinity
- Sudden increases indicates salt water flow

### **Anhydrite and gypsum**

- Forms of calcium sulphate ( $\text{CaSO}_4$ )
- Formation containing anhydrite and gypsum are common in massive or interbedded
- Contamination leads to clay flocculation, increase viscosity, yield strength, filtrate loss and gel strength
- Caustic soda and chrome lignosulphonate are added to mud to drill these formation
- Sodium carbonate ( $\text{Na}_2\text{CO}_3$ ) can added to treat mud

### **Cement**

- Enter mud from poor cement jobs or squeeze cementing
- Increase viscosity, yield point and gel strength
- Discard mud used to drill cement
- Mud contaminated with cement treated with sodium bicarbonate
- Calcium content should be below 200 ppm

### **Mud conditioning**

- Mud prepared by mixing water or oil with bentonite or attapulgite, barite and various chemicals
- Mud carries drilled cuttings to surface
- Mud loose much of its desired properties if drilled solids are not removed, and cause potential problems such as lost of circulation
- Mud conditioning equipment remove unwanted solids
- Three sections are available
  - Suction tank
  - Addition and mixing section
  - Removal section

### **The addition and mixing section**

- Mixing operation involves pouring of mud solids or chemicals through a hopper connected to high shear jet
- The shear jet homogenize the mixture
- The resulting mud is again agitated with mud gun or an agitator



- The resulting mud is then directed to the suction tank
- The mud in the suction tank is handled with a centrifugal or charge pumps
- The charge pumps give the mud a pressure of 89 to 90 psi (5.5-6.2 bar) before it delivers to the main rig pump
- This improve the rig pump efficiency
- From the rig pump the mud flows through the circulation system

### **The removal section**

- Consists of:
  - Shale shaker
  - Hydrocyclone
  - Mud cleaner
  - Centrifuge

### **Shale shaker**

- A vibrating or rotating sieve
- Sieves have opening enough to pass mud and its solids
- Cuttings retained on the sieve and collected in a pit
- Can be single- or double-decker shaker
- Mud from shale shaker pass to sand trap below shale shaker
- Small drill cutting removed by gravity

### **Desander and desilter**

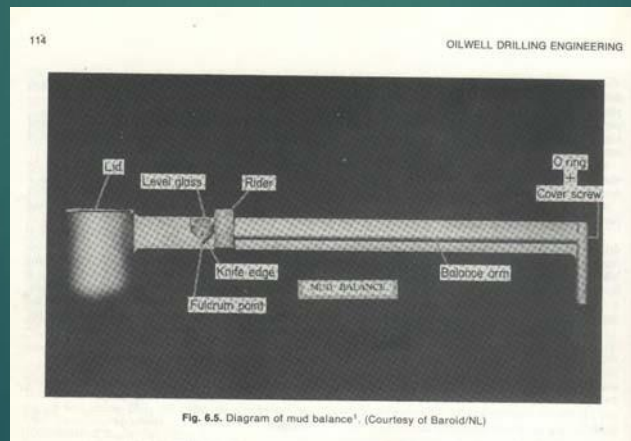
- Mud from sand trap sent to desander and desilter (hydrocyclone)
- Centrifugal force separate solids from mud
- Hydrocyclones contain no moving parts
- Consists of:
  - An upper cylindrical section with a tangential feed tube and fitted with a vortex
  - A conical section ending with an apex
- Solids flow through the apex and discharged
- Clean mud flows through the vortex and send to the active pit
- Large size used for sandy particles (above 74 micron)
- Small-sized used for silty particles (2-74 micron)
- Desander diameter is from 6-12 in optimum 10 in
- Desilter diameter is from 4-5 in., not used with weighted mud

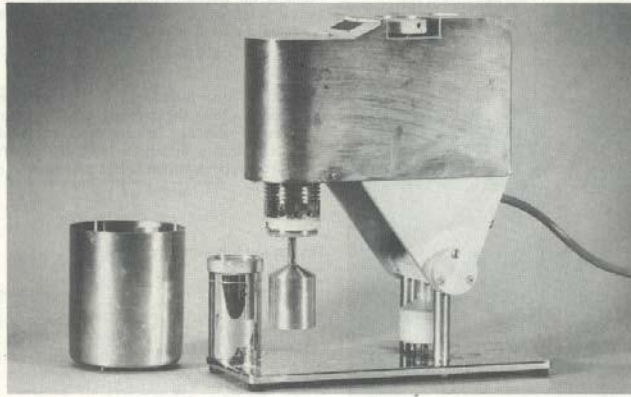
## Mud cleaner

- Replaces desander and desilter for weighted mud
- Used to save barite
- Consists of a hydrocyclone with 4 in diameter above a high-energy vibrating screen with openings of 10-125 micron
- The barite will pass through the screen and reused
- Advantage is to save barite, KCl, oil and mud
- Waste is much drier and need fewer disposal problems

## Centrifuges

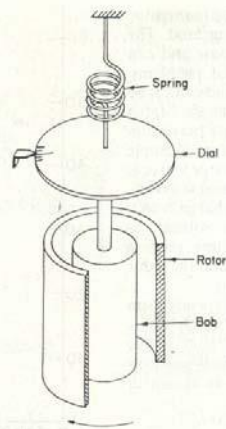
- Use centrifugal forces
- Separate heavy solids from liquid and lighter component
- Consists of:
  - Horizontal conical steel bowl, rotating at high speed
  - Double screw type conveyor inside the bowl rotated at low speed
  - The conveyor contains a hollow spindle for feeding mud
- The solids removed from the liquid by centrifugal forces
- The rotation of the bowl holds the slurry in bond against the wall of the bowl
- The conveyor blades scrapes or pushes the settled solids towards a narrow end of the bowl
- The solids collected are a dump particles with no fluids
- The liquid and clay particles collected as an overflow from ports at the large end of the bowl
- Clean mud requires treatment if properties changed





(b)

Fig. 6.6. (a) Diagram of concentric cylinder viscometer<sup>2</sup>; (b) apparatus for measuring viscosity, yield point and gel strength (rheometer). (Courtesy of API)<sup>6</sup>

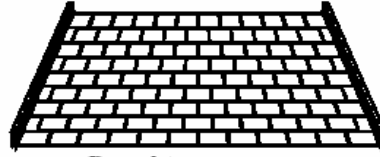


(a)

### Two-dimensional

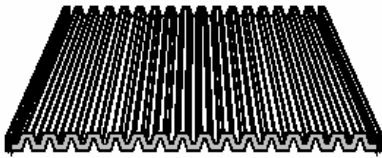


Two-layer nonperforated  
plate panel

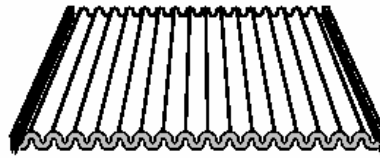


Panel type screen

### Three-dimensional

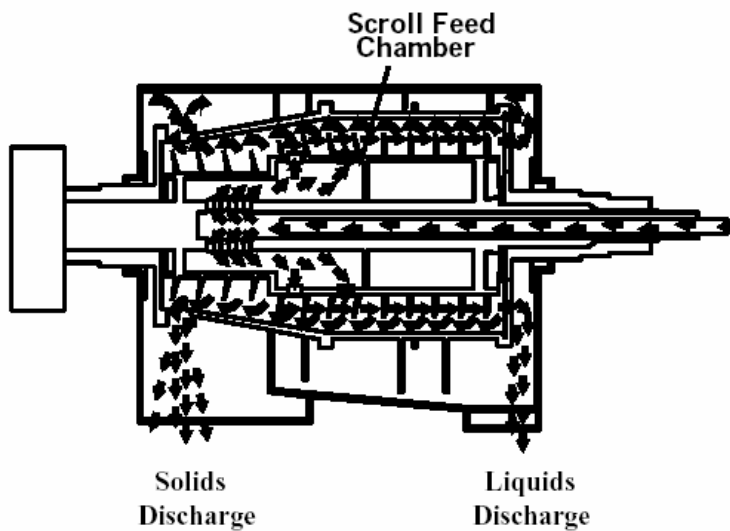


Plateau

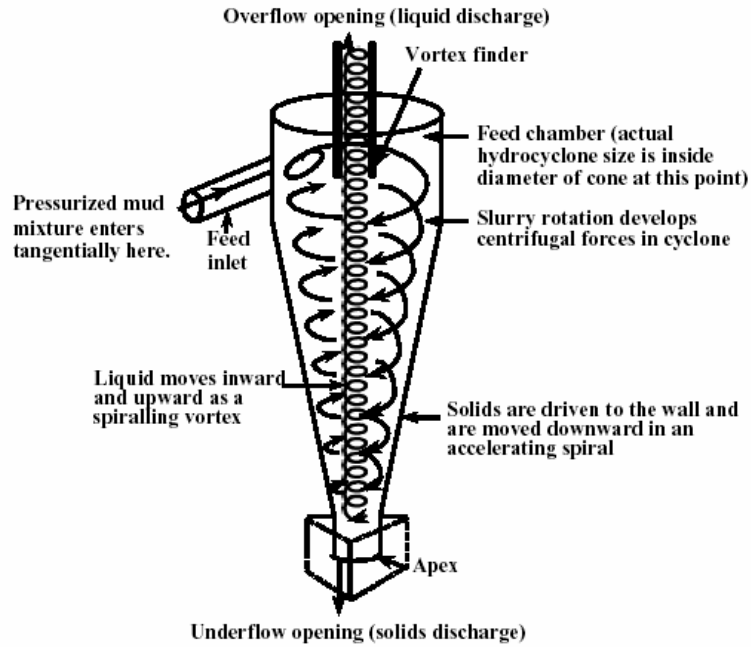


Pyramid

### Decanting centrifuge cross-section



### Hydrocyclone solids-removal process



### Hydrocyclone operating ranges

Equivalent size cut removed (in microns)

