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# **Understanding the Role of Drilling Fluids: A Functional Overview for Well Engineers**

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**ABSTRACT**: Drilling fluids are indispensable to the safety, efficiency, and success of hydrocarbon well construction. Despite their multifaceted roles in well control, cuttings transport, pressure management, and tool protection, these functions are often underrepresented in technical literature and engineering curricula. This review provides a systematic, function-by-function analysis of drilling mud's critical responsibilities, synthesizing insights from academic research, industry standards, and field experience. Eleven key functions are examined: (1) cleaning the wellbore face, (2) transporting cuttings to the surface, (3) controlling formation pressure, (4) forming a filter cake, (5) cooling and lubricating tools, (6) supporting drill string weight via buoyancy, (7) transmitting hydraulic power, (8) maintaining physicochemical equilibrium with formations, (9) suspending solids during circulation stops, (10) providing geological and pressure data, and (11) aiding rock destruction. Each function strategies. The article underscores that a holistic understanding of these roles enables engineers to design safer, more economical drilling programs while mitigating risks such as well kicks, stuck pipe, and formation damage. By demystifying mud's technological contributions, this work serves as a foundational resource for well engineers and educators alike.

KEYWORDS: Drilling Fluids, Well Engineering, Hydrostatic Pressure, Cuttings Transport, Wellbore Stability.

#### **I. INTRODUCTION**

Drilling a well is a complex and highly coordinated operation that is fundamental to accessing subsurface hydrocarbon resources. At its core, the well represents a deep cylindrical excavation—a form of underground mining with a depth that greatly exceeds its diameter [1]. Key elements of a well include the wellhead, the walls of the borehole (wellbore), the axis, and the bottom or face of the well [1]. The drilling process may be carried out through full-face penetration or via core-sampling techniques, depending on the objectives and formation characteristics. Well diameter is usually expressed in inches (1 in  $\approx 25.4$  mm), while depth may be recorded in meters or feet, either in real time or as final measured depth [1][2].

This subsurface structure is created through two essential processes. First, the mechanical destruction of rock at the bottom of the well using a cutting tool such as a bit [3]. Second, the continuous removal of rock fragments (cuttings) from the borehole. This removal is achieved by circulating a specially formulated fluid—drilling mud—which flushes cuttings to the surface [3][4].

Drilling mud performs a wide range of critical functions during the drilling process. It transports cuttings, maintains hydrostatic pressure to balance formation pressures, cools and lubricates the bit and drill string, stabilizes the borehole, controls fluid losses, supports downhole measurements and logging, and more—all contributing to well control, efficiency, and safety [2][4][5]. Despite the essential nature of these roles, many of them are underemphasized in both technical literature and engineering education. This review article provides a clear, function-by-function overview of the roles performed by drilling mud, integrating insights from academic sources, industry manuals, and personal field experience. Each function is examined with the significance it merits, offering new engineers a practical and comprehensive resource to better understand and manage this essential component of well construction.





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## **II. LITERATURE SURVEY**

Drilling fluids are classified as disperse systems or suspensions. These complex mixtures are governed by interfacial surface phenomena at the boundaries between phases, which play a fundamental role in determining the behavior of the system. These interactions directly influence essential characteristics such as fluid stability, chemical responsiveness, and the functional performance of the fluid [6][7].

Every material body is enclosed by a surface where specific molecular interactions may occur. In disperse systems, such interactions take place at the interfacial boundary layer formed between the dispersed and continuous phases. At this interface, unsaturated atomic and molecular forces result in structural organization that gives the material properties not found in the individual bulk phases. These are known as emergent properties — system-level characteristics that arise only from the interaction of components, and which are widely recognized across the physical and natural sciences [8].

Disperse systems are heterogeneous in nature and consist of at least two phases. One phase, the continuous medium or dispersion phase, provides the environment in which another phase is distributed. This second phase, the dispersed phase, consists of finely divided solid particles or liquid droplets. A useful classification method is based on the physical state of each phase. Since both phases may exist as solids, liquids, or gases, there are nine basic combinations of disperse systems [7][9].

In drilling applications, the focus is primarily on liquid-based systems. Water-based drilling fluids, for example, are typically composed of water as the continuous medium and clays, such as bentonite, as the dispersed solid phase. These clay-water suspensions exhibit key rheological behaviors — such as gel strength, yield point, and thixotropy — that do not arise from their components in isolation. Instead, they emerge from the physicochemical interactions occurring within the dispersed system [9][10].

A commonly accepted classification system categorizes drilling fluids based on the type of continuous phase or dispersion medium. In these terms, the classification would be as follows:

1. Water-Based Drilling Fluids; Water-based fluids are the most widely used due to their environmental compatibility and cost-effectiveness. They are categorized into fresh water-based and mineralized water-based systems [11].

1.1 Fresh Water-Based Fluids;

- Simple (unprocessed) fluids are made by mixing clay with water. Densities range from 1080 to 1400 kg/m<sup>3</sup> with clay content between 120-730 kg/m<sup>3</sup>. These are used in shallow wells or upper intervals of deeper wells. Advantages include low cost and high drilling speed. However, they tend to increase in viscosity and density due to dispersed cuttings and lack sufficient inhibition [12].
- Processed fluids incorporate reagents like caustic soda, lime, and ferrochrome lignosulfonate (FCLS) to adjust pH, rheology, and filtration. FCLS reduces viscosity and improves thermal stability (up to 120°C), while also inhibiting clay swelling. Other additives include hexametaphosphate, starch, and polyacrylamide [13][14].
- 1.2 Mineralized Water-Based Fluids (Inhibited Systems); These prevent hydration and swelling of clay formations using various ionic inhibitors [15].
  - Calcium-Based Fluids:
    - Lime-Based Fluids: contain Ca(OH)<sub>2</sub> and additives to reduce viscosity and filtration. Benefits include stability in formations with gypsum or salt content (3-4%) and reduced clay swelling. Their limitations include sensitivity to temperature and increased static tension [16].
    - o Gypsum Fluids use CaSO<sub>4</sub>: they improve thixotropy but require additives to manage viscosity. They withstand high temperatures (up to 200°C) and salt contamination [17].
    - Calcium Chloride Fluids (CaCl<sub>2</sub>): offer high Ca<sup>2+</sup> concentrations for strong inhibition and clay stabilization. Ion exchange processes reduce clay swelling [18].
  - Salt-Based Fluids (NaCl): These inhibit clay hydration by reducing electrokinetic potential through Na<sup>+</sup> and Cl<sup>-</sup> interactions. Their effectiveness depends on concentration and mixing order. Saturated brines (32-34% NaCl) are used in salt formations or high-pressure zones. Downsides include foaming, corrosion, and high cost [19].





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- Potassium-Based Fluids (KCl): Potassium ions, due to their ionic radius and hydration energy, offer strong inhibition against swelling. They are particularly effective in dispersing reactive shales [20].
- Silicate-Based Fluids: These contain 25-29% sodium silicate, improving wellbore stability in clay-rich formations. They are often used with cellulose and FCLS. Limitations include high viscosity and difficulty in property control [21].
- 2. Oil-Based Drilling Fluids; Used under special conditions, especially for avoiding reservoir damage and drilling reactive formations [22].
- 2.1 Pure Oil-Based Fluids; Comprised of diesel or crude oil, emulsifiers, lime, and weighting agents. Oxidized asphalt improves rheology similarly to clays in water-based systems. These fluids offer excellent inhibition, corrosion protection, and lubricity, but have high costs, environmental concerns, and safety risks [23].
- 2.2 Emulsion Fluids;
  - Direct Emulsions: Oil dispersed in water (5-40%). Lower density and high lubricity are typical; barite is used for weighting [17]. (Arvind D. Patel, 1999)
  - Reverse Emulsions: Water dispersed in oil (30-40% water). Common in reservoir drilling due to minimal formation damage [17].

Advantages include superior lubrication, bit protection, and reduced differential sticking. However, they complicate geophysical logging, are expensive, and pose fire hazards [25].

 Low-Solid Fluid; Designed to avoid reservoir contamination and maintain rheological properties without solid additives. Density is achieved using dissolved salts, and rheological control is via polymers. Their success relies on avoiding salt crystallization during use [14].

4. Gaseated Drilling Fluids; Used in formations with high permeability and strength. Types include:

- Air or Natural Gas: Offers low hydrostatic pressure, high drilling speed, and minimal formation damage [26].
- Aerated Fluids: Gas is injected into liquid base, increasing lifting capacity and enabling use in deeper wells [27].
- Foams: Require surfactants (foam stabilizers) and are suited for high ROP and sensitive formations [28].

Limitations include poor pressure control, corrosion risk, and depth restrictions.

The drilling fluid performs its cleaning and transport functions by circulating continuously in a closed loop within the well. The fluid circulation system is generally divided into two main parts:

The surface system consists of the mud pumps, high-pressure transmission lines, flexible hoses, the rotary hose, the swivel or top drive, the solid control equipment (such as shale shakers, desanders, desilters), and the mud tanks used for settling and fluid storage [12][29][30].

The subsurface system includes the drill string with all its components (drill pipe, drill collars, stabilizers, and the bit), and the annular space between the wellbore wall and the drill string. Through this annular space, the returning fluid carries the drilled cuttings back to the surface for separation and treatment before being recirculated [29][31][32].

## **III. DRILLING MUD FUNCTIONS**

Drilling mud plays a crucial role in the drilling process by performing a range of technological functions that ensure the efficiency and safety of well operations. These functions include cleaning the wellbore face from crushed rock fragments and carrying these cuttings to the surface, controlling formation pressure by exerting the necessary counterpressure, and cooling and lubricating the drill bit and drill pipes [33]. Additionally, drilling mud helps form a clay cake on the wellbore walls to prevent formation collapse, supports part of the drilling string and casing weight through buoyancy (Archimedes' principle), and maintains the suspension of weighting materials and cuttings when circulation stops [14]. It ensures the physicochemical balance of interactions between the drilling fluid and the formations being drilled, transmits the hydraulic power required for the drill bit and downhole tools, and provides valuable information about the formations and their fluids [11]. Moreover, drilling mud actively participates in the rock-breaking process at the well face [34]. These functions are essential for successful and economical operations in the oil and gas industry





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[12]. Each of these key functions will now be discussed in detail to better understand their significance and how they are achieved in drilling operations:

## A. Cleaning the Wellbore Face from Mud and Cuttings

Cleaning the wellbore face from crushed rock fragments is the drilling fluid's ability to carry the mud and cuttings from the well face into the annular space. To perform this function effectively, the velocity of removing the cuttings created by one drill bit tooth must be such that when the next tooth arrives, it finds the wellbore face clean of cuttings [14]. The rate of cleaning the wellbore face from crushed rock is an important factor for improving drilling parameters [34]. The main role in this regard is played by the volume of drilling fluid delivered per unit time to the well face (flow rate Q). The term flow rate refers to the volume of fluid passing through a given cross-section per unit time [12]. Since the flow rate tells us the volume of fluid passing through a cross-section per unit time, it can be expressed as [35]:

$$Q = \frac{V}{t} \qquad (m^3/s) \qquad (1)$$

Where: Q =flow rate (m<sup>3</sup>/s); V = volume of fluid (m<sup>3</sup>); t = time (s);



Figure 1. The concept of flow rate [35].

For example, if the volume of fluid has a cylindrical shape (usually pipes have this shape), then the volume V can be expressed as the product of the pipe's cross-sectional area S and the height h [35]:

$$V = S * h \to Q = \frac{v}{t} = \frac{S * h}{t} = S * v \qquad (2)$$

Where : where v (m/s) is the velocity of fluid flow.



Figure 2. Different form of expressing the flow rate [35].





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Since drilling fluids are incompressible, the law of volume conservation applies. Thus, the volume flow rate Q is constant through any two cross-sections [35]:

$$Q_1 = Q_2 = Q = c^{st} \tag{3}$$

$$Q = S * v = c^{te} = S_1 * v_1 = S_2 * v_2 \tag{4}$$



Figure 3. Constant flow rate through different section [35].

Drilling bit performance improves with increasing drilling fluid flow rate, but only up to a certain point. Beyond this point, further increases in flow rate no longer improve drilling parameters [12]:



Figure 4. Drilling speed as a function of mud rate.

$$for \ 0 \le Q \le Q_{op} \to Q_1 < Q_2 < Q_3 \to ROP_1 < ROP_2 < ROP_3$$
(5)

$$for \ Q \ge Q_{op} \to ROP = constant \tag{6}$$

As the flow rate Q increases, more drilling fluid is delivered to the wellbore face, improving the removal of cuttings and cleaning efficiency. However, beyond a certain optimal flow rate  $Q_{op}$ , all the cuttings produced by each drill bit tooth are effectively cleared. At this point, the wellbore face is already clean when the next tooth arrives, so increasing Q further does not provide additional benefits [14]. Essentially, once the cuttings are completely removed, higher flow rates cannot improve drilling parameters any further because there is simply no additional debris to transport away [11]. How is the required flow rate for cleaning the wellbore face determined? Three criteria are used, each producing a flow rate value, and the maximum of these is chosen [34]:

- 1. Minimal velocity the drilling fluid must have in the annular space to transport cuttings,  $v_{min}=0.5$  m/s;
- 2. Specific pump flow rate,  $q_{sp}=0.043 (l/s)/cm^2$ ;
- 3. Percentage of cuttings in the drilling fluid  $\leq 2\%$  solids;

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$$Q_{op} = Q_{max} \begin{cases} Q_1 = v_{min} * S_{an} \\ Q_2 = q_{sp} * S_w \\ Q_3 = \frac{Q_s}{0.02} \end{cases}$$
(7)

Where:

 $S_{\text{an}}-$  Surface area of the annular space;

Sw – Surface area of the well;

 $Q_s$  – Production rate of solids,  $Q_s = ROP * S_w$ ;

ROP - Rate of penetration (drilling speed) [36];

The type and parameters of the drilling fluid are also very important, as they must be able to remove the cuttings from the wellbore face as quickly as possible.

Hydraulics at the wellbore face is especially important when using jet-assisted bits that utilize the hydraulic power of the drilling fluid to assist in rock destruction [31].

Besides the flow rate of the drilling fluid, another important parameter is the pressure P (Pa).

Pressure P is the force exerted by a fluid per unit area in a direction normal (perpendicular) to the surface [37].

$$P = \frac{F}{S} \tag{8}$$

Where:

P - Pressure (Pa) (1 Pa =  $1 \text{ N/m}^2$ );

F - Force (N);

S - Surface area (m<sup>2</sup>);



Figure 5. The concept of pressure [38].

To identify the factors affecting fluid pressure, consider a static volume of fluid shaped as a cuboid with surface area S and height h as in Figure 6.



Figure 6. Static volume of fluid shaped as a cuboid [37].





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According to Newton's second law:

 $F = m * a = m * g \tag{9}$ 

where m is mass and g is gravitational acceleration. Expressing pressure:

$$P = \frac{F}{s} = \frac{m * g}{s} \tag{10}$$

(11)

Mass is the product of volume and density:

where V is volume and  $\rho$  is fluid density. Volume is:

 $V = S * h \tag{12}$ 

Therefore:

$$P = \frac{F}{S} = \frac{m * g}{S} = \frac{V * \rho * g}{S} = \frac{S * h * \rho * g}{S} = \rho * g * h$$
(13)

Thus, the pressure inside a fluid depends on the fluid's density and depth of immersion. Pressure properties include:

- The force exerted by a fluid on the container walls is always perpendicular to the surface.

 $m = V * \rho$ 

- Fluid pressure depends on the fluid density and depth.
- At a given depth, fluid pressure is constant.
- Fluid pressure is independent of the shape or surface area of the container [39] [40].

The pressure provided by the pump to the drilling fluid will be equal to the sum of the hydraulic pressure losses throughout the drilling fluid circulation system.

$$P = \Delta p 1 + \Delta p 2 + \Delta p 3 + \Delta p 4 + \Delta p 5 + \Delta p 6 + \dots + \Delta p n$$
(14)

Where:

 $\Delta p1$ - Pressure loss in transport pipes;

 $\Delta p^2$ - Pressure loss in the hose;

 $\Delta p3$ - Pressure loss in drill pipe;

 $\Delta p4$ - Pressure loss in heavy weight drill pipe;

 $\Delta p5$ - Pressure loss in drill collars;

 $\Delta p6$ - Pressure loss in annulus;

... and so on, depending on circulation system components.

Thus, the pump pressure depends on the hydraulic resistances generated in the circulation system. The power of the drilling fluid pump is a constant magnitude:

The power is a function of the production of flow rate and pressure:

$$\mathsf{N} = f(P * Q) \tag{16}$$

P \* Q = constant (17)

Where: P- Pressure generated from the pump; Q- Flow rate;

So:





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As the well depth increases and drilling progresses, the length of the circulation system also grows. Consequently, hydraulic losses increase due to the longer distance and greater friction that the drilling fluid encounters while traveling through the system. This requires the pump to generate a higher pressure P to overcome these resistances, which in turn may reduce the achievable flow rate Q due to power limitations. It is therefore essential to select pumps with sufficient capacity to deliver the maximum required pressure  $P_{max}$  while still maintaining the necessary flow rate for efficient cleaning and drilling operations [14][31].

The greater the hydraulic resistance, the higher the pressure that must be developed by the pump. However, this pressure increase must not exceed the design limits of the circulation system, as doing so could lead to failures in the tubing or even in the pump itself. The most critical component in this circulation system is the drill hose — the flexible hose that connects the delivery pipe to the injection head. This component must function reliably, especially under high-pressure conditions. To ensure safety and reliability, the drill hose is pressure-tested at 1.5 times its working pressure [12].

Wellbore cleaning methods can be categorized into three main types: direct circulation, reverse circulation, and combined circulation [14]. In direct circulation, the drilling fluid is pumped from the surface through the drill string down to the bit, where it exits through jet nozzles. This method cools and lubricates the bit, helps break the rock, and transports cuttings up the annular space. Its advantages include high exit velocity at the bit, support for borehole wall stability through mud cake formation, and continued drilling even during partial mud losses [11]. However, it can cause erosion of the core and borehole walls, especially in narrow annular spaces, and requires high flow rates to maintain efficient cuttings transport [34].

In reverse circulation, the fluid flows directly down the annular space, reaches the bit to cool and clean it, then returns to the surface through the inner drill string, carrying the cuttings. This method provides good bottom-hole cleaning but is unsuitable when mud losses occur [31]. It also increases erosion risk due to cuttings-rich fluid flowing inside the pipe and demands strong suction pumps and proper sealing at the wellhead [12].

Combined circulation uses both methods: direct circulation is applied down to the core barrel, while reverse circulation is activated deeper in the hole using special equipment. This technique increases core recovery but requires complex and specialized tools [36].

#### **B.** Transporting Rock Cuttings to the Surface

During well drilling, a significant volume of rock is mechanically destroyed. The drilling fluid must effectively carry these cuttings to the surface through the annular space. Each rock particle in the annulus is subjected to multiple forces, with the net force needing to act upward to ensure the particle moves toward the surface. These forces are [14]:  $P_1$  – Gravitational Force (Weight of the particle):

$$P_1 = V * \rho_c * g = \frac{\pi}{6} * d^3 * \rho_c * g$$
(18)

P2 – Buoyant Force (Archimedes' Principle):

$$P_2 = V * \rho_{mud} * g = \frac{\pi}{6} * d^3 * \rho_{mud} * g$$
(19)

P<sub>3</sub> – Hydrodynamic Drag Force (for laminar flow):

$$P_3 = \psi * A * \rho_{mud} * g = \frac{v_s^2}{2*g} * \frac{\pi * d^2}{4} \rho_{mud} * g = \frac{v_s^2}{2} * \frac{\pi * d^2}{4} \rho_{mud}$$
(20)

Where:

- V volume of the cutting;
- A Efficient Area of the cutting;
- $\rho_c$  density of the cutting;

d - diameter of the cutting;

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 $\rho_{mud}$  – density of the drilling mud;  $v_s$  – settling velocity; g - acceleration due to gravity;  $\psi$  – drag coefficient;





On the other hand, the velocity at which the cutting particle will rise in the annular space will be equal to the difference between the velocity of the drilling fluid in the annular space and the settling velocity. To ensure the particle is transported upward, this condition must be satisfied [11]:

$$v_{ct} = v_{mud} - \alpha * v_s > 0 \tag{21}$$

Where:

 $v_{ct}$  – velocity of the cutting;  $v_{mud}$  – velocity of the drilling mud in the anulus,

$$v_{mud} = \frac{Q_{mud}}{S_{an}} = \frac{Q_{mud}}{0.785(D_{db}^2 - D_{dp}^2)}$$
(22)

 $Q_{mud}$  – mud flow rate in the well;

 $S_{an}$  – surface area of the anulus;

 $D_{db}$  – drilling bit diameter;

 $D_{dp}$  – drilling string outer diameter;

v<sub>s</sub> – settling velocity, (for laminar flow and Newtonian fluids)

$$v_s = \frac{g_{*d^2(\rho_c - \rho_{mud})}}{18\eta}$$
(23) [14]

 $\eta$  – drilling mud viscosity;

 $\alpha$  - the cavernosity coefficient accounting for irregularities in the annular space;

Additionally, the circulation cycle of the drilling fluid is defined as the path a fluid particle travels from the surface through the drillstring, into the well, and back up to the surface through the annulus. The cycle time  $t_{cy}$  is the total time for one complete circulation and is calculated as [31]:

$$t_{cy} = \frac{v_{mud}}{q_{mud}} = t_t + t_c \tag{24}$$

Where:

 $V_{mud}$  – volume of the drilling mud;

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| $t_t$ – the time required for the drilling fluid to travel through the     | the tubing, $t_t = \frac{H}{v_t}$         | (25) |
|--|---|------|
| $t_c$ – the time required for the drilling fluid to travel through the     | the casing/annulus, $t_c = \frac{H}{v_c}$ |      |
| H- well (current) depth;   |   |      |
| $v_t$ – drilling mud velocity in tubing, $v_t = \frac{Q_{mud}}{S_t}$       | (27)                                      |      |
| $v_c$ – drilling mud velocity in casing/annulus, $v_c = \frac{Q_{mud}}{c}$ | (28)                                      |      |

 $v_c$  – drilling mud velocity in casing/annulus,  $v_c = \frac{c_m a_m}{S_c}$ 

 $S_t$  – surface area of tubing;

 $S_c$  – surface area of casing;

## **C. Formation Pressure Control**

As drilling advances to greater depths, the well encounters increasing lithostatic pressure—a fundamental geomechanical force in the subsurface. This pressure results from the weight of the overlying rock layers pressing down on the deeper formations. Its magnitude is governed by the thickness and density of these overlying strata, and it increases approximately linearly with depth under normal conditions [41].

Lithostatic pressure is not transmitted uniformly; it is partitioned into two primary components:

- Rock (or matrix) stress, also known as effective stress or mineral pressure, which is the portion of pressure transmitted through the solid rock framework [42].
- Pore pressure, which is the component of lithostatic pressure transferred to the fluids-such as water, oil, or gas—contained in the pores of the rock [43].

The pore pressure is particularly critical in drilling operations, as it represents the pressure the drilling mud must counteract to prevent fluid influx into the wellbore. This is achieved through the hydrostatic pressure exerted by the column of drilling fluid, calculated as [14]:

$$P_h = \rho_{mud} * g * H \tag{29}$$

Where:  $P_h$  - The mud hydrostatic pressure;  $\rho_{mud}$  - The mud density; g - acceleration due to gravity; H – Well vertical depth;

The pressure gradient is a physical operator that expresses the rate and direction of pressure change with depth. Each type of pressure encountered during drilling—such as lithostatic pressure, pore pressure, fracture pressure, and the hydrostatic pressure of the drilling mud—has its own corresponding pressure gradient [11].

The pore pressure gradient is considered normal when its value is  $G_{pn} = 10,094$  Pa/m. Gradients with values greater or lower than this are classified as abnormal [44]. Specifically, during drilling operations, formations may exhibit the following types of pore pressure gradients:

- Normal:  $G_p = G_{pn} = 10,094 \text{ Pa/m}$
- Overpressure (Abnormally High):  $G_p > 10,094$  Pa/m
- Underpressure (Abnormally Low):  $G_p < 10,094$  Pa/m

To calculate the pore pressure, it is sufficient to multiply the pore pressure gradient by the depth of the well:

$$P_P = G_p * H$$
 (30) [11]

Where:  $P_p$  – the pore pressure;

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 $G_p$  – the pore pressure gradient; H – the depth;

The drilling mud has its own hydrostatic pressure gradient, which depends directly on its density. This gradient determines how much pressure the mud column exerts per unit of depth.

$$G_h = \frac{P_h}{H} = \frac{\rho_{mud} * g * H}{H} = \rho_{mud} * g$$
 (31) [14]

The difference between these two pressures is called the **differential pressure** ( $\Delta P$ ) [12]:

 $\Delta \mathbf{P} = P_h - P_P \tag{32}$ 

Where:

P<sub>h</sub> - the mud hydrostatic pressure;

 $P_p$  - the formation pore pressure;

The sign of  $\Delta P$  determines the flow direction between the wellbore and the formation:

- If  $\Delta P > 0$ : the mud pressure exceeds the formation pressure, and the drilling fluid will invade the formation, potentially leading to lost circulation.
- If  $\Delta P < 0$ : the formation pressure exceeds the mud pressure, and formation fluids may enter the well, potentially causing a kick or even well blowout.
- If  $\Delta P \approx 0$ : the well is in balanced condition, and no flow occurs between the wellbore and the formation [36].



Figure 8. Diferential pressure into the well.

During the drilling process, we cannot control the pore pressure, as it depends on the geostatic pressure and various geological and geometrical factors. Therefore, it is not a function of drilling technique or technology.

What we can control, however, is the hydrostatic pressure of the drilling mud, since it is directly dependent on the mud density and the well depth [34].

The depth of the well is a parameter that increases progressively during drilling until the target hydrocarbon-bearing formation is reached at the planned depth. However, at any given moment, it is not possible to increase or decrease the well depth in order to raise or lower the hydrostatic pressure.





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Therefore, we arrive at the conclusion that the only practical factor used to control the hydrostatic pressure of the drilling mud is its density.

The condition to prevent a well kick (well influx) is:

 $\Delta P \ge 0 \to P_h - P_P \ge 0 \to P_h \ge P_P \tag{33} [12]$ 

Expressing hydrostatic pressure as a function of mud density  $\rho_{mud}$ , gravity g, and well depth H:

$$P_h \ge P_P \to \rho_{ll} * g * H \ge P_P \to \rho_{ll} \ge \frac{P_P}{g * H} \qquad (34) [14]$$

Thus, mud density must satisfy:

$$\rho_{ll} \ge \frac{P_P}{g_{*H}} \leftrightarrow \rho_{ll} \ge \frac{G_P * H}{g_{*H}} \leftrightarrow \rho_{ll} \ge \frac{G_P}{g}$$
(35) [11]

To achieve wellbore pressure balance, the hydrostatic pressure must be within a safe operating window:

- Lower than the fracture pressure of the formation (to avoid fracturing and loss of circulation).
- Higher than the pore pressure of the formation (to prevent formation fluids from entering the wellbore).

This range is called the pressure margin or mud weight window, and it is crucial in well control engineering [45]. If the mud density is too low, the formation pressure will exceed the hydrostatic pressure, and formation fluids (oil, gas, water) can enter the wellbore, leading to a kick.

If the mud density is too high, the pressure can exceed the formation's fracture gradient, causing loss of circulation where mud escapes into the formation, compromising well control and possibly causing formation damage.

Thus, accurate control and continuous monitoring of mud weight are essential during drilling operations, particularly when approaching overpressured zones or transitional formations [11].

Therefore, if we encounter overpressure zones, it becomes necessary to increase the mud density to prevent well kicks. If we encounter underpressure zones, then mud density should be decreased to reduce circulation losses.

When performing the tripping out operation—that is, removing the drill string from the well—it is necessary to increase the density of the drilling mud in the tubing. This is done because we want to prevent the drilling mud from flowing back up to the wellhead through the tubing.

When mud circulation is stopped to perform the tripping operation, the pressure in the casing (P<sub>c</sub>) is higher than the pressure in the tubing (P<sub>t</sub>) due to the higher density of the mud in the casing. The mud in the casing has a higher density,  $\rho_{mudc}$  because it contains cuttings suspended within it.

As a result, this difference in pressure gradient would cause the flow of drilling mud to reverse direction—from the casing into the tubing—carrying cuttings with it. These cuttings could potentially block the flow channels in the drill bit and cause mud to spill into the rotor base [14].

By increasing the mud density in the tubing, we make it possible to:

 $P_t > P_c \tag{36}$ 

Where:

 $P_c = \rho_{mudc} * g * H$ (37)  $P_t = \rho_{mudt} * g * H$ (38)

D. Formation of Filter Cake on the Wellbore Walls

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The formation of a clay filter cake on the wellbore walls is one of the characteristic features of drilling fluids related to filtration phenomena. Since most of the time the drilling fluid pressure is higher than the formation pressure encountered during drilling, the fluid tends to filter into the pores and voids of the rocks that form the wellbore walls [11]. However, the size of these pores, fractures, and cavities is such that only water can pass through them. This causes the clay particles dispersed in the water to deposit on the wellbore walls, thereby creating a clay filter cake surrounding these walls [14]. It is important whether this filter cake is thin and impermeable or thick and permeable. A thick filter cake reduces the wellbore diameter, which can cause problems such as tool sticking, difficulty running casing, and poor cementing quality [12][46]. However, a thick filter cake is friable and does not reduce the dynamic filtration of the drilling fluid since it remains permeable [19].

All positive functions of the filter cake are associated with a thin, strong, and impermeable cake:

- A thin, strong, impermeable cake reduces the amount of filtrate entering the formation, thus limiting the potential for formation damage and wellbore collapse [14][36].
- It increases the mechanical stability of the wellbore walls by acting as a "plaster" for them[14].
- It serves as a mechanical barrier that limits wellbore erosion, thereby preventing cavings [12].
- The filter cake provides a lubricating function that reduces friction forces and coefficients between the drill pipe and the wellbore walls [33].



Figure 9. Filter cake formation [46][47].

#### E. Cooling and Lubricating the Drilling Tool

The rotation of the drill bit and drill pipes generates heat as a result of friction between them and the rock formations. Part of this heat is absorbed by the formations, while the majority is dissipated into the drilling fluid, which continuously circulates in the wellbore. This circulation cools the drill bit and the drilling tool [14].

Cooling the rock-breaking tool significantly reduces its wear, thereby improving drilling performance and efficiency [33].





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Figure 10. Conventional circulation mud [48].

In high-pressure and high-temperature drilling at the wellbore, it is recommended to use a device called a mud cooler. This equipment is connected to the drilling fluid circulation system at the surface and enables the reduction of the temperature of the drilling fluid returning from the pits [49]. In this system, insulated drilling pipes are used to minimize heat loss during fluid circulation, ensuring more efficient cooling [50].



Figure 11. Comparison between conventional and mud cooler circulation [48].

High-temperature drilling fluid enters the cooler and, through a piping system, passes through what is called the cooling tower.

Inside the cooling tower, on the outer surface of the pipes containing the drilling fluid, cold water and air circulate. The water moves in a cyclic circulation while the air is supplied by a fan [51].





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Figure 12. Schematic diagram illustrating the working principle of a mud cooler [51].

Lubrication: In roller cone bits, the drilling mud serves to lubricate the bearings, thereby extending their lifespan as well as that of the drilling tool [14].



Figure 13. (A) Cone bits [52]; (B) Spherical bearings [53]; Tapered Bearings [54]

On the other hand, the drilling fluid and the clay filter cake formed on the wellbore walls help reduce the friction coefficient between the drill string and the well walls.

If the drilling fluid possesses proper lubricating properties, it can reduce torque, frictional resistance, and the sticking of drill pipes caused by differential pressure between the formation and the wellbore [33].

During the drilling process, the drill string may stick to the wellbore walls. This phenomenon is also known as differential sticking [55]. It occurs when the drill string becomes stuck against the wellbore wall due to a pressure imbalance—specifically when the hydrostatic pressure of the drilling mud (P<sub>h</sub>) is significantly greater than the formation pore pressure (P<sub>p</sub>). The resulting differential pressure ( $\Delta P$ ) presses the drill pipe against the well wall, and due to the friction coefficient (f) and the contact area (S<sub>tn</sub>), a substantial pulling force (T) is required to free it [12]:



Figure 14. Differential sticking and its elements.





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The clay-based filter cake influences two key factors:

- The value of the friction coefficient (f): If the filter cake is thick, the friction coefficient between the drill string and the wellbore wall increases, resulting in a higher pulling force required from the surface. Conversely, a thin filter cake reduces the friction coefficient between the drill pipe and the wellbore wall, thus lowering the required pulling force (T) [45].
- The contact surface area (S<sub>tn</sub>): With a thick filter cake, the contact surface area between the drill string and the wellbore wall is larger, increasing the pulling force needed to free the pipe. A thin, uniform filter cake reduces this contact surface, and as a result, less pulling force is required [45].

There are cases where the required pulling force exceeds the tensile strength of the drill pipes. In such situations, efforts must be made to reduce the force:

$$T = f * \Delta P * S_{tn} = f * (P_h - P_p) * S_{tn}$$
(40)

One approach is to reduce the hydrostatic pressure of the drilling mud. However, this can be dangerous and may lead to well kick or blowout if the formation pressure exceeds the mud pressure [56].

An alternative method is to further reduce the friction coefficient by introducing a specific volume of oil-based drilling fluid or lubricants into the well. Using surface equipment and sensors, it is possible to identify the depth interval where the drill string is stuck. Then, a calculated volume of lubricating mud is pumped downhole to submerge the stuck portion of the drill string [55].

If these efforts fail, the drill string must be unscrewed above the stuck point. The upper part is retrieved, and a fishing tool or a milling bit is run into the hole to recover or grind away the stuck portion remaining in the well [33].

## F. Supporting a Portion of the Drill String Weight

This function is based on the existence of a force that acts in the same direction but in the opposite sense to the gravitational force acting on the submerged drill string. This force is known as Archimedes' force (buoyant force) [33]. When the drill string and other components of the bottom hole assembly are immersed in drilling mud, they experience an upward force equal to the weight of the displaced fluid. This reduces the effective weight of the string on the hook and lowers the axial load on the drill bit, which helps minimize wear and mechanical stress on the drilling equipment [14].

In practice, understanding and utilizing this buoyant effect is essential for:

- Accurately controlling the weight on bit (WOB)
- Reducing the risk of drill string failures
- Ensuring better stability of the drill assembly, especially in deviated or extended-reach wells [12]

The effective mass of the drill pipes when submerged in drilling mud is reduced due to buoyancy and can be calculated using the following expression:

$$m' = m * (1 - \frac{\rho_{mud}}{\rho_{steel}})$$
 (41) [57]

Where:

m' - the effective (reduced) mass of the drill pipe in mud; m - the actual mass of the pipe in air;  $\rho_{mud}$  - the density of the drilling mud;  $\rho_{steel}$  - the density of the pipe material (usually steel);

The effectiveness of this function depends directly on the density of the drilling fluid—the higher the mud weight, the greater the buoyant force, and the more of the drill string's mass it can support.

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This shows that the higher the density of the drilling mud, the greater the buoyant force, and thus the greater the reduction in the effective weight of the drill string [44].

For two mud densities  $\rho_{mud1} < \rho_{mud2}$ , we can say:

$$m_1 = m * (1 - \frac{\rho_{mud1}}{\rho_{steel}}) > m_2 = m * (1 - \frac{\rho_{mud2}}{\rho_{steel}})$$
(42)

So, as the mud density increases, the effective mass of the submerged pipes decreases, improving weight support by the fluid and reducing mechanical load on the rig equipment.

#### G. Hydraulic Power Transmission

This function includes two main cases: the first involves the use of downhole motors, and the second applies when using jet bits (hydromonitor bits).

In downhole motor drilling, particularly with turbine motors, the hydraulic energy of the drilling fluid is used to rotate the bit directly. The drilling mud flows through the turbine, causing its rotor to spin. Since the rotor is mechanically connected to the drill bit, the bit rotates accordingly. This method is widely used in directional, high-inclination, and horizontal wells due to its ability to provide rotation at the bit without rotating the entire drill string [12].

When a turbine motor is used, it is essential to review the mud program and pump specifications. The drilling fluid must have the proper rheological properties, and the pumps must provide sufficient pressure and flow rate to both drive the turbine blades effectively and overcome the hydraulic losses in the circulation system. In addition, the mud must be well-filtered to prevent solids from entering and damaging the motor, ensuring efficient power transfer and continuous operation [14].



Figure 15. Drilling turbine design [58].

In the case of jet bits or hydromonitor bits, the transmission of hydraulic power occurs differently. These bits are equipped with high-pressure nozzles rather than open flow channels. As the drilling mud passes through these nozzles, its pressure is converted into high-velocity fluid jets. These jets strike the rock directly at the bottom of the hole, contributing to its destruction through hydraulic erosion and assisting the mechanical action of the bit [16].

The effective use of jet bits requires that the exit velocity of the fluid be very high, which again depends on the pumping capacity and pressure in the system. The fluid must be clean enough to avoid nozzle blockage, and the pressure must be carefully selected to ensure that the bit can perform both rock destruction and proper cuttings removal while still managing overall hydraulic losses [57].





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Figure 16. (A) Jet bits [59]; (B) Nozzles.

In both cases, the quality and management of the drilling fluid—including its pressure, velocity, and cleanliness—are crucial for the successful transmission of hydraulic energy to the bit and for maximizing drilling performance [60].

#### H. Ensuring the Physico-Chemical Balance Between Drilling Mud and Formation

Physico-chemical balance means maintaining the chemical activity of the drilling mud so that it matches that of the formation. In other words, the chemical composition of the drilling fluid should not cause complications or damage to the rock formations being drilled. For example, if the drilling mud contains nitrates, these can react with clays in the formation and cause their swelling (called "clay hydration" or "clay swelling") [61]. To prevent this, the mud is saturated with ions such as Ca++ and Na+, often added in the form of compounds like CaCl<sub>2</sub>, Ca(OH)<sub>2</sub>, or CaSO<sub>4</sub>·2H<sub>2</sub>O. These ions inhibit clay swelling because their ionic sizes are roughly similar to the pores in the clays. By occupying these pores, the ions block water from entering, thus stabilizing the clays [11]. In formations with very high clay content, it is necessary to dehydrate the clays through osmosis. This requires the salt concentration in the drilling fluid to be higher than that of the water inside the clays. This osmotic process helps prevent clay swelling [19]. If clay swelling and subsequent collapse occur, the borehole diameter will no longer be uniform along the wellbore. Areas with swollen clay will have reduced diameter, and where clay collapses, enlarged cavities form with diameters larger than the wellbore. The presence of multiple diameters complicates the calculation of drilling fluid parameters and composition. Variations in diameter translate into changes in fluid circulation speed and hydraulic losses, complicating drilling operations [12] [14].

#### I. Maintaining the Solid Phase in Suspension

One of the most important requirements for drilling fluids is their ability to keep the cuttings and weighting materials suspended when circulation stops for any reason [11].

If the drilling fluid fails to perform this function effectively, the cuttings will settle and accumulate on the drill bit and in areas where the borehole diameter changes. This reduces the effective diameter of the wellbore and can cause the drill bit to get stuck. This function is especially critical when the fluid contains weighting materials, which must not settle either in the well or in surface circulation equipment. Otherwise, a large amount of weighting material will be wasted, increasing drilling costs [14].

Suspension of cuttings and weighting materials is achieved by drilling fluids with good structural properties. Such fluids, when at rest, gel and form a stable spatial network (structure) that holds the cuttings and weighting materials, preventing their settling [12].

Closed-loop circulation systems require that the drilling fluid be cleaned of cuttings as it exits the wellbore. To accomplish this, the gel structure must be broken so the fluid can pass through cleaning equipment such as shaker screens, hydrocyclones, riffle channels, and settling tanks [16].

Therefore, it is important that the drilling fluid exhibits thixotropic behavior — the ability to form a gel structure when circulation stops and to immediately break down that structure when circulation resumes [11].





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#### J. Drilling Mud as a Source of Information

During drilling, the drilling mud returns to the surface, where a comparison is made between the parameters of the mud entering the well and the mud exiting it. From this comparison, we determine what causes the changes observed. The drilling mud provides information about:

- The formations being drilled
- The formation fluids encountered
- The well-formation pressure balance [11][14].

Information on the composition of the formations drilled - The drilling mud informs us in two ways:

- Through its physicochemical parameters
- Through the cuttings (rock fragments) brought to the surface [11].

Let's examine the role of the main drilling mud parameters in the information they provide:

Mud density: Mud density is affected by all types of formations drilled.

For example, when drilling clay formations, the density of the drilling mud increases. Monitoring changes in mud density over time also helps assess the solubility of formations in the mud, allowing estimation of the wellbore diameter. Density increases are also caused by formations such as gypsum and salts. When drilling salt formations, mud density rises due to dissolution of NaCl. An increase in density is also noticed when drilling carbonate formations (especially when using diamond bits), since along with large fragments, small particles increase the solid phase in the drilling fluid. Thus, mud density provides information about the solubility and chemical-mineralogical nature of the drilled formations. A slow increase in mud density indicates formations that dissolve only slightly [11][12].

Chemical parameters and filter cake formation: When encountering formations with high porosity and fissures, more mud filtrate penetrates the formation, leading to a thicker clay filter cake on the wellbore walls, which reduces the well diameter.

If an increase in mud density is observed but it is unclear whether it is due to clay, salt, carbonate, or gypsum formations, chemical analysis is performed to determine the concentrations of:

- Chloride ions (Cl<sup>-</sup>): High values indicate salt formations.
- Calcium ions (Ca<sup>2+</sup>): High values indicate gypsum or carbonate formations.
- Alkalinity (carbonate ions CO<sub>3</sub><sup>2-</sup>): High concentrations suggest carbonate formations.
- Rheological parameters: When clay formations are drilled, clay dissolves into the mud, increasing its concentration and thus its viscosity.
- pH: A decrease in mud pH during drilling indicates the presence of salt or gypsum formations.
- Bentonite indicator: Bentonite is a component of clay. An increase in its concentration in the drilling mud directly indicates clay formations [11][12].

Information from cuttings: Accurate information about the composition of formations is also obtained from the cuttings (rock fragments) brought to the surface during drilling. Compared to the mud parameters, this information is delayed because the rate at which cuttings reach the surface is always slower than the mud flow rate. When cuttings arrive at the surface, it is important to determine the depth from which they originated [16].





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When the cuttings arrive at the surface, it is important to determine the depth from which these cuttings originate. Let us denote this depth by x. By considering known parameters, we can estimate the depth x that corresponds to the cutting particles reaching the surface.

To understand the mathematics behind this estimation, consider a simplified case: During the drilling process at depth x, a cutting particle of a certain size and density is created (Figure 17). Based on the properties of the drilling mud and the particle itself, the cutting requires a time  $t_{ct}$  to reach the surface. Meanwhile, as the particle travels upward, the wellbore deepens further, reaching a total depth H.

The key to solving this problem lies in the fact that the time  $t_{ct}$  for the cutting to reach the surface is equal to the time  $t_{drilling}$  required for the drill string to advance through the segment *H*-x.

$$t_{ct} = t_{drilling} \tag{43}$$

Where:  $t_{ct}$  - the time needed for the cutting particle to travel from depth x to the surface;  $t_{drilling}$  -the time needed for the drill to drill the segment from depth x to H; We know that:

 $t_{ct} = \frac{x}{v_{ct}} \tag{44}$ 

And:

$$t_{drilling} = \frac{H - x}{ROP} \tag{45}$$

Where:

 $v_{ct}$  - the velocity of the cutting particle traveling up the annulus; ROP (Rate of Penetration) - the mechanical drilling speed, i.e., the rate at which the well depth increases; Therefore, the relation becomes:

$$\frac{x}{v_{ct}} = \frac{H-x}{ROP} \tag{46}$$

This equation can be solved to estimate the depth xxx from which the cuttings originated, based on known or measured parameters.

Information Regarding Formation Fluids - The main goal of drilling wells is the exploration, discovery, and exploitation of oil and gas. The first source of information related to this objective is the drilling mud.





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To ensure accurate information about the gas and oil content of the formations being drilled, the drilling mud must not contain petroleum by-products that are commonly added for technological purposes. Therefore, water-based drilling fluids are used in exploration and appraisal wells, while oil-based fluids are used during the development of productive formations [11][14].

If water-bearing formations are encountered, a decrease in the density and rheological parameters of the drilling mud will be observed. This occurs due to the increased concentration of water in the mud volume.

When oil-bearing formations are encountered, the oil contained in the crushed rock enters the drilling mud as droplets of varying sizes, which can be clearly seen in the mud tanks. Due to differences in buoyancy, part of the oil rises to the surface of the mud, forming a film. If the oil is light, its rise velocity will be higher than that of the drilling mud, thus the information about the presence of oil is transmitted quickly [11][14].

In the case of gas-bearing formations, the gas contained in the crushed rock enters the drilling mud and begins to rise to the surface. While rising, the gas expands, increasing its volume. This increase in gas volume causes an increase in the mud volume and a decrease in circulation pressure. These initial signs indicate that a gas-bearing formation has been encountered, and drilling is immediately stopped [62].

Next, a full circulation of the drilling mud is performed, passing it through degassing centrifuges. When gasified drilling mud appears at the surface, the cause can be one of two reasons:

- Encountering a gas-bearing formation at the well bottom
- Aeration of the drilling mud due to air being sucked in by the pump [62]

To determine which case applies, specialized equipment called gas cut detectors is used, which monitor the hydrocarbon content in the drilling mud.

Well-Formation Pressure Balance - When drilling into formations with pressures higher than the hydrostatic pressure of the drilling mud column in the wellbore, formation fluid can enter the annular space, filling it to a height h. This causes an increase in the volume of drilling mud in the mud tanks by an amount  $\Delta V$ . The volume increase in the mud tanks  $\Delta V$  relates to the height h of formation fluid in the annular space by the equation:

$$\Delta V = h^* 0.785 (D_w^2 - D_{ds}^2) \to h = \frac{\Delta V}{0.785 (D_w^2 - D_{ds}^2)}$$
(47)

Where:

 $\Delta V$  - change in volume of drilling mud in the mud tanks;

h - height of formation fluid displaced into the annular space;

D<sub>w</sub> - wellbore diameter;

D<sub>ds</sub> - outer diameter of the drill string [16];



Figure 18. Formation fluids entering the well





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Knowing the pressures measured at the surface in the tubing ( $P_{st}$ ) and casing annulus ( $P_{sc}$ ) we can calculate the density of the invading formation fluid  $\rho_f$  using the pressure balance equation:

 $P_{st} + \rho_{mudt} * g * H = h * \rho_{f} * g + (H - h) * \rho_{mudc} * g + P_{sk}$ (48)

Therefore:

 $\rho_{f=}\frac{(P_{st}+\rho_{mudt}*g*H)-[(H-h)*\rho_{mudc}*g+P_{sc}]}{h*g}$ 

(49)

Where:

$$\begin{split} \rho_{f} &- \text{ density of the formation fluid (fluid that entered the well);} \\ P_{st} &- \text{ tubing pressure measured at surface;} \\ \rho_{mudt} &- \text{ density of drilling mud in the tubing;} \\ g &- \text{ acceleration due to gravity;} \\ H &= \text{ total depth of the well;} \\ h &- \text{ height of the formation fluid column in the annular space;} \\ \rho_{mudc} &- \text{ density of drilling mud in the casing/annular;} \\ P_{sc} &- \text{ casing pressure measured at surface [11][12];} \end{split}$$

K. Participation in Rock Destruction

Direct action (Jet bits): In this method, high-pressure jets of drilling fluid are directed at the rock face through special nozzles on the bit. The kinetic energy of the fluid physically breaks and dislodges rock fragments, aiding in efficient drilling [11][14].

Indirect action (External environment):

The drilling fluid also affects the rock through the surrounding environment, contributing to weakening the rock structure by various processes:

- Wetting: The fluid penetrates into the rock's pores and microfractures, reducing the cohesive forces that bind the rock grains together. This makes the rock easier to break by mechanical means [63].
- Erosion: Continuous flow of fluid carries away the loosened rock particles from the wellbore, preventing accumulation around the bit and maintaining effective drilling [11][14][63].

## IV. DISCUSSIONS AND CONCLUSIONS

Drilling fluids orchestrate a complex interplay of physical, chemical, and hydraulic functions that collectively determine the success of well construction. This review dissects these roles to highlight their interdependence and operational nuances. For instance, cuttings transport (Function B) relies not only on annular velocity but also on mud rheology—where thixotropy ensures suspension during circulation pauses (Function I). Similarly, pressure control (Function C) is inseparable from filter cake formation (Function D): an impermeable cake minimizes fluid loss, preserving hydrostatic balance and reducing differential sticking risks. The analysis reveals that underemphasized functions, such as mud's role as an information source (Function J), are equally critical; real-time mud logging detects formation fluids, enabling rapid response to kicks or losses.

Operational trade-offs emerge prominently. High flow rates enhance bit cleaning (Function A) but escalate erosion and hydraulic losses, while excessive mud density prevents influxes (Function C) yet heightens fracture risks. The buoyancy effect (Function F) reduces drill string weight but complicates WOB management in deviated wells. Downhole tools (Function G) exemplify mud's versatility: turbine motors convert hydraulic energy to rotation, while jet bits leverage fluid momentum for rock destruction—both demanding stringent fluid cleanliness to avoid damage. Physicochemical balance (Function H) further illustrates mud's adaptive nature, where inhibition chemistry (e.g.,  $K^+/Ca^{2+}$  saturation) counters clay swelling but requires precise ion management.

Field data and literature confirm that failures often stem from overlooking these interdependencies. Stuck pipe incidents (Function E) correlate with poor filter cake quality and inadequate lubrication, while lost circulation arises





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from unoptimized density windows. The review also notes gaps in current practices, such as underestimating annular geometry's impact on cuttings transport or overlooking temperature effects on rheology in deep wells.

Drilling mud is the lifeblood of well construction, integrating eleven non-negotiable functions that ensure safety, efficiency, and geological insight. This review consolidates these roles into a coherent framework, emphasizing that:

- 1. Multifunctionality is non-negotiable: No single role operates in isolation; mud density, for example, governs pressure control, buoyancy, and differential sticking simultaneously.
- 2. Optimization hinges on balance: Engineers must navigate trade-offs (e.g., flow rate vs. erosion, density vs. fracture risk) using real-time monitoring and adaptive fluid design.
- 3. Education gaps impede best practices: Underprioritized functions, like physicochemical balance or suspended solids management, warrant greater emphasis in training.
- 4. Innovation pathways exist: Smart fluids with autonomous rheological adjustments, biodegradable inhibitors, and enhanced downhole sensors could address current limitations.

For new engineers, this functional overview demystifies mud's centrality—transforming it from a "supporting actor" to a system demanding scientific rigor. For veterans, it reaffirms that holistic mud management is the cornerstone of operational excellence. Future work should expand on high-temperature formulations, environmental sustainability, and machine learning-driven fluid optimization. Ultimately, mastering drilling fluids is not merely technical—it is foundational to unlocking subsurface resources safely and economically.

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