Abstract
Implementing the correct dilution rate for water-based muds is a complex, dynamic and critical task that warrants careful planning and execution. Vastly improved wellsite monitoring and reporting capabilities have made time management for the mud engineer more important than ever. Reacting to constantly changing variables and adjusting dilution rates accordingly is difficult at best and can easily take a back seat to numerous other responsibilities. However, setting dilution rates without constant vigilance and due consideration for all contributing factors can lead to runaway mud cost, excessive swab and surge pressure, wellbore pressure containment issues and, in extreme cases, loss of well. Done right, dilution can have a positive impact on a project’s overall productive time and significantly reduce well construction cost. This paper discusses the physical factors that dictate dilution rates and offers solutions to help improve performance based on proper and proactive implementation.

Introduction
For consistency sake, the mud system referenced in this paper is a water-based mud (WBM), but the principals discussed remain true for invert emulsions as well. Additionally, ‘diluting’ a mud system is defined as the act of altering the fluid’s base physical and chemical properties by admixture. In this light, any additive (liquid or solid), including drilled cuttings and barite, ‘dilutes’ the base system, as these components become a part of the end product.

In general, the industry does a good job measuring volumes and concentrations of each additive after they are in the system; however, this is only a starting point, or new base, for the pro-active mud engineer. Further system treatments should then be based on:
- Schedule of physical and chemical property specifications
- Mandated target levels for various products (inhibitors, etc)
- Total solids
- Target low gravity solids
- Retained drilled solids
- Clay content (MBT)
- Total circulating volume
- Cycle volume (the amount of fluid that can be discarded and replaced with new volume).

Values for each of these ‘dilution components’ are either assigned, measured directly or estimated within an acceptable range to allow a mass-balance approach to planning remedial or maintenance treatments.

Field Observations
Prior to recent software developments, tools to measure dilution on a typical full-service job was a 5-gallon bucket, a stopwatch, and a chart converting 5-gallon fill times to barrels per hour. A mud engineer’s personal experience in the area was also invaluable. Additionally, dilution rates were based on mud weight maintenance, funnel viscosity, MBT, gel strengths, low gravity solids and pit volume. This forced even the most experienced mud engineer to omit from their analysis many of the critical factors that dictate actual dilution requirements. Chemical and physical properties deviating from specifications due to improper dilution underwent remedial treatment immediately thereafter. This method is reactive and inefficient by today’s standards, resulting in constant lab testing to ‘fix’ an unstable system, depriving the mud engineer of time and testing needed to plan ahead of the bit and optimize the system for the myriad of certain and potential upcoming well events.

On a well that underlined the need for training in proactive dilution, the operator was drilling 12 ¾” hole at 150 ft/hr with approximately 3,000 ft of hole remaining and a water delivery capability of 70 bbl/hr. The low gravity solids (LGS) in the 9.4 ppg fresh water system were reported at 9% by volume while diluting at a rate of 8 sec/5-gal (± 54 bbl/hr). Even if the surface volume was lowered to minimum safe levels, it would have been
impossible to achieve a target LGS of 6% for break-over ‘on the fly’ to an inhibitive mud. Due to volumes involved, displacement with over 2,000 bbl of new mud would have been required, taking longer to mix than the time required to drill the remaining hole.

The reality of the above situation is that a water delivery capability of 70 bbl/hr allows a maximum ROP (in a 12 ¼” hole) of 105 ft/hr with 75% solids control efficiency. The operator was in fact drilling beyond its means of maintaining low gravity solids at safe and specified levels. Due to the complexity of dilution and the tools available at that time, the over-matched water delivery capability went unnoticed until the damage was done. The chart below illustrates ROP vs dilution rate for various hole sizes at 75% solids removal efficiency and retention of 5% by volume drilled cuttings.

It should also be noted that reducing the 5-gallon bucket fill time from 8 seconds to 6 seconds increases the dilution rate from 54 bbl/hr to 71 bbl/hr (max). This is mentioned to highlight the large difference in water delivery with such a small differential in time, and illustrates the absolute need for water meters on lines feeding the active mud pits.

Fortunately, today’s mud engineer is equipped with powerful laptops and software to incorporate all the dynamics for proper dilution. Even with excellent training, sophisticated well-monitoring equipment and ample processing power, many dilution factors have unknown and/or constantly changing values. Typically, unknowns such as solids removal efficiency and actual hole size are estimated or back-calculated within reasonable accuracy. Other variables are averaged at values that will keep the system stable. The importance of doing it right the first time benefits the entire operation and allows the drill team to focus on progress and improving performance. No longer is it acceptable to set water addition rates without mathematically considering the effects of all critical dilution factors. Too much is at stake if the setting is off even by a small amount. The mud engineer should be reasonably certain that for the conditions at hand, all factors have been properly considered.

**Critical Dilution Factors**

Independent from the previously mentioned list, critical dilution factors are only those that are part of the math needed to calculate projected dilution requirements. They are as follows:

- Current and target low gravity solids content
- Specific gravity of drilled solids
- Current and target mud weight
- Amount and specific gravity of barite to be used
- Amount and specific gravity of each mud additive scheduled to be used
- Rate of penetration
- Hole or bit size
- Solids Removal Efficiency
- Retained Low Gravity Solids
- Active pit volume
- Cycle volume
- Percentage of total dilution from reserve pit or water-recovery unit
- Density and low gravity solids content of reserve pit water or fluid from water-recovery unit (if used).

The basis for calculating the volume of fluid needed to dilute a mud system to retain a tolerable or specified level of drilled cuttings (LGS$_D$) is as follows$^2$:

**Equation 1**

$$V_D = \frac{(1.0 – SRE)(V_R)(1.0 – \text{LGS}_D)}{\text{LGS}_D}$$

Where:

- $V_D$ (in bbl)—the volume of dilution fluid needed to maintain a given concentration of LGS
- $SRE$—the known percent efficiency
- $V_R$ (in bbl)—the volume of cuttings removed from the wellbore
- $\text{LGS}_D$—the percent desired concentration of LGS in the fluid system.
Using Equation 1 above, solids removal efficiency (SRE) can then be backed out as follows:

**Equation 2**

\[
SRE = 1.0 - \left\{ \frac{V_D(LGS_{AVG})}{(1.0 - LGS_{AVG})(V_R)} \right\}...
\]

Where:
- \(V_D\) (in bbl)—the volume of dilution fluid used in the interval
- SRE—the determined efficiency of all solids control equipment in use
- \(V_R\) (in bbl)—the volume of cuttings removed from the wellbore
- \(LGS_{AVG}\)—the average percent concentration of LGS in the fluid system.

Simply put, as much drilled solids is removed as possible and the remainder is diluted back to a specified or tolerable working level. Although the concept is correct, the equation is overly simplified since, by definition, dilution includes any additive that adulterates the base volume. The addition of barite also takes up volume and reduces the volume fraction of low gravity solids. Mud chemicals, depending on their specific gravity, also consume volume and reduce the volume percentage of low gravity drilled solids.

The mathematical relationship between all critical dilution components would take more space than this venue allows. Suffice to say, Baroid has developed software that integrates all critical dilution factors in a material balance format and can allow the mud engineer to view a variety of ‘what-if’ scenarios.

**Diluting High Performance Water-Based Muds**

A well thought-out and executed dilution plan is recommended on any well, but is especially critical if the industry is to realize the potential offered by recent high performance water-based muds (HPWBM). Major mud companies and operators spend millions of dollars each year to develop and apply promising products intended to reduce well construction cost. HPWBM can quickly become an expense if the value created is out-stripped by the cost of improperly applying the technology. A good dilution plan can assure that these systems are run properly, allowing a fair assessment of their application and value.

**Summary and Conclusions**

The introduction of high-power laptops, software and links to the home office has greatly enhanced the mud engineer’s ability to record, analyze and report complex volumes of data. This, however, is but a starting point in the mud engineer’s core business – cost-effective treatment planning and proactive systems management, in a word, diluting.

The complexity involved in the simple act of setting water addition rates has been underrated for many years. Dilution in some cases had become a remedial tactic to ‘fix’ systems in disrepair from improper dilution. A mud engineer’s proficiency at dilution can impact hydraulic performance, inventory management, waste management, solids control, mud cost and overall system effectiveness. Baroid has addressed this by developing software and providing the necessary training to mud engineers. Finally, since measuring is used to properly manage and small errors in measuring can have costly consequences, water meters should be standard equipment on all lines feeding the active mud pits.

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**References**
