CERTIFICATION OF APPROVAL

Simulation of Drilled Cuttings Transport through an Inclined Wellbore by Using CFD

by

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Approved by,

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken by unspecified sources or persons.

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Makuach James Makeny

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ABSTRACT

Introduction: Efficient transportation of cuttings is a vital factor for optimization of a good drilling operation. This study investigated the influence of a range of variables such as mud weight, cutting size, viscosity and circulation rate on cutting transport efficiency in an inclined well using CFD software. **Problem statement**: Poor hole cleaning may be responsible for up to 70% of all drilling problems such as: pipe sticking, premature bit wear, slow drilling rate, formation fracturing and high torque and drag consequently extending drilling time and increasing drilling cost. **Objectives:** The main objectives of this study are: to determine parameters those affecting the transport of drilled cuttings in inclined wells, to simulate a section of annulus with combination of drill pipe and casing to define the variables affecting drill cutting transportation and to develop a graphical correlation between cutting transport ratio to the annular velocity to illustrate the magnitude of the effect of different variables that influence hole cleaning in inclined wells. **Approach**: Throughout the study, two different methodologies were used which are analytical and simulation methods. In analytical method, two governing equations of motion, Continuity equation and Navier-Stokes equations are derived in accordance to the assumptions made. In simulation method a combination of casing-drill pipe annulus section was simulated and a model called 'discrete phase model' was used to observe the transportation of cuttings in the annulus section of an inclined (45°) wellbore. **Results:** the simulation carried out to date had shown that an increase in mud weight slightly enhances cuttings transport as long as there is not an accompanying increase in viscosity, Size of drilled Cuttings the medium-sized cuttings are easier to transport than the smallest or the largest cuttings, the best way to pick up cuttings is with a low viscosity fluid in turbulent flow. And as ROP increases, the hydraulic requirements for effective cuttings transport increases. **Conclusion:** The main conclusion was that the model predictions exhibit good agreement with laboratory experimental results and observations, for the majority of the case

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CHAPTER - 1

INTRODUCTION

1.1 Background of Study

Transport of drilled cuttings is the ability of a drilling fluid to suspend and transport drilled cuttings from down hole to the surface. The ability to transport such cuttings is universally referred to as the carrying capacity of a drilling fluid i.e. the removal of drilled cuttings at the hole bottom and from the bit teeth and efficient transportation of cuttings to the surface. Cuttings must also be transported to the surface and easily separated from the fluid by the shale shakers and should also arrive at the surface intact.

Effective removal of cuttings or annular hole cleaning is an important aspect of any drilling operation. Improper annulus hole cleaning while drilling vertical or horizontal wells can lead to any or a combination of any of the following problems; low rate of penetration, overload on the mud pumps, increase in torque and drag on the drill string increased potential of pipe sticking, tool wear and inadequate hole cleaning. This, in turn, will lead to higher drilling cost. Therefore, it is essential that effective removal of cutting can take place and at the same time alleviate drilling problems. The parameters that affect the transportation of cuttings in annulus can be divided into three groups. The first group consists of fluid parameters include:

- Fluid density
- Fluid viscosity
- Fluid flow rate

The second group consists of cutting parameters include:

- Cutting density
- Cutting size and shape
- Cutting concentration

The third group consists of angle of inclination, pipe rotation, speed and eccentricity in the hole

1.2 Problem Statement

Although in the past, extensive research has been made in the area of cutting transport with experimental study, software was not used to verify the parameters affect on cutting transportation. In this study, section of the annulus will be simulated and series of runs will be conducted under discrete phase model to observe the effect of fluid rheology, particle properties and drilling rate on cutting transportation in vertical and horizontal section of a well bore. The discrete phase model will be used where cuttings are injected separately with mud at the annulus inlet. Therefore, the objectives of the study are to identify the primary and essential factors affecting cutting transport in high-angle wells, determine forces balance acting on a particle and to investigate the effect of fluid characteristics and operational parameters on cutting transport in vertical and horizontal wells. With the aid of the CFD simulation and analyses, the transport of drilled cuttings performance can be investigated. Further required data can be obtained from operating site.

1.3 Objectives and Scopes of Project

The purpose of this study is to investigate the effect of fluid characteristics and operational parameters on the circulation rate required to ensure that the drilled cuttings in inclined well bore hole are efficiently transported to surface. The specific objectives of this work are as follows:

- To simulate a section of annulus with combination of drill pipe and casing to define the variables affecting drill cutting transportation.
- To verify the simulated results with reported values.
- To develop a graphical correlation between cutting transport ratio to the annular velocity to illustrate the magnitude of the effect of different variables that influence hole cleaning in inclined wells.

This project will study in detail the behavior of the drilling mud, Transport of drilled cuttings, and Factors that affect the transport of drilled cuttings. Thus, detailed study on the rheological behavior of the drilling fluids and the factors that affects the capability of the drilling fluid in performing its function and will be carried out throughout the project. This study will finally lead to a simulation of the circulation of the drilling fluid in an annulus.

1.4 Significance and Relevancy of the Project

The selection and optimization of drilling fluids are very crucial in petroleum drilling. The main concern in this industry is the cost factor where the cost of equipment and drilling mud materials are enormously high. Thus, it would be an advantage if the performance of drilling mud is optimized. Thus this project will assist in:

- The selection and optimization of drilling fluids in petroleum drilling.
- Improve and optimize the drilling operation
- hole cleaning becomes more efficient ,
- we can speed up the drilling operation,
- And reduce the total cost to drill a well.

1.5 FEASIBILITY OF THE PROJECT WITHIN THE SCOPE AND TIME FRAME

- Time allocated approximately 24 weeks
- Sufficient, for data acquisition and analysis on each procedures & compilation
- No equipment or lab experiment needed
- Computer lab –CFD-TECPLOT, DITIGITALIZER & FLUENT
- Sufficient research paper/journal : One petro website
- Reference books & manual available : UTP IRC

Therefore, all the necessary equipment and the information are available for the study and the project is expected to be finished within the time frame.

CHAPTER 2

LITERATURE REVIEW AND THEORY

2.1 Drilling Process

In petroleum drilling, it is important to remove drilled solids. Drilled solids can increase drilling costs, damage reservoirs, and create disposal costs. Thus, the best way to drill safely, fast and under budget is to remove the drilled solids. Good-drilled solids removal procedures start at the drill bit. Cuttings should be removed before another drill bit cutter crushes rock that has already been removed from the formation. These cuttings should be transported to the surface with as little disintegration as possible. In addition to the cuttings produced by the drill bits, silvers or chunks of rocks from the well-bore walls also enter the drilling fluid steam. Large drilled solids are easier to remove than small ones.

While drilling wells, drilling fluid is processed at the surface to remove drilled solids and blend the necessary additives to allow drilling fluid to meet specifications. Drill bit cuttings and pieces of formation that have sloughed into the well-bore are brought to the surface by the drilling fluid. The drilling fluid flows across a shaker before entering the mud pits. Most shale shakers impart a vibratory motion to a wire or plastic mesh screen and removes particle larger than the openings in the screen. Usually, drilled solids must be maintained at some relatively low concentration.

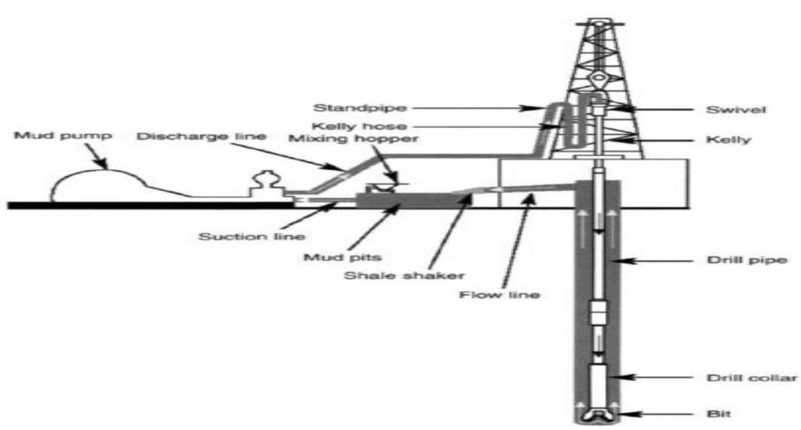


Figure 2.1: Drilling fluid

2.2 Drilling Fluids

Drilling fluid was used in the mid-1800s in cable tool (percussion) drilling to suspend the cuttings until they were bailed from the drilled hole. With the advent rotary drilling in the water-well drilling industry, drilling fluid was well understood to cool the drill bit and to suspend drilled cuttings for removal from the well-bore. Clays were being added to the drilling fluid by the 1890s. At the time that Spindle top, near Beaumont, Texas, was discovered in 1901, suspended solids (clay) in the drilling fluid were considered necessary to support the walls of bore-bole. With the advent of rotary drilling at Spindle top, cuttings needed to be brought to the surface by circulating the fluid. Water was insufficient so mud from mud puddles, spiked with some hay, was circulated downhole to bring rock cuttings to the surface. Most of the solids in the circulating system (predominantly clays) resulted from the so-called disaggregation of formations penetrated by the drill bit. The term disaggregation was used to describe what happened to the drilled clays. Clays would cause the circulating fluid to thicken, thus increasing the fluid of viscosity. Some of the formation drilled would not disperse but remain as rock particles of various sizes commonly called cuttings. Drilling fluid was recirculated and water was added to maintain the best fluid density and viscosity for the specific drilling conditions. Cuttings that are not dispersed by water, required removal from the drilling fluid in order to continue the drilling operation. At the sole discretion of the driller or tool pusher, a system of pits and ditches were dug on site to separate the cuttings from the drilling fluid by gravity settling. This system included a ditch from well, or possibly a bell nipple, settling pits and a suction pit from which the clean drilling fluid was picked up by the mud pump and recirculated.

2.2.1 Drilling Fluids Capability

Drilling fluid must satisfy many needs in their capacity to do the following:

i. suspend cuttings (drilled solids), remove them from the bottom of the hole and the well-bore, and release them at the surface
ii. control formation pressure and maintain well-bore stability
iii. seal permeable formations
iv. cool, lubricate, and support the drilling assembly
v. transmit hydraulic energy to tools and bit
vi. minimize reservoir damage
vii. permit adequate formation evaluation
viii. control corrosion
ix. facilitate cementing and completion
x. minimize impact on the environment
xi. inhibit gas hydrate formation

2.22 Types of Drilling Fluid

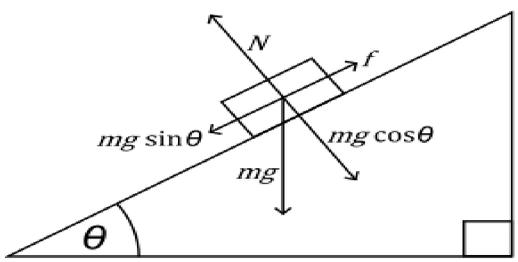
Drilling fluids are classified according to the type of base fluid and other primary ingredients:

i. gaseous: Air, nitrogen
ii. aqueous: gasified – foam, energized (including aphrons)
clay, polymer, emulsion
iii. nonaqueous: oil or synthetic – all oil, invert emulsion

True foams contain at least 70% gas (usually N_2, CO_2, or air) at the surface of the hole, while energized fluids, including aphrons, contain lesser amount of gas. Aphrons are specially stabilized bubbles that function as a bridging or lost circulation material (LCM) to reduce mud losses to permeable and microfractured formations. Aqueous drilling fluids are generally dubbed water-based muds (WBMs), while non aqueous drilling fluids (NAFs) are often referred to as oil-based muds (OBMs) or synthetic-based muds (SBMs). OBMs are based on NAFs that are distilled from crude oil; they include diesel mineral oils, and refined linear paraffins (LPs). SBMs, which are also known as pseudo-oil-based muds, are based on chemical reaction products of common feedstock materials like ethylene; they include olefins, esters, and synthetic LPs. Above the concentration of a few weight percent, dispersed drilled solids can generate excessive low-shear-rate and high-shear-rate viscosities, greatly reduce drilling rates, and excessively thick filter cakes. As the drilling mud density increases (increasing concentration of weighting material), the high-shear-rate viscosity rises continuously even as the concentration of drilled solids with low-gravity is reduced.

2.23 Theory about Transport of Drilled Cutting.

The flow of cutting in the annulus is a dynamic process and is subject to many forces in existence, such as those of gravity, buoyancy, drag, inertia, friction and antiparticle contact. The movement of a particle in the annulus is dictated by the dominating force. The forces acting on a single particle are shown below.



N = Normal force that is perpendicular to the plane
m = Mass of object
g = Acceleration due to gravity
θ (theta) = Angle of elevation of the plane
f = frictional force of the inclined plane

Figure 2.2: Forces acting on a single particle

2.24 Types of Fluid - Newtonian or Non-Newtonian

The majority of hydraulic parameters are dependent on what type of fluid the Drilling mud is and therefore which model is used for the calculations. The categories are determined by the fluid behavior when it is subjected to an applied force (shear stress). Precisely, in terms of fluid behavior, we are concerned with:-

At what point of applied shear stress is movement initiated in the fluid. Once movement has been initiated, what is the nature of the fluid movement (Shear Rate)

Shear Rate.....in a simple flow, is the change in fluid velocity divided by the width of the Channel through which the fluid is moving.

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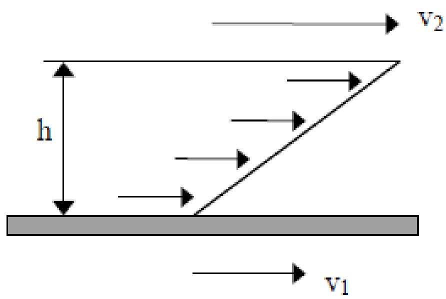
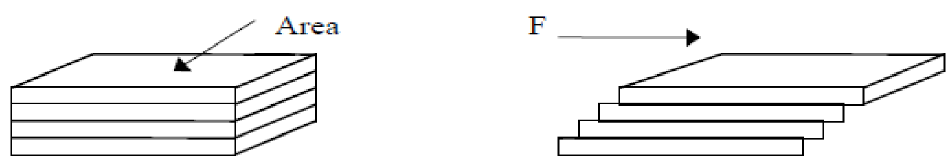


$$\text{Shear Rate } (\gamma) = \frac{v_2 - v_1}{h} = \sec^{-1}$$

Figure 2.3: Relationship Between Shear Stress and Shear rate

Shear Stress is the force per unit area required to move a fluid at a given shear rate.



$$\text{Shear Stress } (\tau) = F/A \quad = \frac{\text{lb. ft}}{\text{in}^2} \quad \text{or} \quad \frac{\text{lb. ft}}{100\text{ft}^2} \quad \text{or} \quad \frac{\text{dynes}}{\text{cm}^2}$$

Figure 2.4: Shear Stress

Newtonian Fluids: The fluid will begin to move the instant that shear stress is applied. Thereafter, the degree of movement is proportional to the stress applied...

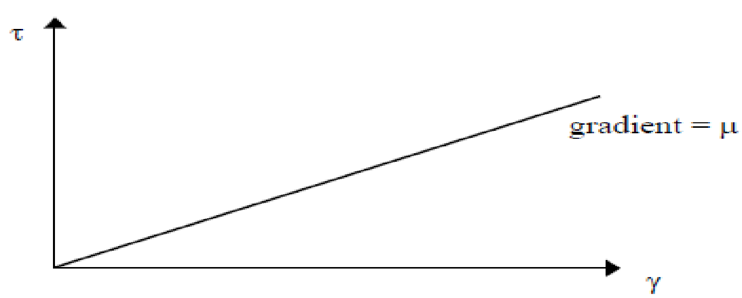


Figure 2.4: relationship exists between Shear Stress (t) and Shear Rate (g).

I.e. A linear relationship exists between Shear Stress (t) and Shear Rate (g).

Rheogram Summary of the Drilling Fluid Models.

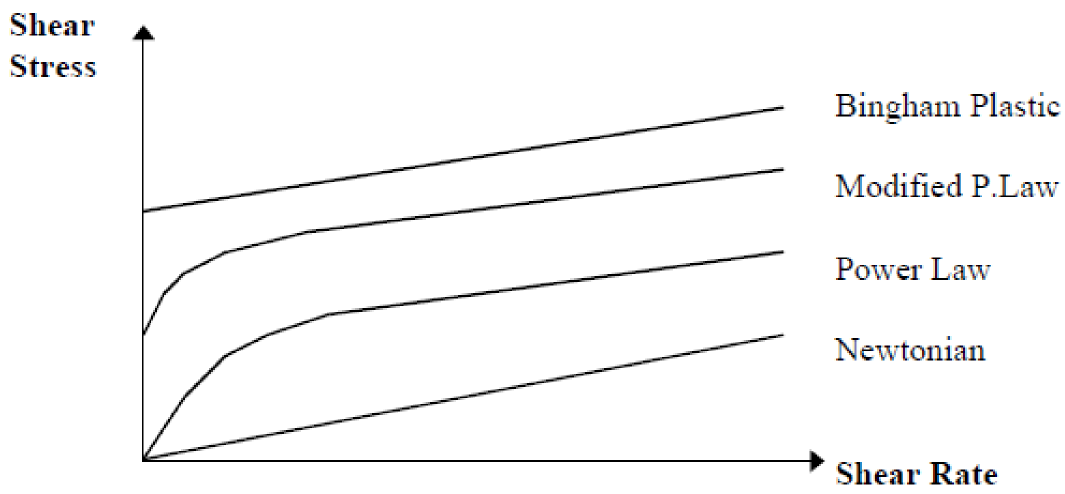


Figure 2.4: Rheogram Summary of the Drilling Fluid Models

Non Newtonian Fluids.

For these fluids, the flow will not necessarily be parabolic. As the fluid becomes 'increasingly' non-Newtonian, the velocity profile will become increasingly flatter towards the centre. This is known as *plugged flow*. Using the Power Law as a basis, when 'n' is equal to one, the fluid is Newtonian and the velocity profile will indeed be parabolic.

As the value of 'n' decreases, i.e. the fluid becomes increasingly non-Newtonian and the velocity profile will become increasingly flatter. In this flat part of the profile, the shear rate will be close to zero (i.e. very little movement between adjacent laminae). Fluids that exhibit a high viscosity in this near zero shear rate condition offer significant improvements in hole cleaning efficiency.

Laminar, Turbulent and Transitional Flow Patterns.

The type of flow pattern will be governed by the fluid velocity, the annular diameters and the characteristics of the mud. In general, the lower the fluid velocity and the greater the annular diameter, the more likely the flow is to be laminar. A turbulent flow pattern is more likely when the fluid velocity is high and when there is a small annular clearance i.e. around the drill collar section.

Determination of Flow Type.

It is necessary to know what type of flow pattern is present, not only because of the physical affects, but in order to calculate pressure losses in the string and the annulus, a very important part of hydraulic analysis. Fluid velocity and annular diameters are used to determine the type of flow, in conjunction with mud density and mud viscosity. These parameters are used to determine the ***Reynolds Number***, Reynolds number (N_{Re}) is defined as the ratio of fluid momentum force to viscous shear force. The Reynolds number can be expressed as a dimensionless group defined as a dimensionless number:

$$Re = \frac{DV\rho}{\mu_e}$$

where D = diameter

V = fluid velocity

ρ = density

μ_e = effective viscosity

2.3 Cuttings Transport

In engineering point of view, cuttings transport is dependent on:

- Cuttings Slip Velocity
- Annular Mud Velocity
- Flow Regime of Fluid
- Annular Velocity Profile
- Cuttings Bed Formation (in inclined annuli only)
- Drill Pipe Rotary Speed and Drilling Rate
- Fluid Rheological Properties
- Hole Inclination
- Factors Related to Cuttings (size, density, shape, concentration, size distribution)

To better understand the effects of some of the parameters affecting the cutting transportation, parameters were classified into four groups (1) mud weight, (2) cutting size, (3) mud viscosity, and (4) drilling rate. Some important definitions are illustrated below prior to detail study of the parameters.

Cuttings slip velocity.

Drilled cuttings have the tendency to fall down (slip) through the fluid medium at a velocity referred to as the Cuttings slip velocity.

In the case of vertical annuli, there is only one axial component of slip velocity,

$$v_s = v_{as}$$

In contrast when an annulus is inclined at an angle θ from vertical, there will be two components for the slip velocity.

$$\bar{v}_{sa} = \bar{v}_s \cos\theta \qquad \bar{v}_{sr} = \bar{v}_s \sin\theta$$

Where $\mathbf{v_{sa}}$ and $\mathbf{v_{sr}}$ are the axial and radial components of the average slip velocity, respectively, When these conditions are taken into account, all factors that may lead to improved cuttings transport by a reduction of the particle slip velocity will have a diminishing effect while the angle of inclination is increasing.

Cuttings transport (rise) velocity.

For the fluid to lift the cuttings to the surface, the fluid annular average velocity, v_a must be in excess of the cuttings average slip velocity, v_s. The relative velocity between v_a and v_s is termed the average cuttings transport (rise) velocity, v_t that is,

$$\frac{v_t}{v_a} = 1 - \frac{v_s}{v_a} = R_t \qquad v_t = v_a - v_s$$

Where R_t is the cuttings transport ratio, as defined by Sifferman et al. In vertical well drilling, it is recommended that R_t be a minimum of 0.5-0.55.

Annular fluid velocity.

The increasing radial component of particle slip velocity pushes the particle toward the lower wall of the annulus, causing a cuttings bed to form. Consequently, the annular fluid velocity has to be sufficient to avoid (or at least to limit) the bed formation. For limitation of cuttings bed formation, the annular fluid velocity in directional drilling has to be generally much higher than in vertical drilling.

2.4 Studies on Past Literature Review

2.40 Mud Rheology

Belavadi and Chukwu (1994) used experimental flow loop with transparent acrylic casing – drill pipe annulus. Four different weights of bentonite mud samples 8.9 ppg, 9.3 ppg, 12 ppg and 13 ppg) with cutting chips of graded sizes small, medium and large were introduced into the annular column from the bottom section of the transparent acrylic pipe. They used a non – dimensional approach and observed that an increase in the flow rate at higher fluid densities greatly increase the transport ratio. This effect is almost negligible when using low density fluids to transport large size cuttings. They reported that the fluid density to viscosity ratio concept can be applied to control drilling through sensitive formations. A small increase in the fluid density to viscosity ratio results to a rapid decrease in the transport ratio. Similarly, a small increase in the drag coefficient on the cuttings results to a large increase in the transport ratio.

Walker and Li (2000) used a flow loop that consisted of a 20 ft long transparent Lexan pipe with a 5.0 in. inner diameter to simulate the open hole and a 2 3/8 –in. steel inner pipe to simulate coiled tubing. Three different muds of HEC, Xanvis polymer and water with particle sizes ranging from 0.15 mm to 7.0 mm were used for the study. They showed that fluid rheology plays an important role for solid transport and to achieve optimum results for hole cleaning, the best way to pick up solids is with a low viscosity fluid in turbulent flow but to maximize the carrying capacity a gel or a multiphase system should be used to transport the solids out of the well bore.

2.41 Annular Flow Rate

Belavadi and Chukwu (1994) reported that small variations in the annular flow rate can result to a substantial increase in the transport ratio. Transport ratios are greatly increased at high mud flow rates with pipe rotation when small to medium sized cuttings are transported.Work by Martin, et. al. (1987), said that the particle transfer rate depends to a large extent on the flow rate. When the flow rate is too low, the particle is no longer separated in the annulus.

2.42 Cutting Size

Belavadi and Chukwu (1994), conducted experimental study with three different particle sizes and concluded that the removal of small size cutting particles is greatly enhanced with pipe rotation when drilling with high density mud circulated at high flow rates.

Walker and Li (2000), investigated experimental study in the laboratory for particles up to 7 mm in diameter. They reported that cutting size had significant effect on solids transport. Fine particles are the easiest to clean out and spherical particles with an average size of 7.6 mm pose the greatest difficulty for solids transport.

2.43 Mud Weight

Belavadi and Chukwu (1994) used a dimensionless approach where the ratio of cuttings to mud densities was used to analyze the effect of mud weight on cuttings transportation. They used three different cutting sizes with different mud weigh and showed that an increase in mud weight to an increase in the transport ratio.

Sifferman, et. al. (1973), reported that the mud weight had a moderate effect on cutting transport.

2.44 Viscosity

Becker et.at. (1989), investigated experimentally the effects of viscosity and gel formation on cutting transport properties in deviated wells for 15 different water based drilling fluid systems viscosified with bentonite and polymers. They found that the hole cleaning performance correlated to the 3 rpm shear stress measured on a VG meter. They also observed that the cuttings bed size was reduced if the shear stress at the actual pump rate was increased.

Seeberger et al. (1989) claimed that the low shear viscosity parameters should be evaluated to obtain good hole cleaning.

CHAPTER - 3

RESEARCH METHODOLOGY

There were two different approaches used in completing this project. They are analytical approach, and simulation approach.

3.0 Project Activities and Work Flow.

Throughout this project, steps that are carried out were planned carefully. The following figure describes the process.

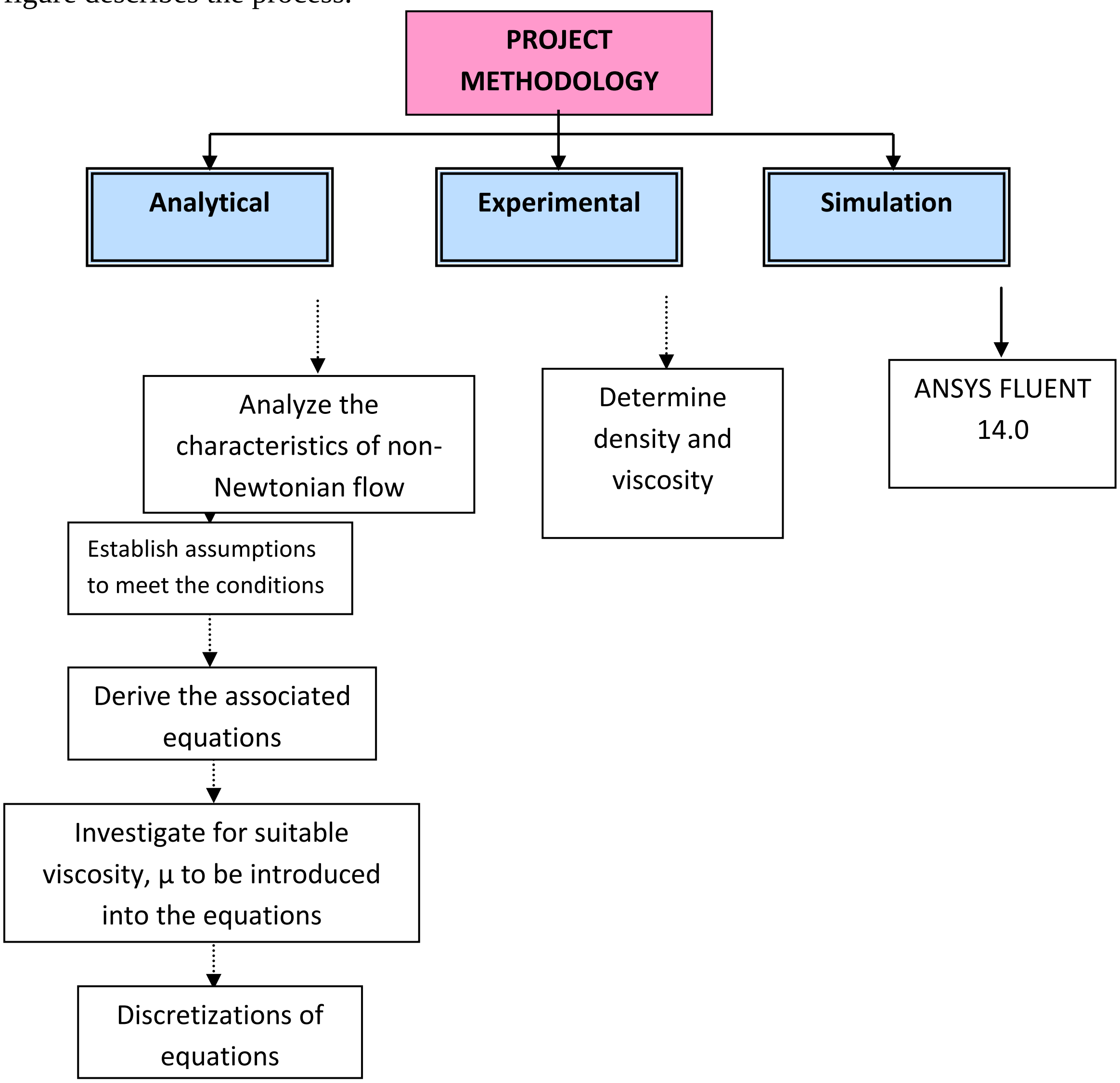


Figure 3.0: Workflow throughout the project

3.1 PROJECT PROGRESS

Milestones Weeks	1	2	3	4	5	6	7		8	9	10	11	12	13	14
Topic selection															
Preliminary research															
Literature review															
Transport drilled cuttings Study															
Learning the software															
Modeling with software															
Comparison and analysis of model data and actual data															
Final Report (FYP-1)															
	15	16	17	18	19	20	21		22	23	24	25	26	27	28
Topic selection															
Preliminary research															
Literature review															
Transport of drilled cuttings Study															
Learning the software															
Modeling with software															
Comparison and analysis of model data and actual data															
Final Report (FYP-2)															

Table 3-0. Project Gantt chart.

3.11 Project activities and Tools required.

1) Computer workstation Lab equipment.
    - Computer
    - CFD software(CFX-FLUENT**, STAR-CD, ,FLUENT
    - Workstation

GAMBIT software is used for the modeling of the annulus and FLUENT software is used for the simulation. In all approaches the same basic procedure is followed.

- During preprocessing
    - The geometry (physical bounds) of the problem is defined.
    - The volume occupied by the fluid is divided into discrete cells (the mesh). The mesh may be uniform or non uniform.
    - The physical modeling is defined
    - Boundary conditions are defined. This involves specifying the fluid behaviour and properties at the boundaries of the problem. For transient problems, the initial conditions are also defined.
- The simulation is started and the equations are solved iteratively as a steady-state or transient.
- Finally a postprocessor is used for the analysis and visualization of the resulting solution.

3.12 Computer workstation Lab experiment

Preliminary Research

- Conduct literature review on transport of drilled cuttings, current technology of evaluating the effectiveness of CFD and perform literature review on CFD

↓

Hardware Setup

- Variable Identification: Factors That Affect the Transport of Drilled Cuttings
- Processing Identification: The geometry (physical bounds) of the problem is defined. The volume occupied by the fluid is divided into the mesh, and Boundary conditions are defined

↓

Analysis of Results

- The simulation is started and the equations are solved iteratively as a steady-state or transient.
- Finally a postprocessor is used for the analysis and visualization of the resulting

↓

Discussion of Analysis

- Discuss the findings from the results obtained and make a conclusion out of the study, determine if the objective has been met

↓

Report Writing

- Compilation of all research findings, literature reviews, simulation works and outcomes into a final report

3.2 Analytical Approach

In analyzing the flow, two governing equations have been manipulated to illustrate the motion of fluid. These equations which are continuity equations and Navier Stokes equations have been simplified based on the assumptions made below.

i. Two-Dimensional Flows
ii. Fully Developed Flows
iii. Steady State Flows
iv. Adiabatic

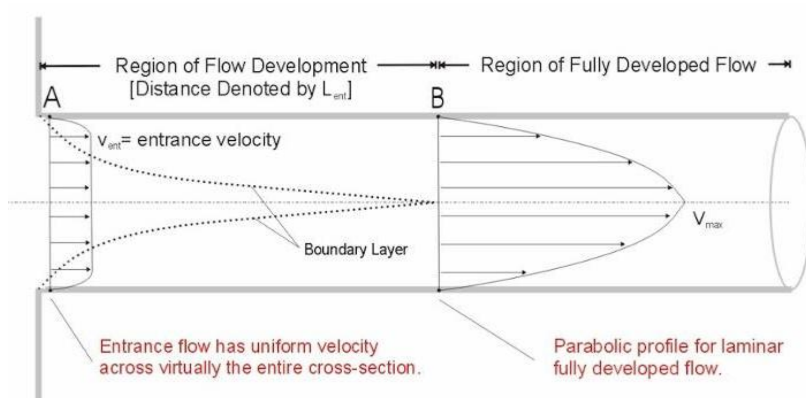


Figure 3.1: Velocity profile

Since we are studying a steady flow of fluid through a circular pipe, the velocity everywhere on the pipe surface is zero because of no-slip condition.

The flow is two-dimensional in the entrance region of the pipe since the velocity changes in both the *r*- and *z*- directions. The velocity profile develops fully and remains unchanged after some distance from the inlet (about 10 pipe diameters in turbulent flow, and less in laminar pipe flow, as in Fig 3), and the flow in this region is said to be fully developed. The fully developed flow in a circular pipe is one-dimensional since the velocity varies in the radial, *r*- direction, from r_{in} to r_{out} but not in the angular, θ- or axial, *z*- directions. Thus, the velocity profile is the same at any axial *z*- location, and it is symmetric about the axis of the pipe.

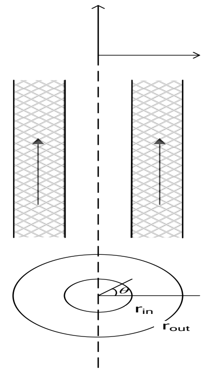


Figure 3.2: Cross-sectional area of the well

The derivation of the equations is as follow:

Remember that the fully developed flow has no velocity in angular, θ- direction. Thus, $v_\theta = 0$, or;

$\frac{\partial}{\partial\theta} = 0$. The steady state flows then relate to this equation: $\frac{\partial}{\partial t} = 0$.

<u>Continuity Equations: -</u> The continuity equations in cylindrical coordinate for constant density is

$\frac{1}{r}\frac{\partial}{\partial r}(rv_r) + \frac{1}{r}\frac{\partial}{\partial\theta}(v_\theta) + \frac{\partial}{\partial z}(v_z) = 0$, Since $\frac{\partial}{\partial\theta} = 0$, the equation becomes $\frac{1}{r}\frac{\partial}{\partial r}(rv_r) + \frac{\partial}{\partial z}(v_z) = 0$

<u>Navier-Stokes Equations:-</u> The Navier-Stokes equations in cylindrical coordinates for constant density and viscosity are

r- component: $\rho\left(\frac{\partial v_r}{\partial t} + v_r\frac{\partial v_r}{\partial r} + \frac{v_\theta}{r}\frac{\partial v_r}{\partial\theta} - \frac{{v_\theta}^2}{r} + v_z\frac{\partial v_r}{\partial z}\right)$

$$= \rho g_r - \frac{\partial p}{\partial r} + \mu\left\{\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}[rv_r]\right) + \frac{1}{r^2}\frac{\partial^2 v_r}{\partial\theta^2} - \frac{2}{r^2}\frac{\partial v_\theta}{\partial\theta} + \frac{\partial^2 v_r}{\partial z^2}\right\}$$

θ- component $\rho\left(\frac{\partial v_\theta}{\partial t} + v_r\frac{\partial v_\theta}{\partial r} + \frac{v_\theta}{r}\frac{\partial v_\theta}{\partial\theta} + \frac{v_r v_\theta}{r} + v_z\frac{\partial v_\theta}{\partial z}\right)$

$$= \rho g_\theta - \frac{1}{r}\frac{\partial p}{\partial \theta} + \mu\left\{\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}[rv_\theta]\right) + \frac{1}{r^2}\frac{\partial^2 v_\theta}{\partial \theta^2} + \frac{2}{r^2}\frac{\partial v_r}{\partial \theta} + \frac{\partial^2 v_\theta}{\partial z^2}\right\}$$

z- component $\rho\left(\frac{\partial v_z}{\partial t} + v_r\frac{\partial v_z}{\partial r} + \frac{v_\theta}{r}\frac{\partial v_z}{\partial \theta} + v_z\frac{\partial v_z}{\partial z}\right)$

$$= \rho g_z - \frac{\partial p}{\partial z} + \mu\left\{\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 v_z}{\partial \theta^2} + \frac{\partial^2 v_z}{\partial z^2}\right\}$$

Because the flow is considered as 2-D flow and steady, the $\frac{\partial}{\partial \theta}$ and $\frac{\partial}{\partial t}$ terms are cancelled out. Thus, the above momentum equations become *r*- component $\rho\left(v_r\frac{\partial v_r}{\partial r} + v_z\frac{\partial v_r}{\partial z}\right)$

$$= \rho g_r - \frac{\partial p}{\partial r} + \mu\left\{\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}[rv_r]\right) + \frac{\partial^2 v_r}{\partial z^2}\right\}$$

z- component $\rho\left(v_r\frac{\partial v_z}{\partial r} + v_z\frac{\partial v_z}{\partial z}\right) = \rho g_z - \frac{\partial p}{\partial z} + \mu\left\{\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right) + \frac{\partial^2 v_z}{\partial z^2}\right\}$

Note that there is no equation developed in θ direction since all the significant terms all are cancelled out.

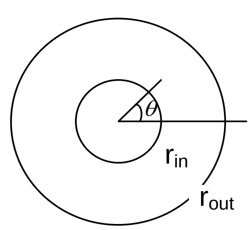


Figure 3.3: Top view of the well

Observe that there is no velocity in *r* direction but a variation of velocity from r_{in} to r_{out}.

$V = v(r)$ and $v_r = 0$

These new conditions yield new equations for the above continuity and Navier-Stokes equations.

Continuity equation:

$\frac{\partial}{\partial z}\left(v_z\right) = 0$, which means $V_z = v_z(r)$

Navier-Stokes equations:

Momentum in *r*-direction

$\rho g_r = \frac{\partial p}{\partial r}$ Gravitational force in vertical pipe only acts in *z*-direction. Thus, $g_r = 0$ and $\frac{\partial p}{\partial r} = 0$ which means the pressure varies in *z*-direction only $p = P(z)$, $\frac{\partial p}{\partial z} = \frac{dp}{dz}$ Momentum in *z*-direction, $0 = \rho g_z - \frac{\partial p}{\partial z} + \mu\left\{\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right)\right\}$,

rearrange; $\mu\left\{\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right)\right\} = \frac{\partial p}{\partial z} - \rho g_z$

Since $V_z = v_z(r)$ only, then $\frac{\partial v_z}{\partial r} = \frac{dv_z}{dr}$, $\frac{\partial^2 v_z}{\partial r^2} = \frac{d^2 v_z}{dr^2}$

Observe that the partial derivatives of v_z and v^2_z are converted into ordinary term. Thus the above equation becomes

$\mu\left\{\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{dv_z}{dr}\right)\right\} = \frac{dp}{dz} - \rho g_z$ Or; $\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{dv_z}{dr}\right) = \frac{1}{\mu}\left[\frac{dp}{dz} - \rho g_z\right]$

Further rearrange and solve for the equation, $r\frac{dv_z}{dr} = \frac{r}{\mu}\int\left[\frac{dp}{dz} - \rho g\right]\partial r$

$r\frac{dv_z}{dr} = \frac{P(z) - \rho g}{\mu}\left(\frac{r^2}{2}\right) + C_1$,

$V_z(r) = \int\frac{1}{r}\left[\frac{P(z) - \rho g}{\mu}\left(\frac{r^2}{2}\right) + C_1\right]dr$, $V_z(r) = \frac{P(z) - \rho g}{\mu}\int\left(\frac{r}{2} + \frac{C_1}{r}\right)dr$

$$V_z(r) = \frac{P(z) - \rho g}{\mu} \times \frac{r^2}{4} + C_1 \ln r + C_2$$ By applying the boundary conditions;

At ri_n , V_z $(ri_n) = 0$, at r_{out}, V_z $(r_{out}) = 0$,

$$V_z(r_{in}) = 0 = \frac{P(z) - \rho g}{\mu} \times \frac{r_{in}^{\ 2}}{4} + C_1 \ln r_{in} + C_2 \qquad \text{(i)}$$

$$V_z(r_{out}) = 0 = \frac{P(z) - \rho g}{\mu} \times \frac{r_{out}^{\ 2}}{4} + C_1 \ln r_{out} + C_2 \qquad \text{(ii)}$$

By subtracting (ii) from (i),

$$0 = \left[\frac{P(z) - \rho g}{\mu} \times \frac{r_{in}^{\ 2}}{4} + C_1 \ln r_{in} + C_2 \right] - \left[\frac{P(z) - \rho g}{\mu} \times \frac{r_{out}^{\ 2}}{4} + C_1 \ln r_{out} + C_2 \right]$$

$$0 = \frac{P(z) - \rho g}{4\mu} \left(r_{in}^{\ 2} - r_{out}^{\ 2} \right) + C_1 \ln \frac{r_{in}}{r_{out}} \ , \ C_1 = \frac{\frac{P(z) - \rho g}{4\mu} \left(r_{out}^{\ 2} - r_{in}^{\ 2} \right)}{\ln \frac{r_{in}}{r_{out}}}$$

Substitute the above equation into (i) will yield

$$0 = \frac{P(z) - \rho g}{\mu} \times \frac{r_{in}^{\ 2}}{4} + \frac{\frac{P(z) - \rho g}{4\mu} \left(r_{out}^{\ 2} - r_{in}^{\ 2} \right)}{\ln \frac{r_{in}}{r_{out}}} \ln r_{in} + C_2$$, Whereby

$$C_2 = -\frac{P(z) - \rho g}{\mu} \times \frac{r_{in}^{\ 2}}{4} - \frac{\frac{P(z) - \rho g}{4\mu} \left(r_{out}^{\ 2} - r_{in}^{\ 2} \right)}{\ln \frac{r_{in}}{r_{out}}} \ln r_{in}$$. The equation will be solved completely once ri_n and r_{out} are known and the viscosity term, μ is substituted by the flow model.

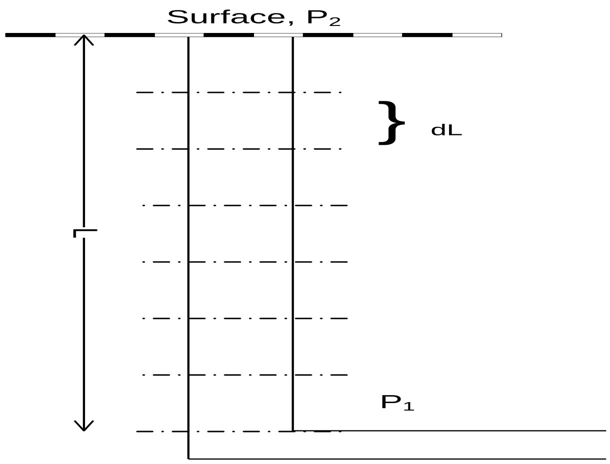


Figure 3.4: Segments of the vertical well bore

Accordingly, $\frac{dP}{dz} = \frac{P_2 - P_1}{\Delta L}$. Note that it is possible to consider linear reduction in the pressure and we can compensate $\frac{dP}{dL}$ as well.

3.3 FEATURES OF COMPUTATIONAL FLUID DYNAMICS (CFD) PROGRAM.

The simulation work will be done using ANSYS WORKBENCH 14.0 CFD. Density and viscosity related data from experiments and geometrical dimension from field as well as pressure and velocity as well as pressure and velocity were fed into the ANSYS. The term ‘CFD’ stands for Computational Fluid Dynamics. Computational Fluid Dynamics is a powerful numerical modeling tool virtually possible to apply every problem. CFD can be used for modeling fluid flow and heat transfer in complex geometry. CFD solves flow problems with unstructured meshes in a relatively ease. CFD particularly useful for accurately predicting flow fields in regions with large gradients, such as free shear layers and boundary layers. CFD reduces the computational effort required to achieve a desired level of accuracy.

CFD approach can be used to model the following:

- Flow in 2D or 3D geometries using unstructured solution-adaptive triangular/tetrahedral, quadrilateral/hexahedral, or mixed (hybrid) grids.
- Incompressible or compressible flows and Steady-state or transient analysis
- In viscid, laminar, and turbulent flows or Newtonian or non-Newtonian flow
- Convective heat transfer, including natural or forced convection coupled conduction/convective heat transfer
- Inertial (stationary) or non-inertial (rotating) reference frame models
- Multiple moving reference frames, including sliding mesh interfaces and mixing planes for rotor/stator interaction modeling
- Chemical species mixing and reaction, including combustion submodels and surface deposition reaction models
- Arbitrary volumetric sources of heat, mass, momentum, turbulence, and chemical species
- Lagrangian trajectory calculations for a dispersed phase of particles/droplets/bubbles, including coupling with the continuous phase
- Flow through porous media and in One-dimensional fan/heat-exchanger performance models
- Two-phase flows, including cavitations and Free-surface flows with complex surface shapes.

In summary, CFD ideally suited for incompressible and compressible fluid flow simulations in complex geometries.

3.4 SIMULATION APPROACH

To execute the simulation of parameters studied in this work of computational fluid dynamics on cutting transportation in inclined wells, a section of 100 m long hole with an 8.0 in. diameter and a 4.0 inch drill pipe was simulated by software. Coopers mesh was generated in the annulus volume because fluid can flow only in the annulus mesh area. The discrete phase model was used where cuttings are introduced separately with mud at the annulus inlet. The basic principle of computational fluid dynamics is to split the annulus section into infinitesimal length of steps and solve the equation of motion over the length of annulus section with reasonable short computational time steps so that particle can reach to the surface. To better understand the effects of some of the parameters affecting the cutting transportation, parameters were classified into four groups (1) mud weight, (2) cutting size, (3) mud viscosity, (4) drilling rate and (5) angle of inclination.

3.41 FLOW CHART OF PROGRAM FLOW / EXECUTION

Once the important features of the problem have determined to solve, the basic procedural steps to be followed:

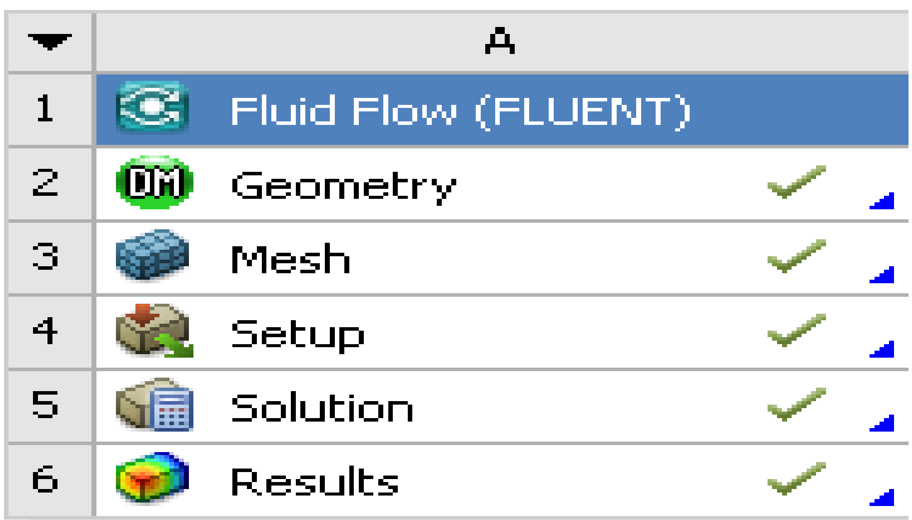


Figure 3.30: basic procedural steps

1. Geometry

It allows you to define the geometrical constraints of your analysis. . You can use the context menu (by right-clicking on the cell) to import a pre-existing geometry into the system. Double-clicking on the Geometry cell opens ANSYS DesignModeler where you can create a new geometry or modify an existing geometry.

2. Mesh

It allows you to define and generate a computational mesh for your analysis. Double-clicking on the Mesh cell opens ANSYS Meshing and loads the current mesh database (or the geometry defined by the Geometry cell) if you have not yet begun working on the mesh. Alternatively, you can use the context menu (by right-clicking on the Mesh cell) to import a pre-existing FLUENT mesh into the system.

3. Setup

It allows you to define the boundary conditions, physical models and solver settings for the FLUENT analysis. Double-clicking on the Setup cell opens FLUENT and loads the mesh defined by the Mesh cell as well as any FLUENT settings that have already been specified

4. Solution

It allows you to calculate a solution in FLUENT. Double-clicking on the Solution cell opens FLUENT and loads the current FLUENT case and data files. If you have not yet performed any calculations, FLUENT will load the mesh file as well as any settings that have been specified.

5. Results

It allows you to display and analyze the results of the CFD analysis.

Double-clicking on the Results cell opens CFD-Post and loads the current FLUENT case and data files as well as the current CFD-Post state file.

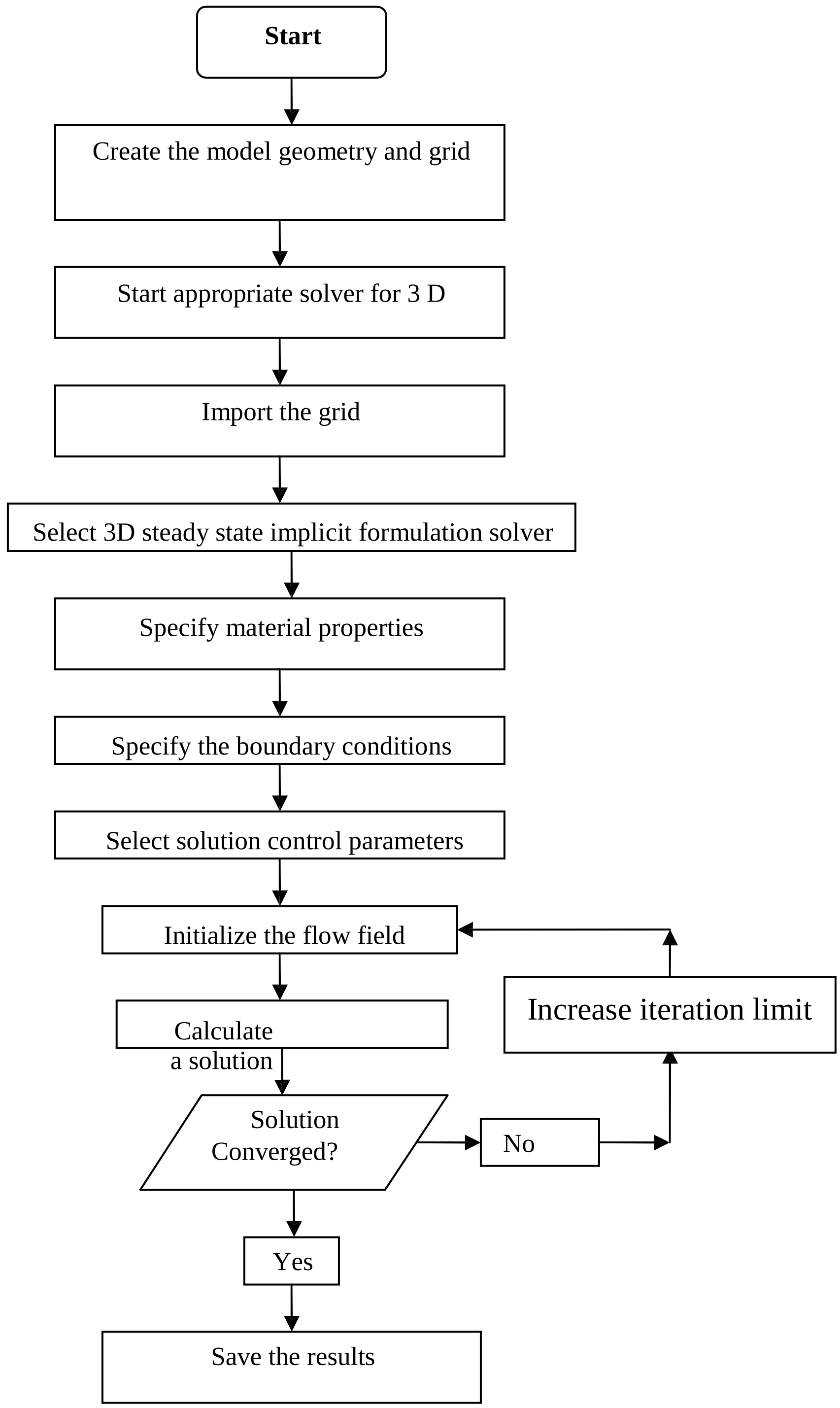


Figure 3.31: Flow Chart

3.5 MODELSETUP

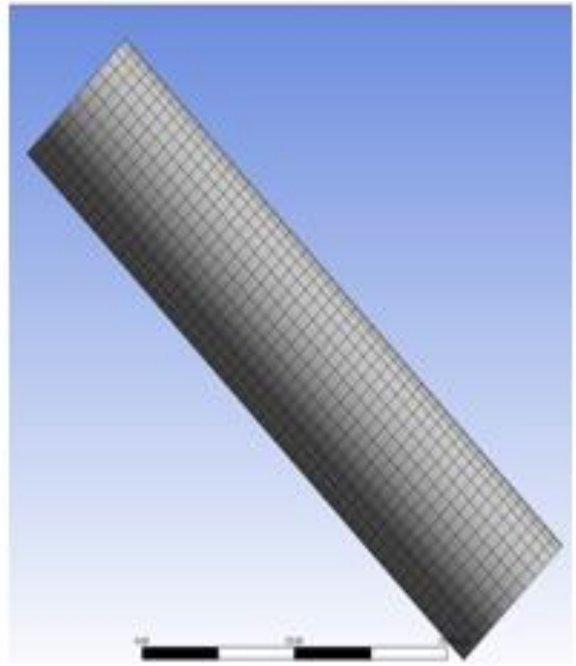
Physical Model

A section of the annulus as shown below was used throughout this study. The section consists of 100 meters long hole with an 8.0 inch diameter and a 4.0 inch drill pipe. Any combination of casing – drill pipe with required length of annulus can be created by this software. However a reasonable length was selected to study several parameters with reasonable short computational times. But the drill pipe doesn't rotate and its position can't be changed to vary the eccentricity.

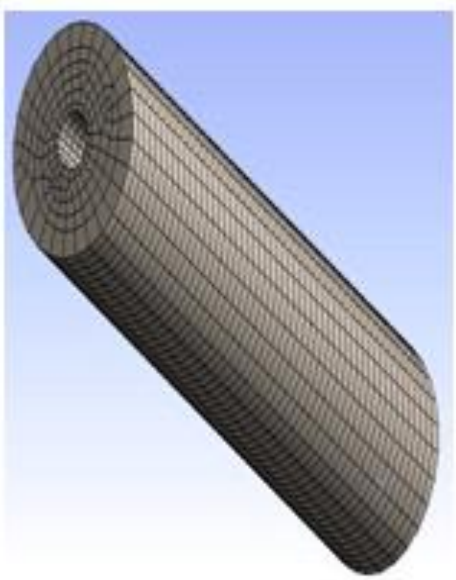
Coopers mesh was generated in the annular volume and Fluent was chosen as a solver. The boundary conditions at the inlet and outlet of simulated section were defined and mesh was exported to solve. A mesh file was created with Fluent Version and case file was run and checked the grid. While conducting runs, the operating pressure was chosen at 35 atm. at all runs and reference pressure location, gravitational force and range of mud density values were (0,0,0), - 9.8 m/s^2, and 833 kg/m^3 to 1800 kg/m^3 . In the boundary condition, range of mass flow rate 8 kg/s to 75 kg/s, component of flow direction Z or X (depends on model), and flow rate weighting 1.0 were used. Cuttings were injected by specifying cutting diameters 0.1 in. to 0.275 in., cutting velocity 0.0123 ft/s to 0.0369 ft/s and amount of cuttings introduced 15 lbs/min. to 45Lbs/min. The solution for first order differential equation was selected and the solution was initialized by defining the maximum number of steps 5000 with 0.03 m of reporting steps. Once the iteration has been completed velocity profile was drawn and average annular velocity was measured from the velocity profile.

Simulation of Casing Drill Pipes

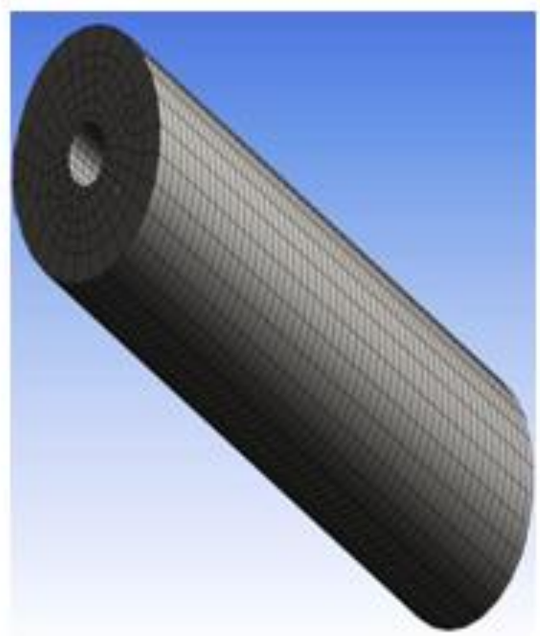
At 90°



At 60°



At 45°



At 30°

3.6 PROPERTIES STUDIED IN THIS WORK.

Mud Weight

The effect of mud weight on cutting transport were studied using three different muds (10 ppg,12 ppg, 15 ppg) and water with three different cutting sizes 0.1 in., 0.175 in., and 0.275 in.. For each mud, the flow rate was varied while the cutting size and all other operating conditions were kept constant. The appendix B shows the runs conducted with 10 ppg, 12 ppg, 15 ppg mud and water for 0.1 in., 0.175 in. and 0.275 in. cutting sizes while the cutting mass rate was 15 lbs/min. The flow direction was opposite to the gravitational force and the negative gravitational force values were computed for all runs.

Cutting sizes

Three different cutting sizes were used to see the effect of cutting size on cutting transport. For each mud weight the test was carried out for three different cutting sizes. Figure 12 through Figure 19 show the runs conducted with 0.1 in., 0.175 in. and 0.275 in. cutting sizes with the mud weighs of 8.33 ppg, 10 ppg, 12 ppg and 15 ppg. Although cutting size was varied, the cutting rate was constant at 15 lbs/min. in every case. During the run it was assumed that the particles are non spherical and uniform in size.

Drilling Rate

Three different drilling rates of 16 ft/hr, 32 ft/hr and 48 ft/hr were studied to observe the effect of mud rate on cutting concentration in annulus. To eliminate other effects, same mud flow rate was used for different drilling rates. Runs conducted with three different drilling rates for three different cutting sizes of 0.1 in., 0.175 in. and 0.275 in. In all runs 10 ppg mud was used and the cutting density was 2.57 gm / cc.

Mud viscosity

In runs conducted to determine the effect of viscosity on cutting transport, 10 ppg, 12 ppg and 15 ppg mud densities with viscosities ranging from 10cp to 30 cp were used with cutting sizes between 0.1 and 0.275 inch. The cutting mass rate was 15 lbs / min. in all runs.

Table 3.2: INPUT DATA USED AND RANGE OF VARIABLES

Property	Unit	Values
Mud Weight	PPG	8.33, 10.0, 12.0, 15.0
Viscosity	CP	10, 20, 30
Drilling Rate	FT/HR	16, 32, 48
Cutting Size	INCH	0.10, 0.175 , 0.275
Cutting Density	GM/CC	2.57
Inclination Angle	DEGREE	90◦, 60◦, 45◦, 30◦
Length of inclined wells	FT	100
Outer diameter of pipe	INCH	8
inner diameter of pipe	INCH	4

CHAPTER 4

RESULTS AND DISCUSSION

4.1 DISCUSSION ON RESULTS

In this chapter, the proposed models results are compared with the experimental data. All simulation results are found in the appendix B.

Effect of Mud weight:

The cutting transport is studied for three muds of widely varying rheological properties and water. The results for 10 ppg, 12 ppg, 15 ppg mud and water with three different cutting sizes are plotted in Figure 5 through 7 for various inclined wells. In all runs a smooth continuous curve is obtained starting with the initiation of cutting transport. The point at which transport begins is approximated by the cutting terminal settling velocity. At low annular velocities, there is a greater divergence, while at higher velocities the curves begin to approach each other. This is based on the percent contribution to total fluid thinning due to particle fall is greater at low flow rates and less important at high flow rates. The weight of circulation fluid has an effect on cutting transport. Therefore, flow regime, geometric combination of hole and tubing also affect the mud properties and has a significant impact on cutting transport.

The mud weight has also had an effect on cutting transport. The 15 ppg mud does indeed move the cuttings more rapidly through the annulus. Mud properties can be tailored to efficiently transport drill cuttings at low annular velocities when necessary. The most important concept to understand is that the greater solids carrying capacity a fluid has, the more efficiently the hole can be cleaned. Thus an increase in mud weight slightly enhances cuttings transport as long as there is not an accompanying increase in viscosity. The effect that mud weight has on hole cleaning is more pronounced for high angle-wells.

Effect of cutting size

The characteristics of cuttings, such as size, shape and density, are related to their dynamic behavior in a flowing media. The terminal velocity, drag force, buoyancy corrected gravity force and shear forces between cuttings are affected by both the characteristics of the cuttings and the properties of the circulated fluids. The cutting size has moderate effect on cutting transport. The runs conducted with cutting sizes of 0.1 in., 0.175 in. and 0.275 in. with mud weights of 10 ppg, 12 ppg, 15 ppg and water for inclined wells are shown in appendix B. These plots indicate that a very slight increase in cutting size decreases the cutting transport. Therefore For high angle wellbores, smaller sized cuttings are harder to transport due to the higher lift force requirements. And at low angles of inclination, medium-sized cuttings are easier to transport than the smallest or the largest cuttings. Generally at high inclination angles, it is harder to transport smaller cuttings. At low inclination angles, it is easier to transport medium-sized cuttings than it is to move the smallest or largest-sized particles.

Effect of viscosity

To study the effect of viscosity in the non – Newtonian fluid, runs were conducted with three different mud weights (10 ppg, 12 ppg and 15 ppg) and with three different cutting sizes (0.10 in., 0.175 in. and 0.275 in.) where viscosity values ranged from 10 to 30 cp. A consistent family of curves was obtained showing increasing cutting transport with increasing viscosity. Again, the initiation of transport occurred near the terminal settling velocity obtained for each mud. Generally, fluid rheology plays an important role for cuttings transport. To achieve optimum results for hole cleaning, the best way to pick up cuttings is with a low viscosity fluid in turbulent flow but to maximize the carrying capacity a high density mud should be used to transport the solids out of the wellbore.

Effect of drilling rate.

There exists a linear relationship between drilling rate and cutting concentration in annulus. The runs conducted to show the effect of drilling rate on cutting concentration in annulus for three different drilling rates (16 ft / hr, 32 ft / hr and 48 ft / hr) with the10 ppg mud and cutting sizes of 0.10 in., 0.175 in. and 0.275 in. are shown in Figures 55 thru 57 for inclined wells In all runs, As ROP increases, the hydraulic requirements for effective cuttings transport increases. Experiences showed that, the relation between the increase in ROP and required critical transport fluid velocity is linear**.** Therefore, drilling rate has an important effect on the quantitative aspect of cuttings transport. Increased drilling rates tend to increase the hydraulics requirements for effective cuttings removal. There is a linear relationship between drilling rate and required critical transport fluid velocity.

CHAPTER: 5

CONCLUSIONS AND RECOMMENDATION

5.1 CONCLUSIONS

The following conclusions are based on the results obtained in the steady state cutting transport test in an inclined wells:

1. *Effect of mud weight*:

   An increase in mud weight slightly enhances cuttings transport as long as there is not an accompanying increase in viscosity. The effect that mud weight has on hole cleaning is more pronounced for high angle-wells.
2. *Effect of Size of drilled Cuttings:*
   - For high angle wellbores, smaller sized cuttings are harder to transport due to the higher lift force requirements.
   - at low angles of inclination, medium-sized cuttings are easier to transport than the smallest or the largest cuttings
3. *Rate of Penetration:*

   As ROP increases, the hydraulic requirements for effective cuttings transport increases. Experiences showed that, the relation between the increase in ROP and required critical transport fluid velocity is linear
4. *Wellbore deviation* has a major impact in particle transport and hole cleaning becomes more difficult as the angle increases.
5. *Effect of viscosity:* fluid rheology plays an important role for cuttings transport. To achieve optimum results for hole cleaning, the best way to pick up cuttings is with a low viscosity fluid in turbulent flow but to maximize the carrying capacity a high density mud should be used to transport the solids out of the wellbore.

5.2 RECOMMENDATIONS

1. The rheological parameters presented in this study are valid for the Newtonian fluid used. Determination of universal rheological parameters for any non-Newtonian fluid must be included in the models.

2. The accuracy of the proposed models can be improved by focusing on the friction factors between the cuttings bed and the second layer, drag and lift coefficients, interactions between cuttings and the concept of wall slip in the wellbores.

3. More work is needed for cuttings transport with drilled fluid at wellbore inclinations between 15°,20°,30°,40°and 70° from horizontal
4. New runs needed to study the wellbore characteristics when the non-uniform cutting sizes are introduced to the wellbore in deferent concentrations.
5. Repeat runs with drill pipe rotation to compare results
6. Include eccentricity of drill pipe to verify if there is a significant effect of eccentricity on average annular fluid velocity.
7. Perform similar runs using air or foam as drilling fluid.

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APPENDIX - A

Cutting Transport Velocity

Average Volumetric Cuttings Concentration after simplification and in field units, volumetric cuttings concentration can be derived as

$$\overline{C}_c = \frac{(ROP)D_b}{1466.95\left(1 - \frac{v_s}{\overline{v}_a}\right)Q}$$

Where ROP is in ft/hr, Db is in inches and Q is in gpm.

$$\overline{C}_c = \frac{(ROP)D_b}{1466.95 R_t Q}$$

APPENDIX- B

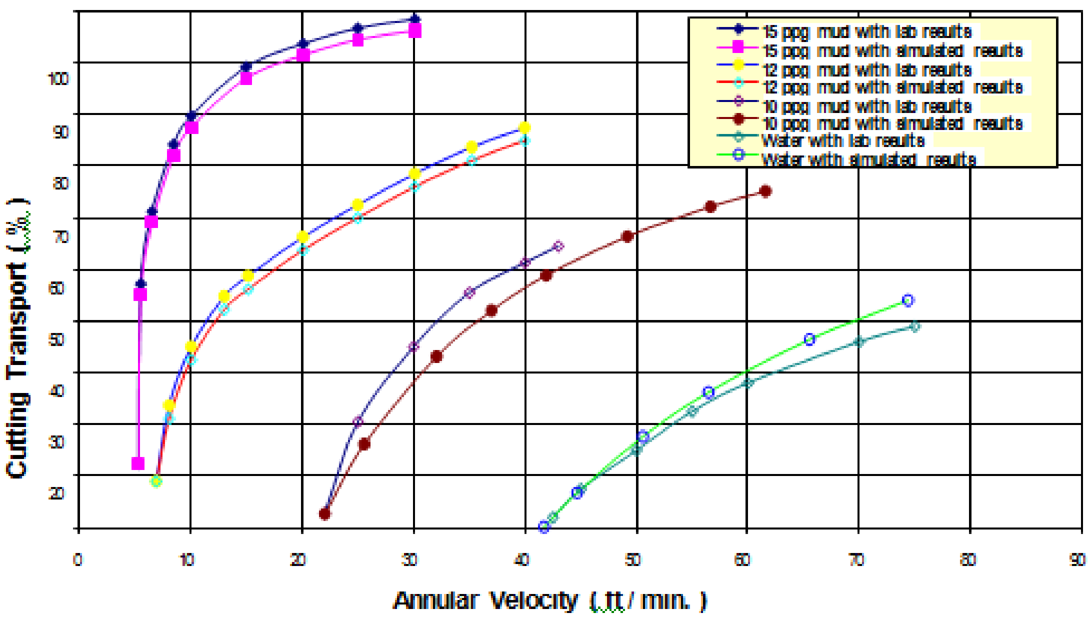

Figure 6: Verification of Physical Model Runs with Lab Data (12 X 3 1/2 -in. annulus, 0.125 in. cutting)

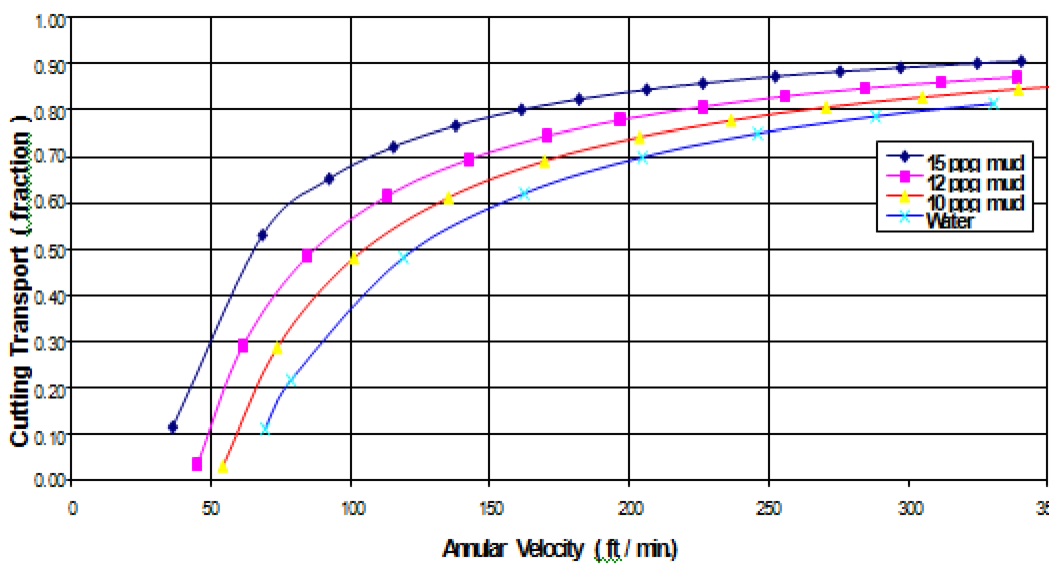

Figure 7: Effect of Mud Weight on Cutting Transport in Inclined Well (8 X 4 -in. anulus, ROP 16 ft / hr, 0.1 in. cutting)

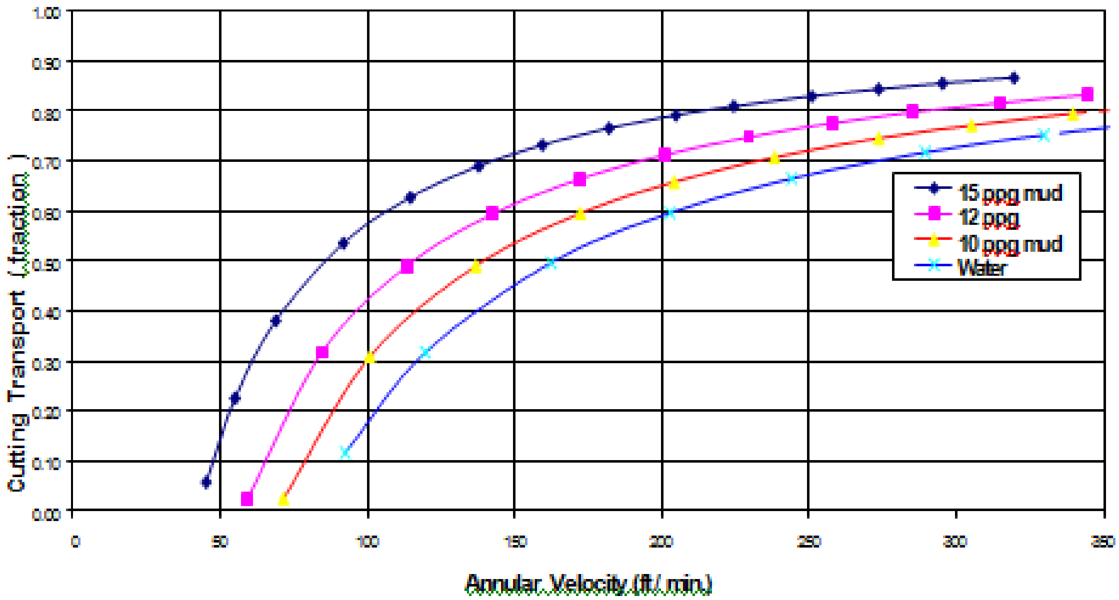

Figure 8 : Effect of Mud Weight on Cutting Transport in Inclined Well(8 X 4 -in. annulus, ROP 16 ft / hr, 0.175 in. cutting

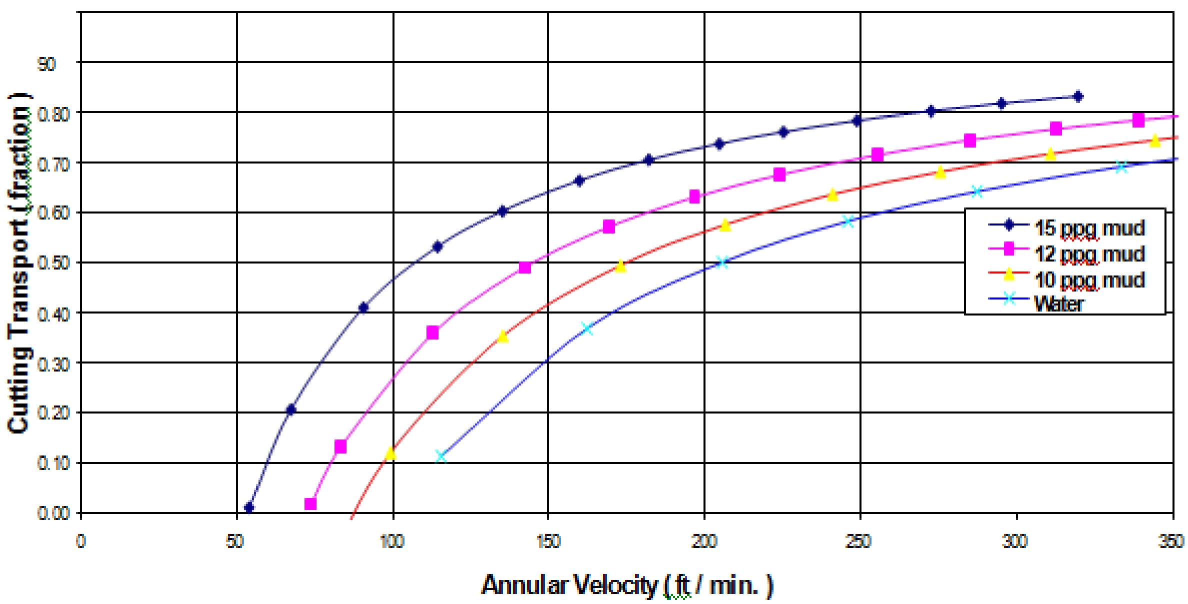

Figure 9: Effect of Mud Weight on Cutting Transport in Inclined Well (8 X 4 -in. annulus, ROP 16 ft / hr, 0.275 in. cutting)

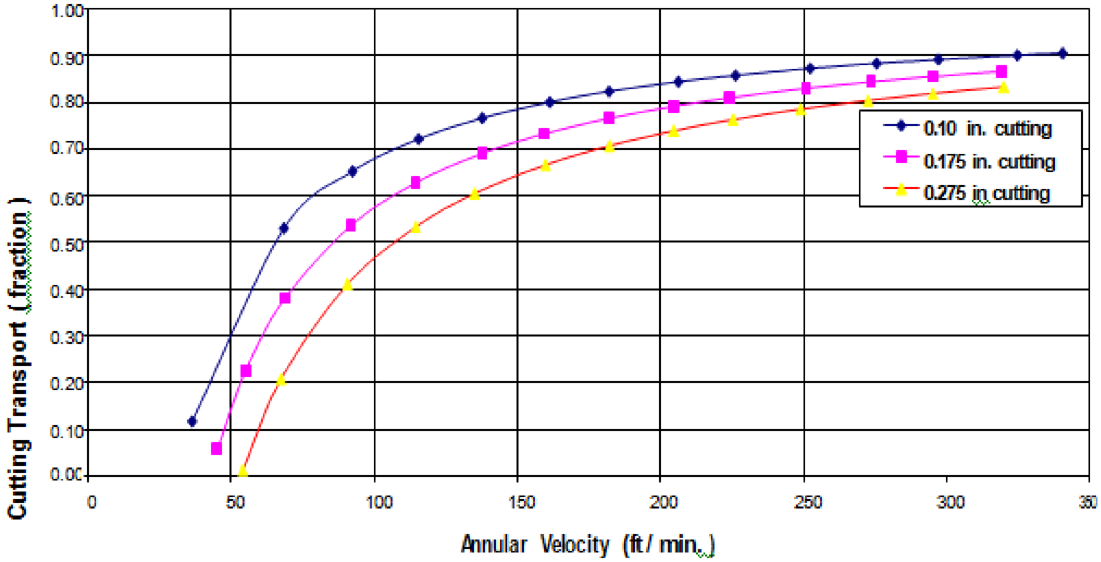

Figure 10: Effect of Cutting Size on Cutting Transport in inclined Well (8 X 4 -in. annulus, ROP 16 ft / hr, 15 ppg mud)

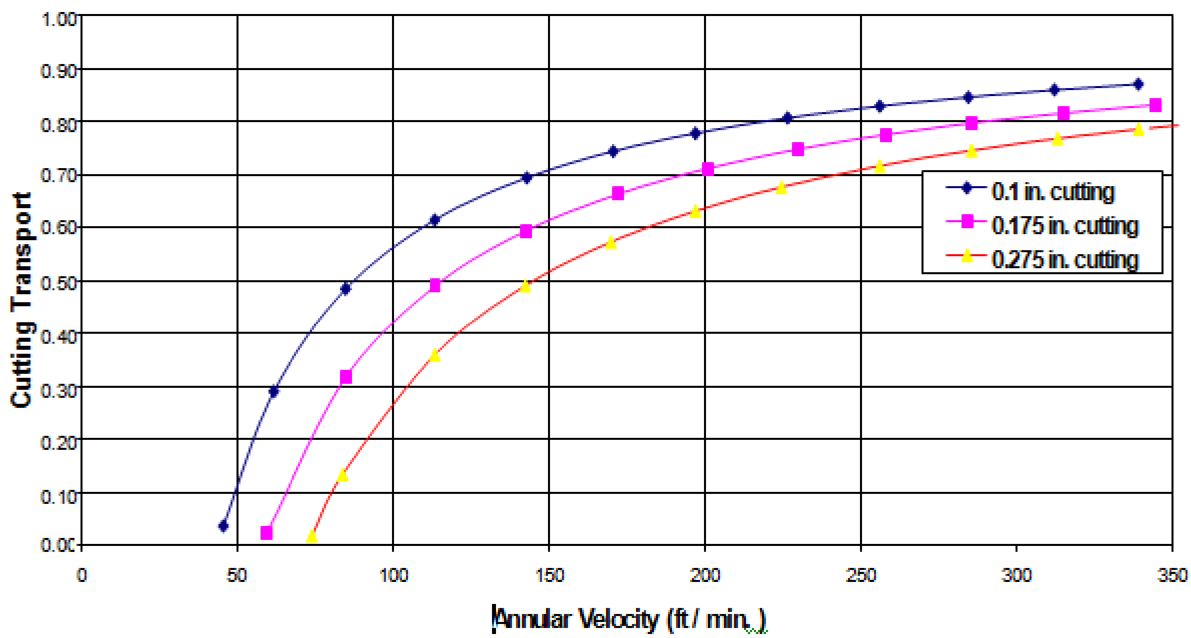

Figure 11: Effect of Cutting Size on Cutting Transport in inclined Well (8 X 4 -in. annulus, ROP 16 ft / hr, 12 ppg mud)

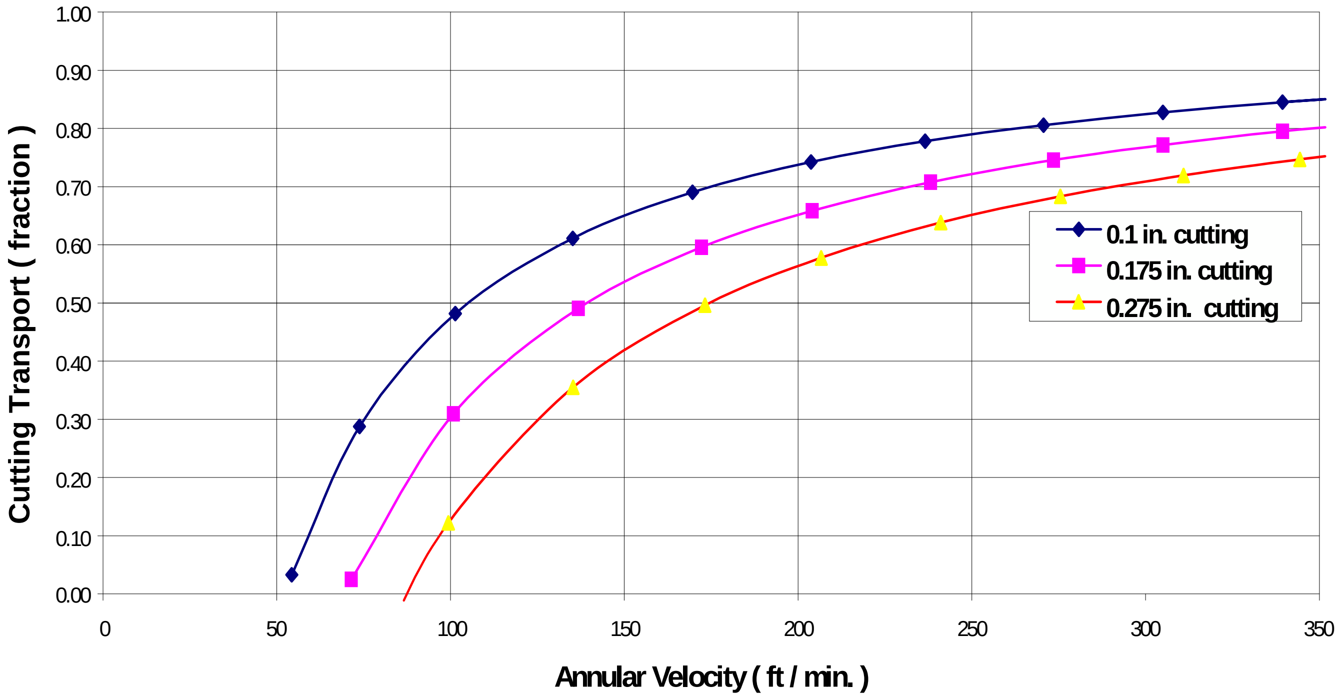

Figure 12 : Effect of Cutting Size on Cutting Transportation in inclined Well (8 X 4 -in. annulus, ROP 16 ft / hr, 10 ppg mud)

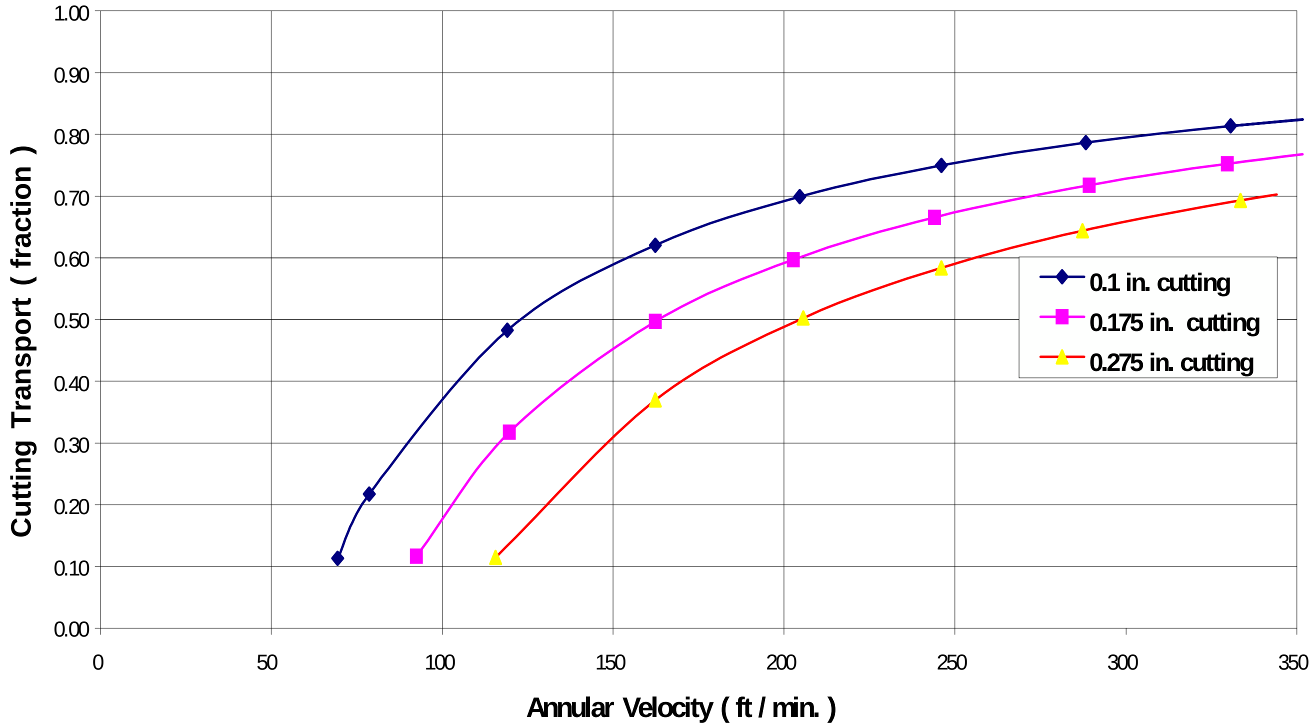

Figure 13 : Effect of Cutting Size on Cutting Transport inclined Well (8 X 4 -in. annulus, ROP 16 ft / hr, Water)

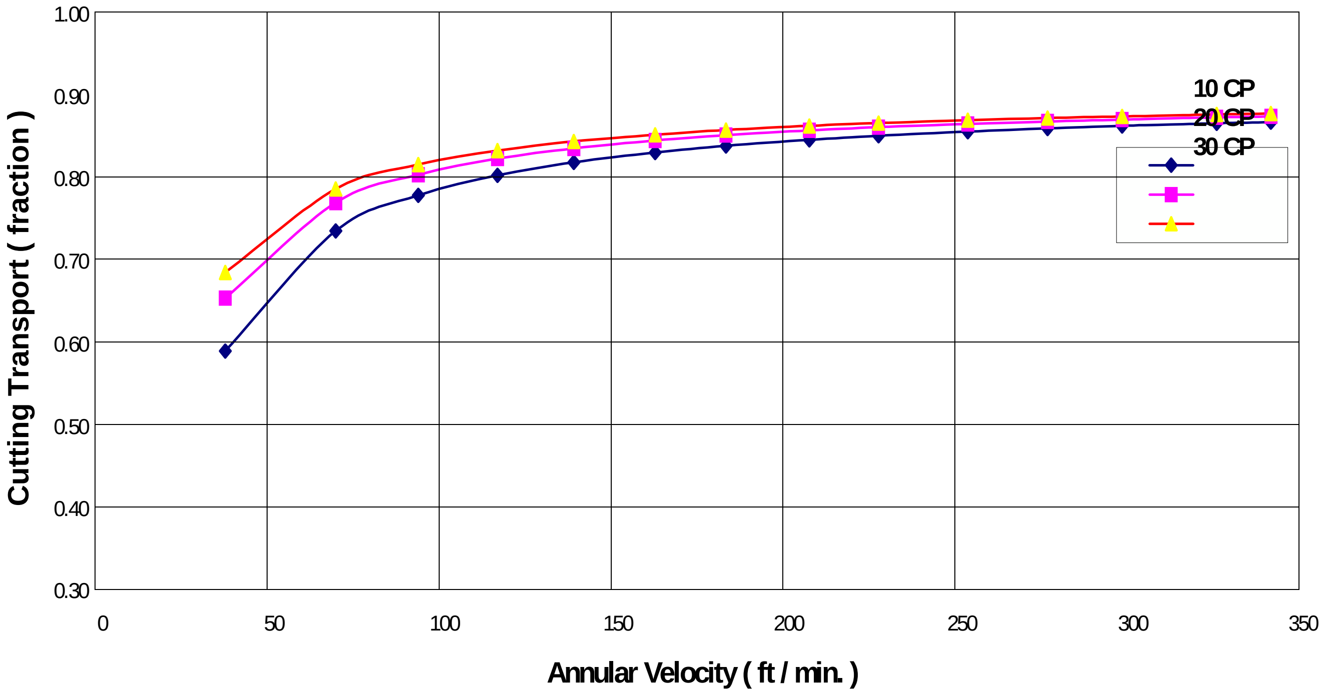

Figure 14: Effect of Viscosity on Cutting Transport in inclined Well (8 X 4 -in. annulus, ROP 16 ft / hr, 15 ppg mud, 0.1 in. cutting)

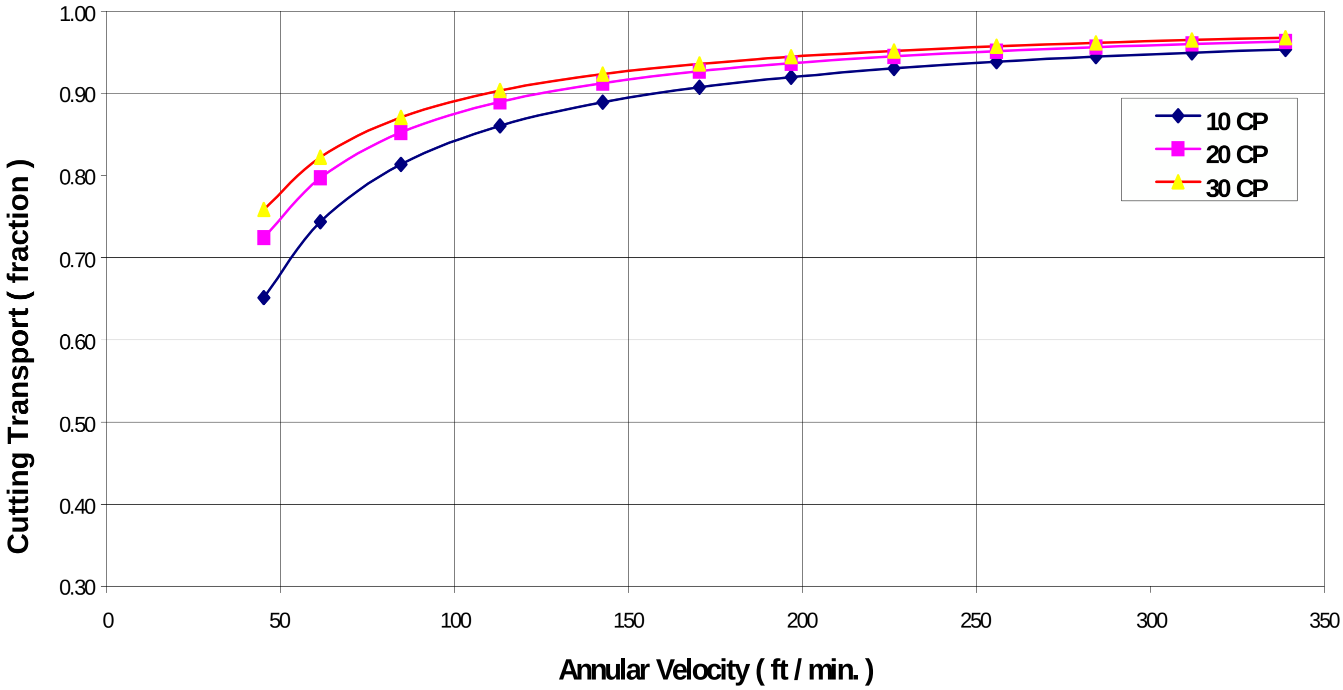

Figure 15: Effect of Viscosity on Cutting Transport in inclined Well
(8 X 4 -in. annulus, ROP 16 ft / hr, 12 ppg mud, 0.1 in. cutting)

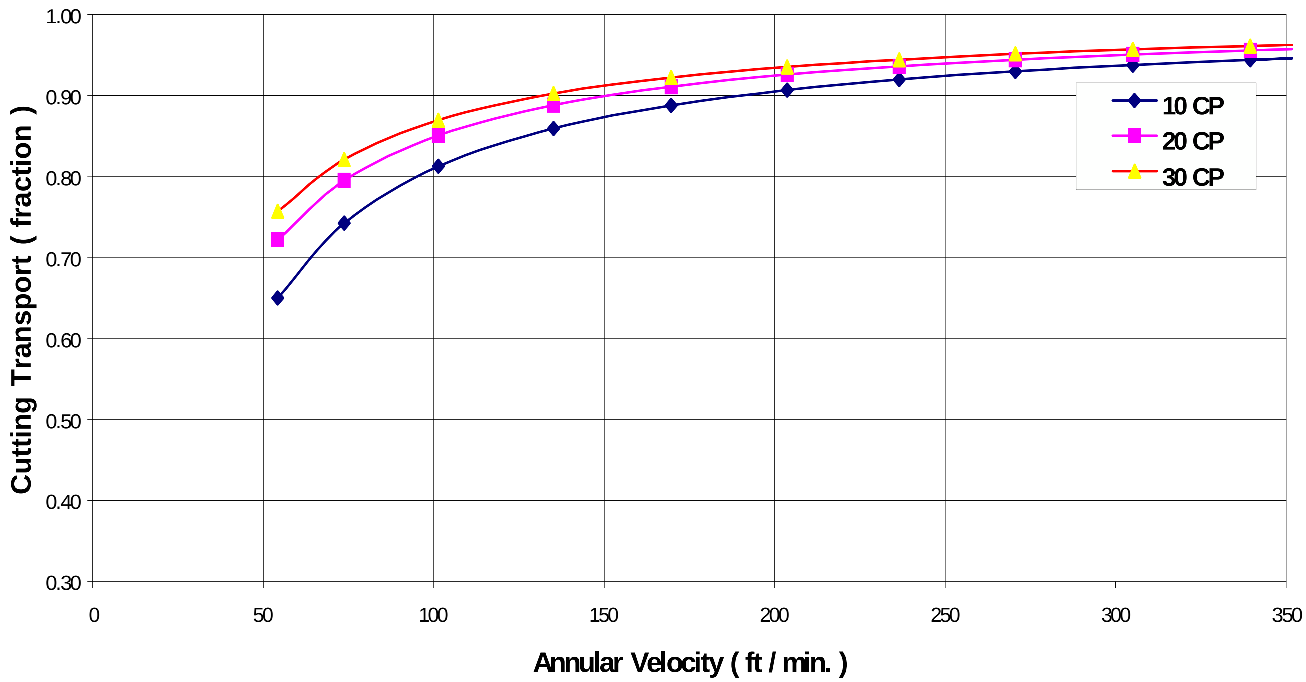

Figure 16: Effect of Viscosity on Cutting Transport in inclined Well
(8 X 4 -in. annulus, ROP 16 ft / hr, 10 ppg mud, 0.1 in. cutting)

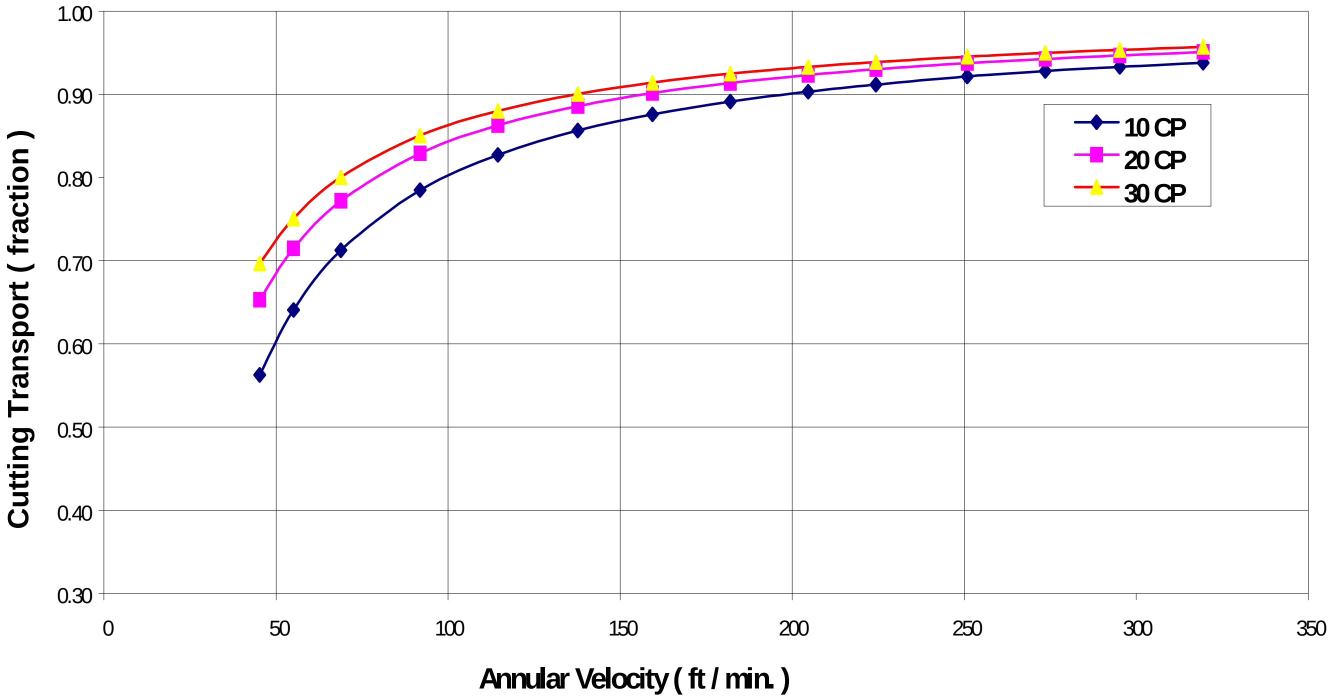

Figure 17 : Effect of Viscosity on Cutting Transport in inclined Well
(8 X 4 -in. annulus, ROP 16 ft / hr, 15 ppg mud, 0.175 in. cutting)

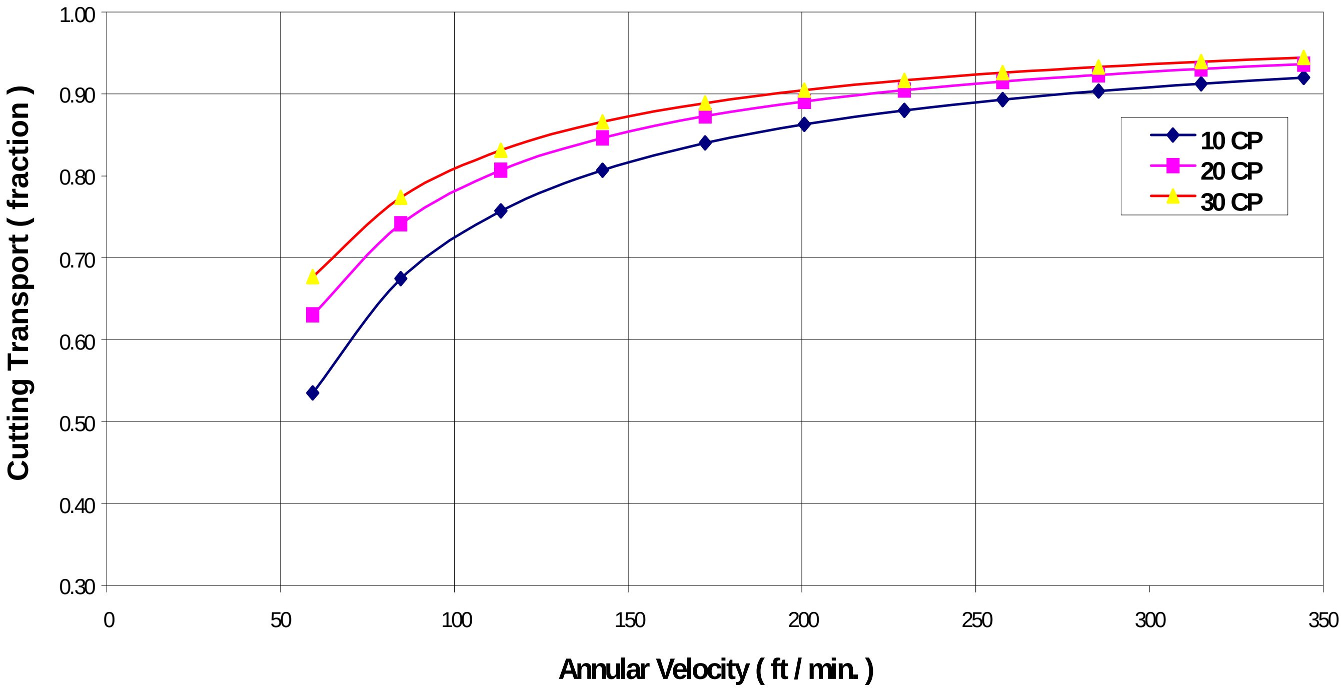

Figure 18: Effect of Viscosity on Cutting Transport in inclined Well (8 X 4 -in. annulus, ROP 16 ft / hr, 12 ppg mud, 0.175 in. cutting)

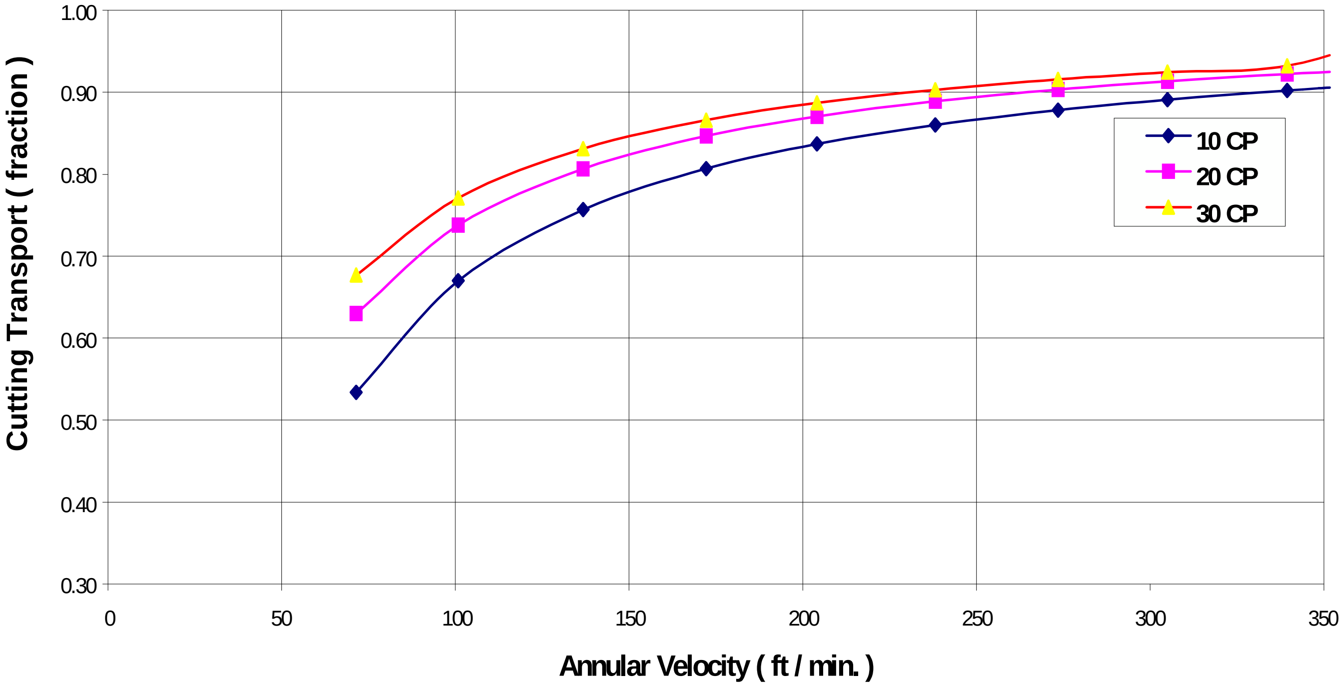

Figure 19
Effect of Viscosity on Cutting Transport in inclined Well
(8 X 4 -in. annulus, ROP 16 ft / hr, 10 ppg mud, 0.175 in. cutting)

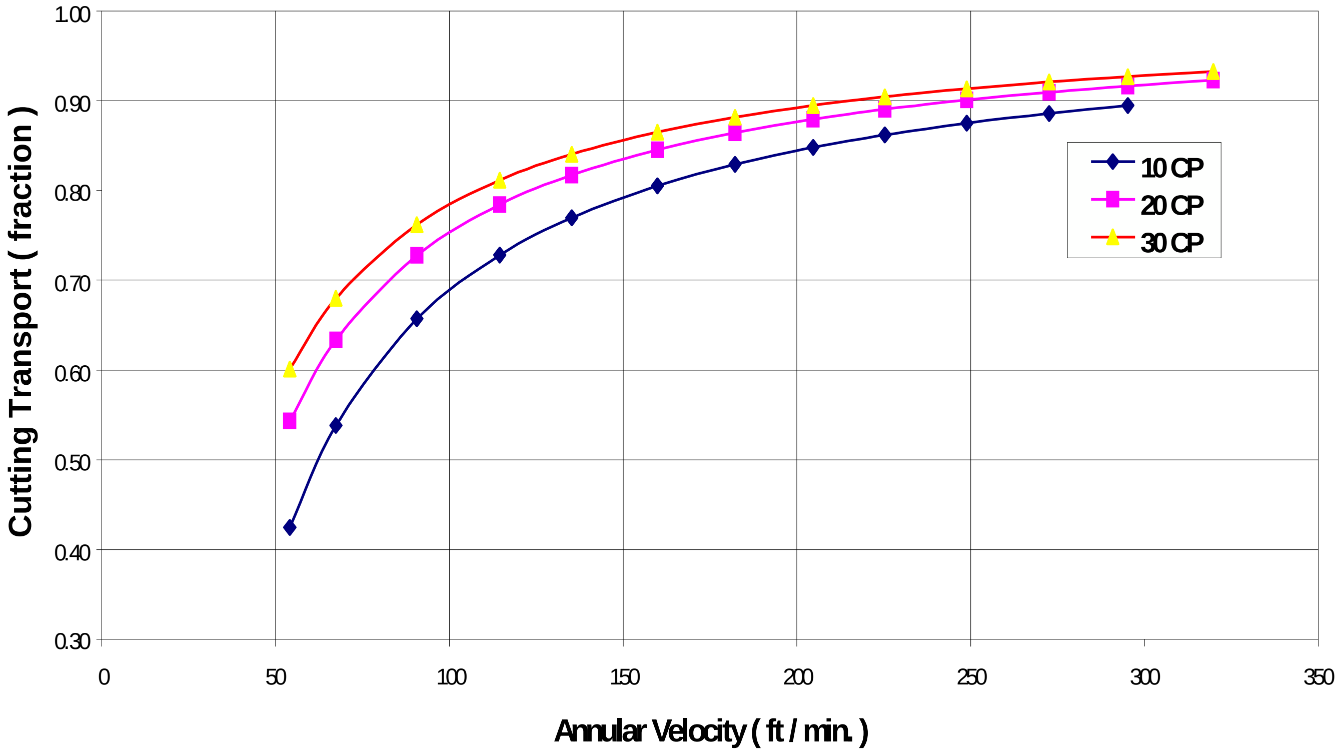

Figure 20 : Effect of Viscosity on Cutting Transport in Inclined Well (8 X 4 -in. annulus, ROP 16 ft / hr, 15 ppg mud, 0.275 in.cutting)

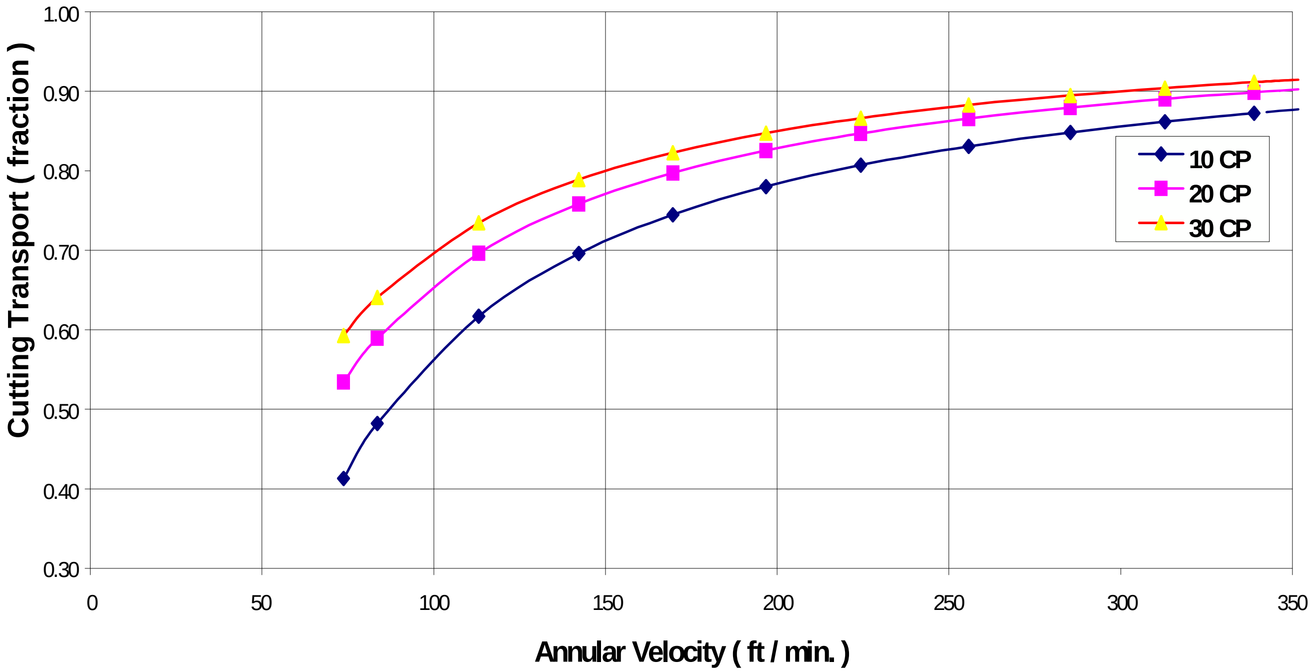

Figure 21 : Effect of Viscosity on Cutting Transport inclined Well
(8 X 4 -in. annulus, ROP 16 ft / hr, 12 ppg mud, 0.275 in. cutting)

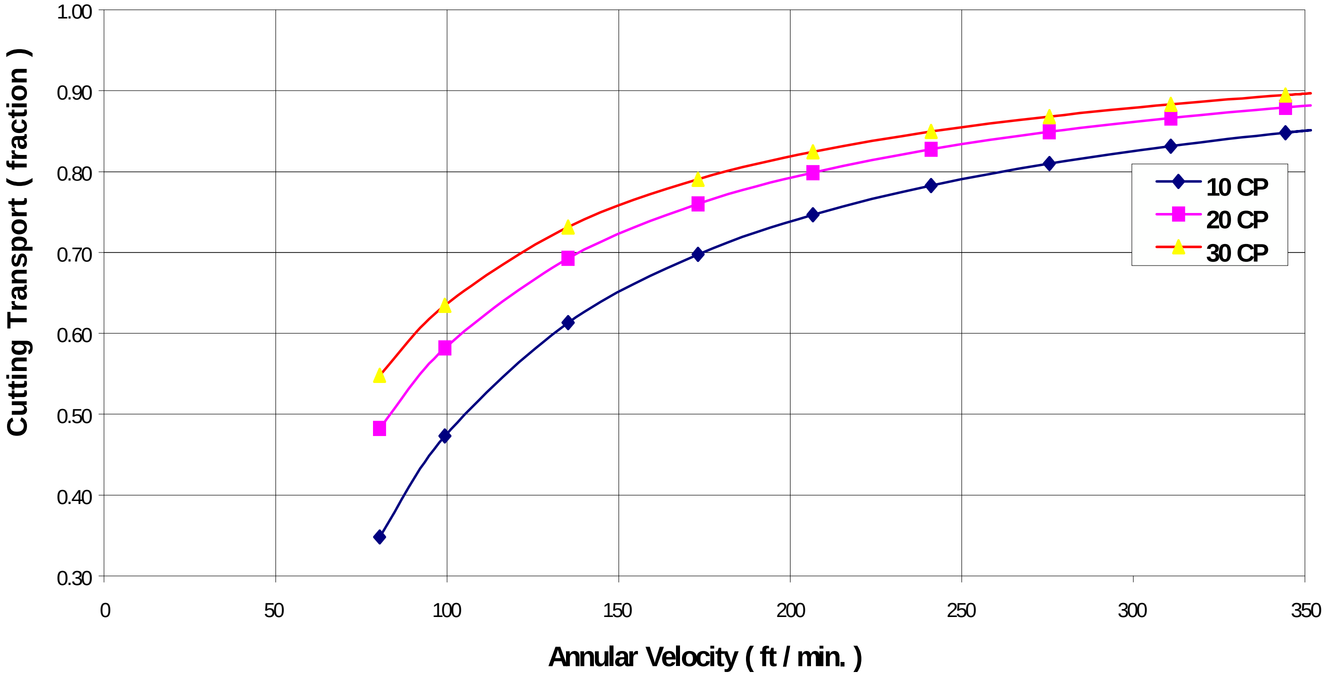

Figure 22 : Effect of Viscosity on Cutting Transport in inclined Well
(8 X 4 -in. annulus, ROP 16 ft / hr, 10 ppg mud, 0.275 in. cutting)

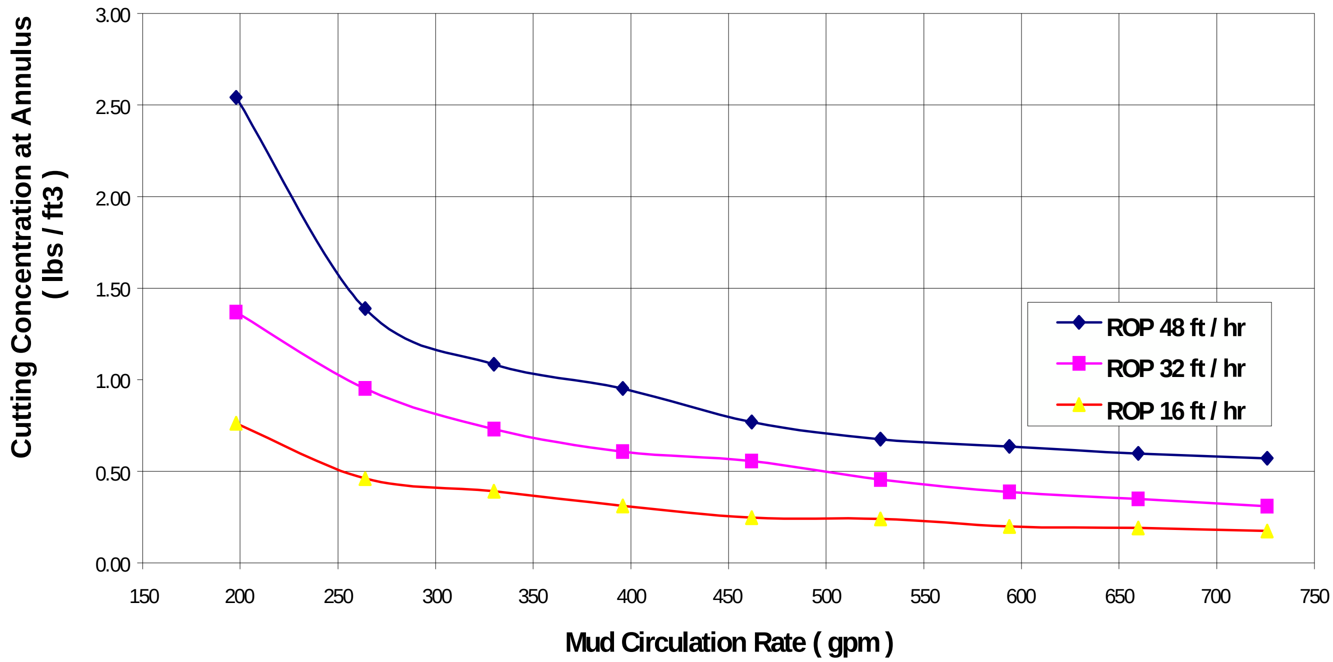

Figure 23 : Effect of Drilling Rate on Cutting Concentration in Annulus (8 X 4 -in. annulus, 10 ppg mud, 0.10 in. cutting)

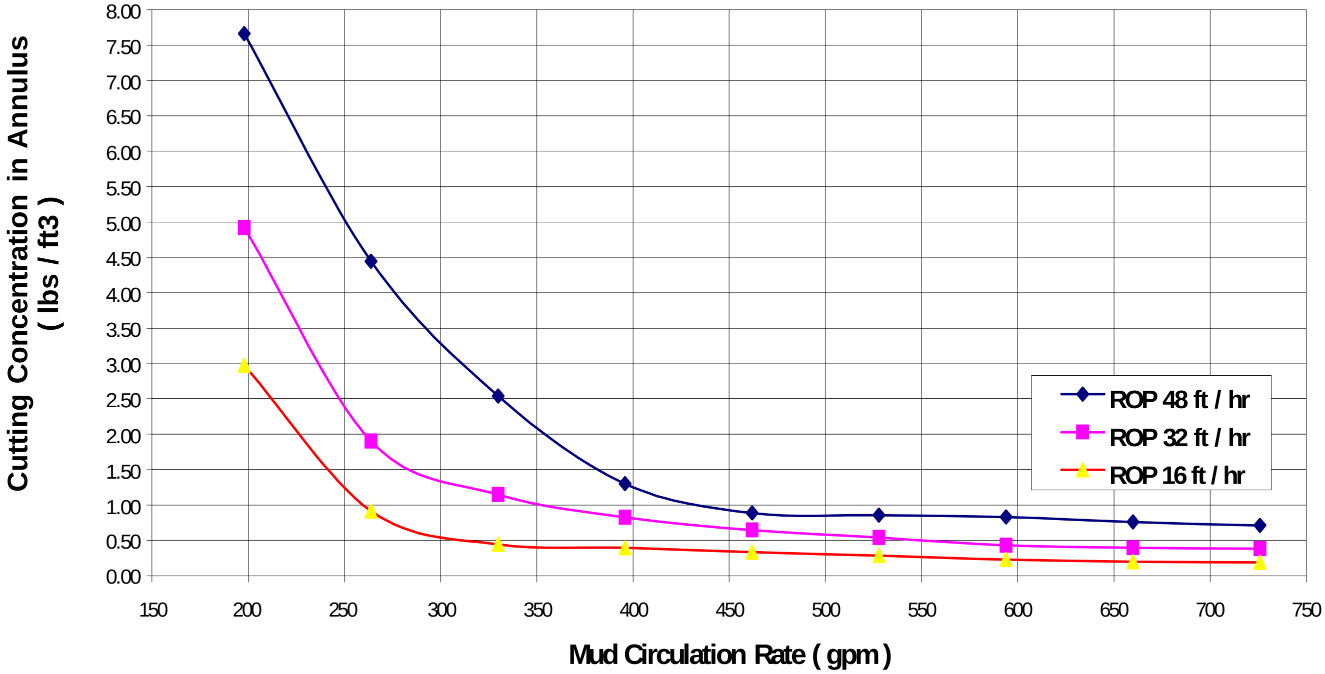

Figure 24
Effect of Drilling Rate on Cutting Concentration in Annulus
(8 X 4 -in. annulus, 10 ppg mud, 0.175 in. cutting)

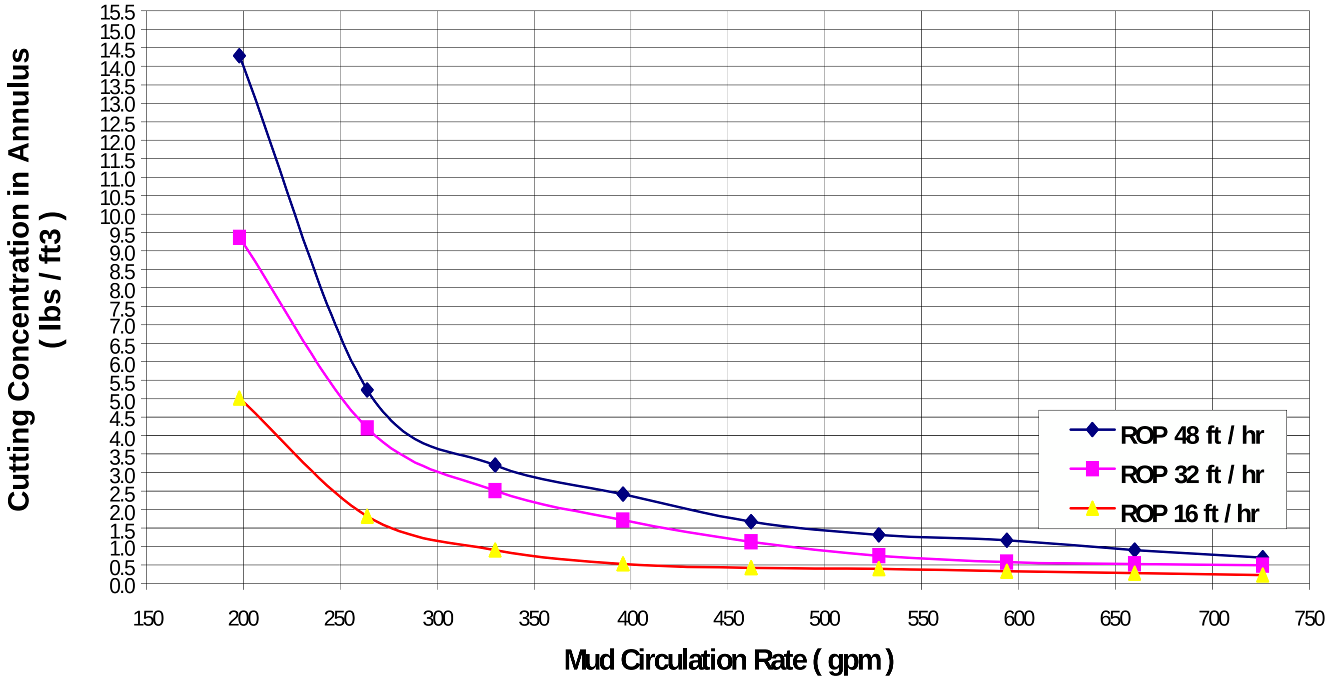

Figure 25
Effect of Drilling Rate on Cutting Concentration in Annulus
(8 X 4 -in. annulus, 10 ppg mud, 0.275 in. cutting)

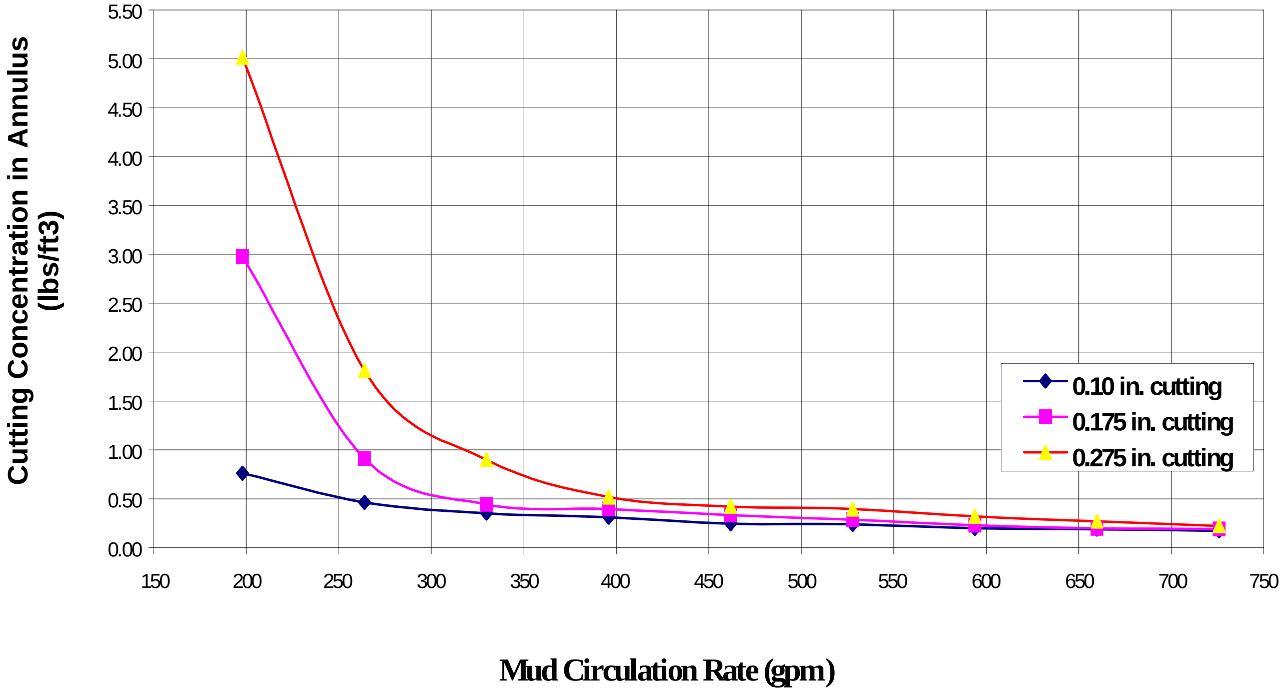

Figure 26
Effect of Drilling Rate on Cutting Size in Annulus
(8 X 4 -in. annulus, ROP 16 ft/hr, 10 ppg mud)

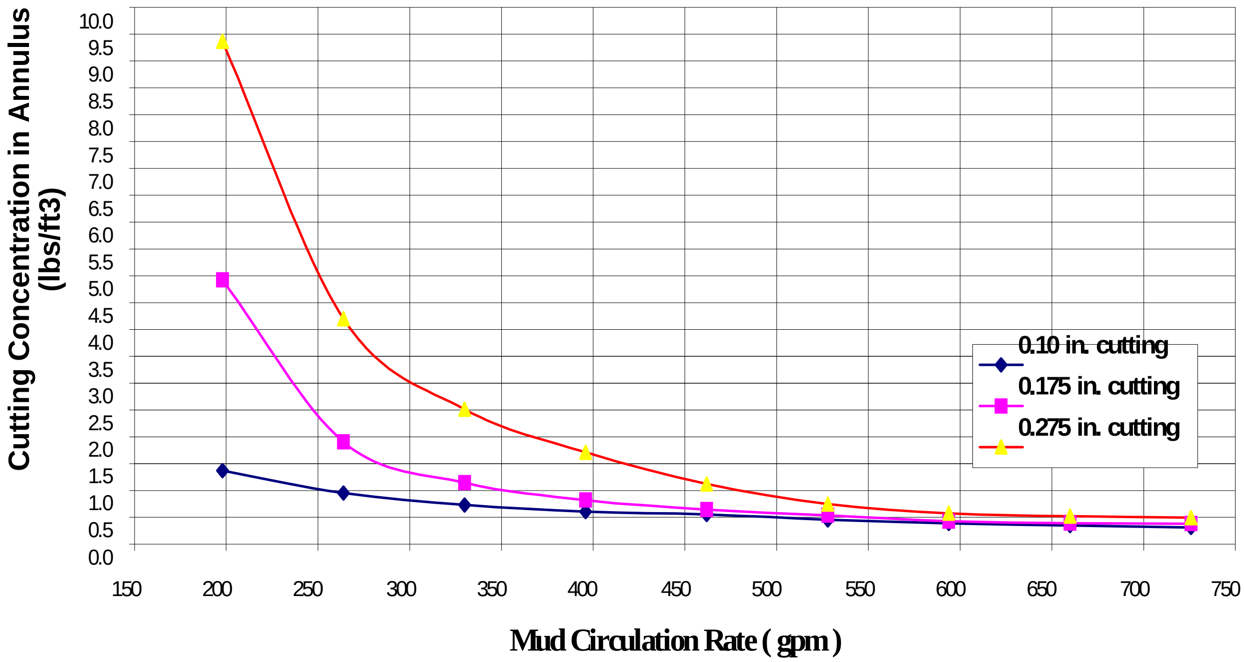

Figure 27Effect of Drilling Rate on Cutting Size in Annulus
(8 x 4 -in. annulus, ROP 32 ft/hr, 10 ppg mud)

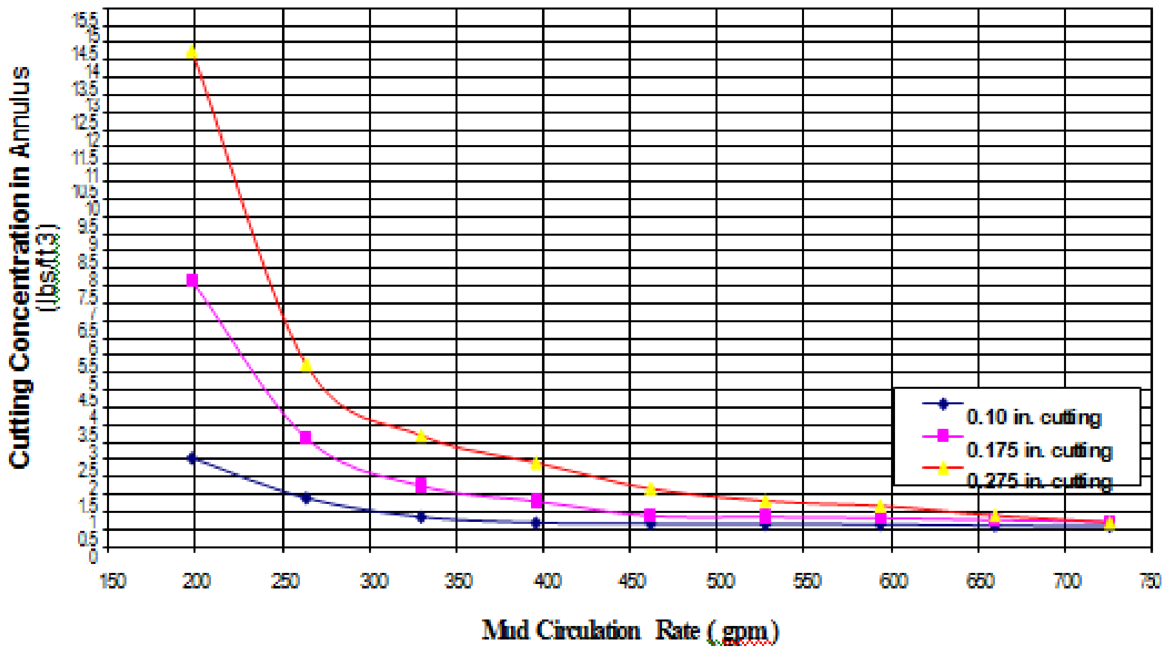

Figure 28
Effect of Drilling Rate on Cutting Size in Annulus
(8 X 4 -in. annulus, ROP 48 ft/hr)