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DEVELOPMENT OF AN EXPERT SYSTEM FOR SELECTION OF DRILLING FLUIDS AND SOLIDS CONTROL EQUIPMENT

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VIBHAS PANDEY

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DEVELOPMENT OF AN EXPERT SYSTEM FOR SELECTION OF DRILLING FLUIDS AND SOLIDS CONTROL EQUIPMENT

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BY

[redacted]

[redacted]

[redacted]

Dr. Michael L. W[redacted]

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This thesis was initiated in an attempt to develop an expert system to aid in selection of drilling fluids and solids control equipment for the drilling industry. The objectives of this research were to identify several factors governing the selection process and then convert them into heuristics and algorithms to give them a form of a computer program that could emulate the thought process of experts.

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ABSTRACT

Proper drilling fluids and a good solids control program, hold the keys to a successful drilling operation. In most of the cases the spudding of a well can be done using native water or very lightly treated bentonite muds. However, as the depth increases and the lithologies change, drilling fluid design becomes critically important. At this stage, any poorly designed fluid can lead to complications like hole washouts, stuck pipes, high torque and drag and in worst cases the well may have to be abandoned. These effects will be further magnified if the unwanted drilled solids entering the drilling fluid are not removed efficiently. Thus, considering both the effects, it is important to select the right kind of fluid and maintain the designed properties by choosing a proper solids control equipment.

An expert system is a rule based tool that can be successfully employed to provide solutions to such problems where a large number of variables are involved and more than one solution exist. Since finding out the best option for drilling fluids and solids control equipment on the rig involves a lot of factors, such a problem can be successfully handled by an expert system

In this study a user friendly expert system, ©**FLUIDSOL** was developed. It is capable of providing solutions to problems related to selection of drilling fluids and solids control equipment. ©**FLUIDSOL** is capable of carrying out a detailed drilling fluid design and selection for situations prevailing in the field, and can also help in selection of solids control equipment for weighted or unweighted mud systems. Apart from this, its mathematical modules allow the user to carry out fluid related calculations with great ease

and convenience. The database section permits the user to access the drilling fluid practices prevalent in several states in U.S and also allows him to append or edit the existing data. Lastly, **©FLUIDSOL** permits the user to enter any relevant experience for future reference by other users.

The following are the major contributions of this work:

1. Development of a user friendly expert system called **©FLUIDSOL**, that can be used by mud engineers at the drilling site.
2. **©FLUIDSOL** provides ways to select or design drilling fluids as well as solids control equipment.

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CHAPTER ONE

FORMULATION OF THE PROBLEM

1.1 Introduction

The successful and economic drilling of an oil or a gas well depends on many factors. These include a proper rig selection, manpower, and finding immediate solutions to drilling related problems. Minimizing the drilling related problems is an area that is fairly controllable and can be a major contributor towards economic drilling of wells.

A properly designed drilling fluid and an efficient solids control program are two very important aspects of an oil-well drilling program. In general, the average cost of drilling fluid is relatively small compared to the total well cost. Experience has shown that a poorly designed drilling fluid can lead to complications like borehole instability that may result in caving, stuck pipe, lost circulation, high torque and drag, and reduced rate of penetration. In the case of a directional well, poorly maintained drilling fluid properties can lead to doglegs and keyseats. Another factor involving the drilling fluid design is the one that does not come into play till after the completion of the well. If the drilling fluid did not have adequate fluid loss control, excessive formation damage can take place. Stimulation of such wells to remove the damage is generally expensive. At the same time, a lack of proper solids control equipment can further create problems resulting in excessive rig days to even well-abandonment. Thus, a good drilling fluid program and an efficient solids control equipment are very important to the successful drilling of wells.

1.2 Literature Review

Many authors[1-21] have extensively written about the drilling fluids design procedures, thereby highlighting the criteria involved in selection or design of a drilling fluids. Other authors[22-32] have given special attention to the importance of having a proper solids control while drilling, and have provided solutions to common solids control related drilling problems. Based on an extensive literature review it is clear that both these features (i.e. drilling fluid design and solids control), are interrelated.

The underlying principles involved in the design of drilling fluids remain the same. However, drilling fluid composition varies for various applications and the design procedures are often based on available knowledge of the area to be drilled. A drilling fluid designed for one location may not necessarily work well at another location. This is because the formation lithologies change from location to location and database for the formations to be drilled becomes extremely important.

Selection or design of a drilling fluid involves taking into consideration several factors like formation geology, formation pressure, geothermal temperature, availability and quality of make-up water, formation evaluation, completion procedures, and ecological considerations. The drilling fluid once formulated, is required to carry out certain functions like cuttings transport, bit cooling, well control, wellbore stability, and friction reduction between drill pipe and formation. It is also necessary that it remains cheap, chemically inert, and is harmless to rig-site personnel and equipment. Achieving these objectives requires a very careful planning and is often based on primary factors like:

a. availability of products,

b. knowledge of the field,

c. knowledge of prevalent drilling fluid practices, and

d. personal experience.

The first factor can be determined locally, whereas the second and the third are obtained from offset wells drilling data. The last, and one of the most important, can however only be obtained after significant exposure to a certain field. It is practically impossible to make available the services of an expert every time a drilling fluid is designed for a project. Again, not only is it important to have a good design, but it is equally important to maintain the drilling fluid properties prescribed in the design. An efficient and effective solids control program is one way of maintaining these properties.

A number of case studies[3-8,12] have been documented in the literature where a specific type of drilling fluid was tested on a particular type of formation and it subsequently resulted in improved drilling performance. Use of such special additives in drilling fluids may not become very popular unless product related information is provided to users. The user may be aware of the prevalent practices in his field but he also needs to know other alternatives at hand. Though, it is important for a drilling fluid to meet all the requirements prescribed, it is equally important to keep the cost of the drilling fluid low. Knowledge of cheap additives and product awareness among users can be of great benefit here. From the above discussion, it is very clear that the drilling fluid design and the selection of solids control equipment are complex problems. Hence, there is a need for a computer system that is capable of carrying out detailed drilling fluid design and solids control selection, based upon the factors listed above.

1.3 Development of Expert Systems

A computer is one system that can be utilized extensively for the purpose of arriving at various solutions to difficult problems because of its capability to handle lots of variables. In certain cases, computer outputs can be utilized as a decision making tool. What is needed is a tool that has the capability to "learn" with experience. There is a need to develop a computer based tool that is user-friendly, effective and has the attributes of an "artificial intelligence device". That is, one that is capable of accepting inputs and providing outputs conforming to the standards of an expert in the field.

Solutions to most engineering problems involve mathematical calculations, large data manipulations, statistical analysis, real-time information management, system optimization, and man-machine interfaces. One popular way of arriving at solutions to these intensive problems is Artificial Intelligence (AI). AI is a process through which computers, based upon the knowledge base created within them, do the thinking for humans. Due to the continued efforts of the experts all over the world, a significant progress has been achieved in this field.

For the case presented here, an **Expert System**[33] can be an ideal answer. By definition, an **Expert System** is an interactive computer-based decision tool that simulates the thought process of human expert to solve complex problems in a specific domain. The need for expert systems have risen by the fact that several limitations are associated with human decision making processes. A few of these include limited expertise, limited working memory, poor retention of large data, and biased decision making. As of today most of the tasks previously performed by humans are being efficiently replaced by the computers. Development of an expert system is one of such jobs that can replace experts to a large extent and still come up with fruitful solutions. An expert system by nature uses both facts and heuristics to solve difficult decision problems based on knowledge acquired from an expert.

1.4 Objective of the Study

The objective of this study is to develop one such Expert System that is capable of designing the best drilling fluid program for a particular well and also to suggest the best solids control equipment to be used. The type of the outputs expected from an Artificial Intelligence usually governs the development of such a system. To achieve the objective of this study the following procedures were adopted:

1. creation of modules on the basis of several factors like existing well conditions, lithology type, expected pore pressures, expected formation temperatures, expected drilling complications, etc.,
2. creation of a knowledge base for each of these modules, and
3. development of computer codes to create user interface that enables the user to input data and obtain the required out put.

Each of the modules developed is an extensive independent program in itself which upon execution has the capability to access any of the knowledge bases created. In general, the output is in a text form suggesting the drilling fluid composition for different depths. This also includes the type and amount of additives to be added to the fluid, and the numerical value of the fluid properties, that should be maintained. Further, the output also provides the user with the best possible solids control equipment layout. The system also has a calculation option which assists the user in carrying out all drilling fluid and solids control related calculations.

The expert system developed in this study is one tool that has a direct application in the field and can prove very effective in developing on-the-site drilling fluid programs. With its ability to "learn", it also provides the user to continuously "update" its data bank. This help in providing better solutions to the situations presently unforeseen by the system.

CHAPTER TWO

A REVIEW OF DRILLING FLUID TECHNOLOGY : TYPES, SELECTION CRITERIA AND NEW CONCEPTS

2.1 Introduction

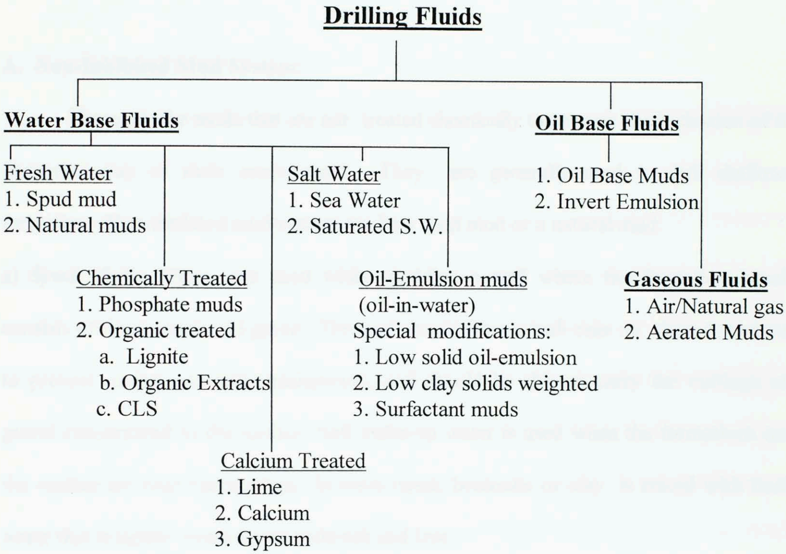
The circulation of drilling fluid is the heart of rotary drilling technology and drilling operations. Drilling fluid engineering is one of the most important aspects of drilling operations. The performance of the drilling fluid is related directly or indirectly to most drilling problems. The essentials of drilling fluid technology and engineering can be categorized into four areas: a) classification, b) properties, c) additives, and d) new concepts. A summary of these four areas follows.

2.2 Drilling Fluids Classification

Drilling fluids can be broadly classified[20,21] as water-based, oil-based, or gaseous drilling fluids. Figure 2.1 shows the general classifications of drilling fluids. Water-base fluids are predominantly used when drilling for oil and gas. Hence, this is the focus of this study.

2.2.1 Water Base Drilling Fluid

As is shown in Figure 2.1, water base fluid can further be divided into fresh-water, chemically-treated, calcium-treated, salt-water, and oil emulsion (oil-in-water) drilling fluids.



CLS : Chrome Lignosulfonate
S.W : Salt Water

Figure 2.1: A general classification of drilling fluids.

2.2.1.1 Fresh -Water Mud

This mud system uses fresh water as a base. It can be further sub-divided into two categories namely:

A. Non-inhibited mud, and

B. Inhibited mud system.

A. Non-Inhibited Mud System:

These are the muds that are not treated chemically to prevent the hydration of the formation clay or shale encountered. They are generally used to drill shallower formation. Non-inhibited mud system can be a spud mud or a natural mud.

a) ***Spud Muds:*** These are used while spudding a well where the formation usually consists of loose sand and gravel. The mud should form a wall cake on these formations to prevent caving and hole enlargement, and should be able to carry the cuttings and gravel encountered to the surface. Soft make-up water is used when the formations near the surface are mud-making type. In some cases, bentonite or clay is mixed with fresh-water that is lightly treated with soda-ash and lime.

b) ***Natural Muds:*** Natural muds are those composed of water and natural clays from the formations drilled, with little chemical treatment and with only minor amounts of bentonite or other clays. In the shallower regions low mud weight and viscosity are permissible. If these properties are allowed to increase, the drilling rate is reduced and there is much more risk of stuck pipe and lost circulation. Large volumes of water is required to keep the mud weight and viscosity in the desired low ranges.

B. Inhibited Mud System:

Inhibited mud[35] is the one in which the ability of active clays to hydrate has been greatly reduced. This fluid prevents formation solids from readily disintegrating into extremely fine particles. They offer high resistance to contaminants encountered during drilling operations.

2.2.1.2 Chemically Treated Muds

No calcium compounds are added to these muds. They are generally phosphate or organic treated muds.

a) **Phosphate treated muds:** Phosphate treatment is usually limited to areas where soft fresh water and good mud making formations provide a good natural mud base. In general, small amount of bentonite is added to fresh water first and then complex phosphates in concentrations of 0.1 to 0.2 lbm/bbl are added to impart the desired effect.

b) **Organic treated muds:** Natural muds treated with hemlock bark and chrome lignosulfonate fall in this category. The compositions depend on the hole conditions. For example, modified hemlock bark extract serving as deflocculants are added to freshwater and salt-water muds containing up to 3% salt - 18,200 parts per million (ppm) of chloride. The extracts are stable to high temperatures and are quite effective in reducing filtration rates.

In another case, chrome lignosulfonate added in concentrations ranging from 4 to 6 lb./bbl of mud serves as excellent deflocculant even in presence of sodium, calcium and magnesium ions. Such mud systems have low filtration loss properties and perform well even at temperatures close to 400°F.

2.2.1.3 Calcium-Treated Muds

The property of calcium ions and magnesium ions to suppress or inhibit the swelling of the clays and shales is used here. At high temperatures severe gelation takes place and deflouucculants like chrome lignosulfonate may be added. In general, calcium or magnesium salts are added to provide calcium and magnesium ion concentration from 100 to 1200 ppm.

2.2.1.4 Salt Water Muds

Muds are classified as saltwater muds when they contain over one percent by weight of salt (6,000 ppm chloride) and have not been converted to another type of mud such as a lime mud or a lignosulfonate mud. These muds are essentially used to drill massive salt beds or domes. High salt concentration is required because under-saturated muds will cause the formation salts to dissolve in the mud and lead to hole enlargement. Salt is added to fresh make-up water in concentrations of 125 lbm/bbl. Salt water clay like attapulgite is added in concentrations of 28 to 30 lbm/bbl to provide the necessary viscosity.

2.2.1.5 Oil Emulsion muds

An oil emulsion mud is a water-base mud in which small amount of oil is added. The water is the continuous phase and oil is the discontinuous phase. Certain emulsifiers must be added into the system to provide stability. Some of the advantages of oil emulsion muds are :

1. Reduces the friction between drill string and the formation, causing a reduction in the torque from 20 to 50 percent, and providing a cleaner drill string.
2. Helps make troublesome shales more stable, hole enlargement almost ceases, and sloughing and caving are reduced to considerable extent.
3. Provides a better bit lubrication with fewer incidents of bit locking. This results in fewer trips and reduction in drilling costs.

Oil in concentrations varying from 3 to 40% is added to water depending on the weight and water loss desired. Range of 5 to 15 % is most common. The effect of oil additions on mud density is presented in Appendix A. Emulsifiers such as lignites, quebracho, lignosulfonates, starch, carboxymethyl cellulose (CMC), and ionic and nonionic surfactants are added in appropriate quantities to form a stable emulsion.

2.2.1.6 Polymer muds

Polymer muds are used in drilling fluids when the desired properties cannot be obtained with colloidal clays. Polymer in a concentration of 0.5 to 1.0 lbm/bbl and 20 % that amount of chromic chloride per barrel is normally sufficient to make polymer muds. Chromic chloride or chrome-alum produce pronounced viscosity increases as they cause cross-linking of the long polymer chains. Approximately 0.4 lbm/bbl of bactericide like paraformaldehyde is added because most of the polymers are readily attacked by various strains of bacteria. Advantages of polymer muds are:

1. Its high viscosity at low rates of shear in the annulus is good for lifting cuttings; and very low viscosity at high shear rates at the bit and the bottom of the hole, is good for rapid drilling.

2. The thinning at high rates of shear is also helpful in removing solids with a desander or desilter, as the high shear in these units effectively thins the fluid for separation of the solids.

2.2.2 Oil Base Fluids

Water based fluids have some inherent deficiencies like:

a) their ability to dissolve salts,

b) to interfere with flow of oil and gas through porous rocks,

c) to promote the disintegration and dispersion of clays, and

d) to effect corrosion of iron.

In order to overcome these deficiencies, oil base drilling fluids were developed. In addition, oil muds offer potential advantages such as: better lubricating qualities, high boiling points and lower freezing points. Because the cost of preparing an oil mud is always more than that of the same density water mud, there must be some economic justification for using an oil mud.

2.2.2.1 Oil Based Muds

These are fluids in which oil is the continuous liquid phase, diesel oil being the most commonly used. Oil-based fluids can be classified as oil-based or invert emulsion (i.e. water-in-oil) fluids. The basic components are oil (diesel or mineral oil), water, emulsifier, wettability reversal agent, viscosity, filtration, alkalinity, and density control agents. Water is present in the oil in the form of an emulsion. Water tends to increase viscosity. With increase in density, water content must be decreased to prevent excessive viscosity. Fresh water is used if there is no shale problem. If shale problem are anticipated, then the electrolyte concentration of the water must be increased. Hence, sodium chloride or calcium chloride is added. Calcium chloride salt is generally used to alter the activity of water in the oil mud.

An emulsifier is added so that a stable emulsion is formed at all times. Emulsions are generally fatty acid soap. Soap is formed by the reaction of an organic fatty acid with a base. The long hydrocarbon chain portion of the soap molecules tends to be soluble in oil and the ionic portion tends to be soluble in water. When soap is introduced to a mixture of oil and water, the soap molecule will accumulate at the oil/water interfaces with the water-soluble end residing in the water and the oil-soluble end residing in the oil. This greatly reduces the surface energy of interface and permits the formation of a stable emulsion. The solids and water contents in oil muds cannot be controlled by hydrocyclones and centrifuges because a significant volume of the expensive liquid phase would be discarded by these devices. Dilution (addition of diesel) is also quite expensive. Hence, screening is the only economical means of solids control for oil muds. The major disadvantages of an oil mud are higher initial and cuttings disposal costs, and requirement of more stringent environmental control procedures.

2.2.3 Air and Gaseous Drilling Fluids

These are fluids in which air or gas is the continuous phase. Air or gas is used as a circulating fluid for one basic reason: lowest density fluid available, hence minimum pressure on the formation, and maximum penetration. Also used in special cases to prevent formation damage while drilling into production zones and to circumvent lost circulation problems. High annular velocity (2500-3500 ft/min) is used to compensate for the extremely low viscosity of the fluid.

Gaseous drilling fluids can be classified as dry drilling fluid, mist or foam fluid (water or a special mud) is injected with a foaming agent into the air stream, stable foam, or "froth" fluid, and aerated fluid. Generally, the use of these types of fluid requires additional equipment and materials such as air compressors, source high pressure gas, blow line and special safety measures.

The advantages of using air as a circulating fluid are as follows:

1. It is most readily available low density fluid.
2. It places minimum pressure on the formation to be drilled.
3. Relief of vertical stresses in the formation being drilled causes the cuttings to literally explode beneath the bit teeth, allowing maximum penetration rates to be achieved.
4. Air drilling can be used in special cases to prevent formation damage while drilling into production zones, and to control severe lost circulation problems.

Dusting:

This involves the injection of dry air or gas into the standpipe at a rate sufficient to achieve annular velocities of 2,000 - 3,000 ft/min.. The capacity of the pump must be in accordance with the depth to be drilled to avoid any confusions at a later stage. In certain soft, unstable formations, too much air can cause hole enlargement and hence thorough experience gained in an area is very important. Mud ringing occurs when there is enough water to dampen the cuttings and in some cases lead to a stuckpipe if allowed to progress. "Mud ringing" is indicated by a slow increase in standpipe pressure. Injecting a few gallons of detergent foamer and/or by raising and lowering the drill string, passing the tool joints a few times can cure this problem.

Mist or Foam or Froth drilling:

It is helpful when water or oil sands are encountered which produce too much fluid to be dried up. A mixture of foaming agent and water is injected into the air stream. The foam keeps the cuttings separated so that they do not stick together, and helps remove fluid from the hole. Mist drilling usually requires at least 30-35% greater amounts of air because of the extra weight of the fluids being carried by air-stream. When extra water is encountered, the system becomes deficient in air. If water sensitive formations are exposed, misting often causes sloughing of the unsupported formation. This leads to an enlarged hole, which requires larger air volume to clean the hole of cuttings. In order to cure this "mud-misting", a thin mud slurry can be used. The slurry coats the wall of the hole with a thin protective film and provides top quality foam for quickest removal of cuttings and produced fluids. Many long chain, high viscosity polymers may be used instead of CMC as a foam stabilizer.

Aerated Muds:

These may be used when it is impossible to drill with air alone because of extensive water coupled with a problem of lost circulation. Air injection into the mud column helps in reducing the hydrostatic head. Using results from calculations of air/mud ratios, the hydrostatic head can be reduced to that of the formation pressure at the point of lost circulation. The penetration rate increases at the same time. However, care must be taken to de-aerate the mud before it enters the pump again after one cycle. High pH maintenance will prevent corrosion.

2.3 Drilling Fluids Properties

Drilling fluids are characterized by some physical and chemical properties. Drilling fluid engineers alter these properties in order to make the fluid suitable for a particular application. Major physical properties are density, rheological properties, and filtration properties

2.3.1 Density

Density is defined as weight per unit volume. It is expressed either in pounds per gallon (lbm/gal.), pounds per cubic foot (lbm/ft^3), psi/ft or kilograms per cubic meter (kg/m^3). Sometimes it is also expressed as specific gravity (SG). The density of a drilling fluid is an important property that relates to kick prevention, borehole stability, and rate of penetration. Very high values of density can cause the formation to rupture and initiate loss of circulation. Higher densities also retard the penetration by increasing the chip hold down pressure.

2.3.2 Rheological properties

The three important rheological properties of a drilling fluid are viscosity, yield point, and gel strength. Viscosity of a fluid is the measure of resistance to flow offered by the fluid. In field, viscosity may be measured using a funnel or a rheometer. Funnel viscosity is measured in seconds/quart and rheometer viscosity is measured in centipoise.

Inert solids like barite, silt, feldspar, etc. increase the viscosity of fluids. Viscosity is related to pressure losses while circulating the fluid. In general an increase in viscosity implies higher pressure losses.

Yield point is a measure of the electrical content of the drilling fluid. It is measured in lbf/100 ft^2. Presence of active solids like bentonite and clays increase the yield point. Generally, a high yield point to plastic viscosity ratio is desired for high penetration rates. Gel strength is the measure of thickening properties of the fluid when at rest. The higher the gel strength, the higher the pump pressures nēeded to break the gel and initiate the circulation.

2.3.3 Filtration properties

These are related to the ability of the fluid to seal permeable formations exposed by the bit with a thin, low permeability filter cake. The pressure of the mud column is usually greater than the formation pore pressure, hence the fluid filtrate continuously invades permeable formations if a thin filter cake is not formed. The filtration properties required for the successful completion of a well, depend largely on the nature of the formations to be drilled. Stable formations with low permeabilities, such as dense carbonates, sandstones, and lithified shales, can usually be drilled with little or no control of filtration properties. In permeable formations, filtration properties must be controlled in order to prevent formation of thick filter cakes which can cause drilling problem known as differential pipe sticking. Both filtration rate and the mud spurt must be minimized when penetrating potentially productive formations, in order to minimize formation damage.

2.3.4 Other Drilling Fluid Properties

Other important drilling fluid properties are pH, alkalinity, cation exchange capacity, electrical conductivity, lubricity, and corrosivity. Some of these properties are incorporated in the development of the expert system.

2.3.5 Drilling Fluid Related Problems

In order to avoid major drilling complications[21] and therefore reduced drilling costs, it is important that drilling fluid properties be maintained at the designed values as closely as possible. Failure to do so can result into any one of the following problems:

1. shale problems,
2. lost circulation,
3. stuck pipes, and
4. kicks.

1. Shale Problems

Troublesome shales are described as sloughing shale, heaving shale, running shale, bentonitic shale, mud-making shale, plastic flow shale, gas bearing shale, and pressured shale. Shale instability problems arise when the water from the drilling fluid comes in contact with the shale in formation.

Control of hydration can be helpful in combating shale-instability problems. An ideal drilling fluid to drill shales would be one that does not alter the shales adversely. A wide variety of drilling fluids have been tried on different types of shales with varying degrees of success. No one fluid has been completely satisfactory in all cases. One mud may work slightly better than another through a certain shale section, with the reverse true in another area. A few valuable suggestions good for almost any type of shales are :

1. maintaining good mud density control,
2. maintaining proper rheological properties of the fluid employed,
3. controlling fluid losses, and
4. avoiding abnormally high annular velocities.

2. Lost Circulation

Lost circulation occurs at any depth where total pressure exerted against the formation exceeds the total pressure of the formation. Formations that are prone to lost circulation are:

1. cavernous and open-fissured formation,
2. very coarse and permeable shallow formations,
3. natural or intrinsic fractured formations,
4. easily fractured formations, and
5. subnormal pressure formations.

Many different types of bulk materials have been used to prevent loss of mud to the formation or to restore circulation. Lost returns materials may be grouped as follows:

1. Short, weak fibers such as leather, paper, pulp, wood, and cane,
2. longer, strong, fibers such as hemp or flax,
3. flakes of cork, mica, and cellophane,

4. heat-expanded minerals such as flue ash, volcanic ash, or the perlites, granular materials with angular edges such as crushed rock, ground plastics, and walnut or almond hulls.

In addition to these so-called bulk materials used for soil plugs, the thickening or cementing compositions that have been employed are:

1. thickened oil base mud plugs,
2. diesel oil-bentonite plugs,
3. diesel oil-cement plugs,
4. bentonite-cement plugs,
5. silica-clay plugs,
6. time-setting clay plugs, and
7. neat cement plugs.

Loss circulation problems can be more efficiently corrected if the loss zone is accurately known. Several methods like temperature survey, spinner survey, radioactive tracer survey, hot wire survey, and pressure transducer survey are available for locating the point of loss.

3. *Stuck Pipes*

Stuck pipe is a phenomena that causes the string to stick in the open hole while drilling is in progress. Stuckpipe can be classified as mechanical or differential. Mechanical pipe sticking occurs if the hole collapses on the drill string, or if there is an insufficient cuttings removal or if severe doglegs or key seats exist in the well. Poor drilling fluids design can cause hole cave-in.

Differential stuckpipe occurs when the drill string is held against the mud cake by hydrostatic pressure in the wellbore. This generally occurs when hydrostatic pressure is severely greater than the formation pressure. Fluid properties associated with this type of sticking are density, fluid loss and lubricity. Low density and fluid loss, combined with good lubricity can help in avoiding stuck ups to a large extent.

4. Kicks

Entry of the formation fluid into the wellbore while drilling or tripping is in progress, is termed a kick. Uncontrollable kicks are called blowouts - and pose a great danger to the whole operations. Kick occurs when the hydrostatic head exerted by the fluid column is less than the formation pressure. The drilling fluid property that is associated with a 'kick' is the density. Based upon the available offset well data, the formation pore pressure can be determined. The density of the drilling fluid should be such that a static fluid column exerts a pressure at least 200 psi greater that the anticipated pore pressure. Surge and swab allowances of 0.3 ppg each should also be added to this density to account for pressure surges during the tripping in the well.

Appendix B summarizes various drilling fluid related problems and provides remedial measures for the same.

2.4 Drilling Fluid Additives

Certain additives are added to a drilling fluid in order for the fluid to perform certain functions[21,22]. Drilling fluid additives are chemical compounds and can be categorized as:

1. clay and weighting materials,
2. viscosifiers and filtration control agents,
3. thinners and dispersants,
4. detergents and lubricants,
5. specialty additives, and
6. inorganic chemicals.

Appendix C contains the list of such additives and their basic functions.

2.5 New Concepts in Drilling fluids

In the recent years, as a result of continuous efforts by researchers[3-12], several new concepts have been developed in the field of drilling fluids engineering. Most of these concepts have been developed in order to achieve shale stability, and to enhance the performance of drilling fluids used in drilling of geothermal wells. Experiments carried out in the laboratory and later in the fields, resulted into establishing new concepts. This section discusses a few of these new concepts.

2.5.1 Borehole Stability

In water-base systems, one mechanism thought of as responsible for shale stability is the addition of some cation to muds to retard the adsorption of water by the clay minerals in shales. O'Brien and Chenevert[21] demonstrated that the potassium ion (K^+) works well because of its low hydrational energy, high polarization power and size. Similarly, in oil mud, controlling the activity of water portion of the fluid such that water by osmosis enters the fluid from the formation, is supposed to result in borehole stability. In general, the three established ways of combating the shale problems are, deflocculation, polymer encapsulation, and inhibition of clay hydration by chemical reaction.

Chrome lignosulfonate system[13] (CLS) is by and large the most popular fluid system utilizing the principles of deflocculation. This is because of its simplicity in formulating and handling, insensitivity to chemical over-treatment, use of cheap chemicals, and high-temperature stability. An alternative to CLS, based on the principle of polymer encapsulation is a polymer system such as partially hydrolyzed polyacrylates[4] (PHPA). These systems are successful in many cases in preventing hydration but are very expensive and non solids or electrolyte tolerant. They require the use of the absolute best solids control equipment available.

2.5.1.1 Research and Experiments

Following is a brief account of new drilling fluid concepts being developed in the area of borehole shale stability.

1. Low Solids-Polymer Extended (LSPE) muds

Between 35% and 40% of all well drilled in the Rocky Mountains since 1986 by Exxon have been drilled using Low Solids-Polymer Extended (LSPE) muds, also referred to as Low Solids Non-Dispersed (LSND) muds and as Partially Hydrolyzed Polyacrylamide (PHPA). The typical range for low-gravity solids on LSPE muds is maintained between 2.5-4%. These mud systems helped in alleviating majority of the problems prevalent in the area. Hole cleaning improved owing to their superior rheological properties, and torque and drag reduced due to the natural lubricity of polymers. Faster rates of penetration were possible due to (a) shear-thinning properties of fluid at high shear rates near the bit, and (b) the reduced low-gravity solids content, reflected in the lower plastic viscosities.

LSPE muds were successfully used[6] in the Rocky Mountain's Darby/Absaroka Overthrust region in southwestern Wyoming, Moxa Arch in southern Uinta County, Wyoming, and in the Fish Creek Basin to the north of the Gros Ventre Uplift in Teton County. This fluid system utilizes dual, high speed, linear motion shakers with the screens inclined toward the rear. Screen sizes varied between 175 mesh and 275 mesh, depending on actual flow volume and amount of cuttings being generated.

PHPA on other hand, was extensively[4] used as a protective colloid in over 300 wells on the Louisiana and Texas Gulf Coast. They not only imparted excellent borehole stability but also enhanced the drilling rate. Their use resulted in increased bit life, less stuck pipes, and less mud to dispose of than other water base systems.

2. Potassium Hydroxide-Low Lime Graft Copolymer Lignosulfonate (KOH-GCPLS)

The results obtained from tests conducted by Chevron[5] in 1987 on highly reactive shales and gumbos bearing close resemblance to the one found in U.S. Gulf Coast, demonstrated that highest hole washouts were reported when common chrome lignosulfonate systems were used and the least when fluids containing only potassium hydroxide were used. As a result, KOH-GCPLS system, which provided most hole gauge at a cost approximately equal to that of a chrome lignosulfonate system, was developed. Potassium hydroxide-GCPLS-lime system was an easy system for the mud engineers trained in Gulf Coast because of its resemblance to the sodium hydroxide and potassium hydroxide based chrome lignosulfonate-lime system. Use of polymers had to be minimized, as many of the polymers used for water loss and assisting rheology are sensitive to high concentrations of calcium and presence of hydroxyl ions.

3. Inhibited muds

Green[3] in 1989 proposed a new technique based on the analysis of a formation for its clay content and then further analysis of the clay fraction and other mineralogical characteristics for individual mineral contents. He carried out such experiments for shales from offshore Louisiana and Texas Gulf Coast.

Two oil base drilling fluid systems, one with 36.5% by weight $CaCl_2$ and another with polymer system with 6% by volume asphalt proved favorable. The most common water base system producing excellent results was a polymer system with a minimum 1% potassium chloride (KCl) to aid in the inhibition process. For polymer system to function, it was observed that the pH should be higher than 9.2 because encapsulation needs some help from a free cation. Exact tailoring of the mud again depends on the experience in the area.

4. Thermally Activated Mud Emulsions (TAME) systems

Downs et al[8] proposed new generation water-based drilling fluids designed to minimize hydraulic pressure differential related penetration of fluid in the pores by reducing either the shale's permeability to aqueous fluids or rate at which fluids can flow in shales. These are thermally activated mud emulsions (TAME) systems, utilizing a combination of a surfactant solution and emulsion phase. The system was developed on the fact that alcohol alkoxylates, a specific group of polymeric surfactants, separate from water with increasing temperature, called "clouding out".

TAME was first field tested by Shell Expro in development wells located in Quadrant 21 of the UK North Sea. Conventional water base muds using KCl-polymer inhibition resulted into several problems ranging from logistics to stuck-pipes, low rate of penetration, bit balling, and stuck logging tools. When TAME was employed, high rates of penetration from 40 ft/hour to 70-100 ft/hour were obtained and no hole problems were encountered at all. Also for the first time in this field, logging was trouble free. Another important feature of this system is its low toxicity levels that permit dumping any amount of drilled cutting or waste in the sea as per the UK laws. Also, TAME is cheaper than polyglycerol muds but slightly more expensive than KCl-polymer. However, the efficiency in operation justifies that cost.

5. Fluids for High and Low Permeability Shales

Oort et al[9] suggest that the electro-osmotic water transport driven electrical potential gradient may provide an exciting new, benign means for stabilizing shale formations. They conducted pressure transmission tests with an exchange to concentrated solutions of KCl, calcium chloride ($CaCl_2$), and aluminum sulfate ($Al_2(SO_4)_3$)on low-permeability shales like Pierre shale. By comparison they found that $Al_2(SO_4)_3$ penetrates slowly as compared to KCl and $CaCl_2$ and further reaffirmed that the low-permeability shales can be stabilized by low-activity drilling fluids.

Pressure transmission and osmosis tests on high permeability shales indicate that these shales are in general non-selective and therefore do not sustain osmotic flow, or weak osmotic flow is completely dominated by the much stronger hydraulic flow. Stabilization of high-permeability/fractured shales should focus on reducing the hydraulic flow, which is accomplished by an increase in fluid filtrate viscosity and/or a reduction of shale permeability. Low-molecular-weight viscosifiers like concentrated solutions of saccharides, some concentrated brines (e.g. $CaCl_2$, NaCOOH, KCOOH) and low-molecular weight polymers are more appropriate for high permeability shales.

Reduction of shale permeability may be accomplished by agents that plug shale pores and (micro-) fractures, or coat/film on shale surfaces and alter clay wettabilities. Even systems like silicate solutions have proved very effective by constituting very low-permeability barriers in shale pore-throats through irreversible gelling or precipitation.

6. *Synthetic Based Muds*

Xiao and Piatti[11] proposed to substitute the toxic mineral oil based muds need to be fully investigated and compared on the basis of both performance and environmental acceptability. They formulated two compete synthetic drilling fluids, one of oil water ratio of 70:30 and another of 80:20 and conducted tests to determine their stability to hot rolling aging, tolerance to solids, seawater and cement contamination, lubricity, emulsion stability, high-pressure and high-temperature rheology, and seepage and filtrate loss control using low-toxicity plugging materials, and compatibility with cementing operation. Analyses of the test results demonstrated that in overall performance, the synthetic oils guarantee higher safety and environmental acceptability than the traditional oil base muds.

According to them the synthetic based muds' technical performance shows that it is one option worth considering for drilling critical well sections where stability is of utmost importance.

7. KCl-Polyols Systems

The term "polyols" includes glycols, glycerols, polyethylene glycols, polyalkylene glycols, and alcohol ethoxylates. Reid and Bernadette[10] studied the adsorption of three such polyols on montmorillonite from Swy-1, Crook County, Wyoming. The primary reason of undertaking the study was to know more about the mechanism(s) behind the shale inhibition while employing polyols water base muds. These are typically added to water base muds at concentrations between 3 and 10% by weight and are more commonly used in conjunction with a KCl-polymer base fluid, but have also been added to a wide range of systems including freshwater, seawater, sodium chloride, calcium chloride and gypsum muds.

Tests conducted on the shale sample included adsorption, X-ray diffraction, infrared spectroscopy, and shale inhibition. Test results showed that when KCl is present there is a good correlation between adsorption of polyol, formation of an ordered 14 A^o polyol/clay complex and inhibition of the clay or shale. From this it was concluded that when K^+ ions are absent, more polyol is adsorbed and complexes with basal spacing of about 17.5 A^o are formed. However, it was also shown that adsorption of polyol is not sufficient for inhibition and that K^+ must also be present.

8. Brine Based Drilling Fluids

Brine based drilling fluids are formulated with a brine as a liquid phase, selected bridging solids and polymers. The brine liquid phase may be composed of chlorides of ammonium, potassium, sodium and calcium, or bromides of potassium, sodium, zinc and calcium as single or multiple salt solutions. Bridging solids can be water soluble or acid soluble. Polymers are then added to provide proper suspension and desired rheological properties.

Brine based drilling fluids were found to be very efficient for drilling highly deviated wells or even for under-reaming operations. Swartwout and Pearcy[12] present two case studies where brine based drilling fluids were used. On the first well, sodium bromide was used for first section, and later calcium bromide treated with shale inhibitors was used for the second section. The desired production interval was successfully drilled upto a depth of 10,500 feet. In the second well, underreaming operation in a well in Gulf of Mexico was successfully carried out using sized calcium carbonate drilling system. This system utilized calcium chloride brine base.

2.5.2 Geothermal Wells

Geothermal wells pose technical challenges like temperature- induced gelation, potential for saline or hard brine influxes, presence of CO_2 and H_2S in formation fluids, and environmental accommodation. Oil-base fluids have traditionally been considered most effective in drilling geothermal wells. A lot of environmental damages, however, are associated with them and also kicks cannot be detected quickly. These shortcomings often overshadow their advantages which lie in the fact that they are not affected by any brine contamination, and that they are thermally stable up to temperature as high as 500°F. This section deals with the latest trends in the geothermal fluids and does a literature review of the same.

2.5.2.1 Research and Experiments

Following is a brief account of new concepts developed on the basis of research and experiments in the area of drilling fluids for geothermal wells.

1. Saudi Palygorskite Drilling Fluid

Experiments[16] were conducted on geothermal drilling fluids, formulated by adding Palygorskite clay mineral found in Umm er Radhuma formation hear Khurays, Saudi Arabia. Experimental set up involved a capillary viscometer to effectively measure the effective viscosity at high shear rates usually present near the bit and a high temperature high pressure fluid loss cell was used to measure filtration properties.

Results from the experiment showed that the viscosity, gel strength and filtration loss tends increase after 150°F. It was also found that bioploymers are the best chemical additives that reduce filtration and maintain excellent rheology of fibrous clays in sea water. The temperature effects on pH for fresh water base fluids are negligible. They recommended sodium hydroxide for raising pH and for dispersing the mixture.

2. *Drilling Fluid using Zirconium(IV) Thinner*

Use of chromium-based thinners too frequently is causing a lot of environmental concern. Zirconium-based rheology control additive of low toxicity has been found very effective at extending the rheological stability of both chromium-containing and chromium-free bentonite muds at high temperature.

Experiments[19] involved preparing drilling fluid using Wyoming bentonite clay and commercial barite, and mixing in it additives like, lignin-based fluid loss control additive, ferro or ferrochrome, chromium or caustic lignite, chromium free sulfonated tannin and finally adding ZrC (citrate complex of zirconium). The results of the experiment showed that ZrC is an effective high-temperature rheology "extender" for chromium-free aqueous bentonite muds. It is also broadly compatible with the usual range of mud additives, and is also less toxic. The fluid becomes unstable above 329°F. This type of fluid is initially acidic when the Zr additive is added, therefore, an addition of appropriate amount of caustic soda (NaOH) is required.

3. *Low-Molecular-Weight Copolymer Drilling Fluid*

A sodium salt of a sulfonated styrene maleic anhydride copolymer (SSMA) that adequately met the requirements of a high-temperature deflocculant and rheological stabilizer were prepared. Four case histories[15] were reported in the literature. These were in East Lake Pontchartrain Field near New Orleans, Cerro Prieto Geothermal Field in State of Baja California, Brazoria County in Texas, and Washita County in Oklahoma. Based on the studies carried out in the field and laboratory, it could be said that the SSMA polymer has greatly extended the temperature range of water-based muds. Results showed that it is very stable up to a temperature as high as 500°F and is environmentally safe. It is acidic in nature but the acidity can be removed by using sodium hydroxide.

4. Experimental High Temperature (EHT) Fluid

After a lot of laboratory work and research Exxon[17] could make effective use of this water-based drilling fluid for its drilling operations in Mobile Bay, a deep, sour dry gas objective in the Norphlet aeolian sandstone, located in a series of periodic crested dunes below 21,000 feet and at temperatures typically at or above 400°F.

Laboratory data, clearly indicated that EHT fluid appeared to be applicable for wells with temperatures to 475°F at densities up to about 16 lbm/gal, and up to 400°F at higher density. Field applications have been limited only to 420°F with 12.5 lbm/gal fluid and 370°F with 15.5 lbm/gal fluid. During the tests the EHT was designed to maintain a flat rheological profile between 50 and 100 cp. viscosity over an extended temperature range, coupled with hysteresis between heating and cooling.

Laboratory tests proved that this fluid is thermally stable up to a temperature of 400°F and is also stable in presence of high levels of salinity and hardness, and relatively insensitive to carbonate contamination. It is also acidic in nature and the use of caustic soda is required to maintain pH.

2.6 Summary

Large number of drilling fluids are employed in the drilling industry and hence it is very important to classify them for a better understanding. Drilling fluids can be broadly classified as water-base, oil-base or aerated drilling fluids. Each one of these classes are further sub-divided to accommodate the variations. Application of a particular drilling fluid type for a particular situation primarily depends on several factors, especially on effectiveness and cost.

Drilling fluids are characterized mainly by properties like density, rheology, and fluid loss. Once the fluid is designed, it is of utmost importance to maintain these properties, if optimum drilling performance is to be achieved. Drilling fluid-formation interaction often changes the properties originally designed for a well and it requires processes like solids control and chemical treatment to restore them to their original value. Drilling fluid additives play a very important role in converting a simple bentonitic gel or any other type of mud into the type of fluid that is efficient and stable under conditions for which it is designed.

Bore hole stability and high temperature well drilling are two areas of great concern in the drilling fluid industry. Continuous research in these areas has led to several new concepts. New fluids have been formulated and tested in the field with a varying degree of success.

CHAPTER THREE

SOLIDS CONTROL OF DRILLING FLUIDS

3.1 Introduction

The drilling fluid comes in contact with new formation as the drilling progresses and this often changes its physical and chemical properties. More than often such changes in the fluid have detrimental effect on drilling performance, especially if the solids are not efficiently removed from the system at all. Drilled solids can be divided into two categories:

a) Active drilled solids that hydrate easily, and
b) Inactive drilled solids such as sand, silt, limestone, and feldspar. These solids are undesirable in muds.

Hydration of active solids can alter fluid properties such as viscosity, yield point, gel strength, etc. Inactive solids will lead to increase in density which can cause an increase in frictional pressure drop, alteration in viscosity, and formation of thick filter cake. This can further lead to problems like stuck pipe, excessive pipe torque and drag, loss of circulation, and poor cementing.

George Ormsby[22] describes how a proper set-up of solids control equipment can help in increasing cuttings removal efficiency and overall cost reduction. A closed-loop[2] system for solids-removal has been advocated because the valuable liquid phase of non-weighted muds may be recovered from the underflows of desanders and desilters. In order to achieve this objective it is important to understand the drilling fluid system and solids control equipment.

3.2 Drilling Fluid Treatment and Solids Control Equipment

The treatment of drilling fluids is a three step procedure where the first step is to remove active drilled solids, the second to add natural solids or their equivalents, and lastly to treat solids chemically. This is important, in order to achieve the desired drilling fluid properties. Usually, commercial clay and polymers are added to increase yield point, gel strength, plastic viscosity, and to decrease filtration rate with minimum weight increase. Barite is added to increase the density of the slurry with minimum effect on the mud properties and solids volume.

To remove the drilled solids from the drilling fluid, a standard set of equipment[22,23,35] is used on the rigs. The equipment is generally set-up in the following order: shale-shakers, sand-traps, degasser, desander, desilter, mud-cleaner, and centrifuge. However, some of these devices may be bypassed or their constituents, eg. screens, hydrocyclones, etc. changed to suit specific situations. A brief description of these equipment is provided below.

3.2.1 Shale Shakers

This is the first solids control equipment that the returning fluid from the annulus comes in contact with. It is also called as shaking screen, a vibrating screen, or an oscillating screen.

Shale shakers, can either be single or dual deck depending on the anticipated amount of solids they have to handle. Figure 3.1 shows a shale shaker. Several type of screens can be installed depending upon the particle size distribution of the solids to control. It should, however be kept always in mind that shale shaker efficiency often decreases as the screen sizes decrease. The capacity of a shale shaker to transport the solids is determined primarily by the screen amplitude and motion.

Brandt[31] presented the first evidence that mud properties affected screen slurry throughput. Hoberock[32] later presented laboratory data obtained under closely controlled conditions that indicated that the major factor affecting screen slurry throughput was plastic viscosity which actually supports Brandt's work. In most instances, plastic viscosity unavoidably must increase as mud weight increases. Among the disasters for screens would be near size plugging, or wedging. When this occurs, finer screens often work better than coarser ones. However, if the liquid throughput requires more open area (when not plugged), coarser screens must be used. Sometimes with dual stage (upper and lower mesh in series) a change in the size of both screens can eliminate the problem. In any case, screens should not be bypassed, even partially, because this quickly makes all downstream equipment ineffective.

3.2.2 The Sand Trap

Sand traps are essentially gravity settling tanks and they work on the principle of settling velocities of different drilled solids particles. The fluid from the well after being screened by the shale shaker falls into this tank whose one side is inclined to accumulate

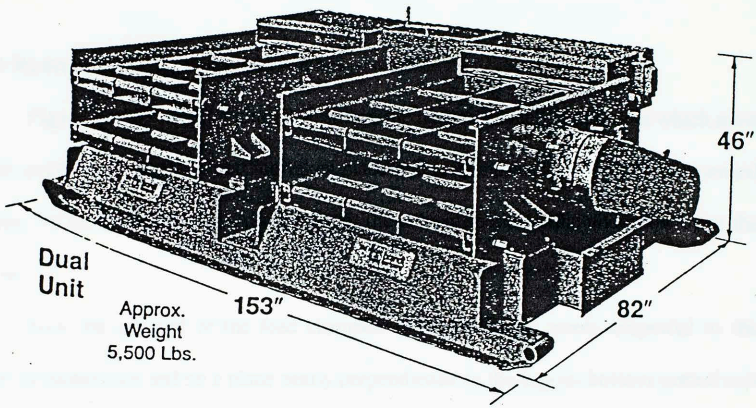


Figure 3.1 : Brandt Tandem Screen Shale Shaker - Dual Unit[39].

solids. A dump valve is provided at the bottom to dump the settled solids and care must be taken to avoid dumping drilling fluid. Other precautions include:

1. No stirring should be carried out and it should not be used as a suction compartment for any removal process.
2. The sand trap must not be bypassed if there is any problem with any other solids removal apparatus.

3.2.3 Hydrocyclones

Figure 3.2 shows the hydrocyclone. It has a conical shaped portion in which most of the settling takes place and a cylindrical feed chamber at the large end of the conical section. At the apex of the conical section is the underflow opening which is usually at the bottom.

Near the top end of the feed chamber, the inlet nozzle enters tangential to the inside circumference and on a plane nearly perpendicular to the top-to- bottom central axis of the hydrocyclone. A hollow cylinder, called the vortex-finder, extends axially from the top into the barrel of the hydrocyclone past the inlet. The overflow opening is much larger than the underflow opening. The hydrocyclone obtains its centrifugal field from the tangential velocity of the slurry entering the feed chamber. There are two main design types of hydrocyclones: 1) balanced design, and 2) choke bottom design.

1. Balanced Design

In a normal hydrocyclone, the stream spirals down along the wall of the conical section toward the underflow opening, reverses axial direction, and spirals upward to exit at the

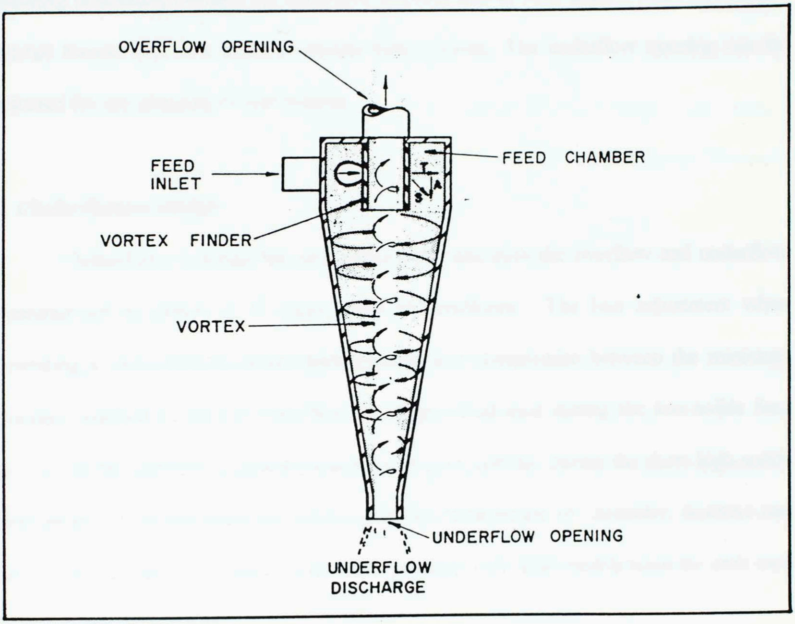


Figure 3.2 : A Typical Hydrocyclone[37].

overflow opening. The liquid stream is forced to the top of the hydrocyclone by the very high centrifugal force combined with the large overflow opening and small underflow opening. When the liquid stream reverses to spiral upward, the solids particles continue spiraling downward through the underflow opening due to their greater mass and higher inertial forces. This is a balanced design hydrocyclone. The underflow opening can be adjusted for dry plugging or wet bottom.

2. Choke-Bottom Design

Choke-bottom design has no balance point and both the overflow and underflow openings act as chokes at all times under all conditions. The best adjustment when operating a choke-bottom design hydrocyclone is a compromise between the minimum opening required to prevent underflow discharge of all mud during the low-solids feed period and the maximum opening required to remove cuttings during the short high-solids feed period . Hydrocyclones are employed in the construction of desander, desilters and mud cleaners. They all operate on the same principle with little modification for each case based on the particle size.

3.2.4 Desander

Particle sizes from 35 microns upwards are more commonly found in the desander underflow. Desanders should not be used if the system is weighted, because the typical range of API barite particle is between 3 and 100 microns, where the median is around 25 microns. If a desander is used, costly barite is lost.

3.2.5 Desilter

Desilter is a solids control device primarily used for removing medium sized particles like fine to very fine sand and to certain extent silt. Two common cone sizes usual sizes of cones used in desilters are 4 inch and 6 inch and are employed depending on the discharge rates. Particle sizes from 15 microns upwards can be more commonly found in the desilter underflow. Desilters should not be used if the system is weighted, because the typical range of API barite particle is between 3 and 100 microns, where the median is around 25 microns. Figure 3.3 shows a typical desilter.

3.2.6 Mud Cleaner

Mud cleaner is a solids control device primarily used for removing very fine particles like clay and silts. Two usual sizes of cones used in desilters are 4 inch and 6 inch and are employed depending on the discharge rates. Figure 3.4 shows a typical mud cleaner.

3.2.7 Decanting Centrifuges

The decanting centrifuge was first tested and proved adaptable as a practical field tool in 1953. The decanting centrifuge is the only liquid-solids separation device used to remove (decant) all free liquid from the separated solids particles, leaving only adsorbed moisture on the surface area of the solids. Figure 3.5 shows a decanting centrifuge.

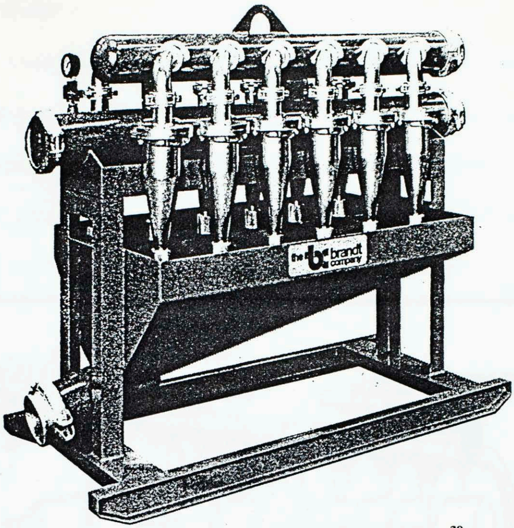


Figure 3.3 : The Brandt Company Desilter[39].

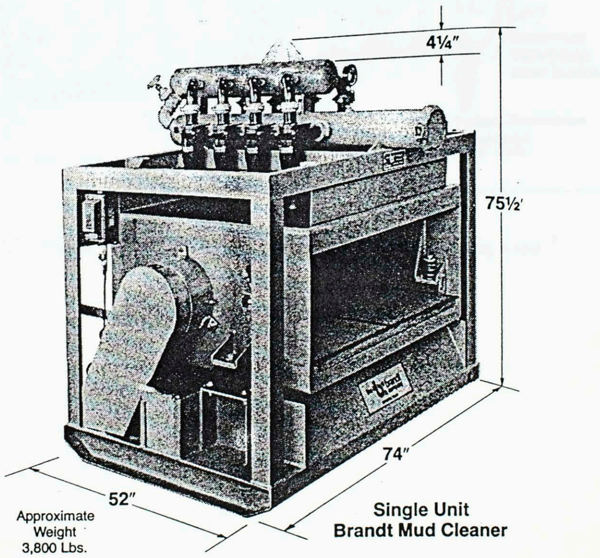


Figure 3.4 : Single Unit Brandt Mud Cleaner[39].

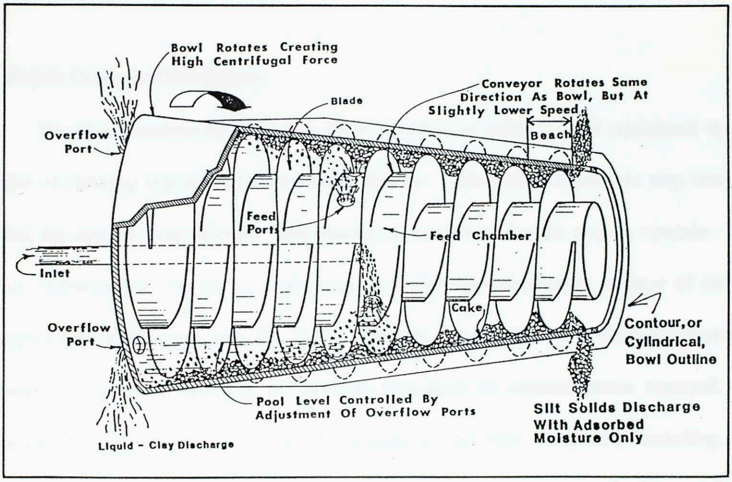


Figure 3.5 : Decanting Centrifuge, typical sectional operating view[37].

3.2.8 Dilution Water

Water is constantly lost from a drilling fluid while drilling is in progress and hence must be constantly replaced, to restore the initial properties. This is done by adding water which is termed as dilution. On the other hand if water is added to replace solids removed from a system, it might change the system total solids. Solids added by the bit do increase the total percent solids, but they also increase the surface system level.

3.3 Solids Control Calculations

The expert system developed to aid in selection of solids control equipment is also capable of carrying out several relevant calculations. This feature is another step towards making the system "user-friendly" and making it convenient for the user to operate. The system developed is capable of performing the following calculations: volume of cutting generated and solids content in the fluid. Appendix D contains the necessary equations. Appendix E provides the basis of chemical treatment for contamination removal, and Appendix F provides solids control equipment selection criteria including the recommended ranges of yield point and plastic viscosity, and the maximum recommended solids content , for water based drilling muds.

3.4 Summary

The proper selection of solids control equipment is essential to keep drilling costs low. Drilled solids often alter the properties of the designed fluid and can drastically effect drilling operations. It is recommended that rig designers should work closely with drilling or mud engineers who can guide them in this aspect. A few factors essential for the selection of solids control equipment includes maximum depth the rig is designed for, anticipated maximum flow rates, anticipated lithology, and allocated cost for the solids control equipment. Where the costs are not of a great concern, for example on offshore rigs, the equipment capacity should be such as to accommodate maximum flow rates. For greater economic returns in the future, the installed equipment should be regularly maintained and utilized to its maximum capability whenever possible.

CHAPTER FOUR

DEVELOPMENT PROCESS OF THE EXPERT SYSTEM

4.1 Introduction

The preceding chapters clearly enumerated two things (1) that a proper selection of drilling fluids and solids control equipment is very important to a successful drilling operation, and (2) that the selection criteria in itself involves several factors. It can be fairly deduced from this that a unique solution for the situations encountered in the field is generally not available, and that the selection of proper drilling fluids and solids control equipment would require services of personnel from several departments like geology, geophysics, and engineering. Further modification of any fluid selected after the interaction of these personnel largely depends on its performance in the field and users' engineering judgement.

Clearly, the problems at hand involve a large number of variables for which more than one solution generally exists. Hence, an expert system is the ideal approach to solving the problem.

4.2 Expert Systems

By definition an **Expert System**[33] is an interactive computer-based decision tool that simulates the thought process of human expert to solving complex problems in a specific domain. The need for expert systems is increasing daily because several limitations are associated with human decision making processes. A few of these limitations include limited expertise, limited working memory, poor retention of large data, and biased decision making. As of today, most of the tasks previously performed by humans are being efficiently replaced by the computers. Development of expert systems is one of such jobs that can replace experts to a large extent and still come up with useful solutions. An expert system by nature uses both facts and heuristics to solve difficult decision making problems based on knowledge acquired from an expert.

The construction of an expert system involves writing down the program in a special language. The program is usually written in the form "if- then" rules. The following section briefly describes the fundamentals involved in typical expert systems. An expert system called ©**FLUIDSOL** is developed to aid in the selection of drilling fluids and solids control equipment.

4.2.1 Typical Expert Systems

Expert systems are generally organized in three distinct levels:

a. Knowledge Base: This consists of problem solving rules, procedures, and intrinsic data relevant to the problem domain.

b. Working Memory: This refers to task specific data for the problems under consideration.

c. Inference Engine: This is a generic control mechanism that applies the axiomatic knowledge in the knowledge base to the task-specific data to arrive at some solution or conclusions.

Before an expert system is developed to perform any specific task, it is extremely important to determine if that particular problem can be an ideal candidate. Problems that are deterministic in nature or ones with one specific solution are generally not considered ideal candidates for expert systems. This is because they defeat the purpose of expert systems which is essentially resorted to when several combinations are possible and many solutions exist. It is the task of an expert system to inform the user of all the possible answers and also recommend the best ones based on a special rating called the confidence number. The confidence numbers are assigned by experts.

Once it is clearly established that construction of expert system will be beneficial for solving a particular problem the next action is to organize the development process into three distinct steps. It is important that the developer understands the underlying principles first before bringing the computer into picture. It is not mandatory that the developer (hereafter referred to as knowledge engineer) be an expert in concerned field, but familiarity with the problem is always advantageous.

4.2.2 Step I : Problem Identification and Ground Work

It is important for the knowledge engineer to identify the problem that needs an expert system. If the knowledge engineer is familiar with the problem beforehand, the development of the expert system becomes relatively easy. However, if the problem pertains to an area in which the engineer is not familiar, it must be ensured that enough data is available to carry out the development process smoothly. In both the cases, the knowledge engineer is required to go through the following:

1. Identify and understand the problem and decide on the type of output expected.
2. Make a list of experts in the field of concern.

3. Prepare the questionnaire to be filled in later on by expert.
4. Plan on how to acquire knowledge from other sources.

4.2.3 Step II: Consultation with Experts and Literature Review

This step involves accumulating data and creating a working memory for the expert system. Upon identifying the problem identification, the knowledge engineer is required to construct a questionnaire based on major factors involved in decision making and expected type of situations. After this, meetings with all the experts in the fields has to be arranged. During the consultation, the experts provide answers to the questions while the knowledge engineer analyzes the answers.

The other source of data, equally significant is literature survey. This source of information technology helps in providing up to date data and documentation on field results. The quality and quantity of data to be incorporated in the expert system, however depends on the size of program intended and the expected outcomes.

4.2.4 Step III : Creation of Knowledge Base

At the end of step II the knowledge engineer has enough data required to create a knowledge base. After the consultations with experts and reviewing the literature, the knowledge engineer decides on the output format. Based on this, the knowledge is converted into several "if-then" type of rules. This is accomplished by assigning different variables to all the factors involved.

Knowledge base is essentially a computer program that is written in a special language depending upon the expert system package that is used. The program forms the main body of the entire expert system and hence must be written in a way that makes the execution fast. If the size of program is very big, the knowledge engineer may choose to divide it into several small programs. Also the knowledge base program need not hold all the data, instead it should have ability to access the database. Another important aspect of creating a knowledge base is to construct a user's interface or customer front end. If the knowledge engineer chooses to make mouse based interface then the user decides the execution sequence, making the program faster and more bug-free. On the other hand, if the mouse support is not provided, then, the program asks the question in a sequence decided as the rules are assigned.

The details involved in the development of an expert system for drilling fluid selection and solids control equipment selection and design are as follows.

4.3 Development ©FLUIDSOL, Expert System

An expert system called **©FLUIDSOL** was developed to aid in the selection of drilling fluid and solids control equipment. It was constructed by following the basic steps discussed in section 4.2. The development process was divided into three principle steps, and each step was further divided into sub-steps to accomplish the task primarily assigned in the main step.

4.3.1 Step I : Problem Identification

Though it was required to develop an expert system to solve two distinct problems, the two are inter-related. Selection of solids control equipment in many ways depends on the type of the drilling fluid in use. This must be kept in mind during the development process. The inter-dependence must be applied when preparing the questionnaire for the expert and during the literature review. Important tasks covered in this step are as follows:

1. Checking if the problem qualifies as an expert system candidate.
2. Identifying the factors affecting the selection of drilling fluids.
3. Identifying the factors affecting the selection of solids control equipment.
4. Preparing the questionnaire to be answered by the expert or through literature review.
5. Identifying sources of data acquisition.

1. Checking the Problem:

Primary literature review [1-32] and consultation with experienced personnel in the field revealed that the problem selected was a matter of great concern in the field and that on many occasions more than one fluid or more than one type of solids control equipment arrangement was the possible solution. It was further revealed that the success of these choices could be actually predicted based on the data available. In terms of expert systems design, this means that confidence numbers can be assigned to different solutions. Based on these, it was clear that the problem selected was an ideal candidate and that there was ample scope for development of an expert system to provide solutions for different situations.

2. Factors Affecting the Selection of Drilling Fluids

The following factors[1] were identified as the important ones for selection of drilling fluids:

1. Type of the well - exploratory or development.
2. Location of the well - onland or offshore.
3. Type of lithology being drilled
4. Temperature of the formation to be drilled
5. Expected pore pressures
6. Type of water available for making fluid e.g. fresh water or sea water
7. If oil-base muds were environmentally acceptable
8. Availability of bulk material like bentonite, attapulgite, lime, gypsum, and diesel, and also availability of additives like NaCl, KCl, and polymers.
9. Specific problems like troublesome shales, drill string stuck, lost circulation, salt or fresh water flows, or high pressure gas zones.

3. Factors Affecting the Selection of Solids Control Equipment

The following factors were identified as the important ones for the selection of solids control equipment:

1. Drilling Fluid Type - weighted or unweighted.
2. Type of the cuttings obtained at the returns.
3. Fluid returns rate.
4. Density of the returns fluid.
5. Viscosity of the returns fluid, and
6. Feeder pump rate.

4. Preparation of Questionnaire for Experts

Table 4.1 shows a typical questionnaire developed for the experts.

5. *Identifying Sources for Data Acquisition*

Apart from consultation, a sizeable amount of practical data had to be obtained to back up the design process. Under this step the sources containing such data were identified. They comprise mainly of printed material documented in the form of papers, books and articles in various journals. These are all shown under the references section.

4.3.2 Step II Consultation with Experts and Literature Review

Consultation with Experts

The questionnaire prepared at the end of Step II is presented to the expert for his comments and for assigning confidence numbers to different variables. Consultation is a tedious and slow process and the outcomes may change several times. An important aspect in this step is to somehow have a "sneak-preview" of expert's problem solving style. It is this unique style of the expert that the computer program has to emulate in order to be truly classified as an expert system. It must be capable of providing solutions to all possible combinations of the variables and also identify situations that are practically impossible and consequently warn the user if he tries that kind of input.

Table 4.1 : Typical questionnaire for experts.

Drilling Fluid Types	Factors affecting the selection of drilling fluid												
	Geological Factors			Availability of Materials									
				Water			Clay type				Materials		
	LI	PR	TM	FW	SW	Both	WB	PC	CC	AT	NaCl	KCl	Poly
Spud Muds													
Native Muds													
Low Solids Muds													
NaCl Polymer													
S.S.W.													
Sea Water Muds													
Lime Muds													
Gypsum Muds													
LSBE													
KCl - Polymer													
Gyp-lignosul.													
CL-CLS													
Invert O.E													
LSBM													
Surfactant Muds													
Oil Base Muds													
Polymer Muds													

Legend:

LI : Effect of lithology
PR : Effect of expected formation pore pressure
TM : Effect of expected formation temperature
FW : Effect of fresh water availability
SW : Effect of sea water availability
Both : Effect of availability of both sea and fresh water
WB : Effect of availability of Wyoming Bentonite
PC : Effect of availability of Premium Clay
CC : Effect of availability of Common Clay
AT : Effect of availability of Attapulgite Clay
NaCl : Effect of availability of sodium chloride
KCl : Effect of availability of potassium chloride
Poly : Effect of availability of polymers
S.S.W. : Saturated salt water muds
LSBE : Low solids bentonite extenders
KCl - Polymer : Potassium chloride-polymer muds
Gyp-lignosul. : Gypsum lignosulfonate muds
CL - CLS : Chrome lignite - chrome lignosulfonate systems
Invert O. E : Invert oil emulsions

Literature Review

This was the data acquisition phase of Step II. Though answers to most of the problems can be handled by consultation with experts, it is not possible to obtain field or real-time data from them. The idea of constructing an expert system is to overcome human weaknesses, such as poor retention and poor judgement. Hence, it is necessary that a data bank or an active database be created. The expert system constructed, has several of such databases and the information included in them was obtained from an extensive literature review.

4.3.3 Step III Creation of Knowledge Base and User's Interface

This was singularly the most exhaustive of all steps because it involved writing a computed program which incorporated the results of consultation and the immense amount of data that was obtained from the literature. Expert system programs are written in special language and it requires a special software that is compatible with the operating system on knowledge engineer's computer.

The software chosen for constructing **©FLUIDSOL** is VP Expert®, version 3.1 by WORDTECH Systems[38]. To run the system a minimum of 450K or more RAM, and DOS version 2.xx, 3.xx, 4.xx, or 5.xx. is required. The system, though a DOS based application permits the use of the mouse. Such mouse-driven programs can be written and executed in a special mode termed as graphics mode which requires IBM or equivalent CGA, EGA or VGA. The complete list of different type of graphics mode ranging from color to Black and White development can be seen from Figure 4.1. The current program is a mouse-based application and is in 'Gmode 18' which requires only a VGA that gives

Setting	Description	Adapter					
		MDA	CGA	MCGA	EGA	VGA	HGC
-1	restores screen to original mode.	✓	✓	✓	✓	✓	✓
0	40 x 25 [text], 16 grey.	✓	✓	✓	✓	✓	
1	40 x 25 [text], 16/8 color.		✓	✓	✓	✓	
2	80 x 25 [text], 16 grey.	✓	✓	✓	✓	✓	✓
3	80 x 25 [text], 16/8 color.		✓	✓	✓	✓	
4	320 x 200 [graphics],4color.		✓	✓	✓	✓	
5	320 x 200 [graphics],4 grey.		✓	✓	✓	✓	
6	640 x 200 [graphics], BW.		✓	✓	✓	✓	
7	80 x 25 [text], BW.	✓	✓	✓	✓	✓	✓
8	720 x 348 [graphics], BW for HGC.						✓
13	320 x 200 [graphics], 16 color.		✓	✓	✓	✓	
14	640 x 200 [graphics], 16 color.			✓	✓	✓	
15	640 x 350 [graphics], BW.				✓	✓	
16	640 x 350 [graphics], 4 or 16 color.				✓	✓	
17	640 x 480 [graphics], BW.				✓	✓	
18	640 x 480 [graphics], 16 color.					✓	
19	320 x 200 [graphics], 256 color.			✓		✓	

Adapter Code	Description
MDA	Monochrome Display Adapter
CGA	Color Graphics Adapter
MCGA	MultiColor Graphics Array
EGA	Enhanced Graphics Adapter
VGA	Video Graphics Array
HGC	Hercules Graphics Card

Figure 4.1 : GMODE Setting Codes for VP-Expert™ Systems, Version 3.1[38].

a monitor screen resolution of 640 x 480 pixels for 256 colors. The text that follows elaborates on the procedures involved in construction of ©**FLUIDSOL**.

Chaining of Programs

The 'chain' command provided in the expert system software enables the linking of several small and individual programs. This facility allows the knowledge engineer to divide a bigger program into several small programs and then link them together for faster execution. Program execution error problems associated with single large problems are removed, and identifying flaws in program becomes very easy.

Special Programming Features

©**FLUIDSOL** is a DOS-based application, but allows the user to use the mouse. User interfaces are provided to make the program 'user-friendly'. The instructions to use the program, in most cases, are provided in the interface preceding to the main one. Several features were incorporated in each of the interfaces developed to make the program easy-to-use and for field application. These features are as follows:

1. Headers

Each one of the user's interfaces, bears the name of the program in the form of header. The illuminated sky blue button below it indicates the purpose of a particular interface. This was created using the 'Lbutton' command. In the windows environment, these could be thought of as small label boxes.

2. Pull Down Menu Boxes

While the user is using the program, he may be required to choose from several available options. The program incorporates several pull down or drop down menu boxes in order to make the choosing process easy and convenient. These boxes are all magenta colored and were created using the 'Form Field' command.

3. Return, Restart, Reset or End Buttons

The first three buttons are all yellow in color and take the user to location designated by the text written in front of them. 'Restart' button restarts the program in which the user currently is, while the 'reset' button resets all the input boxes and the 'return' button takes the user back to interface of the main program ©**FLUIDSOL** or in some cases to the main interface of 'Solids control'. In any case, when the program is done running and providing its user with the results, it restarts itself for second set of inputs. The buttons were all created using the 'Lbutton' command.

4. Calculations

In the solids control section, the calculations option makes use of special dynamic gauges termed 'vertical gauges' that can be created by using 'Vgauge' command and allow the user to vary the input by sliding on the level indicated by them. Output boxes created using the 'Form Field' command give the varying outputs and hence allow the user to visualize the effect of change in variables without continuously inputting the figures manually.

5. The Quick-View Option

Using the 'Hypertext' command a special text box was created in the graphics mode. Within this special text box are held all the terms, highlighted by a glow. When clicked on, they provide the user with the meaning of the terms. The text file which accommodate this clause must be specially constructed.

6. Program Output

The output of consultation, in most of the expert systems is in the form of text display. This is made possible by commands like 'Display' if one has to just view the output, 'Pdisplay' if one has to only print the out put and 'Printon' preceding 'Display' if one has to view and print the output. 'Printoff' clause at the end of the 'Display' shuts off the printer.

7. Appending the Text

'Smart-Form' ability of the expert systems is utilized for appending the text files. 'Form Fields' are created for the user to fill in any important observation, or solution to any problem that may have been encountered at site. The user is required to fill in information like name, title, well name and location, formation being drilled, fluid-type, encountered problems, and solutions to those problems. After filling the form and clicking on the accept button, all the text that he entered is transferred over to a pre-designated text file along with the time and date. The transfer of the data is made possible by the 'Fdisplay' command.

7. Viewing, Editing and Appending the Database Files

Expert systems ability to interact with database files is used here. Several database files containing data regarding drilling fluid additives and drilling fluid practices in several states of U.S are stored in the program. Utilizing the 'Put' command the data from any particular cell can be replaced by a new one (termed as editing here) and using the 'Append' command new data can be added on to the existing database. Using the 'Menu' and 'Get' command the values of different fields can be stored.

4.4 Program Description

To use ©**FLUIDSOL**, VP-Expert must first be loaded on to the users' computer. This can be set up on the hard drive easily. After the set up procedures are over, the user has to go to the MS-DOS mode. The user can enter the VPX directory by typing c:\vpx\vpx. The first screen that the user comes across describes the VPX software. On pressing the 'enter' key, a new screen with 'consult' option at default, opens up. On pressing 'enter' twice, the user is ready to use ©**FLUIDSOL**.

4.4.1 First interface - The Nucleus

As discussed earlier, the first user's interface (obtained after pressing 'enter' as prompted by the preliminary information window), is the nucleus of the entire program. From here the user can run the entire program, carry out consultations, consult several files, edit or append the existing data, or even end the program. Following options are provided to the user when the menu button is clicked on:

1. Fluid Design
2. Fluid Hydraulics
3. Fluid Additives
4. Append Database
5. Edit Database
6. Read Literature
7. States Database
8. Field Experience, and
9. Solids Control.

These individual options are by themselves links to several knowledge base files that can be run on user's commands. The following discussions explain how the program works and what knowledge base, database or text files are linked when the command is activated.

4.4.1.1 Fluid Design

This is the first option that the user will see in the menu drop box. On choosing the 'Fluid Design' option the user is further prompted to choose the lithology for which the design has to be carried out. On choosing the lithology, a new knowledge base file corresponding to the lithology chosen is opened. To carry out the consultation the user is now required to fill in all the 'Form Fields' requesting for information. Figure 4.2 shows an example interface for fluid design option. Other fluid design related interfaces are provided in the example problem.

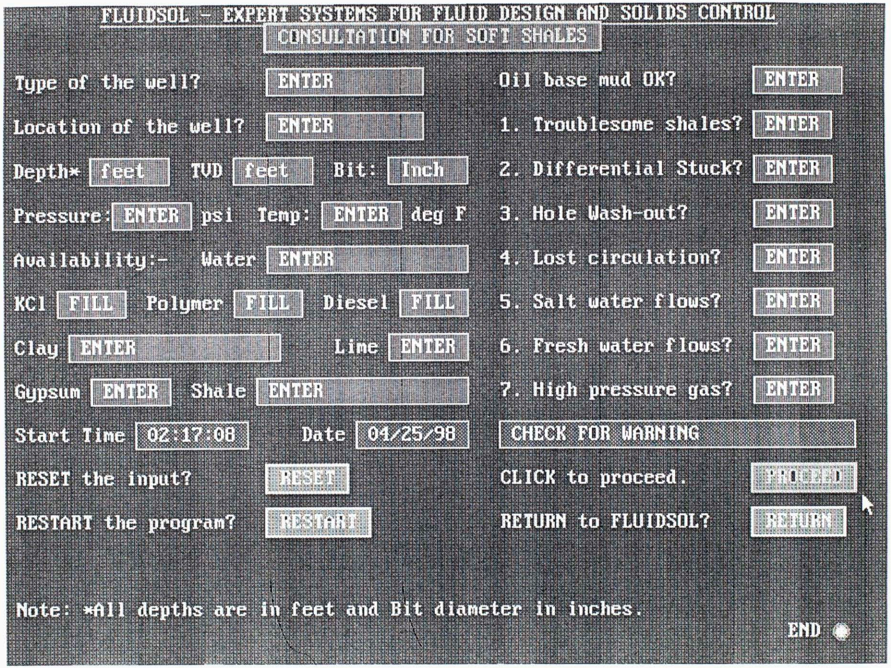


Figure 4.2 : Typical Interface for Fluids Design.

The initial approach that was adopted for development of fluid design module of **©FLUIDSOL** incorporated several 'Form Fields' on one interface inviting the user to choose the lithology first, and then fill in the depth interval, expected temperature and pressure for that interval. Along with this the user had to fill in the information regarding the location i.e. the state, region and the county. Based on the input of the user, the program was to first suggest the type of drilling fluids appropriate for that particular depth-interval, and then compare the same with the drilling fluid practices prevalent in that region. This approach, however never did work because of the following reasons:-

1. The well was divided into eight depth intervals and the user could assign any one of eight lithologies, e.g. gumbo shales, salt zones, anhydrite-gypsum, soft shales, hard shales, limestones, fractured limestones, and sandstones to each one of the interval. Several 'if-then' rules had to be written to take into consideration most of, if not all, the possible combinations that exist for eight lithologies and eight depth intervals. This caused the program length to increase to an extent where frequent 'jamming' was encountered and the program refused to run.
2. The user interface is created by using 'Gmode 18' (refer Figure 4.1) which allows a screen resolution of 640 x 480 pixels. This graphic mode permits 29 rows in all, in which programming features like 'Form Fields' can be written for rows 1 to 24 from the top of the screen. With this restriction in hand, it was not possible to create 'Form Fields' for other factors like temperature, pressure, make-up water availability, and environmental restrictions, that influence fluid design selection.
3. The idea of clearing the first user interface screen (by retaining the entered values) using 'gcls' command and opening another one to allow the user to continue entering

did not work too, because unless 'reset all' is used before 'gcls', the 'Form Fields' of previous screen continue to occupy their positions on the screen though not visible at first. If, however, the user accidentally clicks on any 'space' not currently occupied by any 'Form Field' in the new interface, and it happens to be the slot for some 'Form Field' in the previous screen, the previous 'Form Field' becomes active again - creating a lot of confusion. Alternatively, if 'reset all' command is used before 'gcls', the values of all the variables previously entered by the user are set to unknown. If this occurs, entering any further inputs will not lead to any results.

An alternate approach was adopted to overcome the problems encountered. This, included assigning the lithologies first, and then creating individual interfaces for each one of them, on the basis of drilling fluids frequently used for their drilling. The types of drilling fluids available, were now incorporated in the individual programs and would be assigned as a probable answer if all the conditions required for their assignment were satisfied. In order to compare the results of consultation with the prevalent drilling fluid practices, a separate module (section 4.4.1.7) was created. This has the ability to access the database files and return the values asked for, to the user. Since the results obtained at the end of consultation are much more explicit in nature, they can be more relied upon than only the database which is based on publication[20] dating back to 1969. Moreover, the size of the database in its present form is very small to encompass the data for all the depth ranges, or even all the regions.

The present approach would imply multiple runs, but given the fact that each run takes about as much time as it takes the user to input the values, the time consumed is justifiable. In the preparatory or well planning stage, it is important to carefully develop an efficient drilling fluids program to prevent any complications at a later stage.

4.4.1.1.1 Confidence Numbers

At the end of consultation, comprising one run each for all the lithologies, **©FLUIDSOL** provides the user with type(s) of drilling fluids that can be used for the input situation. Each one of the drilling fluids is provided with a unique number called as confidence number that is representative of experts' level of confidence in them. Since confidence numbers are based purely on experts opinions, they may vary from one expert to the other. These numbers become more meaningful when the result of consultation shows that more than one drilling fluid can be used to drill a particular lithology under the conditions input by the user. In such cases, these numbers provide a basis of comparison of the relative performances of the fluids for the same situation. The numbers range from 1 to 100 and it is advised to use the drilling fluid corresponding to the highest confidence number. In case of **©FLUIDSOL**, the confidence numbers are primarily based on literature review carried out by the knowledge engineer and also on the opinion of the expert consulted.

4.4.1.1.2 Tailoring of Results

Engineering judgement of the user is important when it comes to drawing the final drilling fluids program. On the basis of the consultation the user can tabulate the results (example problem in section 4.6) and then choose the appropriate drilling fluid, using confidence numbers as a guideline. Some of the factors that may be taken into consideration here are drilling fluid cost, length of the section that has to be drilled using one particular fluid, if the fluid can be used for other zone by just adding a few additives, and finally if it is possible to store it temporarily (e.g. if loss is encountered, one might resort to bentonite gel or even water) to be reused again for another interval. Since **©FLUIDSOL** cannot combine the results of consultation for all the lithologies, this has to be done by the user.

4.4.1.1.3 The 'if-then' Rules

©FLUIDSOL uses several 'if-then' rules to decide the type of drilling fluid that could be used for a particular situation. The factors involved in the selection process have to be assigned definitive values that fire a command causing the system to look for the rules that are being satisfied. Depending on the rules that are satisfied, the system concludes the consultation with suggestions on the type of drilling fluids. Other relevant information like fluid components, and fluid properties are then calculated and presented to the user. Such rules are being written for each one of the lithologies and Figure 4.3 shows the drilling fluid selection procedure for soft shales.

4.4.1.2 Fluid Hydraulics

This option allows the user to calculate the hydraulic losses in annulus and pipe under laminar and turbulent conditions. The three models for which pressure losses can be calculated are Newtonian, Bingham Plastic, and Power Law. Bingham plastic parameters, the yield point and plastic viscosity as well as the power law parameters, n and K can be obtained from the interface itself. The interface is shown in Figure 4.4 and a typical input

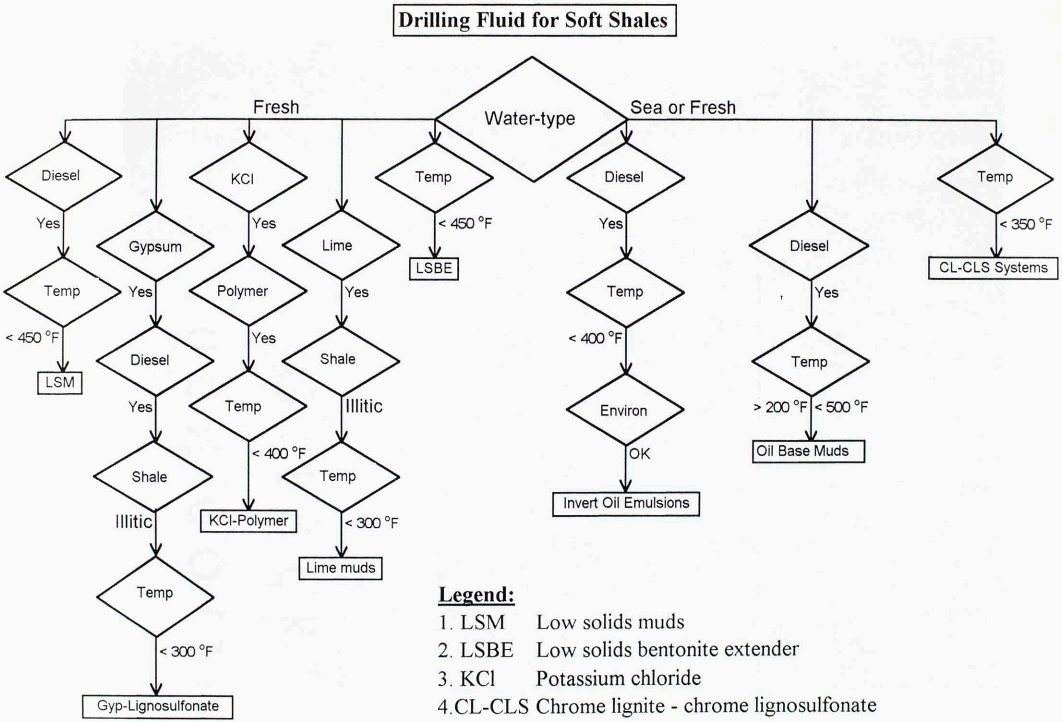


Figure 4.3 : Drilling Fluid selection procedure for Soft Shales sections.

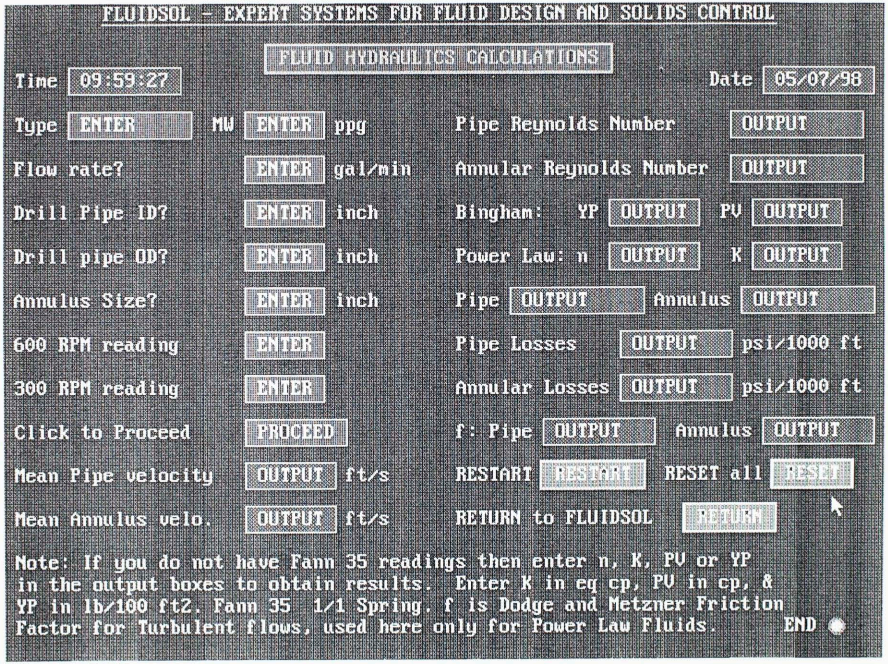


Figure 4.4 : Interface for Fluid Hydraulic Calculations.

and output for Power Law fluid is shown in Figure 4.5. For Bingham Plastic fluids the input and output are provided in Figure 4.6. Appendix G shows the equations used for calculating pressure drops using these models. Figure G1 shows the plot used for determining Dodge and Metzner friction factor, and also for determining critical Reynolds number for pipe and annulus flows for power law fluids. Figure G2 shows the plot used for selecting critical Reynolds number for Bingham Plastic fluids.

4.4.1.3 Fluid Additives

The interface is shown in Figure 4.7. Database files containing information about drilling fluid additives like thinners, emulsifiers, weighting materials, lost control materials, filtration loss agents, etc. are handled by individual programs when the user chooses this option. When user points the mouse and clicks on any one of the buttons shown, the associated program opens up the database file storing the information requested, enabling the user to browse through the contents of the file. The 'append' and 'edit' buttons seen in the interface link this interface with 'append' and 'edit' modules. These modules are described in the text below.

4.4.1.4 Append Database

The information regarding drilling fluid additives mentioned in section 4.4.1.3 may become obsolete with time or new products may be launched in the market The 'append database' option allows the user to update all database files containing data pertaining to drilling fluid additives. Any information entered by the user is appended to the files and is

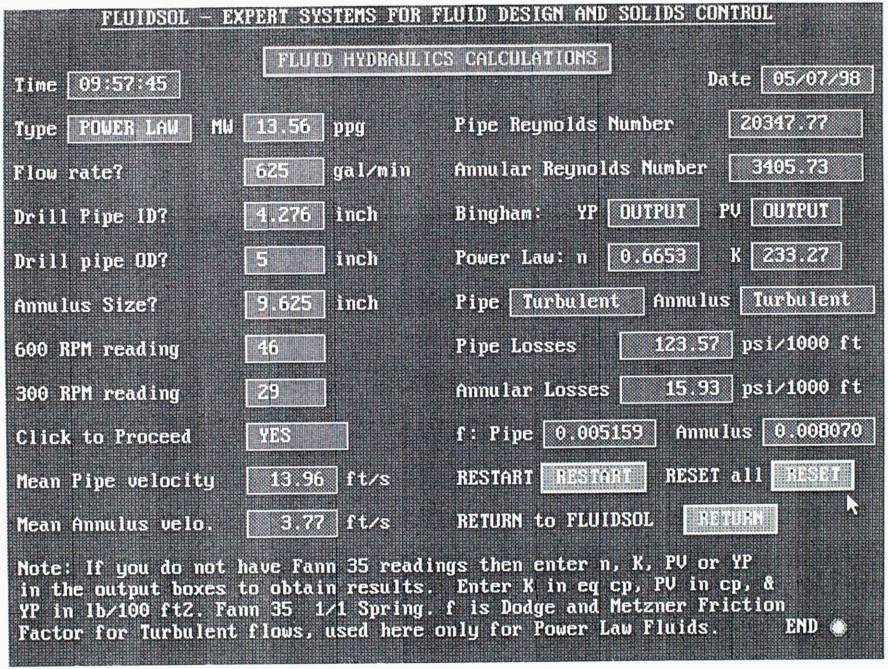


Figure 4.5: Input for Example Problem in Fluid Hydraulics Calculations - Power Law Fluids.

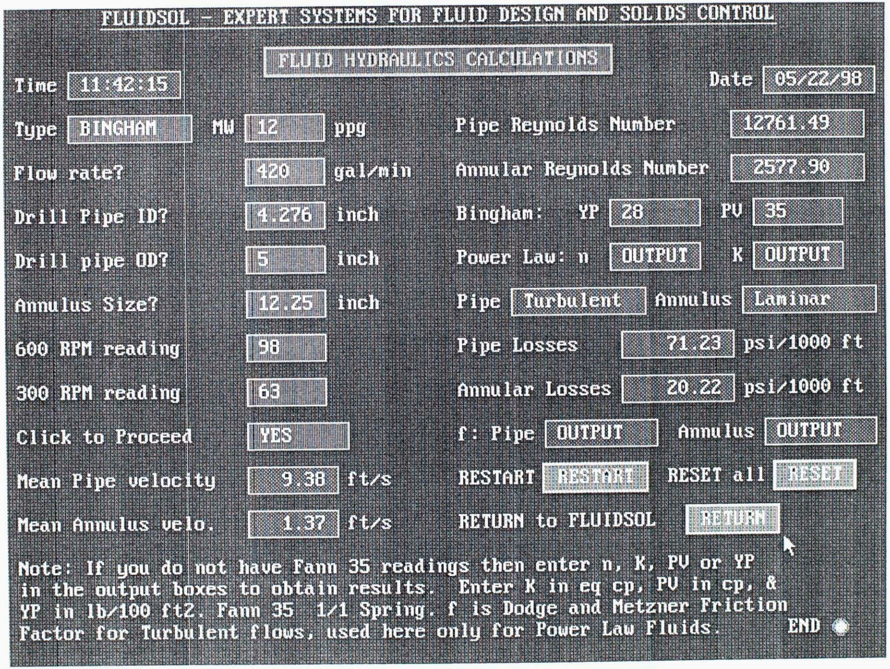


Figure 4.6 : Input for Example Problem in Fluid Hydraulics Calculations - Bingham Plastic Fluid.

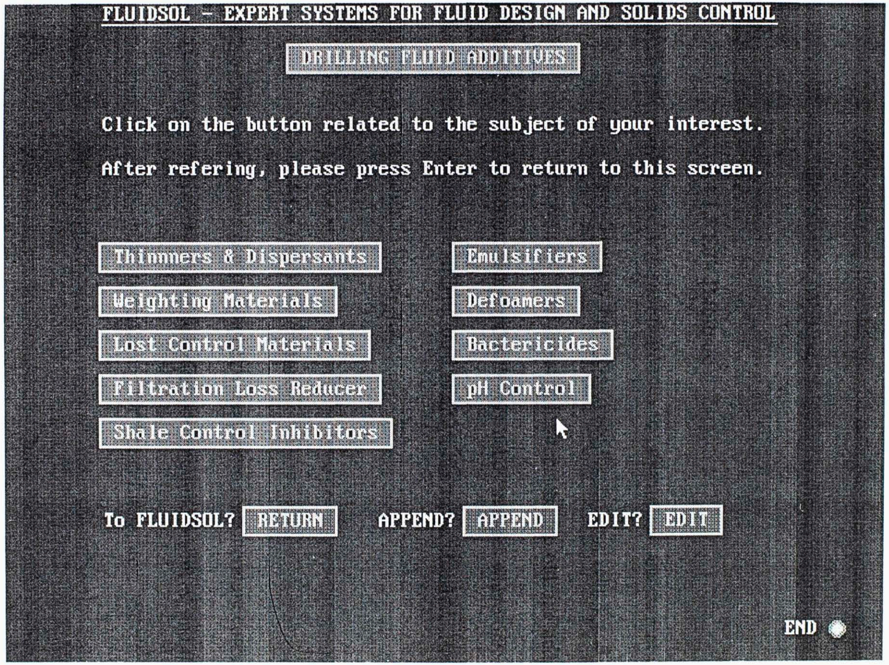


Figure 4.7 : Interface for Drilling Fluids Additives with Append and Edit Facilities.

not overwritten. This option does not require a mouse facility. Once the new values are entered and the accept command issued, the program starts a non-stop display of all the existing data and continues doing so once the latest values are displayed. This helps in confirming that the entered data has been successfully stored in the database file. The interface for "Append Database" is shown in Figure 4.8.

4.4.1.5 Edit Database

This option permits the user to edit the current entries or information on the data base. The user first gets to see the existing values, and then on a prompt he can assign a new value. The latest value replaces the old one and is stored in the same cell as the previous. This option is very handy in cases where only selective information regarding a particular drilling fluid additive has to be changed. The interface for "Edit Database" is shown in Figure 4.9.

4.4.1.6 Read Literature

This option helps the user to read literature concerning drilling fluid additives, new concepts in drilling fluids, drilling fluid practices, and fluids for geothermal wells. Figure 4.10 shows the interface for "Read Literature". Several terms frequently used in drilling fluid industry are incorporated under special section called as "Quick-view". Figure 4.11 shows a typical interface for "Quick view" facility where the user can click on any one of the high lighted buttons to read the definition of that term. The button on the lower right is the 'exit' button which takes the program out of 'hypertext' mode and makes it ready for another round of execution.

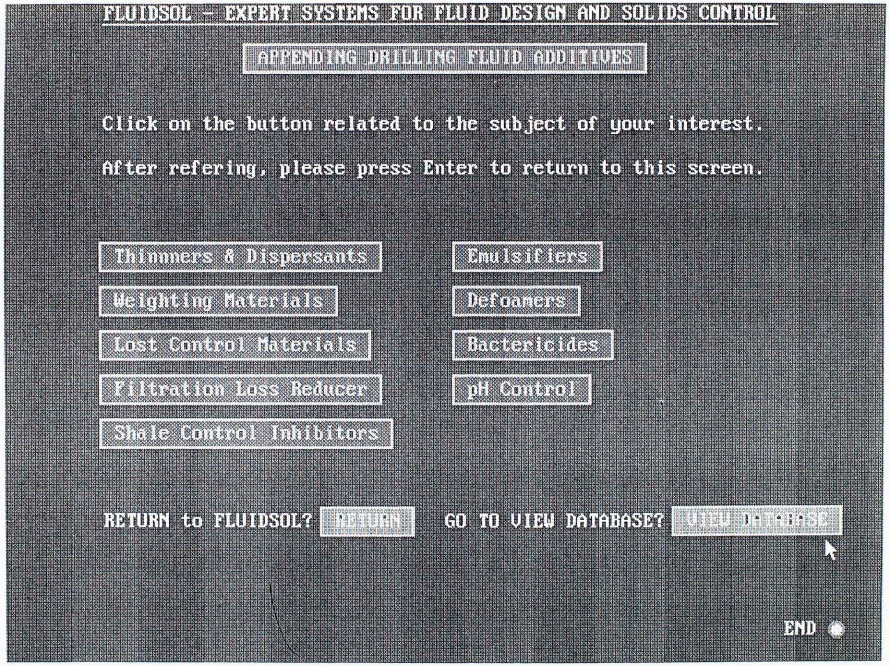


Figure 4.8 : Interface for Append Database for Drilling Fluid Additives.

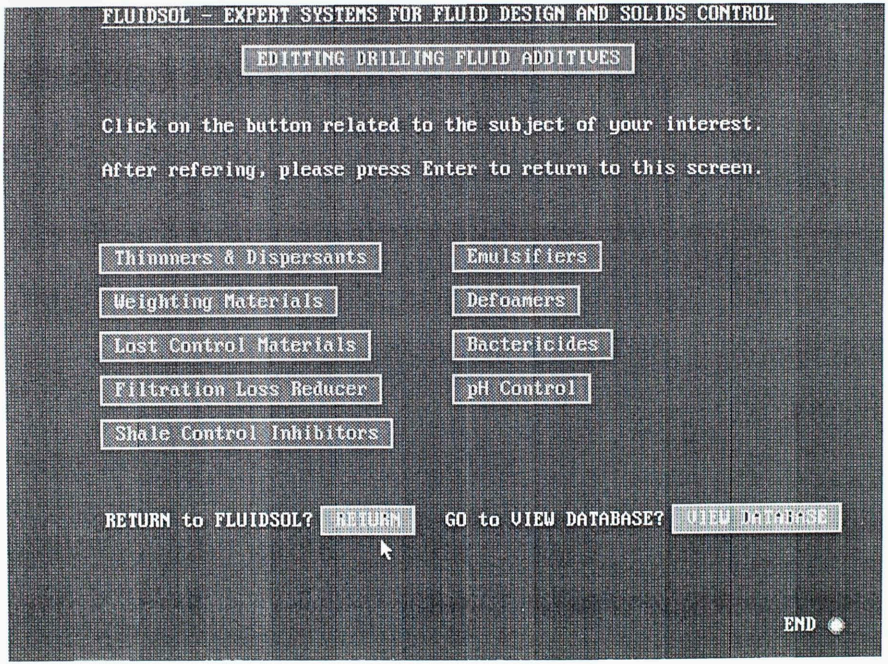


Figure 4.9 : Interface for Edit Database for Drilling Fluid Additives.

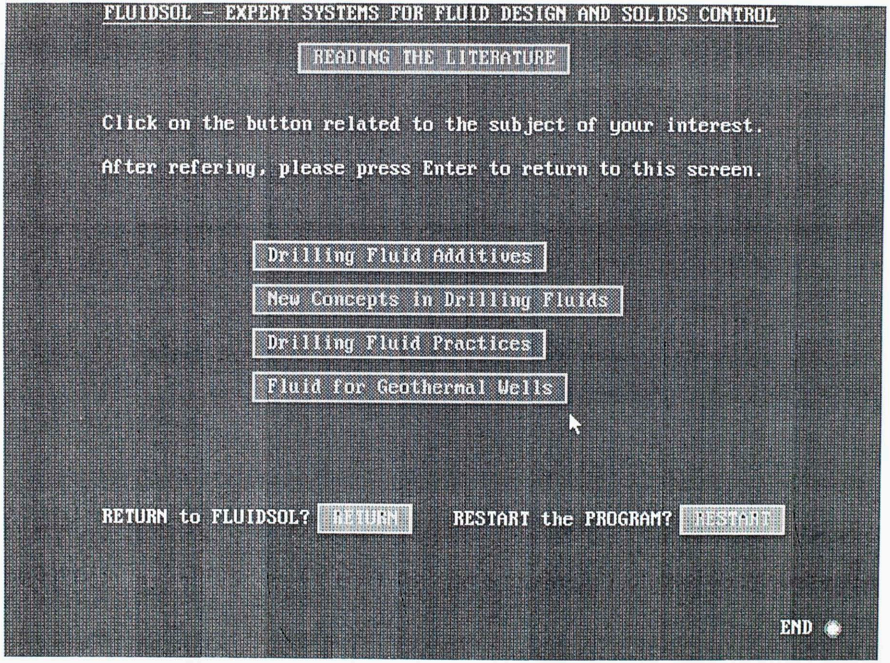


Figure 4.10 : Interface for “Read Literature”.

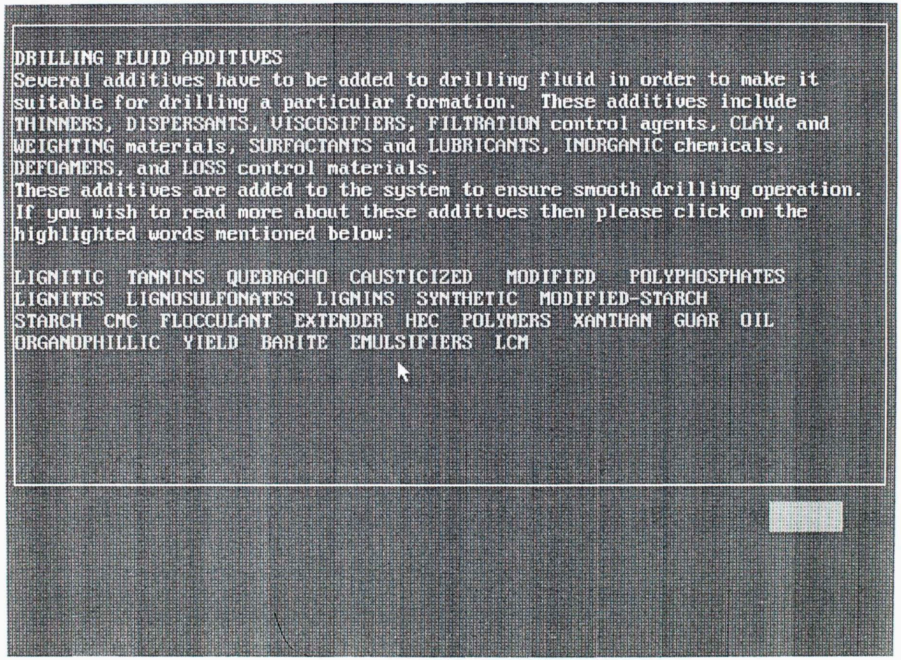


Figure 4.11: Example of a Typical Interface for "Quick-View" Facility.

4.4.1.7 States Database

The fluids design module, discussed in section 4.4.1.1 provides the user with the types of drilling fluids that can be used to drill a particular lithology. In the 'states database' module a database file summarizing drilling fluid practices in various states/regions, like Texas, Oklahoma, Kansas, California, Pacific Coast, and Rocky Mountains has been created. If the region of interest falls in the domain of the current database, the user can compare the drilling fluid obtained at the end of consultation with the drilling fluid practices prevalent in that area.

The data in this database file is based on the publication[20] that dates back to 1969. Hence, a provision to update the data has been provided in the form of edit and append options. New records can be appended to the current file and in some cases existing information can be replaced by the latest. Figure 4.12 shows the interface for States Database.

4.4.1.8 Field Experience

The first interface that the user comes across after selecting this option, prompts him to either fill up the experience form, view experience files, or 'trouble-shoot' various drilling fluid related problems. The "fill-up the experience form" option used the 'smart-form' ability of the expert system. The user can make notes related to drilling fluid design and store them on a file for future reference. Records input by the user do not delete the previous ones , instead they get appended to the file. The view file option enables the user to view such previously posted experiences. Figure 4.13 shows the interface for field experience.

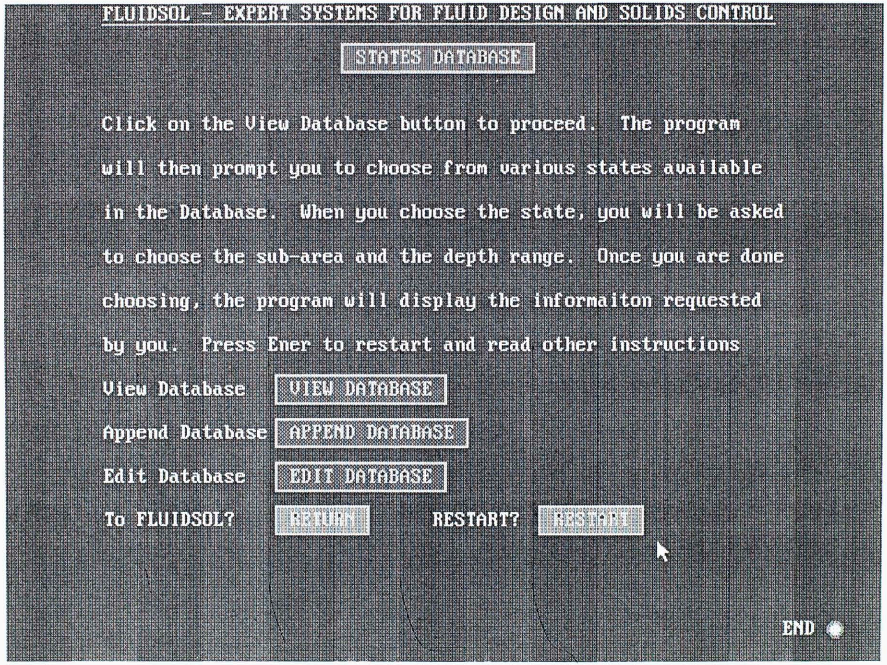


Figure 4.12 : Interface for States Database.

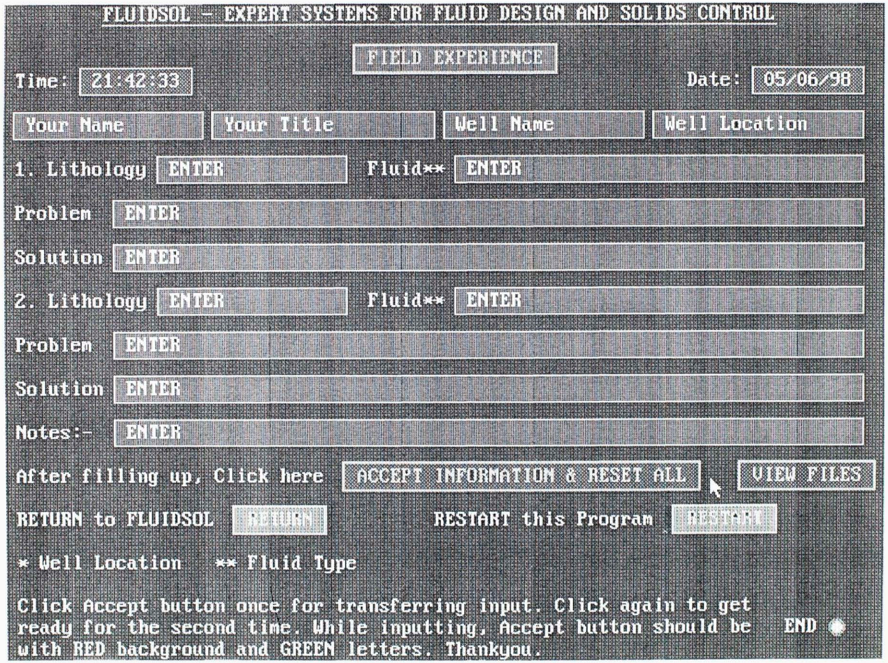


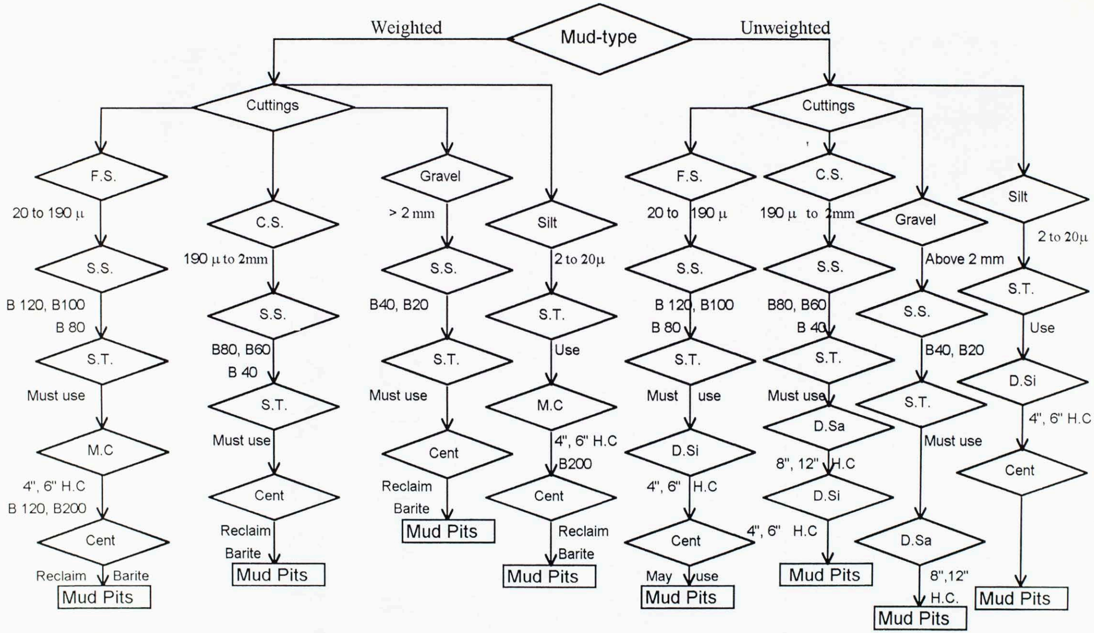
Figure 4.13 : Interface for Field Experience.

4.4.1.9 Solids Control

Presented in the form of a module that can be accessed from the nucleus of **©FLUIDSOL**, solids control in itself is a collection of several programs that enable the users to carry out equipment consultation, calculations, literature review, and enter their experience. The last three options are in many ways similar to the ones created for fluid design, whereas the first is based on the knowledge acquired after literature survey.

Selection procedure of solids control equipment becomes more simplified once it is known whether the drilling fluid system is weighted or unweighted, because it helps in identifying the primary equipment. In **©FLUIDSOL**, any mud that contains barite as a weighting material is considered to be weighted. Primary selection of equipment is based on the cuttings type obtained at the surface. Four cuttings type namely gravel, coarse sand, fine sand, and silt are included in the program. Other relevant information required by the system includes mud returns rate, return mud density, viscosity, and yield point, if the return mud is gas-cut, type of contaminant (if any), and hydrocyclone slurry ejection rate. For weighted muds, cation exchange capacity for drilling muds, bentonite and drilled solids is also required. To decide the number of hydrocyclones that should be used, the rig centrifugal feeder pump rate is needed. Two example problems, one for weighted and other for unweighted mud, are provided under section 4.7. The knowledge base used for this is provided in Appendix F. Further, Figure 4.14 shows the selection procedure adopted by the program in selection of solids control equipment.

Figure 4.15 shows the interface for solids control consultation and Figure 4.16 shows one of the several interfaces created for carrying out calculations related to solids



Legend:

S.S : Shale Shaker	Cent : Centrifuge	H.C. : Hydrocyclone	C.S. : Coarse Sand
S.T : Sand Trap	D.Si : Desilter	B# : U.S. mesh size	μ : microns
M.C : Mud Cleaner	D.Sa: Desander	F.S : Fine Sand	mm : millimeters

Figure 4.14 : Solids Control Equipment selection for Weighted and Unweighted muds.

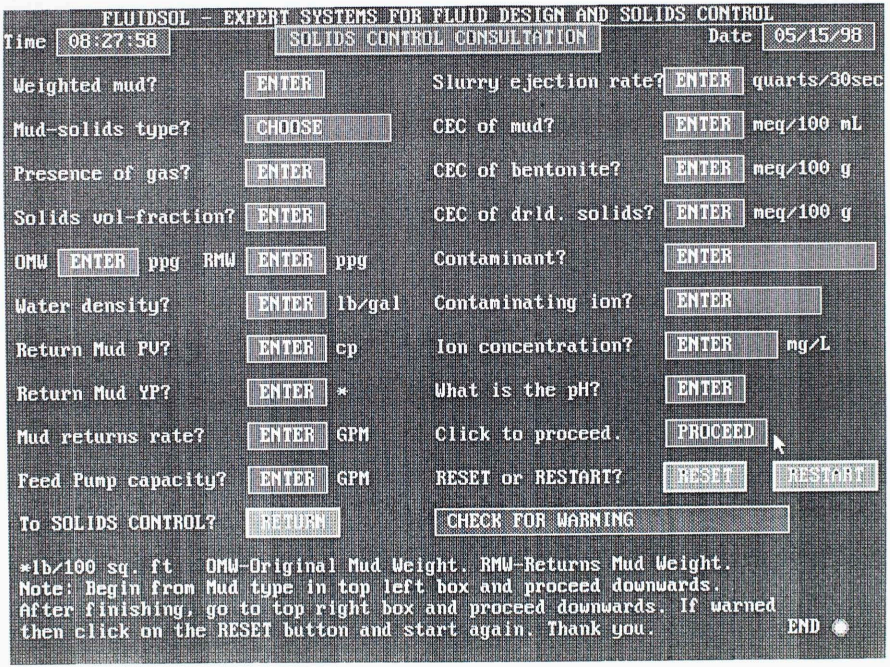


Figure 4.15 : Interface for Solids Control Consultation.

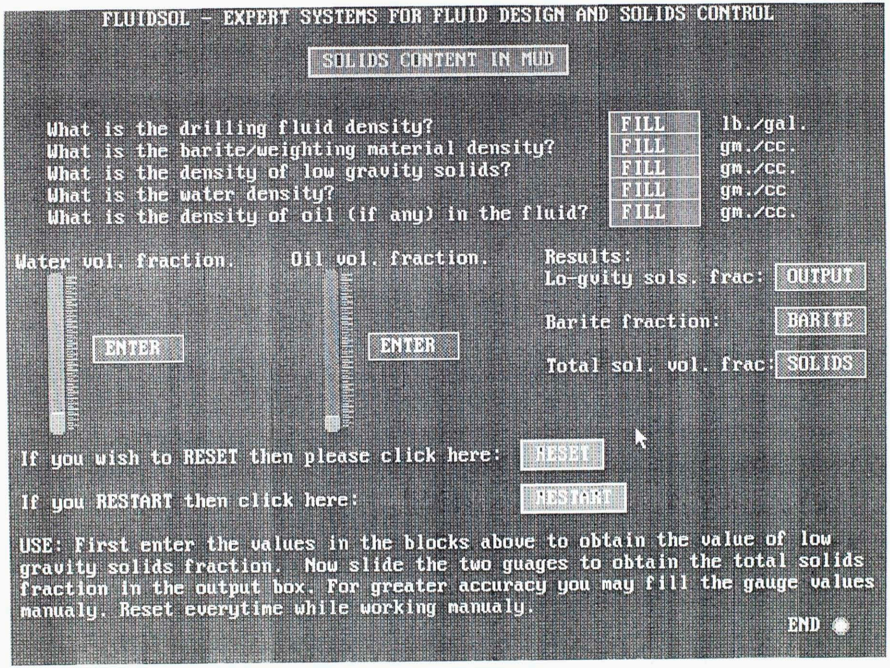


Figure 4.16 : One of the Solids Control Calculation Interfaces.

control. The vertical gauges shown in this figure are the "dynamic calculators" that allow the user to vary the input by just dragging the mouse on the level on the gauges, and obtaining subsequent outputs without actually having to input them using the keys.

4.5 Program Layout

A total of nine main modules comprising sixty-six programs or knowledge base files are incorporated in **©FLUIDSOL**. All the main modules are linked to the main program fluidsol.kbs, and in some cases the modules are interconnected. Although it is possible to link all the modules together, this was deliberately not done to avoid confusion in the mind of the user. In the present set up the user can go from one module over to the other by first returning to 'fluidsol' and then opting for a new module. If the user is using one of the modules of solids control option, then he must return to solids control main program to reach over to 'fluidsol'. At all the times however, the program header on each one of the interfaces will inform the user of the module he is in. Figure 4.17 and Figure 4.18 show the program layouts.

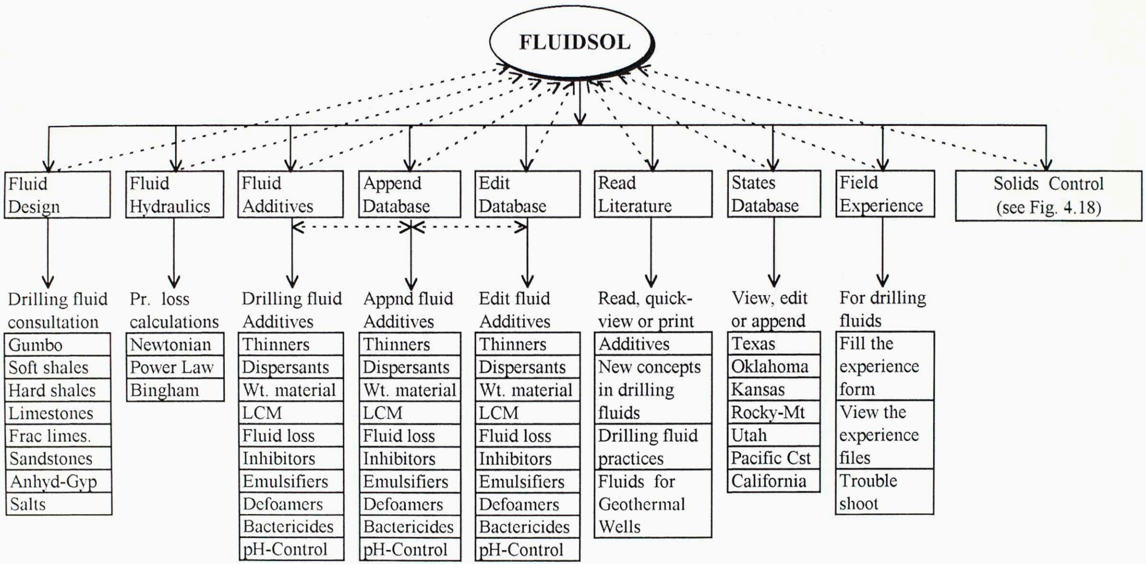


Figure 4.17 : Program Layout of FLUIDSOL for Drilling Fluid Selection.

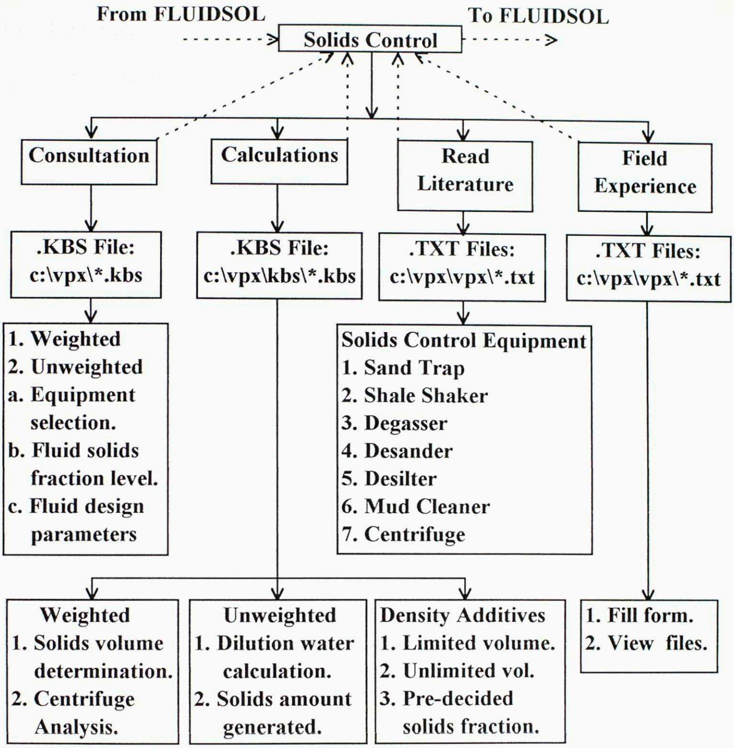


Figure 4.18 : Program Layout for Solids Control Equipment.

4.6 Example Problem for Drilling Fluids Design

©**FLUIDSOL**, developed at the end of the study can provide solutions to real time field situations. The capability of the program to select a particular fluid-type for a given situation was tested using the following case study. Table 4.2 provides the details of a particular well to be drilled. Proper drilling fluid for same has to be selected. The summary of the consultation is given in Table 4.3 and the solution, based on the confidence numbers and the engineering judgement of the user, is provided in Table 4.4. Computer printouts of the outputs from consultation are presented in Tables 4.5 to 4.7. Inputs to the system are provided at the end of each consultation.

Table 4.2 : Data for Example Problem for Drilling Fluid Selection and Design

Available Data:

Well Type: Development **Well Location: Offshore**

Target Depth: 12427 feet **True Vertical Depth: 12427 feet**

Vertical Well

Expected Lithology	Zone Depth, ft	TVD feet	Bit Size, inches	Max Temp.	Expected Press. psi	Remarks
Gumbo Shales	0 to 2100	1950	17.5	70 °F	920	Mud-making Bit balling
Salt Zone	2100 to 3500	3450	17.5	120 °F	1628	Hole washouts Salt water Flow
Anhydrite-Gypsum	3500 to 4725	4700	12.25	160 °F	2220	Hole washouts Salt water Flow
Soft Shales	4725 to 7375	7350	12.25	210 °F	3470	Problem Shales Hole Washouts
Hard Shales	7375 to 9125	9107	12.25	275 °F	4312	Slow ROP Bit bouncing
Limestone	9125 to 10310	10300	8.5	325 °F	5231	Pipe Sticking Lost Circulation
Sandstone	10310 to 12427	12407	8.5	350°F	7350	Pipe Sticking Unconsolidated

Table 4.3 : Summary of Consultation for the Example Problem for Drilling Fluids Selection and Design

Lithology	Zone Depth, ft	Max Temp.	Min. M.W.	Max. M.W.	Recommended D.F. Types	CNF
Gumbo Shales	0 to 2100	70 °F	9.37 ppg	18.65 ppg	1. Low Solids Muds 2. Spud Muds 3. Natural Muds, 4. NaCl Polymer	85 90 80 75
Salt Zone	2100 to 3500	120 °F	9.37 ppg	10.13 ppg	1. Saturated Salt Water 2. Sea Water Muds	85 88
Anhydrite-Gypsum	3500 to 4725	160 °F	9.38 ppg	12.27 ppg	1. Lime Muds 2. Saturated Salt Water	75 85
Soft Shales	4725 to 7375	210 °F	9.37 ppg	11.04 ppg	1. Low Solids Bent-Ex 2. KCl-Polymer Muds 3. Gyp-Lignosulfonate 4. Low Solids Muds 5. CL-CLS Systems	81 90 86 88 85
Hard Shales	7375 to 9125	275 °F	9.40 ppg	11.49 ppg	1. Low Solids Bent-Ex 2. KCl-Polymer Muds 3. Low Solids Muds	83 91 92
Limestone	9125 to 10310	325 °F	10.06 ppg	11.98 ppg	1. Low Solids Bent-Ex 2. Lignite Surfactant	90 86
Sandstone	10310 to 12427	350°F	11.69 ppg	13.81 ppg	1. KCl Polymer Muds 2. Invert Oil Emulsions	87 82

Legend:

Min. M.W.	: Minimum Mud Weight
Max. M.W.	: Maximum Mud Weight
CNF	: Confidence Numbers
ppg	: pounds per gallon (lbm/gal)
D.F.	: Drilling Fluids
KCl	: Potassium Chloride
CL-CLS	: Chrome Lignite-Chrome Lignosulfonate
NaCl	: Sodium Chloride
Low Solids Bent-Ex	: Low Solids Bentonite-Extender.

Table 4.4 : Solution of Example Problem for Drilling Fluid Selection and Design

Lithology	Min. M.W	PV cp.	YP lbf/100 ft^2	Recommended Drilling Fluid	Remarks
Gumbo Shales	9.37 ppg	8.46	15.5	Spud Muds	Gumbo is mud making type.
Salt Zone	9.37 ppg	8.46	15.5	Saturated Salt Water	Add Salt to Fresh or Sea Water.
Anhydrite-Gypsum	9.38 ppg	8.47	15.5	Saturated Salt Water	Continue with same mud as above.
Soft Shales	9.37 ppg	8.47	15.5	KCl-Polymer Muds	KCl for inhibition.
Hard Shales	9.40 ppg	85	15.48	KCl-Polymer Muds	Continue with same mud as above.
Limestone	10.06 ppg	9.72	14.46	Low Solids Bentonite Extender	Store KCl-polymer and prepare limited volume of Low Solids Bentonite Extender.
Sandstone	11.69 ppg	14.6	12.41	KCl-Polymer Muds	Reuse KCl-Polymer as sands are undifferentiated with shales.

Legend:

Min. M.W. : Minimum recommended mud weight.

PV : Mean recommended value of Plastic Viscosity for water base muds.

YP : Mean recommended value of Yield Point for water base muds.

ppg : pounds per gallon (lbm/gal.)

KCl : Potassium Chloride.

Table 4.5 : Results of Consultation for Gumbo Shales - Surface to 2100 feet.

RESULT OF CONSULTATION FOR GUMBO SHALES

The well-type is Development hence designing the fluid is not very difficult. Data obtained from the experience in the area can be of great help.

1. LITHOLOGY CHARACTERISTICS:
Fluid design for Gumbo Shales is requested. Gumbo shales are usually characterized by:
1. Predominantly sodium montmorillonite
2. High water content
3. Yielding plastically when loaded.
The main concerns while drilling Gumbo shales are drill bit balling, prevention of clay hydration, and prevention of overloading of solids control equipment.

2. FLUID TYPE SELECTION:
Gumbo shales can be drilled using Low solids muds, Spud muds, Natural muds, NaCl polymer systems.
For current situation use either of
a. Low solids muds, 85
b. Spud muds, 90
c. Natural muds, 80 or
d. NaCl Polymer muds 75.
Fluid with highest confidence number should be used.

3. DRILLING FLUID - TYPE & BASIC FORMULATION:

a. Low solids muds
Formulate this mud by adding
1. 5% by volume of diesel oil,
2. 0.03% by volume of polyoxyethylene sorbitan tall-oil ester, and
3. 10% by volume of hydrolyzed polyacrylamide co-polymer to 624.62 bbls of fresh water.

b. Spud muds
Formulate this mud by adding
1. 20 lb per bbl of bentonite,
2. 1 lb per bbl of Lime,
3. 2 lb per bbl of soda-ash to 624.62 bbls of water.

c. Natural muds
Formulate this mud by adding
1. 10 to 15 bbl per bbl of bentonite to 624.62 bbls of fresh water.

d. NaCl Polymer muds
Formulate this mud by adding
1. 90 lb per bbl of sodium chloride,
2. 0.035% by volume of potassium chloride, and
3. 1 lb per bbl of Xanthan gum to 624.62 bbls of fresh water.

4. DRILLING FLUID PARAMETERS:
A. Based upon your formation pressure it is advised that you keep your mud weight at least 9.37 ppg and not more than 18.65 ppg. The fracture pressure based upon overburden of 0.97 psi/ft and Poisson's ratio of 0.5 for Gumbo Shales is 1891.5 psi. For fresh-water use mud of 9.37 ppg. The upper and the lower limits of Yield point are 2.46 and 28.59 lb/100 sq. ft.
The Plastic viscosity should vary between 4.24 to 12.68 cp.
B. Low solids muds:
Following the recommendations from section above we obtain a maximum mud mud weight of 8.75 ppg. Since this value is less you should increase the weight.

C. Spud muds:
Following the recommendations from section above we obtain a maximum mud mud weight of 8.88 ppg. Since this value is less you should increase the weight.
D. Natural muds:
Following the recommendations from section above we obtain a maximum mud mud weight of 10.50 ppg. Since this value is more you should keep it below maximum mud weight.
E. NaCl Polymer muds:
Following the recommendations from section above we obtain a maximum mud mud weight of 8.69 ppg. Since this value is less you should increase the weight.

Table 4.5 (cont'd...)

```
6. SOLIDS CONTROL EQUIPMENT:
   For Gumbo shales use Shale shaker screens of B20 or B20 type. Control the
   drilling rate. Location of the site is Offshore hence
   dump unobjectionable parts & ship the remaining solids for onland burial.
   For density control calculations choose Solids Control option in main menu.

7. YOUR INPUT:
   1. Type of well: Development.
   2. Well Location: Offshore.
   3. Depth of the Well: 2100 feet.
   4. True Vertical Depth: 1950 feet.
   5. Bit size : 17.5 inches.
   6. Type of water available: Both Fresh & Sea water.
   7. NaCl available: YES.
   8. Polymer available: YES.
   9. Diesel available: YES.
   10.Type of clay available: Wyoming bentonite.
   11.Bottomhole temperature: 70 deg Farenheit.
   12.Pore pressure: 920 psi.
   13.Expected problems:-
      a. Bit balling: YES.
      b. Overflowing channels: YES.
      c. High viscosity returns: NO.
      d. High pressure gas: YES.

  This program was last used on 05/18/98 at 12:00:17 hours.
```

Table 4.6 : Results of Consultation for Soft Shales - 4725 to 7375 feet.

```
RESULT OF CONSULTATION FOR SOFT SHALES

The well-type is Development hence designing the fluid is not very difficult.
Data obtained from the experience in the area can be of great help.
1. LITHOLOGY CHARACTERISTICS:
Fluid design for Soft Shales is requested.  Soft shales are usually
characterized by:
1. Clayey formations,
2. Unconsolidated formations, and.
3. Sloughing, swelling and caving of shales on hydration.
Main concerns while drilling soft shales are maintaining low annular
velocities, preventing excessive drill-string vibrations, preventing bit
balling, and fluid loss control.

2. FLUID TYPE SELECTION:
Soft shales can be drilled using Low Solids Bentonite Extender, KCl-polymer
systems, Lime muds, Gyp-Lignosulfonate muds, Oil base muds, Low solids
muds, Invert Oil emulsions, and CL-CLS systems.
For current situation use either of
a. Low solids Bentonite Extender, 81
b. KCl Polymer muds, 91     .
c. ,
d. Gyp-Lignosulfonate muds, 86
e. ,
f. Low solids muds, 88
g. ,  or
h. CL-CLS Systems, 85.
Use the fluids with maximum confidence number or in that order.

3. DRILLING FLUID - TYPE & BASIC FORMULATION:
a. Low solids Bentonite Extender
Formulate this mud by adding
1. 3% by weight of bentonite,
2. 0.01% by weight of XC-polymer or PHPA or cellulose,and
3. 0.05% by weight of soda ash in 1074.8 bbls
   of fresh water.

b. KCl Polymer muds
Formulate this mud by adding
1. 15 lb per bbl of potassium chloride, and
2. 0.5 lb per bbl of polyacrylamide polyacrylate copolymer, to 1074.8 bbls
   of  water.

c.
Formulate this mud by adding
1.  of ,
2.  of  ,and
3.  of  to 1074.8 bbls
   of fresh water.

d. Gyp-Lignosulfonate muds
Formulate this mud by adding
1. 8 lb per bbl of gypsum,
2. 1 lb per bbl of sodium Chromate ,and
3. 0.05% by volume of diesel to 1074.8 bbls
   of fresh water.

e.
Formulate this mud by adding
1.  of ,
2.  of , and
3.  of  to 1074.8 bbls
   of fresh water.

f. Low solids muds
Formulate this mud by adding
1. 5% by volume of diesel oil,
2. 0.03% by volume of polyoxyethylene sorbitan tall-oil ester ,and
3. 10% by volume of hydrolyzed polyacrylamide co-polymer to 1074.8 bbls
   of fresh water.
```

Table 4.6 (cont'd...)

```
g.
Formulate this mud by adding
1.  of ,
2.  of , and
3.  of  to 1074.8 bbls of fresh water.

h. CL-CLS Systems
Formulate this mud by adding
1. 20 lb per bbl of wyoming bentonite,
2. 1.5 lb per bbl of caustic soda ,and
3. 10 lb per bbl of chrome lignite to 1074.8 bbls of fresh water.

4. DRILLING FLUID PARAMETERS:
A. Based upon your formation pressure it is advised that you keep your mud
   weight at least  9.37 ppg and not more than 11.04 ppg. The fracture
   pressure based upon overburden of 0.97 psi/ft  and Poisson's ratio of 0.17
   for Soft Shales is 4219.5 psi. For fresh-water use mud of 9.37 ppg.
   The upper and the lower limits of Yield point are   2.46 and
    28.59 lb/100 sq. ft.
   The Plastic viscosity should vary between   4.24 to  12.68 cp.

B. Low solids Bentonite Extender:
   Following the recommendations from section above we obtain a maximum mud
   mud weight of  8.36 ppg.  Since this value is less you should
   increase the weight.
   For temperatures of less  than 250 deg F use   5374 lbm
   chrome lignosulfonate  as thinner for 1074.8 bbls mud.
   Use 107.48 lbm  vinylacetate maelicacid copolymer as viscosifier
   for 1074.8 bbls of mud.
C. KCl Polymer muds:
   Following the recommendations from section above we obtain a maximum mud
   mud weight of  8.70 ppg.  Since this value is less you should
   increase the weight. Weight can be increased by adding KCl.
   For temperatures of less than 250 deg F use 4836.6 lbm
   lignosulfonates as thinner
   for 1074.8 bbls mud.
D. :
   Following the recommendations from section above we obtain a maximum mud
   mud weight of  ppg.  Since this value is  you should
   .
   For temperatures  than 200 deg F use  lbm
   as  for 1074.8 bbls mud or use   lbm
    as .
E. Gyp-Lignosulfonate muds:
   Following the recommendations from section above we obtain a maximum mud
   mud weight of  8.55 ppg.  Since this value is less you should
   increase the weight.
   For temperatures more than 200 deg F use   2687 lbm lignites as
   thinner for 1074.8 bbls mud or use    5374 lbm
   carboxymethyl cellulose as filtration control agent.
F. :
   Following the recommendations from section above we obtain a maximum mud
   mud weight of  ppg.  Since this value is  you should
   .
   Mud weight can be increased by adding calcium carbonate or barite.
G. Low solids muds:
   Following the recommendations from section above we obtain a maximum mud
   mud weight of  8.75 ppg.  Since this value is less you should
   increase the weight.  Addition of barite will make the
   system 'non-dispersed'.

H. :
   Following the recommendations from section above we obtain a maximum mud
   mud weight of  ppg.  Since this value is  you should
   . Mud weight can be changed by
   varying amounts of organophilic clays in the mud.
   .
```

Table 4.6 (cont'd...)

```
I. CL-CLS Systems:
   Following the recommendations from section above we obtain a maximum mud
   mud weight of  8.61 ppg.  Since this value is less you should
   increase the weight.
   Mud weight can be changed by varying amounts of bentonite or barite.
   For temperatures less  than 250 deg F use  53.74 lbm
   chrome lignosulfonate as filtration control agent for
   1074.8 bbls mud.

5. NOTES ON EXPECTED PROBLEMS:
   1. You mentioned that troublesome shales problem exists.
      Use inhibited mud system and reduce drill-string vibrations.
   2. You mentioned that differential sticking problem exists.
      Reduce the mud weight and oil-spot if necessary.
   3. You mentioned that hole washout problem exists.
      Reduce annular velocity and control fluid loss.
   4. You mentioned that loss ciruclation problem does not exist.
      .
   5. You mentioned that salt water flow problem does not exist.
      .
   6. You mentioned that fresh water flow problem does not exist.
      .
   7. You mentioned that high pressure gas problem does not exist.
      .

6. SOLIDS CONTROL EQUIPMENT:
   For Soft Shales use Shale shaker screens of B40, B60 or B80 type.
   Use desilter and desander for unweighted system and mudcleaner and
   centrifuge for weighted system. Location of site is Offshore hence
   dump unobjectionable parts & ship the remaining solids for onland burial.

7. YOUR INPUT:
   1. Type of well: Development.
   2. Well Location: Offshore.
   3. Depth of the Well: 7375 feet.
   4. True Vertical Depth: 7350 feet.
   5. Bit size : 12.25 inches.
   6. Type of water available: Both Fresh & Sea water.
   7. KCl available: YES.
   8. Polymer available: YES.
   9. Diesel available: YES.
   10.Lime available: NO.
   11.Gypsum available: YES.
   12.Type of clay available: Wyoming bentonite.
   13.Bottomhole temperature: 210 deg Farenheit.
   14.Pore pressure: 3470 psi.
   15.Are oil base muds OK: Not Ok.
   16.Type of Shales: Illitic.

   17.Expected problems:-
      a. Troublesome Shales: YES.
      b. Differential Sticking: YES.
      c. Hole Washouts: YES.
      d. Loss Circulation: NO.
      e. Sea Water Flow: NO.
      f. Fresh Water Flow: NO.
      g. High Pressure Gas: NO.

    This program was last consulted on 05/18/98 at 12:43:17 hours.
```

Table 4.7 : Result of Consultation for Hard Shales - 7375 to 9125 feet.

```
RESULT OF CONSULTATION FOR HARD SHALES

The well-type is Development hence designing the fluid is not very difficult.
Data obtained from the experience in the area can be of great help.
1. LITHOLOGY CHARACTERISTICS:
Fluid design for hard shales is requested.  Hard shales are usually
characterized by:
1. Compact formations, and
2. Less of mechanical failure.
Main concerns while drilling hard shales are maintaining low solids
content, prevention of clay hydration, and control of filtration fluid
losses.

2. FLUID TYPE SELECTION:
Hard shales can be drilled using Low Solids Bentonite Extender, KCl-polymer
systems, Lime muds, Gyp-Lignosulfonate muds, oil base muds and Low solids
muds.

For current situation use either of
a. Low solids Bentonite Extender, 83
b. KCl Polymer muds, 90
c. ,
d. ,
e. ,  or
f. Low solids muds  92.
Use the mud with highest confidence number or in that order.

3. DRILLING FLUID - TYPE & BASIC FORMULATION:
a. Low solids Bentonite Extender
Formulate this mud by adding
1. 3% by weight of bentonite,
2. 0.01% by weight of XC-polymer or PHPA or cellulose,and
3. 0.05% by weight of soda ash in 1337.2 bbls of fresh water.

b. KCl Polymer muds
Formulate this mud by adding
1. 90 lb per bbl of potassium chloride, and
2. 0.2 lb per bbl of Xanthan gum, to 1337.2 bbls of  water.

c.
Formulate this mud by adding
1.  of ,
2.  of  ,and
3.  of  to 1337.2 bbls
   of fresh water.

d.
Formulate this mud by adding
1.  of ,
2.  of  ,and
3.  of  to 1337.2 bbls
   of fresh water.

e.
Formulate this mud by adding
1.  of ,
2.  of , and
3.  of  to 1337.2 bbls
   of fresh water.

f. Low solids muds
Formulate this mud by adding
1.  of ,
2. 5% by volume of diesel oil, and
3. 0.03% by volume of tall oil ester to 1337.2 bbls
   of fresh water.
```

Table 4.7 (cont'd...)

```
4. DRILLING FLUID PARAMETERS:
A. Based upon your formation pressure it is advised that you keep your mud
   weight at least  9.40 ppg and not more than 11.49 ppg. The fracture
   pressure based upon overburden of 0.97 psi/ft  and Poisson's ratio of 0.2
   for Hard shales is 5442.4 psi. For fresh-water use mud of
    9.40 ppg. The upper and the lower limits of Yield point are
     2.48 and  28.48 lb/100 sq. ft.
   The Plastic viscosity should vary between   4.24 to  12.76 cp.

B. Low solids Bentonite Extender:
   Following the recommendations from section above we obtain a maximum mud
   mud weight of  8.36 ppg.  Since this value is less you should
   increase the weight.
   For temperatures of more  than 250 deg F use   6686 lbm
   lignite or sodium lignosulfonate as thinner for 1337.2 bbls mud.
   Use 133.72 lbm vinylacetate maelicacid copolymer as viscosifier for
   1337.2 bbls of mud.
C. KCl Polymer muds:
   Following the recommendations from section above we obtain a maximum mud
   mud weight of 10.48 ppg.  Since this value is more you should
   keep it below maximum mud weight.
   For temperatures of more than 250 deg F use 6017.4 lbm
   lignite as thinner  for 1337.2 bbls mud.

D. :
   Following the recommendations from section above we obtain a maximum mud
   mud weight of  ppg.  Since this value is  you should
   .
   For temperatures  than 200 deg F use  lbm
     for 1337.2 bbls mud or
   use   lbm  as
   .
E. :
   Following the recommendations from section above we obtain a maximum mud
   mud weight of  ppg.  Since this value is  you should
   .
   For temperatures  than 200 deg F use  lbm
    as  for 1337.2 bbls mud or
   use   lbm  as .

F. :
   Following the recommendations from section above we obtain a maximum mud
   mud weight of  ppg.  Since this value is  you should
   .
   Density can be increased by adding calcium carbonate or barite.
G. Low solids muds:
   Following the recommendations from section above we obtain a maximum mud
   mud weight of  9.58 ppg.  Since this value is more you should
   keep it below maximum mud weight.
   If barite is added
5. NOTES ON EXPECTED PROBLEMS:
   1. You mentioned that troublesome shales problem does not exist.
      .
   2. You mentioned that excessive bit bouncing problem exists.
      Increase the yeild point and remove mud solids efficiently.
   3. You mentioned that hole washout problem does not exist.
      .
   4. You mentioned that loss ciruclation problem does not exist.
      .
   5. You mentioned that salt water flow problem does not exist.
      .
   6. You mentioned that fresh water flow problem does not exist.
      .
   7. You mentioned that high pressure gas problem does not exist.
      .
```

Table 4.7 (cont'd...)

```
6. SOLIDS CONTROL EQUIPMENT:
   For Hard Shales use Shale shaker screens of B60, B80 or B100 type.
   Use desilter and desander for unweighted system and mudcleaner and
   centrifuge for weighted system. Location of the site is Offshore hence
   dump unobjectionable parts & ship the remaining solids for onland burial.

7. YOUR INPUT:
   1. Type of well: Development.
   2. Well Location: Offshore.
   3. Depth of the Well: 9175 feet.
   4. True Vertical Depth: 9107 feet.
   5. Bit size : 12.25 inches.
   6. Type of water available: Both Fresh & Sea water.
   7. KCl available: YES.
   8. Polymer available: YES.
   9. Diesel available: YES.
   10.Lime available: NO.
   11.Gypsum available: YES.
   12.Type of clay available: Wyoming bentonite.
   13.Bottomhole temperature: 275 deg Farenheit.
   14.Pore pressure: 4312 psi.
   15.Are oil base muds OK: Not Ok.

   16.Expected problems:-
      a. Troublesome Shales: NO.
      b. Is penetration rate very low: YES.
      c. Hole Washouts: NO.
      d. Loss Circulation: NO.
      e. Sea Water Flow: NO.
      f. Fresh Water Flow: NO.
      g. High Pressure Gas: NO.
```

4.7 Example Problem for Solids Control

©**FLUIDSOL** is also capable of carrying out consultation for solids control equipment. Two cases are presented here: unweighted drilling fluid and weighted drilling fluid. Weighted muds are classified as one having barite as weighting material and unweighted are the ones without barite.

4.7.1 Example Problem for Solids Control of Weighted Drilling Fluid

The filled-out interface shown in Figure 4.19, is the system input. The solution to the problem, obtained at the end of consultation is summarized in Table 4.8. The computer printouts of the outputs from consultation are presented in Table 4.9.

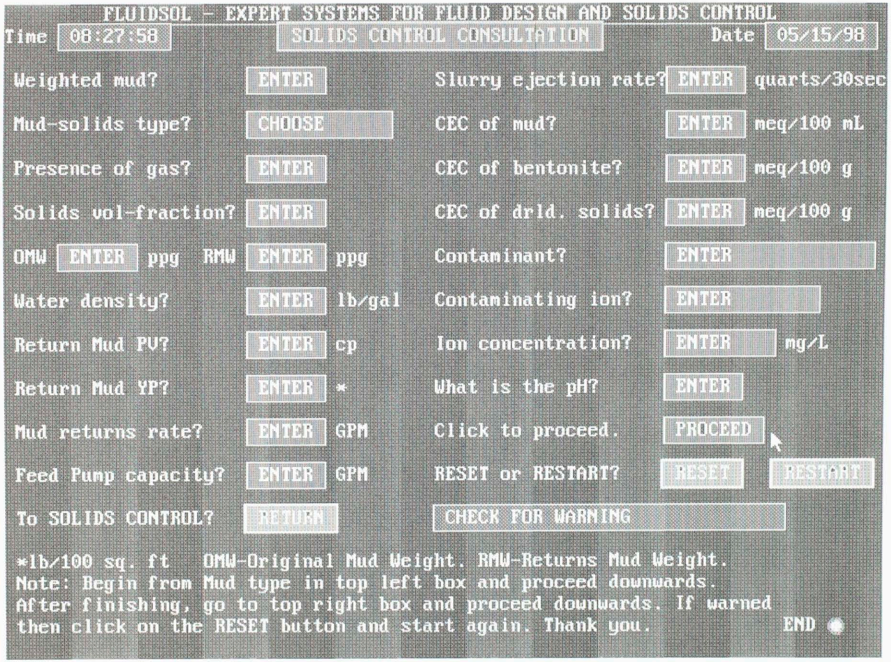


Figure 4.15 : Interface for Solids Control Consultation.

Table 4.8 : Summary of Results - Example Problem of Solids Control of a Weighted Drilling Fluid

Equipment	Use	Specifications	Remarks
Shale Shaker	Must Use	Use mesh sizes, B80, B100 or B120. Else use S50 or S60.	For Brandt Tandem Screen Dual Unit, the allowable flow rates for B80, B100 and B120 are 661.18, 466.26 and 195 gallons per minute for out-coming mud weight of 17 ppg.
Sand Trap	Important		Fine sand settling rate is 0.066 to 5 feet per minute. Dump Trap accordingly.
Degasser	Must		Yield Point is more than 10 lb/100 ft^2 hence degasser is important as Shale Shaker alone cannot remove the gas from the system.
Desander	Do not use	-none	Do not use in weighted systems.
Desilter	Do not use	-none	Do not use in weighted systems.
Mud Cleaner	Must use	B120 B200 mesh 4"-13 nos. H.C. or 6"- 8 nos. H.C.	On the basis of slurry ejection rate, maintain water dilution rate of 16.5 GPM.
Centrifuge	Important		Reclaim barite. Especially important here because viscosity has to be decreased.

Legend:

H.C. : Hydrocyclone
GPM : gallons per minute
B# : US mesh size screens (oblong openings)
S# : US mesh size screens (square openings)

Table 4.9 : Results of Consultation for Solids Control of a Weighted Mud.

```
TIME: 13:36:38 hrs                                          DATE: 05/18/98

                    WEIGHTED SYSTEMS - RESULTS OF CONSULTATION

Since the mud is weighted, barite is assumed to be present in the system.
1. Based on returns mud weight 17 ppg, solids volume fraction 0.45
   and Cation Exchange Capacity values:
   A. Low gravity solids fraction is 0.2494,
   B. Clay fraction is 0.0146,
   C. Drilled solids fraction is 0.2347, and
   D. Barite fraction is 0.2006.
   Recommended range of solids fraction  for water base bentonitic mud of
   13 ppg is from 0.1751 to 0.2325.
2. Amount of bentonite content in the system is  13.34 lbm/bbl.
3. Present viscosity is 26 cp.  For 13 ppg mud the recommended
   range is  11.15 cp to  26.31 cp. The mean of the range is
   18.734 cp. On mean viscosity basis your present viscosity is more.
   You are required to decrease by  at least  7.26 cp.

4. Present Yield Point is 16 lb/100 ft2.  The recommended range
   is   4.20 to  18.25 lb/100 ft2. Decide freely on this one.
5. Contaminant HYDROGEN SULFIDE and contaminating ion SULFIDE is present
   in 100 mg/L amount.  To remove use:
   a. ZINC BASIC CARBONATE in 0.1230 lbm/bbl concentration, or
   b. -none in -none lbm/bbl concentration.

Since the mud is weighted, the best  treatment recommended is screening,
forced Settling, using Mudcleaners, and using Centrifuge.
For FINE SAND the particles size range between 20 and 190 microns.
Hence it is advisable to primarily use Mud Cleaner.

Equipment-wise recommendation:-
1. SHALE-SHAKERS:
   For FINE SAND you may use Shaleshakers.  Use B80 or S50 mesh, B100 or S60
   mesh or B120 mesh with Shaleshakers. Usually the maximum recommended
   flow rates for these mesh sizes for mud weight of 17 ppg are
    661.18 GPM,  466.26 GPM and     195 GPM respectively. (Brandt
   Tandem  Screen Separators - Dual Unit).

2. SAND-TRAP:
   For FINE SAND, Sand Traps are important.  For FINE SAND the
   settling rate of particles is roughly 0.066 to 5 feet per minute in
   68 deg F water. Check the sand-trap for dumping accordingly. Do not
   dump completely however.
3. DEGASSER:
   There is gas in the system, so line up Degasser. The Yield Point
   of the mud is more than 10 lb/100 sq. ft., hence the role of Degasser
   is very important as the  Shale-shaker will not be able to handle the gas
   alone. Degassification is essential before fluid enters hydrocyclones.
4. DESANDER:
   The system is weighted, so using Desander is risky. Since cuttings type
   is FINE SAND you should never use it. If using Desander then
   use -none inch minimum -none nos. or -none inch minimum  -none number
   of Hydrocyclones for 650 GPM of the feeder pump. (Round-off number
   of cyclones to next higher whole number).
5. DESILTER:
   The system is weighted, so avoid using Desilters.

6. MUDCLEANER:
   Return fluid contains FINE SAND, so Use Mudcleaner. Use
   B120 mesh or B200 mesh.   For FINE SAND use 4
   inch or 6 inch Hydrocyclones  and use minimum    13 nos.
   or  7.64 nos. respectively for 650 GPM of the feeder pump
   flow. (Round-off nos. to next whole number). Maintain the dilution water
   flow rate around  16.50 gallons per hour.
```

Table 4.9 (cont'd...)

```
7. CENTRIFUGE:
   Mudtype is weighted, and cutting type is FINE SAND, hence use of
   Centrifuge is very significant. Since you are required to decrease the
   viscosity, use of Centrifuge is essential.
   Reclaim barite from underflow.

NOTE:1. Advisable to agitate the mud in suction tanks of Mudcleaner.
        No agitation in Sand-trap.
     2. If you wish you to carry out calculations regarding Centrifuge
        Analysis please choose Calculations from main option.
     3. If any answer is prefixed by '-none' then that part is not applicable
        for this case.
                              END OF CONSULTATION

                         INPUT TO THE WEIGHTED SYSTEM...
1. Type of the mud is weighted.
2. Type of cuttings in returns FINE SAND.
3. Total solids fraction in the mud 0.45.
4. Original Density of the mud 13 ppg.
5. Density of the Return mud 17 ppg.
6. Density of water 8.33 ppg.
7. Viscosity of Return mud 26 cp.
8. Yield point of Return mud 16 lb/100 sq. ft.
9. The return flow rate is 700 gal/min.
10. Feeder pump flow rate 650 gal/min.
11.Hydrocyclone slurry ejection rate 1 qts./30 secs.
12.Drilled solids type HYDROGEN SULFIDE.
13.Cation Exchange Capacity of mud 9 meq/100 g.
14.Cation Exchange Capacity of bentonite 92 meq/100 g.
15.Cation Exchange Capacity of drilled solids 9 meq/100 g.
16 Drilled solids major content FINE SAND.
17.Major contaminant in mud HYDROGEN SULFIDE.
18.Contaminating ion SULFIDE.
19.Contaminating ion concentration 100 mg/mL.
```

Other results obtained from consultations are:

1. Fine Sands particle size ranges between 20 and 190 microns.
2. Low gravity solids fraction is 0.2494.
3. Clay fraction is 0.0146.
4. Total drilled solids fraction is 0.2347.
5. Barite fraction is 0.2006.
6. Bentonite content in mud is 13.34 lbm/bbl.
7. Present solids fraction is 0.45 while the recommended solids fraction for 13 ppg original mud weight is from 0.1751 to 0.2345 for weighted water base muds.
8. Present viscosity is 26 cp. Recommended range for original mud weight of 13 ppg is 11.15 to 26.31 cp. The mean viscosity is 18.734 cp. and on this basis, it has to be decreased by 7.26 cp.
9. Present yield point is 16 lbf/100 ft^2 while the recommended range of yield point for original 13 ppg mud is 4.2 to 18.25 lbf/100 ft^2.
10. To remove the contaminating ion sulfide, present in concentration of 100 milligram/Liter, maintain pH above 10 and add zinc basic carbonate in concentrations of 0.1230 lbm/ bbl.

4.7.2 Example Problem for Solids Control of Unweighted Drilling Fluid:

The filled-out interface shown in Figure 4.20, is the system input. The solution to the problem, obtained at the end of consultation is summarized in Table 4.10. The computer printouts of the outputs from consultation are presented in Table 4.11.

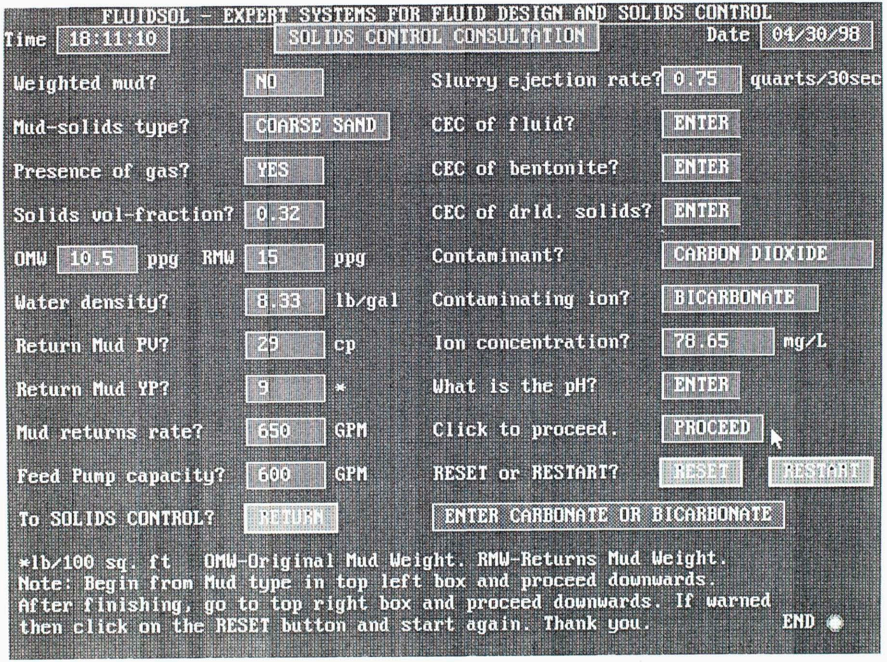


Figure 4.20 : Input for Example Problem in Solids Control for Unweighted Muds.

Table 4.10 : Summary of Results - Example Problem of Solids Control for an Unweighted Drilling Fluid.

Equipment	Use	Specifications	Remarks
Shale Shaker	Must Use	Use mesh sizes, B40, B60 or B80. Else use S30, S40 or S50.	For Brandt Tandem Screen Dual Unit, the allowable flow rates for B40, B60 and B80 are 1166.8, 930 and 763 gallons per minute for out-coming mud weight of 15 ppg.
Sand Trap	Extremely Important		Fine sand settling rate is 5 to 35 feet per minute. Dump Trap accordingly.
Degasser	Must		Yield Point is less than 10 lbf/100 ft^2 hence degasser is less significant as Shale Shaker alone can remove the gas from the system.
Desander	Use	8"-4 nos. H.C or 12"- 2 nos. H.C.	For coarse sand it must be used.
Desilter	Use	4"-12 nos. H.C or 6"- 8 nos. H.C.	May be used for coarse sand. Dilution water rate should be 15.3 GPM.
Mud Cleaner	Don't Use		
Centrifuge	Don't Use		

Legend:

H.C. : Hydrocyclone
GPM : gallons per minute
B# : US mesh size screens (oblong openings)
S# : US mesh size screens (square openings)

Table 4.11 : Results of Consultation for Solids Control of an Unweighted Mud.

```
TIME: 13:54:30 hrs                                                    DATE: 05/18/98

                    UNWEIGHTED SYSTEMS-RESULTS OF CONSULTATION

The mud is unweighted, so no barite is assumed to be present in the system.
1. The returns mud weight is 15 ppg, and solids fraction in the
   fluid is 0.32.  The recommended range of solids fraction for water base
   bentonitic mud of 10.5 ppg is from 0.0814 to 0.1637.
2. Returns mud viscosity is 29 cp. For mud of 10.5 ppg the
   recommended range is  from    5.31 cp to  16.43 cp. The mean of
   the range is 10.878 cp.  Your present viscosity is more.
   You are required to decrease by at least 18.12 cp.
3. Present Yield Point is 9 lb/100 ft2.  The recommended range
   is    3.00 to  24.70 lb/100 ft2. Decide freely on this one.

4. Contaminant CARBON DIOXIDE and contaminating ion BICARBONATE is present
   in 78.65 mg/L amount.  To remove use:
   a. LIME in 0.0333 lbm/bbl concentration, or
   b. -none in -none lbm/bbl concentration.

Since the mud type is unweighted, the usual treatment is screening,
forced settling, chemical flocculation, and dilution.
For COARSE SAND the particles size range between 190 and 1850 microns.
It is advisable to primarily use Shaleshaker & Desilter.
Note the following:
1. SHALE-SHAKERS:
   For COARSE SAND use Shaleshakers.  Use B40 or S30 mesh, B60 or S40
   mesh or B80 or S50 mesh with Shaleshakers. Usually the maximum
   recommended flow rates for these mesh sizes for mud weight of 15 ppg
   are 1166.85 GPM,      930 GPM and      763 GPM respectively.
   Data from Brandt  Tandem  Screen Separators - Dual Unit.

2. SAND-TRAP:
   For COARSE SAND, Sand Traps are extremely important.  For COARSE SAND the
   settling rate of particles is roughly 5 to 35 feet per minute in
   68 deg F water. Check the sand-trap for dumping accordingly. Do not
   dump completely however.

3. DEGASSER:
   There is gas in the system, so line up Degasser. The yieldpoint
   of the mud is less than 10 lb/100 sq. ft., hence the role of Degasser
   is less significant as the  Shale-shaker will be able to handle the gas
   alone. Degassification is essential before fluid enters hydrocyclones.
4. DESANDER:
   The system is unweighted, Desander can be used freely. Since cuttings type
   is COARSE SAND you must use it. If using Desander then
   use 8 inch minimum      4 nos. or 12 inch minimum    1.71 number
   of Hydrocyclones for 600 GPM of the feeder pump. (Round-off number
   of cyclones to next higher whole number).
5. DESILTER:
   The system is unweighted, so Desilters can be used. If cuttings type is
   COARSE SAND then you may use Desilters.  If using them, then use
   4 inch or 6 inch Hydrocyclones  and use minimum     12 nos.

   or   7.05 nos. respectively for 600 GPM of the feeder pump
   flow. (Round-off nos. to next whole number). Maintain the dilution water
   flow rate around  15.30 gallons per hour.
```

Table 4.11 (cont'd...)

```
6. MUDCLEANER:
   Since the system is unweighted, Mud Cleaners may not be used.
7. CENTRIFUGE:
   Mudtype is unweighted, and cutting type is COARSE SAND, hence use of
   Centrifuge is less important.
Note:1. If using Centrifuges then line-up Desanders before them to avoid
        overloading. Centrifuges help in reclaiming liquids.
     2. Advisable to agitate the mud in suction tanks of Desilter,Desander
        or Mudcleaner. No agitation in Sand-trap.
     3. If any answer is prefixed by '-none' then that part is not applicable
        for this case.
                          END OF CONSULTATION


                 INPUT TO THE UNWEIGHTED SYSTEM...
1. Type of the mud is unweighted.
2. Type of cuttings in returns COARSE SAND.
3. Total.solids fraction in the mud 0.32.
4. Original Density of the mud 10.5 ppg.
5. Density of the Retrun mud 15 ppg.
6. Viscosity of mud 29 cp.
7. Yield point of mud 9 lb/100 sq. ft.
8. The return flow rate is 650 gal/min.
9. Feeder pump flow rate 600 gal/min.
10. Hydrocyclone slurry ejection rate 0.75 quart/30 secs.
11.Drilled solids type CARBON DIOXIDE.
12.Drilled solids major content COARSE SAND.
13.Major contaminant in mud CARBON DIOXIDE.
14.Contaminating ion BICARBONATE.
15.Contaminating ion concentration 78.65 mg/mL.
```

Other results obtained from consultations are:

1. Coarse sand particle size ranges between 190 and 1850 microns.
2. Present solids fraction is 0.32 while the recommended solids fraction for 10.5 ppg original mud weight is from 0.0814 to 0.1637 for unweighted water base muds.
3. Present viscosity is 29 cp. Recommended range for original mud weight of 10.5 ppg is 5.31 to 16.43 cp. The mean viscosity is 10.878 cp. and on this basis, it has to be decreased by 18.12 cp.
4. Present yield point is 9 lbf/100 ft^2 while the recommended range of yield point for original 10.5 ppg mud is 3 to 24.70 lbf/100 ft^2.
5. To remove the contaminating ion bicarbonate, present in concentration of 78.65 milligram/liter, use lime in concentrations of 0.0333 lbm/ bbl.

4.8 Summary

Expert systems are the type of computer-based tools that can be of great help in handling complex problems like selecting solids control equipment or designing drilling fluids.

A typical expert system is comprised of a main body called knowledge base, which is further divided into rule base, data base, and executive programs. The development of any expert system requires working in a direction that links these three together. Defining the problem, consultation with experts, and finally writing the program, are the three distinct steps that help in achieving these goals.

Two keys to successful drilling of a well are a good drilling fluid system and an efficient solids control program. The selection of both requires a knowledge about several variables and hence they are candidates for expert systems. An expert system called **©FLUIDSOL** has been developed, and the example problems presented here demonstrate its capability in solving drilling fluid design and solids control equipment problems. Apart from consultations, **©FLUIDSOL** is capable of carrying out several other operations, typical of any expert system. Outstanding among them are accessing large databases, capability to edit or append records in it, and lastly, allowing the user to input other observations for future use. This ability of the expert system developed in this study is associated with its continuous "learning" along with the user's experience.

CHAPTER 5

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

The goal of any drilling operation is to optimize drilling and at the same time minimize total well cost. Optimizing drilling fluids program and selecting proper solids control equipment, are effective ways of minimizing drilling costs. The cost of a drilling fluid system accounts for a small fraction of the entire well cost, but its effects on drilling performance are significant. Similarly, installation of solids control equipment on the rig is only a one time investment but proper selection of the equipment can help in improving drilling operations.

Drilling fluids and solids control equipment selection, depend on several variables. It is generally not possible for a single person to make decision regarding the drilling fluid system or solids control equipment to be used on a well. An expert system named **©FLUIDSOL** has been developed in this study to help the mud engineer and drilling personnel to make quick and right decision. Expert-systems are computer based tools that simulate the thought process of human experts and provide answers to those complex problems that have several solutions. The selection of drilling fluids and solids control equipment are two such problems.

5.2 Summary

A large number of drilling fluids are employed in drilling industry and hence it is very important to classify them for a better understanding. Drilling fluids can be classified into several classes and application of any particular class of fluids, for a particular situation primarily depends on several factors, most important of which are effectiveness and economy. Continuous research in this area has led to several new concepts. New fluids, formulated in various laboratories, have been tested in the field with a varying degree of success. They have helped in developing new concepts and it is expected that over a period of time better products will be launched.

Proper selection of solids control equipment is another aspect that helps is maintaining a low drilling cost. It is important to remove unwanted solids from the drilling fluid in order to make the drilling fluid more effective. For better solids control systems on the rigs, it is recommended that rig designers work closely with drilling or mud engineers who can guide them in this aspect.

The development of expert systems was the most crucial phase of this project as it involved putting the vast amount of data, field observations and expert's opinions in the form of a computer program capable of providing answers to users queries.

The Expert system **©FLUIDSOL**, developed at the end of the study, has several modules like fluid design, fluid hydraulics, solids control, fluid additives, append database, edit database, read literature, states database, and my experience. Each one these modules are in themselves individual programs and they further lead to several smaller sub-programs upon user's choice. The type of output for consultations is in text mode which can be read from the screen or printed if a printer is online. For calculations, the output can be viewed from users' screen. A VGA with Microsoft mouse facility, is however a primary requirement for the system to run. Every attempt has been made to make the program as user-friendly as possible.

Some problems, encountered in the development phase resulted in alteration of the initial approach. These problems were related to the size of the program. In the earlier approach, a single interface to carryout consultations for all the eight lithologies, presently incorporated, was created. Nine 'Form Fields' to accommodate probable zones were created on this interface. When other 'Form Fields', associated with factors governing the selection were incorporated on the screen, and programming rules associated with their inputs were included in the knowledge base, the program refused to run. This was because of the excessive length of a single program and thousands of probable combinations of nine zones with eight lithologies. It was at this time, that the program was split into several small programs and all these programs were chained together. The result was a fast and efficient running program. Now the user has to select the lithologies first, run individual consultations, and then on the basis of confidence numbers, decide on drilling fluid to be used.

5.3 Conclusions

1. An expert system that holds the key to the selection of drilling fluids and solids control equipment is developed. Introduction of an expert system like **©FLUIDSOL**, to the drilling industry will enhance drilling operations.
2. **©FLUIDSOL** contains nine modules namely fluid design, solids control, fluid hydraulics, fluid additives, append database, edit database, read literature, states

database, and field experience. These modules aid the user in carrying out several operations including consultations for fluid design and solids control equipment, fluid hydraulics calculations, solids control related calculations, view databases, reading literature etc.

3. Sixty-six individual programs were linked together to form **©FLUIDSOL**. The expert system thus created can be installed easily on to user's computer and is "user-friendly" and very easy to run.
4. The current version of **©FLUIDSOL** can be used only if the user has a VGA and a Microsoft-compatible mouse. Also, the present version primarily deals with drilling fluids for vertical or near vertical wells.
5. The current version of the developed expert system, **©FLUIDSOL** can be regularly updated or modified to meet the other challenges.

5.4 Recommendations

1. A shale database must be incorporated into the developed expert system in order to simplify the drilling of troublesome shale sections.
2. To improve the authenticity of confidence numbers more experts in the field of drilling fluids engineering should be consulted.
3. Present output is in the form of a plain text. Modifications of the current program can be made so that output in forms of tables can be obtained.

NOMENCLATURE

AI : Artificial Intelligence

API : American Petroleum Institute

^{o}C : Degree Centigrade

c_d : Desired deflocculant concentration, lbm/bbl.

c_m : Desired concentration of clay in mud, lbm/bbl.

cp : Centipoise, gram/(centimeter-sec)

d : Bit diameter, inches

$\frac{dD}{dt}$: Penetration rate of the bit, feet/ hour

$\frac{dP_f}{dL}$: Frictional pressure drop over some length, psi/ft

DOS : Disk operated systems

d_1 : Inside diameter of tubular, inches

d_2 : Casing inner diameter or hole diameter, inches

^{o}F : Degree Fahrenheit

f : Dodge and Metzner friction factor for turbulent flows in annulus and pipe

f_B : Volume fraction of API barite in drilling fluids

f_c : Bentonite clay fraction

f_{c_1} : Initial volume fraction of solids

f_{c_2} : Final volume fraction of solids

f_{lg} : Volume fraction-low gravity solids

f_o : Volume fraction of oil in drilling fluids

f_s : Total solids fraction in drilling fluids

f_{um} : Fraction of old mud in centrifuge underflow

f_w : Volume fraction of water in drilling fluids

K : Consistency index for Power Law fluids, lbf-sec^n/100ft^2 (or cp-sec^n)

m_B : Mass of Barite, pounds

mg/L : milligram/liter

m_s : Mass rate of slurry rejection, lb/hour

m_w : Volume rate of dilution water to be added, gal/hour

n : Flow behavior index for Power Law fluids

N_{REC} : Critical Reynolds Number

N_{RE} : Reynolds Number

ppg : pounds per gallon

ppm : parts per million

PV : Plastic Viscosity, cp.

q : Flow rate, gal./min

q_m : Mud flow rate, gal./min

q_s : Slurry ejection rate quarts/30 sec

q_u : Under flow rate, gal./min

q_{w1} : Water flow rate, gal./min

q_{w2} : Water flow rate into the mixing pit, gal./min

RAM : Random Access Memory

$\overline{v}$: Average drilling fluid velocity in pipe or annulus velocity , ft/sec

V_d : Volume of drilling fluid be discarded, barrels

V_s : Cuttings volume generated while drilling, barrels/hour

V_{twB} : Total Volume of water needed for barite, barrels

V_w : Volume of water needed, barrels

V_{WB} : Water requirement of barite, gal./lbm.

V_1 : Drilling fluid volume before treatment, barrels

V_2 : Drilling fluid volume after treatment, barrels

w_B : Mass flow rate of barite in tank, lbm/min

w_c : Mass rate of clay, lbm/min

w_d : Mass rate flow of deflocculant, lbm/min

YP : Yield Point, lbf/100 ft^2

$\overline{Z}_{Vc}$: Cation Exchange Capacity of bentonite clay, milliequivalent of methylene blue per 100 g of solids

$\overline{Z}_{Vds}$: Cation Exchange Capacity of drilled solids, milliequivalent of methylene blue per 100 g of solids

$\overline{Z}_{Vm}$: Cation Exchange Capacity of mud, milliequivalent of methylene blue per 100 g of solids

ϕ : Average formation porosity

μ_p : Plastic Viscosity, cp.

θ_{300} : 300 rpm Fann 35 reading, cp.

θ_{600} : 600 rpm Fann 35 reading, cp.

ρ_B : Barite density, lbm/gal

ρ_c : Density of clay, lbm/gal

ρ_d : Density of deflocculant, lbm/gal

ρ_{lg} : Density of low gravity solids, lbm/gal

ρ_m : Drilling fluid density, lbm/gal

ρ_o : Density of overflow, lbm/gal

ρ_s : Density of slurry ejected from hydrocyclone, lbm/gal

ρ_u : Density under flow, lbm/gal

ρ_w : Density of water, lbm/gal

ρ_1 : Drilling fluid density before treatment , lbm/gal

ρ_2 : Drilling fluid density after treatment, lbm/gal

τ_y : Yield point of drilling fluid, lbf /100 ft^2

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APPENDIX A

EFFECT OF OIL ON MUD WEIGHT

Effect of Oil on Mud Weight*

Oil Added bbl/100bbl Mud	Oil in Resulting Mud, percent by volume	Weight of Resulting mud , lb./gal								
0	0	10	11	12	13	14	15	16	17	18
1	1.0	10	10.9	11.9	12.9	13.9	14.9	15.9	16.9	17.8
5	4.8	9.8	10.8	11.7	12.7	13.7	14.6	15.6	16.5	17.5
8	7.4	9.7	10.7	11.6	12.5	13.5	14.4	15.3	16.3	17.2
10	9.1	9.7	10.6	11.5	12.4	13.3	14.3	15.2	16.0	17.0
11	9.9	9.7	10.6	11.5	12.4	13.3	14.2	15.1	16.0	16.9
13	11.5	9.6	10.5	11.4	12.3	13.2	14.0	14.9	15.8	16.7
15	13.1	9.5	10.4	11.3	12.2	13.0	13.9	14.7	15.7	16.5
18	15.3	9.5	10.3	11.2	12.0	12.9	13.7	14.5	15.4	16.2
20	16.7	9.4	10.3	11.1	12.0	12.8	13.6	14.4	15.3	16.1
25	20	9.3	10.1	11.0	11.7	12.5	13.3	14.2	15.0	15.8

* Weight reduction calculated for addition of 40° API oil[20].

APPENDIX B

COMMON DRILLING FLUID RELATED PROBLEMS AND THEIR SOLUTIONS (ref 34)

Table B 1 : Common drilling fluid related problems and their solutions

Sl. No.	Problem	Symptoms/Causes	Remedial Measures
1.	Bit Balling	1. Slow rate of penetration 2. Swabbing during connections or trips 3. Minimum wear of bit 4. Bit enveloped with plastic cuttings	1. Use drilling detergent 2. Reduce viscosity and gel strength 3. Proper flushing of hole before connection
2.	Hydratable formations	1. Increase in viscosity and gel strength 2. Increase in solid contents 3. Tight spots 4. Slow drilling due to improper weight on bit	1. Adjust viscosity and gel strength 2. Provide inhibition to mud 3. Increase mud weight to confine the bore hole stresses if required
3.	Shale instability due to cavings and sloughing	1. Encounter hole fill ups and bridges after trips. 2. Heavy cuttings on shakers 3. Increase in pump pressure if sloughs heavily 4. Tight pull during connection	1. Control filtration loss. 2. Add additives to seal micro-fractures 3. Increase viscosity for efficient hole cleaning 4. Maximize inhibition 5. Laminar flow in the annulus
4.	Mud loss	1. Sub hydrostatic pressure 2. Encountering fractured formations	1. Decrease mud weight if possible 2. Use fibrous, flaky and granular type lost circulation materials.
5.	Gas cut mud	1. Reduction in mud weight after trips and normalizes rapidly. 2. Encounter in surges during drilling	1. Reduce rheological properties of the mud to reduce swab pressure 2. Run degasser to degas the mud 3. Circulate to normalize 4. Increase mud weight if needed 5. Avoid use of BOP if possible
6.	Gas or water influx	1. Increase in pit volume 2. Mud flow continues even after the pump stops	1. Shut in the well 2. Record SIDPP and SICP 3. Start well killing
7.	Stuck pipe	1. High fluid loss and permeable cake 2. Permeable formation 3. High solid content 4. Excessive differential pressure	1. Reduce mud weight if possible 2. Spot diesel along with surfactants 3. Reduce HT - HP fluid loss 4. Reduce solid contents

Table B 1 (contd/-...)

Sl. No	Problem	Symptoms/Causes	Remedial Measures
8.	Increase in viscosity	1. Increase in viscosity, fluid loss, gel strength, YP and solids content 2. Increase in Methylene Blue Content	1. Use solids control equipment to remove sub-micron size particles 2. Add water 3. Use thinner if required
		1. Increase in viscosity, fluid loss, gel and YP but solids are normal 2. No increase in MBC 3. Increase in contaminants	1. Treat and remove contaminants such as salts, carbonates and bicarbonates by $NaHCO_3$ and Lime respectively
		1. Increase in low density solids 2. Low Methyl Blue Content	1. Add prehydrated bentonite 2. Maximize the use of solids control equipment
9.	Reduction in viscosity	1. Reduction in MBC	1. Use prehydrated bentonite
		2. MBC is high and solids contents are limited	2. Control the use of thinner
		3. Bivalent salt level increases	3. Treat and remove Ca^{++}/Mg^{++} ions
10.	Surface foams	1. No reduction in mud weight 2. Foam other than observed during conversion of mud.	1. Spray water jet 2. Use defoamer to break foam 3. Add prehydrated bentonite if MBC is low
11.	Internal foam	1. Reduction in mud weight 2. Increase in viscosity 3. Fluffy appearance of mud 4. Rattling of mud pump	1. Adjust rheological parameters to allow escape of air easily 2. Foam generating mechanical devices can be avoided 3. Add defoamer
12.	Increase in filtration loss	1. No change in viscosity	1. Increase concentration of fluid loss prevention agents
		1. Observe change in viscosity 2.Fluffy soft and thick filter cake 3. Increase in salt /other contaminants	1. Treat and remove contaminants 2. Add bentonite if MBC is low 3. Fluid loss additive for low MBC
13.	Unstable mud	1. Low Methylene Blue Content 2. Settling of barite	1. Increase viscosity using viscosifier 2. Add prehydrated bentonite
14.	High temperature gelation	1. Increase in viscosity, gel strength and fluid loss during bottoms up 2. Decrease in alkalinity 3. Increase in Ca^{++}	1. Add water and bentonite 2. Use sodium dichromate 3. Use thinners if required

APPENDIX C

DRILLING FLUID ADDITIVES AND THEIR PRIMARY APPLICATIONS (ref 34)

1. Primary Applications of Clay and Weighting Materials

Sl. No.	Additives, specific gravity	Primary Applications
1.	Bentonite, 2.4	For viscosity and filtration control in fresh water mud systems.
2.	Attapulgite, 2.6	Viscosity and filtration control in salt water mud system.
3.	Calcium Carbonate, 2.7	Acid soluble weighting agents for drilling, completion and workover fluids.
4.	Hematite, 5.0	Weighting agent for both water and oil-based system
5.	Barite, 4.2	Weighting agent for both water and oil-based system
6.	Galena, 6.7 to 7.0	Weighting material for high weight mud requirement
7.	Illominite, 4.7	Weighting material for water and oil based system
8.	Asbestos	For viscosities in both fresh and salt water system.

2. Primary Applications of Viscosifiers Filtration Control agents

Sl. No	Additives	Primary Applications
1.	Polyvinyl Acetate/Maleic anhydrite, co-polymer	Selective flocculent for fresh water and a bentonite extender.
2.	CMC (High viscosity)	Same as above with greater viscosity
3.	CMC (Low viscosity)	For fluid loss control in fresh and brackish water base system. Impart dispensing properties in salt water.
4.	Pregelatinized Starch	For fluid loss control and viscosity in fresh water and salt water systems.
5.	PAC (High and Low viscosity grade)	For fluid loss control and viscosity in fresh and salt water systems.
6.	Hydroxyethyl Cellulose	For viscosity in salt solution
7.	Sodium Polyacrylonitirle	Weighting material for water and oil based system
8.	Resinated Lignite	For filtration control under high temperature conditions.
9	Synthetic Polymer	For viscosity and reduction in fluid loss

3. *Primary Applications of Thinners and Dispersants*

Sl. No.	Additives	Primary Applications
1.	Chrome Lignosulfonate	Thinner also contributes to fluid loss control at higher temperature.
2.	Chrome-free Lignosulfonate	Thinner also contributes to fluid loss control at higher temperature.
3.	Calcium Lignosulfonate	Provide thinning to water based system
4.	Causticized Lignite	Thinner and fluid loss control at high temperature in water base system.
5.	Processed Lignite	Thinner, filtration control agent and stabilizer for O/W emulsion.
6.	Tannin Compound	For thinning in high pH fresh water base system

4. *Primary Applications of Detergents and Lubricants*

Sl. No.	Additives	Primary Applications
1.	Drilling detergent	Minimizes bit balling and reduces torque and drag in water base mud system
2.	Emulsifier (A blend of anionic surfactant)	For emulsifying oil in fresh and salt water mud systems
3.	Oil soluble surfactant	Used for freeing differential stuck pipe
4.	Graphite	Provides lubricity to mud
5.	Lubricants	Provides lubricity to water base mud under extreme pressure and temperature conditions
6.	Oil soluble surfactant (weighable)	For freeing differentially stuck pipe in high pressure wells.

5. *Primary Applications of Special Additives*

Sl. No	Additives	Primary Applications
1.	Water dispersible Asphalt	Seal micro-fractures to control shale hydration and fluid loss in water base mud
2.	Aluminum Stearate	For defoaming in water base mud
3.	2-Ethyl Hexanol	For defoaming in water base system
4.	Asphalt	For hole stabilization, lubricity and HTHP filtration control.

6. *Primary Applications of Inorganic Chemicals*

Sl. No.	Chemicals	Primary Applications
1	Caustic Soda ($NaOH$)	Used for pH control in water base muds.
2	Potassium Hydroxide (KOH)	For alkalinity control in KCl mud an source of potassium in salt free fluids
3	Sodium Chloride ($NaCl$)	Used in packer and work over fluids for density control and in drilling fluids for salinity control.
4	Potassium Chloride	Used in KCl - Polymer muds for shale inhibition
5	Soda Ash (Na_2CO_3)	Used for removal of Ca^{++} contaminants in water base
6	Sodium Bicarbonate ($NaHCO_3$)	Used for removal of Ca^{++} contaminants in water base mud
7	Lime ($Ca(OH)_2$)	Used in lime base mud system and also control carbonate contamination
8	Gypsum ($CaSO_4$,	Used as source of soluble Ca^{++} in gypsum base mud.
9	Calcium Chloride ($CaCl_2$)	Used in completion fluids, packer fluids, and in oil base mud for activity control.

APPENDIX D

LIST OF EQUATIONS USED IN SOLIDS CONTROL CALCUALTIONS MODULE (ref. 35)

1. **Cuttings volume generated**:

The volume of rock fragments generated by the bit, V_s is given as

$$V_s = 9.7142 \times 10^{-4}(1-\phi\ )d^2 \frac{dD}{dt}$$

V_s = solids volume of rock fragments entering the mud, bbl/hr

ϕ = average formation porosity,

d = bit diameter, inches

$\frac{dD}{dt}$ = penetration rate of the bit, ft/hr.

2. **Solids determination in mud**:

a. Fraction of low gravity solids in mud, f_{lg}

$$f_{\lg} = \frac{\rho_w f_w + (1 - f_o - f_w)\rho_B + \rho_o f_o - \rho_m}{\rho_B - \rho_{\lg}}$$

b. Fraction of solids in mud, f_s:

$$f_s = \frac{\rho_m + f_{\lg}(\rho_B - \rho_{\lg}) - \rho_W}{\rho_B - \rho_W}$$

c. Volume fraction of API Barite in mud:

$$f_B = 1 - f_{\lg} - f_w - f_o$$

f_B = volume fraction of API barite in mud

f_w = volume fraction of water in mud

f_{lg} = volume fraction-low gravity solids

f_o = volume fraction of oil in mud

ρ_m = mud density, lbm/gal

ρ_B = barite density, lbm/gal

ρ_{lg} = density of low gravity solids, lbm/gal

ρ_w= density of water, lbm/gal

3. **Calculation for dilution water** :

a. Volume fraction of solids in mud, f_s:

$$f_s = \frac{\rho_s - \rho_W}{\rho_{lg} - \rho_W}$$

f_s = volume fraction of solids in mud

ρ_s = density of slurry ejected from hydrocyclone, lbm/gal

ρ_{lg} = density of low gravity solids, lbm/gal

ρ_w= density of dilution water, lbm/gal

b. Mass rate of solids ejected, m_s:

$m_s = 19530 f_s q_s$

q_s = slurry ejection rate quarts/30 secs

c. Volume rate of dilution water to be added, m_w:

$m_w = 900 (1-f_s) q_s$ gal./hour

4. **Density control additives:**

a. Case I : Unlimited volume

1. Final Volume, V_2:

$$V_2 = V_1 \frac{(\rho_B - \rho_1)}{(\rho_B - \rho_2)} \text{ bbls}$$

2. Mass of Barite to be added, $\boldsymbol{m_B}$:

$$m_B = V_1 \rho_B \left(\frac{\rho_B - \rho_1}{\rho_B - \rho_2} - 1 \right) \text{lbm}$$

V_1 = initial volume, bbls

ρ_B = barite density, lbm/gal

ρ_1 = initial density of mud, lbm/gal

ρ_2 = desired density of mud, lbm/gal

b. Case II: Limited volume

1. Mass of Barite to be added, $\boldsymbol{m_B}$:

$$m_B = \frac{\rho_B}{1 + \rho_B V_{WB}} \times \left[V_2 - V_2 \left\{ \frac{\rho_B \left(\frac{1 + \rho_W V_{WB}}{1 + \rho_B V_{WB}} - \rho_2 \right)}{\rho_B \left(\frac{1 + \rho_W V_{WB}}{1 + \rho_B V_{WB}} - \rho_1 \right)} \right\} \right] \text{lbm}$$

V_2 = final limited volume. bbls

ρ_B = density of Barite, lbm/gal

ρ_w = density of water, lbm/gal

V_{wB} = water requirement of barite, gal./lbm

ρ_1 = initial density of mud, lbm/gal

ρ_2 = density desired, lbm/gal

m_B = mass of barite to be added, lbm.

2. Volume of old mud to be discarded, V_d :

$V_d = V_2 - V_1$ bbls

3. Total Volume of water needed for barite, V_{twB} :

$V_{twB} = V_{wB}\ m_B$ bbls

c) Case III : When volume fraction of solids is pre-decided :

$$V_1 = V_2 \frac{f_{c_2}}{f_{c_1}} \text{ bbls}$$

$$V_W = \frac{(\rho_B - \rho_2)V_2 - (\rho_B - \rho_1)V_1}{(\rho_B - \rho_W)}$$

$m_B = (V_2 - V_1 - V_w)\ \rho_B$ lbm.

f_{c_1} = initial volume fraction of solids

f_{c_2} = final volume fraction of solids

V_w = volume of water needed, bbls

m_B = mass of barite, lbm.

5. <u>Centrifuge Analysis</u>:

a. Underflow rate, q_u:

$$q_u = \frac{q_m(\rho_m - \rho_o) - q_{w1}(\rho_o - \rho_W)}{(\rho_u - \rho_o)}$$

q_u = under flow rate, gal./min

q_m = mud flow rate, gal./min

q_{w1} = water flow rate, gal./min

ρ_m = density of mud, lbm/gal

ρ_o = density of overflow, lbm/gal

ρ_u = density under flow, lbm/gal

b. Fraction of old mud in centrifuge underflow, f_{um}:

$$f_{um} = \frac{(\rho_B - \rho_u)}{\rho_B - \rho_m + \dfrac{q_{w1}}{q_m}(\rho_B - \rho_W)}$$

q_{w1} = rate of dilution water entry, gal./min

q_m = rate of mud entry , gal./min

c. Mass rate of clay, w_c :

$$w_c = \frac{c_m(q_m - q_u f_{um})}{42} \quad \text{lb./min}$$

w_c = mass flow rate of clay, lb./min

c_m = desired concentration of clay in mud

q_m = flow rate of mud, gal./min

d. Calculate mass rate of deflocculant, w_d :

$$w_d = \frac{c_d(q_m - q_u f_{um})}{42} \text{ lb./min}$$

w_d = mass flow rate of deflocculant, lb./min

c_d = desired deflocculant concentration

e. Calculate water flow rate into the mixing pit, q_{w2}:

$$q_{w2} = \frac{\left[q_m(r_B - r_m) - q_u(r_B - r_u) - w_d\left(\frac{r_B}{r_d} - 1\right) - w_c\left(\frac{r_B}{r_c} - 1\right)\right]}{(r_B - r_W)}$$

q_{w2} = flow rate of water, gal./min

ρ_c= density of clay , lbm/gal

ρ_d = density of deflocculant, lbm/gal

f. Calculate mass flow rate of barite in

the tank, w_B:

$$w_B = \left(q_m - q_u - q_{w2} - \frac{w_c}{\rho_c} - \frac{w_d}{\rho_d} \right) \rho_B$$

w_B = mass flow rate of barite in tank, lbm/min

6. <u>CEC tests:</u>

$$f_c = \frac{\overline{Z}_{Vm} - 2.6 f_{lg} \overline{Z}_{Vds}}{2.6\left(\overline{Z}_{Vc} - \overline{Z}_{Vds}\right)}$$

f_c = bentonite clay fraction

$\overline{Z}_{Vm}$ = CEC of mud, meq/100 g of solids.

$\overline{Z}_{Vc}$ = CEC of bentonite clay, meq/100 g of solids.

$\overline{Z}_{Vds}$ = CEC of drilled solids, meq/100 g of solids.

f_{lg} = volume fraction-low gravity solids

APPENDIX E

QUANTITY OF TREATING AGENT PER BARREL TREATED NEEDED FOR EACH PPM OF CONTAMINANT (ref. 35)

Contaminant	Contaminating Ion	To Remove Add	Amount of Treating Agent to Add to Remove 1 mg/L Contaminant (lbm/bbl)
Gypsum or anhydrite	calcium (Ca^{2+})	soda Ash if pH okay SAPP if pH too high sodium bicarbonate if pH too high	0.000928 lbm/bbl/mg/L 0.000971 lbm/bbl/mg/L 0.00147 lbm/bbl/mg/L
Cement	calcium (Ca^{2+}) hydroxide (OH^-)	SAPP or sodium bicarbonate	0.000971 lbm/bbl/mg/L 0.00147 lbm/bbl/mg/L
Lime	calcium (Ca^{2+}) hydroxide (OH^-)	sodium bicarbonate SAPP or sodium bicarbonate	0.00147 lbm/bbl/mg/L 0.000535 lbm/bbl/mg/L 0.000397 lbm/bbl/mg/L
Hard water	magnesium (Mg^{2+}) calcium (Ca^{2+})	caustic soda to pH 10.5 then add soda ash soda ash	0.00116 lbm/bbl/mg/L 0.000928 lbm/bbl/mg/L
Hydrogen sulfide	sulfide (S^{2-})	keep pH above 10 and add zinc basic carbonate	0.00123 lbm/bbl/mg/L
Carbon dioxide	carbonate (CO_3^{2-}) bicarbonate (HCO_3^-)	gypsum if pH okay lime if pH too low lime	0.00100 lbm/bbl/mg/L 0.000432 lbm/bbl/mg/L 0.000424 lbm/bbl/mg/L

Quantity of Treating Agent per barrel treated (lbm/bbl) needed for each parts per million (ppm) of Contaminant.

APPENDIX F

SOLIDS CONTROL EQUIPMENT SELECTION CRITERION
(ref 35, 37 and 39)

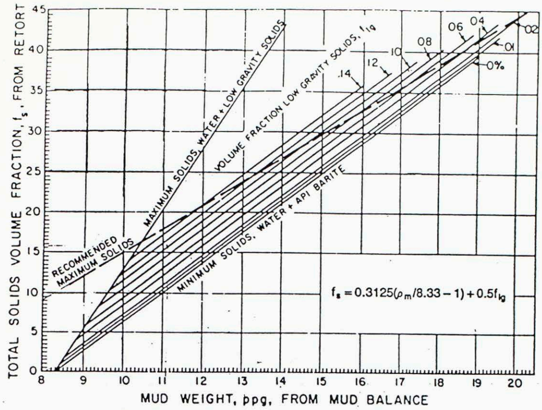
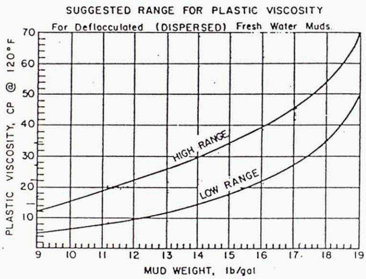


Figure F 1: Solids content vs. mud weight for fresh water muds



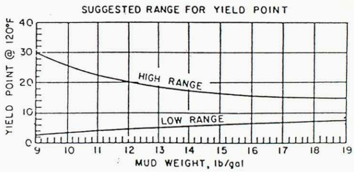


Figure F 2: Typical range of acceptable viscosities for clay/water muds.

Figure F 3 :Typical range of acceptable yield points for clay/water muds.

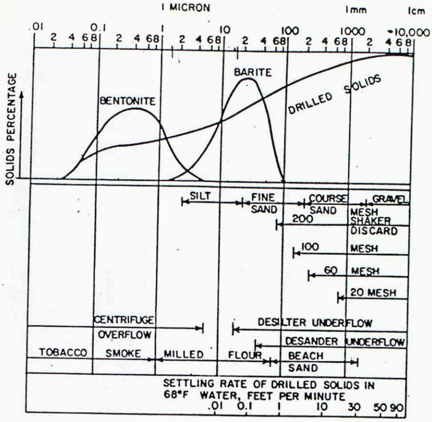


Figure F 4 : Particle size range for common solids found in weighted water-base muds[35].

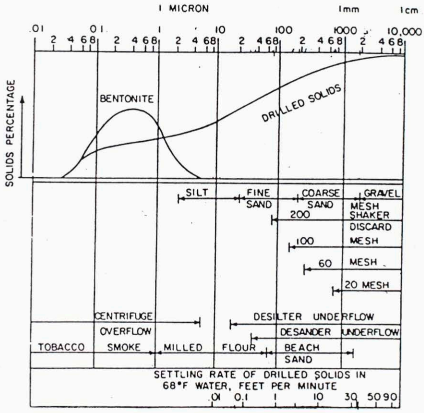
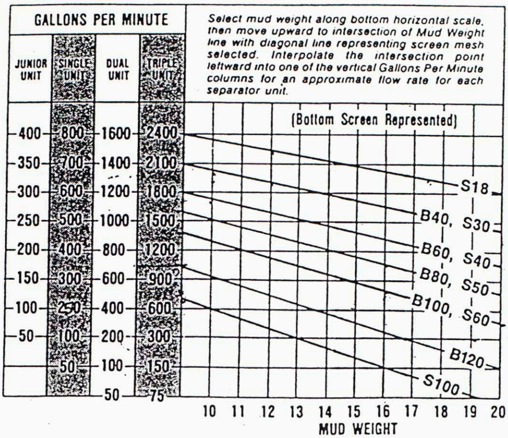


Figure F 5 : Particle size range for common solids found in unweighted water-base muds[35].



All S screens are square mesh. All B screens are oblong mesh.

Figure F 6 : Flow Rates for Brandt Tandem Screen Separators - Dual Unit. (ref 39)

Original order of removal efficiency. Also, approximate increasing order of equipment cost for equal underflow solids removal rates.

Cone			Rating A	Rating B	A × B
Make	Diameter, in.	Feed, gpm	UF Solids as Vol Rate % of Feed Solids	UF Solids wt% of Total UF	Total Ratings
W	3	16.76	11.72	56.25	670
X	2	22.03	11.69	49.30	575
W	4	57.12	8.94	56.83	507
X	6	108.39	5.95	47.26	281
Y	4	62.65	4.55	47.96	218
W*	6*	88.73*	3.28	59.31	194
Z	4	44.90	1.55	65.25	101
X	12	407.00	1.80	54.46	98
Z	8	167.70	0.746	66.70	49.8

* Company W requested, prior to any evaluation work, that their 6-in. cone test be deleted because it was not taking the proper feed volume due to an undetermined malfunction. Request denied.

Figure F 7 : Mohole Hydrocyclone Evaluation (from timed and measured data taken during tests - ref 37).

APPENDIX G

FLUID HYDRAULICS EQUATIONS AND OTHER RELEVANT DATA (ref 35)

Summary of equations used for pressure drop calculations in the "Fluid Hydraulics" module of ©FLUIDSOL (ref 35).

	Newtonian Model	Bingham Plastic Model	Power-Law Model
Mean Velocity, $\bar{v}$	Pipe		
	$\bar{v} = \dfrac{q}{2.448d^2}$	$\bar{v} = \dfrac{q}{2.448d^2}$	$\bar{v} = \dfrac{q}{2.448d^2}$
	Annulus		
	$\bar{v} = \dfrac{q}{2.448(d_2^{\,2} - d_1^{\,2})}$	$\bar{v} = \dfrac{q}{2.448(d_2^{\,2} - d_1^{\,2})}$	$\bar{v} = \dfrac{q}{2.448(d_2^{\,2} - d_1^{\,2})}$
Flow Behavior Parameters	$\mu = \theta_{300}$	$\mu_p = \theta_{600} - \theta_{300}$	$n = 3.32 \log \dfrac{\theta_{600}}{\theta_{300}}$
		$\tau_y = \theta_{300} - \mu_p$	$K = \dfrac{510\,\theta_{300}}{511^n}$
Turbulence Criteria	Pipe		
	$N_{Rec} = 2{,}100$	$N_{He} = \dfrac{37{,}100\,\rho\,\tau_y\,d^2}{\mu_p^{\,2}}$	N_{Rec} from **Fig. G 1**
	$N_{Re} = \dfrac{928\,\rho\,\bar{v}\,d}{\mu}$	N_{Rec} from **Fig. G 2**	$N_{Re} = \dfrac{89{,}100\,\rho\bar{v}^{\,2-n}}{K}\left(\dfrac{0.0416d}{3+1/n}\right)^n$
		$N_{Re} = \dfrac{928\,\rho\,\bar{v}\,d}{\mu_p}$	
	Annulus		
	$N_{Rec} = 2{,}100$	$N_{He} = \dfrac{24{,}700\,\rho\,\tau_y\,(d_2 - d_1)^2}{\mu_p^{\,2}}$	N_{Rec} from **Fig. G 1**
	$N_{Re} = \dfrac{757\,\rho\bar{v}(d_2 - d_1)}{\mu}$	$N_{Re} = \dfrac{757\,\rho\bar{v}(d_2 - d_1)}{\mu_p}$	$N_{Re} = \dfrac{109{,}000\,\rho(\bar{v})^{2-n}}{K}\left[\dfrac{0.0208(d_2 - d_1)}{2+1/n}\right]^n$
Laminar Flow Frictional Pressure Loss	Pipe		
	$\dfrac{dp_f}{dL} = \dfrac{\mu\bar{v}}{1{,}500\,d^2}$	$\dfrac{dp_f}{dL} = \dfrac{\mu_p\bar{v}}{1{,}500\,d^2} + \dfrac{\tau_y}{225\,d}$	$\dfrac{dp_f}{dL} = \dfrac{K\bar{v}^{\,n}\left(\dfrac{3+1/n}{0.0416}\right)^n}{144{,}000\,d^{1+n}}$
	Annulus		
	$\dfrac{dp_f}{dL} = \dfrac{\mu\bar{v}}{1{,}000\,(d_2 - d_1)^2}$	$\dfrac{dp_f}{dL} = \dfrac{\mu_p\bar{v}}{1{,}000\,(d_2 - d_1)^2} + \dfrac{\tau_y}{200\,(d_2 - d_1)}$	$\dfrac{dp_f}{dL} = \dfrac{K\bar{v}^{\,n}\left(\dfrac{2+1/n}{0.0208}\right)^n}{144{,}000\,(d_2 - d_1)^{1+n}}$
Turbulent Flow Frictional Pressure Loss	Pipe		
	$\dfrac{dp_f}{dL} = \dfrac{f\,\rho\,\bar{v}^2}{25.8\,d}$	$\dfrac{dp_f}{dL} = \dfrac{f\,\rho\,\bar{v}^2}{25.8\,d}$	$\dfrac{dp_f}{dL} = \dfrac{f\,\rho\,\bar{v}^2}{25.8\,d}$
	or	or	
	$\dfrac{dp_f}{dL} = \dfrac{\rho^{0.75}\bar{v}^{1.75}\mu^{0.25}}{1{,}800\,d^{1.25}}$	$\dfrac{dp_f}{dL} = \dfrac{\rho^{0.75}\bar{v}^{1.75}\mu_p^{\,0.25}}{1{,}800\,d^{1.25}}$	
	Annulus		
	$\dfrac{dp_f}{dL} = \dfrac{f\,\rho\,\bar{v}^2}{21.1\,(d_2 - d_1)}$	$\dfrac{dp_f}{dL} = \dfrac{f\,\rho\,\bar{v}^2}{21.1\,(d_2 - d_1)}$	$\dfrac{dp_f}{dL} = \dfrac{f\,\rho\,\bar{v}^2}{21.1\,(d_2 - d_1)}$
	or	or	
	$\dfrac{dp_f}{dL} = \dfrac{\rho^{0.75}\bar{v}^{1.75}\mu^{0.25}}{1{,}396\,(d_2 - d_1)^{1.25}}$	$\dfrac{dp_f}{dL} = \dfrac{\rho^{0.75}\bar{v}^{1.75}\mu^{0.25}}{1{,}396\,(d_2 - d_1)^{1.25}}$	

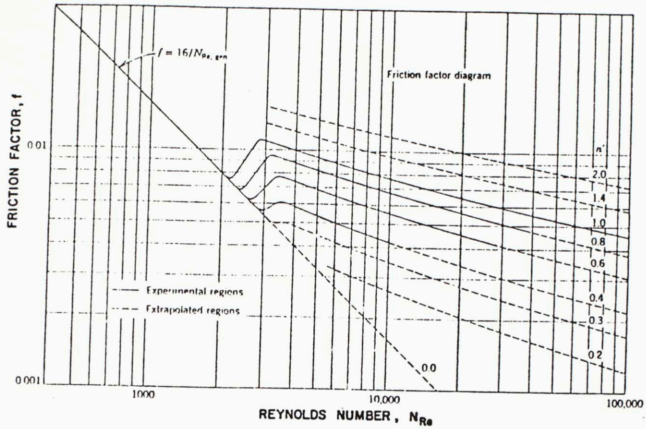


Figure G 1 : Friction factors for power-law fluid model[40].

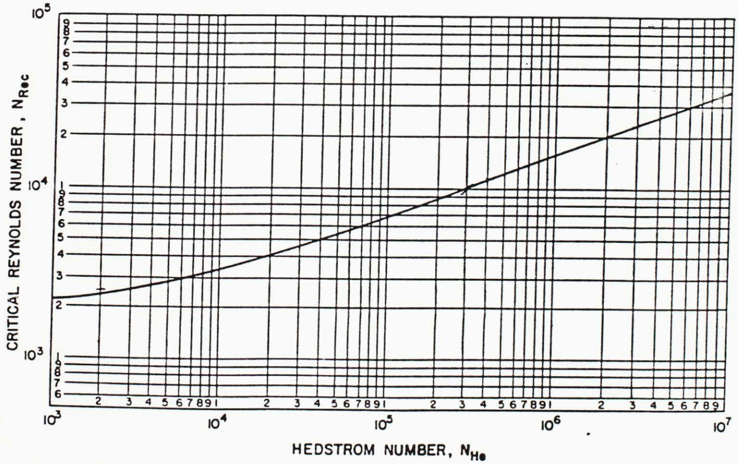


Figure G 2 : Critical Reynolds number for Bingham Plastic fluids[35].