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Development and Testing of Underbalanced Drilling Products

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Development and Testing of Underbalanced Drilling Products

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Period of Performance September 30, 1994 to November 30, 1997

Schedule and Milestones::

TASKS	FY95												FY96												FY97	
	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N
1. Research Existing Models	x	x	x																							
2. Develop Foam Model				x	x	x	x	x	x																	
3. Validate Model										x	x	x														
4. Study Market Potential	x	x	x	x	x	x	x	x	x	x	x	x														
5. Research LWSA	x	x	x	x	x	x	x	x	x	x																
6. Modify LWSA/Equipment									x	x																
7. Yard Test Additives & Equipment										x	x	x														
8. Test Plan													x	x												
9. Field Tests															x	x	x	x	x	x	x	x	x	x	x	x
10. Technology Transfer																	x					x				

-/-

Development and Testing of Underbalanced Drilling Products

OBJECTIVES:

The first objective of this project is to develop a user-friendly, PC, foam drilling computer model, FOAM, which will accurately predict frictional pressure drops, cuttings lifting velocity, foam quality, and other drilling variables. The model will allow operating and service companies to accurately predict pressures and flow rates required at the surface and downhole to efficiently drill oil and gas wells with foam systems.

The second objective of this project is to develop a lightweight drilling fluid that utilizes hollow glass spheres to reduce the density of the fluid and allow drilling underbalanced in low-pressure reservoirs. Since the resulting fluid will be incompressible, hydraulics calculations are greatly simplified, and expensive air compressors and booster pumps are eliminated. This lightweight fluid will also eliminate corrosion and downhole fire problems encountered with aerated fluids.

BACKGROUND INFORMATION

In the late 1940s, oil companies began air drilling to increase drilling rates in hard rock and to overcome severe loss circulation problems. Other benefits of air drilling include reduced formation damage and reduced differential sticking problems.

The most important benefit of underbalanced drilling is increased drilling rate due to reduced differential pressure at the hole bottom as shown in Figure 1.

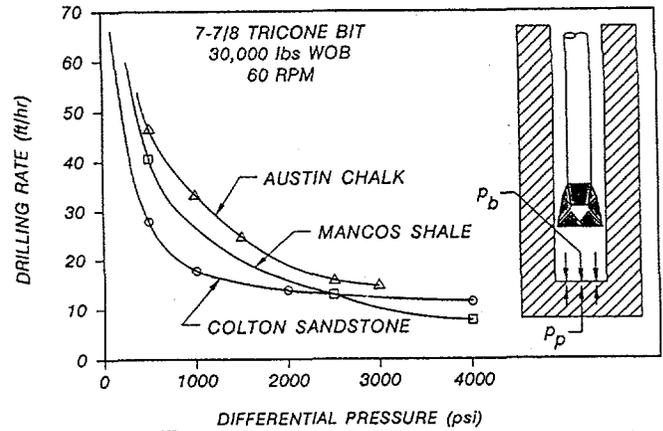


Figure 1. Effect of Differential Pressure on Drilling Rate (Moffitt, 1991)

The beneficial effect of reduced hydrostatic pressure occurs at all bit weights as shown in Figure 2.

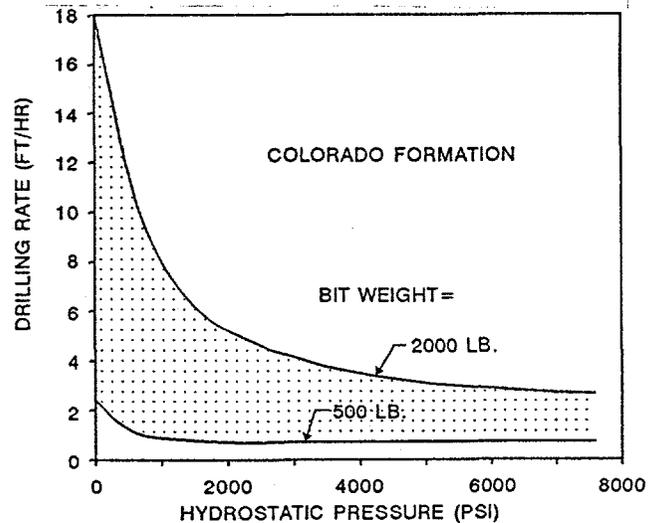


Figure 2. Effect of Hydrostatic Pressure on Drilling Rate (Murray & Cunningham, 1955)

Many tight-gas reservoirs in the United States are attractive targets for underbalanced drilling because they are located in hard-rock country where tight, low-permeability formations compound the effect of formation damage encountered with conventional drilling fluids.

Drilling underbalanced in under-pressured or depleted reservoirs requires fluids lighter than water (Sp. Gr. < 1). Many types of fluids systems are used, ranging from 100 percent air to 100 percent liquid, with all fluids having densities below 6.9 ppg (SG = 0.83) containing gas or air in some form (Figure 3).

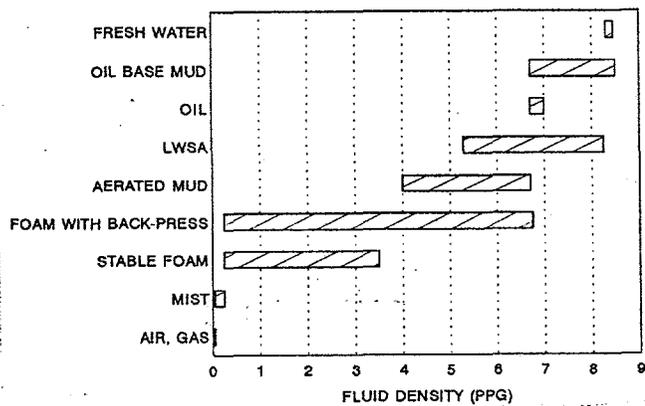


Figure 3. Fluid Density Range

During the 1950s and 1960s, drilling techniques expanded to include mist, foam, and aerated fluids, but the introduction of two-phase fluids increased the difficulty of predicting fluid flow parameters with these compressible fluids. All of the two-phase systems shown in Figure 4 have been used successfully for drilling during the past four decades.

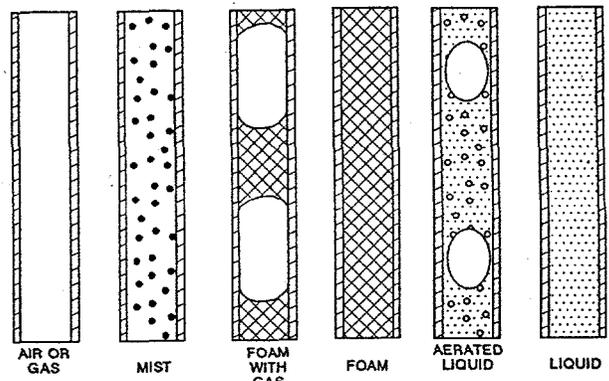


Figure 4. Types of Flow Regimes (Lorenz, 1980)

The hydraulics for 100 percent fluid is relatively easy to predict because this fluid is essentially incompressible. The 100 percent gas fluid is harder to model, due to its compressibility, even though it is still one continuous phase.

The hydraulics of mist and foam are much more difficult to model since they are compressible, and they are two phase fluids. Foam is generally defined as any two-phase fluid with liquid as the continuous phase (having a gas emulsified in it), while mist is defined as a two-phase fluid having gas as the continuous phase, as shown in Figure 5. Gas becomes the continuous phase at concentrations above 97-98 percent by volume.

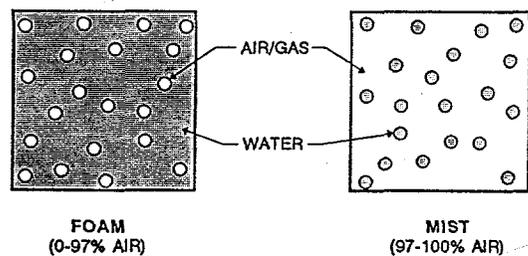


Figure 5. Fluid Phase Continuity

Advantages and disadvantages of different lightweight fluids are presented in Table I. The

major advantage of underbalanced fluids in increased ROP.

Table I. Advantages of Underbalanced Fluids

AIR/GAS/MIST	FOAM/LWSA
HIGH ROP	HANDLE WATER INFLUX
LOW CHEMICAL COST	IMPROVE HOLE STABILITY
EASY TO USE	EXCELLENT HOLE CLEANING
REDUCED ENVIRONMENTAL IMPACT	REDUCE COMPRESSORS
	NO DOWNHOLE FIRES
	MUD PULSE MWD (LWSA)

Fluids having gas or air as the continuous phase have the advantage of simplicity, low additive cost, and minimal equipment requirements. They also produce less environmental damage since there is minimal liquid waste disposal.

Table II compares the disadvantages of the different underbalanced drilling fluids.

Table II. Disadvantages of Underbalanced Fluids

AIR/GAS/MIST	FOAM/LWSA
WATER INFLUX	ADDITIVE COST
HOLE EROSION	MEASUREMENT/CALCULATION
DOWNHOLE FIRES	COMPLEXITY
HOLE INSTABILITY	

The major disadvantage of air, gas or mist fluids is their inability to handle formation fluid influxes. When the influx becomes too great for air or mists to handle, the fluid system is usually switched to foam or aerated fluid.

Foam and the proposed Lightweight Solid Additive (LWSA) muds consisting of hollow glass spheres eliminate many of the problems associated with air, gas, and mist drilling fluids including

borehole stability problems, excessive compressor requirements, and downhole fires and explosions. Their greatest advantage is their ability to handle large influxes of oil or water.

Foam has the additional advantage of increased cuttings carrying capacity. Figure 6 shows that as the foam quality increases (i.e. the percent air increases) the lifting force increases. The maximum lifting force is achieved with 2 to 5 percent liquid, just within the region defined as a foam.

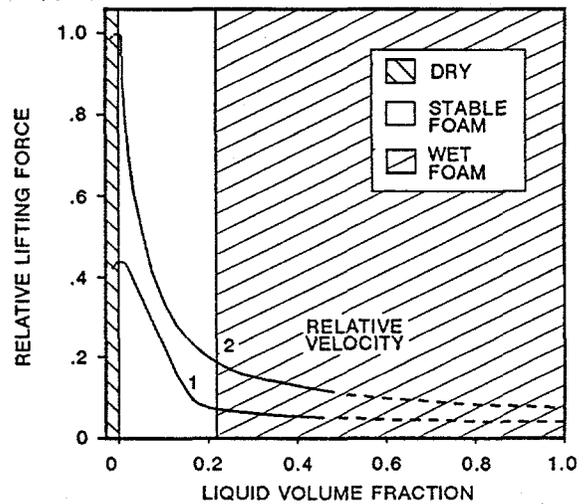


Figure 6. Foam Lifting Capacity (Beyer et al., SPE 3986)

As a foam becomes wetter, its viscosity decreases along with its ability to carry cuttings. As the fluid crosses over into a gas-continuous phase it lifts the cuttings well, but its ability to hold cuttings in suspension at very low velocities disappears.

Aerated fluid can either be circulated down the drill pipe from the surface, or injected at some point in the drill-string casing annulus through a "parasite" string strapped to the outside of the casing as shown in Figure 7. Air can also be injected down the annulus of dual wall drill pipe. The injected air reduces the pump pressure at the surface and lowers the hydrostatic head in the annulus.

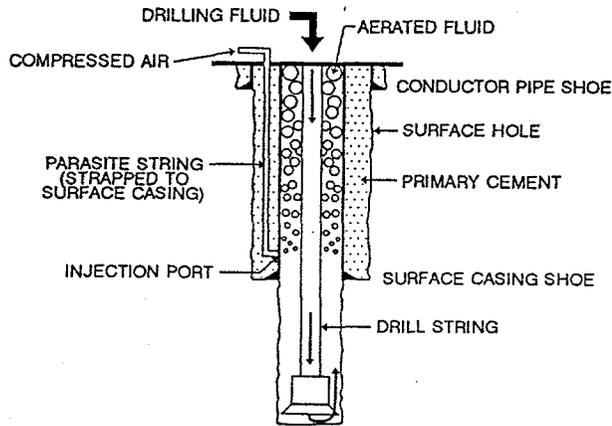


Figure 7. Typical Parasite String

Downhole fires and explosions are a problem when drilling with air, especially in long horizontal wells where days or weeks are spent drilling in oil or gas pay zones. Explosive mixtures of air and hydrocarbon gas are shown in Figure 8. If a flammable mixture of oxygen and natural gas or oil exists downhole, ignition can occur due to heat generated by friction or by sparks generated by the drill bit.

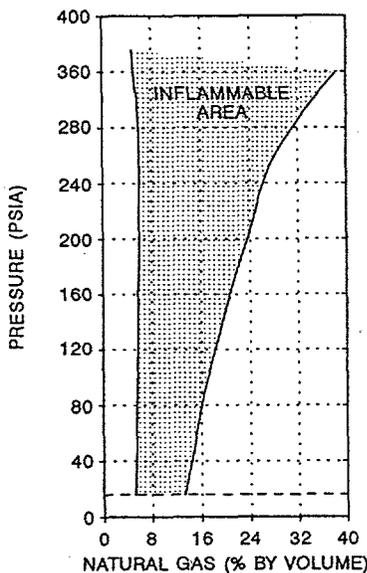


Figure 8. Explosive Mixtures (Hook et al., 1977)

Although foam or aerated muds eliminate the fire and explosion problem, they are hindered by the increasingly complex hydraulic calculations and the high cost of foam chemicals.

Prior to computers it was nearly impossible to accurately calculate circulating pressures for compressible fluids. The tedious manual calculations led to the development of nomographs and charts (Figure 9), rules-of-thumb, and correction factors which gave approximate answers and decreased the engineers' ability to scientifically use these fluids.

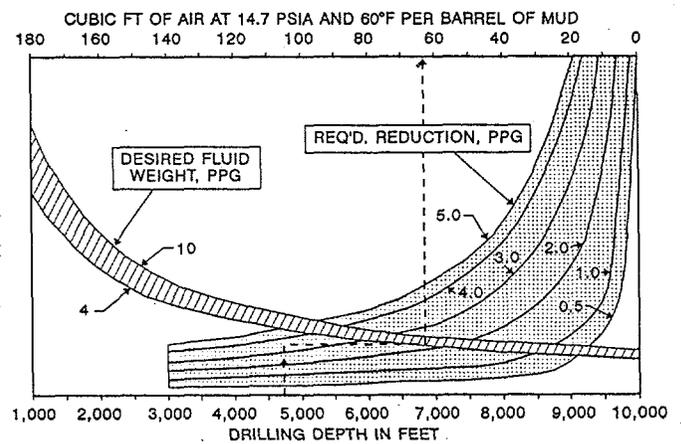


Figure 9. Volume Requirement Chart (Poettman, et al., 1995)

An accurate hydraulic model is needed for foam drilling to allow engineers to better plan and drill wells. Chevron developed a mainframe computer model for foam circulation in the early 1970s that was state-of-the-art at that time, but its availability to field engineers is limited.

Similarly, there is a need for incompressible drilling fluids that utilize solid additives (e.g., hollow glass spheres) to lighten the fluid. This type of fluid would overcome the severe fire, explosion, and corrosion associated with aerated drilling fluids.

In the late 1960s, the Russians tested lightweight fluids that utilized hollow glass spheres to reduce the fluid density. Data available on the Russian spheres are presented in Table III.

Table III. Russian Hollow Spheres

FIRST MANUFACTURED	—	1968
FIRST USE IN DRILLING	—	1970-71
MATERIAL	—	GLASS
COMPRESSIVE STRENGTH	—	3200-3600 PSI
SPECIFIC GRAVITY	—	0.26-0.36
AVERAGE DIAMETER	—	50-60 MICRONS

Oil-field service companies have used hollow glass spheres and other lightweight additives for years to reduce the density of cements and the hydrostatic head in lost circulation areas. To the best of our knowledge, hollow glass spheres were never used in lightweight drilling fluids outside of Russia until this DOE project.

A fluid incorporating lightweight solid additives (S.G.= 0.3 to 0.6) would have many advantages over aerated fluids as shown in Table IV

Table IV. Benefits of Hollow Sphere Mud

- | |
|---|
| <ul style="list-style-type: none"> • ALLOWS USE OF MWD TOOLS • ELIMINATES EXPENSIVE COMPRESSORS • REDUCES CORROSION PROBLEMS • ELIMINATES DOWNHOLE FIRES • ELIMINATES NITROGEN • IMPROVES MOTOR PERFORMANCE • IMPROVES HOLE STABILITY • SIMPLIFIES PRESSURE CALCULATIONS • REDUCES DRILL-STRING VIBRATIONS |
|---|

PROJECT DESCRIPTION

Phase I includes development of 1) a foam hydraulics model, FOAM, that will accurately calculate circulating pressures, cuttings lifting velocities, and compressor requirements, and 2) lightweight drilling fluids that utilize hollow glass spheres to reduce the fluid density.

Phase II includes field testing of the foam drilling computer model and the lightweight drilling fluids utilizing hollow glass spheres.

Foam Computer Model

A literature search was used to identify all available mathematic models related to the pressure and flow characteristics of foam fluids including calculation of downhole pressures, flow rates, volumes, foam quality, foam rheology and cuttings carrying capacity. In addition, unpublished laboratory tests and unpublished mathematical models provided by Chevron and other sources were reviewed.

The Chevron information was of significant value since Chevron spent many man-years and many millions of dollars developing foam computer models in the 1970s.

Air and foam drilling service companies were contacted to determine which computer models, if any, were in general use within the industry. Invariably, service companies either use the Chevron model under license, or models based on the Chevron model. One service company uses a proprietary spreadsheet model developed by a third party. These proprietary models are not generally available to the industry.

A PC-based model for foam fluids developed in conjunction with a Gas Research Institute contract, based on an "EXCEL" spreadsheet with no

graphics, was identified. A copy of this model was also obtained for comparison with the DOE foam model.

A PC-based, Windows foam drilling model is being developed on this DOE project using the best mathematical models in the industry. The model will be user-friendly, accurate, and available in a form compatible with rugged well-site usage. The program format will be similar to the twenty user-friendly PC programs developed by Maurer Engineering for the 120 DEA-44 Horizontal Well Technology Participants across the world.

During Phase I, the results generated by this foam hydraulics computer program will be validated by comparison with other foam models (e.g., Chevron model) and available laboratory and field data.

During Phase II, at least two field tests of the computer model will be conducted while wells are being drilled with foam. Surface and downhole data (e.g., pressures and temperatures) will be collected for comparison with the model's output.

Lightweight Solid Additives

Commercially available hollow glass spheres used as extenders in paints and other materials have been identified and the best candidates have been selected for laboratory and field testing. A Phase I test plan has been developed that includes laboratory and yard testing of drilling muds containing hollow spheres.

The laboratory tests include standard API drilling fluid tests such as density, filtration loss, and rheology of fluids composed of various concentrations of hollow glass spheres in water-base and oil-base muds.

Phase I yard testing will study the effectiveness of existing solids handling equipment on

LWSA fluids with regard to both damage and recovery of the LWSA. Modifications of existing solids-control equipment will be carried out as required.

During Phase II, at least two field tests will be carried out using LWSA drilling fluids. Chevron and other operators have expressed high interest in field testing these fluids on their wells, because they see a major payout in their field operations if the DOE tests are successful.

Market Study

A market study for underbalanced drilling fluids in the United States will be carried out. Preliminary findings are that underbalanced drilling is expanding rapidly and will become a major factor worldwide within the next five years.

Reports

Topical reports covering Phase I and Phase II efforts will be prepared and the technology developed will be transferred to the industry via technical articles and forums.

RESULTS

Foam Computer Model

To date, all known, available mathematical foam models have been studied, and modified and improved as needed for inclusion in this DOE foam model. A prototype version of the program has been developed for demonstration. Beta versions of this program are being tested by air and foam drilling service companies. Work is continuing to complete an operational model by the end of Phase I.

The PC-based model runs under a WINDOWS environment, and is fully transportable to

the rig site where real-time adjustments to the operation can be made as conditions change.

Site specific input data includes basic project description, directional survey data, drill string and wellbore descriptions, and planned drilling parameters such as gas and liquid injection rates and properties, anticipated drilling rates, pore pressures, and fracture gradients.

The compiled output is in both tabular and enhanced graphics form with a series of graphs illustrating the different parameters required by the drilling engineer when planning or troubleshooting field wells.

The primary concern of drilling engineers is the circulating pressure throughout the well, as shown in Figure 10. This pressure profile is useful in determining the amount of compression needed at the surface and to ensure that downhole pressures do not fracture the formation, allow unwanted fluid influxes into the well, or allow the wellbore to collapse.

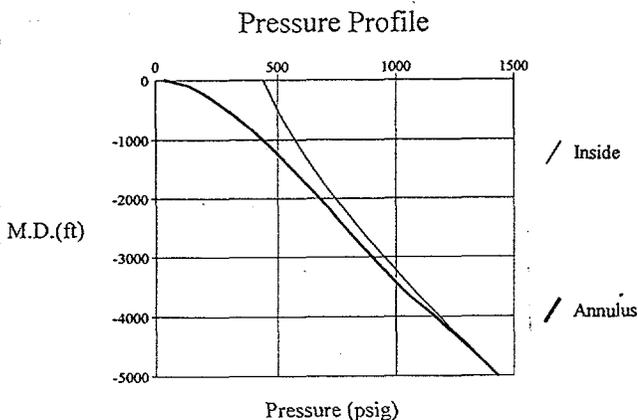


Figure 10. Pressure Profile

Foam density, plotted in Figure 11, is useful to the drilling engineer for various reasons including its effect on downhole motor performance in terms of cooling and lubrication.

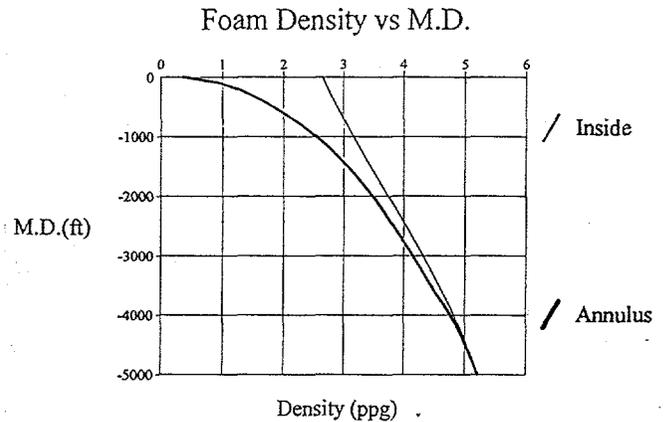


Figure 11. Foam Density

Foam quality, shown in Figure 12 relates to viscosity and the ability of foam to lift cuttings in the annulus. Drilling engineers use a rule of thumb that the foam quality should be above fifty-five percent to prevent the breakdown of foam into water or slug flow and to maintain adequate cuttings carrying capacity.

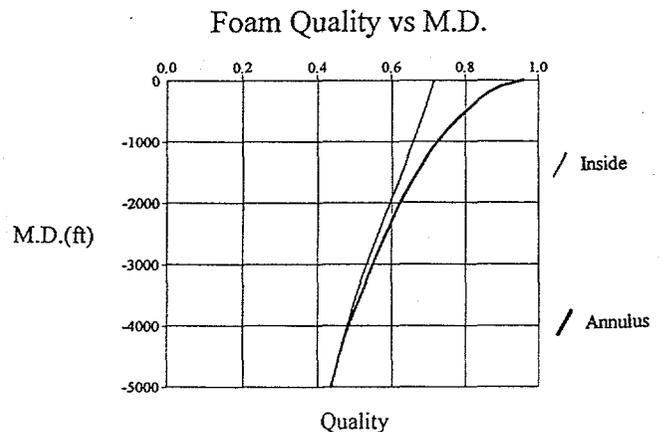


Figure 12. Foam Quality

Cuttings lifting velocity is one of the most important parameters since many field problems

(e.g., mud rings, downhole fires, stuck pipe, fishing jobs) occur because of inadequate hole cleaning.

Figure 13 shows an example where the cuttings lifting velocity is lowest at the top of the drill collars. In many air drilled wells, large cuttings remain at the top of the collars until they are reground to the point where they are small enough to be lifted to the surface.

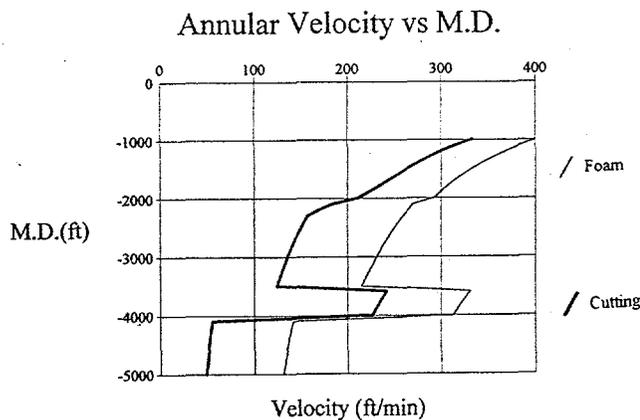


Figure 13. Cuttings Lifting Velocity

An additional feature of the program is the ability to design or troubleshoot field jobs by running sensitivity analyses on input parameters.

Figure 14 shows the total pressure and the cuttings lifting velocity at total depth for a given input case. Note that at higher gas injection rates, the bottom hole pressure exceeds the formation fracture gradient and loss of circulation would occur. At lower gas injection rates, the lifting velocity becomes negative, indicating an accumulation of cuttings at the bottom. This shows that some input modification is necessary to obtain a viable drilling scenario.

The effect of increasing the input liquid injection from 40 GPM to 100 GPM is illustrated in Figure 15. Both bottom-hole pressure and cutting

lifting velocity move into satisfactory ranges for the given range of gas injection rate.

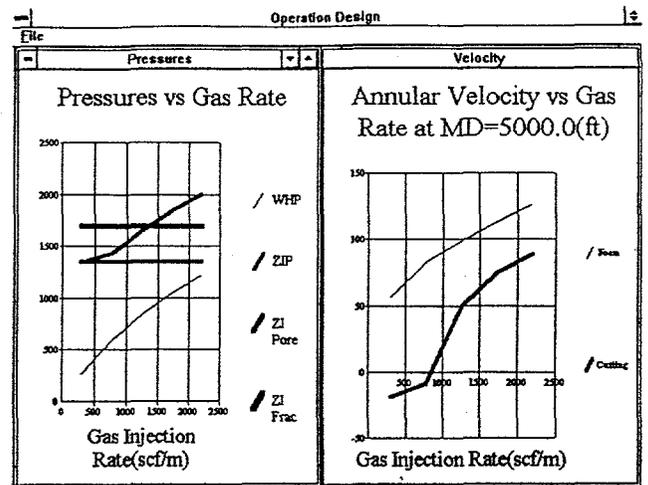


Figure 14. Initial Design Parameters

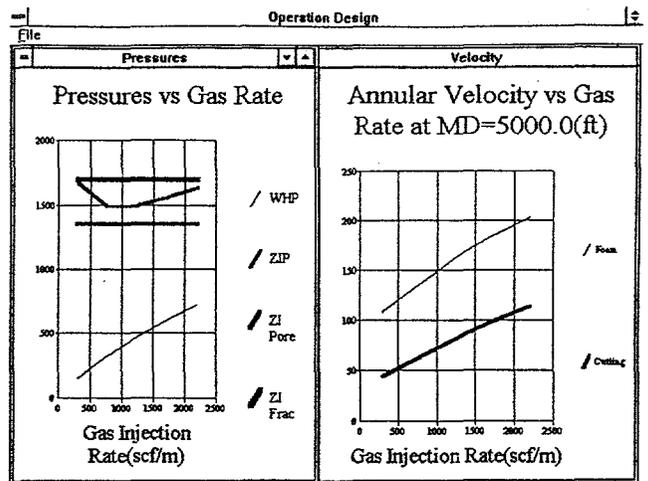


Figure 15. Design Improvement

Hollow Glass Spheres Fluids

Research into lightweight solids having a specific gravity of less than 1.0 led to the identification of several candidate hollow glass spheres (i.e., glass, ceramic, and plastic). Initial candidates include lightweight additives familiar to the industry such as

the crystalline-silica (commonly called Spherelite™) used in lightweight cements.

With cements, hollow glass spheres with specific gravities of 0.7 are adequate since they have a large effect on cements with specific gravities of 1.8 to 2.0. These spheres have minimal effect on water which has a specific gravity of 1.0. Therefore lighter spheres are required (i.e., Sp.Gr. = 0.35 to 0.40) in lightweight drilling fluids.

For example, the addition of 50 percent Spherelite™ by volume (Sp.Gr. = 0.7) would reduce the density of 8.5 ppg mud to only 7.7 ppg. This would not be adequate for most underbalanced drilling applications.

Hollow glass spheres with specific gravities of 0.38 and collapse pressures of 3000 to 4000 psi were found that can be used effectively in drilling fluids. These spheres, used commercially as extenders in paints, glues, and other liquids, are ideal for use in lightweight drilling fluids due to their low specific gravity (Figure 16).

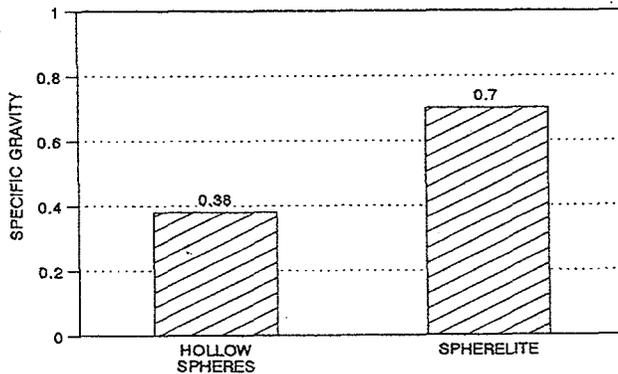


Figure 16. Specific Gravity

A 50-percent concentration of these hollow glass spheres (Sp.Gr. = 0.38) decreases the density of 8.5 ppg mud to 5.8 ppg as shown in Figure 17, which is sufficient for many field applications.

These hollow glass spheres have the added benefit of being nearly incompressible.

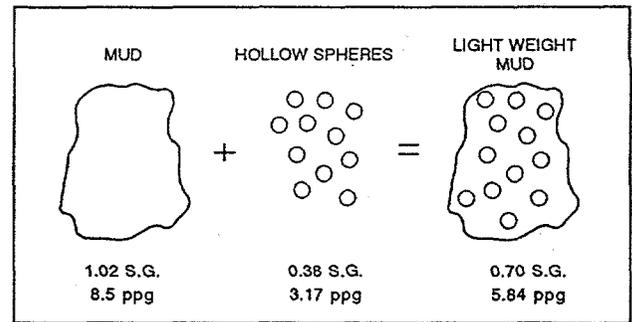


Figure 17. Lightweight Mud

The specific gravity of a sphere is a function of the ratio of its outer diameter to inner diameter (O.D./I.D.) (i.e., wall thickness) as shown in Figure 18.

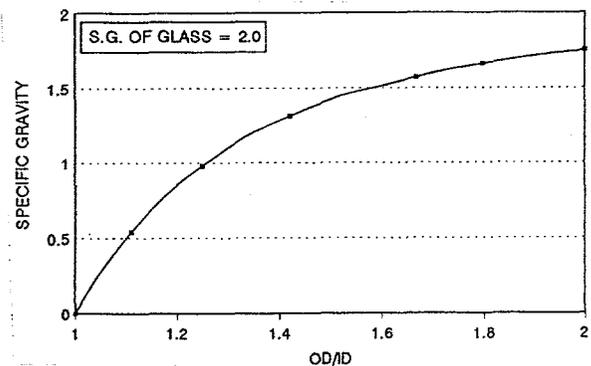


Figure 18. Specific Gravity

The most critical factor beside density is the collapse pressure of the spheres which is proportional to the O.D./I.D. ratio cubed as shown in Figure 19. It is critical that the spheres not collapse at the high fluid pressures existing at the hole bottom of gas wells since this will increase the mud density.

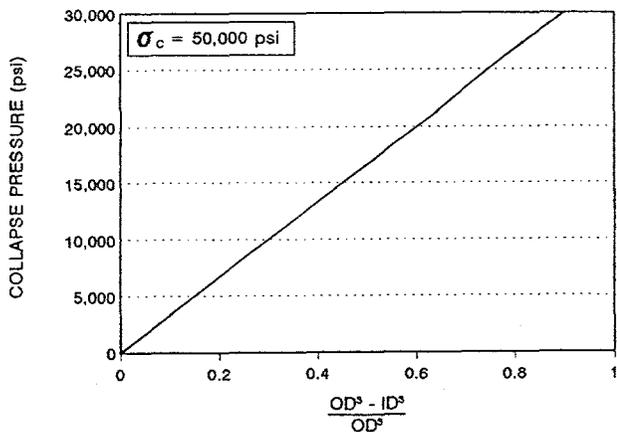


Figure 19. Collapse Pressure

Collapse tests were performed on four candidate, hollow sphere additives. The hollow spheres were mixed with water and placed in a pressure test cell as shown in Figure 20. The percent of “sinkers” was measured first with no pressure applied and then after 2000 psi was applied to the fluid for 24 hours. The collapse test results are shown in Table V.

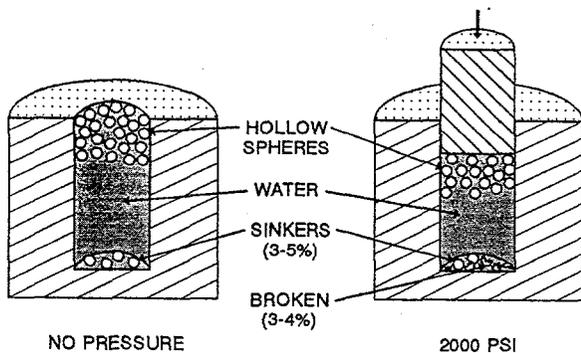


Figure 20. Collapse Pressure Test

Table V. Pressure Test Results on Hollow Spheres

Sphere Identity	Material	Average Specific Gravity (Water=1.0)	Advertised Compressive Strength, psi	Percent “Sinkers”
1	Glass	0.38	4,000	5
2	Glass	0.37	3,000	8
3	Plastic	0.02	2,000	15
4	Glass	0.28	2,000	20

Figure 21 shows how the volume of the mixture containing hollow spheres decreased as the pressure increased. The compressibility of the sphere/water mixture was $3.6 \times 10^{-6} \text{ psi}^{-1}$, compared to $3.2 \times 10^{-6} \text{ psi}^{-1}$ for water alone, which indicated that the hollow spheres are essentially incompressible.

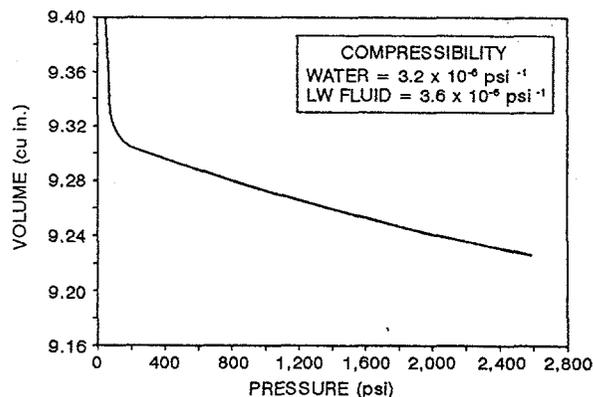


Figure 21. Lightweight Fluid Compressibility

Spheres 1 and 2 were selected for additional testing, because of their higher collapse strength and fewer of them broke and sank.

Table VI lists the standard API drilling fluid tests carried out on the candidate hollow glass spheres in water- and oil-base fluids.

TABLE VI. Hollow Sphere Mud Tests

- FLUID DENSITY
- RHEOLOGY
- FILTRATION
- CONTAMINATION
- HOT ROLLING
- HYDRAULICS

Water-base polymer mud systems containing up to 40 percent by volume of hollow spheres were tested.

Figure 22 shows that the density of 8.8 ppg mud decreased to 6.0 ppg as the concentration of hollow glass spheres (0.38 Sp.Gr.) increased from 0 to 50 percent.

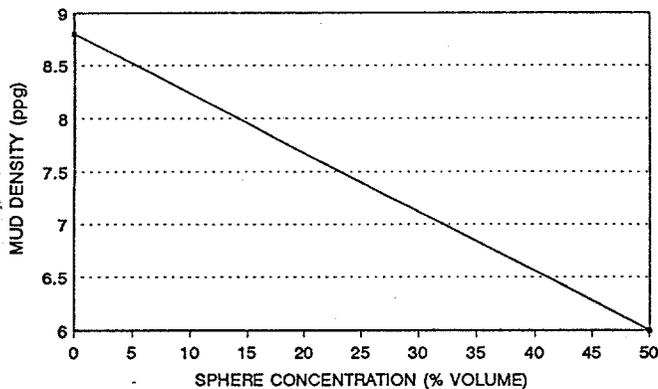


Figure 22. Mud Density

The rheology of lightweight fluids containing hollow glass spheres is similar to that of conventional drilling fluids (Figure 23). Plastic viscosity (PV) increases with increasing solids content in drilling muds. The PV of 60 at a sphere concentration of 40 percent is relatively high, but within acceptable limits for a drilling fluid.

Yield point (YP) is a measure of the fluid's capacity to suspend and carry cuttings. Figure 23 shows that YP increased, but remained within acceptable limits, as the solid concentration was increased to 40 percent.

Figures 24 and 25 show that the PV and YP of a lightweight fluid hot-rolled at 150 degrees F for 16 hours were slightly lower than the same lightweight mud tested at 120 degrees F. These hot-roll tests will be re-run to verify the plateau around 20 percent LWSA concentration.

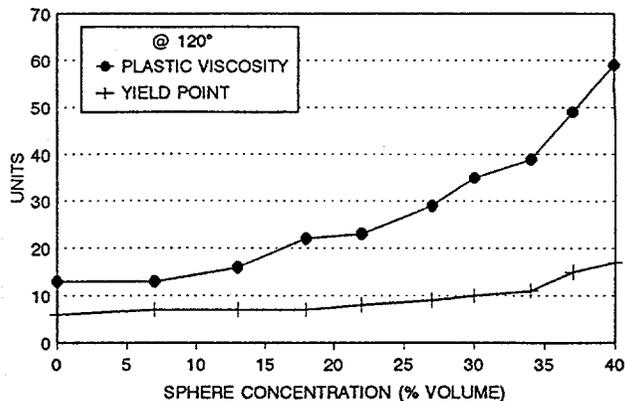


Figure 23. Lightweight Fluid Rheology

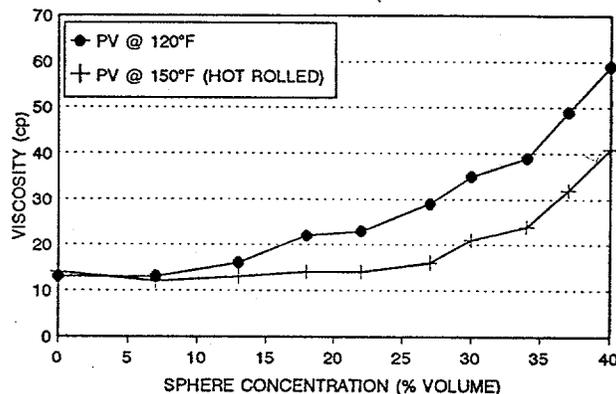


Figure 24. Plastic Viscosity

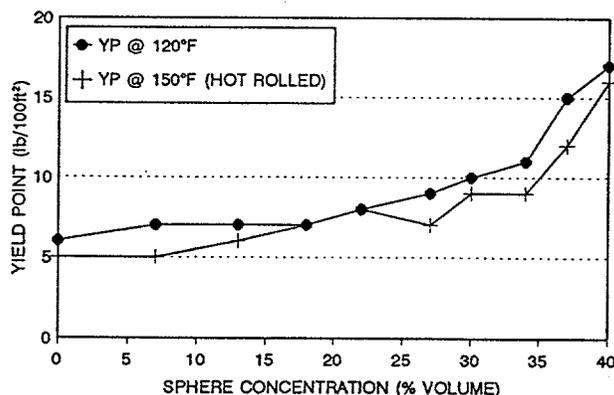


Figure 25. Yield Point

Figure 26 shows that the API filtration loss decreased from 8.3 to 6.2 cc/30 min as the hollow sphere concentration increased from 0 to 25 percent and then increased to 6.5 cc/30 min as the sphere concentration was increased to 40 percent. These filtration values are similar to those for conventional drilling fluids.

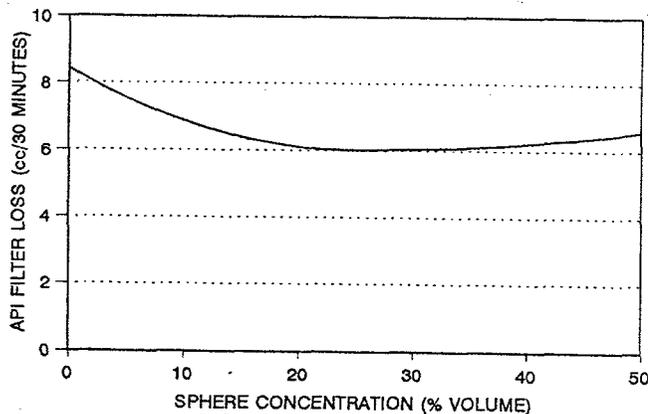


Figure 26. Filtration Loss

A solids control system consisting of a hydrocyclone and shale shaker has been assembled. Preliminary hollow glass sphere fluid testing through the hydrocyclone has started.

FUTURE WORK

Foam Computer Model

Development of the foam drilling computer model is well underway. Additional work still needed includes:

- (1) Methods to handle influxes of gas, oil, or water;
- (2) Adding jet subs, downhole motors, and other features to the model;

- (3) Comparing foam model output with existing laboratory and field data,
- (4) Phase II field verification of the model.

Lightweight Solid Additives

Tests to date have convinced experienced mud engineers that good lightweight drilling fluids can be constructed using hollow glass spheres.

Additional work remaining on lightweight solid additives includes:

- (1) Formulating and testing the LWSA in oil-base and brine water muds,
- (2) Testing the durability and recoverability of the LWSA with conventional solids control equipment,
- (3) Testing the durability of the LWSAs with jet nozzles, pumps, and mixing equipment,
- (4) Determining the effects of contamination on LWSA mud,
- (5) Determining the economics of the LWSA fluid, and
- (6) Phase II field testing of the lightweight fluid.

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