Use of Hollow Glass Spheres for Underbalanced Drilling Fluids

George H. Medley, Jr., SPE, William C. Maurer, Ph.D., SPE, and Ali Y. Garkasi, SPE, Maurer Engineering Inc.

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Abstract

Interest in underbalanced drilling is growing worldwide at a rate not seen for a new drilling technology since the introduction of horizontal drilling. Compressible, multi-phase fluids, often present in well bores, make underbalanced drilling difficult. This is a result of the intentional introduction of gas into the fluid either at the surface or through parasite or concentric strings or because of fluid influxes into the wellbore from the formation. Many underbalanced drilling problems would be eliminated by the successful implementation of the incompressible, lightweight drilling fluid described in this paper.

Introduction

Air drilling was first used in the mid-1800s and became very popular in the 1950s as air drillers discovered the benefits of underbalanced drilling. Historically, the most important benefit has been increased rate of penetration (ROP) possible in hard rocks as documented in the mid-1950s. ROP increases significantly with decreased hydrostatic pressure as shown in Figure 1.

The reduction in differential pressure results in several other benefits including removing drill cuttings from under the bit faster and allowing the bit to drill more efficiently and last longer. Since the differential pressure in true underbalanced drilling is into the wellbore rather than into the formation, lost circulation and differential sticking problems are reduced or eliminated.

Underbalanced drilling also significantly reduces formation damage. Reduced formation damage has been the driving force behind the resurgence in underbalanced drilling during the 1990s, especially in horizontal wells where extensive drilling times can cause major formation damage. Underbalanced drilling has proven useful in the Austin Chalk and has spread rapidly, especially in Canada, as shown in Figure 2.

Aerated Drilling Fluids

Drilling underbalanced in under-pressured or depleted reservoirs requires fluids lighter than water (Sp. Gr. < 1). Many types of fluid systems can be used, ranging from 100% gas (i.e., "air" drilling) to 100% liquid. All drilling fluids with densities below 6.9 ppg (Sp. Gr. = 0.83) currently in use contain gas or air. Besides pure gas, these fluids include mist, foam, and aerated (or nitrified) mud.

While beneficial for underbalanced drilling, the use of compressible fluids results in several problems, as shown in Figure 3.

Compressors and nitrogen can increase the cost of drilling by as much as $20,000-30,000 per day. Drill string corrosion can be a major problem with aerated fluids, because of the oxygen introduced downhole. The introduction of oxygen into an environment containing hydrocarbons (e.g., oil or gas) can result in downhole fires and explosions. Hydraulic calculations are more difficult due to the compressible, multi-phase nature of the fluid. Drill-string vibrations are more severe because aerated fluids do not cushion the pipe as well as pure liquids. Air drilling increases torque and drag since the friction factor in an air hole may be as much as 0.7-0.8, compared to 0.2-0.3
with conventional muds. Cuttings lifting is a major problem in many wells with air and mist drilling, leading to the formation of mud rings, increased pressure drops, and stuck pipe.

Conventional mud-pulse MWDs will not operate in aerated fluids because of rapid signal attenuation in the drill string, a major problem in drilling underbalanced horizontal wells.

Lightweight, Incompressible Drilling Fluid
A lightweight, incompressible fluid, having a density lower than that of water, could overcome most of the problems encountered with aerated fluids while maintaining the benefits of underbalanced drilling. Such a drilling fluid, utilizing hollow glass spheres, is currently being developed and tested on a U.S. Department of Energy project.

In the late 1960s, scientists in Russia utilized lightweight fluids containing hollow glass spheres (HGS) to reduce fluid density in areas where severe lost circulation problems had previously precluded drilling.

Solid spheres have been added to drilling mud to increase lubricity and lower friction factors. Oil-field service companies in the United States have used hollow spheres and other lightweight additives for years to reduce the density of cements in lost circulation areas, but to the best of our knowledge, hollow spheres have never been used in lightweight drilling fluids outside of Russia until this DOE project.

Hollow Glass Sphere Physical Properties
Commercially available hollow glass spheres (HGS) are typically used as extenders in paints, glues, and other liquids. Candidate hollow glass spheres were selected based on their physical properties and their ability to maintain those properties under the high pressures and temperatures encountered in oil and gas wells. The most important factors are the specific gravity and collapse strength of the spheres.

Specific Gravity. Initial candidates included the lightweight crystalline-silica additives commonly used in lightweight cements. With cement, hollow glass spheres with specific gravities of 0.7 are adequate since they significantly reduce the density of cement slurries having specific gravities of 1.8 to 2.0. These spheres have minimal effect on reducing the density of muds having specific gravities of 1.03-1.05, so lighter spheres (i.e., Sp. Gr. = 0.35-0.40) are required in lightweight fluids for underbalanced drilling.

Microscopic hollow glass spheres with a specific gravity of 0.38 and collapse pressure of 3000 to 4000 psi are used in the DOE lightweight drilling fluid. They are ideal for this application because of their low density (Figure 4) and small size (i.e., 8 to 125 microns) as shown in Figure 5.

Collapse Pressure. Collapse pressure tests were performed on the candidate spheres at pressures up to 2400 psi. Figure 6 shows how the volume of the hollow sphere mixture decreased as the pressure increased. The compressibility of the sphere and water mixture was 3.2 x 10^4 psi^-1, compared to 3.4 x 10^4 psi^-1 for water alone, showing that the glass spheres are essentially incompressible.

Three to five percent (by volume) of the hollow glass spheres broke and sank after the application of 2400 psi pressure.

The hollow glass spheres selected for use in the lightweight drilling fluid have properties similar to those used by the Russians (Table 1).

Additional tests were performed with collapse pressures up to 4300 psi at room temperature and at 250°F. The average compressibilities were 4.8 x 10^-4 psi^-1 at room temperature and 4.0 x 10^-4 psi^-1 at 250°F, again showing that these spheres are essentially incompressible.

HGS Fluid Rheology. The effects of hollow glass sphere concentration on rheology and API filtration rate were measured before and after hot rolling for 16 hours at 150°F using standard API test procedures and equipment. The rheology was measured using a Fann 35A viscometer.

Figure 7 shows that the density of the HGS fluid decreases from 8.8 to 6.0 ppg as the hollow glass spheres concentration (0.38 Sp. Gr.) is increased from 0 to 50 percent. The solids content of a mud increases as drill cuttings are added, thus dehydrating the mud. Consequently, a practical limit for HGS drilling fluid concentration is 35-40 percent (i.e., 6.5 to 6.8 ppg).

The rheology of HGS fluid is similar to that of conventional drilling fluids (Figure 8). Plastic viscosity (PV) increases with increased solids content in the mud. The PV of 60 cp at a sphere concentration of 40 percent is relatively high but within acceptable limits for drilling fluid.

Yield Point (YP) is a measure of the fluid's capacity to suspend and carry cuttings. Figure 8 shows that the YP increased, but remained within acceptable limits, as the solids concentration was increased to 40 percent.

Figures 9 and 10 show that the PV and YP of the HGS fluid hot-rolled for 16 hours at 150°F were slightly lower than at 120°F.

HGS Fluid Filtration Loss
Figure 11 shows that the API filtration loss decreased from 8.3 to 6.2 cc/30 min as the sphere concentration was increased from 0 to 25 percent. As the sphere concentration was increased further to 40 percent, the fluid loss increased slightly to 6.5 cc/30 min. These values are similar to conventional PHPA muds and within acceptable limits.

Table 2 compares the properties of a conventional PHPA drilling fluid to a HGS drilling fluid containing 40% by volume of hollow glass spheres.
Solids Contaminant Testing. Test were conducted to study the effects of drill solids on the HGS fluids. During two series of tests, the hollow glass sphere concentration was held constant at 30 and 50 lb/bbl (16 and 26 percent by volume), while the concentration of drill solids (REV dust), was increased from 0 to 90 lb/bbl (approximately 0 to 10 percent by volume.)

Figure 12 shows that the PV increased from 20 to 60 cp while the REV dust concentration was increased to 90 lb/bbl at 120°F. At low drill solids concentrations, hot rolling at 150°F for 16 hours reduced the PV slightly. At higher drill solids concentrations (i.e., over 80 lb/bbl), hot rolling significantly increased the PV.

Figure 13 shows that at high solids concentrations, hot rolling decreased the YP.

Figures 14 and 15 show how the gel strengths increase with increasing drill solids. Without thinners, the gel strengths reach values that are too high to manage in field applications with solids contents above 40 to 50 lb/bbl (5-6 percent by volume). Fortunately, the addition of 0.25 to 1.0 lb/bbl of common polymer thinners lowers the gel strengths to acceptable limits.

An HGS mud composed of 50 lb/bbl (26 percent) hollow glass spheres and 50 lb/bbl (5.5 percent) drill solids was treated with several deflocculants, before and after hot rolling. In a typical test, 1.0 lb/bbl of a common thinner reduced the 120°F, 10-minute gel from 44 to 10 lb/100 ft². After hot-rolling, the thinner reduced the 10-minute gel from 68 to 12 lb/100 ft². The same thinner reduced the hot-rolled PV from 36 to 33 cp and the YP from 20 to 15 lb/100 ft². This shows that thinner will be required with HGS muds containing higher concentrations of spheres and drill solids.

Table 3 shows typical gel strengths of the HGS fluid after hot-rolling. The gel strengths after treatment with three polymeric deflocculants and chrome-free lignosulfonate are compared to the gel strengths of an untreated mud. In all cases, the gel strengths were reduced, with four of the five thinners producing significant reductions.

Lubricity and Casing Wear. Solid plastic and glass spheres are routinely used to reduce friction in high-angle and horizontal wells. Hollow glass spheres therefore have potential for reducing friction and casing wear. To test these properties, hollow spheres were mixed with a conventional water-based mud and tested in a casing wear test machine. During a standard test, 9%-inch, 47 lb/ft, N-80 grade casing is subjected to the grinding action of a conventional smooth steel drill pipe tool joint rotating at 120 rpm under a lateral load of 3,000 lb/ft, simulating the action of a drill string rotated inside casing. This test yields measurements of friction factors and casing wear with different drilling fluids.

A water-based mud containing 35 percent by volume hollow glass spheres was subjected to the standard test for 8 hours. The measured friction factor, 0.18, was comparable to that of a standard fresh-water base fluid, while the casing wear was reduced by 78 percent (i.e., from 18 to 4 percent of the wall thickness). With 2 percent sand added, the casing wear was reduced by 65 percent (i.e., from 20 to 7 percent).

Durability and Recoverability of Spheres
Because of the high cost of the hollow glass spheres, durability and recoverability of the spheres is critical to the economic use of HGS fluid. The spheres must not break when subjected to the forces and pressures exerted by conventional rig pumps and solids control equipment. The percentage of spheres recovered at the conclusion of the well will determine whether the spheres will be competitive with conventional fluids. A sphere recovery rate of 50 to 100 percent should make HGS mud costs competitive with aerated fluids in many applications.

Laboratory Sieve Tests. The primary piece of solids control equipment on a rig is a shale shaker, so the effectiveness of the shale screens with the hollow glass spheres is of major importance. The mud containing the spheres must be able to pass through the shaker, allowing the larger drill cuttings to be retained on the screen without damaging or removing significant portions of the glass spheres.

Standard laboratory sieve tests were used to decide what mesh shaker screens to use in yard tests with conventional rig shakers. A sample of the HGS PHPA mud, containing 45 percent spheres and 2 percent sand was tested with 325, 200, 100, and 50 mesh screens corresponding to opening sizes of 44 microns to 279 microns. Considering the sphere particle size distribution, 44 percent of the hollow glass spheres should have passed through the 325-screen mesh, and 100 percent through the 50- and 100-mesh screens.

In the 10-minute initial test, the sieves were "blinded," or heavily loaded with mud with 100 percent of the mud passing the 50-mesh sieve, 17 percent through the 100-mesh sieve, and none passing through the 325-mesh screen (Figure 16).

In the second test, a smaller volume of HGS mud was poured onto the 200-mesh sieve (74 micron opening) to simulate an "un-blinded" screen. Based on the particle size distribution, 80 to 85 percent of the spheres should have passed the 200-mesh sieve (i.e., 15 to 20 percent should be retained). In actuality, the 200-mesh sieve retained 45 percent of the mud volume, including 20 percent of the original spheres in the mud sample, indicating that typical shale shaker screens should be capable of passing or retaining the expected particle sizes as long as the screens do not become "blinded."

Based on these laboratory tests, 100-mesh and 200-mesh shaker screens were selected for yard testing. The 100-mesh screen should theoretically pass 100 percent of the hollow glass spheres while retaining drill cuttings larger than 140 microns, and the 200-mesh screen should theoretically pass 80 to 85 percent of the hollow spheres while retaining drill cuttings larger than 74 microns.

Gravity Segregation. Conventional low gravity drill solids (sp. gr. = 2.6) and weighting materials such as barite (sp. gr. = 4.3), settle in the drilling fluid, whereas the hollow glass spheres tend to float upward in the drilling fluid because of buoyancy. The density ratio of water and the hollow glass
spheres, 2.6, is about the same as the density ratio of low gravity solids (sandstone, limestone, shale) to water. The rate of gravity segregation should therefore be similar in both cases, except that the hollow glass spheres tend to float upward, whereas drill solids and barite settle downward.

Laboratory tests showed that the simplest and quickest way to recover the hollow spheres from the HGS muds is to take advantage of the natural tendency of the lightweight spheres to float to the surface of the mud, especially when the HGS muds are diluted with water. Laboratory tests were performed to determine the rate and percentage of recovery of hollow glass spheres by flotation techniques.

In the first test, five samples of a clean HGS mud containing 10 lb/bbl of bentonite, 35 percent hollow glass spheres, and two percent sand were tested at water dilution levels of 0 to 80 percent. Fifty percent dilution corresponds to two parts of HGS mud and one part water.

The amount of sphere separation was recorded as a function of time. Sphere recovery from the sample with no dilution reached a plateau of 84 percent after 30 minutes and 88 percent after 24 hours.

The other samples all reached recoveries of 93 percent after 17 minutes, and 93 to 95 percent after 30 minutes. The manufacturer's specification for the spheres is that 90 percent will remain buoyant in long duration tests.

Figure 17 shows that higher dilution rates with water may not increase ultimate recovery, but will slightly accelerate the recovery process in the early time period (i.e., the first 15 minutes).

The second test was conducted with HGS mud containing 38 percent hollow glass spheres and 50 lb/bbl (5.5 percent by volume) simulated drill solids. The samples were diluted with 20 to 100 percent water. The initial dilution of 20 percent was selected because a visual determination of sphere recovery with no dilution was difficult in the dirtier mud.

The sphere recovery rate decreased as the percent of low gravity solids increased, as shown in Figure 18. The ultimate recovery of spheres plateaued and remained nearly constant after 30 minutes.

Figure 18 shows that with 20 percent water dilution, only 40 percent of the spheres were recovered after 15 minutes, whereas with 100 percent dilution, 70 percent were recovered.

These data also show that the rate of recovery and the ultimate recovery both accelerate with increasing amounts of dilution.

Yard Testing

Yard tests were carried out on the HGS muds using conventional drilling rig solids control equipment, including centrifugal pumps, hydrocyclones, and a high-speed centrifuge. Tests involving a conventional rig-type shale shaker are currently underway.

Centrifugal Pumps. Centrifugal pumps, used to transfer drilling fluids between tanks and solids control equipment, impart some of the highest shear stresses experienced by the mud. Tests were conducted to determine if the high-speed impeller blades in these pumps would break the hollow glass spheres.

A 40-HP transfer pump (5 x 6 centrifugal pump, 9.5-inch impeller, 1765 RPM) was used to move the HGS muds during yard testing.

During the first test, an HGS mud containing 37 percent hollow glass spheres was circulated through the centrifugal pump for 4 hours, and during the second test, an HGS mud with 45 percent spheres was circulated for 12 hours. The density of the drilling fluids was measured periodically to determine if hollow sphere breakage was occurring. An increase in mud weight, or fluid density, would indicate that spheres were being damaged to the point of failure, causing them to sink and allowing the entrained air to escape. There was no increase in fluid density in either case, indicating that the spheres were not damaged by the centrifugal pump.

Conventional Hydrocyclones. Hydrocyclones, or cones, when operated properly, can remove smaller particles than shale shakers. Cones separate particles from the mud using centrifugal force to speed up the natural gravity separation process, separation rate being dependent upon both density and particle size.

In normal operation, sand moves to the outside of the cone due to its higher density and flows out of the bottom of the cone. In the liquid flows to the center of the cone and then upward out of the top of the cone. The hollow glass spheres, due to their low density, move to the center of the cone and flow out of the top of the cone with the fluid. Normally, the larger the cone diameter, the higher volume it can handle and the larger the particle size it can separate.

The optimum loading conditions for hydrocyclones depend on the inlet pressure which increases with increased fluid density. For optimum operation, most cones require 70-80 feet of hydraulic head at the inlet. Because the density of HGS muds is much lower than conventional muds, the cones will operate at lower inlet pressures.

A five-inch diameter hydrocyclone was selected for initial testing since this is a readily available oil-field size.

An HGS mud composed of 5 lb/bbl bentonite, 0.25 lb/bbl high molecular weight PHPA, 45 percent hollow glass spheres, and 4 percent sand was circulated through the cone at three different flow rates, corresponding to pressure heads bracketing the manufacturer's recommended head. Table 4 shows the properties of the fluid at the inlet, the overflow, and the underflow of the hydrocyclone during the initial test, made at 75 ft. of pressure head. Additional tests were run at 90 and 105 feet of head.

The density of the underflow indicates that separation is occurring in the hydrocyclone at all inlet pressures (Figure 19).

Figure 20 shows the solids removal rates for the 5-inch cone operating at pressure heads of 75, 90, and 105 feet. At 90 feet of head, the hydrocyclone was most efficient, being 6 percent more efficient than at the manufacturer's recommended head of 75 feet and 13 percent more efficient than at the higher heads used by some operators.
The density of the overflow must be lower than the density of the inlet sample when sand is being removed, but this difference could not be detected due to low rate at which sand is removed. Additional hydrocyclone testing is currently underway to confirm these results.

Conventional Centrifuge. An HGS mud was tested using a drill rig-compatible, decanting, high-speed centrifuge. Multiple tests were undertaken varying the simulated drill solids loading, the speed of the centrifuge, the feed rate to the centrifuge, and the weir height inside the centrifuge. Forty underflow and overflow samples are now being analyzed to determine the effectiveness of the centrifuge on an HGS mud. No data is currently available; however, some observations can be drawn.

In all of the tests, the majority of the fluid exited the centrifuge through the underflow ports where solids normally exit. The maximum flow measured in the overflow was 15 percent of the total flow, this occurring at the lowest feed rate tested.

As the solids content increased, the percent overflow decreased. With lower drill solids contents, feed rate did not affect the percent overflow, whereas with higher solids content, increasing the feed rate decreased the overflow percentage.

As the drill solids increased (i.e., with higher solids concentration in the fluid or at higher feed rates), the auger of the centrifuge began to plug since the machine was designed to handle wet overflows and dryer underflows. With drill solids concentrations of 50 to 55 lb/bbl (5.75%) plugging of the auger rendered the centrifuge unusable.

At high centrifugal forces, the HGS mud is apparently being de-watered, causing the hollow spheres to clump or cake together and plug the centrifuge.

Future laboratory testing is necessary to find appropriate fluid loss additives to prevent this de-watering effect, or to identify surfactants that will prevent the spheres from clumping together under these conditions.

Economics

Many factors determine the economic viability of the hollow glass sphere muds. The cost of the mud itself is the most obvious factor, but sphere recoverability and increases in rate of penetration and well productivity also affect economics. The HGS muds could be highly competitive with aerated and nitrified fluids where compressor and nitrogen costs can be as high as $20,000 to $30,000 per day.

A barrel of conventional 8.8 ppg PHPA mud costs from $1.50 to $2.50. At current glass sphere costs, a comparable barrel of HGS mud containing 30 percent hollow glass spheres, will cost $70 to $80, which is comparable to mineral oil base muds. It is possible that the cost of the hollow glass spheres can be reduced if they find widespread use in the petroleum industry and large quantities are utilized.

The range of expected sphere recovery, based on the previously described lab work and assuming no losses downhole, is 70 to 95 percent, thus recycling the spheres can result in a net mud cost of $5.50 to $25.00/bbl, exclusive of the cost of recovering the spheres. The HGS mud would not have the high environmental cost associated with oil base muds, since the glass spheres are inert and easily disposable.

A conventional PHPA mud system typically represents 8 to 15 percent of the total cost of drilling a well, exclusive of completion costs, whereas a mineral oil base mud system often represents 20 to 25 percent of the total drilling cost. If the maintenance and make-up cost of the HGS mud is comparable to a mineral oil base system, the use of an HGS mud would increase the cost of a 20-day, 9,000-foot total depth, $400,000 well by $40,000 to $75,000, significantly less than the cost of compressors and/or nitrogen.

If increased rate of penetration (ROP) is the sole reason for underbalanced drilling, the ROP would have to be increased by 23 percent to break even (i.e., 550 vs. 450 ft/day), well within the realm of possibility, since 2- to 10-fold ROP increases are often observed in underbalanced drilling.

The potential for improved productivity in wells drilled underbalanced is also high due to the reduction or elimination of formation damage. A small improvement in productivity over the life of a well would justify the additional cost of an HGS mud.

Conclusions

1. An incompressible fluid having a density less than water would overcome many of the problems associated with aerated fluids, opening up many new areas to underbalanced drilling.
2. Lightweight, incompressible drilling fluids can be constructed using commercially available, hollow glass spheres. At lower concentrations, the lightweight muds behave similar to conventional drilling fluids.
3. The HGS muds have potential for significantly reducing underbalanced drilling costs since they would eliminate compressors and nitrogen that can be very expensive.
4. Laboratory tests show that a hollow glass sphere (HGS) drilling fluid will significantly decrease casing wear caused by drill-string rotation.
5. Conventional drilling rig solids control equipment, including centrifugal transfer pumps, do not damage the hollow glass spheres.
6. The 4000-psi collapse pressure of the hollow glass spheres will allow their use in relatively deep underbalanced wells.
7. Drill solids must be removed with large-mesh size shale shaker screens and hydrocyclones. Conventional oil-field centrifuges are not effective in removing drill solids or hollow glass spheres from the mud.
8. Low cost methods of separating the spheres from the whole mud should be possible utilizing a combination of gravity segregation, conventional hydrocyclones, and shale shakers.
9. The cost of HGS muds can be significantly reduced by recovering and recycling the hollow spheres.
10. HGS muds should be competitive with nitrogen drilling without recycling the spheres and should be competitive with conventional air drilling if the spheres can be recycled.
Acknowledgments
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References
4. Eskins, M., 1994: Personal communications, Moscow, Russia, October.

SI Metric Conversion Factors

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*Conversion factor is exact.

TABLE 1. Lightweight Hollow Spheres Properties

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TABLE 2. Comparison of Conventional Mud

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TABLE 3. Effect of Deflocculants on HGS Fluid Gel Strengths

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TABLE 4. 6-Inch Hydrocyclone Data

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FIGURE 1. EFFECT OF DIFFERENTIAL PRESSURE ON DRILLING RATE (Moffitt, 1991)

FIGURE 2. CANADIAN UNDERBALANCED WELLS (Knoll, 1995)

FIGURE 3. AERATED DRILLING PROBLEMS

FIGURE 4. SPECIFIC GRAVITY

FIGURE 5. PARTICLE SIZE DISTRIBUTION OF SPHERES

FIGURE 6. LIGHTWEIGHT FLUID COMPRESSIBILITY
FIGURE 7. MUD DENSITY

FIGURE 10. YIELD POINT

FIGURE 8. LIGHTWEIGHT FLUID RHEOLOGY

FIGURE 11. FILTRATION LOSS

FIGURE 9. PLASTIC VISCOSITY

FIGURE 12. DRILL SOLIDS EFFECT ON HGS MUD PV
FIGURE 13. DRILL SOLIDS EFFECT ON HGS MUD YP

FIGURE 14. SIMULATED DRILL SOLIDS EFFECT ON HGS MUD GEL STRENGTH

FIGURE 15. DRILL SOLIDS EFFECT ON HOT ROLLED HGS MUD

FIGURE 16. "BLINDED" SCREEN TEST

FIGURE 17. SEPARATION OF HGS IN CLEAN MUD

FIGURE 18. SEPARATION OF HGS IN SOLIDS-LOADED MUD
FIGURE 19. HYDROCYCLONE DENSITY EFFECT

FIGURE 20. HYDROCYCLONE CALCULATED SOLIDS REMOVAL