“Enhanced Wellbore Stabilization and Reservoir Productivity with Aphron Drilling Fluid Technology”

QUARTERLY PROGRESS REPORT

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by

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ABSTRACT

During this first Quarter of the Project, a team of five individuals was formed to characterize aphron drilling fluids, with the ultimate objectives to gain acceptance for this novel technology and decrease the costs of drilling mature and multiple-pressure formations in oil and gas wells. Aphron drilling fluids are very high low-shear-rate viscosity fluids laden with specially designed microbubbles, or "aphrons." The focus of the Project is to develop some understanding of the aphron structure and how aphrons and base fluid behave under downhole conditions.

Four tasks were begun during this Quarter. All of these focus on the behavior of aphrons: (a) Aphron Visualization – to evaluate various methods of measuring bubble size distribution, especially Acoustic Bubble Spectroscopy (ABS), in aphron drilling fluids at elevated pressure; (b) Fluid Density – to investigate the effects of pressure, temperature and chemical composition on the survivability of aphrons; (c) Aphron Air Diffusivity – to determine the rate of loss of air from aphrons during pressurization; and (d) Pressure Transmissibility – to determine whether aphron networks (similar to foams) in fractures and pore networks reduce fracture propagation.

The project team installed laboratory facilities and purchased most of the equipment required to carry out the tasks described above. Then work areas were combined to permit centralized data acquisition and communication with internal and external file servers, and electronic and hard copy filing systems were set up to be compatible with ISO 9001 guidelines.

Initial feasibility tests for all four tasks were conducted, which led to some modification of the experimental designs so as to enable measurements with the required accuracy and precision. Preliminary results indicate that the Aphron Visualization, Aphron Air Diffusivity and Pressure Transmissibility tasks should be completed on time. The Fluid Density task, on the other hand, has some fundamental problems that may preclude realization of its objectives; alternative experimental approaches and methods of analysis will be explored during the next Quarter.

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INTRODUCTION

Aphron drilling fluids were developed to enable construction of a wellbore through low-pressure and underbalanced formations without incurring the safety and economic costs of drilling with a low-density fluid.[1] Aphron drilling fluids are thought to seal permeable zones by virtue of their very high low-shear rheology and the unique bridging capability of specially designed micro-bubbles dubbed "aphrons".[2] These aphrons are composed of two fundamental elements:[3] a core of air and a protective shell composed of multiple layers of surfactants and polymers. The outer skin is a surfactant bilayer that renders the aphron hydrophilic and, therefore, compatible with the continuous aqueous phase. However, the structure of the bi-layer is tenuous: the outermost surfactant layer in the bi-layer can be shed by shear or under compression.[2] Thus, when aphrons are forced together in a pore throat or near a fracture tip, they acquire some hydrophobic character which permits them to agglomerate without coalescing and seal off the opening.

Unfortunately, the structure of the aphron and the sealing mechanism described above are mainly conjecture and have not been confirmed under stringent laboratory conditions. Furthermore, there is considerable skepticism about the ability of aphrons to withstand even moderate pressures downhole. Systematic and thorough evaluation of aphron drilling fluids to gain some understanding of the structure of aphrons and how they behave downhole would help greatly to gain acceptance for this novel technology and decrease drilling costs significantly.

The objectives of this project are threefold: (a) to develop a comprehensive understanding of how aphrons behave at elevated pressures and temperatures; (b) to measure the ability of aphron drilling fluids to seal permeable and fractured formations under simulated downhole conditions; and (c) to determine the role played by each component of the drilling fluid.

The scope of this project is divided into two phases, which coincide with the expected two-year duration of the project. Phase I is aimed at developing evidence for the ways in which aphrons behave differently from ordinary surfactant-stabilized bubbles, thereby providing effective, yet minimally damaging, seals of permeable and fractured formations at the elevated pressures and temperatures encountered in any gas or oil well drilling operation. Key properties to be investigated include the effects of pressure on bubble size, the hydrophobic nature of the aphron surface and nature of aphron seals in fractures and pore networks. Initial sealing and formation damage tests also will be carried, using lab-scale apparati designed to simulate permeable and fractured environments. Phase II focuses on sealing and formation damage testing of aphron drilling fluids, including scale-up tests under simulated downhole drilling conditions, so as to furnish irrefutable evidence for the validity of this technology and provide field-usable data.

The current schedule of tasks is provided in Figure 1.

	2003	2004				2005		
Task	4th Q	1st Q	2nd Q	3rd Q	4th Q	1st Q	2nd Q	3rd Q
I. Physical Characterization of Aphrons								
1a. Aphron Visualization	X	X	X	X				
1b. Fluid Density	X	X						
1c. Aphron Air Diffusivity	X	X	X					
2a. In Situ Visualization			X	X				
2b. Pressure Transmissibility	X	X	X					
2c. Aphron Shell Hydrophobicity			X	X				
3a. Sealing of Permeable Media			X	X				
3b. Sealing of Fractured Media			X	X				
II. Characterization of Aphron Drilling Fluids								
1a. Lab Tests Leak-Off/Return Perm					X	X	X	
1b. Field-Sim Tests Leak-Off/Return Perm							X	X
2a. Flow Sim through & Sealing Fractures					X	X	X	X
2b. Fracture Re-Opening Tests						X	X	X

Figure 1. Schedule of Tasks to be Performed in Aphron Drilling Fluid Project

The tasks highlighted in **red** were begun during the 4th Quarter of 2003. These have the following objectives:

1a. Aphron Visualization - Evaluate the Acoustic Bubble Spectrometer (ABS) procedure to determine if the method is applicable for future measurements of bubble size distribution (BSD) in a pressurized environment. Determine the effects of pressure, temperature and chemical composition on the BSD of aphron drilling fluids.

1b. Fluid Density - Investigate the effects of pressure, temperature and chemical composition on the density of aphron drilling fluids.

1c. Aphron Air Diffusivity - Determine the effects of pressure, temperature and chemical composition of aphron drilling fluids on the rate of loss of air from aphrons and, hence, the importance of air loss on the survivability of aphrons.

2b. Pressure Transmissibility - Investigate the rate and magnitude of pressure transmission in simulated fractures and in permeable rock bridged with aphrons to test the hypothesis that aphron networks can reduce mud loss via reduction of pressure transmissibility.

EXECUTIVE SUMMARY

A team was formed to characterize aphron drilling fluids, with the ultimate objectives to gain acceptance for this novel technology and decrease the costs of drilling mature and multiple-pressure formations in oil and gas wells. Aphron drilling fluids are very high low-shear-rate viscosity fluids laden with specially designed microbubbles, or "aphrons." The distinguishing characteristic of this drilling fluid is its ability to enable drilling of low-pressure formations -- including depleted production zones – with minimal mud loss and formation damage. Thus, it serves as an alternative to underbalanced drilling without the economic and safety risks associated with use of low-pressure drilling fluids. However, there is little mechanistic evidence that aphron drilling fluids perform as claimed, and it would be very helpful for the U.S. drilling industry and, ultimately, for the U.S. consumer to develop some understanding of the aphron structure and how aphrons and base fluid behave under downhole conditions in a well-controlled laboratory environment. This is the focus of the Project.

Five individuals with suitable credentials were assembled to carry out the Project. This Project team installed laboratory facilities and purchased most of the equipment required to carry out the tasks in Phase I. Then work areas were combined to permit centralized data acquisition and communication with internal and external file servers, and electronic and hard copy filing systems were set up to be compatible with ISO 9001 guidelines.

Four tasks were begun during this Quarter. All of these focus on the behavior of aphrons: (a) Aphron Visualization – to evaluate various methods of measuring bubble size distribution, especially Acoustic Bubble Spectroscopy (ABS), in aphron drilling fluids at elevated pressure; (b) Fluid Density – to investigate the effects of pressure, temperature and chemical composition on the survivability of aphrons; (c) Aphron Air Diffusivity – to determine the rate of loss of air from aphrons during pressurization; and (d) Pressure Transmissibility – to determine whether aphron aggregates formed in fractures and pore networks reduce fracture propagation.

Initial feasibility tests were conducted for all four tasks, which led to some modification of the experimental designs so as to provide the required accuracy and precision. Preliminary results indicate that the Aphron Visualization task should be completed on time (9/30/04). Although there are difficulties with the Acoustic Bubble Spectroscopy software and with construction of a high-temperature, high-pressure (HTHP) system, it is expected that the software can be modified to provide an accurate bubble size distribution, and the cell for the HTHP system may need to be re-designed and built locally to enable experimentation at the target conditions of 20.7 MPa (3,000 psi) and 121 ^{o}C (250 ^{o}F). To observe the flow and aggregation of aphrons in porous media, a locally available Environmental Scanning Electron Microscope has been checked out and appears to be suitable for in situ visualization of the sealing of pore networks.

The Fluid Density task, on the other hand, has some fundamental problems that may preclude realization of its objectives by the scheduled completion time (3/31/04). Measurement of absolute volume changes accompanying pressurization is fraught with too many uncertainties to per-

mit accurate determination of the persistence of entrained air (aphrons). Alternative experimental approaches and methods of analysis will be explored during the next Quarter.

The Aphron Air Diffusivity task appears to be on schedule (completion date 6/30/04). A specially designed Dissolved Oxygen probe has been identified as the device most likely to provide accurate measurements of the rate of loss of oxygen (and air) through the aphron shell as a function of temperature and pressure. There are some issues, though, that will need to be examined after arrival of the probe, including sensitivity of the probe to surface-active components and viscosity of the drilling fluid.

Finally, the Pressure Transmissibility task is expected to be completed on time (6/30/04), though there have been significant questions about the ability to create aphron aggregates in the experimental apparatus. The most recent apparatus consists of a 6 m (20 ft) straight piece of 0.64 cm (1/4") tubing with a gravity-feed pressure-assisted filling system. Rate of pressure transmission and steady-state pressure drop along the length of the tube are monitored.

EXPERIMENTAL APPROACH

The various approaches used for the four current tasks are detailed below:

Aphron Visualization

- Formulate a mud that is representative of the APHRON ICS mud system, yet transparent to light:

▪ FloVis Plus	8.6 g/L (3 lb/bbl)
▪ 50% NaOH	to pH 10
▪ Blue Streak	2.9 g/L (1 lb/bbl)
▪ EMI-779	1.4 g/L (0.5 lb/bbl)
▪ EMI-780	1.4 g/L (0.5 lb/bbl)

- Measure BSD using photomicrography, laser light scattering and ABS and compare the results of the three methods using the following fluids:
    - Transparent Aphron Mud Formulation without entrained air
    - Transparent Aphron Mud Formulation with varying amounts of entrained air and varying shear history.

Fluid Density

- Determine survivability of aphrons by measuring the effect of pressure on fluid volume and density, from which the concentration of undissolved air can be determined. Initial tests with a modified Huxley-Bertram viscometer indicated that this device is not suitable for precise measurements of fluid volume in an air-laden fluid. Instead, an Isco pump is now being used to generate pressure and monitor volume changes of the fluid.

- Carry out initial tests with a standard aphron-laden drilling fluid containing variable amounts of air, and generate density vs pressure curves over a range of fluid temperatures. Later, examine the effects of different surfactants and polymers on the survivability of the aphrons.

Aphron Air Diffusivity

- To measure the rate of loss of air from aphrons, examine the possibility of measuring the rate of increase of Dissolved Oxygen (DO) in the surrounding aqueous medium. Determine the principle underlying operation of various DO probes, their accuracy and reproducibility, methods of using them, and their limitations, e.g. effect of pressure.
- Construct a vessel that can accommodate a suitable DO probe and enable measurements of DO at elevated pressures and temperatures.
- Run experiments to determine the effects of pressure, temperature and chemical composition on the rate of build-up of dissolved air. If possible, run complementary tests to measure the corresponding change in bubble size that can be correlated with the rate of increase in the concentration of dissolved air in the mud.

Pressure Transmissibility

- Design and construct an appropriate system to monitor the rate, as well as the amplitude, of pressure transmission through aphron drilling fluids and aphron "bridges" in a simulated fracture and permeable rock. Begin by simulating a fracture using an existing 76-m (250 ft) length of 0.64-cm (1/4") OD stainless steel tubing fitted with three pressure transducers along its length.
- When a suitable system has been constructed, measure steady-state pressure drop and the rate of pressure transmission through standard APHRON ICS fluid as a function of the concentration of air and aphron-stabilizing components.

RESULTS AND DISCUSSION

Aphron Visualization

Preliminary ABS tests were run with the transparent Aphron ICS mud formulation at ambient temperature and pressure. At present it appears that the dilution method developed previously (deaerated mud/aerated mud > 100/1) is still required to minimize bubble-bubble interference and obtain an accurate measure of the total volume of bubbles in the fluid and an accurate representation of the BSD. The ABS software has a number of problems, which the provider, Dynaflow, Inc., has been asked to solve. An amplifier was ordered to alleviate some of the issues. However, the SCSI circuit board crashed, preventing running the ABS at all… repairs are being attempted by the supplier.

Some photomicrographs were taken of aphrons in the transparent mud formulation, again at ambient temperature and pressure. A Coulter Particle Size Distribution Analysis system is being examined to determine whether it can yield accurate visual BSD of the aphrons. In addition, the Gas Technology Institute has been asked to submit a proposal for independent confirmation tests using a laser visualization technique.

Initial information was gathered to determine the viability of using an Environmental Scanning Electron Microscope to monitor the flow and sealing of pore networks by aphrons. This looks quite promising, inasmuch as samples can be examined at moderate pressure.

Numerous discussions were held with Dynaflow, Inc. on the design and construction of the HTHP ABS System. Although the system (see Figure 2) is expected to be ready by the end of January, 2004, a number of questions have been raised about the safety and handling of the high-pressure cell.

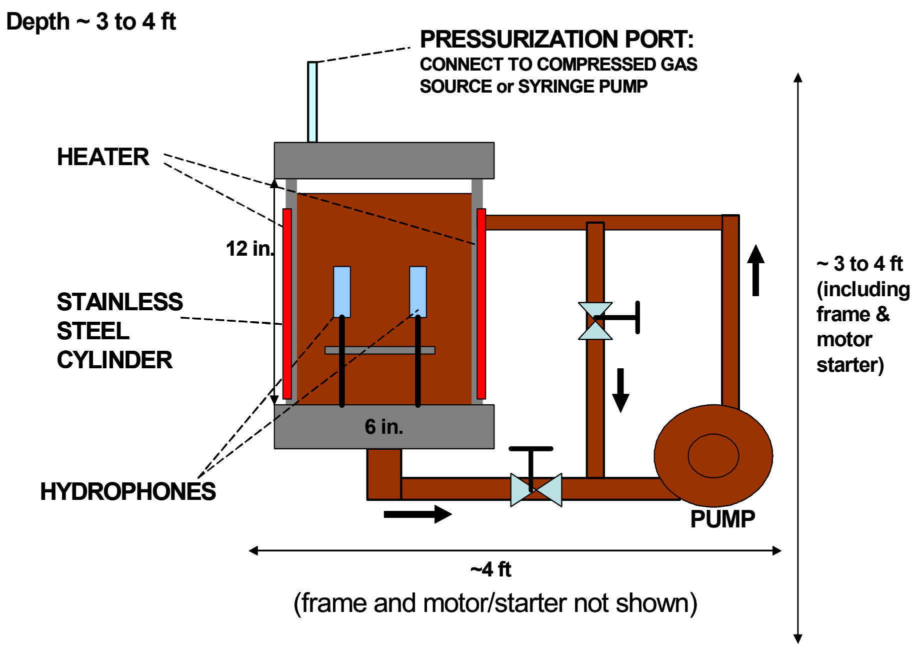

Figure 2. Schematic of HTHP ABS System

Fluid Density

A dual-accumulator system with a total working volume of ~ 1L has been designed and built to work with an Isco syringe pump to generate density vs pressure curves (see Figure 3):

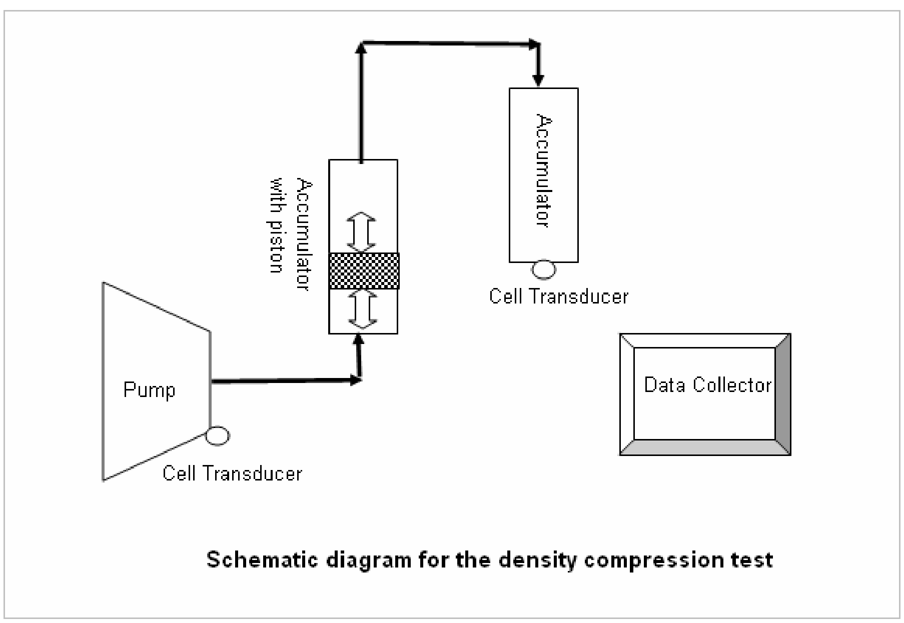

Figure 3. Schematic of Fluid Density Apparatus

A typical example of data generated with the Fluid Density Apparatus is shown in Figure 4:

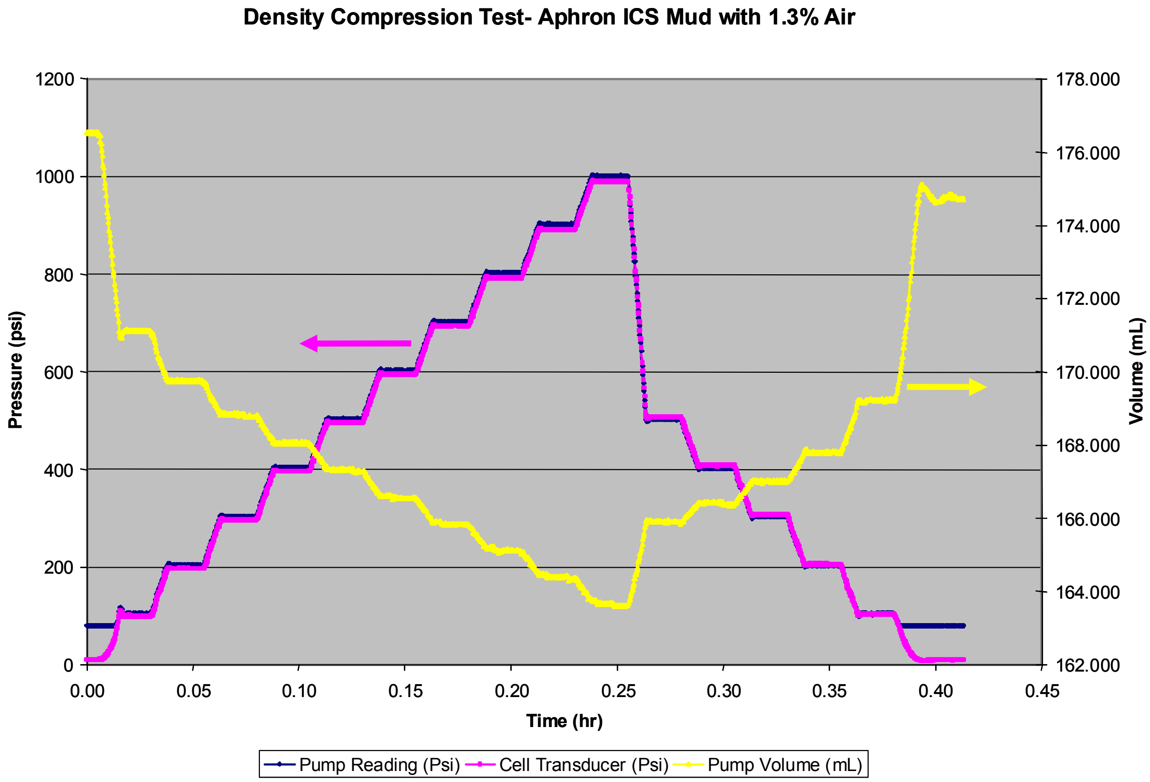

Figure 4. Compression of Aphron ICS Drilling Fluid with 1.3% Air

In this example, as the pressure is ramped up to 6900 kPa (1000 psia) and back down to 0, it appears that the system has a hysteresis of about 8%, i.e. of the 13 mL of air incorporated in the system initially, approximately 1 mL of the air remains dissolved after depressurization. Thus, > 90% of the air incorporated in the system is recovered within minutes, if not seconds, of depressurization. If the air was incorporated initially as aphrons, it suggests that the aphrons (for the most part) maintained their integrity during the pressure ramp.

Initially, it was hoped that the change in volume, ΔV, on compression could be used as an indicator of the survivability of the aphrons. For a typical APHRON ICS mud containing 15% v/v air at ambient pressure (101 kPa, or 14.7 psia), if 100% of the aphrons survive compression, pressurization to 7004 kPa (1015 psia) would reduce the volume of air in a 1L mud sample from 150 mL to 2.22 mL, i.e. $\Delta V_{100\%}$ = 147.78 mL. If all of the air escapes from the aphrons, $\Delta V_{0\%}$ = 150.00 mL. Thus, if the pressure-measuring system is capable of distinguishing between 147.78 and 150.00 mL (and it is), it should be feasible to use this technique to assess the survivability of aphrons. However, $\Delta V_{0\%}$ must be known accurately to +/- 0.1 mL. The actual accuracy of this figure is probably no better than +/- 5 mL in a 1L sample, i.e. the % v/v air in a mud sample is no more accurate than +/- 0.5% v/v. Furthermore, the sample compartment itself will have some air that becomes entrained during the filling process. This ranges from 5 to 15 mL . Thus, there is a combined uncertainty in $\Delta V_{0\%}$ of at least 10 mL. Consequently, the Fluid Density may not be suitable for assessing the survivability of aphrons under pressure.

Aphron Air Diffusivity

Conventional membrane-capped Dissolved Oxygen (DO) probes were tested to determine how suitable they might be to monitor the rate of loss of air from aphrons during pressurization. Although these DO probes are very precise, the membranes are susceptible to blinding by adsorbed bubbles, and the probes appear to measure total O_2, i.e. entrained O_2 (air remaining in the aphrons) along with the dissolved O_2. The former can be alleviated by vigorous stirring to keep the membrane surface free of bubbles; however, no practical method was found to eliminate measurement of entrained (undissolved) air. Another problem: it appears that membrane-capped probes are fairly sensitive to pressure and temperature.

Preliminary investigations by the supplier of a fluorescence probe indicate that this device should provide accurate measurements of DO without the problems mentioned above that plague conventional probes. One possible experimental arrangement is shown in Figure 5.

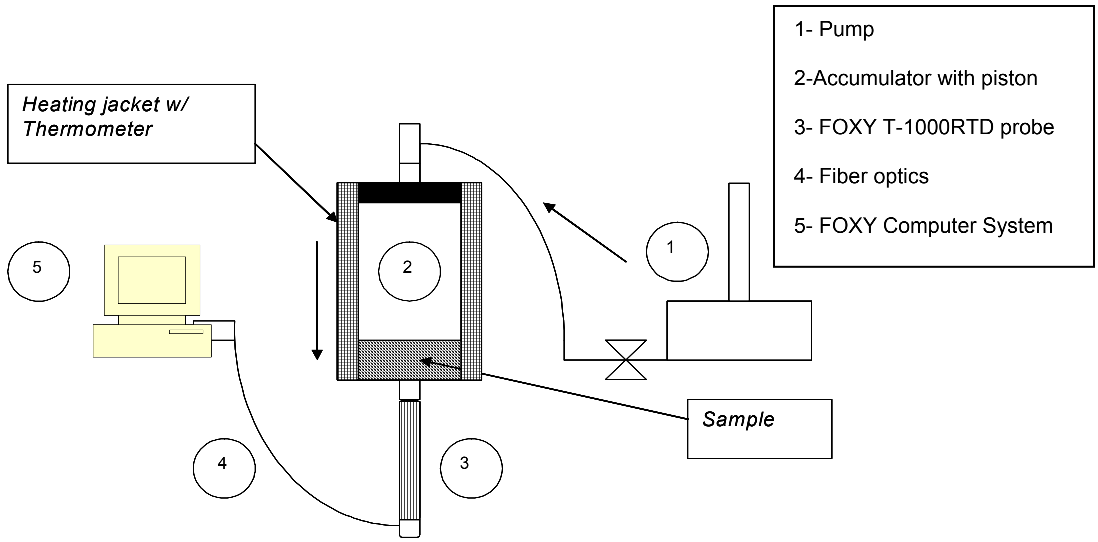

Figure 5. Proposed Schematic of Diffusivity Apparatus w/Fluorescence Probe

Two issues that may still need to be addressed, irrespective of the nature of the probe, are as follows: (a) bubble size is not uniform, and it is expected that the rate of diffusion of air/O_2 from an aphron will depend, to some extent, on bubble size; and (b) the concentration of O_2 measured by the probe may be dominated by the diffusion rate of O_2 through the base fluid, rather than by the diffusion rate through the aphron shell. If these phenomena are found to be important, they will need to be explicitly included in the analyses.

Pressure Transmissibility

The first system considered was designed to simulate a long fracture. It consisted essentially of a 76-m (250 ft) length of 0.64-cm (1/4") OD tubing through a pressure pulse or steady-state pressure was transmitted. This proved unsuitable because of the very high viscosity of the test fluid, which not only made it very difficult to fill such a long, narrow tube, but also because there was very little pressure transmission beyond a few feet. Consequently, a shorter -- 6 m (20 ft) -- straight piece was used in its place, and a gravity-feed pressure-assisted system was added to permit filling the tube with ease (see Figure 6).

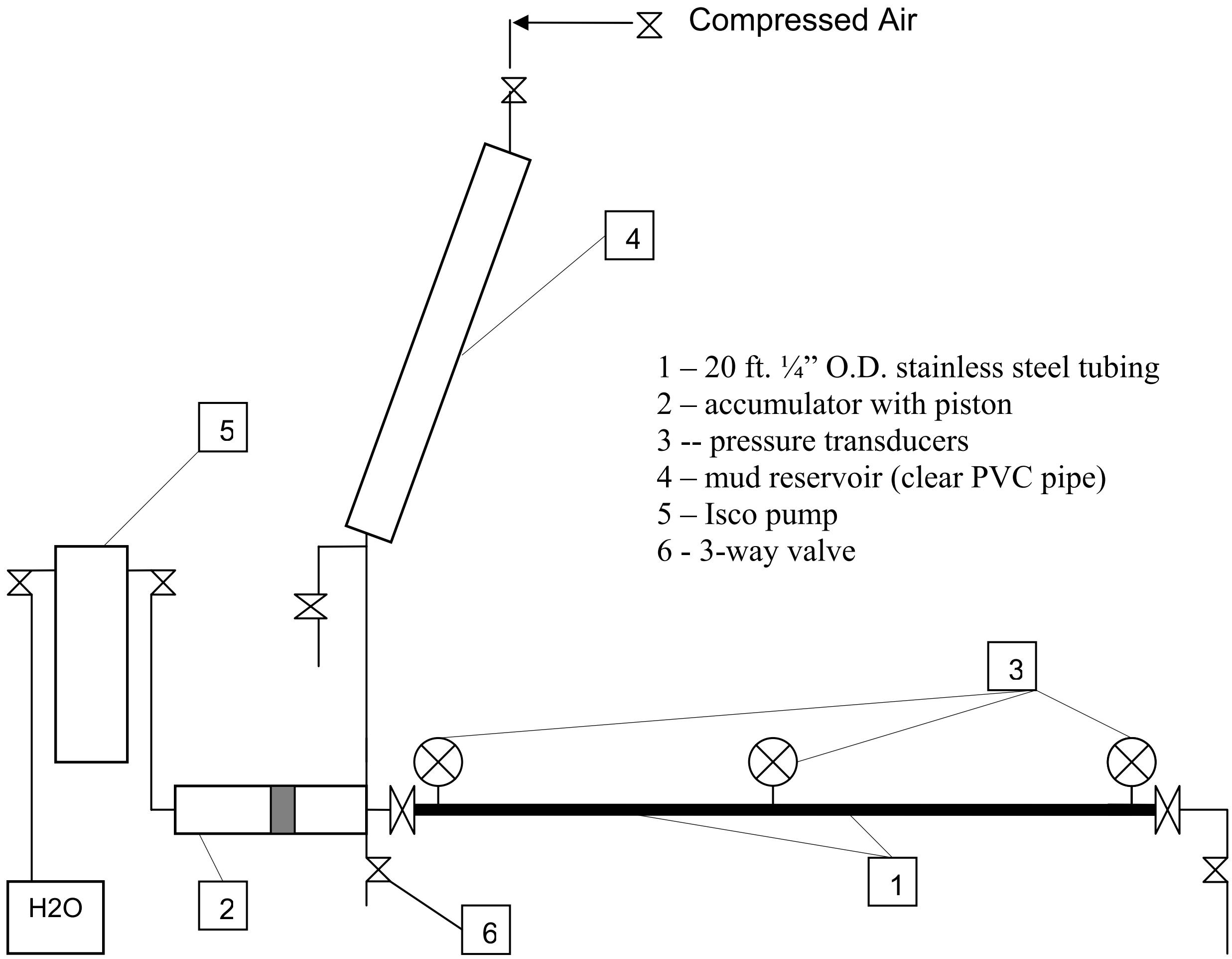

Figure 6. Schematic of Pressure Transmissibility Apparatus

Preliminary tests with water and an APHRON ICS sample suggest that the new experimental apparatus is sensitive enough to determine the validity of the pressure-dampening mechanism.

CONCLUSIONS

The first four tasks of the Project were initiated with feasibility studies to assess if the objectives are achievable and determine if the proposed methodologies can provide the sought-after answers. In three of these cases – Aphron Visualization, Aphron Air Diffusivity and Pressure Transmissibility – the objectives were deemed achievable, though the test methods were found wanting and in need of modification to yield the required precision and accuracy. For the Aphron Visualization tests, the design of the HTHP ABS Cell must be changed to ensure safe and reliable operation at elevated pressures and temperatures; in addition, the algorithm used in the ABS software does not provide accurate BSD measurements, and the analysis may need to be modified. For the Aphron Air Diffusivity tests, conventional membrane-capped DO probes will not be suitable; a fluorescence probe looks very promising and will be purchased, though the roles of diffusion and variation in bubble size must still be established. For the Pressure Transmissibility tests, it is not clear whether a foam-like aphron network can be constructed in the new 6-m long device; that is yet to be determined.

The most troublesome task, Fluid Density, has major issues regarding achievability of the objectives. To assess the survivability of aphrons via analysis of the change in mud volume that accompanies pressurization requires a degree of accuracy of the initial volume of aphrons that is not attainable. Additional study will help to determine whether an alternate method of analysis is feasible.

REFERENCES

1. Montilva, J., Ivan, C. D., Friedheim, J. and Bayter, R.: "Aphron Drilling Fluid: Field Lessons from Successful Application in Drilling Depleted Reservoirs in Lake Maracaibo," OTC 14278, presented at the 2002 Offshore Technology Conference, Houston, Texas, May 6-9, 2002.
2. Growcock, F. B., Khan, A. M. and Simon, G. A.: "Application of Water-Based and Oil-Based Aphrons in Drilling Fluids," SPE 80208, presented at the SPE International Symposium on Oilfield Chemistry, Houston, Texas, Feb. 5–8, 2003.
3. Sebba, F.: *Foams and Biliquid Foams – Aphrons*, John Wiley & Sons Ltd, 1987.

LIST OF ACRONYMS AND ABBREVIATIONS

ABS = Acoustic Bubble Spectroscopy

APHRON ICS = Aphron Invasion Control System

Blue Streak = Surfactant package which serves as aphron generator for the APHRON ICS system

BSD = Bubble Size Distribution

DO = Dissolved Oxygen

EMI-XXX = Experimental M-I *LLC* product

FloVis Plus = Xanthan Gum polymer

HTHP = High Temperature and High Pressure

OD = Outer Diameter

PVC = polyvinyl chloride