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The Fluidic Approach to Mud Pulser Design for Measurement While Drilling Systems

by

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ABSTRACT

This paper describes a fluidic approach to the design of a mud pulsing valve for measurement while drilling applications. The valve operates on vortex flow principles and contains no moving parts other than those used for actuation. In theory the valve utilizes the centrifugal pressure forces developed in a rotating fluid (free vortex) to produce a throttling effect.

The results of several valve experiments are discussed. Principally, the experiments were conducted in a surface flow loop to measure valve response to variable frequency actuator control inputs. Tests were conducted over a frequency range of 3 to 20 hertz and a flow range of 300 to 450 gallons per minute using water and drilling muds as the working fluids. Pressure/flow data is used to compute equivalent valve discharge characteristics in the form of effective valve port areas. Pressure-time traces are included in the report to illustrate response.

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SYMBOLS AND NOTATION

A	drill pipe crossectional area
A_1	effective valve port area without vortex
A_2	effective valve port area with vortex
C	acoustic velocity
k	dimensional constant
P_1	operating pressure drop without vortex
P_2	operating pressure drop with vortex
ΔP_{AV}	average operating pressure drop
P_s	signal pressure
Q	flow rate
Q_1	flow rate without vortex
Q_2	flow rate with vortex
r	radius
r_1	outer radius of vortex chamber
V	velocity
V_1	velocity at outer radius of vortex chamber

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A Fluidic Approach to Mud Pulser Design for Measurement While Drilling Applications

Introduction

As drilling progresses into deeper waters, the need for communicating measurements of conditions at the bottom of the bore hole while drilling increases. Measurements while drilling will not only make drilling the well much safer but will also make it possible to drill faster and more accurately[1].

Several methods for communicating information from the vicinity of the bit to the surface have been investigated by experimenters. Basically, the methods cover embedding wires in the wall of the drill pipe, running cables through the drill pipe, sending acoustic signals through the drill pipe wall, transmitting pressure waves through the fluids circulating through the drill pipe (mud pulsing), and transmitting electromagnetic waves. Thus far, the only method which has proven to be practical and is currently employed in drilling off-shore wells is mud pulsing.

In a mud pulsing system (figure 1) the column of fluid in the drill pipe above the bit serves as a transmissive media for acoustic pulses. The pulses are produced by a valve that opens and partically closes to restrict the circulating flow. The pulses travel through the mud between the valve and the surface at the speed of sound (approximately 4710 feet per second in most drilling fluids). The pulses represent digitally coded information bits from instruments located near the valve. A transducer in the wall of the drill pipe at the surface detects the pulses and converts them into electrical impulses that are decoded electronically and displayed as data from the bit.

[1] Drilling Technology MWD Update: New Systems Operating Oil & Gas Journal, March 1980.

At the present time there are three ways to use a valve to generate pulses in the drilling mud. One method is to operate a valve in series with the drill bit nozzle to produce a positive pressure pulse or data bit each time the valve modulates the flow.[2] The second method employs a rotating valve (siren) that produces a continuous wave at a frequency of approximately 12 hz and a controlled phase shift of a number of cycles to represent the data bit[3]. The third method employs a valve in parallel with the drill bit nozzle to produce a negative pulse or data bit each time the valve vents fluid through the wall of the drill pipe into the hole[4].

The principal advantages of using mud pulsing over other technologies is that it can be accomplished with standard drilling equipment and with very little impact on other rig operations. The primary disadvantage is a slow rate of data transmission (usually in the range of 1 to 3 words per minute depending upon the type of system used).

In mud pulsing several factors combine to influence the rate of data transmission. First, a single piece of information (word) can require numerous pulses (bits) to code depending upon the type of coding used. Second, it is not uncommon for more than one pulse to be required to form an individual bit. Third, the mechanical complexity and relatively large physical size of the pulser valves used in these systems severely limits the rate at which pulses can be

[2] R. F. Spinler and F. A. Stone, "Mud Pulse Logging While Drilling, Telemetry Systems Design, Development & Demonstration", Teleco Oil Field Services, Inc., Transactions of the 1978 Drilling Technology Conference, International Association of Drilling Contractor, IADC, Houston TX.

[3] D. R. Tangay and W. A. Roeller, "Applications of Measurements While Drilling", The Analysist/Schlumberger, Society f Petrolium Engineers, SPE 20324, 1981.

[4]. Marvin Gearhart, "Mud Pulse MWD (Measurement While Drilling Systems)", Society of Petrolium Engineering, SPE, 100053, 1980.

produced. Fourth, theory indicates that pulse amplitude can be severely attenuated at high valve operating frequencies especially when heavily weighted, viscous muds are used[6]. Fifth, drilling and surface pump noise frequently makes it difficult to identy signals over certain frequency band widths

Because of the limited operating speeds of state of the art mechanical systems, most mud pulsing systems are used for transmitting directional parameters namely; direction, orientation and tool face angle. The continuous wave system, being somewhat faster, has the capability of transmitting directional measurements as well as measurements of weight on bit, temperature, formation resistivity and radioactivity. Although the slow operating speeds of these mud pulsing systems are adequate for transmitting a limited number of measurements of slowly changing hole conditions, it is not considered fast enough to transmit the many additional types of measurements which could be made to enhance drilling saftey and efficiency.

In 1978, the U.S. Geological Survey (USGS) Oil and Gas Conservation Division (offshore) now the Research and Development Program of the Offshore Operations Division of the Minerals Management Service, Department of Interior, initiated a program at the U. S. Harry Diamond Laboratories (HDL) to investigate the application of fluidic technology to mud pulser design. The purpose of the work was to determine if a high speed pulsing valve could be developed which would

5 Monroe Knight, "Mud Pulse Telemetry" (Gearhart Owens Industries), Proceedings of Technologies for Measurement While Drilling Symposium. Committee of Engineering Support for Deep Ocean Drilling for Science. National Academy Press, Oct 1981, Washington D.C.

6 W. C. Mauer et, al., "Mud Pulse Tachometer for Drilling Motors", American Society of Mechanical Engineers 81-Pet.-3, 1981

7 Carl W. Buchholz, "Continuous Wave Mud Telemetry", (The Analysist/Schlumberger) Proceedings Technologies for MWD. Symposium National Academy Press. Oct 1981 Washington D.C.

make the transmission of larger volumes of safety-oriented measurements feasible. The objective of the work is to accelerate technological development of mud pulsers for safeguarding oil and gas operations on the outer continental shelf. The approach was to increase operating speeds by eliminating the need to mechanically open and close a port. The approach is one in which the fluid dynamic properties of a vortex flow field are used produce a throttling effect which inturn generates the pulses. The results of this work are summarized in this report

Mechanical Design Considerations

A mud pulsing valve must be designed to operate reliably in a particularly severe environment. The pressure and temperature in the vicinity of the pulser valve can range to 20,000 psi* and 350°F. The shock and vibration environment near the valve can be extremely severe.

The composition of the working fluid (drilling mud) which must be controlled by the mud pulser valve can present formatable errosion and corrosion problems. The mud will genereally contain water as a base and weighting materials such as barite to increase the density up to 20 pounds/gallon**. The mud will frequently contain a substance such as bentonite to control viscosity as well as finely ground particles of the formation being drilled. Ingredients such as H_2S in solution, limestone or even crushed wallnut shells (a material used to re-establish lost circulation) as well as others may also have to pass through a mud pulser valve.

The drilling mud is also a non-Newtonian fluid meaning that it has a plastic viscosity, gel strength and yield point which affects how it flows through the valve. The consistency of the mud can be likened to that of jello, cement and

*(psig) 6.894 = (kPa)
**(ppg) 119.8 = (kg/m^3)

water depending upon the rate of shear between fluid particles or the velocity of flow through the valve. These properties combine to make the mud flow very differently through the valve than does a Newtonian fluid such as water.

A mud pulser valve must reliably complete millions of operating cycles during its lifetime if it is to operate at a high rate of speed. The useable life of state-of-the-art mud pulsing valves is generally desired in the liteture as being in the 500 to a 1000 hour range. However operating lives in the 50 to 100 hour range are frequently reported because of the severity of the operating environment.

A mud pulser valve must also operate on a minimum amount of power because of the problems associated with supplying power in the bottom of a bore hole. A mud pulser valve must never have the ability to jam closed to interrupt the circulating flow. The valve must never turn down enough to create high internal velocities which inturn could cause errosion of internal parts.

A mud pulser valve that operates inseries with the drill bit usually contains a large port (or ports) typically 1.5 - 2.5 square inche* to minimize the operating pressure drop imposed on the circulating system. The valve must control flow rates on the order of 400 to 800 gallons/minute in most applications. The valve must also be small enough to fit into the limited space available across the inner diameter of the drill pipe.

Design Objectives

The objective of the fluidic mud pulser investigations is to design a high speed, high capacity valve with a partial shutdown capability. Specific technical objectives are to develop a valve capable of operating reliably at bit rates to 25 Hz (1500 bits per minute) while flowing at 500 gallons/minute***.

*(in^2) 6.451 = (cm^2)
**(in).394 - (cm)
***(gpm) 6.3×10^{-5} = m^3/s

The approach taken is to achieve response and reliability through the virtual elimination of all moving parts except those used for actuation. In the fluidic approach to mud pulsing the valveing is achieved by using a vortex flow field in place of a moving part, such as a poppet and valve stem.

Operation

The fluidic mud pulser valve operates on vortex flow principles. The vortex is produced in a cylindrical chamber that essentially forms the body of the valve. The vortex is generated in response to electrical commands applied across the coil of a small solenoid.

A drawing showing the internal structure of a vortex type mud pulsing valve stage and associated parts is shown in figure 2. The valve stage contains a vortex chamber, outlet port, inlet port, cover plate and actuation mechanism. The chamber used in the valve is essentially a flat drum shaped cylinder with a centrally located outlet. The wall of the chamber contains a two dimensional inlet port and a small cavity. The cover plate provides a seal between the outer and inner portion of the chamber. The cover contains two slots, one positioned over the inlet and one located directly over the cavity. The cover is secured to the base of the valve with screws (not shown in the figure).

Theory of Operation

When the outer surface of the mud pulser valve stage is pressurized, fluid travels through the chamber to the outlet port as shown in figure 3. With the tab retracted into the cavity, the stream lines form a symmetrical pattern (figure 3a) about the centerline of the chamber inlet. Since very little energy (dynamic pressure) is lost in travelling the short distance through the chamber, the major portion of the total pressure drop across the valve is across the outlet nozzle. Under this condition the valve is operating in the non-vortex mode and is considered to be open.

The pressure flow characteristics of a fluidic mud pulser valve stage are a function of the effective flow area of its outlet port. The effective flow area of a fluidic mud pulser valve stage is defined as that area which, when subjected to the same pressure differential as the valve, passes the same flow rate. The effective flow area of a fluidic pulser valve without a vortex is thus given by general oriface equation

$$A_1 = Q_1/(\frac{\Delta P_1}{\rho}) \qquad (1)$$

where Q_1 equals the flow rate ΔP_1 is the operating pressure drop, ρ equals the density of the fluid and A_1 defines the effective flow area of the outlet nozzle without a vortex.

The valve is considered to be shut down when the tab is moved into the chamber and a vortex is produced. Extending the tab into the valve chamber destroys the geometric symmetry of the chamber and forces the fluid stream slightly to the left (figure 3b). The stream then begins to follow the curvature of the chamber and swirl through the valve. The swirling action creates a strong (free type) vortex in the center of the chamber. In a free vortex, centrifugal pressure forces are developed between the slower moving incoming fluid and low-pressure, faster moving fluid in the center of the valve. The change in pressure produced across the mud pulser valve is a function of the change in tangential velocity (V) between the outer radius (r_1) of the chamber and the inner radius of the outlet nozzle (r) given by

$$V = V_1(\frac{r_1}{r})^n \qquad (2)$$

where n = -1 for a free vortex. Using (V) from equation 2, the change in pressure across the vortex can be expressed as

$$dP = \frac{\rho V^2}{g} \frac{1}{r} dr \qquad (3)$$

in which integration between radius (r) at the outlet and the radius of the chamber (r) gives the total pressure differential

$$\Delta P_2 = \frac{\rho V^2}{2n} \left(1 - \frac{r^{2n}}{r_1^{2n}}\right) \qquad (4)$$

where ΔP_2 represents the change in pressure between the inlet to the valve and central core of the vortex.

The effective port area of a valve operating in the vortex mode is calculated using equation 1,

$$A_2 = Q_2 / \left(\frac{2\Delta P_2}{\rho}\right)^{1/2} \qquad (5)$$

where A_2 represents the effective flow area of the valve with a vortex, and ΔP_2 and Q_2 represent the change in pressure and flow rate.

The ratio between the two areas A_1/A_2 defines valve turn-down. The turn-down ratio actually produced in a valve is determined by geometric factors including the height of the vortex chamber, width of the inlet port as well as the ratio between the inner and outer radii of the chamber and outlet nozzle. The turn-down ratio is also affected, but to a much lesser extent by surface finish in the vortex chamber and fluid viscosity.

The response time of a fluidic type vortex valve depends upon the time required to form the vortex. Response of a vortex type valve has been shown by experimenters to be inversely proportional to flow rate and directly proportional to the volume of the vortex chamber. The response time of a fluidic type mud pulser valve is affected but to a lesser extent by fluid inertia and the viscosity of the fluid. Response is generally determined from measurements of the rate of change in pressure drop during formation (and dissipation) of the vortex. A discussion of response and the factors affecting vortex valve design are summarized in references[8] and[9].

Governing Flow Equations

The theoretical performance of a fluidic mud pulser (or any type of mud pulser) operating in a circulating mud system depends upon the maximum area and change in area (turn down) produced by the valve. At a constant flow rate, the change in pressure produced by an change in area is given by the initial pressure (ΔP_1) multiplied by the square of the turndown ratio, or;

$$\frac{\Delta P_2}{\Delta P_1} = \left(\frac{A_1}{A_2}\right)^2 \qquad (6)$$

If the valve is operated on a 50 percent duty cycle (time open + time shut down/time open = 0.5), the average pressure drop simply equals the sum of the pressure drop produced in vortex and non-vortex operating mode divided by 2 as described by,

$$\overline{\Delta P}_{AV} = 1/2 \left[\Delta P_1 + \Delta P_2\right] \qquad (6)$$

At duty cycles less than 50 percent the average pressure drop approaches the

[8] David N. Wormley, "A Review of Vortex Diode and Triode Static and Dynamic Characteristics", Massachusetts Institute of Technology Proceedings, 1974 Fluidics State of the Art Symposium, Vol.1. Harry Diamond Laboratories, Washington D.C.

[9] S.S. Fineblum, "Vortex Diodes," (Bell Laboratories) 1974 Fluidics State of the Art Symposium, Harry Diamond Laboratories Washington D.C.

level given by ΔP_1 because the valve remains open a major portion of a cycle.

The signal pressure produced by the pulser valve occurs as a result of the change in circulating flow velocity or flow rate in the drill pipe. The signal pressure can be written in terms of the change in flow rate using the equation for water hammer given as

$$Q_1 - Q_2 = - K \left(P_2 - P_1\right) \qquad (7)$$

where Q_1, P_1 are the low resistance flow rate and pressure and P_2,Q_2, is the high resistance pressure and flow rate, K is a proportionality constant given by $K = A/\rho C$ where ρ is the density of the fluid, A is the area of the drill pipe and (c) is the velocity of sound.

The signal pressure and the average pressure drop gives the signal producing efficiency factor for the valve,

$$\eta = P_s/\overline{\Delta P}_{AV} \qquad (8)$$

where $P_s = P_1 - P_2$ (eq.7) and $\overline{\Delta P}_{AV}$ is the average pressure drop given by (eq. 6). In theory the change in flow rate that generates a signal is relatively small (approximately 10 percent of the total flow rate). The change in flow rate is a function of valve flow area, turn down ratio, drill bit nozzle area and pumping rate. It should be noted that the change in flow which takes place as a valve opens and closes is a localized effect produced by the compressibility of the fluid. It should also be noted that when the change in flow occurs rapidly ,as it does in a high speed pulsing system, the inertial properties of the pump providing the flow prevent it from following (speeding up or slowing down) in response to the localized changes in flow. This means that the pump operates at essentially a constant speed and delivers a constant flow rate. For the conditions stated, namely a 50 percent duty cycl, the average flow rate delivered by the pump can be written in terms of change in flow rate Q_1, and Q_2 as,

$$Q = 1/2\ (Q_1 + Q_2) \qquad (9)$$

The flow equations for determining O_2, in terms of flow area, drill pipe area turn down ratio, drill bit area and mud properties are given in reference[10].

Theoretical Performance in a Circulating System

The theoretical performance of a mud pulser valve (mechanical or fluidic) operating in a circulating system can be best illustrated graphically in terms of maximum flow area and turn down. The curves (figures 4 and 5) illustrate the signal pressure and average pressure drop that will be produced by a mud pulser valve operating in series with nozzle in the drill bit. The data is plotted as a function of effective flow areas (A_1) and (A_2). Lines of constant turn-down ratio (A_1)/A_2) are included for convenience. The curves represent the theoretical performance of a mud pulser valve operating in a standard drill pipe (4 1/2 in. OD x 3.75 in. ID) at 400 gallons per minute with 10 pound per gallon mud. The flow rate (400 gallons per minute) and drill bit size (0.036 in^2) selected for the example represent what is generally considered to be an average set of flow conditions in a circulating system. Estimates of pressure drop and signal pressure drop produced by a mud pulser valve using mud weightsother than 10 pounds per gallon can be made by multiplying the values indicated in the figures by the desired mud weight devided by 10.

10 Allen B. Holmes and Stacy E. Geham, "A Fluidic Approach to the Design of a Mud Pulser for Bore Hole Telemetry While Drilling". Harry Diamond Laboratories, HDL-TM-79-21, Aug. 1979.

The two theoretical mud pulser performance curves show that the average pressure drop and the signal pressure do not change much along the lines of constant turn down ratio. When the ratio between the average values of signal pressure and pressure drop from figs. 4 and 5 are replotted as a function of turn town ratio, the resulting curve (fig. 6) shows that the signal producing efficiency ratio does not change much at turn down ratioes much above 3 as= $\frac{P_s}{\Delta P}$ as indicated by the more gradual change in slope. The curve shown in figure 7 is interesting because it describes just how much average pressure drop is required to produce a desired signal level. However, most importantly, the efficiency curve shows that the signal pressure produced by a mud pulser valve will generally be on the order of 35 to 45 percent of the average pressure drop under nominal circulating flow conditions.

Test Hardware

The initial flow studies involving the fluidic mud pulser were conducted on sub-scale (1/10 th scale) models representing various types of circuit geometries. The first attempt to impliment a fluidic mud mulser valve involved using a fluid amplifier to direct mud to a tangential and radial inlet to a vortex chamber. Details of the initial approach are described in reference 10. The amplifier was eventually replaced by a specially shaped radial inlet to the vortex chamber. The modified inlet was used to eliminate the additional pressure drop across the valve imposed by the amplifier and provides the same function (flow diversion with less power) as the amplifier.

The early flow circuits contained a network of two dimensional flow channals machined in a flatplate. A photograph of an assortment of early test hardware is shown in figure 7. Figure 8 shows a photograph of an early full scale, 2-stage fluid amplifier driven vortex valve flow model.

Prototype Valve Design

The prototype fluidic mud pulser valve was developed based on the single stage tab actuated valve stage design configuration shown in figure 2, A 3-stage version of the valve is shown in figure 8. The valve contains three vortex chambers and nozzle assemblies. Each chamber is mounted on a manifold and discharges into a channel (not visible in the figure) that extends along the underside of the manifold plate. The channel is enclosed by the semi circular pipe section welded to the bottom of the manifold plate. The channel leads through the O-ring connection at the end of the assembly.

The solenoids that actuate the valve are housed in an oil filled pressure compensated container to isolate them from the environment. The chamber is located at the forward end of the assembly between the manifold and a conical flow divider at the foward end of the assembly. The compensation is provided by hydraulically ballancing the external pipe pressure across a diaphragm (not visible in the figure) with the pressure of the oil in the housing. Deflection of the diaphragm is also used to compensate for thermal expansion of the oil due to solonoid heating. A metal bellows on the downstream end of the container is used to transmit the motion of the solonoid plunger through the walls of the housing to the rod that moves the tabs into and out of cavities in the vortex chambers.

The valve assembly is designed to fit through a standard 4 1/2* inch internal diameter box type drill pipe connection. The seal between the high pressure and low pressure side of the assembly is provided by the O-ring. Thetest assembly is presently used with a 6 1/2 inch* outside diameter drill pipe. The pipe has standard 4 1/2 inch* API box and pin connections on each end.

Fluid enters the valve assembly from the left (fig. 9) and is dispersed

*(in)2.54 = cm

around the conical flow divider. The fluid pressurizes the outer surfaces of the chamber assemblies. The fluid enters the chambers through the inlet slots in the end of the chamber assemblies and travels through the outlet nozzles then through the manifold channel to the low pressure side of the pipe. A small amount of fluid also enters the chamber through the gap formed between the slot in the cover plate and the tab. This fluid is used to flush the lower cavity of mud particles which might otherwise deposit there. The valve creates a vortex in the chamber when the tab is driven foward (by solenoid) into the chamber. The vortex is disipated when the tab is retracted by a second solenoid back into a cavity in the wall of the vortex chamber.

The materials used in the prototype mud pulser valve are primarily 303 and 304 stainless steel The drill pipe was fabricated in carbon steel. The driving bellows connected to the control rod was of stainless steel. The diaphragm pressure compensating bellows was of neophrene rubber impregnated cloth.

Experimental Program

An experimental program was conducted on both sub scale models and full scale flow models representing mud pulser valve flow geometries. The purpose of the experiments was initially to determine if drilling fluids could be controlled by fluidic type valves and, if so, what would be the effects of drilling mud properties on fluidic operation. The second part of the test program focused on measuring the discharge characteristics and frequency response of prototype valving hardware and to verify reliability through simulated environmental testing.

Testing Procedures

The procedures followed during early investigations consisted of circulating a known volume of specially formulated mud through sub-scale flow models. A diagram of the test set up used for the preliminary experiments is shown in figure 10.

The test set up contains a high pressure supply chamber, a test chamber and an exhaust chamber. High pressure nitrogen was used to circulate the mud between the supply and exhaust chamber at a constant flow rate. The pressure in the supply tank ranged typically between 250 and 400 psi, while the pressure in the exhaust tank was held constant at 200 psi to minimize cavitation. The flow rate was measured in terms of the time required to displace a known volume (3.01 gallons) of fluid between two level detectors in the supply tank.

During a typical experiment, the pressure and flow measurements were made with the model manually set to operate in the vortex and non-vortex mode. The pressure and flow data was then used to calculate effective flow areas in each operating state using equations 1 and 5.

During the later, full-scale experiments, fluid was circulated through the test model while pressure and flow rate measurements were recorded by a digital data acquisition system. Measurements were made of the change in pressure produced across the valve by the vortex and the flow rate. The measurements were used to calculate effective flow areas, turn down ratio, and response time. The set up used for the experiments consisted of a Triplex mud pump, a pulsation damper, bypass choke, exhaust choke and a test chamber containing the flow model. A 1000 psi* variable reluctance differential pressure transducer was used to make the measurements. A schematic of the test setup is shown in figure 12.

*(psi) 6.895 = k(Pa)
**(gpm) $6.31 \times 10^{-5} = m^3/s$

The signals used to actuate the pulser were supplied by a 24 VDC power supply operating in conjunction with an electronic switching circuit and a variable frequency square wave signal generator. During a typical test the frequency of the actuator signals was varied over a range of 1 to 15 Hz while differential pressure measurements were recorded at constant flow. Photographs of the test setup and chamber are contained in figures 13 and 14. The full scale experiments were designed to measure the steady state and dynamic performance of single and multi-stage flow models operating on drilling muds and water.

The drilling muds used in the experiments were formulated using water as a base-bentonite to build viscosity and barite as the weighting material. Table 1 contains a summary of the mud properties used for the subscale and full-scale experiments.

Experimental Results

The effective flow areas of a single subscale fluid amplifier driven valve flow model and a single full scale tab driven vortex valve flow model that were calculated from measurments of pressure drop, flow rate, and fluid density are summarized in figures 14 and 15. The upper and lower curves refer to calculation of effective flow area A_1 and A_2 while operating in the non-vortex and vortex operating modes respectively. The symbols refer to mud composition.

Sub-scale Flow Models

The absolute values of effective flow areas indicated in figure 14 for the sub-scale flow model tests have no real significance other than the higher values indicated (0.021 to 0.026 square inches)* and are significantly less than the actual flow areas (0.0566 square inches)* calculated, based on the diameter of the chamber outlet nozzle. It should be noted that no attempt was made to maximize turn down and or effective flow areas. Of significance, however, is that the data shows that the a wide range of mud viscosities and weights employed produced relatively little change in turn down ratio (2.7 for water as compared to 2.35 for the heavier more viscous muds). It is also interesting to note that the effective flow areas indicated in the figure tended to increase in both the vortex and non- vortex operating mode as the mud viscosity increased. In the non vortex mode, the increase is probably due to decreased turblence in the vortex chamber; in the vortex mode the increase is most probably due to an increase in the radial flow through boundary layer between the tangential flow and the chamber surfaces.

Full Scale Single Stage Vortex Valve Flow Model

Figure 15 describes the effective flow areas calculated for a single tab driven vortex valve and the 2-stage amplifier driven flow model. Here, the absolute values of flow area in the non- vortex mode are significant in that the flow areas were equal to or slightly larger than the real areas (0.395 square inches)* based on diameter. For the amplifier driven vortex vortex valves, the data shows effective flow areas were always approximately 25 percent less than the real areas based on diameter. Based on the data it is estimated that an effective flow area equal or slightly grteater than the actual area of the chamber nozzle is about as large as one might get with any given valve geometry. The corresponding average turn down ratioes for the tab actuated and amplifier driven valves were 3.4 to 3.9 respectively.

In a separate experiment using only the nozzle in the vortex chamber with the cover plate removed, it was possible to essentially calibrate the nozzle in terms of pressure and flow rate. When this was done, it was then possible to estimate the the losses in the vortex chamber in terms of the effective areas of the nozzles alone and the effective area of the nozzles when used in the valve.

*(in^2) 6.45 = cm^2

The area measured without the cover plate was equal to   square inches. Since it is somewhat larger than the actual area based on diameter, this indicates that some pressure was recovered in the outlet. The fact that the effective flow area (0.40 square inches) is less than the area without a cover plate means that some of the total pressure drop across the vortex chamber was most probably due to the sudden expansion of the inlet stream into the vortex chamber and some was lost due to residual vorticity or flow noise in the vortex chamber as might be expected in a flow configuration of this type.

The Dynamic response of the full scale single stage flow model is illustrated in figure 16. The pressure traces describe the change in pressure produced across the vortex as a function of time. The tests were conducted on the single stage model using water at a constant flow rate of 130 gallons per minute.* Figure 16a describes the response of the single stage valve to a 24 volt 1 amp. square wave signal input applied across the coils of the actuating solenoids for a period of one second. Figure 16b shows the same trace on an expanded time scale covering a period of 100 milliseconds. The data shows that the vortex required approximatly 18 milliseconds to form as indicated by the rise time of the pulse and about 40 milliseconds to dissipate as indicated by the decay time of the pulse. This data suggests that higher operating frequencies should be attainable by reducing the on time and off time of the valve. The data showed that the maximum pulse rate that could be produced with the present solonoids was 8 Hz. The noise riding on the pulse shown in the data is partially due to pump noise and random turblence produced by flow instabilities in the vortex.

Prototype 3-Stage Fluidic Mud Pulser Valve Test Results.

The dynamic response of the 3-Stage prototypevalve is illustrated in figures 18 and 19. The measurements were made using water and a water base mud weighted up with Barite to 12 pounds per gallon. The data describes the maximum pulse rate which could be achieved the present actuators. The data shows that the actuators cut off (ceased to operate) at a frequency of 6 hz and a flow rate of 350 gallons per minute when the mud was used as the working fluid. The data shows that the cut off frequency (9 hz) and flow rate (450 gallons per minute) were somewhat higher when water was employed as the working fluid. The difference in the cut off frequencies and the flow rates is attributed to the higher dynnamic pressure forces which are developed in the heavier fluid.

The dynamic pressure forces that act on the valve are produced in two ways, first the fluid that enters the cavities through the slots in the cover plates exerts a force on the rear surface of the tabs, second, a small differential is developed across the driving bellows due to the pressure exerted on the expansion diaphragm and the lower pressure created by the wake behind the driving bellows. The two forces act to ultimately hold the taps in the chamber as indicated by operation ceasing only in the vortex mode.

A comparison between response data for a single stage valve operating at 130 gallons per minute and the three stage valve operating at approximately 400 gallons per minute per stage shows very little difference in wave form. This fact is important because it illustrates that virtually any number of stages can be used to increase valve flow capacity without significantly affecting valve response.

Other Observations

Visual examination of the mud pulser test hardware after approximately 10 hours of testing showed that the inner surface of the nozzles and the area (in the cover plate) over the nozzles had erroded slightly. The errosion pattern on the surfaces indicated that the errosion occured during operation in the vortex mode. A photograph showing the erroded surface in the center of the cover plates is shown in figure 17.

After disassembling the valve, it was also determined that mud had leaked into the solonoid housing. The mud entered the housing through a ruptured diaphragm that had been used to cover and seal an unused 3/4 inch* hole in the endplate containing the metal bellows. The cause of the rupture was attributed to the difference in pressure between the forward end of the housing containing the pressure compensating bellows and in the wake formed at the end of the housing. In addition, measurements of the differential pressure across the valve showed excessive pressure was lost between the inlet and exhaust connections on the valve drill pipe chamber. The excessive drop was approximate 25 percent higher than expected and was attributed to losses primarily in the inlet and exhaust adapters and, to a lesser extent, frictional losses in the inlet and exhaust manifolds.

Summary and Conclusions

Although the development of the fluidic mud pulser valve is not 100 percent complete, operation of the first prototype was demonstrated to 9 Hz at 400 gallons per minute. Certain problems were identified including; errosion in the vortex chamber and nozzle assemblies, excessive pressure losses across the drill pipe housing, and leakage of fluid into the solenoid housing.

A second prototype valve has been constructed and is scheduled for testing on September 82. The modified valve contains a tungsten carbide drill bit nozzle inserts and tungsten carbide discs in the upper section of the vortex chamber. The inner surface of the exhaust manifold is coated with an errosion-resistant

*(in^2) $6.45 = cm^2$

urathane. The inlet and exhaust manifolds have been enlarged to reduce pressure losses, and a fourth stage has been added to reduce flow velocities in the valve. In addition, a vent tube has also been added to equalize the pressure across the solonoid housing with the pressure in the (wake) region behind the aft end plate containing the driving bellows. A photograph of the 4 stage prototype valve model is contained in figure 19.

Based on the results of the fluidic mud pulser design investigations to date, it has been concluded that the fluidic approach to mud pulser valve design offers many possible advantages. These advantages can be summarized as follows;

1. The ability to employ virtually any number of stages permits very high capacity valves to be constructed without affecting response.

2. The ability to use any number of stages or various size nozzles in a given stage permits one tool to be used under a wide range of drilling conditions such as with heavily weighted muds or higher (or lower) than normal circulation rates.

3. The use of replacable tungsten nozzle inserts also permits easy maintenance to prolong the life of a given tool.

4. Based on the analysis data it has been concluded that fluidic mud pulser valves with operating chacteristics similiar to the test models should be capable of producing producing signal pressures equal to between 35 to 45 percent of the average pressure drop produced across the valve under under typical circulating flow conditions, depending upon the turn down ratios employed.

5. Based on the analysis, it has been further concluded that a fluidic mud pulser valve should should be capable of producing data bits at rates up to 30 bits per second when improved actuators are employed.

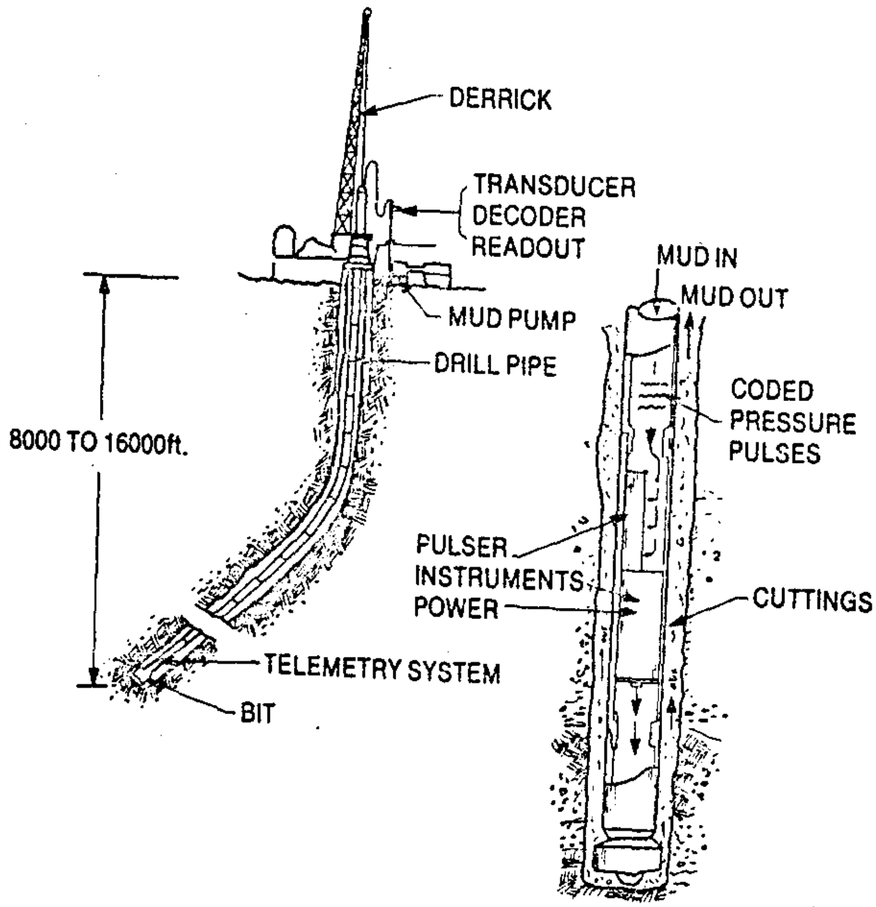

DERRICK
TRANSDUCER
DECODER
READOUT
MUD PUMP
DRILL PIPE
8000 TO 16000ft.
TELEMETRY SYSTEM
BIT
MUD IN
MUD OUT
CODED
PRESSURE
PULSES
PULSER
INSTRUMENTS
POWER
CUTTINGS

fig. 1

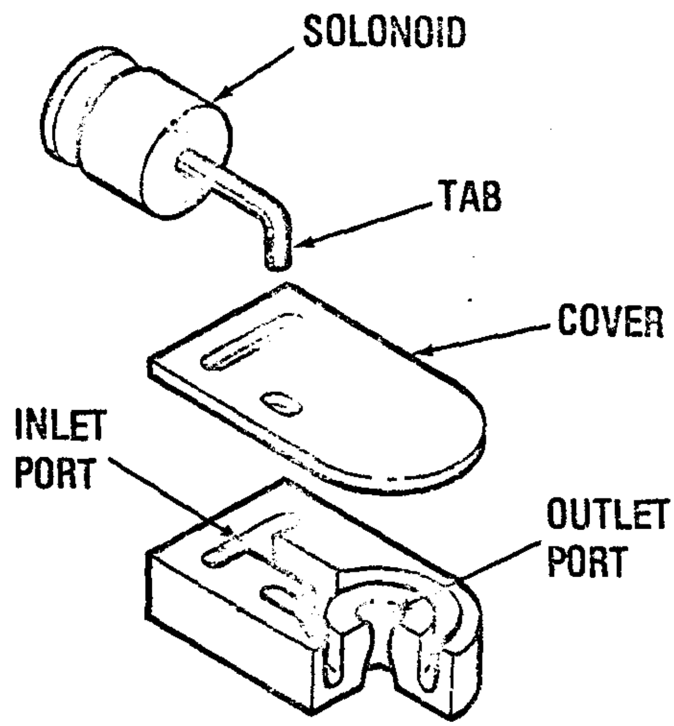
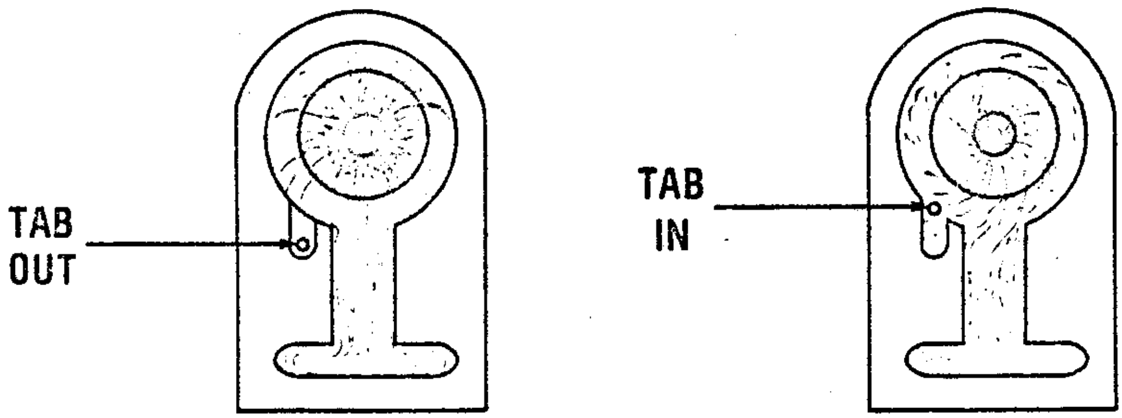


fig 2



RADIAL FLOW
LOW
RESISTANCE

VORTEX FLOW
HIGH
RESISTANCE

Fig. 3

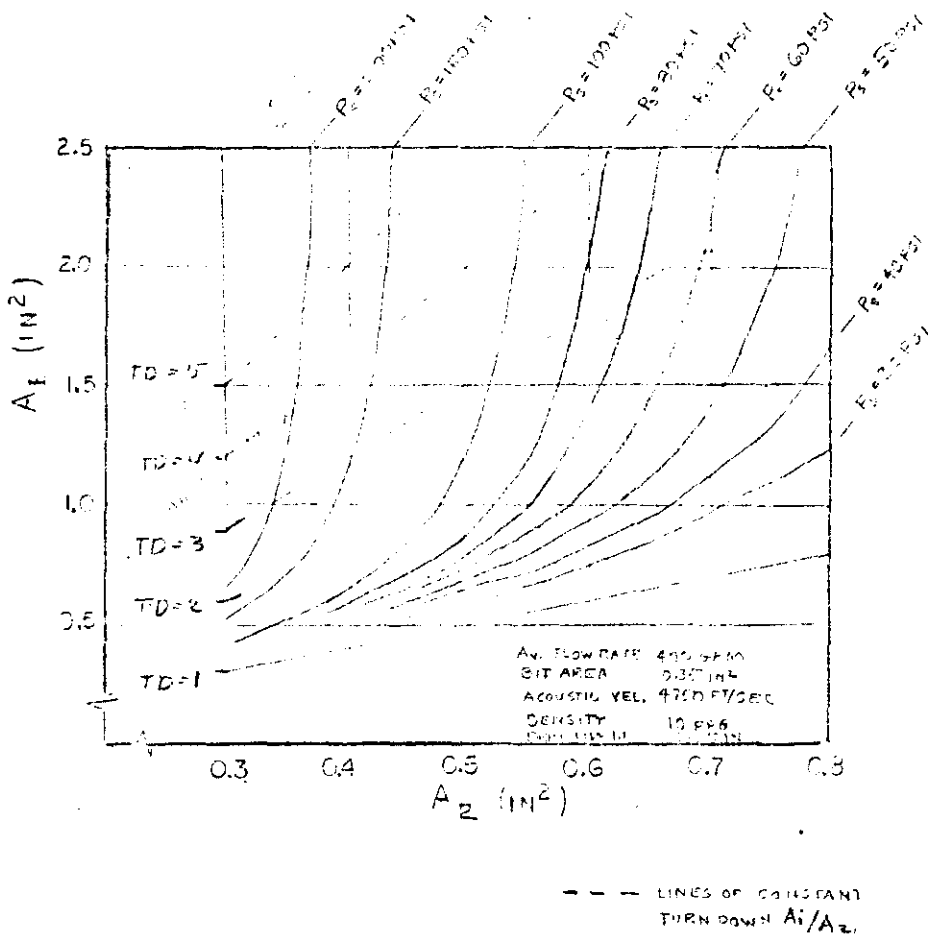
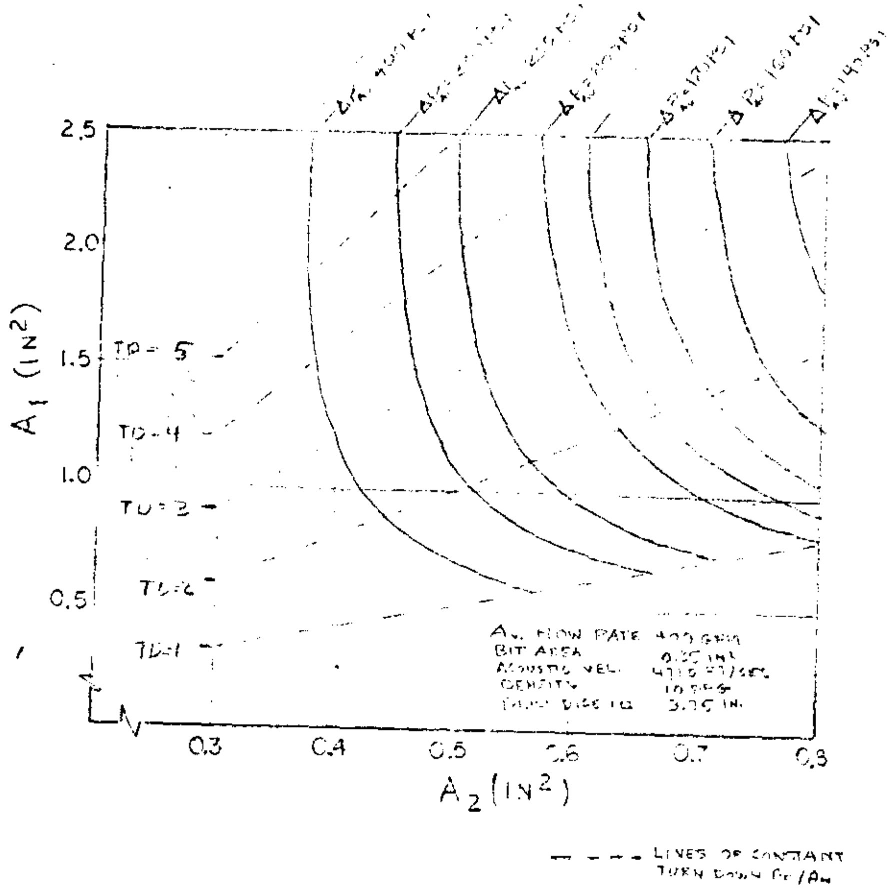
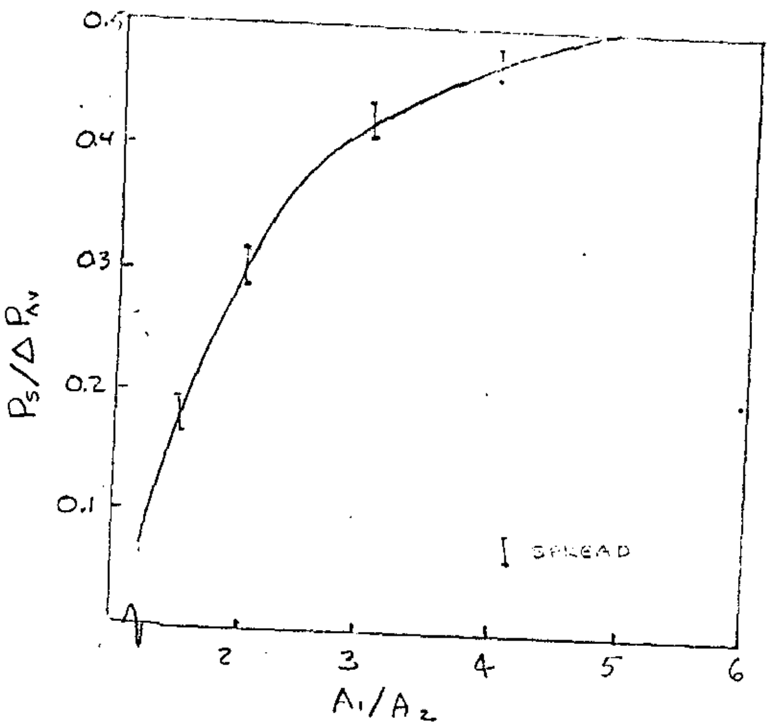

A_1 (IN^2)
A_2 (IN^2)
2.5
2.0
1.5
1.0
0.5
0.3
0.4
0.5
0.6
0.7
0.8
TD = 5
TD = 3
TD = 2
TD = 1
P_3 = 100 PSI
P_3 = 80 PSI
P_3 = 60 PSI
P_3 = 50 PSI
P_3 = 40 PSI
BIT AREA
ACOUSTIC VEL.
DENSITY
— — — LINES OF CONSTANT
TURN DOWN A_i/A_2

Fig. 4


2.5
2.0
1.5
1.0
0.5
A1 (IN2)
TD = 5
TD = 4
TD = 3
TD = 2
TD = 1
0.3
0.4
0.5
0.6
0.7
0.8
A2 (IN2)
BIT AREA
LINES OF CONSTANT


0.5
0.4
0.3
0.2
0.1
$P_s/\Delta P_{AV}$
SPREAD
2
3
4
5
6
A_1/A_2

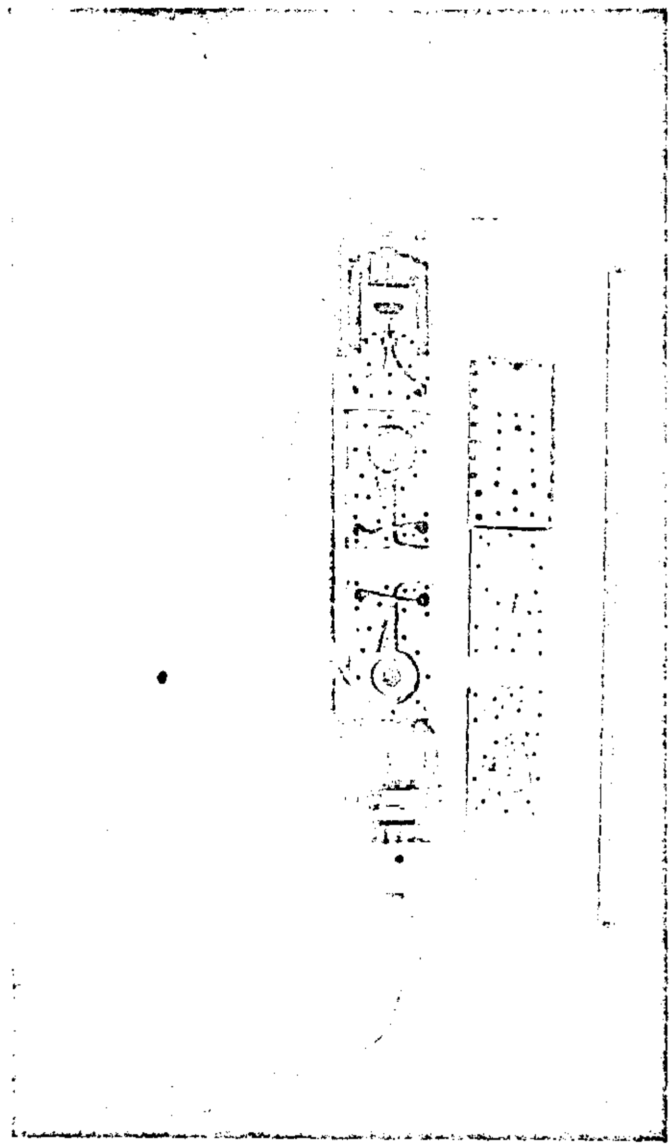


figure 8

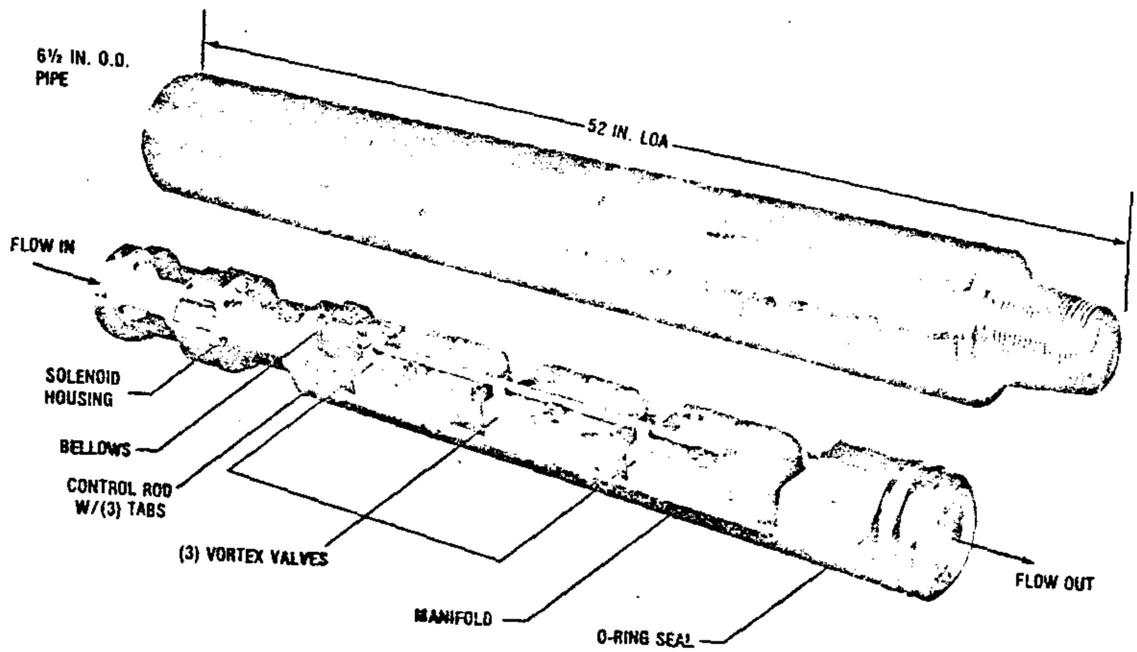
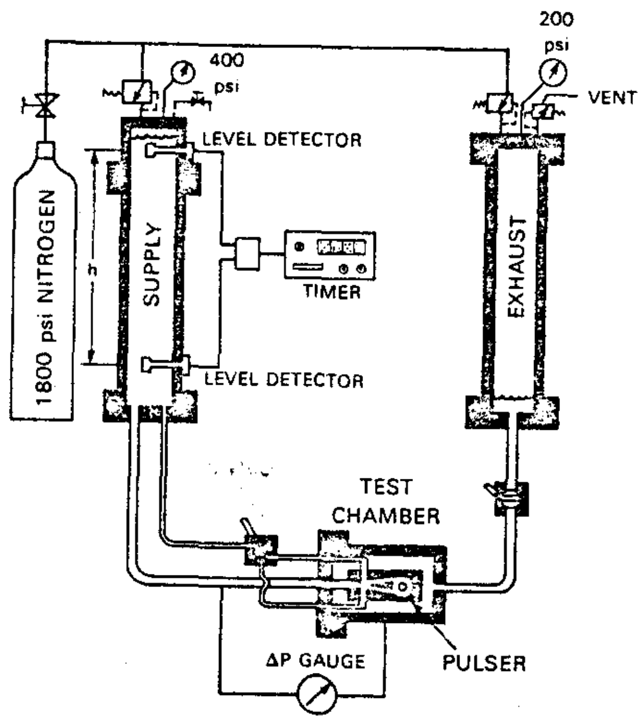

6½ IN. O.D.
PIPE
52 IN. LOA
FLOW IN
SOLENOID
HOUSING
BELLOWS
CONTROL ROD
W/(3) TABS
(3) VORTEX VALVES
MANIFOLD
O-RING SEAL
FLOW OUT

Fig 9



PULSER FLOW DIAGRAM

Fig. 16

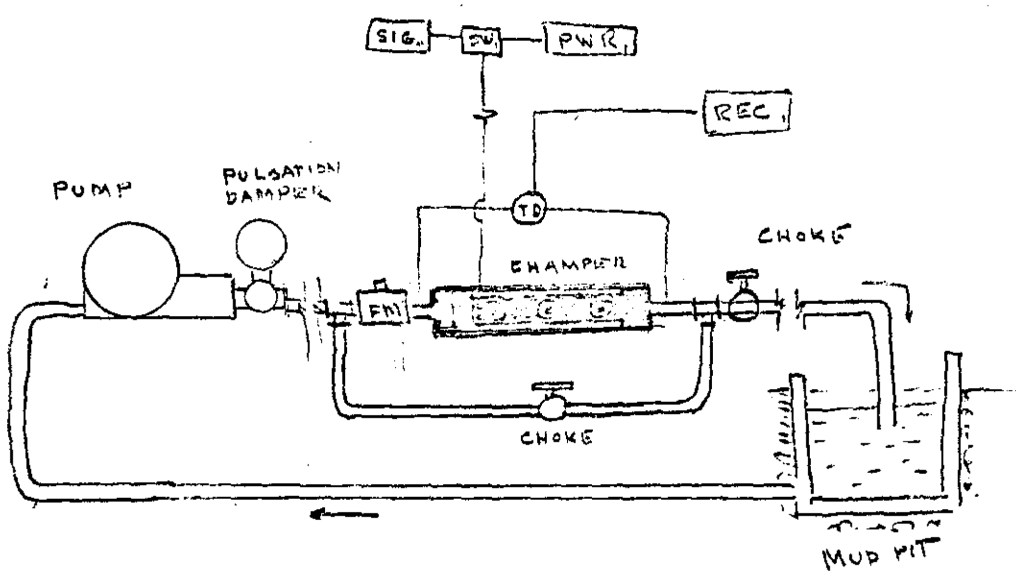

SIG.
SW.
PWR.
REC.
PUMP
PULSATION DAMPER
TD
CHOKE
CHAMPER
FM
CHOKE
MUD PIT

Figure 11.

BLANK

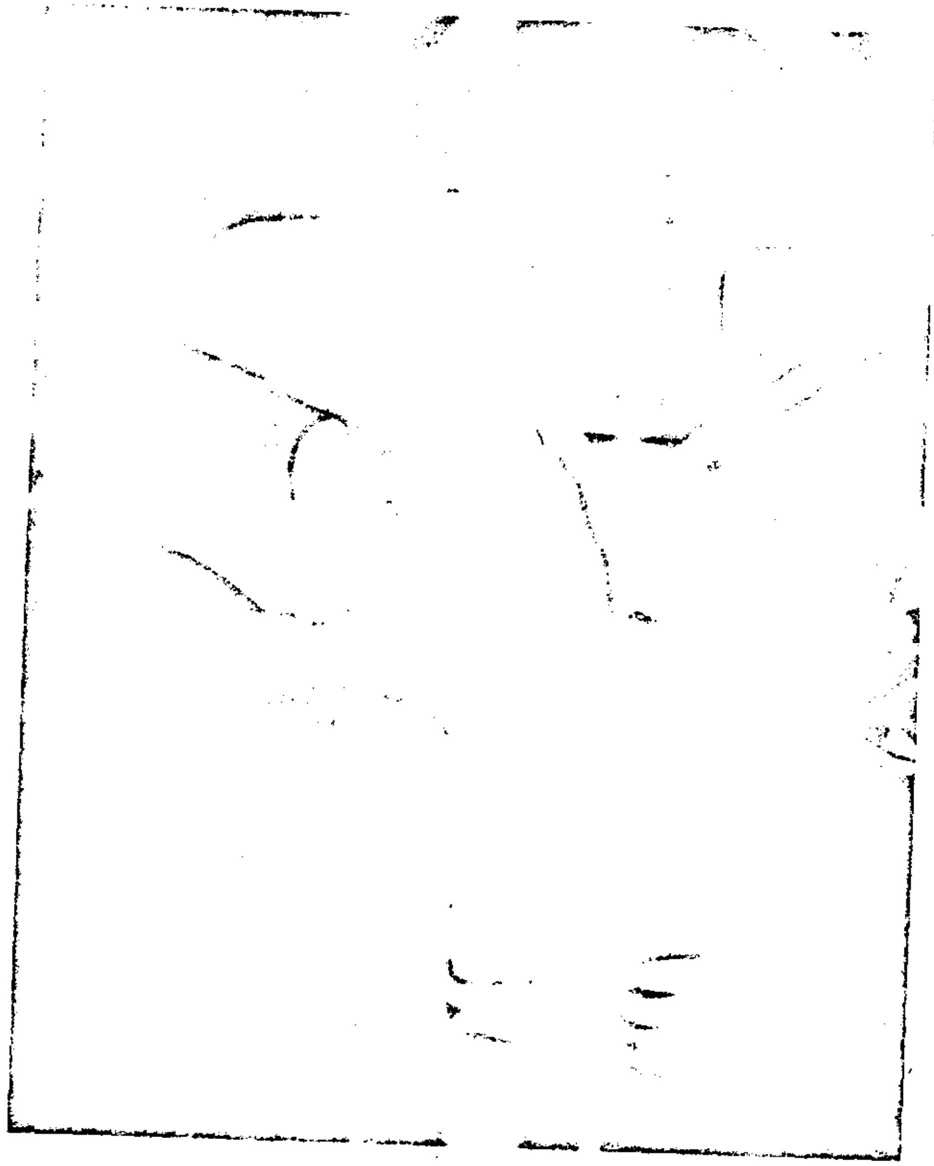


TABLE 1. MUD PROPERTIES

Property	Mud I	Mud II	Mud III
Density (ppg)[a]	8.4	12	15.3
Plastic viscosity (cps)[b]	11	20	27
Yield point ($lb/100\ ft^2$)[c]	8	19	6
Gel strength ($lb/100\ ft^2$)			
10 s	7	30	23
10 min	28	85	51

[a] $(ppg)119.8 = (kg/m^3)$

[b] $(cps)10^{-3} = (Pa \cdot s)$

[c] $(lb/100\ ft^2)0.4788 = (Pa)$

*$(lb/barrel) = \sim(g/350\ cm^3)$.

†$(ppg)119.8 = (kg/m^3)$.

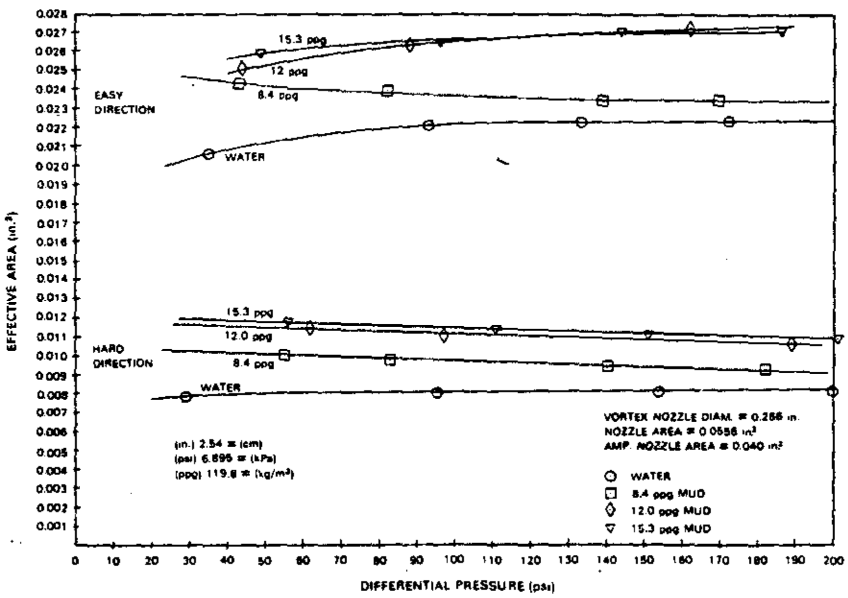


Figure 7. Effective area of circuit A versus pressure drop.

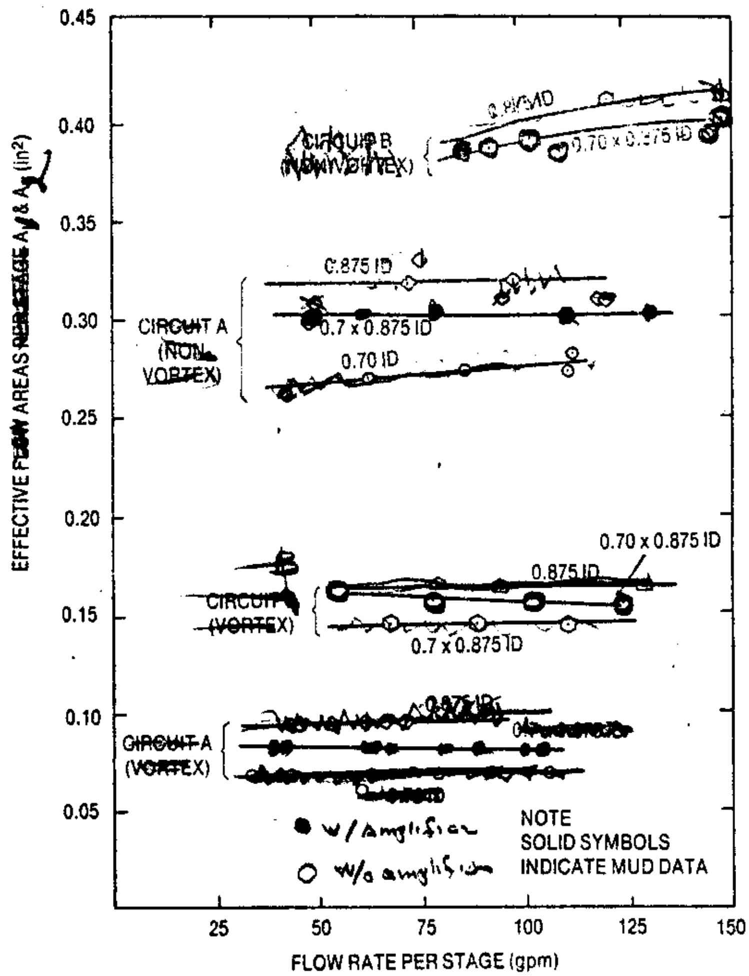
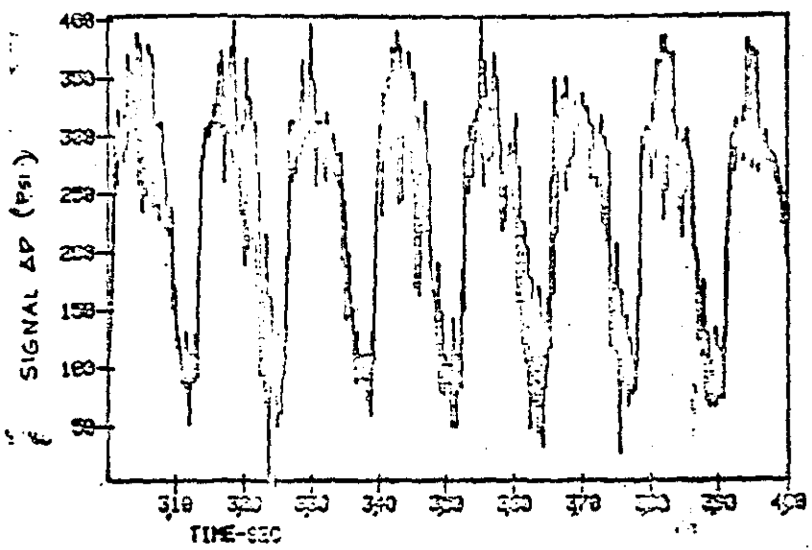
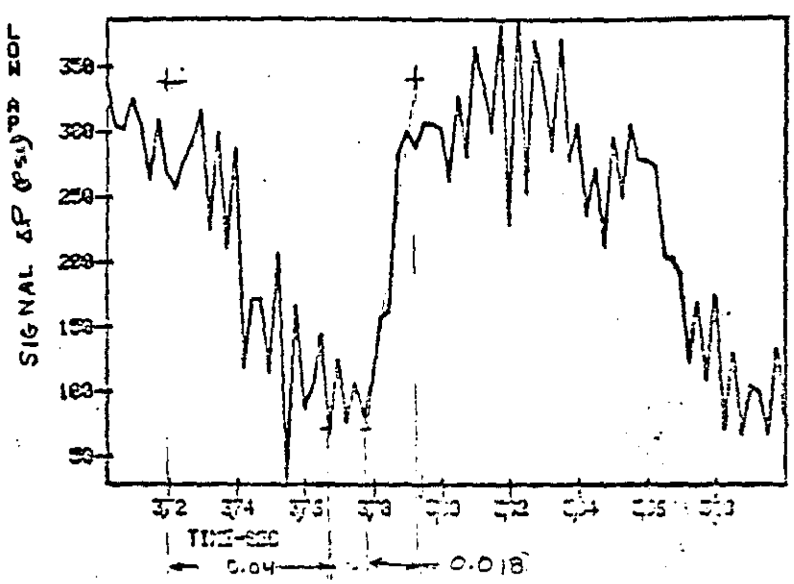


Figure 16. Characteristics of full-scale circuits with water and drilling mud.

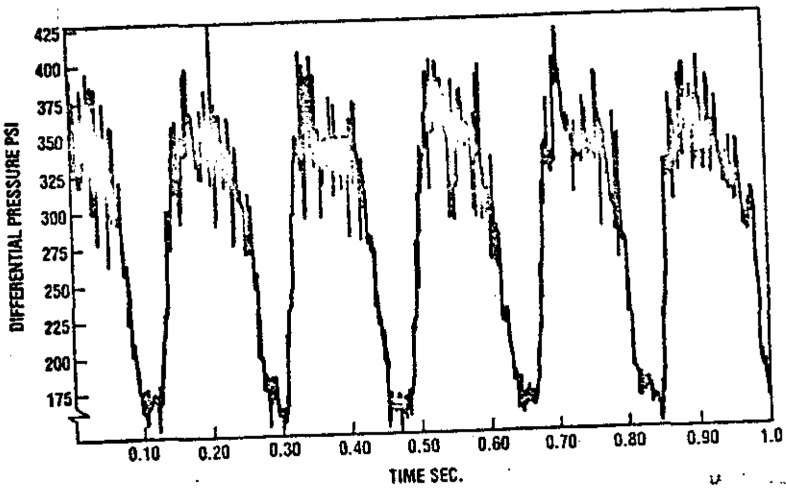


(a)



(b)

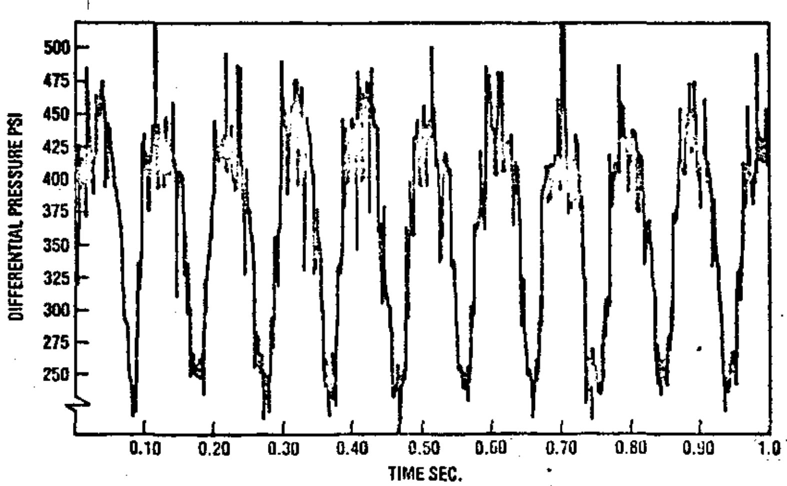
Fig. 16



FLUID — MUD
CIRCULATION RATE 300 GPM
MUD WEIGHT 12 PPG

PULSE FREQUENCY 6 Hz
AVERAGE PRESSURE 260 PSI

(b)



FLUID — WATER
CIRCULATION RATE 400 GPM

PULSE FREQUENCY 10 Hz
AVERAGE PRESSURE 365 PSI

(a)

Fig 17