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Disposable Fiber Optics Telemetry for Measuring While Drilling

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ABSTRACT

The project addressed the need of the oil and gas industry for real-time information about the drilling process and the formations being drilled. An ideal system would allow measuring while drilling (MWD) and would transmit data to the surface immediately at a rate high enough to support video or televiewer systems. A proposed solution was to use an optical fiber as a link between the surface and the instrumentation package. We explored the use of a disposable MWD telemetry cable, drawing on the technology developed for missile guidance which deploys miles of fiber from a small spool at missile speeds approaching half the speed of sound. Emphasis was on the questions of survivability of the unarmored fiber in the drill string environment and deployability. Laboratory and field testing showed the concept worked under realistic conditions; a field demonstration transmitted data at 10 kilobits per second from a depth of 3500 feet.

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Part I
Executive Summary

There is a great need in the oil and gas industry for real-time information about the drilling process and the formations being drilled. Ideally, the information would be measured while drilling (MWD) and transmitted to the surface immediately at a rate high enough to support video or televiewer systems. As the the MWD business generates about $300 million using data transmission rates of 1 to 10 bits per second, the economic implications of increasing the data rates into the megahertz range are clear. High data rates would allow the real-time use of virtually any instrumentation to observe the drilling process and the surrounding formations.

An obvious solution, that has been tried, is to connect an electrical or fiber optic cable to the instrumentation package. The difficulty with this solution lies in arranging to thread and retrieve cable through thousands of feet of drill pipe under operating conditions.

We proposed to develop a disposable MWD telemetry cable . The concept came from the non-line-of-sight missile guidance systems developed in the 80's. At missile speeds approaching Mach 1, 20 km of unarmored optical fiber could be deployed from a small spool (4 inches in diameter, 12 inches long) while real-time video signal was transmitted through the fiber for guidance. For MWD applications such a data link has several important features. The fiber link is light and compact, allowing easy handling on the rig floor by one person. A bandwidth of several megahertz removes the data-transmission bottleneck imposed by the current 10 bit per second data rate for MWD. Deployment would be simple as the entire fiber link could be inserted into the drill string at once. Unarmored fiber is inexpensive compared to reusable logging cable. The key difference from earlier attempts to insert cable in drill pipe is to consider the cable a throwaway item, to be used once and then ground up and flushed out in the drilling mud. If the cable only has to survive for a few hours and need not be retrieved then it may be feasible to use unarmored fiber which is cheap and can be wound into packages small enough to be threaded into the drill pipe during tripping-in without interfering with operations. The extreme lightness and compactness of the fiber cable spool makes it easy to manipulate, compared to the massiveness of a conventional reusable cable.

The task to be addressed was a determination of whether available optical fiber could survive for the required time in the drill string environment. Areas of concern were abrasion due to the sand-laden drilling mud, chemical effects, pressure effects and drag on the fiber due to mud flow down the drill string. Originally, only laboratory testing was planned, but rapid progress made it possible to add a field test.

Laboratory testing showed that commercially-available fiber could withstand the anticipated drill string and mud environment. Abrasion tests in a flow simulator with mud deliberately loaded with sand to increase abrasivity found no damage to the nylon-coated fiber after 24 hours at realistic flow rates of 500 gpm. Tests were done at 5000 psi, 100 $°C$, and a pH of 11 to show that the fiber could survive the chemical, pressure and temperature effects expected in a drill hole. Drag tests were conducted to determine the force on the fiber due to the mud flow in the drill string. For commercially-available fibers, the useful strength is about 100 pounds. From the laboratory drag tests, it was predicted that about 4000 feet of fiber could be deployed in a mud stream of 500 gpm in a 4.5 inch ID pipe. It appeared that this would be the limiting factor.

Because of the unexpectedly-rapid progress of the laboratory program and the availability of a drill rig at the DOE Long Valley Magma Energy site, it was decided to attempt a field test. The fiber tested at Long Valley was a commercially-available, 400 micrometer diameter fiber. More than 1 km of unarmored fiber, with a total weight of about 1 kg (2.2 lbs) was deployed into the drill string. A continuous temperature log was transmitted from the downhole end of the fiber to the surface while mud was circulated through the non-rotating drill string at rates up to 550 gallons per minute.

Several conclusions can be drawn from the field test. 1. Unarmored fiber does have a useful survival time at realistic mud flow rates. 2. Laboratory drag measurements overpredicted the drag by a factor of 2 or 3. Low drag substantially extends the useful depths or flow rates for the fiber link. 3. Using off-the-shelf equipment, the present system could transmit data at about 1 megabit per second, 5 orders of magnitude faster than commercially available MWD transmission systems, without interfering with the drilling process.

Part II
Technical Report

1 Introduction

There is a great need in the oil and gas industry for real-time information about the drilling process and the formaitons being drilled. Ideally, the information would be measured while drilling (MWD) and transmitted to the surface immediately. The bottleneck is the data transmission process; Current technology allows about 1 bit per second transmission rates. Even at this rate, the MWD industry generates about $300 million. There is no shortage of parameters that could be measured:

- Sonic properties

- Elemental analysis (neutron source)

- resistivity

- density

- porosity

- natural radioactivity

- resistivity imaging of bore hole wall

- borehole televiewer, (sonic)

- borehole television camera

- NMR

- hydrocarbon content

- drill bit orientation

- torque and weight on bit at the bit, not at top of string

- temperature pressure

- chemistry

Given the economic incentives for increasing the transmission rate, it is not surprising that a large effort has been put into the search for communication technologies that will surpass the 1 to 10 bit per second rate of the current mud pulse technology. Approaches have included direct sonic transmission of the signal up the steel drill string (Drumheller, 1993, Drumheller, et al., 1995), broadcast of EM signals, wireline retrieval of data, and direct connection of a signal wire to the MWD instrumentaion. As yet none of these efforts have proven successful due to the

constraints of very harsh environment in the drilling operation and high costs of interfering with the drilling process.

The obvious solution of a direct connection to the instrumentation package has been tried in several different ways. The difficulty with this solution lies in arranging to thread and retrieve cable through thousands of feet of drill pipe under operating conditions.

2 Approach

We proposed to develop a disposable MWD telemetry cable . The concept came from the non-line-of-sight missile guidance systems developed in the 80's. At missile speeds approaching Mach 1, 20 km of unarmored optical fiber could be deployed from a small spool (4 inches in diameter, 12 inches long) while real-time video signal was transmitted through the fiber for guidance. For MWD applications such a data link has several important features. The fiber link is light and compact, allowing easy handling on the rig floor by one person. A bandwidth of several megahertz removes the data-transmission bottleneck imposed by the current 10 bit per second data rate for MWD. Deployment would be simple as the entire fiber link could be inserted into the drill string at once. Unarmored fiber is inexpensive compared to reuseable logging cable. The key difference from earlier attempts to insert cable in drill pipe is to consider the cable a throwaway item, to be used once and then ground up and flushed out in the drilling mud. If the cable only has to survive for a few hours and need not be retrieved then it may be feasible to use unarmored fiber which is cheap and can be wound into packages small enough to be threaded into the drill pipe during tripping-in without interfering with operations. The extreme lightness and compactness of the fiber cable spool makes it easy to manipulate, compared to the massiveness of a conventional reuseable cable.

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3 Laboratory Work

Laboratory invesigations were conducted to determine the strength, abrasion resistance, chemical resistance, response to pressure and drag forces for various fibers.

3.1 Fiber Type Chosen

An extensive literature search was carried out to determine suitable candidates for further testing. The dominant parameters were strength and chemical resistance. A number of fiber types were found to be suitable, or perhaps more accurately, were not ruled out. Because of the non-standard application we were proposing, there was little applicable data available for most of the fibers. Typically, response to chemical exposure was not known. Since drilling mud tends to be alkaline (pH $\geq$ 10), and glass is susceptible to corrosion by alkaline fluids, this was a major concern.

Initial results from drag testing, discussed later, were not encouraging; drag forces were higher than anticipated, requiring that the fiber strength be as great as possible. Since all fibers being considered are basically glass, the theoretical strength is that of glass, about 1.2×10^6 psi. Most communications-grade optical fibers are specified and tested to 100,000 psi. Short lengths of fiber may be much stronger, but the statistical distribution of microflaws implies that the theoretical strength will not be approached for fiber lengths exceeding a few meters.

Several fibers were selected as possibly being suitable, including the fiber used for Non-Line of Sight (NLOS), fiber-optic-guided missiles. The most promising fiber (HCP-M0400T-08) was made by Ensign-Bickford as a speciality fiber for maximum light transfer. This fiber had a passivating layer that was designed to supress growth of microflaws, resulting in a specified strength of 200 kpsi. Statistical calculations indicated that the strength could be in the 500 kpsi range for 1 kilometer lengths. In addition, the passivation layer offered a degree of chemical protection.

Fiber diameter was 400 μmeters, with an additional 30 μmeters of cladding. A thicker fiber was available, which would have increased strength as the square of the diameter, but the stiffness increases as the fourth power of the diameter. To meet desired bending radii, the diameter was limited to 400 μ meters. Assuming a 500,000 psi breaking strength, the maximum force supportable by the chosen fiber would be 100 pounds.

3.2 Holding Fixturing

The forces exerted on the fiber by fluid drag on the fiber could be as high as the breaking strength, approximately 100 pounds. This created a problem for attaching the instrumentation can to the fiber, as it is only about 0.5 mm in diameter with the cladding. Various clamping devices and rubber compresson seals were tried and found wanting. The final solution relies on friction around a small non-rotating drum (see Figure 1). The solution is elegant in that it is compact, exerts no concentrated stress on the fiber, can hold any reasonable force and contains no moving parts.

The relevant equations for the force are derived using the following quantities:

- T Tension in the fiber

- $T(0)$ Initial tension in fiber, at seal end

- r Radius of friction drum

- μ Coefficient of friction between drum and fiber

- θ_f Total wrap angle (radians)

From Figure 1, it is seen that the normal force dF_n between a segment of fiber, length dl and the friction drum is twice the component of the tension resolved along the radius of the drum:

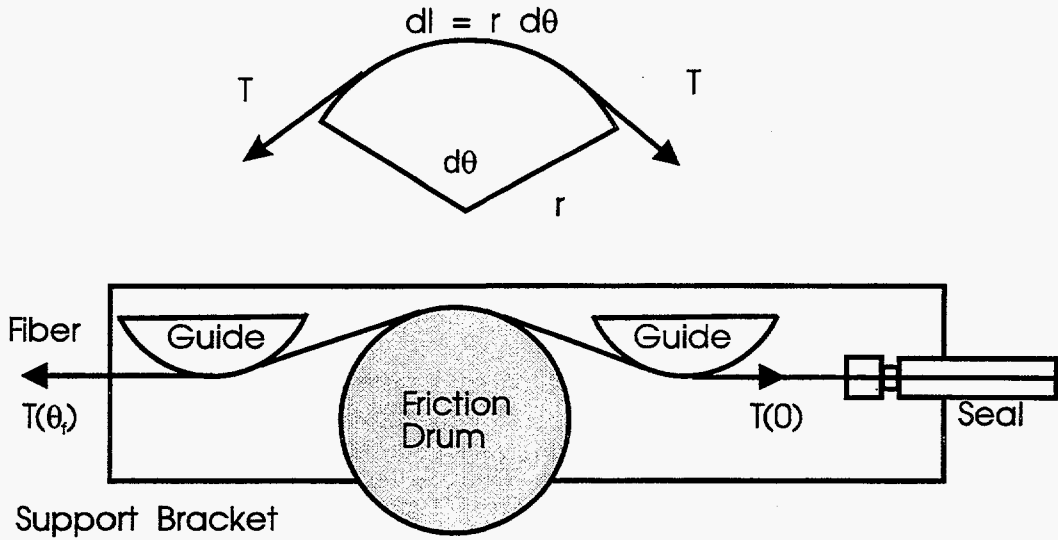$$dF_n = 2T sin(d\theta/2). \qquad (1)$$

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Figure 1: Frictional fixture for attaching instrumentation can to the fiber.

Using the small angle approximation for sin and rearranging, Equation 1 becomes

$$dF_n = Td\theta \tag{2}$$

or, since $dl = rd\theta$,

$$dF_n/dl = T(\theta)/r. \tag{3}$$

The frictional drag force is F_f is proportional to the increment of fiber length and the coefficient of friction. Therefore

$$dF_f = \frac{dF_n}{dl}\mu dl = T(\theta)/r\mu dl \tag{4}$$

$$dF_f = \frac{T(\theta)}{r}\mu dl \tag{5}$$

and substituting $dl = rd\theta$, the increment of frictional drag per increment of wrap around the friction drum is

$$dF_f = T(\theta)\mu d\theta. \tag{6}$$

The quantity of interest is the difference in the fiber tension before and after the tension drum. Across an increment of arc $d\theta$, the tension that can be supported increases by the increment of frictional force, given by equation 6. Thus

$$T(\theta + d\theta) = T(\theta) + dF_f(\theta), \tag{7}$$

assuming the fiber is being pulled in the direction of increasing θ. Then, using Equation 6, the increment of supportable tension becomes

$$dT(\theta) = dF_f(\theta) = T(\theta)\mu d\theta. \tag{8}$$

Integrating over the total angle of wrap, which can exceed 2π for multiple turns, results in an expression for the tension that can be supported as a function of angle wrapped θ_f, coefficient of friction μ and initial tension $T(0)$.
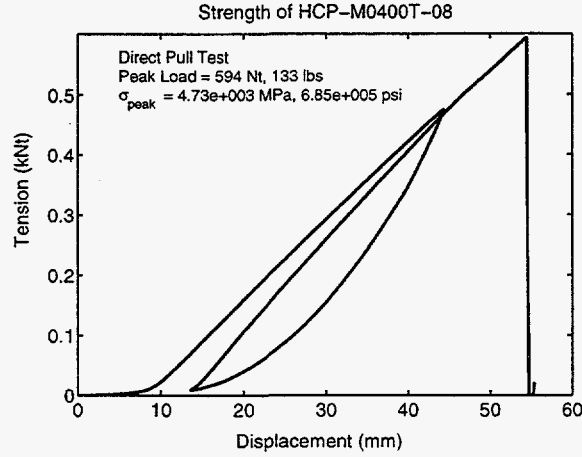
Figure 2: Strength versus displacement for fiber using a frictional holding fixture.

$$\int_0^{\theta_f} \frac{dT(\theta)}{T(\theta)} d\theta = \int_0^{\theta_f} \mu d\theta \tag{9}$$

Integrating and rearranging leads to the desired expression

$$\theta_f = \frac{\ln\left(\frac{T(\theta_f)}{T(0)}\right)}{\mu}. \tag{10}$$

We found that the instrumentation can seal could hold about a 10 pound tension and the maximum expected tension was the breaking strength of 100 pounds, so $T(\theta_f)/T(0) \leq 10$. For $\mu = 0.1$ or 0.2, the wrapping angle required would be four and two turns, respectively.

3.3 Strength

To test the holding strength of the friction fixture and get an idea of the actual strength of the fiber, a direct pull test was conducted. A short length (343 mm) of fiber was tested to failure in tension, with one end held by the fixture described earlier and the other wrapped around a drum. Results are shown in Figure 2, where tension in kNt is shown as a function of displacement to failure. The fiber was briefly unloaded from about 0.48 kNt, before continuing to failure. A failure stress of 685,000 psi (4.7 GPa) was observed, assuming a diameter of 400 μmeters, corresponding to about 50% of the theoretical maximum. The force required was 133 pounds (594 Nt). Maximum stretch was about 40 mm over a length of 343 mm, corresponding to a peak strain of 13% and a Young's modulus of about 5.3×10^6 psi (36 GPa). These results are in accord with expectations for a glass fiber with few flaws.

3.4 Effects of Heat, pH and Pressure

Drilling conditions are a harsh environment for the slender glass thread we are proposing to use as a telemetry link: temperatures in excess of $100°$ C, presssures of several thousand psi and an

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alkaline drilling mud that is corrosive to glass. For the unarmored fiber to be practical, it must survive during a complete drilling cycle of tripping in the pipe and removal for bit changes. This can be in excess of 24 hours.

A series of tests were run to determine the sensitivity of the fiber to realistic drilling conditions. All tests were conducted with about 2 meters of fiber inside a standard pressure vessel. Feedthroughs were provided to bring the fiber into the test vessel and back out, allowing a pulsed light signal to be sent through the fiber as monitor of its condition.

It was found that for tests up to 24 hours in duration, the fiber was essentially unaffected by any of the test parameters. The maximum pressure applied was 5000 psi. Temperatures up to 100° C were used, in conjunction with a fluid bath having a pH=10.8. As judged by signal amplitude, the fiber was not degraded significantly by any of these conditions.

4 Flow Effects

In operation, the optical fiber would be inside the drill string, subjected to abrasion and drag by the visocus drilling mud. Sand and rock cuttings in the drilling mud are extremely abrasive, requiring the use of tungsten carbide inserts in the jets at the drill bit. Drag on the fiber is cumulative over the long lengths (up to 3 km). Even small amounts of drag would quickly build up and break the fiber. To understand and quantify these effects, a flow facility was set up that could expose 3 meter lengths of fiber to realistic mud flow conditions while signal transmission and drag forces were measured.

Figure 3 shows the flow section of the apparatus. Not shown is a mud pump and return tank. In operation, drilling mud was circulated through the 3 inch pipe at a rate of up to 500 gpm. A pulsed light signal was sent through the fiber to test integrity and drag forces were measured using a strain gage in the fixture shown in Figure 4. Strain measurements were made at the base of the flow section using a thin-beam strain gage mounted on a cantilever bridge, which in turn was attached to the fiber by a variation of the friction fixture described earlier. By winding the fiber around the 1/2 inch steel tube shown near the center of Figure 4 it was possible to get a solid mechanical attachment. A monofilament string was then used to connect the tube to the strain-gaged cantilever bridge just below.

4.1 Abrasion

Abrasion testing consisted of monitoring the signal level for light transmitted through three meters of the test fiber mounteded in the flow apparatus shown in Figure 3, while various drilling fluids were circulated.

Tests were done using plain water, bentonite mud and bentonite mud with added sand. For all tests flow rates were approximately 500 gpm in a 3 inch tube. Mud viscosities ranged up to 35 cp at densities of about 9 pounds per gallon. For tests with added sand, about 2% sand by volume was added to the mud. Tests were not done under representative pressures or temperatures, so these were not definitive tests. However, the results were encouraging in that no signal degradation was detected.
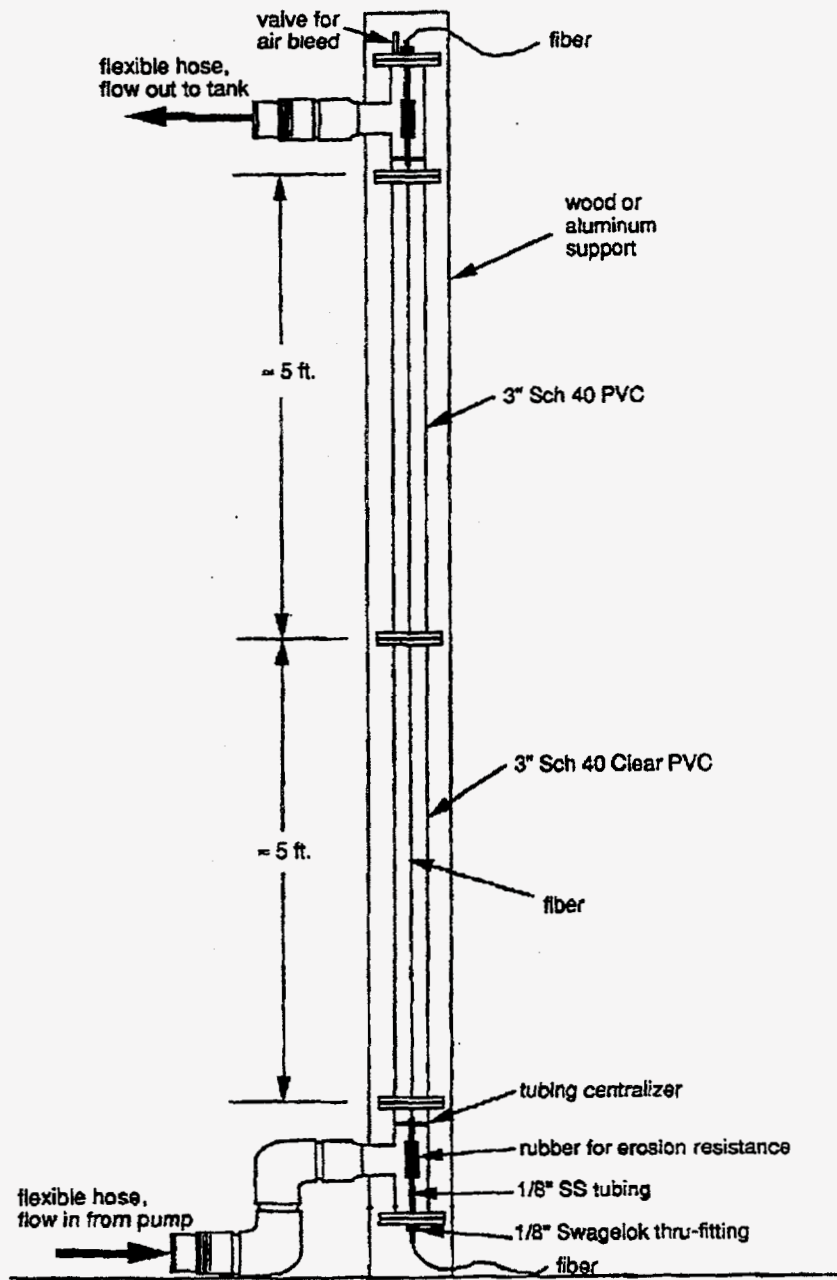
Figure 3: Apparatus used for drag and abrasion testing.

Thin-Beam Strain Gage Mounting Design

1/2" Steel Tube

Swagelok Pass-Thru
Tube Fitting

2" PVC Pipe Cap

2" PVC Pipe

Fiber

1/2" Steel Tube,
3/8" Wide

Monofilament
String

2" PVC Pipe
Coupling,
Cut Half Length

Setscrew

3.5"

3" PVC Pipe
Flange

Threaded
Rod
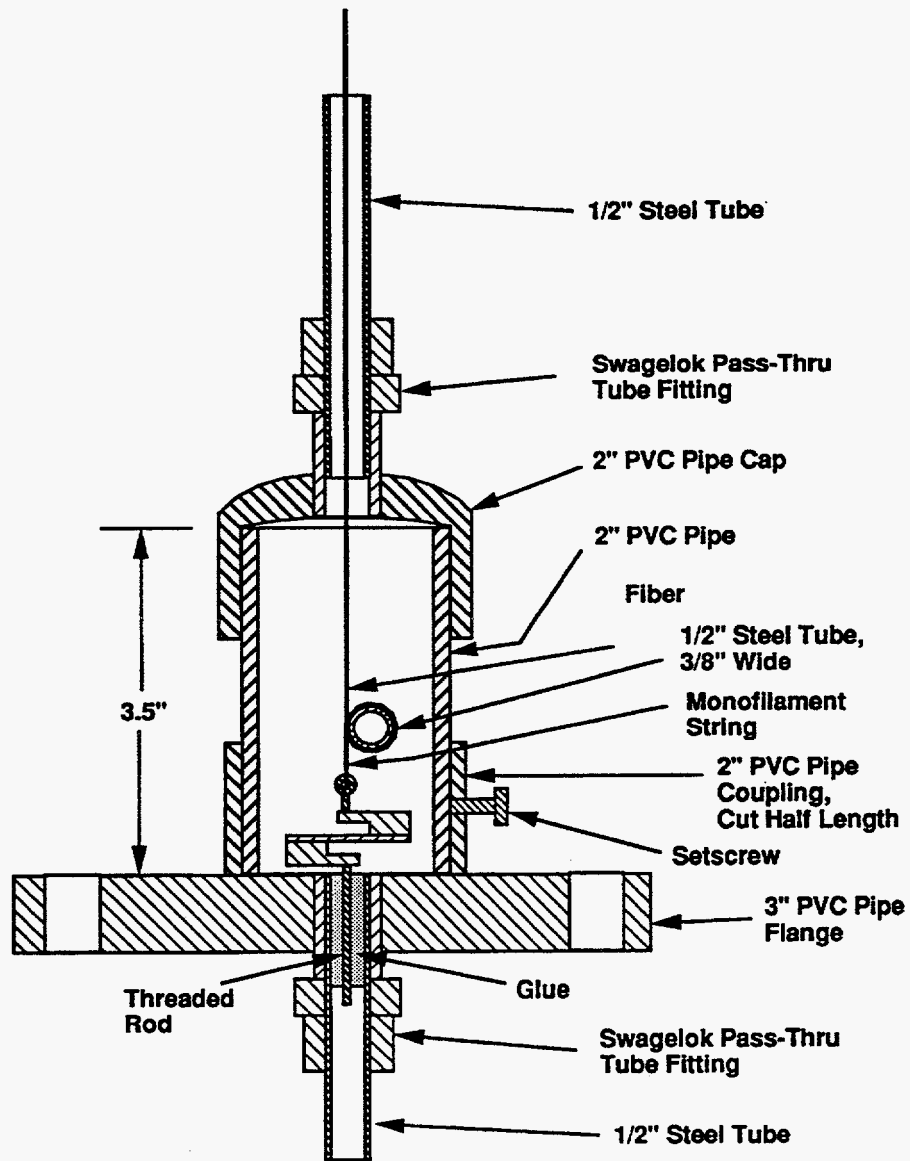
Glue

Swagelok Pass-Thru
Tube Fitting

1/2" Steel Tube

Figure 4: Cross section of mounting fixture for measuring drag exerted on the fiber by drilling mud.

4.2 Drag

Drag was the factor of greatest concern for the survivability of the fiber. Chemical attack and abrasion could be ameliorated by suitable coatings, although that proved not to be necessary. Drag on the fiber presented a more fundamental problem, with no obvious way of diminishing drag forces. The great lengths of fiber, combined with the cumulative effect of drag, required that specific drag be less than T_b/L, where the breaking tension $T_b \approx 100$ pounds and the length could be in excess of 10,000 feet. A specific drag approaching 0.01 pounds per foot would be cause for concern.

Drag was measured directly using a thin-beam strain gage coupled to the fiber (see Figure 4. A lengthy series of developmental tests was necessitated by the difficulties encountered while trying to couple the clad fiber to the strain gage. The final configuration wrapped the fiber around a small drum, relying on friction to hold the fiber without slippage.

Results for drag were not encouraging. Figure 5 shows measured specific drag in pounds per foot for the HCPM0400T fiber as a function of flow rate in the 3 inch i.d. tube. The mud used for this test had a viscosity of 15 cp. A power law dependence on flow rate was fitted to the data, showing that the specific drag f in pounds per foot was well described by

$$f = 8.436 \times 10^{-6} Q^{1.48}, \tag{11}$$

where Q is in gallons per minute. A similar test carried out with water (not shown) found that the specific drag was well fit by

$$f = 1.13 \times 10^{-6} Q^{1.78}. \tag{12}$$

Flow rates are expressed in gpm for a 3 inch i.d. tube and must be appropriately scaled for the actual cross sectional area through which the mud flows. At mud flow rates in excess of 100 gpm, the specific drag force began to exceed the desired maximum of 0.01 pounds per foot, with a power law dependence on flow rate. At rates expected in an actual drilling operation, the specific drag was nearly an order of magnitude above the maximum desired.

Two factors convinced us to continue. First, the small forces involved made the measurements difficult, leaving open the possibility that we were over-estimating the drag forces. Second, in a larger diameter drill pipe, the scaled flow rate would decrease as the square of the diameter, leading to greatly reduced drag forces.

5 Field Experiment

Although the drag results were discouraging, all other tests indicated a good chance that the unarmored fiber could survive for a useful length of time in the drilling environment. Anticipating that in a full scale test, mitigating factors might lead to decreased drag, and given the availability of a drilling rig and drill hole at the DOE Long Valley Magna Energy site, it was decided to proceed with a field test. The objectives were :

1. Demonstrate an actual working data transmission system, transmitting data from a depth of 3500 feet (maximum single fiber length available).

2. Determine actual drag forces

**Experimental Data and Possible Curve Fit
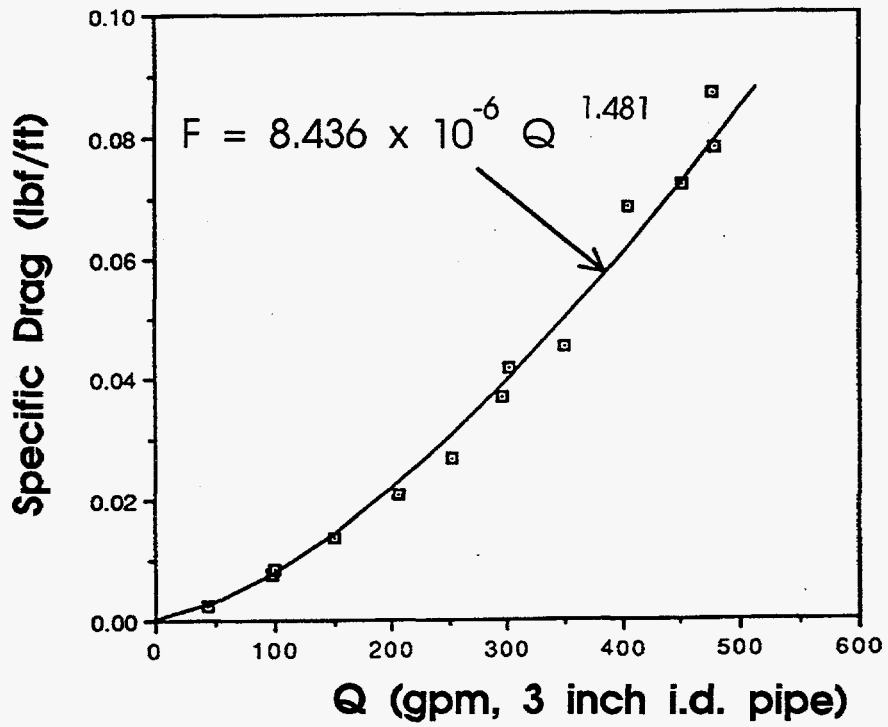Fiber HCPM0400T Drag Force vs. Flow Rate
in Drilling Mud**

$$F = 8.436 \times 10^{-6} \, Q^{1.481}$$

Figure 5: Drag forces on the 400 μmeter diameter HCPM0400T fiber as a function of flow rate, using 15 cp mud in a 3 inch i.d. tube.

3. Test the fiber to failure by increasing flow rates

An instrument can was needed to protect the transmitting LED connected to the bottom end of the fiber and the other circuitry associated with measuring bottom hole temperature, the parameter we decided to measure. Requirements were that the can fit into the drill string, pass the pipe joints which had a 4 inch i.d., withstand pressures up to 2000 psi for 24 hours, withstand the alkaline drill mud, have a bottom contact sensor and connect to the lower end of the fiber with a pressure-tight seal. Figures 6 – 11 show the realization of these specifications.

An aluminum tube was used for the body with hemispherical ends sealed to the tubular body by standard O-ring piston seals. The electronics contained in the body (see Figures 8 and 9 consisted of a battery-powered 555 timer chip driving an LED whose output was coupled to the downhole end of the fiber. The frequency of the timer was used for two purposes: bottom contact sensing and temperature signaling. Bottom contact was detected by a simple contact switch, consisting of an aluminum plunger protruding from the lower hemispherical end and three contact points epoxied into the bulkhead between the hemispherical end and the interior of the instrument can. When the plunger was forced upward by contact with the catcher assembly at the end of the drill string, two or more of the contact points were shorted by the conductive plunger. Internally, the contact points were electrically connected to the three resistor network (4.7 k, 4.7k and 10KOhm) that formed part of the RC timing circuit for the 555 timer (see Figure 8). Shorting any two contacts, shorted one of the resistors and changed the output frequency of the 555 and connected LED. By monitoring the frequency as the fiber and attached electronics can were lowered into the drill string, it was possible to detect contact with the bottom.

Temperature was measured using a thermistor in series with the resistor network used for bottom contact. Once on bottom the frequency was determined by the combined resistance of the resistor network and the thermistor. Assuming that the resistance of the closure switch network would not change after bottom was reached, then the instrument can be calibrated to give temperature as a function of frequency. Temperature was chosen, not because of any great importance, but because it was the simplest, cheapest measurement to implement. Any other parameter could be measured, and encoded with a suitable signal processing system for transmission up the fiber.

Once encoded as a frequency by the 555 timer, the signal was used to drive an LED coupled to the fiber by an inexpensive optical coupler. Because of the large diameter of the fiber, simple alignment techniques produced an acceptable light signal. After traveling through 3000 feet of fiber, the signal was detected and amplified by the simple circuit in Figure 9. All components were off-the-shelf and chosen more for convenience than for hardiness or performance. In particular, the transmission frequency was set to about 10Khz because the resistor network worked out well. The fiber bandwidth at this distance is specified to be better than 1 Mhz.

Coupling to the fiber was done in the protected environment inside the electronics can. Exiting the can was done via a pressure seal similar to that shown in Figure 7. The fiber passes through a loading nut, a metal pusher slug and a split rubber cylinder. By tightening the loading nut, the rubber cylinder is compressed, providing a seal that was tested to 2000 psi with out damage to the fiber or leakage. At the top of the drill string, the fiber exited through this seal.

To hold the fiber, the frictional holding fixture shown in Figure 1 was welded to the pressure seal (see Figure 6 and 11. With about a 10 pound tension at the pressure seal, this arrangement could hold tensions in the main fiber exceeding the predicted breaking strength. Despite the high
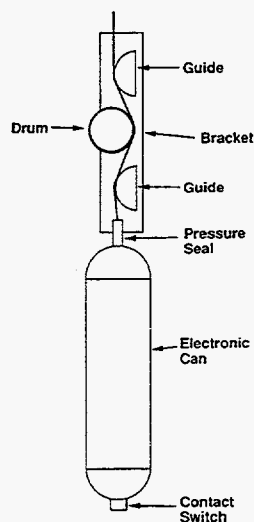
Figure 6: Drawing of instrumentation can and frictional holding fixture.

forces, no damage was done to the fiber by the fixture.

The simplicity and ruggedness of the design and the fiber is shown by the photograph of the final assembly process, connecting the fiber to the electronics can (Figure 10). This was actually done on the rig floor in about 15 minutes. The only danger of damage was if someone had actually stepped hard on the fiber.

Deployment of the fiber is a crucial operational issue which will be briefly discussed later. For the field test, there was no opportunity, funding or need to develop a prototype deployment system. As survivability was the main issue, all that was necessary was a system to smoothly unwind the reels of fiber into the drill string. The deployment system actually served several purposes. A revolution counter was used to keep track of the deployed length of fiber. This made it easier to know when to expect bottom contact and avoid introducing large amounts of kink-prone extra fiber into the drill string. A locking mechanism was used to keep the fiber from being unreeled into the drill string by the drag of the mud flow. Finally, a closure for the top of the drill string was incorporated as part of the support structure. Operational mud pressures could reach about 700 psi with flow rates of 500 gpm, so safety was a paramount concern. Figure 12 is a sketch of the system in place on the drill string, showing the fiber reel in place,fiber entering the drill string through a pressure seal, and the connected electronics can ready to be lowered 3000 feet into the drill string. Actual insertion of the can into the drill string is seen in Figure 14. The reel portion of the apparatus with fiber reel mounted, is seen in Figure 14. Figures 15 and 16 are mechanical drawings in side and front view.

It is important to note that the deployment system shown here is totally unlike what would be used in an operational deployment system. Much of its massive construction (several hundred pounds), dwarfing the actual fiber weight of about 2 pounds, was necessitated by the need to provide a top closure and mud acess for the drill string.
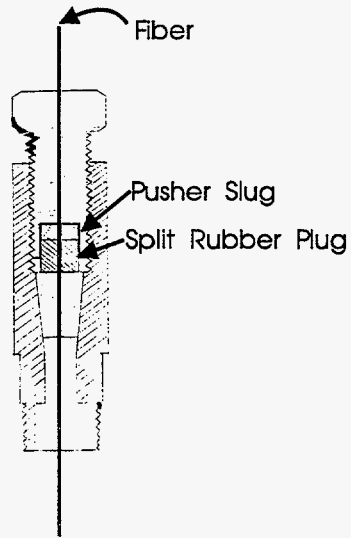
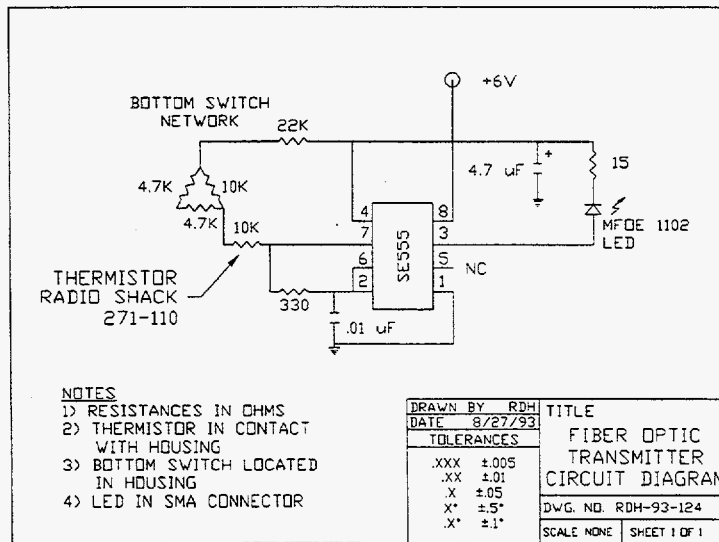Figure 7: Drawing of pressure seal for fiber at entrance to wellbore.

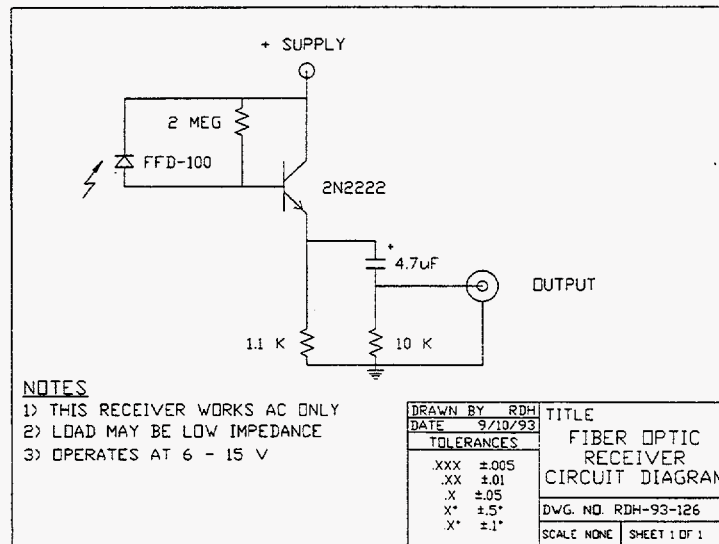Figure 8: Schematic of downhole instrumentation and LED source.

NOTES
1) THIS RECEIVER WORKS AC ONLY
2) LOAD MAY BE LOW IMPEDANCE
3) OPERATES AT 6 - 15 V

DRAWN BY	RDH	TITLE			
DATE	9/10/93		FIBER OPTIC		
TOLERANCES			RECEIVER		
.XXX	±.005	CIRCUIT DIAGRAM			
.XX	±.01				
.X	±.05				
X°	±.5°	DWG. NO. RDH-93-126			
X°	±.1°	SCALE NONE	SHEET 1 OF 1		

Figure 9: Schematic of tophole LED detector.

5.1 Results of field test

Individual fibers were approximately 3650 feet long. Therefore the test depth was chosen to be 3500 feet, even though the hole depth was in excess of 7000 feet. The test was to be done in a 4.5 inch i.d. drill string with joints narrowing to 4 inches. To protect the hole against debris from the test, a catcher assembly was attached to the down-hole end of the drill string. The catcher was perforated to allow mud flow and had a centralizer to catch and stabilize the electronics can when it reached bottom.

Fiber #1 was deployed into 3491 feet of drill string with few difficulties. At a deliberately slow pace, about 1 hour and 20 minutes were required for full deployment. As the bottom contact switch gave unconvincing indications of closure, with smaller frequency shifts than expected, we relied on the revolution counter to judge that we were close to bottom and then started the mud pumps at 60 gpm. The additional drag of the mud produced a convincing change in pulse frequency as the bottom contact switch closed solidly.

Ideally, the drill string would have been rotated during the test. This was not done because we wanted to monitor the signal continuously and did not have a means for transmitting the signal in a non-contacting way. considering the slow speed of rotation relative to the mud speed, we do not think rotation would have mattered.

The same drilling mud was used for this test as was used for drilling the hole, with a density of 8.9 lb/gal and a viscosity of 30 sec. No attempt was made to filter out sand, weeds or any of the other material that ends up in an open mud pit.

Drag measurements were made by measuring the fiber tension at the deployment reel using a force-deflection technique. A spring scale was attached to the fiber midway between the reel and the pressure seal. Then a known deflection was applied and the force required was measured using the scale. Knowing the lengths and the deflection force, it is a simple matter to calculate the tension in the fiber.
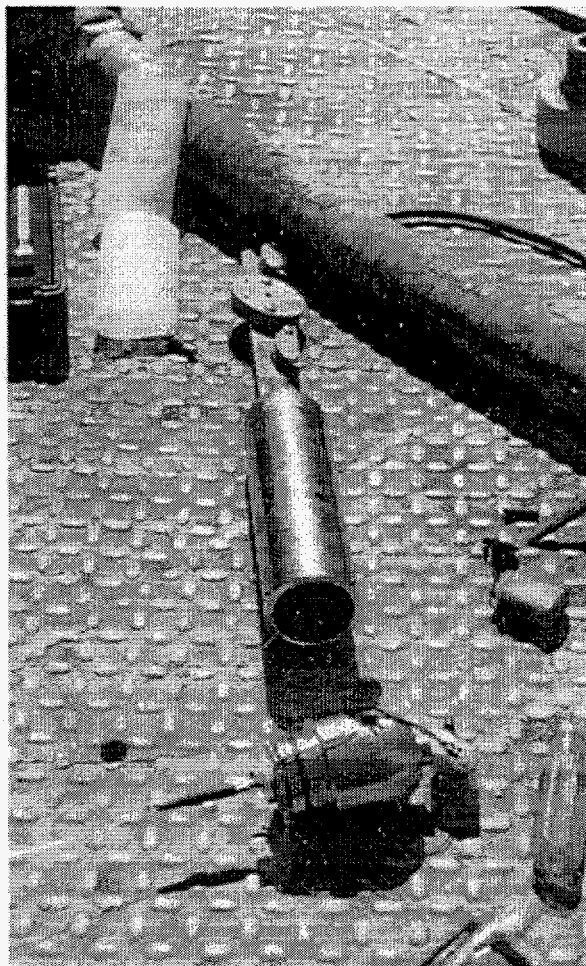
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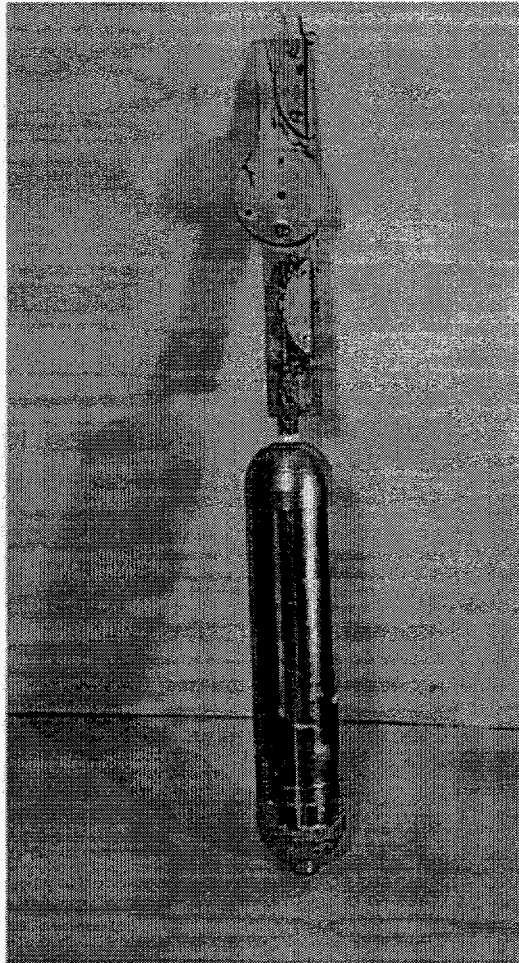Figure 10: Instrument can and frictional holding fixture laid out on rig floor prior to final assembly.

Figure 11: Instrument can and frictional holding fixture

Deployment Reel

Fiber Pressure Seal

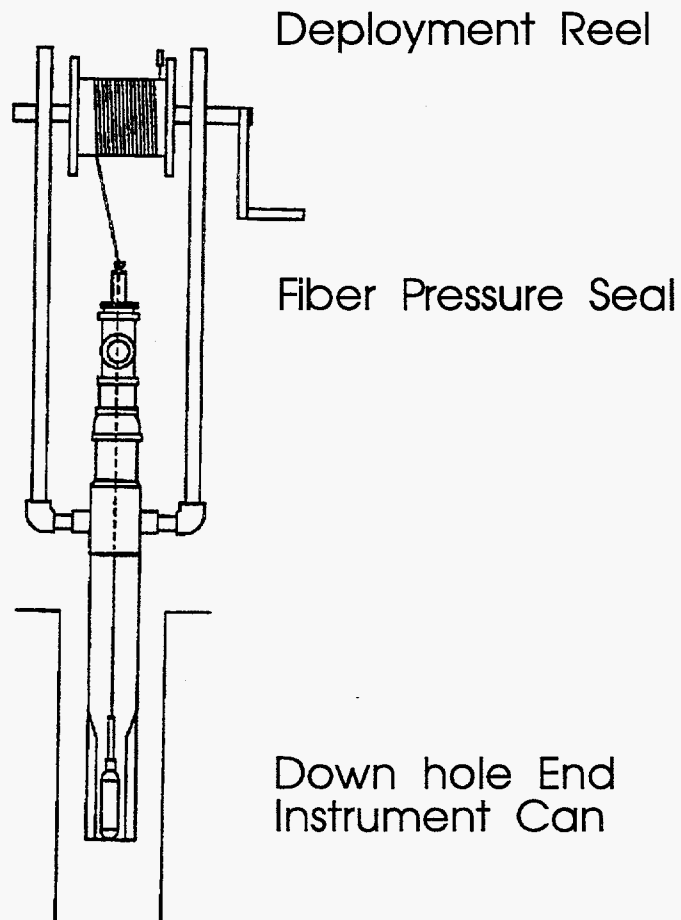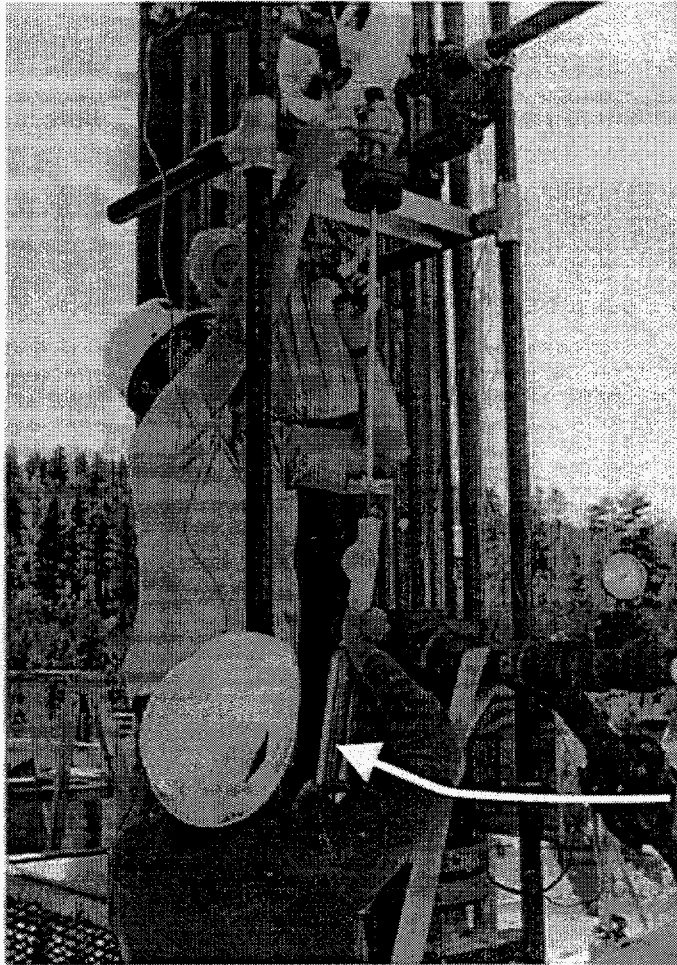Down hole End
Instrument Can

Figure 12: Sketch of deployment assembly in position on well head, with instrument can in wellbore.

Instrument
Can
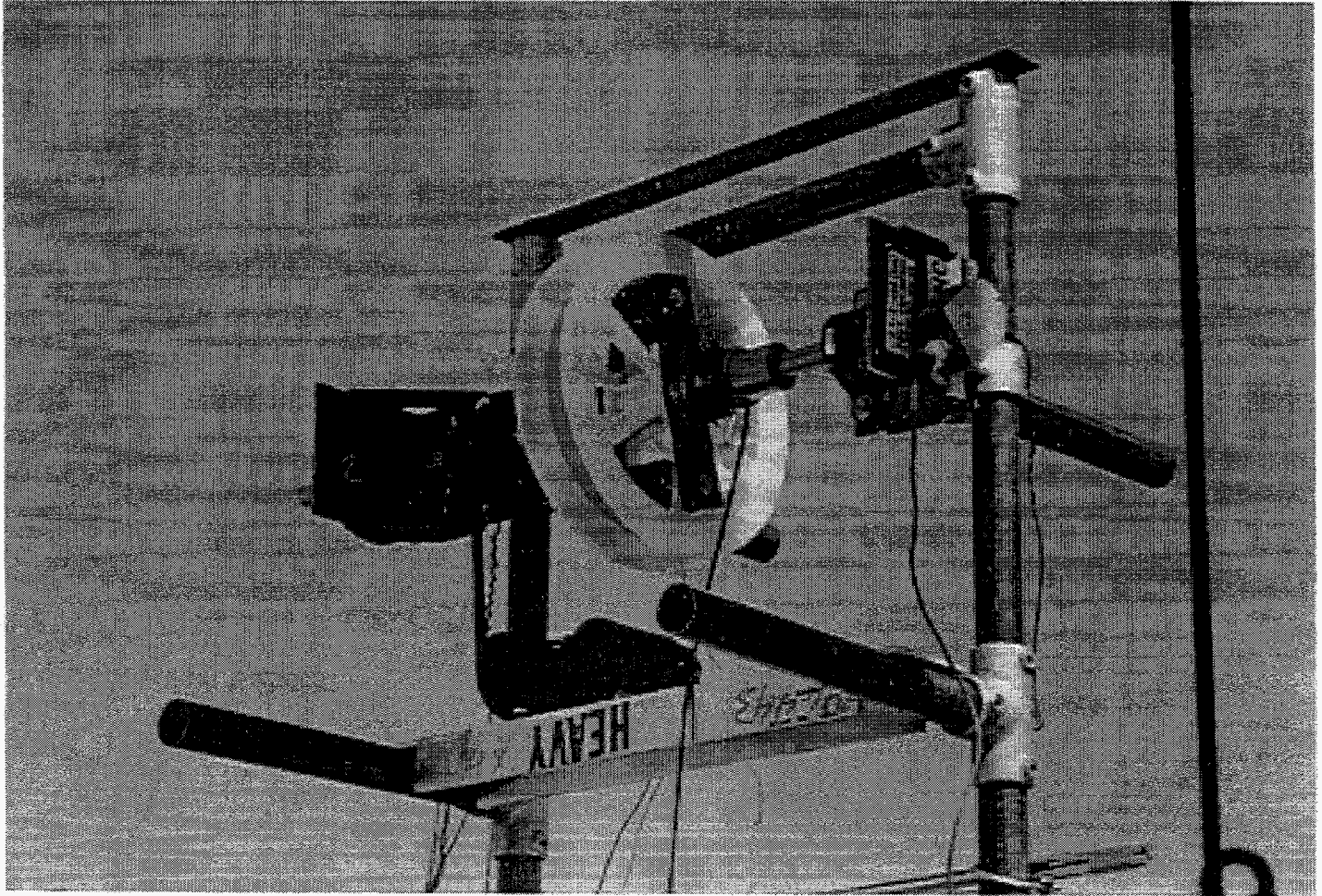
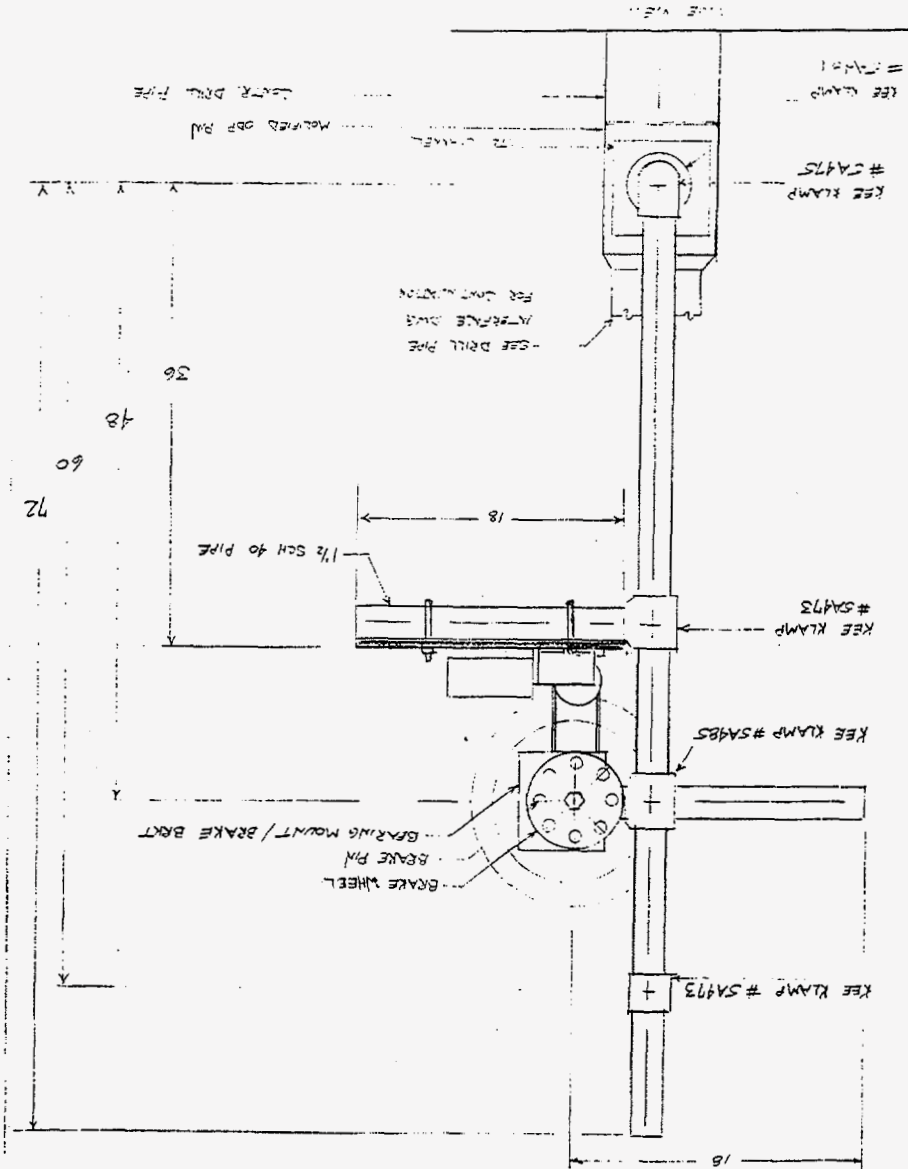Figure 13: Preparing to deploy fiber.

Figure 14: Fiber deploying apparatus in position.

Figure 15: Deployment assembly used for the field test (Side view)
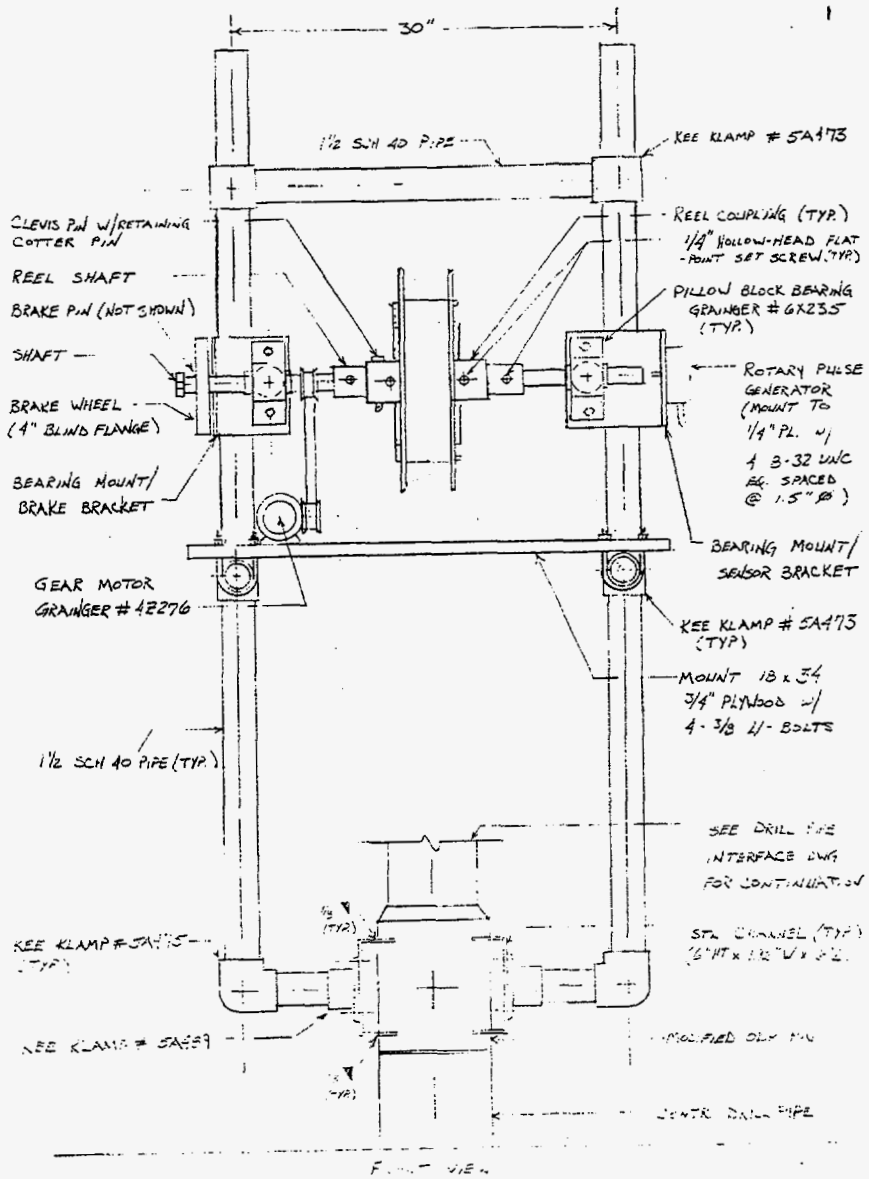
Figure 16: Deployment assembly used for the field test (Front view)

Flow was gradually increased to 200 gpm while monitoring the frequency of the received light signal. Pumping continued for 16 hours at the 200 gpm rate with no degradation in signal. The electronics functioned perfectly, reporting bottom hole temperature at a data rate of 10,000 Hz. Figure 17 shows the bottom hole mud temperature slowly declining during the cold autumn night as the mud pit cooled and then abruptly dropping when water was added to the mud pit at about 6 a.m., before beginning to warm up. The temperature is of no particular significance, except to show the ease with which data can be transmitted using this system. Data rates could have been increased by about two orders of magnitude by using a slightly more complex transmitter.

Having established the survivability of the fiber under realistic, but low flow rates, a destruction test was initiated. Over the course of 4 hours the flow rate was increased in steps, with pauses to check tension, rewind fiber to prevent loop over (more about that later) and monitor the fiber using the received signal. No degradation was observed until the fiber abruptly failed at 560 gpm. Mud flow was cut off and the fiber retrieved by winding back onto the shipping reel. The broken end, found at 550 feet, was abraded to a taper, implying that the failure mode was a loop whipping back and forth in the flow until the coating abraded through. At the down-hole end, the other 3000 feet of fiber were a tangled mass, easily removed by hand.

A second fiber was deployed and run for 5 hours at 360 gpm until a mud pump failure apparently led to fiber failure. Although the pump was restarted gradually, the fiber failed within minutes after flow was reestablished. This may have been coincidence, but we think the failure was due to kinking in the fiber introduced when the tensioned fiber recoiled up the drill string while the mud drag was absent. When mud flow resumed, we believe a kink in the fiber was pulled tight and caused a break.

Using an OTDR (optical time domain reflectometer), the distance to the broken end was found to be 1470 feet, to an accuracy of better than a foot. An OTDR measures time-of-flight for a light pulse traveling down the fiber and reflecting off the broken end. In an attempt to directly measure the stretching of the fiber due to mud drag, the mud pump was restarted and the OTDR used to measure fiber length as a function of flow rate. To our surprise, no change in length was observed even at rates of 400 gpm, where our calculations had led us to expect 20 or 30 feet of stretch.

5.2 Drag Measurements

As discussed earlier, drag was our major concern because of laboratory results that indicated drag forces would reach the breaking tension of the fiber for reasonable lengths and mud flow rates. Another concern was the stretch in the fiber even before failure. Approximately 100 feet of stretch was expected as the failure tension was reached. Because the instrument can was fixed in position at the bottom of the drill string, stretch in the fiber would tend to produce kink-prone loops as the excess fiber settled down around the can. Kinking introduces very high stress concentrations and would rapidly lead to fiber failure.

Direct measurements of the fiber tension, made during the first field test, are plotted in Figure 18 together with drag calculated from the laboratory tests discussed earlier. Calculated drag has been adjusted for the greater diameter of the drill string, as compared to the laboratory test apparatus. A solid line indicates the rapid increase in drag force predicted from the power law dependence observed in the laboratory. Direct tension measurements (+ symbols) did not agree well with the predictions, fortunately. At lower flow rates the measured drag force does increase,
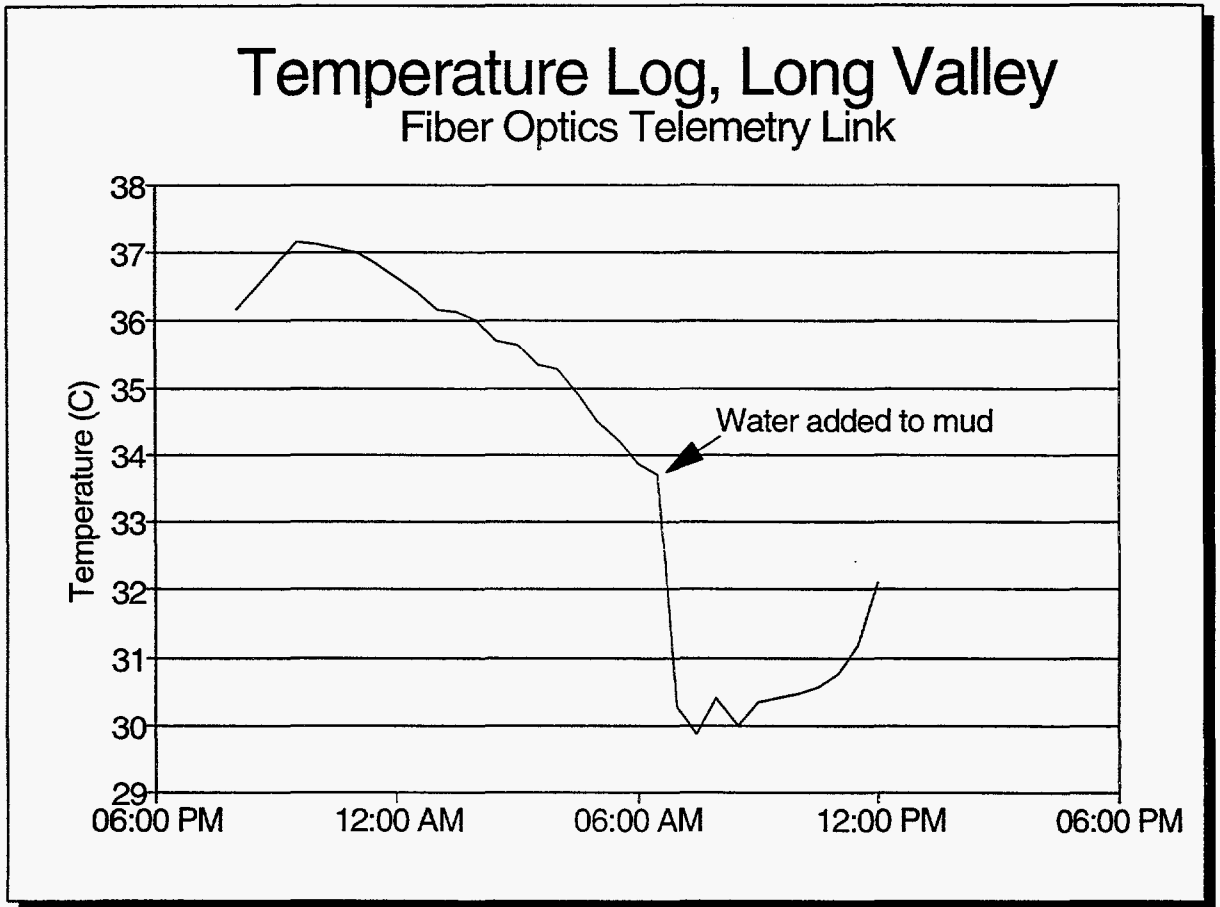
Temperature Log, Long Valley
Fiber Optics Telemetry Link

Figure 17: Temperature of down-hole mud as a function of time. Note the sudden drop when cold water was added to the mud pit.

Drag on HCP-M0400T-08

Field Test
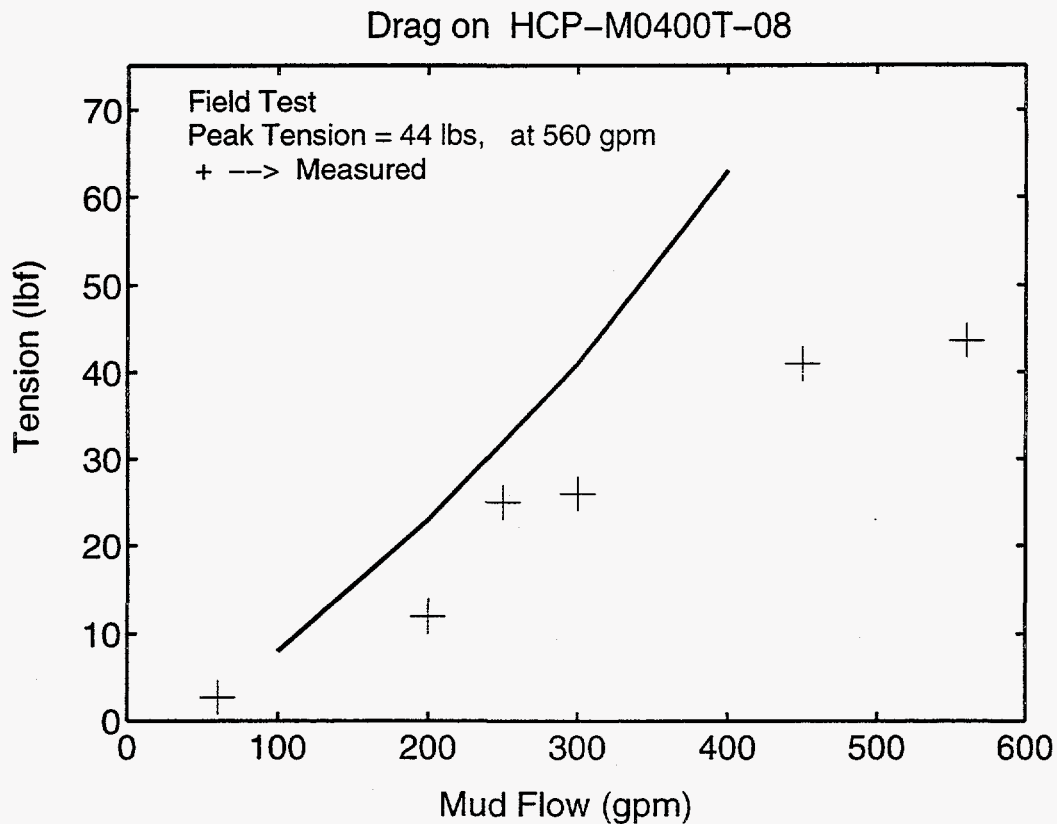**Peak Tension = 44 lbs,   at 560 gpm**
+ --> Measured

Figure 18: A comparison of calculated (solid line) and observed (+ symbols) tension in the fiber as a function of flow rate

but seems to saturate at flow rates above 400 gpm. Lower drag forces mean greater lengths of fiber can be deployed without incurring drag-induced tension failures.

In fact, it is not at all clear what tension would have been induced in the fiber by mud drag. Because of our concern that the stretching fiber would loop and kink, the fiber was rewound by the amount of calculated stretch corresponding to the mud flow rate. Each time the flow rate was increased, more fiber was rewound. Examining Figure 18 shows that we were probably over-compensating and rewinding too much fiber. If the fiber was free in the drill string, this would result in trying to lift the attached electronics can against the mud flow, an impossible task.

There are indications that the fiber was not free in the drill string and may have been lying against the pipe wall. First, the rate of tension increase was not monotonic with flow as would seem physically reasonable. Second, the results of the tests on the second, broken fiber indicate that the fiber was not stretching. Any reasonable estimate of the drag forces on the fiber indicate that stretch should have been easily detectable. A possible explanation is that the fiber spiralled out against the pipe wall where it would be held by Bernoulli forces. As flow increased drag, the holding force would also increase, protecting the fiber and giving a completely false measure of tension. This is a very important possibility. If true, then drag would not be the limiting factor on using unarmored optical fiber in the drill string.

6 Operational System

Although the field demonstrated that there are no "show stoppers" for the idea of using a a disposable, unarmored fiber optic line for a high speed telemetry link, it is still a long step to a working system for deploying an optical fiber inside a drill string under normal operating conditions. What follows is an attempt to rough out some of the components of such a system. A cartoon of the system components is shown in Figure 19. The key is to take advantage of the compact nature of the optical fiber to insert the entire cable spool into the drill string at one time. The simplest approach is to insert the cable spool just before reattaching the kelly. The cable spool is attached to a rigid "stinger" which serves to convey the signal up through the kelly and a rotating pressure seal to the outside of the drill string. Once inserted in the drill string, the cable spool is protected from most of the hazards of a drill rig. The stinger can also be used as a handle to raise the cable spool as stands of pipe are added during drilling. At the stinger's upper end, data are transmitted, either by light or radio, to the data acquisition system. A non-contact system such as this avoids cables and connections on the rig floor. The fiber, tipped with a receiver module, is deployed by being pumped down the drill string along with the mud flow. At the downhole end, the fiber need not be electrically connected to the MWD package. What is necessary is an information link. By arranging a mechanical stop or catcher at the MWD instrument package, the receiver can be stopped within inches of a transmitter. Over such a short distance, either acoustic or electromagnetic fields can transmit a high-bandwidth signal, avoiding the need for a complex and complicating connection.

Finally, at the downhole end, provision is made for disposing of the fiber when the drill string is tripped out to change the drill bit. As currently envisioned, a mud-driven turbine, located at some point below where the fiber terminates, would drive a set of grinding jaws that would convert the few pounds of silica fiber to particles fine enough to be circulated out by the mud.

7 Conclusions

Several conclusions can be drawn from the test:

1. Unarmored fiber does have a useful survival time at realistic mud flow rates.

2. Laboratory drag measurements grossly overpredicted the drag observed in the field. Low drag substantially extends the useful depths or flow rates for the fiber link.

3. There are clear indications that the fiber was not in fact subject to significant drag at all, possibly because Bernoulli forces held it against the wall of the drill pipe.

4. Using off-the-shelf equipment, the present system could transmit data at about 1 megabit per second, 5 orders of magnitude faster than commercially available MWD transmission systems, without interfering with the drilling process.

As the the MWD business generates about $300 million using data transmission rates of 1 to 10 bits per second, the economic implications of increasing the data rates into the megahertz range are clear. High data rates would allow the real-time use of virtually any instrumentation to observe the drilling process and the surrounding formations.
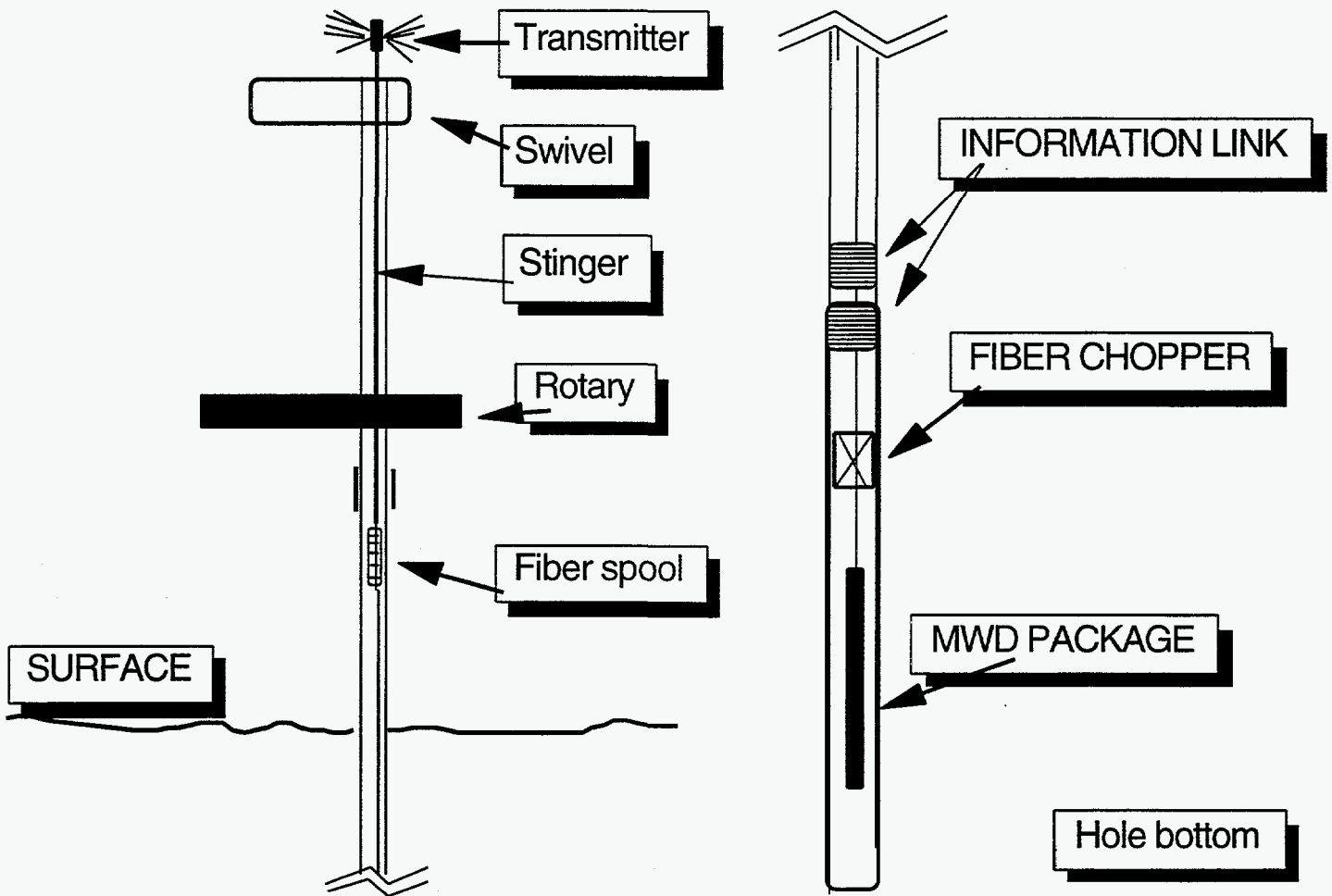
Figure 19: Cartoon of the elements of a deployable system, showing top and bottom end elements.

References

[1] Drumheller, D.S., *Attenuation Of Sound-Waves In Drill Strings,* J. Acoust. Soc. Amer., v. 94(#4) pp. 2387-2396 1993.

[2] Drumheller, D.S. and S.D. Knudsen, *The Propagation Of Sound-Waves In Drill Strings,* J. Acoust. Soc. Amer., v. 97(#4) pp. 2116-2125 1995.

A Supporting Information

- Publications resulting from project: Attached SAND report

- Invention Disclosures: TA SD-5788, 1/23/96.

- Patents: None

- Copyrights: None

- Employee Recruitment: None

- Student Involvement: None