RIBBON ROD DEVELOPMENT FOR BEAM PUMPING APPLICATIONS

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Abstract

Ribbon rod is Continuous Carbon Fiber Sucker Rod which is in the configuration of a reelable "tape" or "ribbon" with current dimensions of 1.45 in. x .212 in. It can be wound on a 10 ft diameter reel, 6 in. wide. It is designed to be run with some steel rods on the bottom similar to fiberglass rods. Its performance can be designed and analyzed using wave equation type mathematical models. Ribbon rod has been successfully tested in the lab and field over the past ten years. It was conceived as a method requiring no couplings, using a corrosion resistant, light weight material. Recent material/construction/design modifications and lab plus field trials reported here, have resulted in a system that can extend beam pumping to production rates beyond that currently possible with beam pump systems using other rod alternatives.

Introduction

The use of Continuous Carbon Fiber Sucker Rods (Ribbon Rod) with beam pump systems, can increase production rates to levels previously thought to be impractical due to high stress loading in steel rods and limited fatigue life in fiberglass rods. This paper will describe the Ribbon Rod manufacturing process, present a historical overview of the product development and testing, and review design techniques. Mathematical modeling predictions are compared to actual measurements

Ribbon Rod Advantages

Because Ribbon Rod is at least 90 percent lighter than steel rods and has a smaller cross sectional area, high production rates can be achieved without overloading existing beam lift equipment. Ribbon Rod's inherent ability to stretch during loading also allows for extended travel of the down hole pump which increases the effective stroke length and production. This high production capability allows Ribbon Rod to be considered for wells which are above the rate possible for beam pumping with fiberglass rods, and are currently on ESP (electrical submersible pump).

Since the Ribbon Rod tape is light and flexible, it is expected to conform to well bore deviations with less rod/tubing friction than steel rods or even glass rods. Also the light weight of the rods reduces loads on the surface unit and would presumably reduce friction loading at this point. However, overall efficiency measurements have not been as impressive as expected. It is believed this is because the retrofit installations use existing units which are oversized for Ribbon Rod, and not optimized for the installation.

Using measured rates, some efficiencies have been recorded that indicate overall energy per rate and depth is not much different that before the installation. However, NABLA has measured energy lifting costs of Ribbon Rod cost/(bpd-1000 ft) to be 5% less than fiberglass rods and 7% less than steel rods on some wells using production inferred from down hole stroke and measured SPM and also using measured production rates (Reference 3). Additional details on energy are mentioned in the following section discussing computer analysis.

Ribbon Rod's carbon fiber composite, construction offers additional advantages in the beam lift environment. Because it is continuous it uses only two rod connections which is one of the major areas for sucker rod failures. Ribbon Rod also resists attack from corrosive elements found in oil wells. Finally, since carbon fibers have outstanding fatigue resistance Ribbon Rod will offer a much longer service life than fiberglass. If Ribbon Rod was to fail, it can be easily repaired without the need to replace the entire rod string. Advantages are summarized below:

- High production capability
- Utilization of standard beam lift equipment
- Energy efficiency
- Long service life
- Corrosion resistance
- Minimum of rod couplings and associated failures
- Reduced loads on surface equipment
- Easy to repair

In the early 1980s, several tapes were tested in wells ranging in depth from 4000-4750 ft. The primary purpose of these early tests was to first prove the concept of replacing conventional jointed sucker rods with Ribbon Rod and secondly to develop a reliable and efficient field truck and service techniques. This series of tests was concluded after a Ribbon Rod that had pumped for four years in a sour gas environment was pulled, inspected and tested in the lab.

The results showed only slight signs of wear on the surface of the tape. In the lab, the tape proved to have a higher ultimate strength than before it was installed in the well four years earlier. This was apparently due the fact that the composite continued to cure in the well. Early testing also highlighted the need to eliminate splices in the Ribbon Rod in order to achieve the higher working stress necessary in high volume production. Details of some of the early work may be found in Reference 1.

Currently there is new emphasis on improving the efficiency of artificial lift and reducing failures in lift systems. The limiting factor in high volume rod pumping is the rod. The earlier thin Ribbon Rods were redesigned to address the specific problem of high production rates from significant depths. Gearbox torque, motor load, and peak polished rod loads, are all reduced by the use of light weight, carbon fiber Ribbon Rod. The high rod loading which typically limits deep-high-rate rod pumping is again addressed by carbon fiber's light weight/high strength characteristics. High cyclic loads and corrosion can cause repeated rod failures and high operating costs. Carbon fiber composites are not subject to corrosion. At 10 million cycles, carbon fiber composites operate at 60% of their ultimate strength, while steel operates at 40% and fiberglass operates at only 20% of its ultimate strength and is still decreasing with additional cycles. This is illustrated in Figure 1 from Reference 2.

Manufacturing and Construction

Ribbon rod is an advanced high performance carbon fiber reinforced composite.

Fiber reinforced composites include a reinforcing fiber along with a binder or matrix material. In the case of Ribbon Rod, Thornel™ T-300 12K carbon fiber manufactured by Amoco Performance Products, Inc., is used as the reinforcement. Thornel™ T-300 12K is a polyacrylonitrile (PAN) fiber which refers to the precursor the fiber is manufactured from. The matrix material is a vinyl ester resin, and Kevlar™ fibers are also added along the edges of the Ribbon Rod to provide improved toughness and damage resistance as well as aid in processing. The product is currently made in the form of a rectangular tape 1.45 in. wide and 0.212 in. thick, in continuous lengths of up to 3,000 feet. Fiber reinforced composites were originally developed due to the demands of the aerospace community for structural materials which had improved performance, light weight and corrosion resistance. Because almost all high strength materials fail due to the propagation of flaws, fiber-reinforced composites offer significant advantages because the size of a flaw is limited by the small cross sectional area of the fiber. In addition, since multiple fibers are typically used, it has been shown that even if a flaw produces a failure in one fiber, it will not propagate to fail the entire assemblage of fibers.

Significant design advantages over conventional materials can also be achieved with fiber reinforced composites. Preferred orientation of the fibers can be used to increase the lengthwise modulus and strength well above isotropic values. This allows for the high strength and modulus (current modulus is 17.4 million psi) of the composite to be tailored to the high load direction of the application. In the case of Ribbon Rod the fibers are all orientated in the longitudinal direction for carrying the loads associated with lifting fluids to the surface. In addition, because of carbon fibers and Vinyl Ester resins light weight, significant advantages in strength to weight ratios are achieved over conventional materials.

Currently glass fiber reinforced composites are the most commonly used in the industrial markets. Carbon fibers, however, offer significant advantages over glass fibers, particularly in the downhole oil production environment. The sensitivity of the glass fiber surface to moisture surface attack as well as the stress rupture failure under long term loading at stress levels above the threshold failure stress, can lead to premature sucker rod failures. Carbon fibers' extremely high strength and modulus, outstanding fatigue resistance along with its inertness to the oil well environment makes it an ideal selection for Ribbon Rod's reinforcing fiber.

So that Ribbon Rod can be attached to metal rods and sinker bars, an end doubler is used to increase the thickness for attachment to an API standard steel connector. Illustrations of the Ribbon Rod, end doubler and steel connector are shown in Figure 2.

Ribbon Rod is manufactured via a continuous pultrusion process. Pultrusion is an ideal process for making composites with a constant cross sectional shape. The process consists of pulling reinforcing fibers through a resin bath. The impregnated fibers then enter a shaping die where the resin is subsequently cured under temperature (see Figure 3).

Statistical Process Control (SPC) is utilized to monitor key process parameters to ensure the quality of Ribbon Rod. In addition, testing is performed in line on every foot of Ribbon Rod produced. This testing provides data which confirms the reliability of the process and that the Ribbon Rod will perform as designed in the down hole environment.

Laboratory Testing

The fatigue loading conditions which Ribbon Rod sees in beam lift pumping can be simulated using laboratory testing equipment. Ribbon Rod samples are constantly tested by Amoco in an Instron 100 Kip servo hydraulic tensile testing machine. Four-foot Ribbon Rod samples are cut out and fitted with the end doubler and steel connector on one end. The samples are cycled between minimum loads of 1,000 pounds and the maximum load being evaluated using a sinusoidal wave form. Frequencies vary between 5 and 10 cycles per second which allows for the simulation of up to five years of pumping in just over one month. The fatigue testing set up is shown below in Figure 4.

In addition to the fatigue testing, Ribbon Rod samples have been extensively tested for chemical resistance to the down hole environment. Double lap shear testing has also been performed on several adhesives to select the one which gives the best bond between the end doubler and the Ribbon Rod. For quality assurance each Ribbon Rod manufactured is also tested for short beam shear strength and 90 degree flexural strength.

Running and Pulling

The ability to provide reliable and responsive service at an economical cost has long been recognized as essential to the overall success of a Ribbon Rod system or any other rod system for beam pumping. The fact that the tape is flat, light weight, compact and reelable results in a simple, inexpensive service unit with the following characteristics:

1. Small in size: 3000 ft of .212 thick tape can be wound on a 10 ft diameter reel 6 in. wide.

2. Positive Drive: The Ribbon Rod is mechanically attached to the service reel and wound up in a method similar to that of movie films.

3. Efficient: A light weight truck carrying a spooling unit rigs up over the wellhead, the tape is then connected to the top sinker bar and reeled nonstop into well. The remaining free end of the tape is attached to a conventional polished rod. Reeling speeds of over 100 fpm are easily achievable.

   Figure 5 shows the service truck and shows Ribbon Rod being run into the well.

Design and Analysis

Obviously, use of the API method (designed for steel rods) is not applicable for the design of a Ribbon Rod installation. However, the wave equation technique of design and analysis is applicable for Ribbon Rod installations just as it is for fiberglass installations.

Although it was anticipated that the Ribbon Rod would be able to be designed/analyzed using a wave equation model, there were some differences that caused concern. The Ribbon Rod is light weight and flexible tending to reduce friction and it has a smaller ratio of cross section to strength. However it does have more surface area for a given cross section compared to a round rod which theoretically could add to fluid friction. However, it is shown below that the net effect of all factors is a rod with fewer losses than conventional rods.

To obtain a design, rod properties must be entered into a wave equation model. The current needed properties are .127 lbs/ft, 17.4 million psi modulus, .212 x 1.45 in. cross section, and 100 lbs/cu-ft density. Currently a "Goodman" type diagram is not specifically available for Ribbon Rod. However, from some field tests and from the results in Figure 1, it is expected, that after a certain number of cycles, no further reduction in strength will be experienced due to fatigue. This would be quite different from glass rods. Currently rods are designed to have a loading below about 80,000 psi, but this may be refined later with additional statistical field and lab data.

To illustrate the comparison of the use of a computer model to the actual field gathered data, an example design computer run, installation results, and diagnostic computer results will be shown. The well conditions are:

String: 3000 ft RR, 900 ft 1" & 250 ft 1.5" Grade D Steel
Unit: A640-305-168
Pump: 2"
SPM: 8.51
Tubing: 2 7/8's
Fluids: High water cut

The predictive wave equation (Amoco in-house) with a pump intake pressure of 114 psi, indicated 473 bpd possible. The loads at the surface and the pump are illustrated in the surface and pump cards shown in Figure 6 for the predictive run.

Next a diagnostic run using a measured surface card from the pumping well was made and the dynamometer cards are shown in Figure 7. The diagnostic run indicated that 461 bpd was being produced. Actual measurements of production indicated that about 455 bpd was being produced. Note that the diagnostic bottom hole card shows an indication of tubing movement from the left hand slope of the bottom calculated card. However, this was later attributed to the position indicator on this particular well. Typically Ribbon Rod wells show a vertical left side to the bottom hole calculated pump card as expected when the tubing is anchored.

Note that the loads, strokes, and general shapes of the predictive and diagnostic wave equation results from Figures 6 and 7 indicate that consistent accurate information can be obtained from wave equation analysis. Further improvements in modeling are to be expected.

Downhole Load Measurements

Although indications are that the wave equation analysis is applicable, some problems with earlier Ribbon Rod installations caused concern as to how well a wave equation model would work. Because of this, Albert Engineering was contacted to allow the use of a down hole tool to measure the loads at the Ribbon Rod while the rod was in the process of pumping the well.

The tool measured axial strain with strain gages. It was battery operated and contains a microprocessor with 128 KB of non-volatile storage with a 50 hz sampling rate. The body was a pump extension with a HF 7/8's coupling on each end. The total length of the tool for these tests was 47.25 in. Load and pressure were measured with time. An internal clock turned the unit on and off and the pumping unit was made sure to be running when data was being collected. The down hole load measuring tool was calibrated when the pumping unit was off, by knowing the buoyant load hanging below the tool when stopping on the down stroke. A picture of some of the internals in the tool are shown in Figure 8.

Raw data from the tool is shown in Figure 9. This data has not been corrected for the calibration. In Figure 10, calculated loads at the depth of the bottom of the Ribbon Rod is compared to the tool measured data after calibration. Although the comparison is not exact in shape or magnitude, it is fairly close. From these tests it was concluded that if no unusual well conditions exist (excessive dog-legs for instance) that a proper wave equation model can predict Ribbon Rod performance, certainly as well as a wave equation model can predict performance with steel and/or fiberglass.

Following these tests, another major oil company has been making measurements with an improved version of the same tool. They have found some cases of diagnostic programs which do not compare well to steel rod loads at depth. They may identify conditions that models should show improvement in at a later date. However, to reiterate, it appears that a Ribbon Rod string can be designed and analyzed at least, if not better, than a corresponding steel or fiberglass/steel rod string by using a proper wave equation model. The reason it may be modeled so well is that the Ribbon Rod does not cause much drag (as much as conventional rods) so a slightly imperfect model of Ribbon Rod drag does not affect the overall results of loading, displacement calculations, etc.

To illustrate the lower rod drag from use of the ribbon rod, Figure 11 shows calculated comparisons of the along ribbon rod vs. some other rod strings from Reference 3.

One other method of checking wave equation results vs. measurements was made. A brass pump barrel with no internal coating was run with a flexite ring plunger at 4,700 ft in the Greyburg formation out of the Amoco Midland Farms Unit. Predictive and diagnostic wave equation runs were made with the Amoco wave equation model. When the plunger was removed, the wear pattern was measured in the barrel. The predictive program indicated 102 in. of travel. The diagnostic program, using a card input from an ACI SPOC, indicated that the plunger was stroking 107 in. The wear pattern measured was 104 in. long.

Field Trials

By 1991, major technical accomplishments had were made in the pultrusion process allowing for 3000 ft splice-free rods. The new tapes were installed in four wells at the Amoco Production Company, Midland Farms Operation Center. By increasing the thickness of the carbon fiber tape from 0.1 to 0.13 in. and eliminating splices, the ultimate strength of the tape was sufficiently strong enough to allow for pumping speeds which produced 400-600 bpd from 4800 ft. A summary of field data using 0.13-in. tape is shown in Table I. However, after four failures in the end doublers (the thickened end termination of the Ribbon Rod which allows bolting to a metal and fitting with API sucker rod upset and threads; see Figure 2), an extensive finite element stress analysis was conducted on the end doubler transition. This led to a new end connection design.

The remaining three Ribbon Rods which were in wells were pulled, cleaned and newly designed end doublers were bonded on. The repairability of Ribbon Rod had also been a question and it was felt important to prove a repair technique that would allow a producer to take advantage of the expected long operating life of the Ribbon Rod. The end doubler is more closely matched to the high ultimate strength of the Ribbon Rod. This new end doubler, bonded onto used Ribbon Rod, has now operated in three test wells for over a year with no failures.

A study (Reference 4) concluded from data collected in a West Texas oil field, on power consumption measurements and failure rates, indicated that beam pumping is preferred over ESP operations for production from 500-1000 bpd at about 4500 ft. The results indicated that the beam efficiencies measured were about 55% and the ESP energy efficiencies were about 35%. In field operations, the relatively short fatigue life of fiberglass rods at high stress levels has made high volume beam pumping expensive. The new Ribbon Rod was designed to operate at stress levels sufficient to produce 1000+ bpd (total). The tape thickness was increased from .13 to the current .212 in.. This combined with the newly designed end doublers extend the capacity of beam pumping far beyond the limits established by steel or fiberglass while offering fatigue life in the expected five year range (see Figure 1) or beyond.

This high volume Ribbon Rod design has been tested in four Amoco wells. Table II presents the field test data collected to date. Recent lab test data suggests this high volume design has the potential to produce up to 1400 bpd from 4900 ft, utilizing a conventional 640 pumping unit, with the usual beam pump overall efficiency.

Summary

Ribbon Rod's unique design and material technology offer significant opportunities to improve the performance of beam lift pumping units. These performance improvements allow oil producers to continue using economical beam lift equipment for high volume applications instead of other pumping technologies such as electric submersible pumps (ESP's).

The Ribbon Rod development effort has shown that continuous carbon fiber reinforced composites can increase beam lift pumping capacity, improve energy efficiency and reduce sucker rod failures. It has also been shown that computer simulation can be used to accurately predict rod string performance for design considerations. Finally, reliable field service equipment and techniques have been established for installing and removing Ribbon Rods.

Amoco Performance Products, Inc. is currently evaluating Ribbon Rod as a commercial business opportunity. On the basis of continuing success with the Ribbon Rod field trials and economic considerations, a decision on offering a commercial product will be made in 1994.

References

1. Hensley, H. N. and Tanner, C. J., "Graphite Composite Tape in Beam-Pumped Oil Wells," SPE 13200, presented at the 1984 59th Annual Meeting of the AIME-SPE, Houston, TX, September 16-19.

2. Delmonte, J., "Properties of Carbon/Graphite Composites," 1987, published by Krieger Publishing Co.

3. NABLA Corporation, Ribbon Rod Evaluation; Test Period, (5-31-91 to 9-23-92), NABLA, Midland, TX, October 14, 1992.

4. Lea, J. F., and Minissale, J. D., "Beam Pumps Surpass ESP Efficiency," Oil and Gas Journal, May 18, 1992, pp. 72-75.

Table 1

Summary of Field Test Data .13 Ribbon Rod

Well Name	MFU 637	MFU 117	MFU 635
New Depth	4700	4725	4925
Rod String	100 ft 1 in. 2300 RR	100 ft 1 in. 2500 RR	100 ft 1 in. 2500 RR
Design	1200 ft 7/8 in. 900 ft 3/4 in. 200 ft 1.25 in.	800 ft 7/8 in. 1200 ft 3/4 in. 125 ft 1.25 in.	700 ft 7/8 in. 1400 ft 3/4 in. 200 ft 1.0 in.
Unit Description	640-365-144 C	456-342-144 AB	456-342-144 AB
SPM	8.9	9.3	7.2
Pump Size	1.5	1.75	1.75
Peak Torque	367	326	283
PPRL	12,720	11,750	11,160
MPRL	3445	2829	3260
BFPD	311	391	288
Installation Date	9/16/92	10/26/92	12/7/92

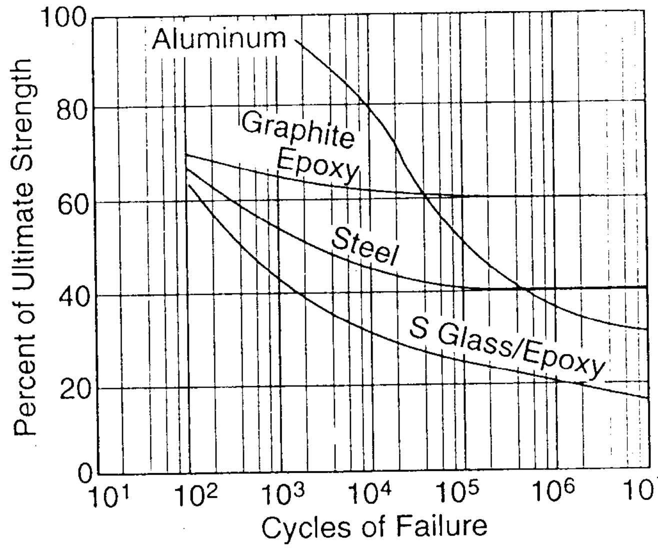

Figure 1 - Comparisons of fatigue resistance

Table 2

Summary of Field Test Data High Volume .212 Ribbon Rod

Well Name	MFU 66	MFU 119	SHU 142	NCU 711
New Depth	4775	4750	4200	4375
Rod String	375 ft 2600 RR	275 ft 2850 RR	200 ft 7/8 in. 2900 RR	100 ft 1 in. 2050 RR
Design	1300 ft 7/8 in. 500 ft 1-1/2 in.	700 ft 1 in. 600 ft 7/8 in. 325 ft 1-1/2 in.	500 ft 7/8 in. 600 ft 1.5 in.	450 ft 1 in. 1400 ft 7/8 in. 375 ft 1-1/2 in.
Unit Description	640-305-168 AB	640-305-168 AB	640-365-144 C	456-305-144
SPM	10.7	10.6	11.1	11
Pump Size	2.25	2.25	2.25	2.25
Peak Torque	550	624	474	541
PPRL	15,600	16,750	14,251	16,025
MPRL	1317	1135	1170	1702
BFPD	850	890	782 Pumping Off	780
Installation Date	4/11/93	5/26/93	9/8/93	9/24/93

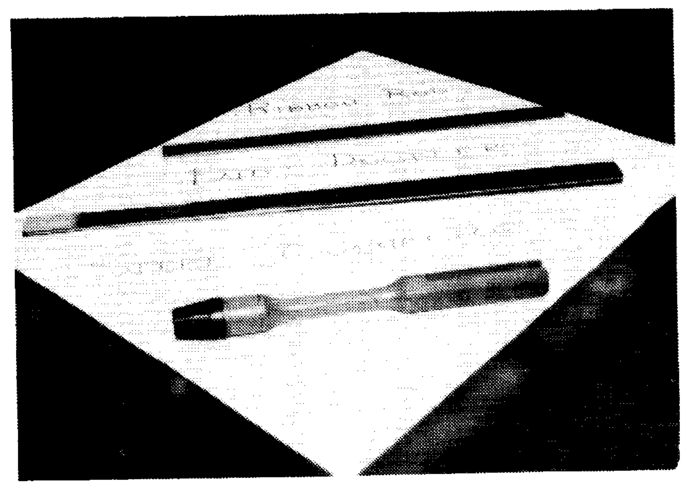

Figure 2 - Ribbon rod body, end doublers, and steel connector

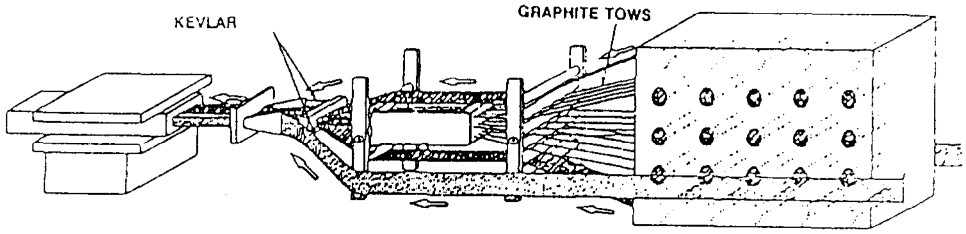

Figure 3 - Schematic of pultrusion process

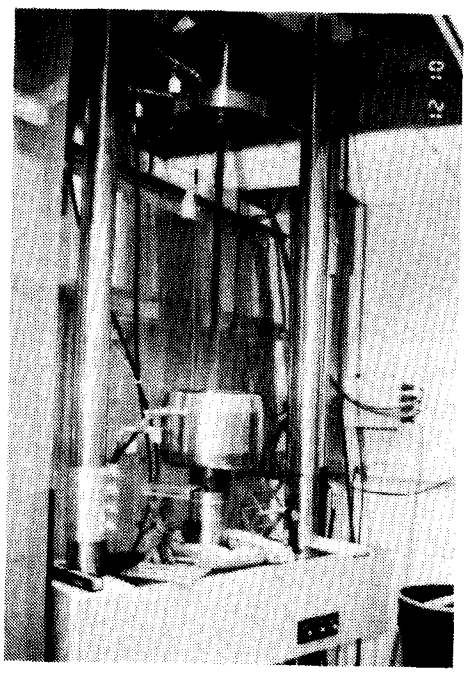

Figure 4 - Instron fatigue testing machine

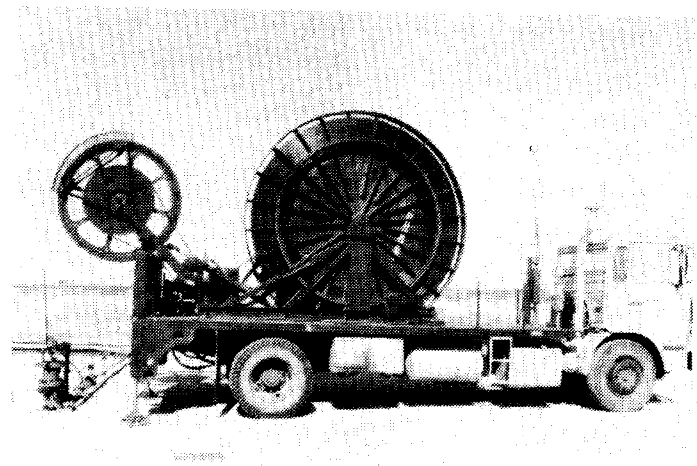

Figure 5a - Ribbon rod service truck

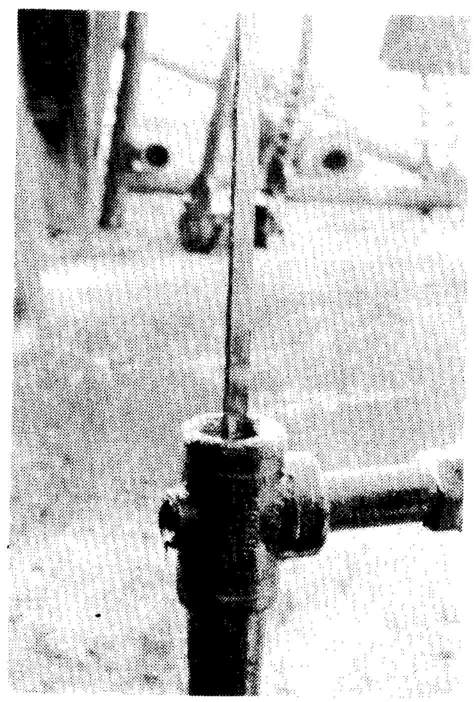

Figure 5b - Ribbon rod entering well

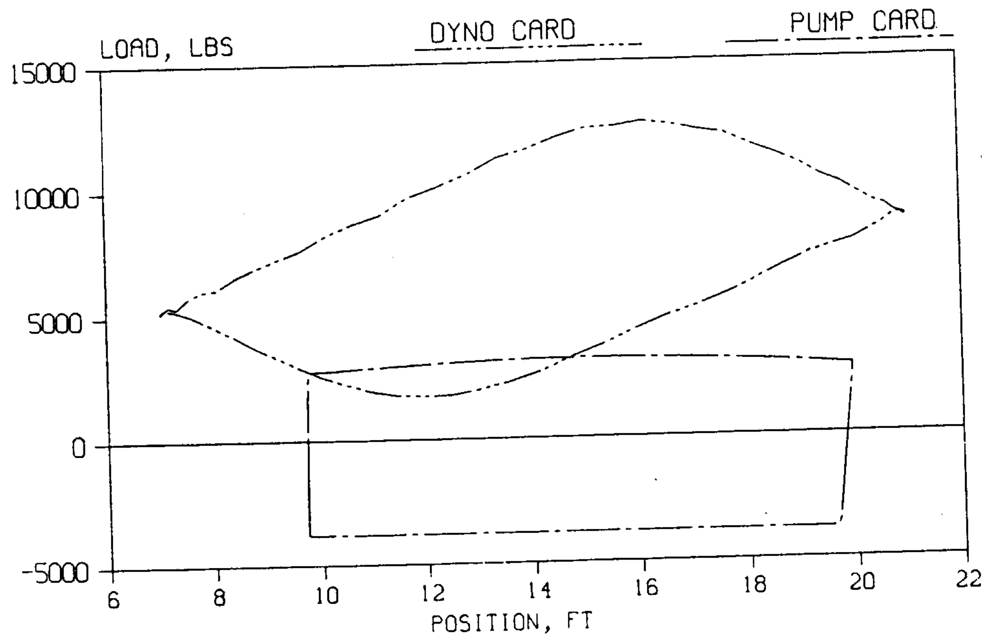

Figure 6 - Predicted results with ribbon rod

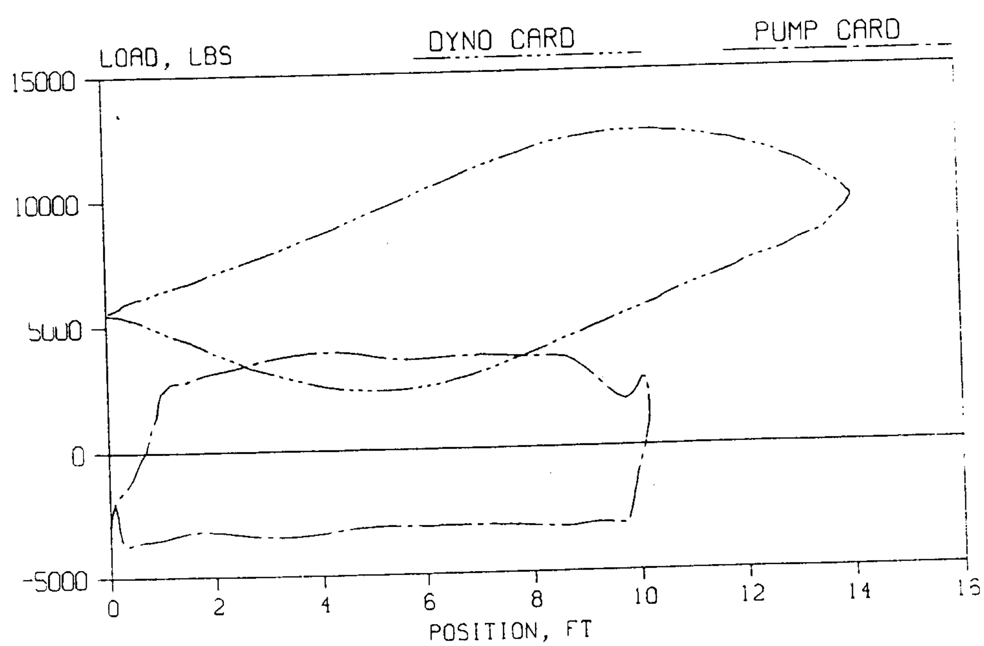

Figure 7 - Diagnostic results with ribbon rod

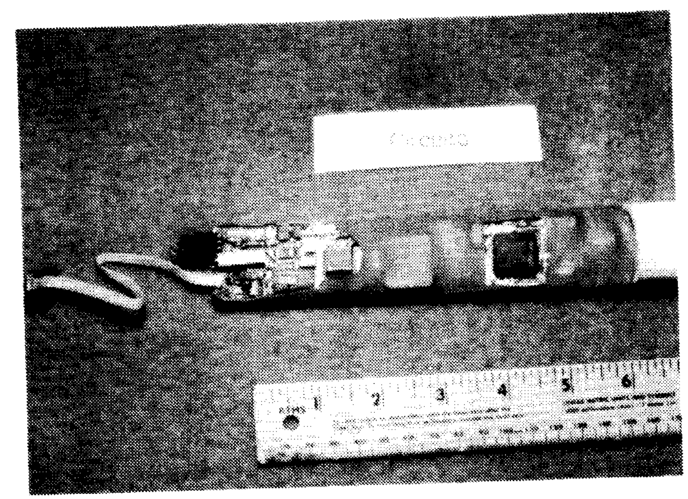

Figure 8 - Down-hole load measuring tool

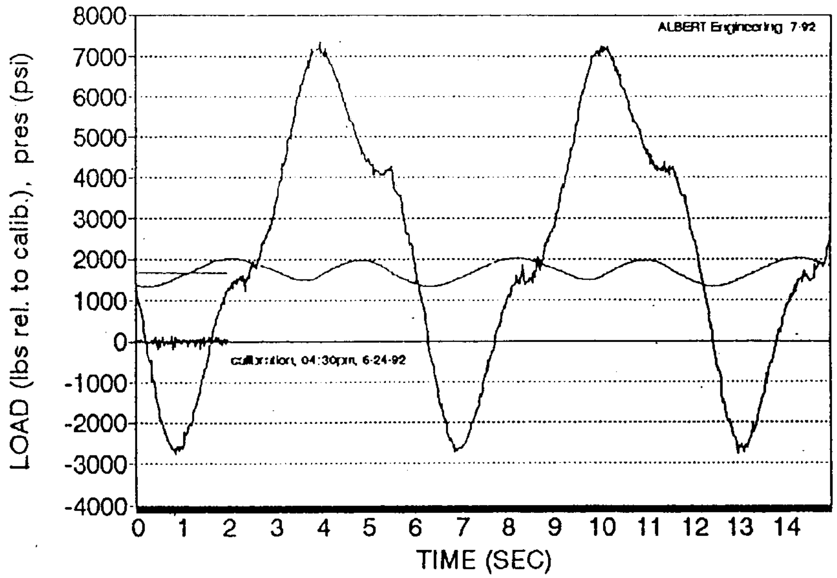

Figure 9 - Raw data from down-hole tool

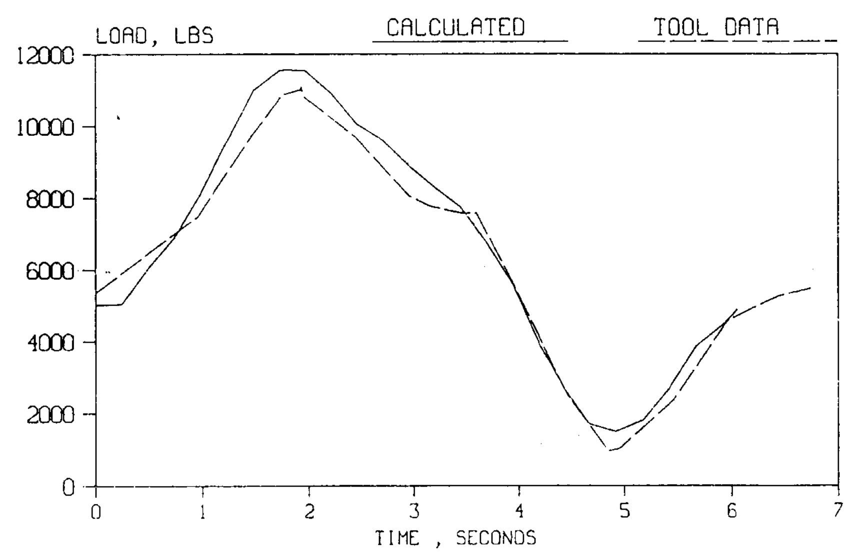

Figure 10 - Measured vs. calculated loads at bottom of ribbon rod

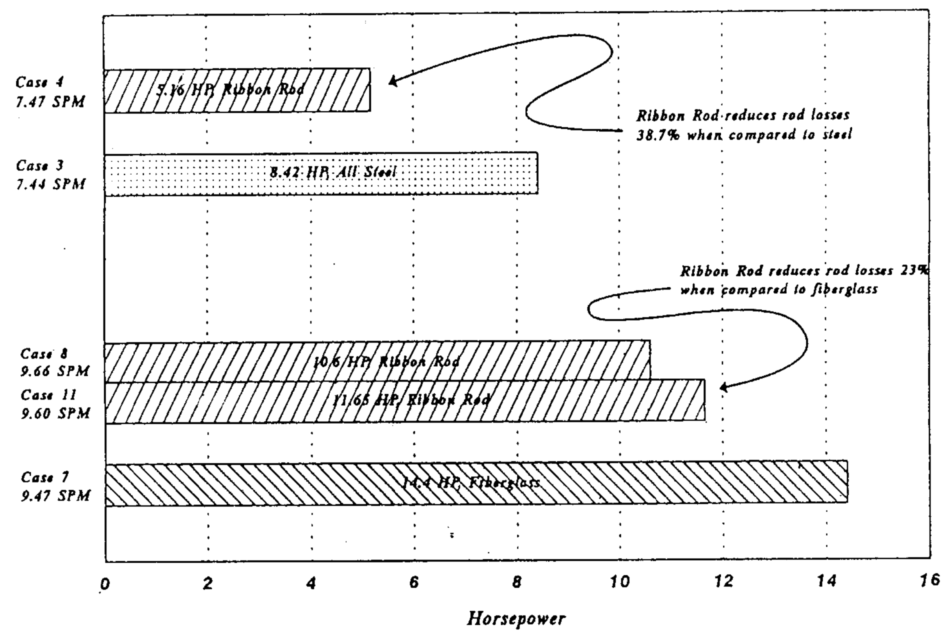

Figure 11 - Sample diagnostic results comparing energy losses for rod strings