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SPE 30679

Development of a Coiled Tubing Cable Installation System

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This paper was prepared for presentation at the SPE Annual Technical Conference & Exhibition held in Dallas, U.S.A. 22-25 October, 1995

Abstract

A system has been developed which installs and de-installs an electric wireline cable in coiled tubing (CT) while the CT is still on the reel. This cable installation system reduces the cost of a cable installation significantly compared with previous installation methods.

This paper discusses the need for such a system, the theory used to develop this system, the various concepts considered, the system that was developed and test installation cases.

Introduction

The first CT strings with a cable inside were used for CT logging in the mid 1980's[1-5]. Initially CT logging grew rapidly because it provided the only practical means to perform logging operations in live horizontal wells. However, the rate of growth of this segment of the CT business soon stagnated because these operations were expensive. The two major reasons for the high cost of these operations were:

- The cost of installing the cable inside the CT and removing it once the CT string reached the end of it's life was high.
- Purpose built tools had not been developed for CT operations. Usually two service companies were required to perform the logging, one to run the CT and one to operate the logging tools

The second of these costs is being addressed by the industry. Recently purpose built tools which require a cable in CT have been developed for some CT logging operations and for CT drilling operations. This paper addresses the first of these costs, cable installation.

In the past, three methods have been used to install cable in CT:

- The CT was hung off in a well and the cable was run into the CT. Then the CT with the cable inside was spooled out of the well.
- The CT was laid out horizontally and the cable was pumped through.
- A thin pull cable was installed in the CT during the manufacturing process. The CT was then laid out horizontally and the pull cable was used to pull the cable through the CT.

All of these installation methods cost between $15,000 and $25,000 per installation. If there was a problem with either the cable or the CT during the life of the string, the cable had to be removed, repairs made and then the cable had to be re-installed.

A system has been developed which allows the cable to be pumped into the CT while it is still on the reel. This method of installation greatly reduces the installation cost and allows cable in CT to be more competitive.

Pumping Cable In and Out of CT

For several years service companies have been able to pump cable out of CT. A pump was connected to one end of the CT with the cable inside, and water was pumped through the CT at an increasing rate until the cable began to move. Cable movement was evident by the rattling sound of the cable vibrating inside the CT, and by the cable moving out of the CT on the opposite end from the pump. Usually the cable movement would be very sporadic, making it impossible to spool the cable neatly on a reel.

At first some felt that the pumping of water past the cable would not cause the cable to move because of the capstan effect. However, vibration or fluttering of the cable inside the CT due to the turbulence of the water removed the friction between the cable and the CT, eliminating the capstan effect. Viscous shear drag forces of the fluid passing the cable gave it a small axial force, causing it to move in the direction of water flow.

Pumping a cable into a reel of CT was much more difficult. Since the cable would move in the same direction as the fluid being pumped, the cable must enter the CT on the same end as the pump (as is shown in Figure 1). A wireline pressure control head, known as a stuffing box, was used to seal around the cable during it's entry against the high pressure fluid from the pump. However, a significant force had to be used to force the cable in against this pressure. The viscous shear drag force discussed earlier was not sufficient to overcome this force which was equal to the pressure times the cross-sectional area of the cable. A device outside of the stuffing box could have been used to push the cable against the pressure, but most cables would be damaged by this large compressive force. Thus, a device was needed which would operate inside of a pressure housing and would pull the cable through the stuffing box. This device was called a "cable injector".

It was found that the cable injector could be used in reverse as is shown in Figure 2. This prevented the sporadic movement of the cable discussed earlier and allowed smooth spooling of the cable on the spool as it was extracted.

Cable Injector Concepts

It was evident that a cable injector was the key to being able to perform successful cable installations and de-installations by pumping. Several different types of devices were considered which would perform the function of pulling a cable through a stuffing box. A simple schematic of each of these concepts is given in Figure 3.

Roller Type Injector. The first concept involved using some powered rollers inside a pressure housing to pull the cable through the stuffing box. There were two major concerns with this type of device. If the cable stopped moving through the CT, the rollers would continue to push the cable putting it in compression and possibly resulting in cable damage. Also, the rollers would have a small area of contact on the cable. If a high force was needed, the rollers would have to squeeze tightly against the cable, possibly damaging it.

Flow Tube Injector. This concept involved using a long flow tube for the cable injector. The cable would pass through the flow tube along with the fluid being used to pump the cable into the CT. The pressure drop and viscous shear drag on the cable would create the force to pull the cable through the stuffing box. Again there was a concern that the cable would be compressed if it stopped moving through the reel. Another company pursued this approach and was successful in developing a cable injector using this method.

Enclosed Wireline Spool. Another concept was considered in which the entire wireline spool would be enclosed in a high pressure housing. The cable would feed out of this housing directly into the CT. This would eliminate the need for a stuffing box and cable injector. However, it would required a large, heavy, expensive pressure housing. There were also concerns about the control of the cable unspooling inside such a pressure vessel.

Snubbing Injector. Some proposed building a cable injector that stroked like a snubbing unit. It would grab the cable, move it forward a certain distance, hold the cable while the grabbing device stroked back, and then repeat the stroke again. Again there was a concern that compression would be applied to the cable when it was not moving in the reel.

Tractor Injector. This device would use a tractor mechanism to pull the cable much like a typical CT injector head moves CT. This tractor would be located inside of a pressure housing. This approach would solve the problem of localized loading on the cable by distributing the loading over the length of the tractor. Again, there was a concern about the ability to control such a device so it would not compress the cable when the cable was not moving.

Capstan Injector. The cable would be wrapped several times around a powered wheel or capstan inside a pressure housing. A rotating wheel with a cable wrapped around it would act as a tension multiplier. If a small tension was pulled on one end of the cable in the direction of rotation, a much larger tension would occur in the opposite end of the cable. This concept was chosen because it is self controlling. The capstan cannot cause the cable to go into compression.

Capstan Theory

The tension amplification caused by the rotating wheel or capstan is referred to as the "capstan effect". The capstan amplification is a function of the friction between the cable and the wheel, and the number of degrees of revolution the cable makes around the wheel. For example, if the cable is wrapped around the wheel twice there are 720 degrees of revolution.

The capstan amplification factor is expressed by the following equation:

$$\frac{T_{output}}{T_{input}} = e^{\beta\mu} \qquad (1)$$

T_{output} = Tension on cable after amplification
T_{input} = Tension on cable before amplification
β = Number of wraps multiplied by 2π radians

μ = Friction coefficient between cable and wheel

For steel on steel a friction coefficient between 0.15 and 0.2 is expected. This equation was used to create amplification factors given in Table 1. Note that if the wheel is covered by grease, the friction coefficient will be less reducing the amplification factor.

The beauty of the capstan concept was that it is self controlling. If the cable stopped in the CT for some reason, there would be no tension at the inlet to the CT reel (T_{input}), making no tension for the capstan to amplify. The capstan could not push a slack cable and cause cable damage due to compression.

However, the capstan concept requires enough initial tension (T_{input}) to develop the required output tension to pull the cable through the stuffing box. There was concern that the viscous shear drag forces on the cable might not be large enough to develop the initial tension required.

To cause some initial tension, the fluid flow from the pump was divided and entered the system through two inlets as is shown in Figure 5. An orifice was placed in the flow between these two inlets and the pressure difference between these inlets was controlled by a choke. This simple system, called a pre-tensioner, supplied the necessary initial tension for the capstan to amplify.

Capstan Injector Design Concepts

Several different types of designs (shown in Figure 4) were considered which use a capstan to move the cable.

Single Wheel with Large Dynamic Seals. This concept involved using large (20 inch diameter) high pressure dynamic seals around the outside rims of the wheel, which sealed inside a pressure housing. This concept was chosen for the initial design because it would be the easiest to assemble and disassemble, making it easy to use in the field. However, it failed to rotate at pressures above 200 psi! The dynamic seals locked up whenever pressure was applied.

Two Wheels Inside Pressure Housing. This concept involved two wheels inside a single pressure housing. These wheels would have grooves for the cable, which is not possible in the single cable design. With two wheels, the cable does not need to slide across a wheel as it does in the single wheel design. This concept was eliminated due to cost concerns.

Reciprocating Tube Concept. This concept involved several revolutions of a wrapped tube, possibly made from CT, which would rock back and forth in a reciprocating motion about the axis of the wrap. The cable would pass through this tube and into the CT. When the tube moved in the direction of cable movement, the cable would be pulled with it. When the tube moved in the opposite direction, the cable would not move. In this manner the cable would be "snubbed" into the reel. This concept was eliminated because the cable would need to move in sporadic movements instead of moving at a constant speed.

Wheel Inside of Pressure Housing. This original concept involved a simple wheel inside a pressure housing. When the first concept above was tried and failed due to the large dynamic seals, this original concept was adopted and used in the final product.

7,500 psi System Design

The final design for the 7,500 psi working pressure version of the system is shown in Figure 6. The components of this system are described moving from left to right through this figure.

Cable Spooling Unit. During testing with used cable it was found that torque in the cable could cause problems at the entry to the cable injector. It was necessary to remove this torque by rotating the spool of cable. The cable spooling unit (shown in Figure 6) allows the spool of cable to be rotated about the vertical axis. This rotation requires a sheave wheel above the spool of cable also located on the vertical axis. The cable then comes down to another sheave wheel to align the cable with the cable injector.

Cable Injector Skid. The left most item on the cable injector skid is a mechanical counter to measure the amount of cable installed. After this counter, the cable enters the stuffing box which seals around the cable. This stuffing box is designed to be used with grease injection to prevent any leakage of wellbore fluids. The grease injection system was not used because the grease on the cable greatly reduces the friction coefficient and thus reduces the effectiveness of the capstan (see Table 1). Instead, water is allowed to flow through the flow tubes and is returned to the storage tank.

The stuffing box is attached to the cable injector shown in detail in Figure 5. The cable enters the cable injector tangent to the wheel in the upper left, wraps around the wheel five times and exits tangent to the wheel in the upper right. A stationary "stator" with thread like grooves guides the cable as it travels across the face of the wheel to avoid tangling of the cable inside the injector. The wheel is powered by a hydraulic motor.

Pre-Tensioner. After leaving the cable injector, the cable enters the pre-tensioner where it passes through an orifice tube with an internal diameter slightly larger than the cable diameter. A choke is then used to control the inlet flow of water between the inlet upstream of the orifice and the inlet downstream of the orifice, thus controlling the pressure drop across the orifice. This pressure drop causes a small tension in the cable between the orifice and the cable injector, giving the cable injector an input tension to amplify.

CT Reel. After leaving the pre-tensioner, the cable and the water flow enter the CT reel. When the water velocity is high enough to cause the cable to fluctuate inside the CT, the viscous shear drag on the cable causes it to move forward through the CT. This fluctuation or "slapping" of the cable inside the CT gives a distinct audible sound.

Speed Measurement. Electronic instrumentation is used to measure the cable speed and the speed of the outside of the wheel. These two speeds should be the same during installation. Usual installation speed is 130 ft/min though speeds in excess of 220 ft/min have been run.

Storage Tank. Continuous pumping using large amounts of power over one or two hours adds significant energy to the water being pumped, causing the temperature to increase. A large storage tank is needed to avoid over heating (boiling) the water.

Conclusions

A system has been developed which greatly reduces the cost of installing and de-installing a cable inside a string of CT. Three of these systems are currently in use and several more are planned. Several successful cable installations have been performed using these systems. A 10,000 psi working pressure version of this system is now being developed to allow installations in longer CT strings.

Acknowledgments

This system was developed by CTES, L.C. as a joint industry project with the following companies participating in the project: Atlas Wireline, Halliburton Energy Services, Nowsco Well Services, Precision Tubing Technology, Quality Tubing, Schlumberger Dowell. CTES, L.C. is grateful to these companies for their support in the development of this system and to Drexel Oilfield Services, Inc. for manufacturing the systems.

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Table 1 - T_{output} / T_{input} Capstan Amplification Factors

m	0.14	0.15	0.16	0.17	0.18	0.19	0.20	0.21
# Wraps								
1	2	3	3	3	3	3	4	4
2	6	7	7	8	10	11	12	14
3	14	17	20	25	30	36	43	52
4	34	43	56	72	92	119	152	196
5	81	111	152	209	286	391	535	733
6	196	286	416	607	885	1,291	1,881	2,743
7	472	733	1,138	1,767	2,743	4,258	6,611	10,263
8	1,138	1,881	3,110	5,142	8,500	14,051	23,228	38,398
9	2,743	4,829	8,500	14,962	26,338	46,363	81,612	143,662
10	6,611	12,392	23,228	43,539	81,612	152,978	286,751	537,503

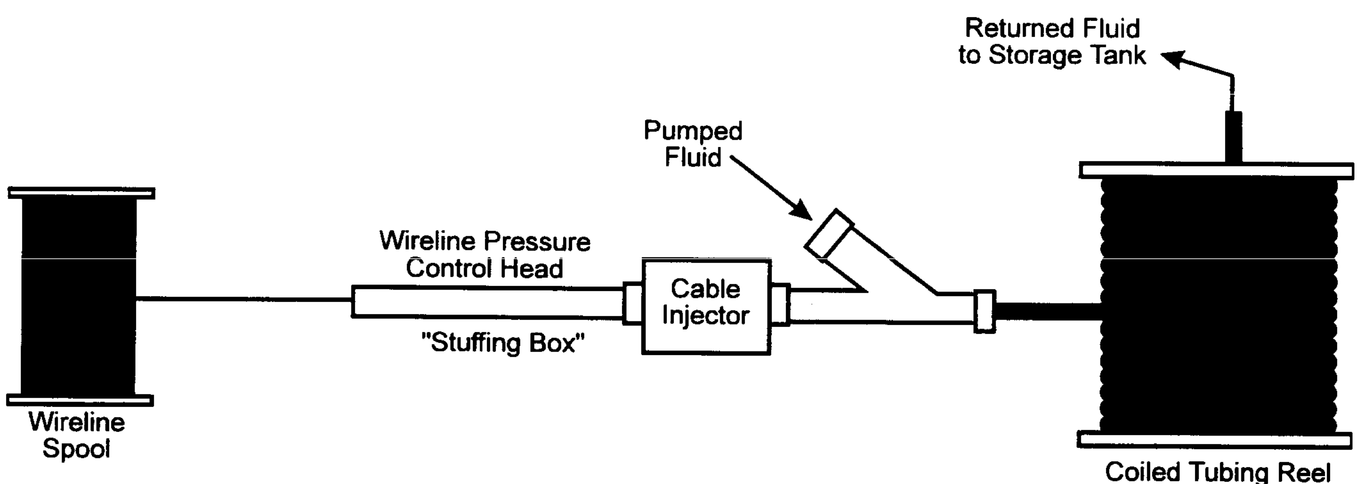

Figure 1 - Pumping Cable into CT

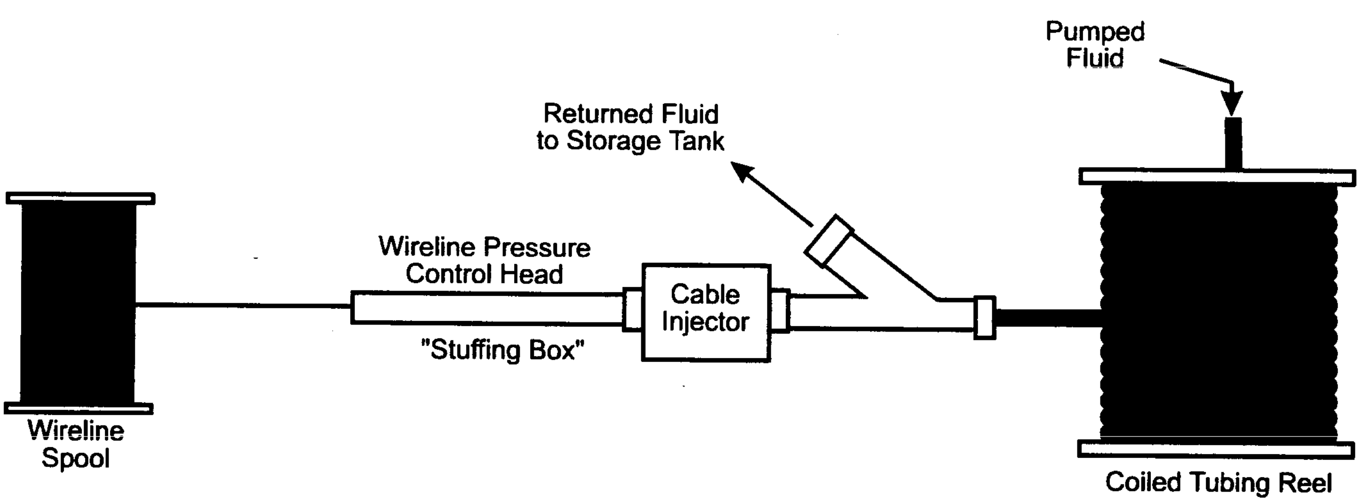

Figure 2 - Pumping Cable out of CT

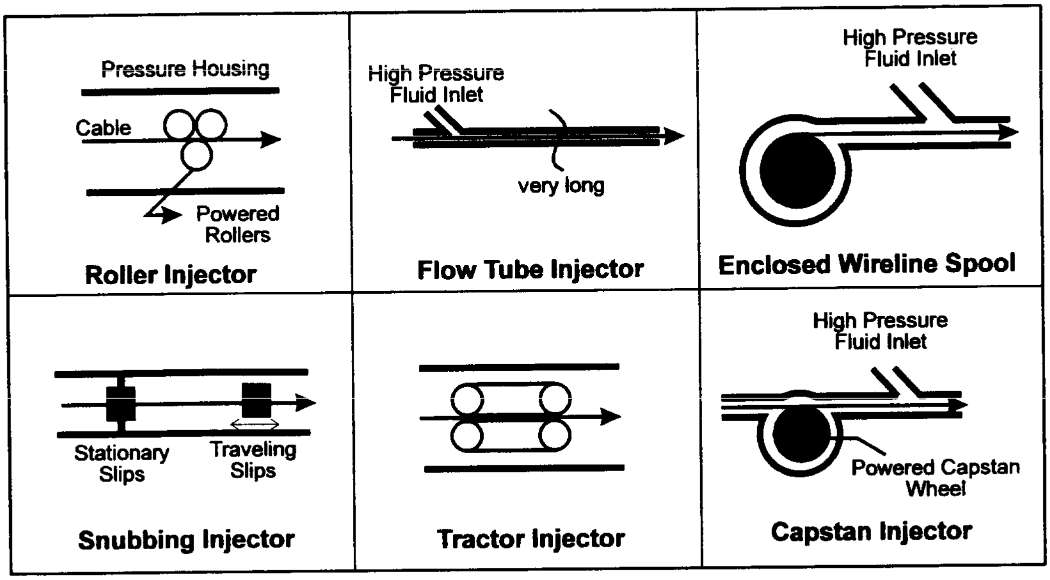

Figure 3 - Cable Injector Concepts

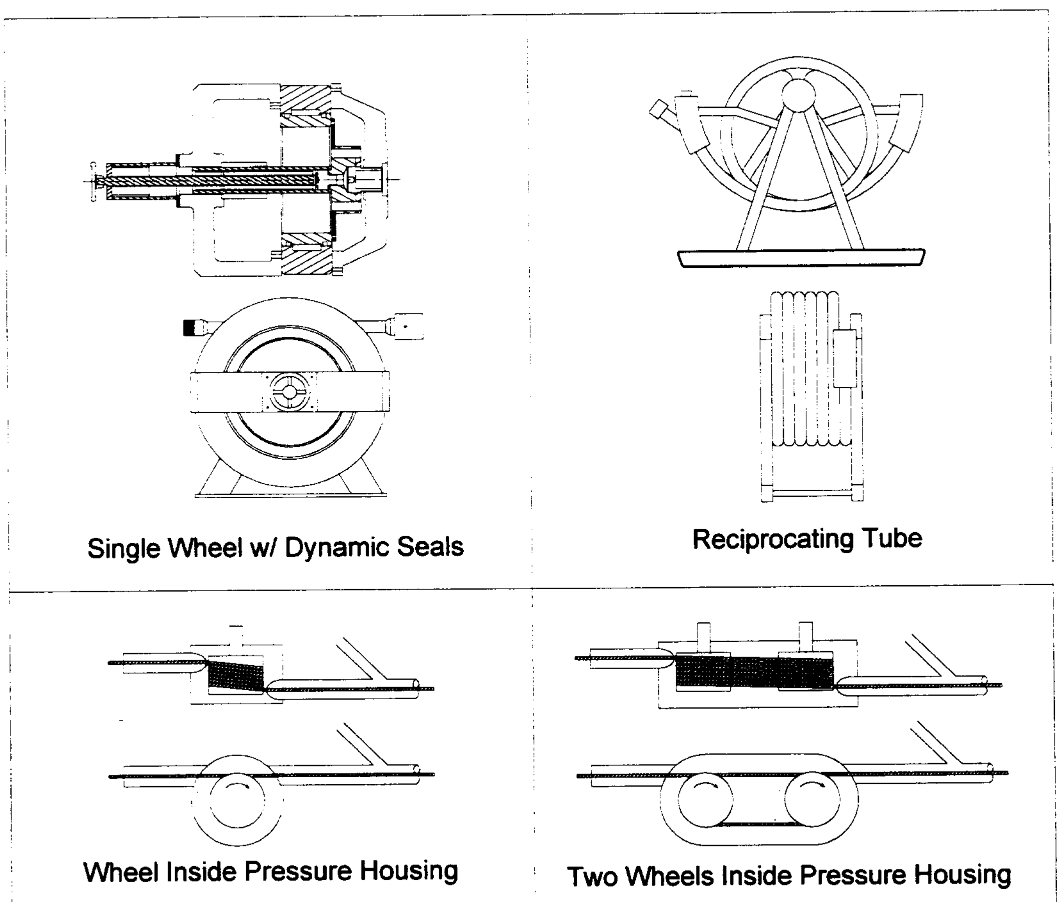

Figure 4 - Capstan Cable Injector Design Concepts

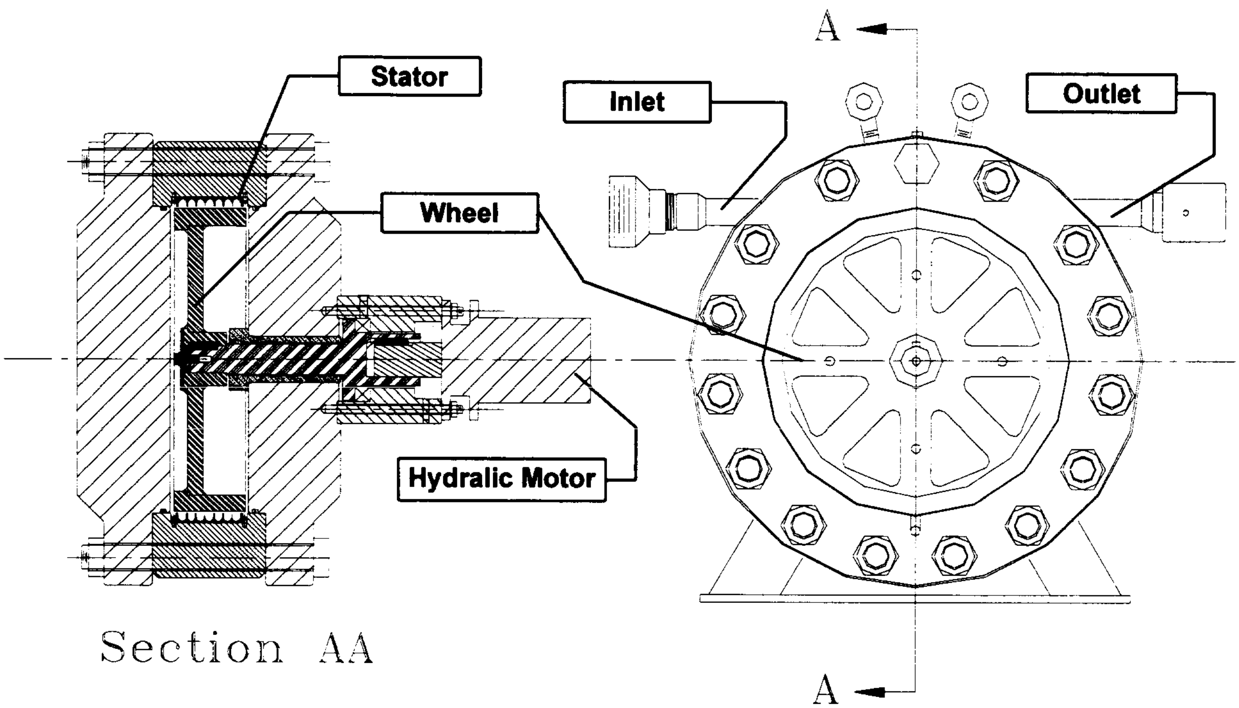

Figure 5 - Cable Injector - Front and Top View

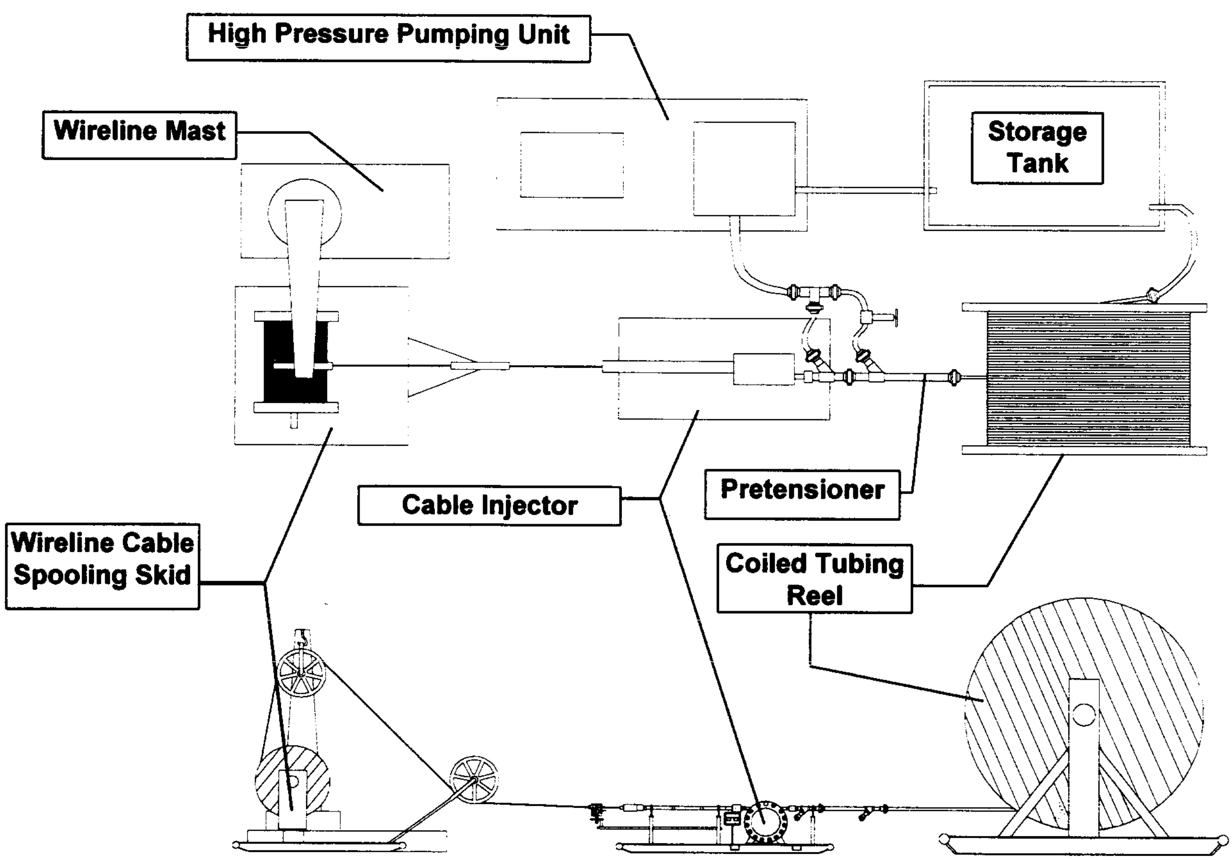

Figure 6 - Cable Injection System - Front and Top Views