An Innovative New Technology for Trenchless Rehabilitation of High Pressure Gas/Liquid Transmission Pipelines

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ABSTRACT

Smart Pipe® is a recently completed, innovative, new technology that has the potential for significantly reducing the cost, public inconvenience, and environmental threats associated with rectifying damaged and degraded high pressure pipelines. As new pipe or as a tight fitting liner, it is a composite material in which the key element is an ultra high strength/light weight fabric that is contra-helically wrapped onto a thermoplastic core pipe. Using a portable factory, the material can be manufactured at a job site, and installed simultaneously. As a liner, it is pulled into an existing pipeline in folded form, then re-rounded under internal pressure to become a tight fitting liner at the inner wall of a damaged/degraded host pipe. In this manner, a Smart Pipe® rehabilitation is fully capable of restoring, or exceeding, the original line pressure.

Smart Pipe® is best suited for rehabilitating long segments of disadvantaged pipe (e.g., general or stress corrosion cracking) in pipelines that operate above 150 psi (10 bar) in diameters of 6 inch (15 cm) and above. In this advanced form of trenchless technology, each segment of the host pipe needs to be exposed at only two points; i.e., the entry point and the termination point of a continuous pull-in operation. These two points can be miles apart; e.g., in a straight host pipeline, a continuous pull-in of up to 10 miles (16 km) is theoretically possible. Thus, it is particularly advantageous for pipelines that are in urbanized areas, wetlands, river and lake crossings, and other difficult to access and/or environmentally sensitive locations. Because the technology additionally provides an embedded sensor system for continuous monitoring of the integrity of the rehabilitated pipeline, the potential exists for entirely eliminating intelligent pigging, cathodic protection and hydrotesting in subsequent operational service.

In preparation for its first installations, engineering, computer simulation, and testing work has perfected all aspects of the Smart Pipe® manufacturing and installation procedures, and its subsequent in-ground service performance. This paper describes the manufacturing/installation technology, briefly outlines the analysis modeling and validation testing that have been utilized to establish the technology, and provides an example comparison with a currently existing conventional rehabilitation repair/replacement method.
1. INTRODUCTION

The hundreds of thousands of miles of steel pipe in the world’s large diameter, high pressure, natural gas and liquid transmission pipeline systems are inexorably aging, and thereby becoming increasingly vulnerable to corrosion, excessive ground movement, third party intrusion, seismic events and malevolent attack. As well as being intrusive, time consuming and expensive -- especially in newly urbanized areas, wetlands, river and lake crossings, environmentally sensitive and otherwise difficult to access locations -- conventional inspection and open trench repair/replace operations are not well suited for repairing very long pipeline segments. The Smart Pipe® technology, shown schematically in Figure 1, has been developed as a superior new form of trenchless technology that fills this gap in present day rehabilitation procedures.

Figure 1: Schematic View of a Smart Pipe

The Smart Pipe® technology is broadly applicable; however, it is primarily intended as a solution for the rehabilitation of larger diameter, higher pressure pipe in long segments that are in difficult to access locations. It can be considered to be a multi-faceted generalization of the now well established U-Liner methodology for the rehabilitation of gravity flow and low pressure pipelines. The main features of this technology that make it unique are:

- a portable factory that can be set up at a job site for simultaneous manufacture and installation of a tight fit liner in an existing host pipe
- the use of modern ultra high strength fabrics that will permit high pressures and miles long installations, with only two locations where the pipe needs to be exposed
- a folding and re-forming process that facilitates long installations in torturous pipe layout without incurring damage to the liner
- embedded fiber optic sensors that can detect and accurately pinpoint leaks, mechanical impacts, and ground movements on a 24/7 basis
- a fully-rated pressure containing design that makes any subsequent corrosion or other damage to the steel host pipe of little consequence

These features are described in the following sections.
2. OVERVIEW OF THE CONCEPT

Smart Pipe® is a continuously manufactured, high strength, light weight, highly durable, self-monitoring, composite of thermoplastic materials. While this technology can be used either as a stand alone pipe or as a tight fitting internal liner to rehabilitate an existing steel pipe, its use in the form of a liner for degraded steel energy transmission pipelines is highlighted in this paper. While other component materials can be used to meet special conditions, in its standard form the liner is composed of a high density polyethylene (HDPE) core that is wrapped contra helically with fabrics consisting of unidirectional E-Glass fibers for lower pressure applications or with Kevlar fibers for higher pressures. The strength layer is overlaid by fiber optic sensor cables and axial direction high strength carbon tapes, with high strength tows (fiber bundles) securing them; with the whole being covered by a waterproof, protective outer coating. In essence, the contra helically wrapped fabrics act as the primary pressure induced hoop load reinforcement, while the longitudinal carbon tapes enable the liner to be pulled in continuously over very long distances and provide supplemental reinforcement for axial direction stresses during service.

As described in more detail in the following, the manufacturing of the liner starts with an HDPE core pipe upon which longitudinal and helically wrapped fabrics, longitudinal direction tapes, fiber optic sensors, and tows are added in stages. After being encased with a thin outer protective layer, the liner material is deformed into a “C” shape for insertion into a host pipe – see Figure 2 - then taped to hold the shape as it is pulled into the host pipe with an ultra high strength rope, and finally reformed under water or air pressure into a tight fitting liner.

Figure 2: Schematic View of a Folded Liner in a Host Pipe

2.1 The Portable Factory

A key feature the Smart Pipe® concept is the ability to transport and set up the factory at a job site where the product can be simultaneously manufactured and installed. This can be done at the rate of 4 feet/min (1.2 m/min), which means that one mile (1.6 km) can be made each 24 hours. For short pipeline rehabilitation segments, folded liner can be coiled and trucked to the job site whereupon the installation rate can much greater. Similarly, for offshore installations, the factory can be moved to a position where the liner can be produced and loaded on barged-based carousels. In all instances, the portable factory functions in the same general manner.
The portable factory can be placed on a footprint that is approximately 400 ft (122 m) in length and 10 ft (3 m) in width. It consists of ten separate stations that are controlled by an integrated software control system. Because the factory is mounted on interlocking polyethylene matting, it can be positioned in any convenient location. With customized tenting and air moving systems, the factory has a climate controlled environment so that the manufacturing can be done at a near constant temperature. Common to all stations in the portable factory are emergency shut down systems that can be activated by an operator or by the control room. Each station incorporates state of the art quality control in accordance with ISO 9001:2000 standards.

2.2 The Manufacturing Procedure

The liner manufacturing process begins with a butt fusion welding operation in which 40 foot sections of the core pipe are fused while traveling along a track section. The welds are ultrasonically inspected by a time-of-flight-diffraction system. The length of track and welding times are synchronized such that an improper weld can be cut out, re-welded, and re-inspected without changing the speed of the manufacturing line. For the machines that require periodic reloading of fabrics, a motorized track system is employed to permit reloading in a “keep up” mode such that the new fabric is spooled and spliced with the line moving. At the completion of these operations the machines restart at the same point and angle to ensure consistency.

The next stations consist of machines that wrap the ultra high strength fiber fabrics helically and counter helically onto the core pipe, and that place carbon pulling tapes and fiber optic sensors in the axial direction, at equidistant intervals around the circumference. Orbital winding machines then lay down contra helical tows of ultra high strength fibers to hold the carbon tapes and fiber optic sensors in place. In the last step before the deformation (folding) operation is conducted, the construction depicted in Figure 1 is completed by the use of an HDPE cover.

The final stage in the manufacturing process involves a folding machine with a complex system of rollers and hydraulic controls that mechanically transform the round pipe into the “C” shape shown in Figure 2 that facilitates insertion into a host pipe. This process reduces the apparent circumference by roughly a factor of two which permits the easy installation of the liner into an existing pipe. A proprietary process is used to maintain the C shape during installation and to allow the reformation upon demand. Immediately following the deformation operation Mylar tape is introduced to hold the liner in the C shape during the installation. The taped liner then passes through a buffer catapuller (i.e., a machine that is a two belted catapuller) that provides the necessary pulling force to the liner as it passes through the folding machine.

2.3 The Installation Procedure

The installation begins with the flushing and cleaning of the existing pipeline. During this operation a small diameter tag line is placed in the pipeline, pulled behind an umbrella or a poly pig, and connected to a high strength, large diameter pulling rope that is pulled to the beginning of the pipeline. The pulling rope is then attached to the liner which is pulled into place using a high tension traction winch. The pulling rope is made of high molecular weight polyethylene fibers which give the rope a strength to weight ratio approaching 200 miles (320 km). A pulling head weaves the carbon fiber pull-in tapes into a rope that is spliced with the pulling rope.
Once the product has been properly positioned within the host pipe, expansion heads are attached to both ends of the liner. Air or water pressure is then applied to expand the product to a tight fit within the host pipe, after which the product is trimmed to length and flanged to the host pipe. The final steps of installation include a poly pig run to ensure full reforming of the product, a hydrotect, and the installation of spool pieces to conclude the pipeline continuity. Swage type connectors are utilized. The end connector is a trap lock system, provided by GMCO®, that goes back to a flanged connection to hook up to an existing flange on the host pipe.

2.4 The Monitoring System

An optical fiber monitoring system is used to provide continuous detection of threats and anomalies following a Smart Pipe® rehabilitation. This technology, which has been used and been proven in many European applications, provides continuous temperature and longitudinal strain readings at three or more (depending on the pipe diameter) positions around the circumference. Each optical sensor cable has multiple optical fibers for redundancy. It has been demonstrated that, in a natural gas line, the temperature measurement can detect even minimal sized leaks in the pipe wall. The temperature measurements have a resolution of 0.01 °C at any point along a 15 mile (24 km) length, while the strain measurements have a resolution of 10 micro-strain over the same distance. Using a concept similar to optical time domain reflectometry, the measured values can be located within 1 metre over a 24-km pipeline.

To address gas permeation through polymer layers in high-pressure gas applications, an annular venting system is used for the collection and accumulation of permeated gases. This is accomplished by the use of continuous axial channels in the outer layer of the liner material. These channels are cross connected to a port at each end of the pipeline to permit either a safe bleed-off or venting of gases, thus preventing any damaging pressure build up. The annular venting system is a standard feature of the liner.

3. VALIDATION PROCEDURES

Generally, there are four basic targets that must be met for a design that provides the pipeline operator with an appropriate level of strength and durability in the most economical manner possible. These targets are primarily associated with:

- an operator specified maximum allowable operating pressure
- the overall length of the host pipe segment for which a continuous pull-in is to be made
- the most challenging combination of bend radius and position that is anticipated
- the long term strength (i.e., durability) of the liner

A preliminary design is based upon a verified burst pressure with a designated factor of safety, and the roughness (friction factor) of the host pipe. This design is iterated upon to cope with sharp bends and/or other constraints in the pipeline. In some instances, the installation will need to be made in a segmented fashion because of a combination of excessive length, bends having severe bend radii, and other obstacles (e.g., laterals). Openings that arise because of the need to cut out a sharp bend or a lateral are typically utilized as either an insertion or pull-in point for a segment with a spool piece being dropped in and connected to the liner following the pull-in.
Three levels of analysis methodologies have been exercised along with experimentation on liners to clearly demonstrate the integrity of the liners. While analysis/testing work continues, sufficient evidence has been acquired to permit installations in the field to be safely and efficiently made. It is further believed that, at least for the segment of the market that the Smart Pipe® concept is best suited for, these installations can be made in a cost competitive manner.

### 3.1 Basic Design Equations

For preliminary scoping purposes, basic engineering models have been developed to determine the construction (i.e., fiber types and amounts and fabric wrap angle) that meet the specifications for a given installation. The first step in a design usually is to select the width of the fabric that is to be used. The geometric relation that governs the contra helical fabric wraps is:

\[ w = 2\pi DC \cos \theta \]  

where \( w \) is the width of the fabric, \( D \) is its mean diameter, \( C \) is the coverage (i.e., the fraction of the core pipe surface that is covered by the fabric), and \( \theta \) is the fabric wrap angle.

For < 100% coverage (i.e., no gaps or overlaps in the helical fabric layers), when the internal pressure acts only to produce a hoop stress failure, assuming that the contribution of the HDPE core and the tows can be neglected, the burst pressure, \( p_b \), of a helically wrapped pipe can be estimated from:

\[ p_b = \frac{2M_h G_h}{D_p} \sin^2 \theta \]  

where \( M_h \) is the total number of fabric plies counting both helical directions (thus always an even number), \( G_h \) is a strength measure known as the grab strength (the units of \( G_h \) are force per unit width), \( D_p \) is the pressure boundary diameter; and \( \theta \) is the wrap angle for the co helical fabrics (relative to the axial direction). The MAOP is the actual value of \( p_b \) determined from short and long term testing divided by a factor of safety of a least three.

Next, assuming that the carbon axial tapes carry the entire load, and the load itself is simply due to the friction between the folded liner and the pipe wall (e.g., when no chill rings or other obstacles are present), the maximum length of liner that can be pulled in during an installation can be determined by considering a straight, smooth walled pipe. This is:

\[ L_{\text{max}} = \frac{M_a F_a \eta_a}{\mu W} \]  

where \( M_a \) is the total number of ends in the axial carbon tapes, \( F_a \) and \( \eta_a \), are, respectively, the carbon end strength and the efficiency factor, \( W \) is the weight of the liner per unit length, and \( \mu \) is the average coefficient of sliding friction between the liner and the host pipe during installation. Use of Eqn (3) for the constituents of most interest, indicates that it is theoretically possible for \( L_{\text{max}} > 10 \) miles (16 km), with a substantial safety factor, in a straight pipeline.
While Eqn (3) is helpful in the initial planning stage, the design of an actual installation normally depends upon determining the force that needs to be applied during the pull-in process in a line with bends and elevation changes. The Smart Pipe® proprietary analysis methodology for determining pull-in forces, in its simple elastic form, can be expressed as:

\[
P = \mu WL + \sum_{i=1}^{N} P_i \exp(\mu \alpha_i)
\]

where \(P\) is the force that is needed to pull the liner over a length \(L\) of straight pipe and past \(N\) bends having a sweep angle \(\alpha_i\), and a force \(P_i\) as it enters the bend, and, as above, \(\mu\) and \(W\) are respectively the coefficient of sliding friction, here assumed to be the same in a bend as in a straight segment, and the weight of the pipe per unit length. In its advanced nonlinear form, the methodology that is here represented by Eqn (4) is used together with the strength properties of the folded liner to determine if a given project can be undertaken with a single pull, or must be done in two or more segments. In the latter case, this methodology is used interactively with ground conditions to find the optimum location of the entry and exit points of each segment.

The basic reason for the performance that is expected from a rehabilitation of a pipeline with a Smart Pipe® liner – both for long continuous pull-ins and very high pressure capabilities after the installation of a liner – is the extraordinary mechanical properties of the fibers that are used in the contra helical wraps and in the longitudinal pull-in tapes. Their elastic moduli are roughly comparable to line pipe steel. However, they generally have much higher strengths and significantly lower densities. Because the primary consideration for a Smart Pipe® application is a fabric that is both light and strong, the key selection criterion is the strength to weight ratio; NB, this ratio has the units of length. The comparison of this ratio of mechanical properties for each of the several leading candidates with line pipe steel that is provided in Figure 3 clearly shows the superiority of the ultra high strength fibers. Of course, there are also other features (e.g., cost, availability, handling ability, critical strain) that also influence the choice.

**Figure 3: Mechanical Properties of Candidate High Strength Fibers and Steel**
Equations (1-4) are the basis for preliminary design calculations. To assess the accuracy of these equations, and more fully understand the mechanics of the current composite structure (i.e., one that does not have the usual binding matrix), a spreadsheet has been developed in which 18 fundamental equations are solved iteratively. The iteration is necessary because the fiber rotations and the axial and hoop strains are too large for a linear theory to apply. A nonlinear finite element analysis (FEA) model, ADINA, was used in parallel with this spreadsheet. It was found that the basic engineering model, the more general spreadsheet model, and the FEA methodology, are generally within 5% of each other in stress calculations. It should be noted that, while the contribution to the burst strength provided by the HDPE core, because of its nonlinear and time dependent constitutive behavior, was not included in any of the three models, because of its relatively low strength, neglecting this contribution is both small and conservative.

3.2 Validation Testing

There are currently no standards governing composite pipe in the U.S. Code of Federal Regulations. The nearest standard currently applicable is API RP15S, “Qualification of Spoolable Composite Pipe”, which has an international counterpart in ISO 18226:2006, “Plastics pipes and fittings -- Reinforced thermoplastics pipe systems for the supply of gaseous fuels for pressures up to 4 MPa (40 bar)”. The testing that is required under either of these documents is generally comparable to the federal regulations for plastic pipe given in 49 CFR 192.121, which is in turn based on ASTM D2992. This standard primarily calls for three main types of tests: quick burst (D1599), sustained constant pressure (D1598), and cyclic pressure (D2143). These tests are currently underway for the standard product design, and complete results are not yet available. However, some earlier results can be used to determine the fidelity of the design equation for burst pressure, as follows.

Preliminary testing was conducted on 9 inch outer diameter liners (as designed for a 10 inch steel line) constructed with a balanced weave of high performance polyethylene (HPPE) fibers with various different helical wrap angles. Carbon tapes were not included in these test articles. The burst pressure predicted for a specimen with a 54.7 degree wrap angle was 967 psi (66 bars). Figure 4 shows the failure mode that occurred at the actual burst pressure of 1175 psi (80 bar).

Figure 4: Common Failure Mode of Test Articles in a Quick Burst Test

A critical comparison of actual burst pressures with those predicted by Eqn (2) for specimens like those in Figure 4, but with different wrap angles, is provided in Figure 5.
It can be seen in Figure 5 that Eqn (2) consistently provides an underestimate of the actual burst pressure; e.g., about 15% in this particular instance. To be assured that this underestimation is actually due to the neglect of the HDPE core pipe, nonlinear calculations were made in which, by an iterative process, the contribution of the HDPE could be included. Figure 5 shows that these results are in quite good agreement with the measurements. It should be noted that for higher design pressures and larger diameters, the relative contribution of the core pipe to the strength will become very small, in which case Eqn (2) will be fully adequate for most design work.

3.3 Nonlinear Finite Element Analyses

In addition to supporting the use of engineering models, finite element analysis (FEA) has been used for the more complex and nonlinear conditions associated with the deforming process, and with the installation of a deformed liner. These analyses have used the ADINA code, which has good large deformation and contact interface capabilities. However, future work will be done with the ABAQUS code.

The result of an ADINA analysis on a C-formed liner is shown in Figure 6. This work was primarily undertaken to help assure that the C-forming would not damage the liner. It was determined from the FEA results that, even with the obviously large deformations that are seen in Figure 6, the maximum strain levels in the liner components were not large enough to cause a failure outright – which is consistent with the empirical observations made in many trial deformations – nor would the level of deformation that is expected generate minute damage that might possibly trigger a long term slow crack growth (SCG) failure.
Having helped to establish the feasibility of the deformation process, by providing material strains and required forces, the FEA was further used to help design the C-former machinery. This equipment is shown in Figure 7. Note that the deformed liner shapes that are shown at the wheels in this apparatus are from the FEA results.

Figure 6: FEA Simulation of the Final Shape in a C-Forming Process

Figure 7: Computer Simulation Design of the Folding Equipment in the Portable Factory
4. CURRENT STATUS

As stated at the outset, the Smart Pipe® technology is not intended to cover the complete range of rehabilitation operations. It is instead a “high-quality high-value” product with particular applicability for long lengths of degraded/damaged pipe, in difficult to access locations. Where the cost of exposing pipe, in order to undertake conventional open trench rehabilitation techniques, is very high, Smart Pipe® is exceptionally cost effective. This is illustrated by the example cost comparison shown in Figure 8.

Figure 8: Comparison of Estimated Installed Cost Per Unit Length of Smart Pipe® with Actual Costs Incurred by a Large U.S. Based Local Gas Distribution Company
For an 8 inch (20 cm) Diameter Pipe with MAOP = 500 psi (34 bars)

In addition to advantageous installation cost in urban locations, the lifetime costs of a Smart Pipe® rehabilitation can be significantly less than a replacement of steel with steel. Because a Smart Pipe® liner will not corrode – and it is designed to carry the entire pressure load – the continued deterioration of the steel host pipe is irrelevant. There is considerable cost saving from the elimination of cathodic protection, intelligent pigging, and in-service hydrotesting that is provided by a stand alone, non corrosive replacement pipe. There is also a valuable saving in project execution time when using the Smart Pipe® solution, from the decision to replace or refurbish a pipeline through to execution and testing.

Another feature that can contribute to significantly lower lifetime costs is the fiber optic sensor system that can detect and pinpoint mechanical impacts, ground movements and other anomalies. In natural gas pipelines, leaks can be readily and instantaneously detected. Additionally, because there is no ceiling on the pressure capacity that can be designed into Smart Pipe®, its use can permit a system to be upgraded to higher pressures, from which the greater through put could make the rehabilitation pay for itself.
There are some physical constraints that limit the applicability of Smart Pipe® installations. One such is that the current factory is set up to produce liners that can be used to rehabilitate pipe in diameters only between 6 inch (15 cm) and 16 inch (40 cm). This is not a major barrier as a design has been made to expand the high end of the diameter range to 42 inch (100 cm). Nevertheless, this design will not be executed until the market demands it. Note, however, that there is not, nor will there be in a new construction, any limit on the pressure capacity of a Smart Pipe® installation, other than the increase in cost that accompanies the increased volume of constituent materials. In principle, therefore, the standard product is most suitable for shipping natural gas and liquids under the following conditions:

- Maximum operating pressures of 150 psi (10 bars) and above
- Host pipe diameters of 6 inch (15 cm) and above
- Continuous installation lengths over 1000 feet (300 m)
- Temperatures up to 176 °F (80 °C)

The standard product might not be cost effective for pipeline layouts having a high frequency of laterals and/or severe bends. But, it is equally applicable for natural gas, liquids, and corrosive products. Additionally, the technology can be tailored for other conditions. As examples, some of the areas in which a non standard Smart Pipe® product is currently under consideration for are:

- High temperature applications (e.g., steam lines)
- Low pressure service in very long installation lengths in non accessible locations
- Very short installation lengths of high pressure pipe in road and rail crossings

Any non standard product would, of course, need to be qualified under the complete battery of testing required by ASTM D 2992.

5. CONCLUDING REMARKS

The engineering research described in this paper demonstrates the veracity of the Smart Pipe® concept, and thereby provides vital support for the initial installations that are expected to be underway by the end of the current year. Anticipating the broadening of the opportunities these first installations will engender, continued internal and collaborative external research is currently being conducted. Its overall goals are to broaden and deepen the applicability of the Smart Pipe® technology to reduce redundant conservatism and to establish performance standards. This research specifically includes further quantifying the ability of C-formed pipe to negotiate severe bends and other types of constraints during installation, devising techniques for continuous installations in pipelines with laterals and other obstructions, and developing quantitative linkages between the signals from fiber optic sensors and the events that cause them.

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