Development of an Inspection Platform and a Suite of Sensors for Assessing Corrosion and Mechanical Damage on Unpiggable Transmission Mains

Quarterly Report

For the period of

October 1, 2003 to December 31 , 2003

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ABSTRACT

This development program is a joint effort among the Northeast Gas Association (formerly New York Gas Group), Foster-Miller, Inc., GE Oil & Gas (PII), and the US Department of Energy (DOE) through the National Energy Technology Laboratory (NETL). The total cost of the project is $772,525, with the National Energy Technology Laboratory of the US Department of Energy contributing $572,525, and the Northeast Gas Association contributing $200,000.

The present report summarizes the accomplishments of the project during its fifth three-month period (from October 2003 through December 2003). The efforts of the project focused during this period in completing the assessment of the tether technology, which is intended to be used as the means of communication between robot and operator, in completing the design of the MFL sensor modules, and in completing the kinematic studies and tractor design. In addition, work on the ovality sensor has been completed, while work on system integration is nearly complete.

Results to date indicate that the robotic system under design will be able to meet most of the design specifications initially prescribed. The kinematic analysis shows that from a locomotor point of view an inspection of a 16”-24” pipe size range with a single platform is most likely possible. However, the limitations imposed by the sensor are more restrictive, final preliminary design results showing that in order to cover this pipe range, two different sensor systems will be needed; one for the 16”-20” pipe size range and one for the 20” – 24” range. Finally, the analysis has shown that tether operation will be limited to flows of less than 30 ft/sec; these results will have to be confirmed experimentally during the next phase of work.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The project has progressed well during this reporting period. GE Oil and Gas (PII) completed work on the sensor and sensor modules in December 2003. The final preliminary designs for the sensor modules were passed to Foster-Miller, which integrated the modules into the platform and initiated final system integration studies. These studies will continue into January 2004. Tether analysis and lab tests were completed as per original schedule. However, following review of the tether integrity tests, it was decided to conduct additional longer term testing to better understand tether-life issues. Winder module design is complete as is that of the ovality sensor module. The ovality sensor will be located in between the two MFL sensor modules. System integration is practically complete, some issues related to the MFL sensor modules still being considered. The final report that was expected to be available by the end of December 2003 is still been written in order to include updates imposed by changes made to the MFL sensor modules and ovality sensors in late December. The report is to be submitted to the funders for review by March 1, 2004.

INTRODUCTION

With the recent advances in robotics and sensor technology, and the occurrence a few unfortunate pipeline accidents, the Office of Pipeline Safety (OPS) of the US Department of Transportation has endorsed the concept that all oil and gas transmission pipelines should be capable of 100 percent inspection. This can be accomplished through the elimination of pipeline obstacles that would allow for pigging, or through the development of innovative inspection technologies, hydro testing, or use of direct assessment techniques. Problems arise when the piping network is older and/or constructed without pigging as a design consideration. This is the situation with countless miles of transmission pipelines owned and operated by local gas distribution utilities. There are many physical "obstacles" in the piping network that makes pigging impossible. The most intractable of these obstacles include:

- Bends/elbows with bend radius less than 1.5 D. This is a very common obstruction.
- Mitered joints/elbows greater than 10 deg. This is an obstacle found in older systems.
- Back to back combinations of bends/joints. Commonly found in tightly spaced areas.
- Reduced port valves. This includes valves with ports smaller in diameter than the pipeline. This is also a very common obstacle.
- Reduction/expansion in pipe diameter greater than 2 in.
- Unbarred branch connections. Pigs are not designed to turn down branch lines, and therefore, branch lines must be barred to prevent the nose of the pig from crashing into the lateral and jamming itself in place.

The Gas Research Institute in a report issued in 1995 (entitled "In-Line Inspection of Un-piggable Natural Gas Pipelines") noted that the cost to replace just two of the most common obstacles would be substantial, costing over $3 billion. Therefore, the development of tools to inspect un-piggable transmission and/or distribution pipelines presents a both a formidable technical challenge as well as a significant financial incentive to the gas industry. The adaptation of current pigging technology may not be viable given the geometric challenges of existing interstate and utility owned pipelines. External direct assessment techniques have not been shown to be universally adequate, accurate or cost-effective. Use of an innovative robotic approach would apparently be dictated.

The inspection of un-piggable gas transmission and distribution pipelines requires the innovative marriage of a highly adaptable/agile robotic platform with advanced sensor technologies operating as an autonomous or semi-autonomous inspection system. The work being conducted under this program is based on a robotic platform that is train-like in nature and is based on Foster-Miller's Pipeline Inspection System (PipeMouse) developed in early to mid 1990's. Both front and rear tractors propel the train in the forward and reverse directions inside the pipeline. Like a train, the platform includes additional "cars" to carry the required payloads. The cars are used for various purposes including the installation and positioning of sensor modules, the power supply, data acquisition/storage, location/position devices and onboard micro-processors/electronics. The onboard intelligence gives the platform the benefit of an engineer steering the train through complicated pipe geometry. The system includes launching and retrieval stations that are similar to that used for conventional pigging systems, but much simpler in design and operation.

The Pipe Mouse was built to a strict set of performance criteria appropriate for low-pressure gas distribution networks. The Mouse was designed to be highly mobile and agile, had the ability to travel long distances from the entry point and steer down branch line of pipe tees, negotiate mitered (zero degrees) elbows, navigate in both the horizontal and vertical planes, pass through partial section valves, and adapt, by a factor of two, to changes in pipe diameter. These same types of obstacles create problems for inspecting un-piggable transmission mains.

General Electric Power Systems (previously PII North America; a subcontractor for this project) has extensive experience designing and working with sensors based on ultrasonics, electromagnetism, eddy-currents and optical methods. For this program, sensor development will be considerably more challenging than for conventional pigging due to the greater variance of pipe diameter and the more difficult obstacles encountered in un-piggable pipelines. The ability to actively expand and retract the onboard sensor will be needed, not just for obstacle avoidance, but to allow upstream (reverse direction) travel.

The robot will be controlled via a fiberoptic tether system, which will be analyzed, designed, and tested as part of this project. The tether is expected to provide sufficient range for the robot to inspect a substantial length of the pipe without the need of many expensive tapings of the pipeline

To power the computer, sensors, data acquisition, and drive wheels some form of energy storage and electrical power supply is required. Of all the various possibilities (e.g., batteries, fuel cells, ultra-capacitors, flywheels, etc.), the battery approach is clearly the simplest, safest and most reliable. To minimize the number of launch and retrieval stations, the batteries should have maximum energy density. The modular platform concept has an advantage in that battery "cars" can be added as needed, up to the length of the launch tube. Certain obstacles (e.g., mitered corners) also impose a length constraint. Different battery and charging modules may also be swapped in and out based on the range requirement, power and availability of recharging stations.

The anticipated benefits derived from the use of this platform include the following:

- Ability to inspect otherwise inaccessible pipelines (transmission and distribution).
- Cost savings from not having to remove pipeline obstacles for conventional pigs.
- Inspection cost much lower ($/mile) than direct assessment or hydro testing.
- A more versatile platform capable of performing a variety of inspection services.

EXPERIMENTAL

During the period of October 1, 2003 to December 31, 2003 work on the project continued at a pace mostly consistent with the timetable presented in the previous report. Some deviations were experienced; the final report will not be issues in early January as anticipated previously, but at the end of the formal project period, i.e. at the end of February.

Task 1: Program Management

Task 1.1. Research Management Plan

Completed

Task 1.2. Technology Assessment

Completed

Task 1.3. Technical Oversight

The last schedule of tasks called for a completion of all component preliminary design work by mid-November 2003, with system integration to be completed by the end of November 2003. Due to some difficult issues, related to the design of shunting devices for the MFL sensors, faced by the PII team, the final sensor modules design was not received until mid-December. As a result the writing of the core of the final report was not initiated until January. The final report is expected to be released to the sponsors on March 1, 2004.

Task 2: Mechanical Design: Robotic Design and Sensor Module

Task 2.1. Robotic Platform

Task 2.1.1 System Engineering

Task 2.1.1.1 Kinematic Analysis

Completed. Presented in the last report.

Task 2.1.1.2: Brainstorming Session

Completed.

Task 2.1.1.3: Tractor Design

The design of the tractor/triad system has been completed with the packaging of the wheel drive assembly, and integration of the clamping motor and lead-screw into the triads. The components selected for this design (see Figure 1) reflect the downgrade in power requirements that was discussed in the last report.

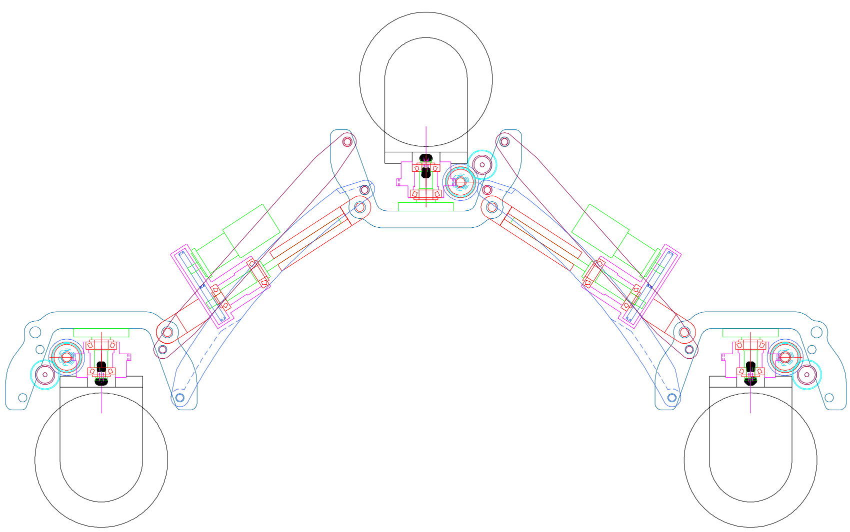

Figure 1. Fully assembled tractor with wheel drive, wheel steering, and clamping system incorporated

Task 2.1.1.4: Winder Design

The packaging of the Winder Module was completed. The housing consists of a 2-piece shell that is supported by a series of bulkheads along the length of the module. Current thinking is to keep the system open to the pressurized gas environment, while individually sealing any electrical/electronic components that are susceptible to damage. A purging sequence for the complete Roboscan system (within the launch tube and prior to removal from the pipeline) will need to be defined in the next phase of the project. The need for a totally sealed system will be evaluated in Phase II depending on the time required to purge the winder car, and any difficulties that arise in protecting electronics individually. The circular bolt pattern on the ends of the vessel will be used for attaching the connecting couplings (typical to all modules).

Task 2.1.1.5: Module Design

Completed.

Task 2.1.1.6: Sensor Deployment Mechanism Design

Completed.

Task 2.1.1.7: System Integration

The electrical design and specification of the major electrical components is complete. Remaining work involves the completion of the inter-module couplings and the integration of the modules into the Roboscan platform.

Task 2.2 Sensor Module

Task 2.2.1 MFL Sensor System Design

The design of the PII MFL sensor module has evolved further (as of last report). As in the previous design iteration, there will be 2 modules, each with 2 magnetizer segments (geometry maintained). Improvements have been made in the actuation mechanism and the centralizing link arms which deploy with the magnetizers. An electric motor and lead-screw, built into each of the modules (two magnetizer modules separated by intermediate vessel), will provide input power to the deployment system. The centralizing link arms will provide support to the system during inspection. Modifications to the geometry of the system along with additional wheels will further reduce drag through plug valves and mitered bends. System compliance for absorbing shock from weld beads and pipe transitions will be accommodated through springs in the link arms. The MFL sensor system will be maintained at or near the pipe centerline by two mechanisms, one on each outboard end.

The Foster-Miller designed centering mechanisms (currently under development) will maintain the elevation of the MFL sensor system at the pipe centerline both during inspection and when retracted. Without the centering mechanism, the magnetizers in the retracted state would have a tendency to pull the module to one side of the pipe (or valve) without the centralizing mechanisms, causing unnecessary drag and possible jamming. PII is continuing to make progress towards a magnetizer shunting system, which will reduce attraction during retraction and valve/bend negotiation. PII is currently weighing the merits of a shunting mechanism with a deployment scheme coupled with the deployment linkage against a hydraulic actuation system.

Task 2.2.2 Module Design Support

The inter-module couplings play a critical role in the Roboscan systems negotiation of the pipeline, keeping the train intact while transferring axial forces (tension and compression) and torsion as a result of the push and pull action, and torque applied by the front and rear tractors. Depending on their location within the train, the couplings may be adjacent to one another (i.e. a bend and rotation coupling in series between 2 modules). The couplings must also accommodate the routing of power, signal, and communication wires between modules. Throughout the train, the following types of inter-module couplings are used:

- Bend
- Curl
- Rotation
- Centralization

A concept being explored for the bend coupling is based to a structure similar to human vertebrae. It consists of a series of spool sections (vertebrae) bolted together with urethane springs that compress and expand in bending. The system accommodates both tension and compression, and has a hollow core for wire routing. This concept will be further evaluated during the next reporting period.

While the Roboscan must traverse a more complex pipe route than the original pipe mouse (i.e. back-back out-of-plane bends), the kinematics of the original pipe mouse have been maintained. One critical feature is the curling link. The tractor locomotion system (one on each end of the train) consists of 2 triads that work in tandem. When entering a bend, the front triad is oriented such that the front wheel “reaches” into the bend. Once properly aligned, the triad is “lifted” into the bend through torque applied by the curling link. The front triad will momentarily lose traction while being lifted by the curling link and pushed by the trailing triad. The concept being explored provides torque through a commercially available clock-spring, which can rotate either gear (attachment points to triads) independent of the other. Our original thinking was to go with an actively controlled curling link. We now believe that a passive system, like that of the original Pipe Mouse, is possible, and will provide the added benefit of somewhat reducing control system complexity. The spring may be locked out during deployment for ease of handling.

Task 2.2.3 Ovality Sensor Design

The ovality sensor design is completed. It is based on a Banner time-of-flight laser distance sensor and has a resolution of +/- 1mm.

Mounted between the MFL modules, centering is achieved through bend-center couplings on each end of MFL modules.

Task 2.3 Camera/Illumination Design

The Roboscan vision requirements are as follows:

- Medium resolution camera fitted to the front and rear of the robot for basic navigation and sight.
- Sufficient lighting for basic navigation
- Higher resolution camera fitted to the robot for visual inspection of the pipe wall. This camera will be outfitted with pan and tilt capabilities.
- Sufficient lighting for detailed pipe wall inspection

For basic navigating, and orientation for obstacle negotiation, vision is required at each leading edge of the robot. Since the robot is bi-directional, cameras will be mounted at both outermost extremes. These cameras will be fixed, and have a large field of view. These cameras will be used for recognizing upcoming obstacles, as well as spotting potentially damaged areas on the pipe wall that require further inspection. If an area on the pipe wall is seen to be suspect, then its approximate location will be tallied, and the robot will continue forward until that area is in the sight of the visual inspection camera located elsewhere on the robot. The visual inspection camera will be located within the ovality sensor module. This camera will have a higher resolution than the basic navigational cameras, and will also have tilt and rotate capabilities. This camera will be used for detailed visual inspection of pipe wall defects that are sighted through the basic navigational cameras.

Each camera system will be matched with a suitable light source. Accompanying the basic navigational cameras, front and rear, will be fixed, HID lighting systems providing ample light for camera operation. The visual inspection camera will make use of a light ring mounted to the perimeter of the ovality module, lighting the entire circumference of the pipe.

Visual inspection camera:

The visual inspection camera system is based around a compact high resolution color DSP, board level camera manufactured by Edmunds Industrial Optics. This camera reaches a resolution of 480 horizontal lines, which will be suitable for close up inspection of the pipe walls. This camera will be coupled to a Computar variable focus lens for optimum adjustability. The camera and its immediate electronics will be packaged into a pressure vessel that is mounted on a custom, 2-axis tilt/rotate mechanism.

Basic navigation camera:

The basic navigation camera system uses a Hitachi miniature board level camera and a custom electronic interface. This camera was chosen for its small size due to the space constraints on the triads. This camera is matched to a fixed focus lens by Edmunds Industrial Optics. These components will be packaged into a pressure vessel housing, and fixed onto each outermost triad.

Task 3: Electrical/Control Design

Battery Power System

The previous estimate of 4 battery modules to power the Roboscan platform still stands if existing commercial battery technology is used. Foster-Miller has discussed options for reducing the number of battery modules with Alegna Innovations, a battery and power management development company. Alegna believes that the number of modules may be reduced to two through an innovative application of Lithium-polymer battery technology. Alegna has proposed a program for developing a 270V/ 35 AH (9.5 KWH) battery and power management system (include health monitoring and charging). Although 1 to 2 years out in terms of the timeframe for developing the first prototype, Foster-Miller believes that the advantages of this system in terms of doubling power density while reducing length and payload for a given mission (recall that increasing the number of battery modules increases drag and power requirements) merit consideration for further development.

As discussed in earlier reports, there are two optimal shapes in terms of volume maximization and obstacle negotiation. In discussing packaging options with Alegna, it turns out that an asymmetric shaped module is more efficient for battery packaging than the symmetric “sausage” shaped module. For this Phase I development effort, Foster-Miller recommends that the oval cross-section module be used for battery packaging, based on the improvements in energy density and the reduction in train complexity (50% less battery modules). The downside to using the oval shaped module is the need to orient the module for plug valve passing (only fits one way), and the challenges in designing a coupling for attaching to adjacent modules in the train. Efforts are currently underway to optimize coupling design. A major concern is the attachment point of the coupling on the battery module. Ideally the coupling point should be on the centerline, but with adjacent modules of circular cross-section and positioned close to the bottom of the pipe, the kinematics, particularly when negotiating bends, becomes more challenging. These issues will be addressed during the next (and last) reporting period.

Task 4: Communication

Task 4.1 Tether Assessment

The remaining tether assessment issues are addressed in this report and may be summarized as follows:

- Attenuation measurement under wound conditions.
- Corner abrasion and attenuation test.
- Plug valve flow

Attenuation Tests

Izumi International Co., a subcontractor of Stocker-Yale (manufacturer of bend-insensitive fiber) was contracted to wind 1 km of the single-mode 900 micron Hytrel/Aramid jacketed fiber (stock number BIF-1310-L2) on a mandrel under 1 lb of tension and measure the resulting signal attenuation. Ultimately the test could not be completed due to mechanical failure (twice) of their winder/tensioner setup. Portions of the fiber were damaged during the second attempt at winding, resulting in a net useable length of 500m. Stocker-Yale, the supplier of the bend-insensitive was able to step in and perform these tension tests in their lab. The 500m of fiber was wound under a tension of 500g (1.1 lb) to simulate the 1 lb design tension utilized in the winder.

The attenuation data for the BIF-1310-L2 fiber were obtained as a function of wavelength. Attenuation was determined in two distinct cases: (a) of the fiber prior to upjacketing, and (b) of the upjacketed fiber (Hytrel/Aramid jacket) under 500 g (1.1 lb) of tension when wound on a 63 mm (2.5 in) mandrel. The 63 mm mandrel is representative of the mandrel diameter in the Roboscan winder module. The fiber was wound to an outside diameter of approximately 4 inches. According to Stocker-Yale, since the outside diameter of the Roboscan spool (2.5 mile capacity) will be 4.25 in (slightly larger than tested spool OD), the attenuation data for the 500 m of fiber tested may be extrapolated linearly to 2.5 miles (4 km). If the Roboscan spool O.D. was less than that tested (4 in), then it would not be fair to assume that the data could be extrapolated linearly out to 2.5 miles. This is due to higher attenuation in the fiber at smaller diameters as a greater percentage of the fiber will experience a tighter bend radius. The testes showed that significant attenuation takes place at frequencies away from the 1310 nm and 1550 nm wavelengths, which are the two traditional telecommunication windows because they are low loss regions. These two windows are used extensively now in telecom and sensor systems because of the availability of components at those wavelengths. Also as another point of interest, attenuation peaks observed at 1380, 1250, 1100, 950 and 720 nm are harmonics of the fundamental OH- vibration (hydroxyl ions). OH- impurities are present in the glass due to processing and the use of hydrogenated precursors. They have no detrimental effect on the glass except if the system is operated in the wavelength range where one of those peaks is located. Thus, the Roboscan fiber optic communication system may be operated at either the 1310 nm or 1550 nm wavelengths.

Table 1. Fiber attenuation (db) as a function of wavelength

Fiber Test Condition	**1310 nm**		**1550 nm**	
	1 km	**4 km (2.5 miles)**	**1 km**	**4 km (2.5 miles)**
Prior to Upjacket, no tension (unwound)	0.73	2.92	0.35	1.4
Upjacketed, 500g tension (wound)	0.81	3.24	0.48	1.92

Table 1 summarizes the attenuation data of the 2 tested conditions at 1310 nm and 1510 nm wavelengths. The increase in attenuation for the tensioned (and jacketed) fiber over the baseline fiber (prior to upjacketing) is relatively small, with the 1310 nm wavelength experiencing 3.24 db (vs. 2.92 baseline) at 4 km (2.5 miles), and the 1550 nm experiencing 1.4db (vs. 1.92 db baseline). The choice of a wavelength will be decided in the next phase based on the performance requirements of the system and the availability of commercial components. Although we cannot predict the loss budget for the Roboscan tether communications system at this time, most likely these low attenuations will not adversely affect the design.

Corner Abrasion Tests

The corner abrasion test was repeated for the Stocker Yale BIF-1310-L2 bend-insensitive fiber in Foster-Miller's labs. Previous tests were conducted on a fiber from a different manufacturer with a similar Hytrel/Aramid jacket. As in the prior test, the jacketed fiber was tested under the maximum laboratory flow conditions of $\rho V^2/2$ $(lb_f/ft^2) = 20$ under the worst-case test conditions of a sharp mitered-corner bend with the tether oscillating under no tension. In order that we could quantity any attenuation in the signal due to potential fiber damage, fiber optic splice connectors were assemble on each end. A baseline power loss reading of -14 dBm was established using a 1310nm laser source and optical power meter. The goal of the test was to determine if there was any damage to the fiber after 8 hours of exposure to these conditions. An attenuation of -13.6 dBm was observed at the 4 hour point of the test. The post-test attenuation reading was -13.7 dBm. Similar to the previous test, a "flattening" of the tether occurred in the area where it contacted the corner of pipe, but no abrasions or cuts in the jacketing were evident. It can be concluded after this test that the ribbon-like shape that the fiber assumes after oscillating in the mitered corner after 8 hours of testing under flow conditions ($\rho V^2/2$ $(lb_f/ft^2) = 20$) more adverse than normal conditions ($\rho V^2/2$ $(lb_f/ft^2) = 6$) does not adversely affect signal quality or tether integrity. The small dBm aberrations in the readings were due to misalignments in the splice connectors between the different sized fibers. However, it was decided to conduct additional abrasion tests, to last a few days, in order to better understand longer term effects of abrasion on tether life.

Task 5: Auxiliary Components

Completed.

PROJECT STATUS BY TASK (*as per December 31, 2003)*[1]

Task 1: Program Management	On-going
Task 1.1: Research mangement Plan	Completed
Task 1.1.1: Requirements Document	Completed
Task 1.2 Technology Assessment	Completed
Task 1.3 Technical Oversight	On-going
Task 2: Mechanical Design: Robotic Platform and Sensor Module	On-going
Task 2.1: Robotic Platform	On-going
Task 2.1.1: Systems Engineering	On-going
Task 2.1.1.1: Kinematics Analysis	Completed
Task 2.1.1.2: Brainstorming Session	Completed
Task 2.1.1.3: Tractor Design	Completed
Task 2.1.1.4: Winder Design	Completed
Task 2.1.1.5: Module Design	Completed
Task 2.1.1.6: Sensor Deployment Mechanism Design	Completed
Task 2.1.1.7: System Integration	On-going
Task 2.2: Sensor Module	On-going
Task 2.2.1: MFL Sensor System Design	On-going
Task 2.2.2: Module Design Support	On-going
Task 2.2.3: Specify Ovality Sensor	Completed
Task 2.3: Specify Camera/Illumination	Completed
Task 3: Eletrical/Control Design	On-going
Task 4: Communication	On-going
Task 4.1 Tether Assessment	On-going
Task 4.1.1: Analysis	Completed
Task 4.1.2: Choose/procure candidate materials	Completed
Task 4.1.3: Test Plan	Completed
Task 4.1.4: Lab Test	On-going
Task 4.1.5: Tether Test Report	On-going
Task 4.2 Specify Communication Components	On-going
Task 5: Auxiliary Components	Completed
Task 6: Management and Reporting	On-going

[1] Items indicated in bold were initiated during this reporting period

RESULTS AND DISCUSSION

Tether assessment is extended to include longer term testing in order to assess resistance of the tether to abrasion over extended periods of time. Otherwise, analysis and some tests indicate that the tether option is viable in the case of low and moderate transmission pipeline pressures and flows, i.e. flows of less than 20 ft/sec and pressures less than 350 psig. These conditions cover more than 70% of operating conditions of Local Distribution Company (LDC) transmission pipelines (details provided in the previous progress report for this project). Tether winder design is complete.

PII has completed the design of the MFL sensor module and sensor modules. The configuration chosen is that of two sensor modules with segmented sensors.

The cameras have been selected. The final recommendation is for two sets of cameras. One, lower resolution set will be placed at the two ends of the platform to provide navigation capabilities. Another camera, this one with high resolution, will be positioned on the ovality sensor module and will be used for high quality review of "trouble spots" identified by the other two cameras.

Regarding the ovality sensor, the choice was made to adopt a commercially available light sensor, due to the reduced development time and costs, established calibration procedures, and minimal computer processing/data storage required. The preliminary design of the ovality sensor system and module is now complete.

CONCLUSION

The project is nearing completion, with most tasks already complete and a few in their very last stages.

The locomotor provides portability in the 16” to 24” pipe diameter range, while the sensor modules provide portability in the 16” to 20” range, and in the 20” to 24” range.

The tether option appears to be viable for low and medium pipeline pressures and flows. Additional testing regarding the life expectancy of the tether (related to abrasion of the cladding) is to be conducted in this last phase of the project.

The MFL sensor and sensor modules have been designed. Two modules will be used in order to provide the necessary coverage of the interior pipe surface.

The ovality sensor is based on a time-of-flight laser distance sensor and has a resolution of +/- 1mm. laser.

Two cameras at the two ends of the platform will provide the necessary vision for navigation. Another higher resolution camera will provide the capability of visual detailed examination of suspected pipeline defects.

REFERENCES

The following paper will be presented at the upcoming GTI (NETL sponsored) conference.

W. Leary, R. Torbin, and G. Vradis, *"Robotic Pipeline Inspection System"***,** Natural Gas Technologies II, Gas Technology Institute, Pointe South Mountain, Phoenix, Arizona, February 8-11, 2004.