

**Final PUBLIC Report on Project**

**COMPLETION OF DEVELOPMENT OF ROBOTICS  
SYSTEMS FOR INSPECTING UNPIGGABLE  
TRANSMISSION PIPELINES**

**DTPH56-10-T-000008**

**SUBMITTED BY:**

*Daphne D'Zurko*

Executive Director, NYSEARCH, Vice President, RD&D NGA

**NYSEARCH/Northeast Gas Association (NGA)**

20 Waterview Boulevard, 4th Floor

Parsippany, NJ 07054

Phone 973.265.1900; Fax 973.263.0919

[ddzurko@northeastgas.org](mailto:ddzurko@northeastgas.org)

**Submitting Organizations:**

NYSEARCH/Northeast Gas Association

and

Invodane Engineering Ltd.

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## **EXECUTIVE SUMMARY**

This document presents the final report for a program focusing on the completion of the research, development and demonstration effort, which was initiated in 2001, for the development of two robotic systems for the in-line, live inspection of unpiggable transmission and distribution natural gas pipelines. Two robotic platforms have been developed and commercialized as a result of this effort: (a) Explorer II (Explorer 6-8), which carries a remote field eddy current (RFEC) sensor for the inspection of 6” and 8” unpiggable pipelines, and (b) Explorer 20-26 (TIGRE), which carries a magnetic flux leakage (MFL) sensor for the inspection of 20” to 26” unpiggable natural gas pipelines. This work will allowed certain design enhancements for the Explorer II system, as identified through the field demonstrations that the systems underwent, as well as the development of commercial grade defect sizing algorithms for the RFEC sensor. This work also completed the development of the TIGRE system, a robotic device for the inspection of 20” to 26” unpiggable natural gas pipelines, which carries a magnetic flux leakage (MFL) sensor for the detection of defects. Through this program a series of five field demonstrations in dead and live pipelines was carried out, culminating with the commercialization of the technology. This work was conducted by a team consisting of NYSEARCH/NGA and Invodane Engineering (IE), the commercializer of this technology, and was funded by NYSEARCH, PHMSA/DoT, and SDTC of Canada.

## **INTRODUCTION**

The 2002 Office of Pipeline Safety (OPS) regulations requiring the inspection of all transmission pipelines, including those that are now deemed “unpiggable”, triggered the search for technologies that would make the inspection of unpiggable pipelines possible. With the option of modifying unpiggable pipelines so that they are rendered piggable, being a prohibitively expensive one in most cases, Direct Assessment and Hydrotesting are at the present time the only technologies available for their assessment. These technologies, while they are playing a role in the overall effort to characterize the pipeline networks, are expensive and cannot provide industry with the comprehensive information that in-line inspection tools can. The use of In-line Inspection (ILI) technologies is the preferred tool among operators because it offers the most comprehensive and accurate means of pipeline inspection.

As a result, in 2001, NYSEARCH initiated an effort to develop ILI technologies for unpiggable pipelines. Following a feasibility study that proved the potential of robotics and sensory technologies to meet the system requirements, a development effort was undertaken in 2004 with cofunding from NYSEARCH, PHMSA/DoT, NETL/DoE and OTD to develop the necessary tools. The Explorer II and TIGRE robotics systems resulted from this effort.

## **PROJECT OBJECTIVES**

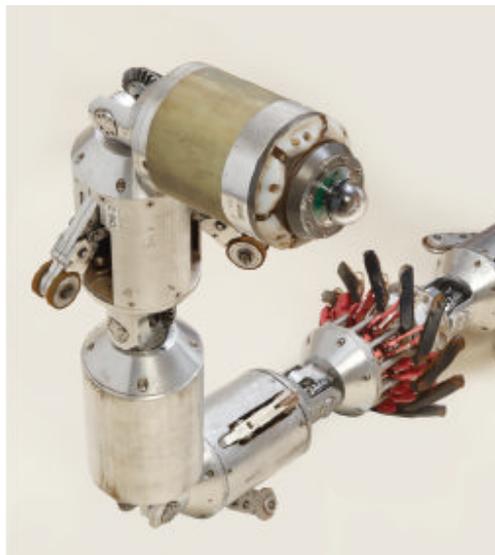
The objective of the proposed project was to complete the development of the Explorer II and TIGRE robotic systems for the inspection of natural gas transmission and distribution unpiggable pipelines. Design modifications, aimed at increasing the reliability of these systems and their operational range, were implemented on the Explorer II platform in order to minimize deployment and operational costs. In addition, commercial grade sizing algorithms were developed for the RFEC sensor, which are essential to the quality of the data generated. Regarding the TIGRE system, and based on experience gained through the first deployment of the system in a dead pipeline network, design modifications were implemented to make the system lighter and smaller, thus conserving power and improving operational deployment characteristics. These system enhancements were followed by a number of three field deployments in live pipelines, which were carried out to prepare it for commercial deployment. The Explorer II effort was completed within 9 months of project initiation (as scheduled), while the TIGRE effort was completed in twenty seven months (as scheduled). The successful completion of the program has led to the commercial deployment of this technology in the US and Canadian markets.

## **WORKSCOPE AND ACCOMPLISHMENTS**

The accomplishments of the program are presented next on a task by task basis as per proposal's approved workscope.

### ***EXPLORER II: TASKS 1.1 THROUGH 1.4***

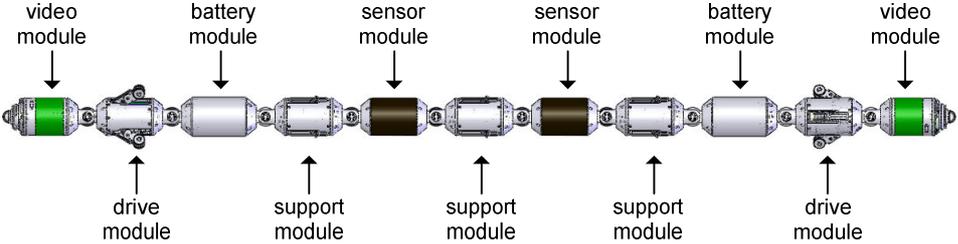
Explorer II (shown in Figure 1) is an un-tethered, modular, remotely controllable inspection robot for the visual and non-destructive in-line inspection of 6 inch and 8 inch natural gas transmission and distribution system pipelines. The Explorer II tool simultaneously records both RFEC sensor data and captures video. The inspection system relies on RFEC sensing technology to assess the wall thickness of a pipeline and a video imaging system for navigation. The Explorer II RFEC system consists of one (1) excitation coil and circumferentially distributed array of sensors.



**Figure 1: Explorer II robotic system for the inspection of 6” to 8”  
unpiggable natural gas pipelines.**

Table 1 shows the specification of Explorer II. Two (2) drive modules move the tool through a pipeline. Video modules at the front and rear of the tool provide video feedback to operators. Three (3) support modules support the sensor and battery modules and center the tool in the pipeline. One sensor module houses the excitation coil, while the other contains the RFEC sensors and associated electrical systems.

**Table 0: Explorer II inspection robot technical data.**

<p><b>Explorer II</b></p>	
<p><b>General Information</b></p>	<p>tool applications pipe mapping and feature detection and analysis          detection technologies RFEC and video capture</p>
<p><b>Mechanical Specifications</b></p>	<p>tool length 9 ft          operational tool weight 65 lbs</p>
<p><b>Pipeline Requirements</b></p>	<p>surveyable pipe diameters 6 or 8 inch          minimum clearance diameter 4.5 in</p>
<p><b>Technical Specifications</b></p>	<p>maximum inspection range 0.6 mi per launch/un-launch site          speed range 0 - 4 in/s          maximum operating pressure 750 psig          launch method hot tap          un-launch method hot tap</p>
<p><b>Detection Technology Details</b></p>	<p>RFEC sensor count 32 (6 inch) or 42 (8 inch)          RFEC axial resolution 0.05 in          RFEC circumferential resolution 0.06 in          video module count 2          video module locations front and rear</p>

**Task 1.1: Explorer II new batteries**

During the Explorer II field demonstration in Brookville, PA, in the summer of 2009, it became obvious that the primary limiting factor for the inspection range of the robot was the capacity of the on-board batteries. Because of this, there has been a continual effort to increase the inspection range. Following a detailed engineering analysis, it was determined that the size of the modules on the robot could be increased with little impact on the operation (such as fitting through a hot tap opening for launch and un-launch). The additional volume inside this increased module size would be best used in the two battery modules, where larger batteries, with increased capacity, would increase the distance the robot could travel before needing to be

recharged. The larger module body has resulted in both an increased diameter and length over the old battery module, yet still allows for 90 degree launches into 8 inch pipelines and 45 degree launches in 6 inch pipelines. Higher capacity batteries were selected that fit inside the larger module, with an effective capacity increase of near 60%.

The final version of the new battery modules was tested successfully in a demonstration in the Oneida, NY, in November 2010.

### **Task 1.2: *Explorer II - Inter-module connectors***

A significant improvement made to Explorer II was re-designing and replacing the electrical connection between each module. As originally designed, power and communication was carried from one module to its mated module through a series of spring-loaded contacts. When the modules were assembled together, these spring contacts would touch exposed pads on a circuit board attached to the mated module. This design resulted in a simple assembly process, where the electrical connection was made automatically requiring no large or wear/damage-prone connectors and eliminating the possibility of damaging (pinching) wires during mechanical assembly. Unfortunately, this design also proved quite unreliable over time as the exposed pads gradually oxidized and wore out during repeated assembly and disassembly. Further, as the robot flexed (as seen during negotiation of a pipeline feature or during launch and un-launch) the spring-loaded contacts would intermittently lose their connection with their mate pad. One obvious symptom of this intermittent electrical contact was that communication with some of the robots modules was occasionally affected.

A new interconnect design was developed by Invodane and adopted following a design review. It features a solid connection between pins and mating sockets. In a mated pair, one board floats relative to the module body and, prior to the mate of the pins and sockets, is aligned to the other circuit board using chamfered guide pins. Then, as the modules are mechanically mated fully, the electrical pins mate with the sockets and protrude far enough into the socket to ensure that any lateral movement during normal operation will not disconnect the pins from the sockets. Further, because one of the mating boards remains floating after the modules are fully assembled, it ensures that any flexure of the robot body does not cause stress to, and consequently damage, any part of the interconnection system. Once the new design had been

fully implemented on Explorer II, extensive testing showed dramatically increased reliability with no change to the operation of the robot. Further, over the remaining duration of the commercialization effort, no system control problems were again observed.

The new design was tested during a demonstration in Oneida, NY, in November 2010. No issues emerged during this challenging field deployment proving the reliability of the design.

### **Task 1.3: *Explorer II - Launch assist system***

Another effort to increase the inspection distance per deployment was the development of the Launch Assist and Tether (or LAT) module. Through our experience with earlier deployments it became apparent that a substantial amount of robot power was being consumed during site preparation, launching Explorer II into the pipeline, unlaunching Explorer II and removing the launcher from the pipeline. Added together, roughly 15% of the available on-board battery capacity was being consumed during these stages in an inspection. Further, one factor in the deployment cost for an inspection is the requirement for the pipeline operator to install a 2 inch hot tap to allow installation of the in-pipe antenna to for wireless communication with Explorer II. If the need for this tap could be eliminated, this would decrease the cost of the inspection for the operator.

As a result, a separate modular mechanical construction, similar to Explorer II, with self-contained drive, battery, tether spool and tether payout modules has been designed and built. A lockable socket would be connected to the end of a short tether that would provide power to Explorer II until the robot was launched into the pipe, at which point in time the socket would be detached from Explorer II's nose module and the robot would return to operation using its internal batteries for the remainder of the inspection. The in-pipe antenna is attached to the end of the LAT sticking into the pipeline. Wireless communication with the robot would take place via this antenna, negating the need for the additional in-pipe antenna. When Explorer II returns to the launch site, it would re-attach to the socket and draw power from the LAT's internal batteries during the unlaunch and retrieval process.

The first live test of the LAT device took place during the live demonstration of the Explorer II system in Oneida, NY, in November 2010. The device was able to deploy and retrieve the Explorer II robot as expected, saving substantial amounts of power on the robot itself and providing communication with the operator without the need to install a different antenna. Some minor technical issues emerged that were dealt with at the time. Review of these issues upon return to the laboratory revealed the need for some minor design changes, which were implemented by the conclusion of this effort. Generally, the Launch Assist vehicle proved to be an invaluable addition to an inspection both by increasing the range of Explorer II but also by eliminating the time sensitivity of the site preparation and launch processes.

In summary all these new features were tested in a 6 inch pipeline under live conditions in a pipeline in Oneida, NY, in November 2010. The operating pressure of the pipeline during the test was approximately 470 psi. Explorer II inspected this pipeline over a 3 days period. All three new features were confirmed to function as expected in live pipeline environments.

#### ***Task 1.4: Explorer II Data Analysis and Sizing of Defects***

RFEC systems consist of an exciter coil and an array of detector coils<sup>1</sup> in a send-receive configuration inside the inspected pipe. The exciter coil and detector coil array are typically axially separated by between two (2) and three (3) pipe diameters. The exciter coil is energized with a low frequency AC current to produce a corresponding magnetic field, termed the excitation field. The excitation field couples to the detector coil array through two (2) distinct paths. The direct path runs inside the pipe along its axis. This field is attenuated rapidly by circumferential eddy currents induced in the pipe's wall. The indirect path passes out of the pipe wall near the exciter coil, travels along the outside of the pipe, and passes back into the pipe. The field along the indirect path is attenuated and phase shifted each time it passes through the pipe wall, but it is attenuated at a much lower rate axially along the pipe than the direct field inside the pipe. The magnetic field magnitude along the inner pipe wall is given by the vector sum of the fields along the direct and indirect paths, and it is separated into three (3) zones. The region in which the direct field dominates is referred to as the direct field zone and generally occurs

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<sup>1</sup> A minimum of one (1) detector coil is required in the detector array. One (1) detector coil RFEC systems typically align the exciter and detector coils axially.

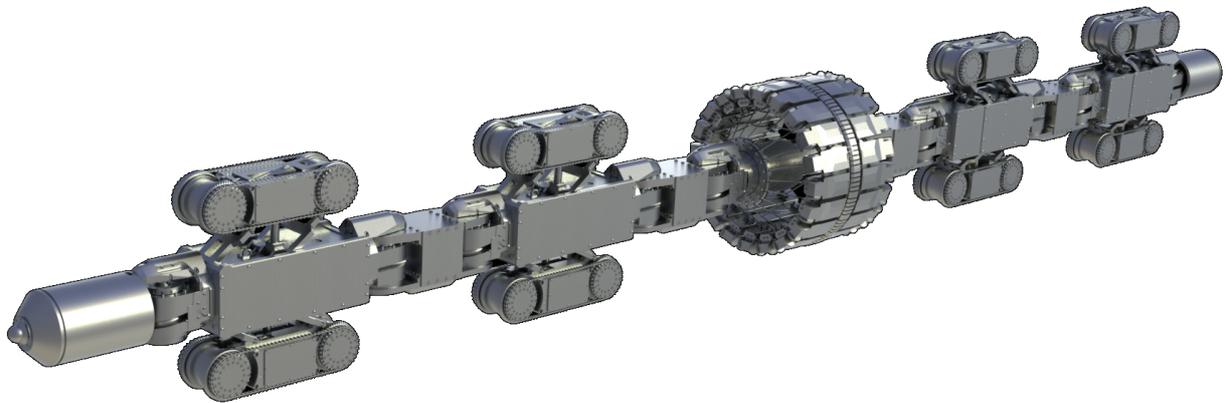
within one (1) pipe diameter of the excitation coil. The region dominated by the indirect field is referred to as the remote field zone and typically occurs beyond two (2) pipe diameters of the excitation coil. Between the direct and remote field zones there is a transition region, termed the transition zone, where the magnetic field magnitude drops sharply. This drop is a result of the direct and indirect field phasors being anti-phase and of similar magnitudes.

Any anomalies present in the pipe wall at any point along the indirect path cause changes in the behavior of the indirect field. Anomalies have the greatest effect on the indirect field when they appear in the vicinity of a through-wall transition of the field. Through-wall transitions occur twice: once as the indirect field exits the inside of the pipe and again when it passes back through the pipe wall and enters the pipe. At these through-wall transitions the indirect field is attenuated and phase shifted. Any anomalies in the pipe wall near these regions result in changes to the attenuation and phase shift of the indirect field. Anomalies can therefore be detected as either the exciter coil or detector coil pass by them, and whether the detector or exciter coil produce a larger signal from the anomaly is dependent on the system. The Explorer II inspection robot is configured to identify anomalies as the detector coil array passes over them, and for the remainder of this report anomalies will be treated as identified only when the detector coil passes by them.

The signal generated by a detector coil passing over an anomaly is a change in the magnitude and phase of the full wall detector coil voltage. In-Phase and Quadrature line plots or color maps are used in anomaly detection but are not used for anomaly analysis. Once anomalies are identified in In-Phase and Quadrature data, voltage plane plots of the anomaly regions are generated with In-Phase data along the  $x$  axis and Quadrature data as the  $y$  axis. The voltage plane representation of an anomaly signal is termed an anomaly signal trace. A line drawn between the two (2) extremes of the anomaly signal trace, termed the signal trace line, has been used to assess anomaly depth and volume. The length of this line, termed the signal trace length ( $L$ ), is proportional to anomaly volume. The angle between the positive  $x$  axis and the signal trace line, termed the signal trace angle ( $\theta$ ), is inversely proportional to anomaly depth.

***EXPLORER 20-26 (TIGRE): TASKS 2.1 THROUGH 2.16***

Explorer 20-26 (TIGRE) is an un-tethered, modular, remotely controllable inspection robot for the visual and non-destructive in-line inspection of 20 inch through 26 inch natural gas transmission and distribution system pipelines. The TIGRE tool simultaneously records both MFL sensor data and captures video. The inspection system relies on MFL sensing technology to assess the wall thickness of a pipeline and a video imaging system for navigation. The TIGRE MFL system consists of one module that carries the magnets and sensors as well as a system to shunt the magnets, something needed when the sensor module navigates through pipeline features.



**Figure 2: TIGRE robotic system for the inspection of 20” to 26”  
unpiggable natural gas pipelines.**

Four (4) drive modules move the tool through a pipeline. Video modules at the front and rear of the tool provide video feedback to operators. One sensor module houses the MFL sensor with its magnets, sensors, shunting system, driving system, and batteries.

Development of the original TIGRE system was originated in 2004. A prototype system was built and tested in the laboratory. A testing of the system followed at the NYSEARCH Test Bed in Binghamton, NY, in November 2007. A number of design improvements were identified during that testing and were implemented in a follow up phase. In the present program, some of the key improvements were tested in a second generation tool and were then implemented in the commercial version of the system, which was designed, built and field tested as part of this program.

**Task 2.1: *TIGRE - Validate design modification in the field***

Key design modifications were tested on a prototype built from the original TIGRE. Examples of such design modifications include simplifying and streamlining the original TIGRE system from its original length and weight of 35 ft and 950 lb to approximately 15 to 20 ft and 600 lb respectively. The number of modules was reduced from 15 to 7. The IE team also exploited opportunities in adopting similar components and/or design from the Explorer II system to reduce development, operational, maintenance, and training cost. Some of the original drive and battery modules eliminated were integrated directly into the MFL sensor module. The transformation of the MFL sensor for negotiation of plug valve and mitered bends was also simplified. This prototype system was then tested in a 20” pipeline with open-end access in southern California in November 2010 (see Figure 3). Several hundred feet of the pipeline was inspected collecting pipeline integrity data. The test pipe consisted of a straight, unpressurized, 1,100 ft run of 22 inch pipe that had been installed in 1956 and abandoned in 1994.

The purpose of this technology test was to verify the performance of this “interim” TIGRE in a realistic pipeline environment and to test the procedures and operational steps required to deploy the equipment reliably. The Interim TIGRE is a development platform for testing the electronics, software, mechanical, and magnetic systems. These were used as building blocks for the final TIGRE design to enhance the overall development cycle and mitigate risks. Quantifiable primary and secondary test objectives were set in order to validate the test.



**Figure 3: Interim TIGRE tool lifted during testing**

The following primary objectives were set as required accomplishments for the test:

1. Scan a minimum of 1,000 ft of pipeline by driving the tool in both forward and reverse directions.
2. Recommend verification dig zones for features identified in the surveyed pipeline.

The following secondary objectives were set as desirable accomplishments, but were not considered requirements for a successful test:

1. Traverse 1,300 ft of test pipeline at least once with acquisition of multiple data sets.
2. Non-standard features present in the pipe are identified through the test.
3. Crew procedures are developed and adjusted to increase reliability and field deployment efficiency.
4. Identify anomaly regions and, if present, verify through excavations.

Implicit in the test objectives are the monitoring of all systems that were design improvements to the original TIGRE tool including:

- Electronic components redesign to ensure all drive, steer and magnet bar units could be constructed using readily available parts, shrink space required, and optimize functionality and board footprint.

- Tire tread design ensuring contact with pipe wall is secure for the full range of tool tow force.
- Tool power systems. Implementing a modular battery placement and charging systems
- Improved data collection circuitry and firmware.
- Firmware including drive module control, steer control, magnet bar data collection.
- Overall tool control techniques including drive functions.
- Nose module software to convert wireless signal for module control throughout the tool.

The tool was run three times in the pipeline on three separate days of testing (see Figure 4). The first day was run without the sensor being deployed, while the second and third day data was collected (with 1,100ft of continuous data collected on day 3). Coupled with the data analysis that followed during the subsequent months, which identified certain regions of interest in the pipe, main objectives of the test were met from a system operations perspective.

The tool performance validation was a success as well, with all systems performing as or better than expected. The data integrity during the scan was affected by moisture in the pipeline, which caused some sensors to remain unresponsive. Some sensors were reclaimed by replacement or at the very minimum cleaning, but the test highlighted the need for improvements to sensor components to be able to handle pipeline environments including those with general moisture concerns.



**Figure 4: Southern California 22” testing launch location. Tool can be seen being lowered into position**

The operator of the tool identified features such as girth welds and seam welds as well as the presence of moisture on the bottom of the pipe using its forward facing video camera. As far as crew procedures were concerned, the checklists developed in the lab were sufficient and minor modifications were made during the course of the testing.

Overall, the performance of the tool was validated through the use of the tool in this manner.

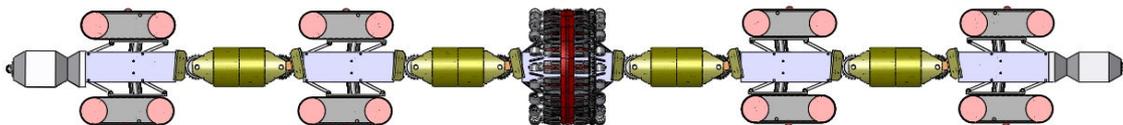
- Electronic systems performed as designed;
- Tire wear was imperceptible, debris was noticed on the outside of the wheel indication of self cleaning tendencies

- Tool power systems were uninterrupted during operations. The need for swappable battery packs was identified due to long field hours where charging and tool maintenance could not be performed at the same time.
- Modular battery placement was a success, and a more strategic charging scheme was recommended focusing on a central charge connection.
- Data collection with healthy sensors was smooth
- Magnet bar control was smooth for all modes of operation
- All firmware behaved as tested in the lab. Video was for the most part clear, however, the lighting of the pipeline could be better directed to optimize the operator field of view.
- Tool control techniques resulted in smooth performance in straight pipe.
- The nose module software was efficient, wireless strength monitors were checked.

Based on the results of this testing, the design requirements for the commercial grade tool and its various system were developed in order to achieve better reliability, performance, and data integrity.

### **Task 2.2: *Streamlining of TIGRE system***

Knowledge acquired from the test of Task 2.1 were incorporated into the final design of TIGRE (shown in Figure 5) prior to manufacturing. These design improvements further enhanced the reliability and performance of TIGRE. Final design modifications were verified at the Invodane indoor pipe testing loop. Drawings and electrical schematics were prepared and issued to qualified vendors for manufacturing.



**Figure 5: Explorer 20/26 (TIGRE) in a four module configuration**

Certain design improvements and concepts were implemented in the” interim” TIGRE to evaluate their viability, characteristics, and/or performance limits in the field (Task 2.1). In addition to these improvements, further optimizations were made with the intention to shorten the overall length (and therefore reduce operational cost and complexity) of the tool. Seen in Figure , the tool has been shortened to a length of 14ft with some adjustability in the tool length dependent upon the mission profile of an inspection. For instance, a three module tool (three drives, three steers) may only be required for shorter inspection runs. A two module tool could conceivably be used in instances where the tool does not have to enter a hot tap or miter bend.

Some of these improvements include:

- Increased length of steer module to articulate the sensing section and each drive module during navigation through a miter bend/hot tap. Adjusted the cross-section profile of the drive module to accommodate a combination drive/battery module
- Replaced obsolete cameras with a commercial readily available device. Implemented a framework where secondary cameras can be mounted near the MFL section for monitoring the system during navigation through tight features.
- Drive force supplied by four individual motors and the deploy of each drive track can be controlled independently of each other. A similar tread pattern as used on the Interim TIGRE was employed.
- Allowed for the efficient replacement of all main battery packs on the tool as well as on-tool charging.
- Wireless strength monitoring in the GUI using units that can be correlated with experiments.
- Improved lighting on the system using a combination of focused and scattered lighting from each end of the tool. The light source itself was upgraded using the latest in super-bright LED technology.
- Magnet bar sensors were upgraded to handle environmental concerns outlined in the field testing of Task 2.1.

The system traversal of key features was laid out including:

- *Hot tap / Miter Bend:* Navigation in and out of a size-on-size hot tap is a key element of the design. Tool body length, diameter, and spacing are key parameters in determining fit. The first drive track is rotated into the hot tap opening using the steer module. After the first body is positioned along the axis of the hot tap, its drive tracks are extended and it is used to assist the rotation and pull of the modules, including the magnetizer, through the feature.
- *Bends:* The bend traversal was designed to navigate without changing the deploy setting on the drive tracks or magnetizer. With this in mind, the tool will be able to traverse bends quickly and efficiently, with minimum operator intervention.
- *Reductions:* All points on the tool are designed to fit into a 75% reduction of the pipe OD along with passage through a plug-valve geometry.
- *Plug valves:* Concentrated efforts were made to simplify the actuation methods on the original sensing section to fit through plug valves.

### **Task 2.3: *TIGRE Manufacturing***

Electrical and mechanical hardware was produced by qualified vendors and off-the-shelf components were sourced. Long-lead time items, in particular, were sourced first to ensure timely delivery of all components. As parts were delivered, they were checked and tested progressively. Sub-assemblies were assembled and tested as parts became available. For example, drive modules were tested and their tow forces under different conditions determined. The nose module was tested for video and data transmission. Some pressure sensitive components were tested in a pressure chamber. The ability of the MFL sensor to magnetize was also verified. Sub-assemblies were then assembled into TIGRE.

#### ***Task 2.4: Software integration***

Firmware on TIGRE was finalized and tested. Firmware was installed onto electrical components as they became available during manufacturing. Debugging and optimization of firmware continued until TIGRE was fully assembled and tested. The functions of the firmware range from communication between the numerous micro-processors, control of actuators, streaming of video and MFL data, driving, and battery power control.

#### ***Task 2.5: Construction of indoor test loop and evaluation of system***

A pipe network was constructed in the indoor facility at Invodane. This pipe network consisted of a plug valve, miter bend, back-to-back 45 degree bend, along with straight pipe sections. After TIGRE was built, it was driven and tested extensively in this indoor pipe network. In addition to negotiation of the features in the pipe network, the MFL sensor was deployed to stream and record data. The purpose of these tests was to reveal issues and deficiencies which were then resolved.

In greater detail, the laboratory tests included:

- Straight line driving to test the effect of accumulated distance on tool components
- Swept bends to test navigation characteristics and control approach
- Swept bends (single and back to back) to test navigation characteristics and control approach
- Mitered bend navigation to test operator control approach
- Plug valve to test operator control approach and confirm that the tool fits
- Sensing section tests to indicate initial data collection performance of module

One key aspect of the tool that was monitored throughout the testing was the ability of the tool to navigate features without being manipulated manually by operator control. In other words, the tool can move around a bend simply by propelling itself forward, similar to a train on

a track. With this capability, driving through most pipeline features is a matter of ensuring that the tool linkages are oriented in the right plane and then driving forward. For miter bends, plug valves, and launch/un-launch, the maneuvers will still be operated by a combination of predetermined steps (scripted) and manual control.

A full scale mockup of the pipe and hot tap were assembled at IE. The hot tap system was connected to this mockup, as seen in Figure . This was an important step for learning how to handle large (and heavy) pieces of equipment.



**Figure 6: Testing Explorer with hot tap system**

The operators drove the tool through the mock operational setup to train and demonstrate the ability of the tool to navigate these features. One of the key segments of the demonstration was how TIGRE turns the largest component (the sensor) through the opening of the hot tap and into the pipe. This involves holding the heavy sensor steady as it is turned from each end at particular angles.

After this capability was demonstrated, the operators practiced the navigation of the tool repeatedly, up to 20-30 times. This repeated practice allowed the operators to drive into the pipe, and out of the pipe in a short time.

***Task 2.6: Test bed demonstration in Binghamton, NY***

TIGRE was tested at the NYSEARCH test bed in Binghamton, NY, in late 2011 (see Figure 7). This underground pipe network, designed to mimic actual pipeline conditions, consists of several hundred feet of 20 inch diameter pipeline, a plug valve, back-to-back 45 degree bends, mitered bends, and open-end access. A large number of defects of various sizes and depths have been built onto the pipe surface. TIGRE's ability to negotiate this pipe network was tested. Prior to the demonstration, logistical operations, mobilization arrangements, and procedures were developed for the Binghamton demonstration. They were revised as needed and used in future deployments.



**Figure7: Handling final TIGRE onsite in preparation for deployment**

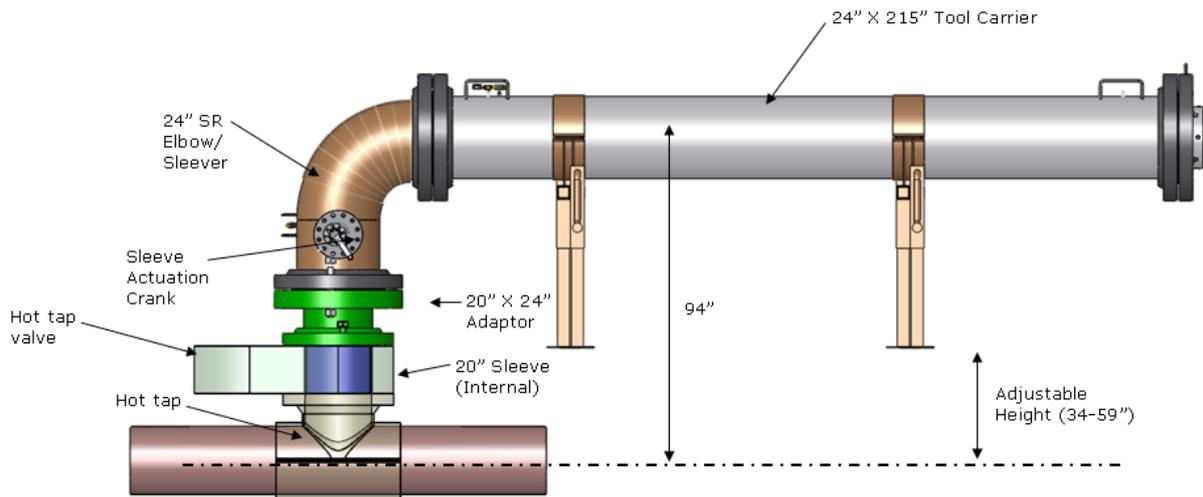
In summary, the results of this testing have as follows:

- Control techniques resulted in smooth tool performance while negotiating various pipeline features. Damage to multiple drive modules was experienced during the testing but its effects was overcome while operating in the pipe, which points towards the robust design of the tool.
- The plug valve actuation was demonstrated outside the pipeline through an actual plug valve because of the damaged drive modules onsite.

- The data set shows multiple (30+) anomalies in the pipe which were verified with the test bed owner for accuracy. Except for two magnet bars, all sensors showed excellent results from a signal stability and sensitivity standpoint.
- Batteries were charged easily, which was an improvement over the previous field testing on the interim TIGRE.
- With the exception of the force feedback firmware, all control systems and software behaved as tested in the lab. Video was clear with suitable lighting. The nose module software was efficient, wireless strength monitors were checked with no degradation of signal over the test distance.
- Overall with some minor improvements, the tool provided a stable platform to test more complex maneuvers, defect sizing, and operations training activities as the program moved forward.

### **Task 2.7: *Launcher development***

A launcher system was designed and built for launching TIGRE into pipelines under live condition via hot tap access. Hot-tapping a pipe requires a fitting which is welded onto the pipe and a valve which sits on the fitting. With these two components in place, a specialized sealed cutter is used to make a hole in the side of the pipe. After this step is completed, the cutter is removed and the valve closed.



**Figure 8: TIGRE (20"-26") Launcher Concept**

A launch system was designed to allow for access to the pipe via the hot tap. The robot would be loaded into the launcher. After following a safety procedure, which is designed to eliminate any contact of natural gas and air, the valve is opened and the launcher is pressurized with natural gas from the pipeline. This launching system (shown in Figure 8) has the following features:

- A horizontal main tube from which the robot is launched. A majority of the weight is carried by special supports instead of being carried by the pipe.
- All pressurized components are designed to fit the full 20-26in sensor configuration according to the specification of the tool (750 [psi]).
- After the valve is opened, a protective sleeve (Figure 9) is placed over the valve sealing surfaces. This is designed to provide a good traction surface for the robot in the valve section and to protect the valve seats from any debris (ferrous and non-ferrous) that may inhibit the valve from closing.



**Figure 9: Hot tap elbow designed to protect valve during deployment**

Figure 10 shows the view from the robot's camera looking down into the vertical section of the launch pipe. The tracks that the tool makes can be seen on the top and bottom of the picture. To aid in tool traction (top & bottom of the picture), low-profile grating has been added on the inside of the sleeve.



**Figure 10: View looking down the extended sleeve into the pipe**

## Task 2.8: Development the Graphical User Interface

The graphical user interface (GUI) for controlling and operating TIGRE was further developed and tested. Many features of the Explorer II GUI were adopted providing a similar appearance to the GUI and minimizing development cost. This also ensures an operator trained to operate Explorer II will learn the TIGRE GUI in less time. Some key features of the GUI include: power indicator, gravity indicator, display of the TIGRE configuration, positional feedback from the various modules, drive power and speed, wireless signal strength, actuator control, camera control, streaming of video and MFL data, and scripting of TIGRE for feature negotiation.

The GUI has been organized into tabs as an application on a laptop. These tabs provide the operator with the ability to receive detailed information on system settings and current parameters.

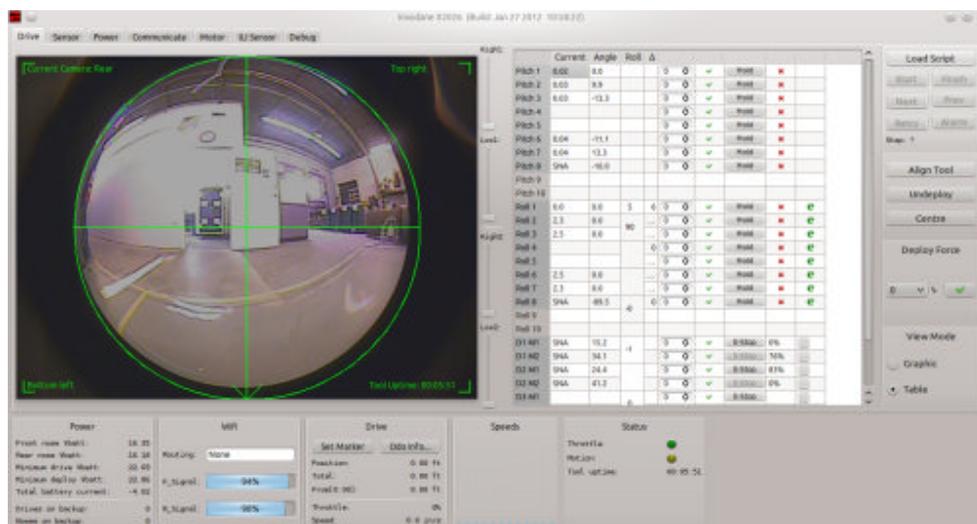
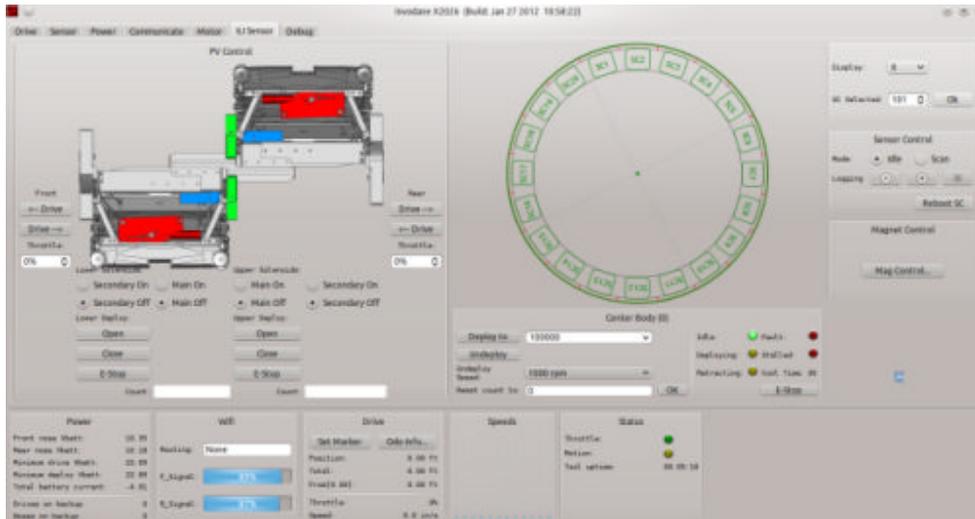


Figure 11: Graphical user interface showing driver view and controls

Shown in Figure 11, the driving tab has four main features:

- The video feed shown in the top left corner provides the operator with a visual feed of the pipe as the tool moves through.
- General tool diagnostic information is shown along the bottom such as wireless strength, antenna selection, and overall system parameters such as bus voltage and current.

- The middle right contains tool parameter control for manual movement of steer joints and driver modules
- The far right contains controls for automatic motion such as scripted maneuvers.



**Figure 12: Plug Valve Sensor GUI**

The driver view can be replaced by a view of the plug valve module (Figure 12) or general inspection sensor module, while the bottom status bar remains the same. However, two new views are available:

- The left side of the screen shows a dynamic view of the plug valve module section extension and compression, i.e. the configuration of the sensor module during plug valve negotiation. Latch status and overall control of the bank actuators are included.
- A view of the sensor module rotation and overall diameter is shown on the right. This will give the operator the ability to rotate the sensor module, if required. Magnet control is also included here.

In summary:

- The GUI has been upgraded and is able to provide extensive feedback to the operator as well as full control of the robot.

- The GUI underwent extensive testing in the laboratory, in the deployment at the NYSEARCH test Bed in Binghamton, NY, and during the subsequent field demonstrations. It has proven to be functional, reliable and robust.
- Improvements to this piece of software, however, will continue as the system moves to commercialization

### **Task 2.9: *Interpretation of sensor data***

Plate samples of various thicknesses with defects were manufactured and MFL signals of the defects were acquired by some magnet bar sub-assemblies of the MFL sensor and compared to the specifications, as a means for an initial testing of the ability of the sensor to detect defects of various sizes and configurations. Given the successful outcome of this effort, an elaborate set of defects of various sizes, orientation, and depths were built onto pipe samples of different diameters and wall thicknesses. The MFL sensor was towed through these pipe samples and MFL data were acquired. The detection capability of the MFL sensor was shown to favorably compare to target specification. The signals from these defects were then processed and analyzed forming the basis of the sizing software developed for this MFL sensor. Signals from the field deployments were analyzed and the sizes of the anomalies were determined following the sizing methods developed here.

The metal loss detection and sizing specifications for TIGRE, shown in Table 2, were set to coincide with common industry standards. The minimum metal loss detection thresholds were referenced to pipe wall thickness (WT), with a minimum detection depth of 10% WT and minimum length and width of 3x WT. Metal loss must exceed the detection threshold in all three (3) dimensions in order to qualify as detectable. Sizing accuracy specifications were set to  $\pm 10\%$  WT in depth and  $\pm 0.5$  in in length and width. An 80% confidence in sizing results was specified across all feature dimensions.

**Table 2- TIGRE metal loss detection and sizing specifications**

<b>Dimension</b>	<b>Detection Threshold</b>	<b>Sizing Accuracy</b>	<b>Sizing Confidence</b>
<b>Depth</b>	10% WT	±10% WT	80%
<b>Length</b>	3x WT	±0.5 in	80%
<b>Width</b>	3x WT	±0.5 in	80%

Metal loss defect sets consisting of 68 different defect geometries were machined into 20 in and 22 in diameter pipes with 0.250 in, 0.375 in, and 0.500 in wall thicknesses. The defect set consisted of circular and racetrack<sup>2</sup> planform area defects varying from 0.125 in to 3.000 in in length and width. Racetracks were manufactured with the long axis in three (3) orientations relative to the pipe axis: 0°, 45°, 90°. Defect depth varied from 10% to 80% pipe wall thickness. The smallest immediately visible defect with 100% detectability across 16 defect pipe scans was 0.5 in diameter circle by 10% WT deep. The dimensions of this defect were less than the minimum reporting specifications presented in Section **Error! Reference source not found.1**, exceeding the metal loss detection specifications. The smallest feature, a 0.125 in diameter circle by 10% WT, was detected in all scans, but only after careful review of the suspected feature location based on the known defect pipe layout.

The features in the 20 in diameter 0.250 in and 0.375 in WT pipes were sized with an interpolation-based sizing algorithm. The sizing accuracy and confidence levels are summarized in Table Table 3. Sizing accuracy and confidence meet or exceed the specifications of Table 2.

**Table 3 - TIGRE defect sizing accuracy and confidence based on defect pipe results**

<b>Dimension</b>	<b>Sizing Accuracy</b>	<b>Sizing Confidence</b>
<b>Depth</b>	±10% WT	86%
<b>Length</b>	±0.25 in	98%
<b>Width</b>	±0.25 in	86%

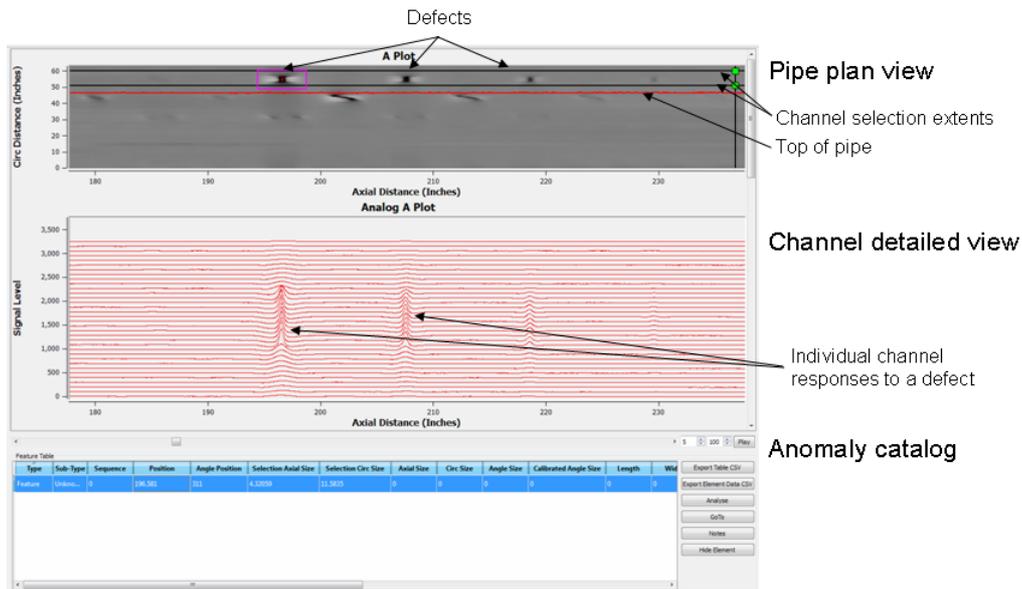
<sup>2</sup> Semi-circular ends connected by a rectangular centre.

### **Task 2.10: *Development of data analysis software***

Software for storing, handling, visualizing, and analyzing pipeline integrity data was developed. Methodologies and algorithm for sizing anomalies in 20, 22, 24, and 26 inch diameter pipes from the MFL data were plugged into the software. The focus of this effort was to develop the backend database for storing and handling of the MFL data sets and to develop all other related functionalities for the reliable and efficient analysis, presentation and reporting of the results.

Software for visualizing of inspection data was developed to handle the data collected by the tool during inspection. A view of a screenshot showing the use of this software can be seen in (Figure 13).

- The top view is the pipe section laid flat with the vertical axis as the circumference of the pipe and the horizontal axis as the axial distance, changes in the magnetic signal can be observed. Grey indicates a baseline value while white and black denote rise and fall of the signal (respectively). A magnetic signal occurs when the magnetic field changes within a local area in the pipe, usually due to wall thickness variation such as a weld, corrosion, or repair. The red line in the pipe plan view indicates the bottom of the pipe.
- The middle view displays the same signal in a line charts on a channel by channel basis (channel detailed view). The selection of these channels is controlled by varying the extents of the channel selection lines (black) in the top chart.
- The bottom view is the anomaly catalog view. When the analyst decides that a feature of interest is, the region is selected and tagged for future analysis and listed in this table.



**Figure 13: 13-ft segment of test pipe as visualized in data analysis software**

The ability to size defects from the collected data was developed from many sets of calibration defect. The calibration defects were a set of defects manufactured into pipes of varying wall thickness that was scanned with the MFL sensor. Various parameters such as wall thickness, signal thresholds, and width of the signal are used to correlate the size and depth of these corrosion features. Some of the smaller defects can be detected, but sizing is not possible since they are smaller than the acceptable accuracy.

**Task 2.11: *First demonstration in a live pipeline***

A set of three live field demonstrations are planned for TIGRE prior to commercialization. Prior to this first field demonstration, TIGRE certain improvements were implemented based on the experience gained from the Binghamton testing.

The demonstration site for the first live deployment was in Van Nuys, CA, at a 22” dia. pipeline (175psi) operated by SoCal Gas. The goal of the demonstration was to inspect a pipeline casing underneath a road. The objectives of the test were:

1. Scan a 60ft casing (approximate length) underneath a road.

2. Collect data from the pipeline leading between tool entry and the casings.

In the weeks before deploying TIGRE in this pipeline, a number of revisions were made to the tool including:

- Drive module improvements including linkage strength, deploy force accuracy, idler wheels, and brake functionality
- A 3D view of the tool orientation from sensor data was implemented in the GUI
- Simplification of data acquisition control for the MFL sensor
- A rotating 2D view of the sensor showing the magnet bar on the top of the pipe
- Graphical representation of drive speed

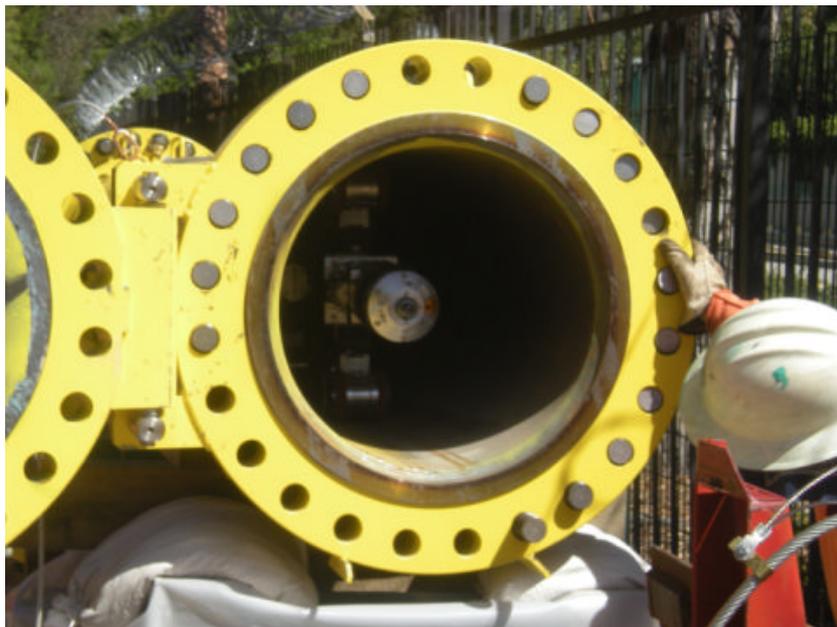
The hot tap fitting, on which the valve and launcher sit, was installed near to the casing (see Figure 14). The excavation was located approximately 15ft from a sharp 90deg bend. The bend was closer to the entry point than originally thought in the planning phase, but the operations team was able to smoothly adapt to this situation drawing on their knowledge from testing the system in the laboratory. The launch system was installed on to the hot tap as shown in Figure 15.



**Figure 1: Hot tap prepared prior to installation of TIGRE launcher**



**Figure 2: Explorer launcher system installed and pressure tested**



**Figure 16: Explorer driven into launch system**

After a final system check, the robot was inserted in the launcher (see Figure 16), the launch system was closed, purged and pressurized. Once in straight pipe the tool went on inspecting the pipe section of interest. The casing was inspected as planned going in and back

out for an approximate total of 200ft of inspection data. No anomalous readings were detected in the casing data. Some issues were identified in the nose module that needed to be addressed during and following the demonstration.

Overall, the tool inspected the planned section of pipe and collected two sets of data. This was a major milestone for this development program and for the pipeline industry. It was the first inspection of this kind on a pipeline without taking it out of service.

### ***Task 2.12: System improvements and development***

Based on the results of the first demonstration in a live pipeline in southern California, TIGRE was further improved and further developed. Hardware and software adjustments and modifications were made accordingly. Extensive testing was completed on the nose modules to ensure that the root cause of the problem encountered in the first field demonstration was well understood. Modifications were implemented and two upgraded modules were built and integrated into TIGRE. Testing was carried out to ensure that temperatures in these modules did not exceed the allowable limits. Upgrades to the firmware were also implemented to better manage the thermal performance of the system. Additional enhancements were implemented in the firmware for improved drivability.

### ***Task 2.13: Second field demonstration in a live pipeline***

The target objective for this second live field deployment was to demonstrate the entire technology from planning through reporting. The pipeline in which this demonstration was carried out was located south of Salt Lake City, UT. It had a nominal diameter of 20 inches and operated at a pressure of 300 [psi] approximately. The focus of the inspection was the inspection of two casings about 1,600 ft apart. The pipeline was hot tapped and the launched installed almost half-way between the two casings.

The hot tap fitting was installed and the pipeline tapped prior to the arrival of the Invodane crew on site. The crew assembled the launch system, as seen in Figure 17, without incident. With the tool passing all pre-run checklists, the crew inserted the tool into and

pressurized the launch system and opened the hot tap valve. The tool was driven into the pipe. While the last of the tool was turning into the pipe, the crew noticed strange power cycling behavior. The main power bus voltage was rising and falling and communication with the tool over the wireless was intermittent. Furthermore, a full drive section was not responsive. After it was determined that the tool could not be driven out of the pipe, the crew collapsed the drive modules and aligned the steer joints prior to powering down the tool.



**Figure 17: Setup of hot tap system south of Salt Lake City, UT**

The pipeline operators de-pressurized the pipeline and the launch assembly was removed revealing the end of the TIGRE tool. With the assistance of an overhead crane, after much effort and manual manipulation by specialized personnel, the tool was slowly extricated from the pipeline through the valve. After the tool was lifted out of the pipe and lowered down onto the cradle, the Invodane crew carried out a complete set of diagnostics to determine the source of failure. It was determined that a circuit board in one of the drive modules had failed.

Following replacement of the failed board, the robot was re-launched without problems. When the robot reached 480 ft from the launch point the same irregular communication from the tool was noted. The robot was driven back to the hot tap and was extracted from the pipeline without any major problem, No data was collected, since that was planned for the segment of the run on the way back to the launching point.

In summary, the results of the demonstration were as follows:

- The operational procedures proved to be robust and no issues arose.
- The temperature of the nose modules, an issue in the previous demo, did not cause issues with this deployment. The module temperature remained below the new specification limit.
- The secondary systems functioned properly and enabled the crew to prepare the tool for manual extraction.
- There was no data collected for this demonstration

**Task 2.14: *System improvement and development***

Based on the results of the second demonstration in a live pipeline, modifications were made to certain components and systems in order to address and correct the issues identified. Extensive testing was completed in the laboratory on the failed board to ensure that the root cause was well understood. A failure at a component level was identified as the main trigger of the actual failure. New hardware, software and firmware was developed and installed to ensure that this component failure did not result in a failure of the entire system. The changes were implemented throughout the robot to ensure robust operation in the future. At the end of this replacement program the sensor was configured for a 20 inch pipeline, in preparation for the next demonstration.

**Task 2.15: *Third field demonstration in a live pipeline***

The last scheduled demonstration of the TIGRE robotic inspection technology took place in Toronto, ON, Canada in late October, 2012. The pipeline was 20 inches in diameter, operating at a pressure of 175 psi. The objective of the demonstration was to inspect 1000ft of pipeline downstream of the access location. The access point where the hot tap fitting was installed was located 500ft before a bend, which then took the pipeline towards a nearby river. Two inch fittings were installed on the pipe for installation of antennas to improve communication with the tool.

As shown in Figure 18, the entry point was a 3-way Spherical Tee where the flow enters the main line from the side and the flanged connection on the top is used to install the valve and the launch system. The 3-way Tee was not the standard fitting used for the launching of TIGRE. For this reason, prior to the deployment the robot was run through a test mock-up of this fitting in the laboratory. While this was not part of the initial plan, it was a great opportunity to demonstrate the capability and flexibility of the system by adapting to a new situation. The launch point was located directly downstream from a compressor station with its connection at a 3-way Tee. The valve used on top of the fitting was the same valve used for normal hot tapping launch.

The typical pre-run system checking and operational procedures were completed on the robot before it was inserted into the launch tube, as shown in Figure 19. After pressurization the main valve was opened after which the robot reported fluctuating readings from a number of onboard sensors. It was determined that the turbulent flow over the 3-way Tee was causing a harmonic vibration on the launch system, which was impacting the tool as well. The valve was closed and the robot returned to its normal state. In order to proceed, the flow through the pipeline was turned off (pipeline remained pressurized) and the robot was launched.



**Figure 18: Spherical 3-way Tee as used for the Enbridge demo**



**Figure 19: Setup of hot tap system at Toronto, ON for Enbridge demo**

As the robot entered the pipeline it was realized that it was covered with a heavy layer of oily particles. The launch process was stopped. Invothane and the pipeline's operational crews did an on-site risk assessment. It was concluded that while the risk to proceed was reasonable, the inspection distance should be decreased in order to increase the available battery supply of the robot upon return to the launcher in order to have enough power in case it was needed for extra maneuvering to unlaunch the robot.

The tool was launched and driven approximately 500ft into the pipeline collecting data. After the tool reached the 500ft mark, and with an extra amount of battery power left on the batteries to get back into the hot tap, the direction of the tool was reversed with the sensors on. In this way, 1000ft data from the pipe was recorded. The tool travelled at 4in/s or faster for the duration of the inspection.

Returning to the hot tap, the tool exited the pipe without difficulty. At the top of the launch system however, the drive bodies started to slip. The tool was able to slowly move up the launcher after the operator carefully ensured that the maximum needed force was exerted on the wheels.

After the inspection, it could be seen from the data that there were anomalies in the magnetic signature of the pipe that needed to be evaluated. An analysis of this data was submitted to the pipeline operator.

### **Task 2.16: *Final optimization before commercialization***

This last field demonstration under live conditions, described in Task 2.25, concluded the field demonstration program for TIGRE and rendered it ready for commercialization. The first commercial job for the system is already scheduled for late March 2013, while substantial interest has been expressed for additional multiple jobs throughout 2013. In the last few weeks of the program, and beyond that, and based on the results and experienced gained through the demonstration program, refinement and optimization of the robot and operational procedures continued prior to commercialization. The main focus of this effort is to improve the efficiency of field operations, and the quality and type of data that system can provide to the pipeline operator. Hardware and software adjustments and modifications were made accordingly. The anomaly sizing method and data analysis software continued to be improved based on the latest experience in sizing field anomalies and comparing findings with previous assessments. All aspects of the TIGRE technologies and systems underwent another re-examination and improvements were made. TIGRE was again tested in the indoor pipe network to verify the improvements. TIGRE is now ready for commercial deployment rendering the present program an unconditional success.

### **Task 3.1: *Invodane Project management***

Invodane Engineering, as the primary technical contractor of the program had the day-to-day responsibility for the technical success of the program, focusing on technical success within the time and budgetary constraints of the program. The successful completion of the program within its original budget and timetable proves the high quality of management by Invodane.

### **Task 4.1: *Consultant – Dr. George Vradis***

Dr. Vradis served as the Team Technical Coordinator. In this capacity he had the overall technical oversight of the project ensuring that technical and operations' related decisions met the requirements and expectations of industry, the end user of this technology. He worked closely with Poul Laursen, President of Invodane Engineering, to ensure that the project met its technical milestones within the proposed timetable and budget. Dr. Vradis served in this

capacity since the project's inception in 2001, and the ultimate success of the program is an indication of the quality of management practices employed.

**Task 5.1: *NYSEARCH Project Management***

NGA/NYSEARCH through its Executive Director, Daphne D'Zurko, and other support staff had the overall management responsibility for the project. This included communication with the project's stakeholders, review and submission of quarterly reports to DoT, addressing programmatic issues as needed, and overall oversight of the technical progress and direction of the project. Through the success of this effort, NYSEARCH has demonstrated again, through this and other numerous DoT supported projects, that it is uniquely qualified to play this role.

## CONCLUSIONS

The objective of this project was to complete the development of the Explorer II and TIGRE robotic systems for the inspection of natural gas transmission and distribution unpiggable pipelines and to introduce them in the market. Design modifications were implemented on the Explorer II platform in order to increase system reliability and operational range, and minimize deployment and operational costs. In addition, commercial grade sizing algorithms were developed for the RFEC sensor, which are essential to the quality of the data generated. Regarding the TIGRE system, and based on experience gained through the first deployment of the system in a dead pipeline network, design modifications were implemented to make the system lighter, smaller, and robust thus, conserving power and improving operational deployment characteristics. These system enhancements were followed by a number of three field deployments in live pipelines, which were carried out to prepare it for commercial deployment. Both systems were successfully introduced to the US and Canadian markets upon their completion. The Explorer II effort was completed within 9 months of project initiation (as scheduled), while the TIGRE effort was completed within twenty seven months of project initiation (as scheduled). The overall program was completed within budget.

The technology commercialized through this program will allow industry to meet the requirements of PHMSA requirements regarding the assessment of the natural gas transmission network and to enhance the reliability and safety of the transmission system. Through parallel efforts (completed and ongoing) industry has developed Explorer 10-14, a similar system for the inspection of 10” to 14” unpiggable pipelines (carrying an MFL sensor), and is developing Explorer 30-36, a similar system for the inspection of 30” to 36” unpiggable pipelines carrying an MFL sensor. Furthermore, also through parallel, industry funded projects, additional sensors are being developed for these robotic platforms for the detection of mechanical damage and cracks, as well as auxiliary equipment, such as in-line charging devices and rescue tools, for the enhanced operational performance and reliability of the robots.