PUBLIC FINAL REPORT

Development of a Hardness Tester for Quantification of Material Properties in Live Natural Gas Transmission Pipelines (WP #570)

NYSEARCH/Northeast Gas Association

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EXECUTIVE SUMMARY

This report presents the work carried out towards the development, laboratory testing, field testing and commercialization of a hardness tester module for the live, in-line non-destructive quantification of material properties (toughness and strength) for natural gas pipelines (piggable and unpiggable). This hardness tester has been integrated on the Explorer 20/26 robotic platform (20”- 26” pipelines), which was developed with PHMSA cofunding and commercialized in 2013 by NYSEARCH and Invodane Engineering (through Pipetel Technologies, the commercial service company of Invodane Engineering) and is already capable of carrying sensors for the detection of corrosion defects, cracks, dents and ovality in pipelines. While the hardness tester was built for the 20”-26” pipe size range, the design is scalable to other pipe sizes. The newly developed hardness tester will add to the existing capabilities of these platforms, further enhancing the ability of the industry to characterize its pipeline assets, as per the proposed PHMSA Integrity Verification Process (IVP). Previously, NYSEARCH funded Invodane Engineering to carry out a feasibility study for the tester, which successfully developed the basic concept for the hardness tester device that was then designed, manufactured, tested and commercialized through the work presented in this final project report.

Table of Contents

1. Introduction 8
2. Approach 11
3. Development 13
   Requirements 13
   System 15
   Mission Profile 21
   Limitations 22
4. Testing 24
5. Field Testing 27
6. Project summary 32
7. Project Intellectual Property 33
8. Acknowledgements 34
9. References 35

TABLE OF FIGURES

Figure 1: Explorer 20/26 8

Figure 2: Explorer launch chamber (left) connected to hot tap (right) on a live pipeine 9

Figure 3: Hardness testing on exterior of pipe (Clark and Amend) 9

Figure 4: Proposed configuration of hardness tester aboard explorer 11

Figure 5: Graphic of prep carriage 12

Figure 6: Graphic of indentation carriage 12

Figure7: Wire brushed area dimensions 15

Figure 8: Wire brush example 16

Figure 9: Wire brush prep wheel on drum 16

Figure 10: Prepped surface dimensions 17

Figure 11: Sanding wheel on drum 17

Figure 12: Prep depth sensor position 18

Figure 13: Determination of prep depth 18

Figure 14: Testing the depth sensor 18

Figure 15: Positioning of indenter on prepped surface 19

Figure 16: Rockwell hardness testing load steps (from ASTM E18) 20

Figure 17: Camera testing prior to installation 21

Figure 18: Phases of operation for in-line hardness testing 22

Figure 19: Indenter on calibration rig (left) calibration test block (right) 24

Figure 20: Testing module in-pipe 25

Figure 21: Wire brush test (left) sanding test (right) 25

Figure 22: Indentation image capture 26

Figure 23: NYSEARCH test loop diagram 27

Figure 24: Sensor aboard Explorer prior to deployment 27

Figure 25: Indentation group on prepped surface on test bed network 28

Figure 26: Indentation group on prepped surface 28

Figure 27: Macro camera of indentation in pipe 29

Figure 28: Site 2 preparation (left) site 3 preparation (right) 30

TABLE OF TABLES

Table 1: In-pipe requirements 13

Table 2: Sensor requirements 13

Table 3: Loads for Rockwell b scale 20

Table 4: Results for hardness measurement 29

Table 5: Sample measurements using various testers 30

TABLE OF EQUATIONS

Equation 1: Rockwell hardness calculation 21

1. Introduction

During the period of 2004 – 2012 the US Department of Transportation (USDoT) through PHMSA, InvoDane Engineering (IE), NYSEARCH/Northeast Gas Association (NYSEARCH/NGA), and Sustainable Development Canada (SDTC), among others, collaborated to develop the Explorer 20-26 robotic platform (Figure 4) and to commercialize the technology. The Explorer 6/8, 10/14, Explorer 16/18, and Explorer 30/36 platforms followed. Explorer is a robotic inspection tool designed to inspect unpiggable natural gas pipelines and is deployed through a pipeline hot-tap (i.e. an access fitting that is welded on the pipe under live conditions). These robots use MFL (magnetic flux leakage) to measure metal loss in the pipe due to corrosion. Through this work, the technology has been demonstrated to be capable of inspecting pipe segments with unpiggable features such as plug valves and 90-deg mitered bends, under flow or no-flow conditions. In the past five years, InvoDane and NGA have also partnered to develop additional sensing and operational capabilities in order to offer a wider range of unpiggable pipeline inspection services.

FIGURE 1: EXPLORER 20/26

The Explorer robots are untethered, remotely controlled, self-powered robots for the visual and inline inspection of natural gas pipelines under live pipeline conditions. The various Explorer robot sizes (6, 8, 10/14, 16/18, 20/26 and 30/36) offer visual and high resolution magnetic flux leakage (MFL) sensing, while the Explorer 6/8 RFEC offers visual and Remote Field Eddy Current (RFEC) sensing.

The Explorer robots can navigate pipelines with a bore reduction up to 75% of outer diameter and a maximum pressure of 750 psig. Pipeline features that these robots can navigate include vertical segments, short radius bends, mitered bends, tees and valves. These robots are bi-directional and travel at a speed of up to 20 ft. per minute.

Inspections are performed under live pipeline conditions without the need of shutting down or reducing gas flow in the pipeline during the inspection. The robot is launched into and retrieved from a pipeline via a hot tap fitting (Figure 2). There is no need for any pre-built infrastructure, such as a trap, for launching and receiving. Explorer provides live video images of the pipeline and integrity data. Video imagery and integrity data acquired by the Explorer robots is analyzed by Pipetel’s team of analysts, using proprietary software.

FIGURE 2: EXPLORER LAUNCH CHAMBER (LEFT) CONNECTED TO HOT TAP (RIGHT) ON A LIVE PIPEINE

In response to the San Bruno incident of 2010, in the summer of 2013 PHMSA published the draft integrity verification process (IVP) that requires the establishment of a materials documentation process by all pipeline operators in the US. The reason for this process is to document the basis used by each operator for establishing a pipeline's MAOP. In the absence of proper material documentation, tests need to be carried out to establish the pipeline's MAOP. Hydro-testing could be used, but such a test is expensive, generates a lot of waste water and provides only pass/fail information. In-situ non-destructive tests could be carried out on the exterior of the pipeline (Figure 3) using portable hardness testers. This solution requires the excavation of the pipeline in multiple locations and the removal of the coating thus, making it expensive and inefficient. Finally, cut outs could be obtained for non-destructive or destructive tests in the laboratory, this method depending on the rather difficult and limited option of obtaining the cut-out samples.

FIGURE 3: HARDNESS TESTING ON EXTERIOR OF PIPE (CLARK AND AMEND)

It is obvious that an in-line tool that would be able to carry a non-destructive test from the inside of the pipe would be the optimal and preferred solution in many, if not, most cases. The availability of the Explorer family of robots provides us with the basic technology capability for such a test. In 2014, with funding from NYSEARCH, InvoDane completed a feasibility study looking at the possibility of implementing an in-line hardness tester to the Explorer family of robots. The study outlined an approach for development of such a sensor for deployment on the 20/26 Explorer. **The development, testing and commercialization of such a sensor for the Explorer 20/26 is the focus of this report.** The concept is scalable, so that the same concept can be employed in other Explorer sizes in the future.

The overall objective of this project is to build and evaluate an actual system that can be implemented on Explorer. The hardness tester module will be able to prepare the pipe surface, perform the measurement using an indentation technique, and log the data for later analysis. The process of obtaining the data is consistent with ASME CRTD 91, *Applications Guide for Determining the Yield Strength of In-Service Pipe by Hardness Evaluation*, 2009.

2. Approach

The approach adopted for this project was to place the hardness tester module (HTM) on Explorer using as many of existing robot components as possible. The configuration of the module as finally adopted is shown in Figure 4. The concept for the in-pipe hardness tester module calls for two units (sub-modules), the surface prep carriage and the hardness tester carriage. Since the surface prep tool is exhausting fine particulates into the gas flow, it is best to keep the two functions isolated from each other. Both units are protected from debris build up when not in use.

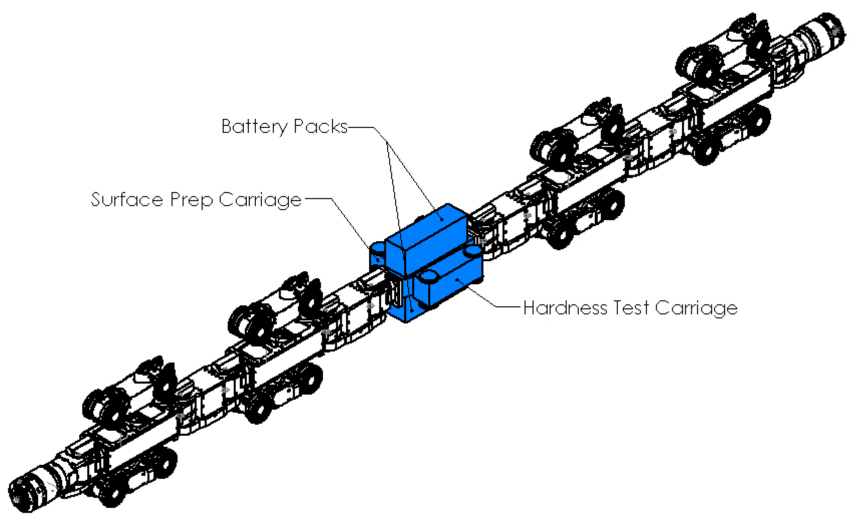


FIGURE 4: CONFIGURATION OF HARDNESS TESTER ABOARD EXPLORER

The surface prep carriage (Figure 5) was designed with the following features:

- A carriage that is deployed to the pipe wall and can be retracted to satisfy the 75% restriction requirement of Explorer. The carriage may remain deployed on the pipe wall for the duration of the run, depending on the cleanliness of the line, features, etc.
- At the front of the carriage is a spring-loaded scraper to perform the function of removing loose debris from the selected region (where the tests will be carried out).
- The preparation of the surface is carried out in two-steps; a first step that uses a wire brush to provide a coarse cleaning of the surface, followed by a finishing tool (for sanding) to provide a fine cleaning of the surface.
- A wire brush system can be deployed to the pipe wall at a 15-deg tilt. This operates in parallel with the scraping operation.
- A camera and light are included in order to evaluate the surface of the pipe after the wire brush cleaning step. The operator can visually detect dents, seam weld, or other surface features that may prevent a good hardness reading. The camera image is recorded to compare to the post surface prep image.

- The surface finishing tool is mounted on an actuated slide to control the axial motion and pressure in order to achieve a suitable surface finish.
- A wall thickness probe or similar device will monitor the progress of the material removal with the sander.

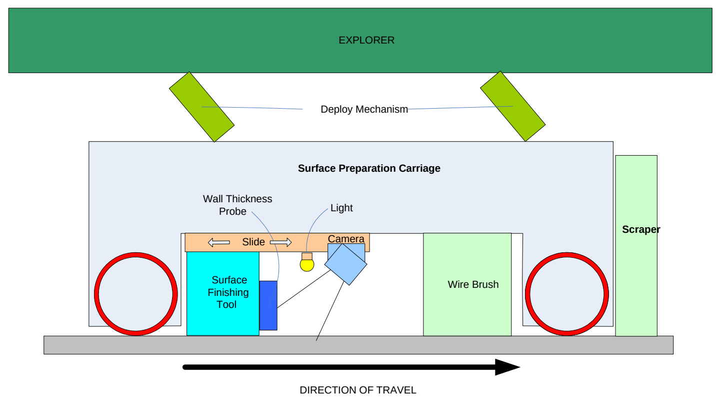


FIGURE 5: GRAPHIC OF SURFACE PREPARATION CARRIAGE

The hardness measuring carriage (Figure 6) was designed to contain the following features:

- The carriage needs to be pressed against the wall with a force higher than the 100 kp required for direct Rockwell testing (Rockwell B).
- A positioning camera is located at the front of the carriage. This is to position the carriage directly in-line with the prepped surface. The positioning camera will be inclined slightly forward to aid the operator in finding the prepped surface.
- A macro camera with high resolution is used to inspect the entire prepped surface. This series of images are recorded. Field of view should be about .5” with as high of resolution as possible.
- The macro camera and direct Rockwell measurement are attached to a slide.
- The hardness tester is engaged and takes a series of 10 measurements automatically, moving approximately 3mm between each measurement. An image is taken of the indent automatically.

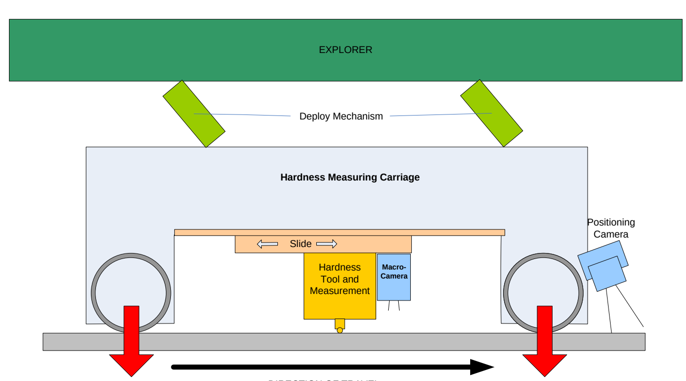


FIGURE 6: GRAPHIC OF INDENTATION CARRIAGE

3. Development

The following section outlines the process undertaken to develop the hardness testing module.

Requirements

Following the feasibility study, the key required features of the cleaning module were reviewed. Many of these requirements were derived directly from CRTD Vol. 91, which specifies the methodology to collect hardness samples from the outside of a pipe. The requirements are briefly described in the following section. Overall the module will be integrated with the robot to achieve current in-pipe functionality. An overview of the module requirements is listed in Table 1:

TABLE 1: IN-PIPE HARDNESS TESTER REQUIREMENTS

Parameter	Value	Unit
Pipe size	20-26	[in]
Pressure	0-750	[psi]
Entry type	Full size Hot Tap	
Negotiate Miter bends	Yes	
Negotiate Plug valves	No	

Overall sensor requirements were reduced to two main parameters, a measurement rate (per hour) and accuracy of the sensor. They are listed in Table 2.

TABLE 2: SENSOR REQUIREMENTS

Parameter	Value	Unit
Measurement rate	2-4	[sites per hour]
Accuracy	96-102% As per CRTD-91	% of lab value

For each phase of the hardness testing process, the following considerations for development (generated at the outset of the project) are listed:

<u>Pre-assessment:</u>

- Determination of sites including ensuring both end and middle of pipe sections are sampled. Sites should be located at least 12in from the end of each pipe. Integrity assessment of selected sites will also be carried out to eliminate possibility of dent, metal loss, or presence of a seam weld.
- The sample should be taken from the side of the pipe rather than the bottom (debris) or the top (increased likelihood of the long seam weld)
- Wall thickness should be greater than 0.250”.

<u>Surface Preparation</u>

- For carrying out preparation of pipeline surface for a direct Rockwell measurement, prepped surface should have no more than 0.010” of material removed.
- Surface preparation for direct Rockwell and Brinell measurements are less stringent than for Leeb and UCI methods due to higher load. The system should have the ability to sand using a coarse grit sandpaper (e.g. 60) and polish with a finer grit (80-200).

<u>Sampling</u>

- Hardness measurement per Rockwell B standard (ASTM E18) which specifies the load profile, indenter type, indenter size, spacing, etc.
- Real time calculation of hardness value
- Visual verification of indentation

<u>Analysis</u>

- Real time evaluation of data
- Criteria for accepting or rejecting readings

With the requirements and considerations, the team conceptualized the structure for the hardness tester module with the following features:

- It is located centrally on an Explorer robot in place of the standard MFL sensing section.
- It is manipulated through pipeline features and can be positioned on the side of the pipe wall via existing modules on the robot.
- It contains an actuator that clamps the sensing section to the pipe wall. The actuator is called the clamp actuator.
- The module contains a drum that can be actuated parallel (feed actuator) to the axis of pipe as well as rotated (drum roll actuator).
- The drum contains surface preparation and indentation features (or carriages as described above) that are moved into position to carry out the hardness measurements.

The hardness test drum has five positions. The positions contain the following components to carry out a hardness measurement of the pipe according to the feasibility study layout:

1. **Wire brush wheel:** The wire brush wheel removes loose debris from the pipe wall which either drops to the bottom of the pipe, or is carried away by the gas flow around the module. The wire brush wheel axial movement is provided by the robot drive modules since the required preparation area exceeds the total feed travel.

2. **Sanding wheel #1:** Like the wire brush, the drum contains two sanding wheels. The purpose of the sanding stations is to accurately remove up to 0.010” of material from the inside of the pipe and leave a surface finish appropriate for hardness testing. They are moved axially by the feed actuator. Each sanding wheel is fit with a camera and a depth sensor to monitor the sanding process during the operation.

In addition to the wire brush wheel, a camera and depth sensor are installed to both monitor and measure the height of the pipe surface before and after the wire brushing process.

3. **Sanding wheel #2:** Identical to sanding wheel #1, sanding wheel #2 position can be fit with the same grit of sandpaper or a finer grit depending on test conditions.

4. **Direct Rockwell Indenter:** The direct Rockwell indenter performs the hardness measurement on the prepped surface in a row parallel to the pipe axis by moving the feed actuator. The indenter also is fit with a secondary camera to take a close-up image of each indentation in the measurement set.

5. **Home position**: Contains control electronics for all measurement functions. Drum is rotated to this position when the module is not making measurements.

Note that a scraper was not implemented in this version of the module; however, it may be implemented in the future on each end of the center body.

System

The next section will describe the implementation of the concept at each position on the drum (wire brush, sanding wheels, and indenter).

Wire Brush

The wire brush position is used to remove any debris that is loosely adhering to the pipe wall. This is so that the sanding wheel and indenter remain relatively clean in the rather dirty pipeline environment. The wire brush aboard the HTM cleans a width of approximately 1.75". The indenter contacts a portion of pipe that is approximately 4" in width. Therefore, three passes of the wire brush (there and back) are required(Figure 7).

Actuation for the wire brush preparation of the pipe surface is achieved by moving the robot. The robot is driven back and forth with the wire brush motor engaged. The whole module is rotated ± 10deg in order to achieve the full 4.25" width of the wire brushed surface.

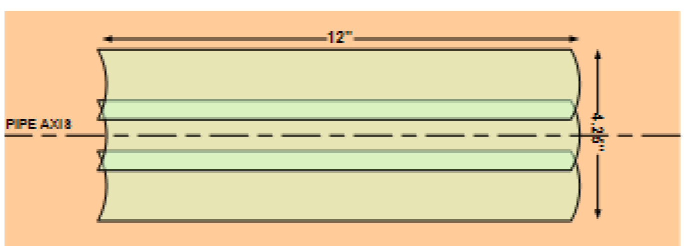


FIGURE 7: WIRE BRUSHED AREA DIMENSIONS

The wire brush used to remove debris from the pipe wall is an off-the-shelf 4.5in diameter stringer bead brush. The 0.020" bristles are twisted together for aggressive cleaning of steel surfaces. The unit is intended for use on bench grinders, CNC machines, and/or angle grinders. Depending on the application, the wheel can be replaced easily on the module, as long as the diameter is 4.5in. In our application, the wheel is spinning at approximately 1000RPM which is significantly lower than the 15,000RPM for which it is rated. The wire brush wheel position contains a camera that monitors the initial pipe wall cleaning process (Figure). If further passes are required, more passes can be performed at the operator's discretion.

FIGURE 8: WIRE BRUSH EXAMPLE

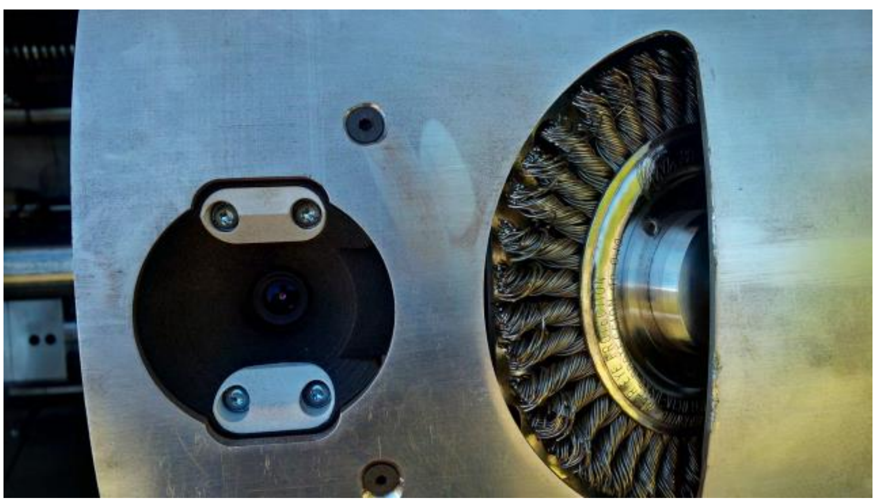
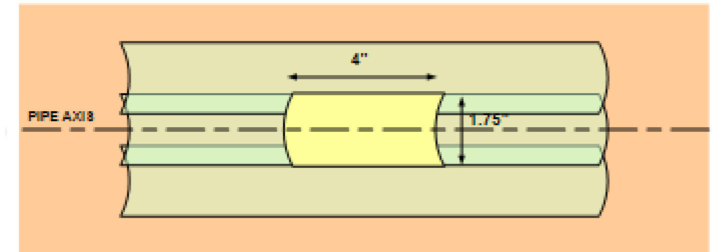


FIGURE 9: WIRE BRUSH PREP WHEEL ON DRUM

<u>Sanding positions 1 and 2</u>

IN A SIMILAR WAY TO THE WIRE BRUSH POSITION (FIGURE 9), THE DRUM HOUSES TWO SANDING WHEEL POSITIONS. THE PURPOSE OF THE SANDING WHEELS IS TO REMOVE 0.010" OF THE PIPE SURFACE AND LEAVE A SURFACE FINISH CONDUCIVE TO TAKE REPEATABLE



MEASUREMENTS. SHOWN IN

Figure 7, this zone is significantly shorter in length than the wire brushed surface. The width of the sanded surface is approximately 1.75" with the most material removed in the middle. The length of the region is approximately 4" long which is enough to accommodate between 15-20 properly spaced measurements (a minimum of 10 is needed and this allows axial distance to repeat measurements). Currently to remove the appropriate amount of material requires 4 passes with a 60 grit sanding head (there and back).

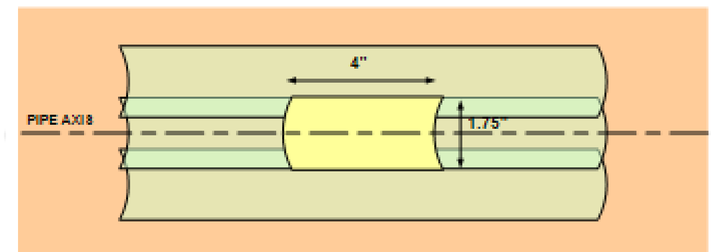


FIGURE 7: PREPPED SURFACE DIMENSIONS

The sanding wheel used is an off-the-shelf 4.5in angled sanding disc made by layering individual fabric backed sandpaper. This standard disc can be purchased in various grits from 36 up to 120 grit and was selected during the feasibility study. The disc is mounted on an angle to the drum so that only a 1.75in wide area is sanded (Figure 11).

FIGURE 8: SANDING WHEEL ON DRUM

Accompanying the sanding wheel is a distance sensor (Figure 9) and camera to monitor the sanding progress. The distance sensor measures the distance between the drum and the surface. Each time the sanding wheel makes a pass the distance sensor records the relative depth of the preparation (Figure 10). When the appropriate depth is recorded, the preparation is stopped. This process was tested (Figure 11) using a sanding motor and sensor in the pipe prior to integrating into the current design.

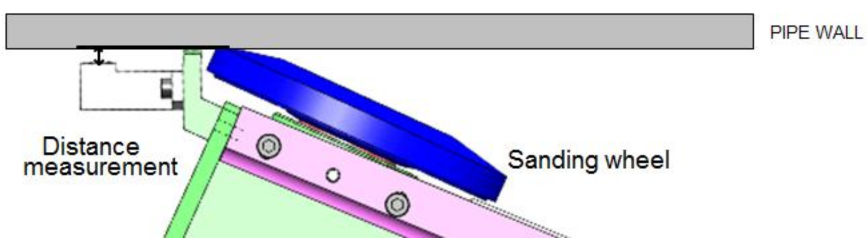


FIGURE 9: PREP DEPTH SENSOR POSITION

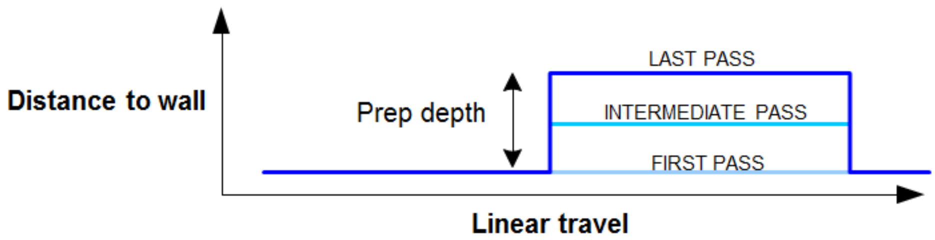


FIGURE 10: DETERMINATION OF PREP DEPTH

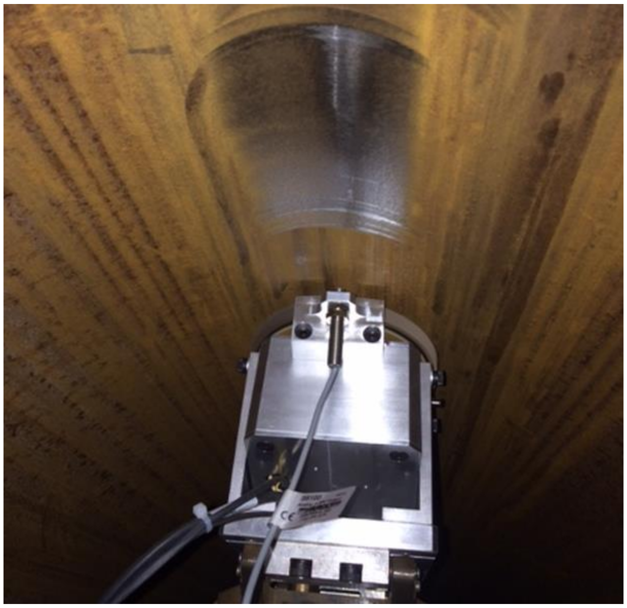
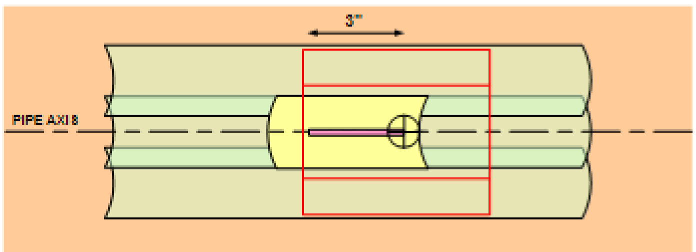


FIGURE 11: TESTING THE DEPTH SENSOR

Rockwell Indenter

THE FOURTH ELEMENT ON THE DRUM HOUSES THE INDENTER UNIT. THIS UNIT INDENTS THE PIPE ACCORDING TO A SET LOADING CONDITION ALONG THE PREPARED SURFACE OF THE PIPE. THE INDENTATIONS ARE MADE ALONG THE CENTER OF



THE PREPPED ZONE (

Figure 12). As can also be seen from the figure, the outline of the indenter element (red lines) fits within the wire brushed zone described earlier.

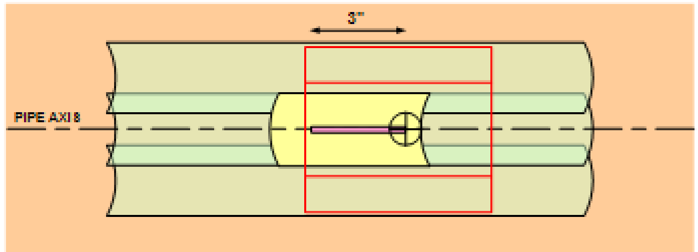


FIGURE 12: POSITIONING OF INDENTER ON PREPPED SURFACE

Test standards for hardness testers provide the following general guidelines for measurement using the Rockwell method on a portable unit (from CRTD Vol. 91):

- The minimum wall thickness for direct Rockwell is 0.250".
- The center of the deformation to the edge of the next indent (or edge of material) should be more than 2.5 times the diameter of the indent. For mild steel, this means that a minimum of 2.5mm should be kept between centers of the indentations.
- For a portable tester to be considered equivalent to a laboratory result, the measurement should be within 96 - 102% of the lab value.
- The coefficient of variation (COV) should not be higher than 0.07. This is calculated to be the ratio of the standard deviation to the mean of the ten measurements.
- The measurement range should not exceed 10% of the mean value.

The indenter unit itself consists of the following components:

- Electromagnets to hold the assembly on the pipe wall; this was proven to be crucial in being able to achieve the desired accuracy
- A 1/16" diameter tungsten steel ball indenter on the end of a linear actuator
- Linear encoder capable of measuring an indentation of 60-120 µm (1µm resolution)
- Load cell up to 100kgf with 0.1% resolution
- Control circuit board

The unit itself is designed to provide proper load magnitudes, contact velocity, and dwell times specified for the Rockwell B scale (ASTM E18). Rockwell B scale was used since it can be directly converted to yield strength values in CRTD Vol 57. The loads for this scenario are described in Table 3.

TABLE 3: LOADS FOR ROCKWELL B SCALE

Parameter	Value	Unit
F_0	10	[kgf]
F_1	100	[kgf]
Indenter size	1.588	[mm]

The steps to be taken in order to obtain a direct Rockwell measurement with the indenter unit developed here are as follows (illustrated in Figure 13):

0. Position unit and turn magnets on
1. Load indenter to 10 (F_0), zero the depth reading.
2. Load indenter up to 100 (F_1)
3. Unload indenter back to (F_0). Take the depth measurement which gives the Rockwell hardness value.

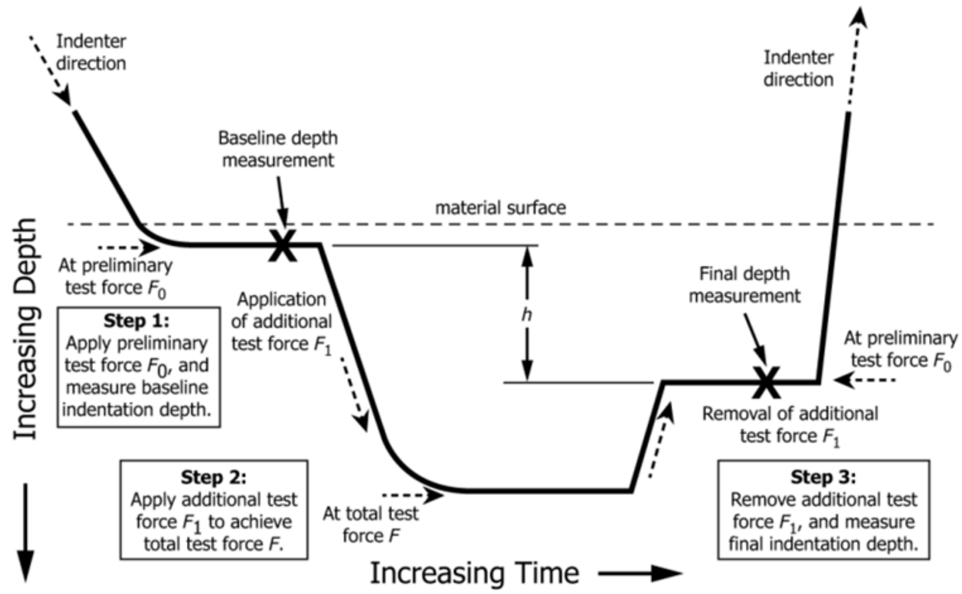


FIGURE 13: ROCKWELL HARDNESS TESTING LOAD STEPS (FROM ASTM E18)

The Rockwell Hardness (for ball indenters) is calculated using the following equation. For our purposes the reading will be listed as HRBW for lab measured values. This indenter is intended to be used as a portable tester and therefore all readings will be appended by a /P.

$$\text{Rockwell Hardness} = 130 - \frac{h^*}{0.002}$$

* [mm], for ball indenters

EQUATION 1: ROCKWELL HARDNESS CALCULATION

In addition to measurement of the indentation depth, a macro camera and lighting were installed aboard the indenter element. The primary purpose of the indenter camera is to visualize and document each indentation so the operator has the capacity to evaluate measurements before advancing to the next test site. Currently, the resolution of the camera allows measurement of the hardness to ±2HRB. In the future, this resolution may be improved with the use of a better camera and with optical path optimization. Note that for the camera to be used for measurement, the optical path will require calibration at pipeline operational pressures. All components in the indenter, including the camera (Figure 17) have been pressure tested to operate in pipeline pressures up to 750 [psi]. This includes control electronics, motors, sensors, and cameras.

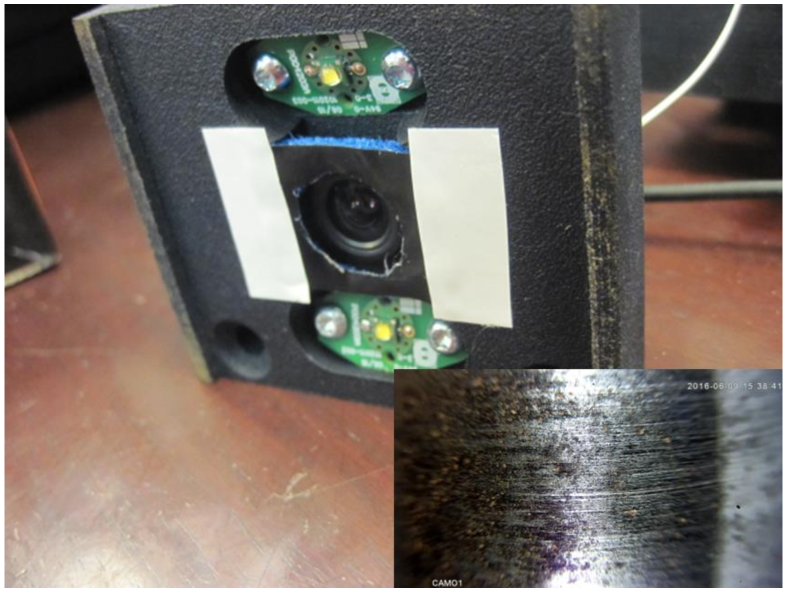


FIGURE 17: CAMERA TESTING PRIOR TO INSTALLATION

Mission Profile

The following steps are required to deploy the in-line hardness tester module in a live pipeline using the Explorer robotic platform:

1) Pre-assessment to determine a uniform sample set and minimum sample size required per CRTD Vol 91. CRTD Vol 91 outlines the selection criteria to establish a uniform sample set and the recommended number of test sites to apply hardness test results to satisfy CRTD 57. These include establishing parameters relating to the pipe (diameter, wall thickness, manufacture year and type, seam type, coating, etc.), construction/maintenance (nominal pipe length, replacement records, ILI data, etc.), operational data (temperature, pressure, etc.), and corrosion-related data (history of internal/external corrosion).
2) Select random sites for measurement along sample set. For non-homogenous sets, it may be necessary to sample every pipe.
3) ILI inspection to determine seam weld position and pipeline integrity at random sites.
4) Select entry and exit points of the pipe according to Explorer robot effective range.
5) Operational planning for inspection. If integrity assessment has been performed using Explorer, it may be advantageous to conduct the hardness testing immediately thereafter.
6) System deployment.

Deployment of Explorer with the hardness tester can be split into 5 distinct phases of operation (Figure).

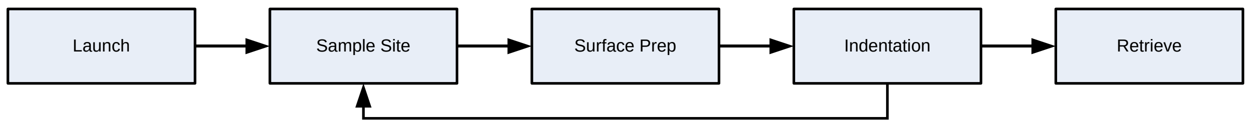


FIGURE 18: PHASES OF OPERATION FOR IN-LINE HARDNESS TESTING

Launch: The entire robot is loaded into a launch chamber, which is subsequently pressurized. The robot is then driven into the pipeline.

Sample site: The hardness testing module is driven through the pipeline features to a position designated during the pre-assessment phase (duration depends on distance between samples).

Surface prep: The pipeline surface is prepped using the wire brush wheel and sanded to remove the decarburized surface layer (duration: ~15 mins).

Indentation: 10 indentations are made on the prepared surface with photographs taken of each indentation. The operator can review the data and determine if the location needs to be re-prepped and measured with 10 more indentations. If any measurements are to be discarded following visual inspection (surface variation, debris contamination, proximity to other indents, etc.), then additional measurements may be taken to reach the necessary 10 measurements per site (duration: ~30 mins if the minimum of 10 measurements are taken; if more than 10 are needed, more time is needed).

The cycle is repeated until the necessary number of samples is completed.

Robot Retrieval: The robot is driven out through the designated hot tap into a waiting chamber. This hot tap can be the same as the launch location or at another location according to operational requirements.

Limitations

The following limitations are applicable to the in-line hardness tester as developed in this project:

- The system is currently targeted at pipe sizes of 20 – 26 inches in diameter.
- As the technology matures, the hardness testing module will be implemented in other platforms to cover the full-size range of Explorer robots, which is currently for pipes 8 – 36 inches in diameter.
- The reduced pipe wall thickness and higher curvature for Rockwell testing may be a constraint for the smallest diameter pipes.
- Very dirty pipes should be cleaned prior to testing.
- Liquid pipelines should be drained and dried.
- The system is not intended for pressures above 750 psig.
- Requires a pre-assessment for integrity and site selection

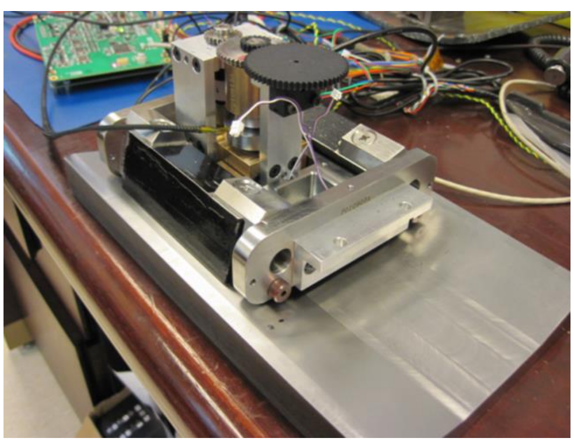
4. Testing

This section outlines the testing performed on the hardness tester prior to field testing. The module and drum were manufactured and assembled in InvoDane's laboratory. The unit underwent a bench test to ensure all motors and sensors were operating correctly. Minimal changes were required at this stage. The indenter was the last unit to be installed on the system, since it underwent its own bench testing steps.

The indenter module underwent bench testing using a special rig for calibration. The rig replicated the pipe curvature (for 20-inch pipe), which was built to hold calibrated hardness test coupons (Figure). The calibration coupons range in hardness from 60 - 95± 1 HRBW.

During testing of the indenter, it was found that on some (but not all) measurements the magnets had a tendency to release away from the rig as the indenter was loaded to 100 [kgf]. The mechanism was reviewed and was found to be very sensitive to contact alignment with the pipe wall. The original mount design used weak springs to ensure the indenter was in contact with the pipe wall after being rotated into place. These springs were replaced with stiffer die springs. The stiffer springs required additional force from the clamp actuator to position the indenter on the pipe wall. This pre-load is sufficient to eliminate any tendency the indenter had on releasing during measurement. The modification was successfully tested on the bench prior to integration with the robot.

ASTM E18 indicates (Table A1.3) that the indirect verification for Rockwell indenters 60 HRBW and above should have repeatability (R) of 1.5 HRB and an error (E) of ±1.0HRB. In order to verify the indenter developed in this project, each test block (from 60 – 95 HRBW) was measured more than five times. The results show the error within acceptable limits and the repeatability can be improved somewhat for 75 and 87 settings. With this in mind, the indenter was mounted to the module to evaluate the entire system together before making any changes.



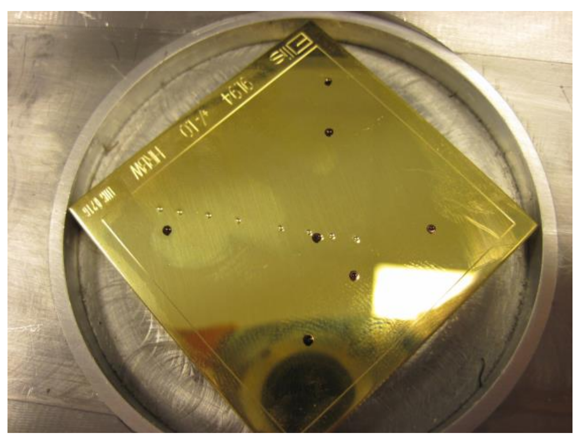


FIGURE 19: INDENTER ON CALIBRATION RIG (LEFT) CALIBRATION TEST BLOCK (RIGHT)

After initial verification, the indenter was installed on the hardness testing module along with the surface preparation elements. The unit was tested in an enclosed pipe (Figure 14) to evaluate the following:

- Wire brush behavior, wall contact positioning and motor settings (Figure 15)
- Sanding behavior including feed rate settings, power settings, and surface finish (Figure 15).
- Camera and lighting settings, resulting in adjustment to lighting intensity on wire brush and sanding motor cameras. (Figure 16)
- Clamp actuator tests, resulting in modification of slide clearance.
- Indent indirect verification and imaging. Installed onto the module, all indirect verification tests prior to field testing resulted in error and repeatability within the acceptable limits.
- Operational procedure definition.
- User interface adjustments based on operational feedback.
- Integration and overall system functionality aboard Explorer.

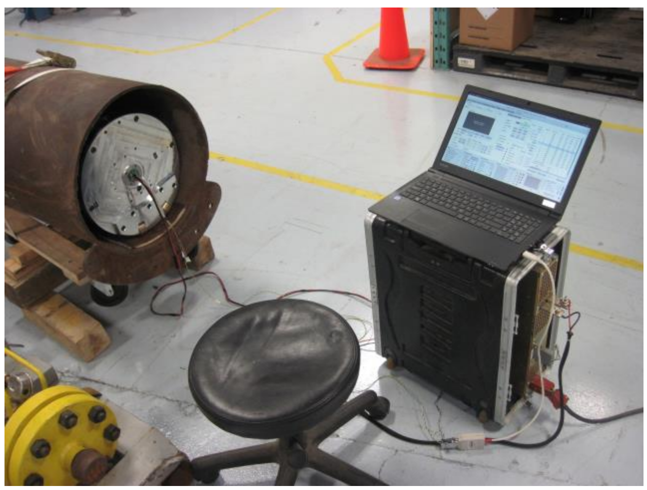


FIGURE 14: TESTING MODULE IN-PIPE

FIGURE 15: WIRE BRUSH TEST (LEFT) SANDING TEST (RIGHT)

FIGURE 16: INDENTATION IMAGE CAPTURE

5. Field Testing

The functionality of the hardness tester module was tested under field conditions according to the project goals. The testing was carried out at the NYSEARCH underground test loop in Johnson City, NY, on September 14, 2016. The test loop contains various pipeline features and configurations at pipe diameters of 20in and 12.75in. The section used in this test was part of the 20in segment and was 345 ft. long, containing multiple swept bends.

The measurement sites were selected based on prior inspection data that provided locations of pipe joints, seam welds and known areas of corrosion. The sites selected are shown in Figure 23. The first site is located approximately 6ft into the test loop. The second site is located immediately after the first swept 90-deg bend. The third site was located at approximately 113 ft. from the first swept bend and the last site was located at 194 ft., just prior to back-to-back 45-deg bends. The robot with the hardness tester prior to launching is shown in Figure 24.

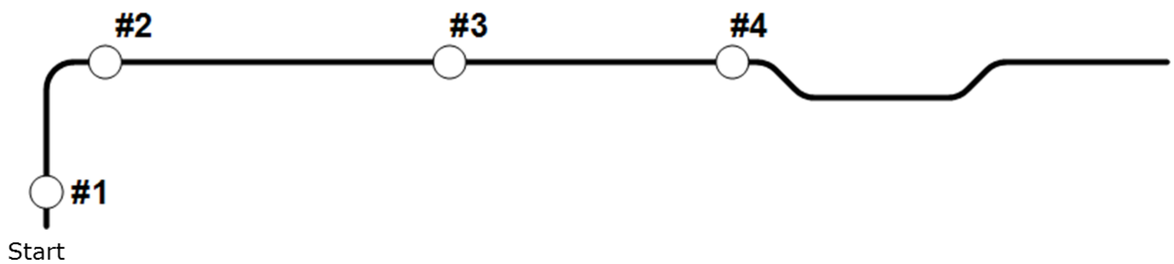


FIGURE 23: BINGHAMTON 20" TEST SECTION (BEFORE PLUG VALVE)

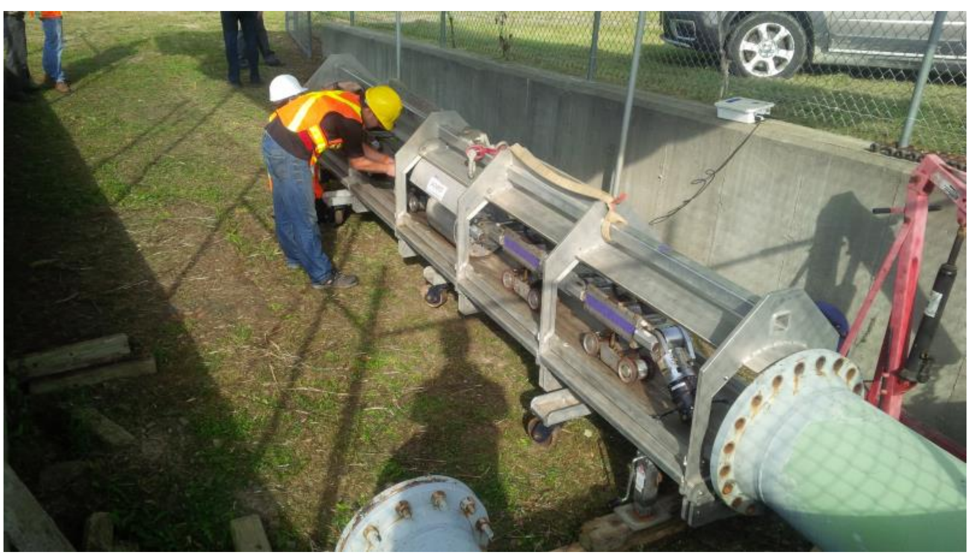


FIGURE 24: SENSOR ABOARD EXPLORER PRIOR TO DEPLOYMENT

Measurements at site #1 were completed per standard operating procedure and acceptable data was recorded. For sites #2 and #4 measurements were carried out with no issues; however, the field team had some difficulties centering the unit in the pipe for site #2. During preparation of the pipe surface in the wire brush and the sanding steps, the motor current was low, indicating that the unit was barely touching the pipe. Investigation of the reason for this indicated that the module was not properly aligned to the pipe wall, a result of the fact that the module had just gone through the 90-deg bend in the pipe (see Fig. 25). Repositioning and realignment of the robot helped somewhat, but no perfect alignment was obtained (this is an issue to be addressed in the immediate future so proper module alignment can be obtained under all operating conditions). Site #2 sensor readings were finally recorded. Due to operating concerns the fourth site was moved to an alternate location between sites #2 and #3, as shown in Figure 25. It is important to note that all sites were located on different pipe segments. The time to collect the measurements took between 45-75mins at each site.

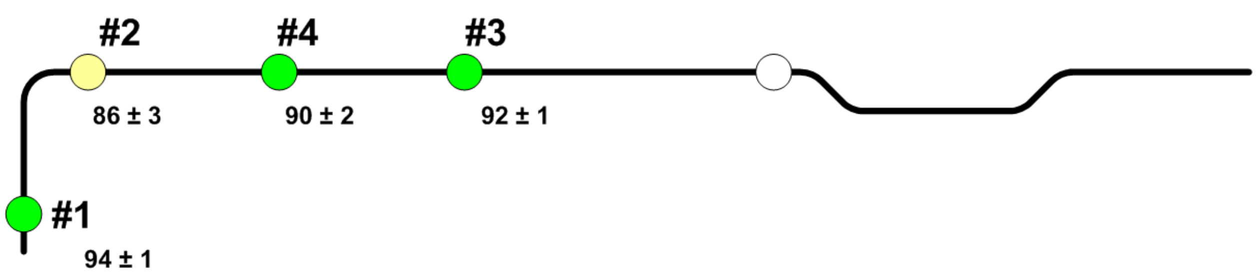


FIGURE 25: BINGHAMTON 20" TEST SECTION WITH FINAL TEST SITES AND RESULTS SHOWN

In general, it was determined that good results could be achieved in terms of repeatability and error, if the surface preparation went smoothly. An example of the indentation set can be seen in Figure and a macro image of the surface prep and indentation can be seen in Figure .

FIGURE 26: INDENTATION GROUP ON PREPPED SURFACE

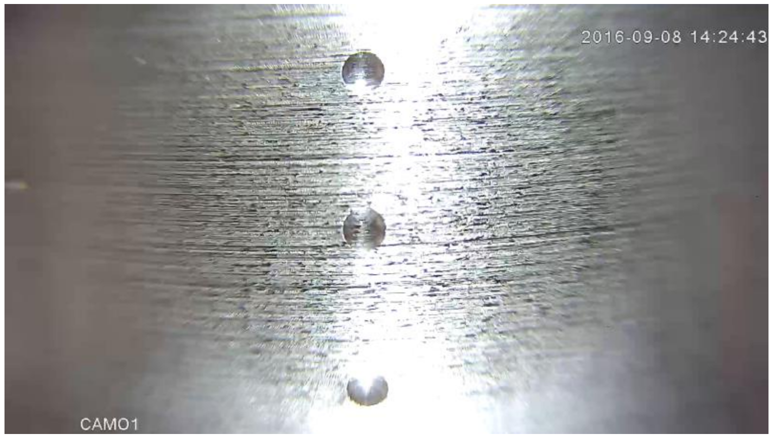


FIGURE 27: MACRO CAMERA OF INDENTATION IN PIPE

Readings for each of the four sites where measurements were taken are shown in Table . Sites #1, #3 and #4 have consistent readings within expectations for repeatability and error (COV and Range % are within 0.007 and 10% respectively, as called for by CRTD-91). It needs to be pointed out however that there seems to be a high variability of hardness values for the different segments of the pipe loop, since the values measured at sites #1, #3, and #4 were 94, 92 and 90 respectively.

Site #2 contains readings where the unit was not centered properly, and therefore the surface preparation and indentations were not lined up correctly. This can be seen in the comparison of indentations in Figure .

TABLE 4: RESULTS FOR HARDNESS MEASUREMENT

Measurement	Site #1	Site #2	Site #3	Site #4
1	94	85.5	91.5	88.5
2	95	89.5	91	92.5
3	95	92	91	92
4	94	86	91	91
5	93.5	83.5	91	89
6	94	89.5	92.5	88.5
7	93.5	84.5	89.5	88.5
8	94	85.5	94	89
9	94	81.5	92	89.5
10	94	85.5	93	89
Average	94.1	86.3	91.7	89.8
Standard Deviation	0.5	3.1	1.3	1.5
Range	1.5	10.5	4.5	4
COV	0.005	0.036	0.014	0.017
Measurement Range %	2%	12%	5%	4%

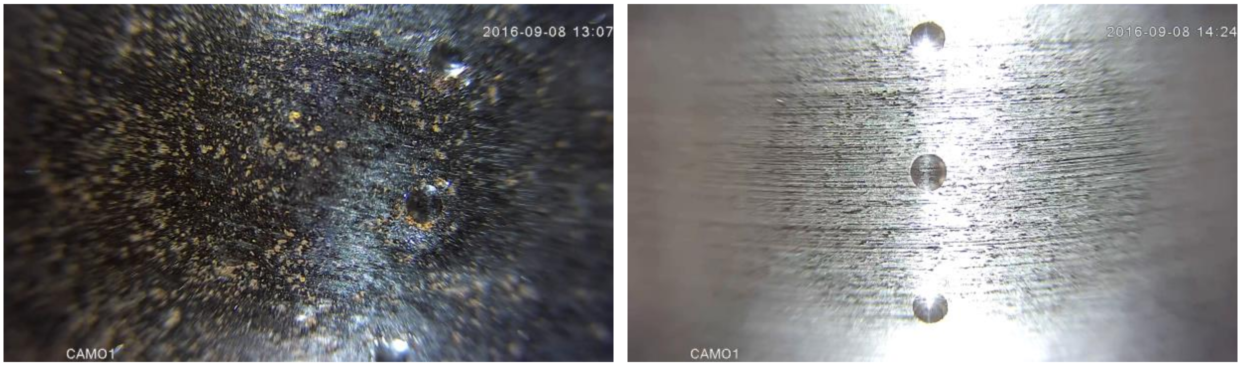


FIGURE 28: SITE #2 PREPARATION (LEFT), SITE 3# PREPARATION (RIGHT)

A section of the pipe loop was found at the site near the entrance point to the loop (left over from original construction of test loop) and was sent to a laboratory to provide a baseline on the actual pipe hardness. Results are shown in Table 5. Two samples were tested, one with a prepared surface and one with an unprepared surface. The prepared sample was tested to be 86±1 HRBW and the unprepared sample was tested to be 85±7 HRBW. Therefore, the readings taken from the test loop are 107% of the lab value which falls outside the target specification.

The discrepancy between the two values (lab value and in-pipe testing value) was analyzed further by taking more readings of the sample in various prepped conditions. One can see that the preparation affects the repeatability rather than the overall average value for the 10 measurements. All the measurements taken with three different hardness testers show the hardness value for this pipe sample to be 86 ± 1 HRBW. Very importantly, the value taken with the hardness tester on the Explorer module meets the CRTD-91 criteria for portable testers when compared to the lab value.

TABLE 5: SAMPLE MEASUREMENTS USING VARIOUS TESTERS

	Method	Prep type	Result [HRBW]
1	Lab	Wire brush	85 ± 7
2	Lab	Polished (200 grit)	86 ± 1
3	Portable	Wire brush	86 ± 1
4	Portable	Polished (200 grit)	85 ± 1
5	HT Module	Wire brush	87 ± 3
6	HT Module	Polished (200 grit)	87 ± 1

Based on the results from this sample of pipe found at the site near the entrance to the loop and the results collected from inside the pipe loop, the sample reading does not match the readings taken from inside the test loop. Most likely, the sample is not from the same type of pipe as those tested on sites 1, 2 and 4. It would be useful if more readings were taken from the actual buried pipe via removed coupons and laboratory testing to ascertain its hardness and compare to the in-pipe readings. In actual inspection scenarios, for newly tapped pipes, a coupon will be available from the hot-tap that can be send to a lab and provide a reference (laboratory grade) value for the hardness value and yield stress at that point of the pipeline.

In summary, overall the field testing produced the following input into the product development:

- The time duration for taking measurement at each site can be improved to achieve the target of completing measurements at two sites per hour, especially when collecting the images of each indentation. Rate of indentation is as fast as it can go based on timings required for proper indentation.
- Better feedback to the operator on module centering in the pipe will allow the unit to be deployed more reliably at designated locations in the pipe, greatly improving accuracy and repeatability.
- Further improvements in the Graphical User Interface (GUI) will allow faster commend-and-control and faster on-time data analysis, further reducing the time required to carry out the hardness measurements.

6. Project summary

Overall the project successfully implemented an in-line hardness tester for operation in live gas pipelines. The team engineered a solution that can remotely access the pipe surface under live conditions from the inside, prepare the surface for measurement, carry out the hardness measurement, and evaluate the result in real time. The team successfully deployed the system to collect hardness data during field testing. Hardness readings were collected with good repeatability at a majority of the sites. Comparison to known pipe samples (using laboratory testing and commercial portable hardness tester) has shown that the value predicted is within the specified accuracy for portable testers, thus further validating the tester developed. The testing carried out established that the preparation of the surface has a profound effect on accuracy and repeatability of measurements.

While measurements can be taken at any point along the circumference of the pipe, it is advisable to take measurements at the 3 o'clock and 9 o'clock positions so that interference from debris in the pipeline (typically found around the six o'clock position) is minimized and dust resulting from the sanding of the surface (during the surface preparation test) does not fall back into the module, potentially causing problems.

The system is currently applicable for pipe sizes from 20" – 26" but the concept can be further developed for pipe sizes from 8" – 36". Based on its present configuration the unit should be able to achieve an inspection pace of 1-2 locations per hour, depending on the distance between these locations. The next step is to complete the commercialization process and introduce the hardness tester to the market.

7. Project Intellectual Property

All intellectual property generated in this project is treated as Trade Secret. No intention to submit any patent applications exist at the time of submission of this report.

8. Acknowledgements

NYSEARCH/Northeast Gas Association and InvoDane would like to acknowledge and thank PHMSA/DoT for its continued support of R&D efforts to expand the capabilities of the Explorer family of robots. We also want to acknowledge and thank the NYSEARCH member companies for their continuing funding of R&D efforts to expand the capabilities of Explorer and for sharing their knowledge and expertise, which is instrumental in bringing this technology to market.

9. References

"Standard Test Methods for Rockwell Hardness of Metallic Materials" ASTM E18, 2016.

"Standard Test Method for Rockwell and Brinell Hardness of Metallic Materials by Portable Hardness Testers". ASTM E110, 2014.

Clark, E.B, Amend, W.E., Applications Guide for Determining the Yield Strength of In-Service Pipe by Hardness Evaluation, Final report, CRTD -Vol. 91,

Burgeon, D.A., Chang, O.C., et.al, Final Report on Determining the Yield Strength of In-service Pipe, CRTD - Vol. 57, ASME, December 1999