REPORT

U.S. DEPARTMENT OF TRANSPORTATION – PIPELINE AND HAZARDOUS MATERIALS SAFETY ADMINISTRATION

PIG MOUNTED TRIALS FOR INTERNAL CORROSION MONITORING FLUIDIZED SENSORS (PROJECT #277)

REPORT NO TAOUS811-EP00168

REVISION NO 2

DNV USA

PIG MOUNTED TRIALS FOR INTERNAL CORROSION MONITORING FLUIDIZED SENSORS (PROJECT #277)

Client:
U.S. DEPARTMENT OF TRANSPORTATION – PIPELINE AND HAZARDOUS MATERIALS SAFETY ADMINISTRATION

DNV USA
MATERIALS AND CORROSION TECHNOLOGY CENTER

5777 Frantz Road
Dublin, Ohio 43017-1386
U.S.A.
Tel: (614)761-1214
Fax: (614)761-1633
http://www.dnvcolumbus.com

Report No.:	TAOUS811-EP00168 Rev. 2	Subject Group:	
Indexing terms:			
Summary:			
Prepared by:	*C. Sean Brossia* *Head of Section – Technology Development*	*Signature*	
Verified by:	*Oliver Moghissi* *Head of Department – Corrosion and Materials Technology Center*	*Signature*	
Approved by:	*Oliver Moghissi* *Head of Department – Corrosion and Materials Technology Center*	*Signature*	
Date of issue:	10/10/2012		
Project No:	EP00168		

- [x] No distribution without permission from the client or responsible organizational unit (however, free distribution for internal use within DNV after 3 years)
- [ ] No distribution without permission from the client or responsible organizational unit
- [ ] Strictly confidential
- [ ] Unrestricted distribution

FINAL REPORT

Table of Contents *Page*

1 INTRODUCTION AND BACKGROUND 2

2 APPROACH 6

3 RESULTS AND DISCUSSION 7
3.1 Increase Knowledge of Cleaning Pig Use and Operations 7
3.2 Sensor Packaging Improvement and Pig-Mounted Sensor Design.......................... 8
3.3 Pig-Mounted Sensor Lab Testing.. 21
3.4 Meetings and Discussions With Pipeline Operators 29
3.5 Field Test of Cleaning Pig-Mounted Sensors 29

4 CONCLUSIONS AND TECHNOLOGY IMPLEMENTATION 29

FINAL REPORT

1 INTRODUCTION AND BACKGROUND

Internal corrosion of natural gas pipelines is the result of interaction between the inside pipe wall and impurities in the product (i.e., natural gas, liquid petroleum, refined products) being transported. Such interactions can lead to an overall loss of material thereby thinning the pipe wall and thus reducing the range of operating pressure. Corrosion, however, tends to be localized along the pipeline with some areas experiencing significant corrosion rates and others much less so. Part of the variability arises from both spatial and temporal differences in the composition of the transported product. For example, chloride-rich brines may be observed in segments of natural gas pipelines close to producing areas (i.e., carry-over of produced water), but condensed water are more likely further downstream (i.e., without chlorides). Some of the common corrosion inducing species includes carbon dioxide, hydrogen sulfide, water, salts (such as chloride), solids and precipitates, organic acids, and microorganisms. As a consequence of the wide range of possible corrosion inducing species, their inherent variability with both position and time within the pipeline, accurate inspection and determination of the true condition within the pipeline is difficult.

Over the last several years, the Pipeline and Hazardous Materials Safety Administration (PHMSA) attributes slightly more than 10% of all natural gas and liquids transmission pipeline accidents to internal corrosion. These incidents include some high profile failures involving fatalities, service/deliverability interruption, and environmental damage. Public safety concerns have provided the driving force for new regulations that require more robust and more frequent pipeline integrity assessments. There are currently three available pipeline assessment methodologies: (a) in-line inspection (ILI), (b) hydrostatic testing, and (c) direct assessment. Depending on the pipeline conditions, one of these methods will tend to be favored over the others. Provided sufficient justification, these methods can be substituted for each other depending on different factors.

In-line inspection (ILI) is capable of detecting internal corrosion. The ability of this technique to find corrosion flaws larger than a certain size (approximately 10 percent of pipe wall thickness) makes it extremely valuable for locating flaws before they become critical and cause pipeline failure (either leaks or rupture)). ILI methods include ultrasonic transmission and magnetic flux leakage. In these cases, the necessary instrumentation is mounted on a tool (pig) that travels inside the pipeline. ILI tools are 3.0 to 5.5 m (10 to 18 ft) in length. The ILI tools must be capable of readily passing through the pipeline and the sensors must be able to produce good contact (MFL tool) or stand-off from the pipe wall (UT tool). For these reasons, pipelines with large buckles, large dents, tight-radius bends, or valves that do not open fully are often difficult to inspect using pigs. That is, these lines might be unpiggable because the tool cannot fit through the pipeline.

Another well-known inspection technique is hydrostatic testing. This however requires a service interruption and has technical drawbacks as an assessment method (e.g., detecting leak without rupture). Another common method for inspection of internal corrosion is insertion of coupons into the pipeline. The main limitation with coupons is that they cannot always be placed at locations that are most likely to experience corrosion. In addition, they only provide a time-averaged indication of the rate of corrosion. That is, the corrosion that is observed on the coupon is assumed to have occurred over the entire time the coupon is in place, when in reality the corrosion may have occurred only during a very short duration giving rise to a significant underestimation of the corrosion rate.

Internal Corrosion direct Assessment (ICDA) was developed for wet and dry gas and liquid hydrocarbon transmission lines. For pipelines that normally carry dry gas but may suffer from short term upsets of liquid water, the ICDA methodology relies on established multiphase flow principles to predict locations of water accumulation. For these nominally dry gas lines, a simple correlation was developed that calculates the critical angle of inclination for water accumulation that can be compared to the actual angle of inclination of the pipe (measured by digital elevation data and depth of cover). Once critical angle sites are identified, the pipe is excavated and one or more direct examination techniques (e.g., ultrasonic inspection) are used to determine whether internal corrosion is present. This is illustrated in Figure 1.

Because of the uncertainties related to ICDA and constraints making some pipelines un-piggable in the traditional sense, other technologies and alternative methods for pipeline inspection have been examined. In a previous PHMSA funded research project, prototype small wireless sensors that can travel inside the pipeline were developed. These sensors took advantage of recent advances in computational and wireless communication technologies. This concept is illustrated in Figures 2 and 3.

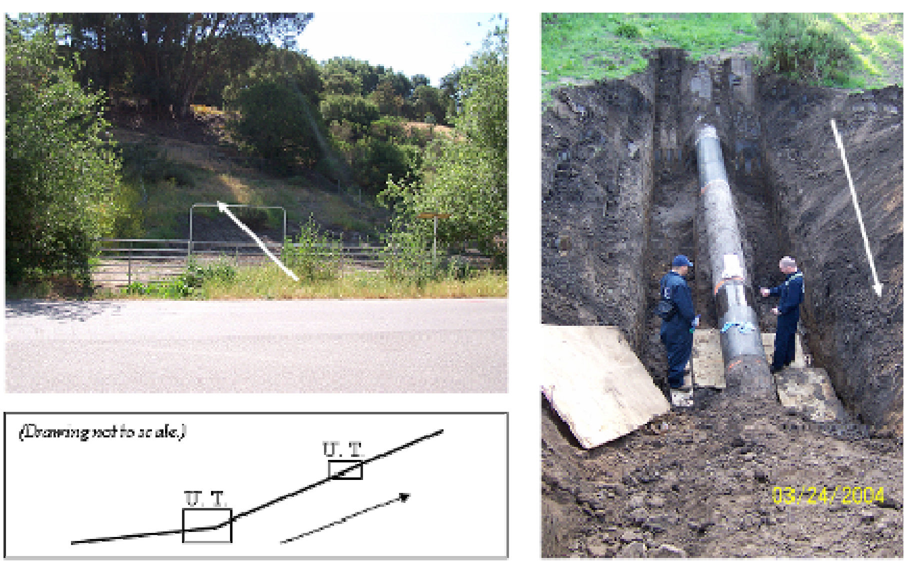

Figure 1. Uncertainty in the extent of pipe to be excavated for ICDA

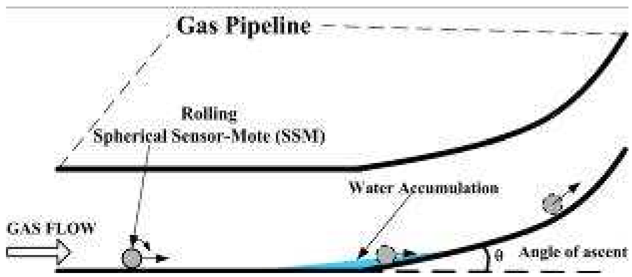

Figure 2. Illustration showing fluidized sensor motion

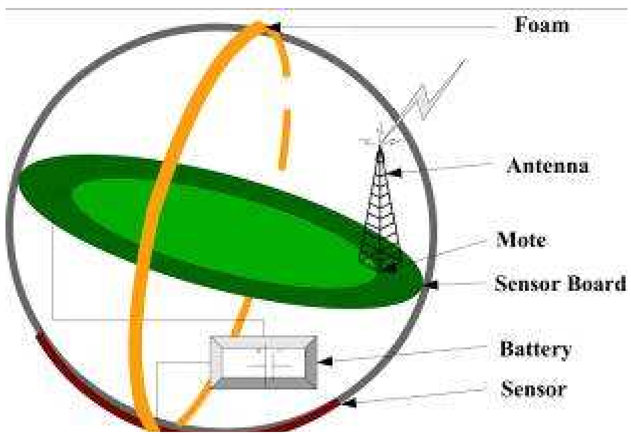

Figure 3: Illustration of spherical sensor.

The approach taken in previous research was to develop and evaluate a sensor platform that could detect water accumulation, provide its approximate location along the pipeline, and estimate the corrosivity of any liquids found. To accomplish this, a spherical sensor system was been developed and evaluated that consists primarily of a microprocessor with wireless communications capability and a corrosivity or corrosion rate sensor and is in the form of a small sphere (~1.5" diameter) that behaves fluid dynamically similar to entrained water in a gas stream.

During the course of the previous research project, two operational conceptual design alternatives emerged based on pipeline operator inputs. The first, which was the original intent of the project, was to create a "leave in place" sensor system. In this configuration, multiple sensors will be injected into a transmission pipeline to monitor for water accumulation at a specific location of interest (e.g., road crossing, critical incline, etc.). A schematic diagram of this configuration is shown in **Error! Reference source not found.**. As part of the internal corrosion monitoring scheme, the sensors will be injected upstream of the location of interest (preferably within 300-1000'; likely closer). Once on station, the sensors would be left in place for a period of up to perhaps several years. Once the sensors were no longer functional, the plan would be to use a cleaning pig to sweep them out.

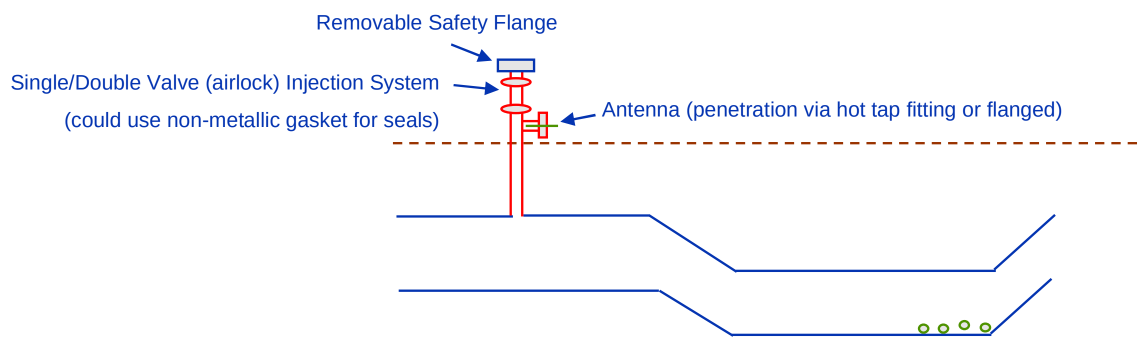

Figure 4: Schematic of "leave in place" configuration.

The second configuration design concept that was envisioned was a “once-through” type system. In this configuration, a mobile version of the sensor system would be used. These sensors will be injected upstream of a location of interest and would flow to a suitable location downstream. Between the injection and retrieval points, the sensors would be continually flowing, collecting data, and storing the data in memory, which will be accessed after completing the run. A schematic diagram of this arrangement wherein the sensors would be collected at a downstream drip is shown in **Error! Reference source not found.**.

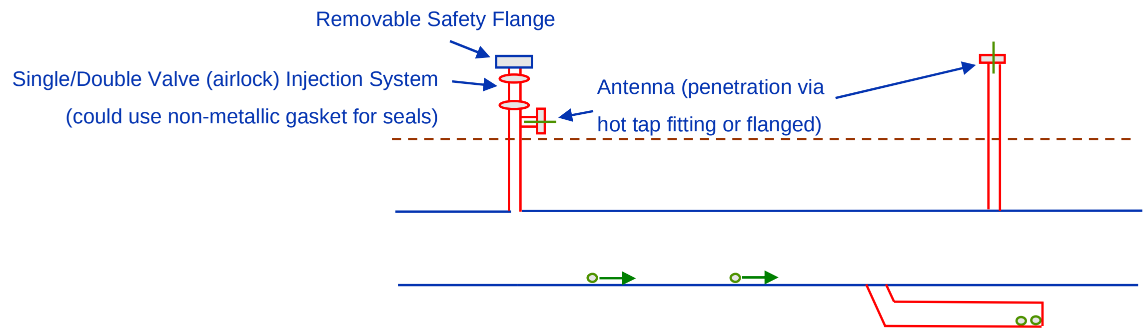

Figure 5: Schematic diagram of flow through field validation test on gathering line using a drip to collect the sensors.

In order to develop these methodologies, the previous research project set out to test and evaluate each of the component technologies. In the tests, each of the component technologies and concepts were successfully demonstrated. Several fully functional prototype systems were been constructed and evaluated thereby going a long way towards validating the technology.

Even though much has been accomplished and the sensor systems have been successfully validated in the flow loop tests, some challenges still remained for full industry acceptance and adoption. Based on input from pipeline operators when this technology was evaluated included:

- Installing sensors on a cleaning pig for first field trial – It was suggested that this be viewed as an intermediary step prior to injection of the sensor balls directly into the pipeline. Thus, the next set of field validation trials should involve installing the sensor systems onto a set of cleaning pigs. The reasoning being that the pigs are already approved for use in pipeline systems and already have multiple components and systems on them so adding one more should be straight forward. Once a few successful runs with the sensors installed on pigs has been demonstrated, it would then be an easier step to then take them off the pigs and run them as independent sensor balls inside the pipeline.
- Improvement of sensor systems and packaging – In the previous research project, the epoxy adhesive used to attach the thin film corrosivity/water detection sensors to the balls appeared to be softened when exposed to mineral oils and liquid hydrocarbons. Alternative approaches needed to be examined.

Thus, the goals of the present project were to examine alternative packaging designs and ultimately to conduct an evaluation of the sensor concept mounted on pigs or cleaning pigs.

2 APPROACH

The overall approach in the present project was to develop and evaluate the possibility of mounting/connecting these sensors onto cleaning pigs in order to improve industry confidence and acceptance. In addition, the selection of testing on cleaning pigs also addresses a technical need for the pipeline industry. At present when hydrotesting is conducted, cleaning/de-watering pigs are run to remove the hydrotest fluid. Any residual hydrotest water can result in a future internal corrosion integrity threat. As a result, several de-watering pig runs are often conducted after completion of hydrotesting. The effectiveness and total number of de-watering pig runs that are needed is uncertain. Thus, operators tend to be conservative and may conduct more de-watering runs than are necessary.

Thus, in this project four main tasks were conducted:

- Increase knowledge of cleaning pig use and operations
- Revise packaging design to ensure mechanical robustness and effective sealing
- Develop pig-mounted sensor system and conduct laboratory tests
- Meet with operators to discuss technology
- Conduct field trial of pig-mounted sensor system

3 RESULTS AND DISCUSSION

Over the course of the project, efforts were aimed at five principal activities:

- Increase knowledge of cleaning pig use and operations: meet with operators to understand potential applications for sensors mounted on pigs and cleaning pigs
- Improvement and evaluation of packaging and pig-mounted sensor design: to enable wireless communications, the sensor package cannot be constructed from a metallic sphere; thus an examination and design of polymeric spheres that could withstand pressures > 1,000 psi was needed; need to improve on previous designs that experienced some leaking; in addition, approaches to mounting the sensors on a cleaning pig needed to be developed
- Laboratory tests of pig-mounted sensors: conduct laboratory tests of pigs with sensors and improve until functioning prototype exists
- Interactions and discussions with operators: interact and meet with pipeline operators about technology; present technology at different meetings; get buy-in for field trial
- Field tests of pig-mounted sensor system: conduct field trial with sensors on cleaning pig

Each of these activities is discussed below.

3.1 Increase Knowledge of Cleaning Pig Use and Operations

DNV, ExxonMobil, and BP staff held several meetings and phone conversations on cleaning pig use and design. The discussion resulted in increased awareness regarding general applications and use of cleaning pigs by operators, the favored types of cleaning pigs based on past experience of pipeline operators, and the different possible methods of incorporating the sensor onto cleaning pigs.

Based on the discussions, it was decided that focusing on mandrel pigs normally used in cleaning and dewatering applications would be a logical first step. The mandrel pig is a good choice because its stackable-disk geometry offers flexibility of sensor placement and it is the preferred pig of the operators. The sensor can be place in front of the pig, incorporated into the pig, or placed between two pigs. These scenarios are depicted in Figure 6.

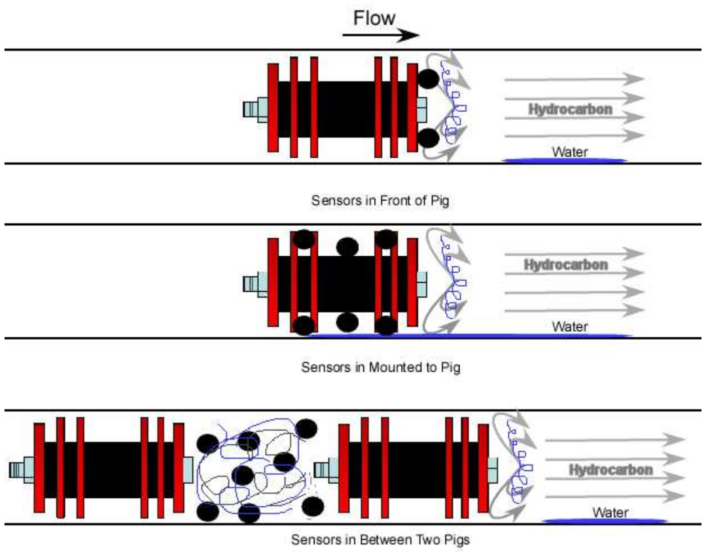

Figure 6: Schematic diagram of different possible pig-sensor combinations.

The environment in front of the cleaning pig travelling through a product-filled liquid or gas pipeline can be a turbulent mixture if sufficient liquid volume exists. Based on results from previous PHMSA research, the sensors should be able to determine the presence of water and its corrosiveness using any of the configurations shown in Figure 6. To verify this, tests were conducted in the laboratory under different flow conditions, water cut (in the case of a liquid hydrocarbon pipeline) and other variables. These results are presented in Section 3.3 below.

3.2 Sensor Packaging Improvement and Pig-Mounted Sensor Design

The sensor packaging design must follow these guidelines and functional requirements:

1) Protect the electronics as they propagate through the pipeline,
2) Be of spherical shape for efficient flow,
3) have a mass of ~20 grams to meet the mass requirements for fluid flow calculations,
4) Be transparent to E-M communication,
5) Survive the pipeline environment for typical run duration of 4 hours.
6) Be cost effective for a disposable product.

FINAL REPORT

In previous research, the sensor packaging experienced some integrity issues related to impact survivability and dissolving of epoxy seals. In both cases, catastrophic failure of the packaging resulted with either the sensors breaking or the electronics getting wet and shorting out. In the present work, two alternative approaches were explored:

1. Replacing the epoxy joining the two hemispheres of the sensor ball with mechanical fasteners and an o-ring seal.
2. Incorporating the sensors directly into a mandrel pig.

A photograph of a sensor that is joined using mechanical fasteners is shown below. The design shown contains the same internal elements as the previous sensor.

Figure 7: A photograph of an alternate packaging design using mechanical fasteners.

Several attempts were made using the sensor packaging design shown in Figure 7. In this design, an o-ring seal was combined with mechanical fasteners (bolts and nuts) in order to create an effective sealing system. This approach, however, was found to not provide the robustness needed to withstand multiple impacts that the sensor would encounter when used in service. In addition, this approach proved to be ineffective at pressures above approximately 400 psi at which point leaking occurred.

Alternative approaches using both Teflon and polycarbonate spherical assemblies with differing wall thicknesses were then tried. Different sealing surface geometries were also attempted, including threaded joints, threaded joints that included a base o-ring gasket, epoxy sealed joints, silicone sealed joints, and other combinations of the above. Photographs of different test systems are shown below. Initial testing of these approaches showed that they could withstand impacts as well as high pressures. Manufacturing the two halves of the sensor housing to have mating threads provided a strong mechanical integrity platform. Then combining this with the different sealing methods of o-rings and other seals provided a viable packaging option.

Figure 8: Photo of duplicate Teflon package trials using threaded connection and gasket. Note water inside.

Figure 9: Photo of thin wall Teflon package that failed due to deformation at 1000 psi.

Because of uncertainty regarding the location of possible leaks (i.e., is the leak at the main thread joint or is it from the sensing elements and leads), another set of tests was performed that included a red dye in the water. Four main combinations were examined in this test:

1. Main joint sealed with epoxy
2. Main joint sealed with silicone
3. Sensing element leads sealed with epoxy
4. Sensing element leads sealed with silicone

Results from some of the tests are shown below. Note that in these tests only two sensor elements were mounted on the package housing. Because the tests that were performed were destructive, it was decided to limit the number of sensor elements that would be destroyed. Thus, only a single sensor element in each hemispherical half was installed. In practice, multiple sensor elements would typically be used in each half to maximize the resolution and sensitivity of the sensor ball.

Figure 10: Photo showing that dye is inside the sensor package after testing at 1000 psi indicating a leak at the main seal.

Figure 11: Photo showing no dye inside sensor package after testing to 1000 psi indicating that the main joint was effectively sealed.

Based on the testing conducted, two viable packaging options are available. For low pressure systems (~ 500 psi), a Teflon based design using threaded joint, a gasket, and silicone is effective and functional over long time periods. To withstand higher pressures, the wall thickness necessary for Teflon results in the sensor ball being too heavy for effective flow and movement. Thus, a polycarbonate design using a threaded, gasketed, and sealed joint was evaluated and found to function well over long time periods.

Additional testing showed that using small wires bonded to the sensing element that is then bonded to the spherical package resulted in poor performance. Shown below is a photo of damage that was noted after testing. Based on several iterations of sensing element packaging, testing has shown that the incorporation of the sensing element in a Teflon or polycarbonate plug that is then bonded to the sphere produces results that are superior to those observed when the wires/leads penetrate the package and are then bonded externally.

Figure 12: Photo of sensing elements after testing.

FINAL REPORT

Several attempts were made using both Teflon and polycarbonate spherical assemblies with differing wall thicknesses. Different sealing surface geometries were also attempted. These included threaded joints, threaded joints that included a base O-ring gasket, epoxy sealed joints, silicone sealed joints, and other combinations of the above. The final identified and tested solution is a heavy wall Teflon sphere that combines epoxy, silicon sealants, and threaded O-ring joints. This configuration withstood both deformation and leak testing at pressures up to 1500 psi for a period of 3 weeks. Several pre- and post-test photographs of the tested packages are shown below. In all cases, package evaluation was conducted using six separate, identical replicates. Replicates were used to help give confidence in the results obtained. In this final configuration, all six replicates passed all aspects of the testing.

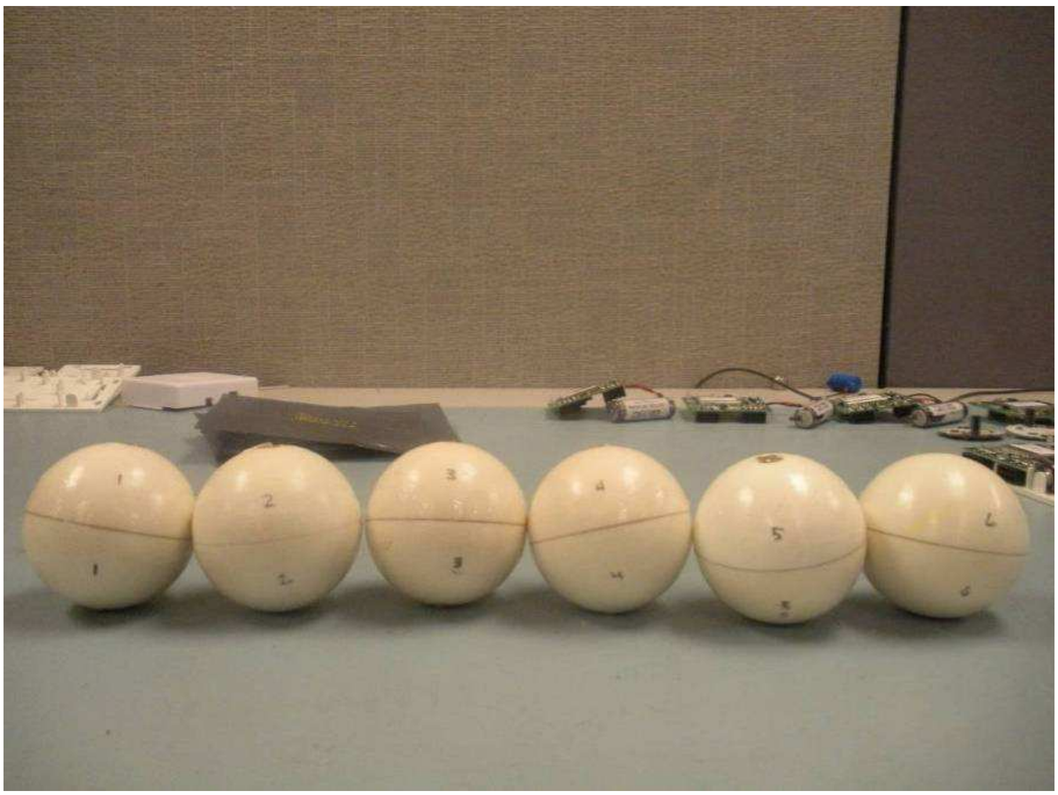

Figure 13: Photograph of six replicates used for packaging final design evaluation.

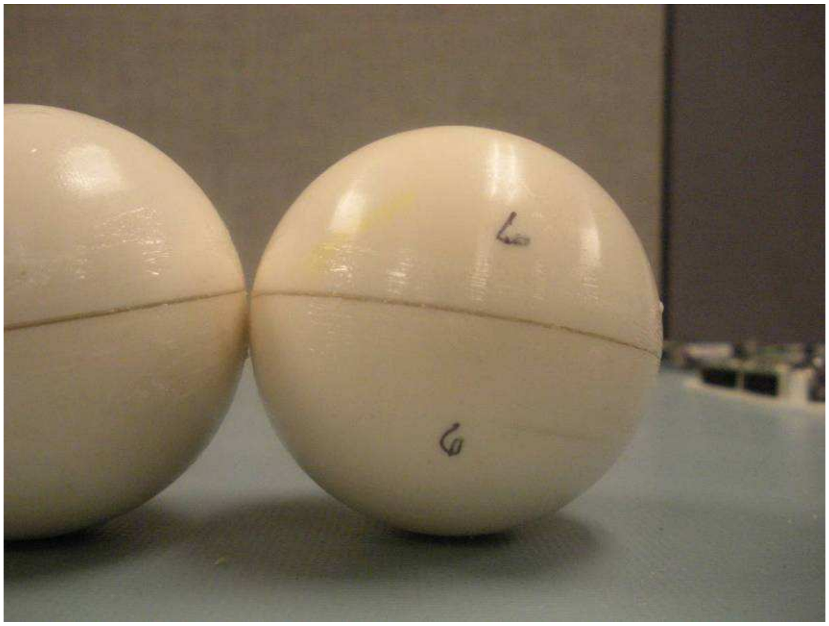

Figure 14: Close up photograph of replicate #6 prior to testing the final packaging design.

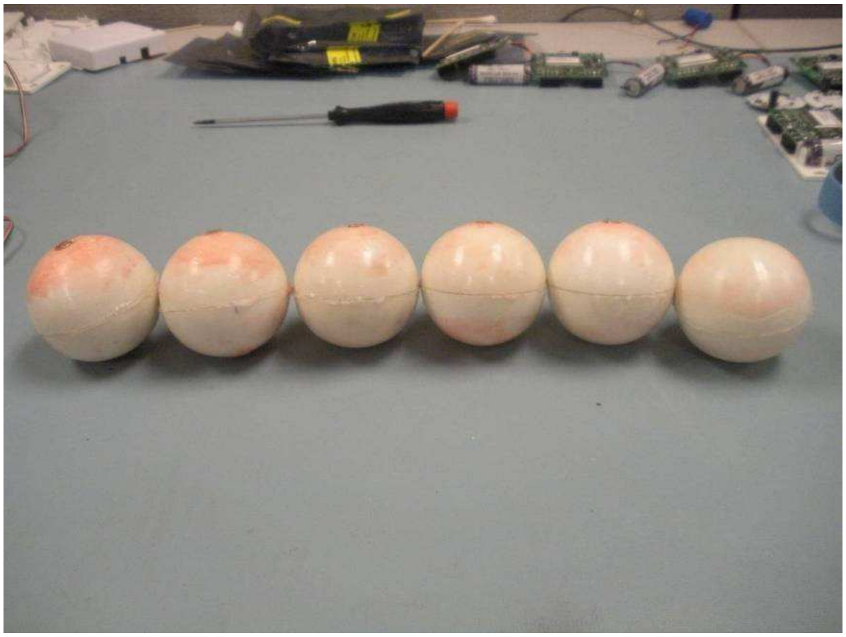

Figure 15: Post-test appearance of all six replicates for final packaging design. Note that the red color is from the dye used to facilitate post-test leak inspections.

Figure 16: Close up appearance of replicate #6 after testing. Note that the red color is from the dye used to facilitate post-test leak inspections.

Figure 17: Post-test interior inspection of replicates 1-3. Note that no red color is evident inside the package indicating that no leaks occured.

The current package design was evaluated for the non-pig mounted sensor configuration, as it is more complex and challenging to ensure proper sealing and pressure resistance. For the pig

FINAL REPORT

mounted version, the sensing elements on the ball surface are replaced by sensing elements on the pig itself. The electronics and packaging used are identical for both applications. In the original pig-mounted configuration, the sensing elements were mounted on the pig face as shown in Figure 18. The sensing elements are the same concept as those used for the ball sensor version and consist of an interdigitated array. When liquid is not present, the resistance between the elements of the interdigitated array is infinite (practically speaking it is on the order of several GΩ). When any sensing element encounters liquid, a short develops across the array that then reduces the resistance. As shown in previous research, the resistance measured is a function of the composition and nature of the liquid. However, these thin film sensors can become easily fouled and in general do not have a long life. As a result, an alternative more robust design was created.

The new sensing head design is based on creating a circumferential ring around the front face of the pig rather than making measurements at four discrete locations (Figure 18). The operating principles of the new head design are illustrated in Figure 19 – 23. In this new design, the resistance of the entire ring is monitored. The ring is composed of alternating segments of steel and non-conductive polymer. Each steel element is connected to the next steel element via a 100 kΩ resistor. Using a resistor of this size enables the elements to remain essentially isolated from each other until a conductive liquid (condensed or entrained water) creates a short. Once the short is created by the presence of the water, then the effective resistance decreases. The final installed ring on the front of the mandrel pig is shown in Figures 24 and 25. The ring is electrically connected to the electronics by passing through the annulus of the mandrel pig (as was done in the original design). The electronics are housed in the spherical package mounted in the rear of the pig.

Figure 18: Front face of cleaning mandrel pig showing sensing elements at the 3, 6, 9, and 12 o'clock positions.

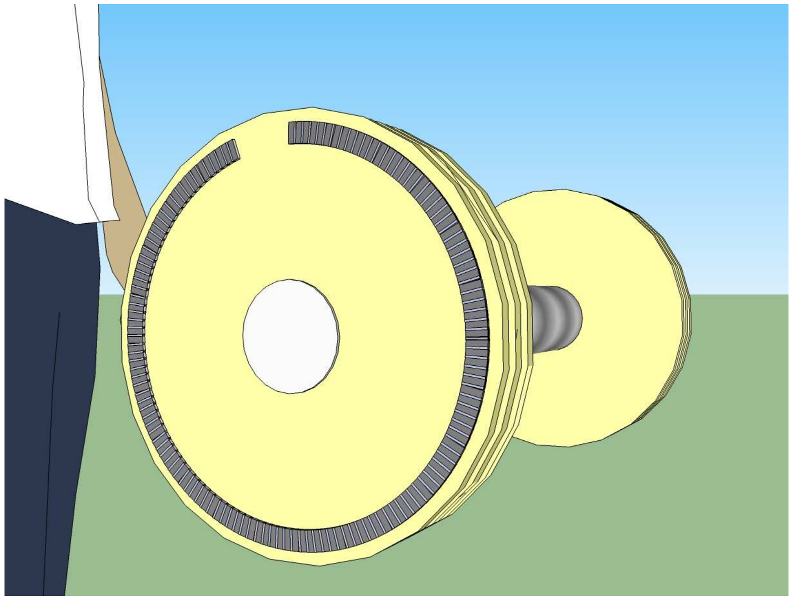

Figure 19: Schematic drawing of improved sensing head design.

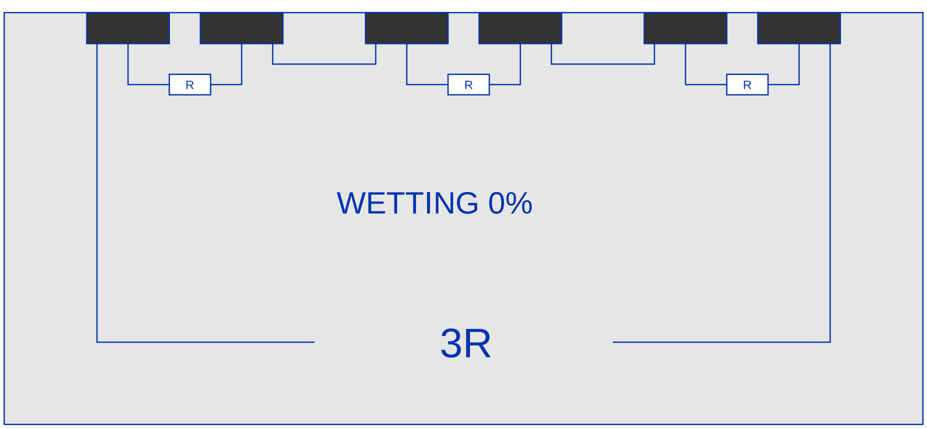

Figure 20: Schematic illustration of the operating principle of the improved sensing head design when no liquid is present.

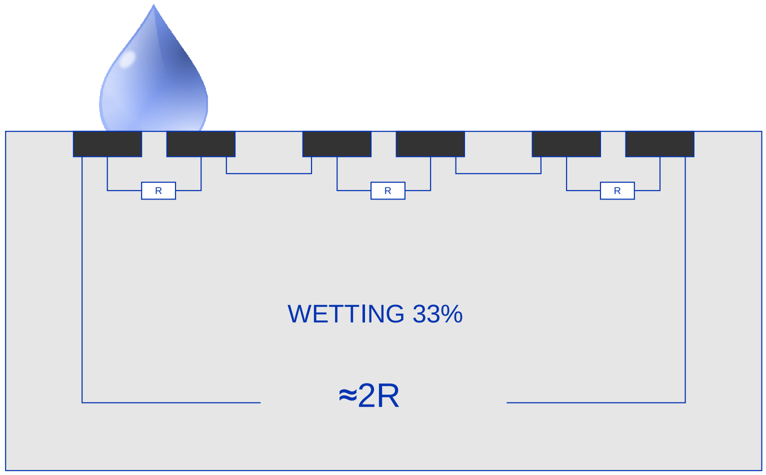

Figure 21: Schematic illustration of the operating principle of the improved sensing head design when enough liquid is present to create a short across only a single set of the elements in the head.

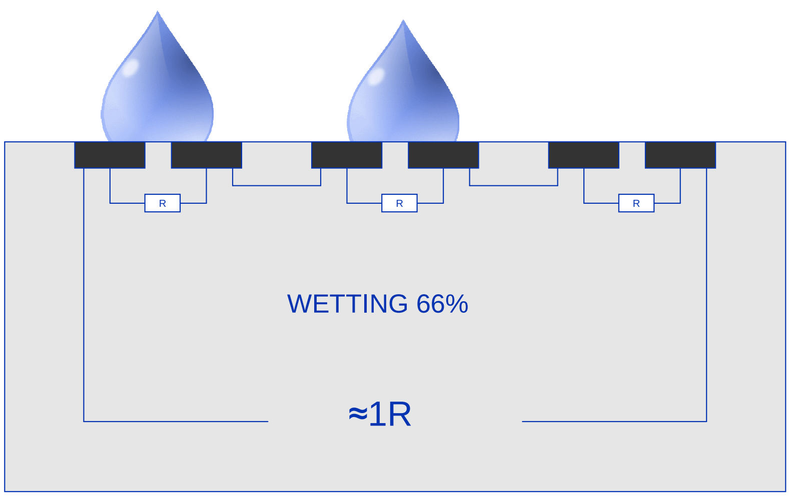

Figure 7: Schematic illustration of the operating principle of the improved sensing head design when enough liquid is present to create a short across only two sets of the elements in the head.

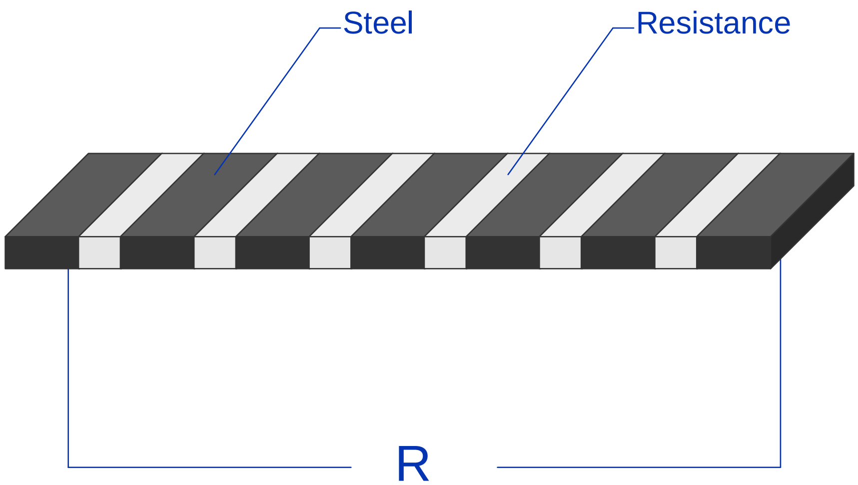

Figure 23: Overall conceptual design schematic of sensing ring.

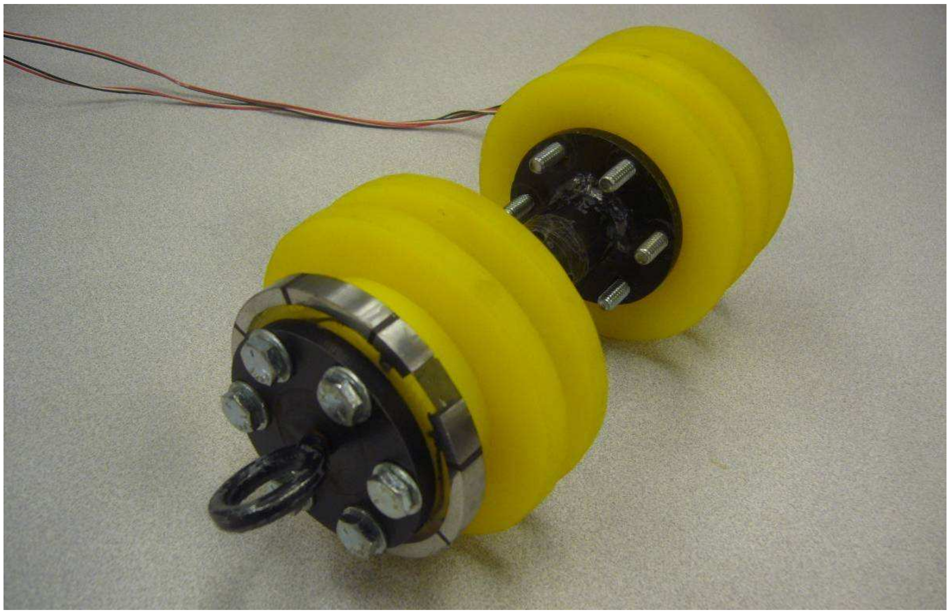

Figure 24: Overall view of the new pig. The metallic ring in the front is the new sensing element.

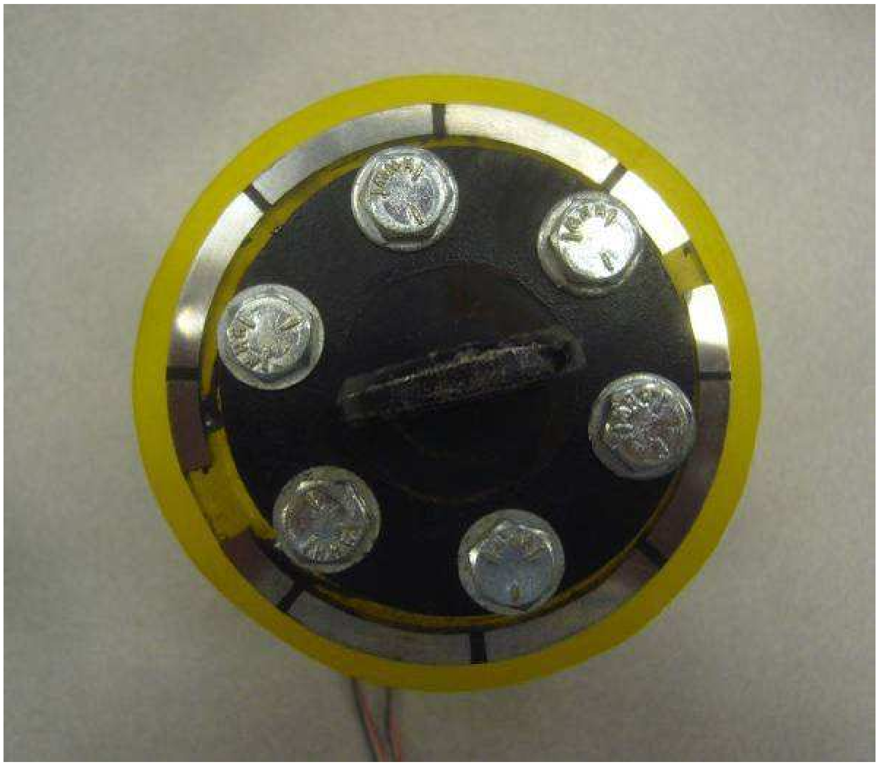

Figure 25: Photograph of front face of the mandrel pig showing the sensing head.

A series of test runs with the modified pig design were conducted in mineral oil with different water cuts. The water contained 0.5 wt% NaCl to try to represent produced water. The results for replicate runs at different water cuts are shown in Figure 26. As can be seen, the replicate runs show very good agreement in resistance measurements. Furthermore, the improved design also demonstrates that differences in water cut can also be determined. Tests using the previous head design showed only a marginal ability to detect differences in water cut (as will be discussed in Section 3.3 below). Thus, the new sensor design provides sensitivity to distinguish between water and liquid hydrocarbons and mixtures in between with a resolution of a few percent. The capability to detect the percent water cut was identified as of key interest by pipeline operators.

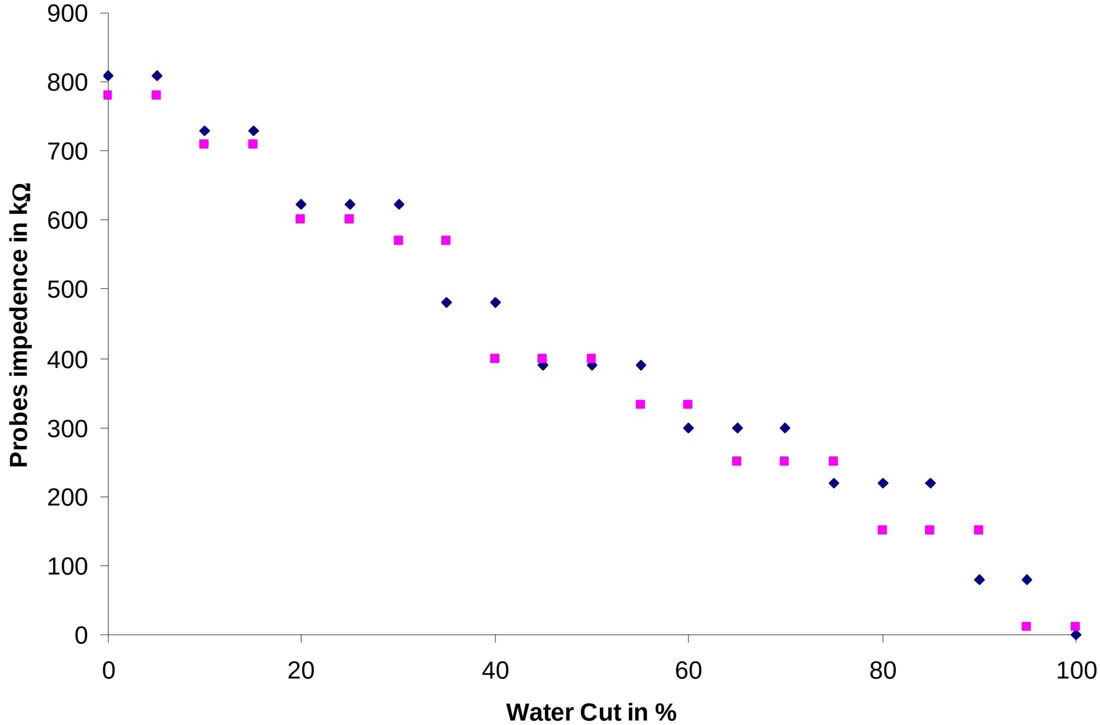

Figure 26: Evolution of the total impedance function of the water cut (original experiment in blue, repeat in pink)

3.3 Pig-Mounted Sensor Lab Testing

A series of lab test runs were conducted using mandrel-type de-watering pigs with sensors. Ideally, this system would have sufficient sensitivity to distinguish between different water cuts at approximately 10% resolution. That is, to what percent water cut accuracy (e.g., 10% increments) can the sensors distinguish. Since it is expected that a mixture of liquid hydrocarbons and water may exist to some degree even in gas pipelines, it is important to be able to determine the relative amount of water present. Irrespective of the accuracy of the water cut measurement, determining if a pipe is completely dry or contains condensed or accumulated water from operations or left over water from hydrotesting is important to operators.

DNV focused on mandrel pigs normally used in cleaning and de-watering applications for the lab-scale evaluations. The mandrel pig is a good choice because its stackable-disk geometry offers flexibility of sensor placement and it is a preferred pig design used by pipeline operators. The lab-scale tests using the mandrel pig were conducted in an outdoor, 100’ long, four-inch diameter acrylic pipeline. The aboveground pipeline was constructed using 5’ long acrylic pipe sections connected by rubber couplings. The beginning and ending pipeline sections are four-inch diameter stainless steel pipes approximately 5' long. The stainless steel sections are in place to minimize damage to the acrylic during pig launching and receiving. In some tests water or a water-hydrocarbon mixture was placed immediately in front of the pig prior to testing. In other tests, two specific locations, at 28 – 34 feet and 54 – 62, were selected for liquid accumulation and the pig then pulled through these locations.

Initial lab-scale testing consisted of incorporated four sensors into the leading disk on the mandrel pig as shown in the figures below. Figure 27 is a photograph of a sensor-equipped pig. The photograph shows the mandrel pig, a collection of wires coming from the back of the pig, and the data acquisition / communication (DAQ / COMM) module. The DAQ/COMM module is a hollow acrylic sphere that opens into two halves. The Aginova electronics inside the sphere measure the sensor outputs and transmit the data wirelessly to a nearby to a laptop computer via wireless router.

Figure 28 is a photograph of the leading disk on the mandrel pig. Sensors are embedded in the disk at approximately ninety-degree intervals about the disk circumference, and positioned near the bolted flange rather than close to the disk edge. Each sensor has two electrically isolated traces printed on the surface. A voltmeter was used to test sensor function following assembly. The sensor was functioning properly if the voltmeter read open (or infinite) resistance when the sensors were dry. Copper traces were chosen for the lab scale testing, and may be changed to a different metal or alloy in the future, if necessary. The wiring for each sensor was routed through the hollow center of the mandrel pig. The wires exited the pig through four holes drilled in the rear flange.

Figure 29 shows a sensor-equipped pig travelling through transparent acrylic pipe during a test. Several labeled white arrows are present in Figure 29. The white arrows point to the water source, the instantaneous position of the DAQ/COMM module, the direction of movement of the pig, the visible sensors, and the swept water in front of the pig inside of the pipe. The water source is a ¼" diameter rubber hose fed by a peristaltic pump operating at approximately 50 mL per minute. The pig is travelling through the pipe at approximately 5 meters/second, or about 11.5 miles per hour. The test was filmed using a high-definition digital camcorder that has the capability to save still screen images during playback.

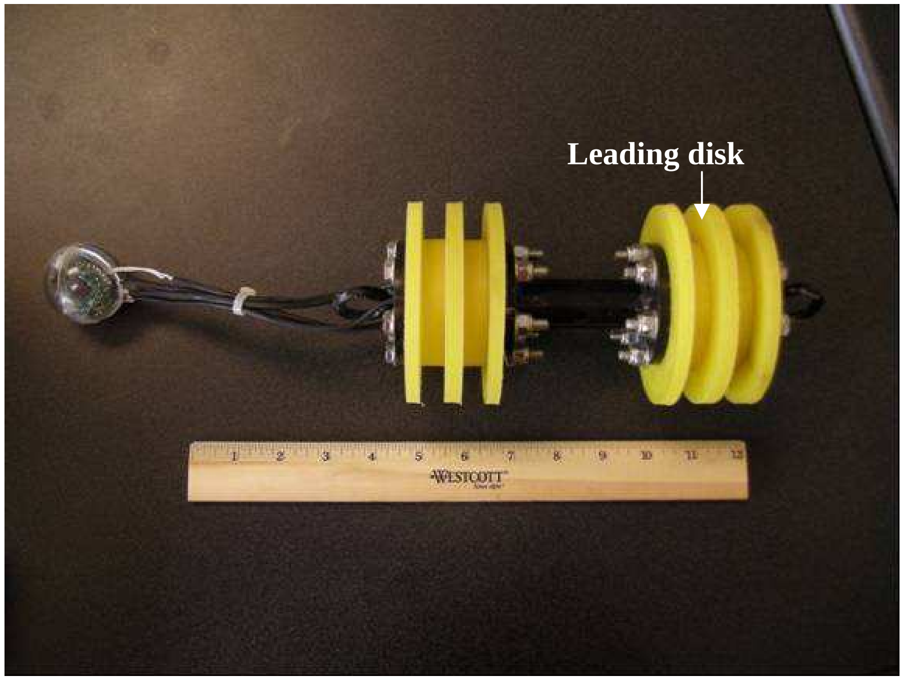

Figure 27: Photograph of mandrel pig with tethered sensor ball attached.

.

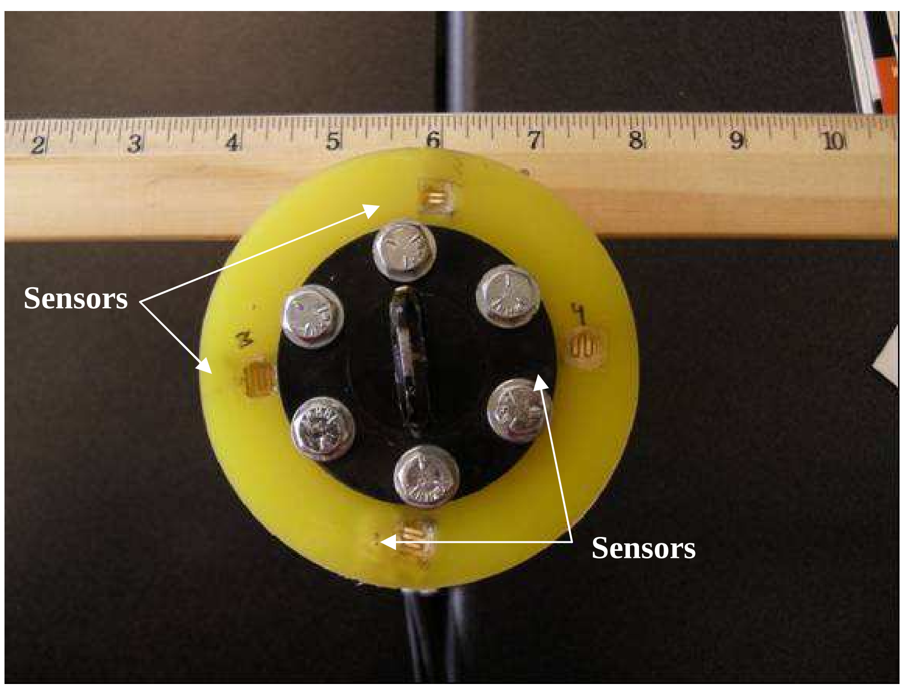

Figure 28: Photograph of front face of the mandrel pig showing water detection sensor installation locations.

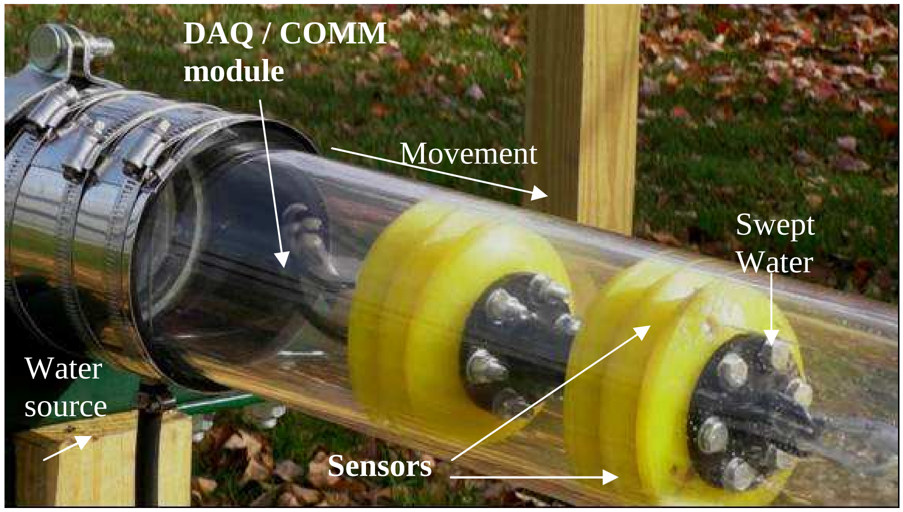

Figure 29: Photograph of pig trial run.

The water cut (WC) analysis was initially performed using two sensor configurations on the pig. The configurations were:

1. Use one sensor to collect AC impedance (Z) and DC resistance (DC) data as the pig traveled through different water-oil emulsions.
2. Use two independent sensors separated by approximately two inches in several oil-water emulsions. One sensor was used as the working electrode and the other sensor was used as the counter electrode.

The water phase in the WC analysis contained 5 weight percent sodium chloride to represent produced water. The oil phase was LVT-200 mineral oil. The water cut was varied in ten percent increments from 0% WC (no water phase present) to 100% WC (no oil phase present).

The results of the water cut analysis using DC measurements showed that the technique cannot be used to determine water cut. The data were strongly affected by the presence of liquid hydrocarbons in which the hydrocarbon created a film on the sensor element that then was not easily displaced. As a result, the sensor detected either an open circuit (> 1GΩ resistance) in the range if 0% WC to 40% WC or very high impedance values for higher WC values. As a result, this approach was not investigated further.

The results of the water-cut analysis using an AC induced signal are shown in Figures 30 – 35. Analysis of the AC impedance data indicated that the sensors can determine the difference between 0WC, 10% WC, 20% WC, 50% WC, and 100% WC at frequencies below 900 Hz. The magnitude of the impedance did not vary significantly between 20% WC and 40% WC using the initial sensor design. Because the sensor elements of the original design are small, it was easy for them to become oil-wet thereby making subsequent measurements suspect and challenging to obtain accurate information. At this point, the alternative ring approach discussed in Section 3.2 was developed and tested.

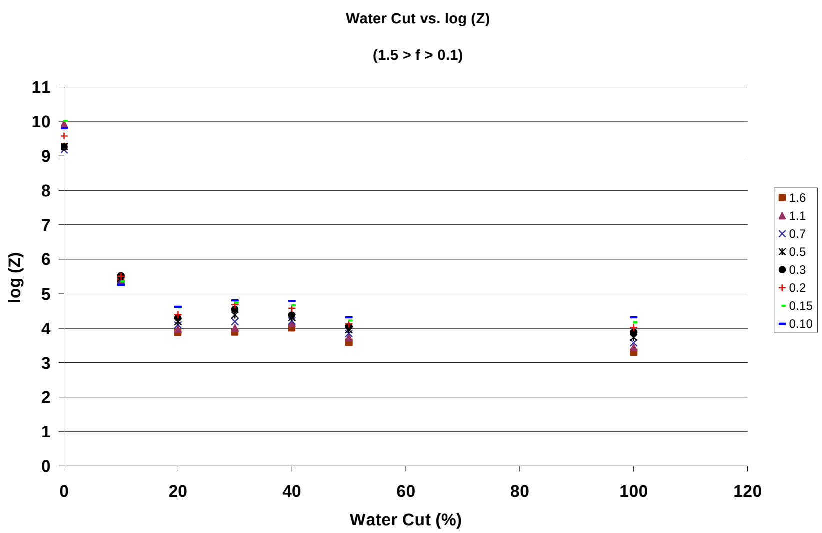

Figure 30. A plot of WC versus log (Z) in the frequency range 0.1 Hz to 1.6 Hz.

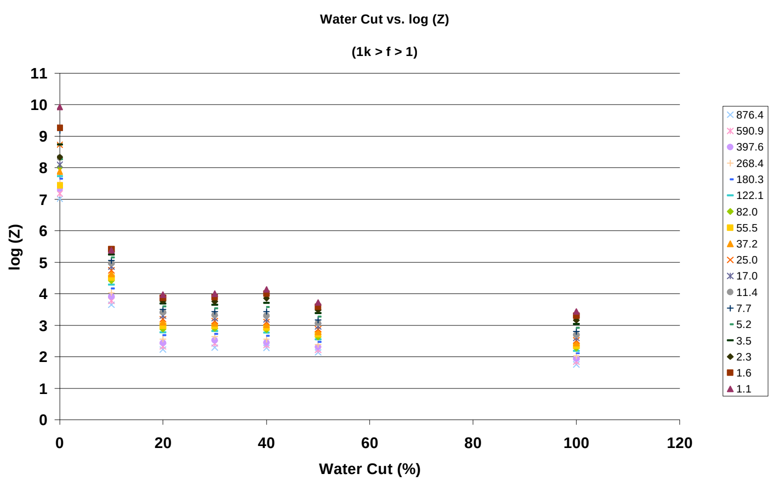

Figure 31. A plot of WC versus log (Z) in the frequency range 1.1 Hz to 876.4 Hz.

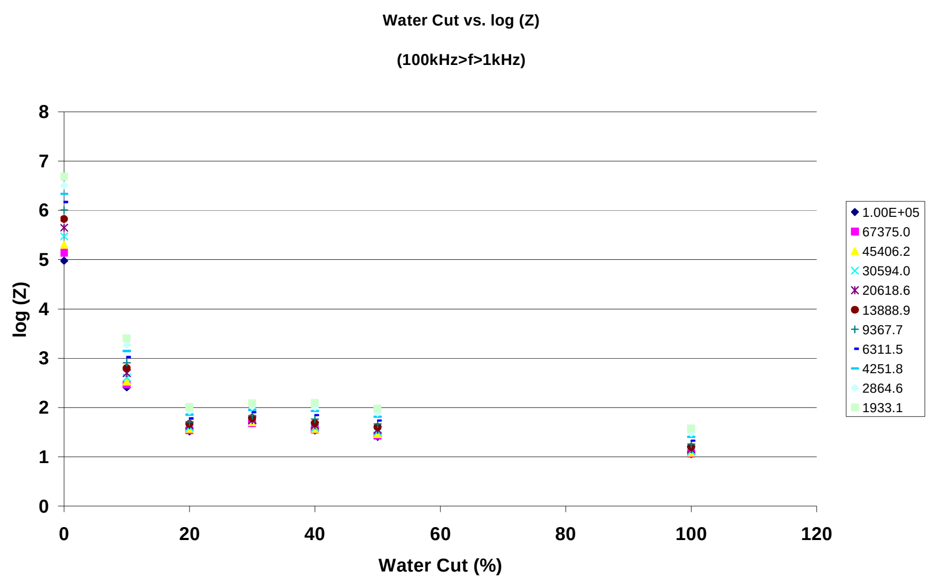

Figure 32. A plot of WC versus log (Z) in the frequency range 1933 Hz to 100 kHz.

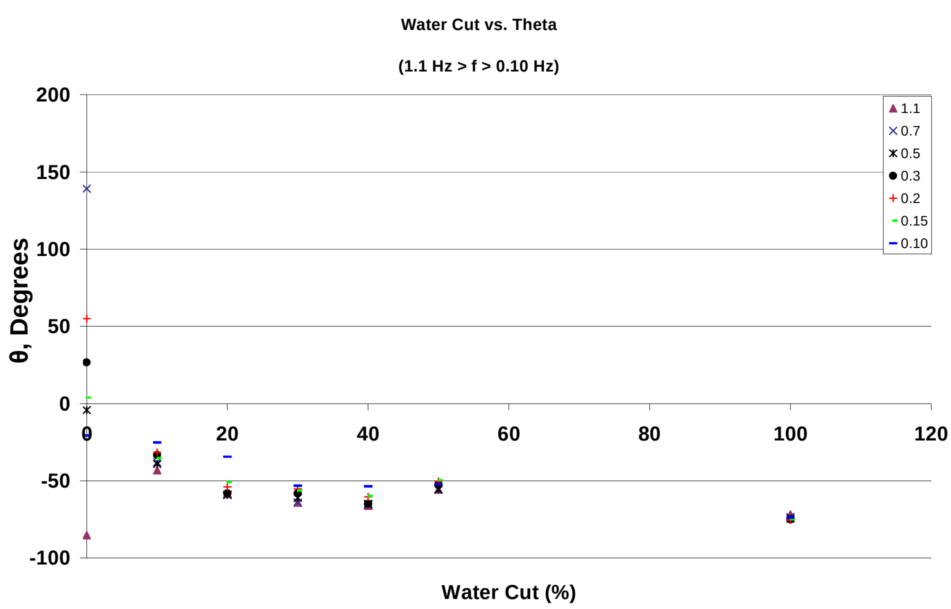

Figure 33. A plot of WC versus the phase angle (θ) in the frequency range 0.1 Hz to 1.1 Hz.

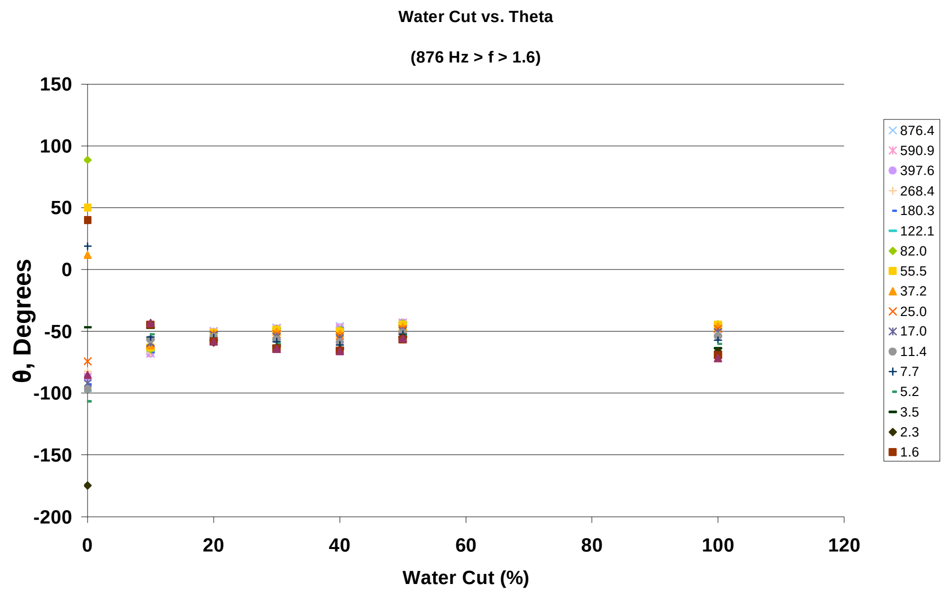

Figure 34. A plot of WC versus the phase angle (θ) in the frequency range 1.6 Hz to 876.4 Hz.

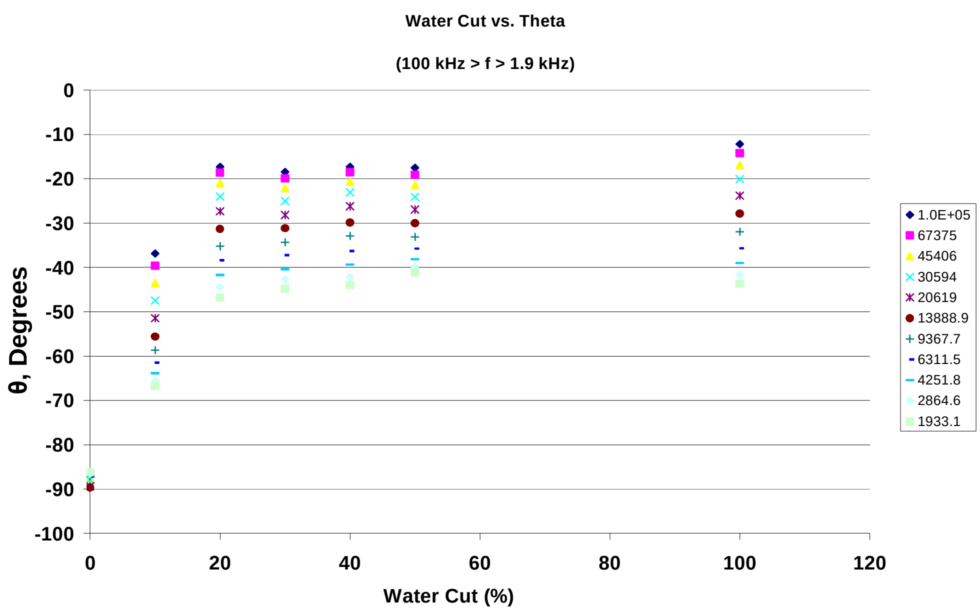

Figure 35. A plot of WC versus the phase angle (θ) in the frequency range 1933 Hz to 100 kHz.

FINAL REPORT

Using the alternative pig ring-sensor design, a series of flow loop tests were conducted with different water cuts. The results are shown in Figure 36. From these results, it is clear that different WCs can be distinguished to at least 25% resolution. Furthermore, it is also evident that when liquid accumulation is at two different locations, these can be distinguished provided that the liquid volume is not so large that the pig is constantly pushing a puddle. In addition, it is also clear that some smearing and/or sluicing of entrained liquids occurs for some distance past the accumulation points before dissipating and thinning out. That is, once the pig encounters liquid this liquid is then pushed forward along the pipe. Due to lack of ovality or damage to the pig such that a tight seal is no longer maintained, the liquid becomes smeared out and thinned causing the sensor to detect the liquid beyond the end point of the accumulation.

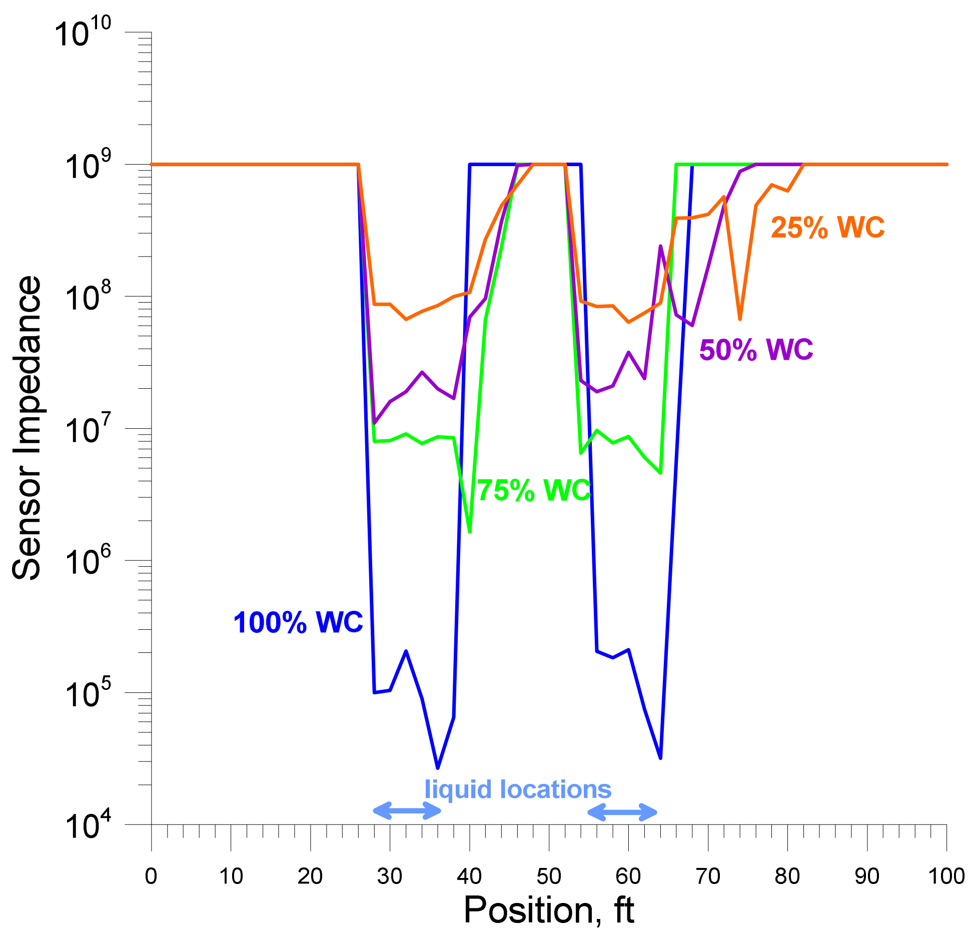

Figure 36. A plot of sensor impedance as a function of position in 100’ test flow loop at different water cut levels.

3.4 Meetings and Discussions With Pipeline Operators

Numerous meetings and discussions were held with different pipeline operators and pigging companies. In these meetings, the technology and concept of an instrumented cleaning or de-watering pig was discussed. The results of lab testing were usually accepted as being positive and in the right direction. As a result, a limited field test was arranged on a side stream pipeline. This line was approximately 5 miles in length. Additional discussions have taken place and a contract with Petrobras is presently being negotiated to conduct an assessment of a longer pipeline using multiple stand-alone sensors and pig-mounted sensors.

3.5 Field Test of Cleaning Pig-Mounted Sensors

A field trial using the pig-mounted ring-sensor was conducted in an operating side stream. The total pipeline length investigated was approximately five miles. The line was hydrotested as a part of the overall integrity management plan. After the hydrotesting, an instrumented de-watering pig was run through until no water was detected by the sensors. As shown in Figure 37, it took 5 pig runs to remove all the water. The first run encountered water approximately 9,600' and then continued to see water the rest of the distance as the pig pushed water out of the line. In the second run, water was encountered farther downstream than the first run at approximately 12,500'. Subsequently, the third and fourth runs also progressively showed the pig encountering water farther downstream. In the fifth run, no water was detected over the distance it was run. These results are very encouraging and demonstrate that the concept will work. As a result, Petrobras has entered into contract negotiations to conduct a long-length pipeline investigation using this technology as well as individual stand-along sensors.

4 CONCLUSIONS AND TECHNOLOGY IMPLEMENTATION

Pipelines pose an enormous challenge to monitoring because of their geographic extent, buried nature, and the need to provide relatively uninterrupted service. Therefore, any monitoring/inspection technology that require excavation or significant interruption of operations are unlikely to be adopted easily. The developed technology aims to provide a monitoring tool that will be more easily adopted because it overcomes many of the limitations of existing technologies. In addition, this technology can be adapted to provide feedback control to various mitigation schemes such as inhibitor or biocide injections as well as a methodology to ensure that all fluid has been swept from the pipeline after hydrotesting.

Through the course of this project, each of the component technologies and concepts has been successfully demonstrated. In addition, several fully functional prototype systems have been constructed and evaluated under laboratory as well as field conditions. Based on feedback from operators, this technology is close enough to production to be reliable and robust. Petrobras is presently planning to utilize the technology in an existing pipeline.

FINAL REPORT

Currently, publishing of the results is planned. It is felt that if a wider audience of pipeline operators is exposed to this technology and the successful testing conducted to date, that more interest would be garnered. With more exposure and more interest additional trials and tests could take place. Additionally, other major suppliers of pipeline inspection and integrity technologies may adopt this technology and further commercialize and utilize it.

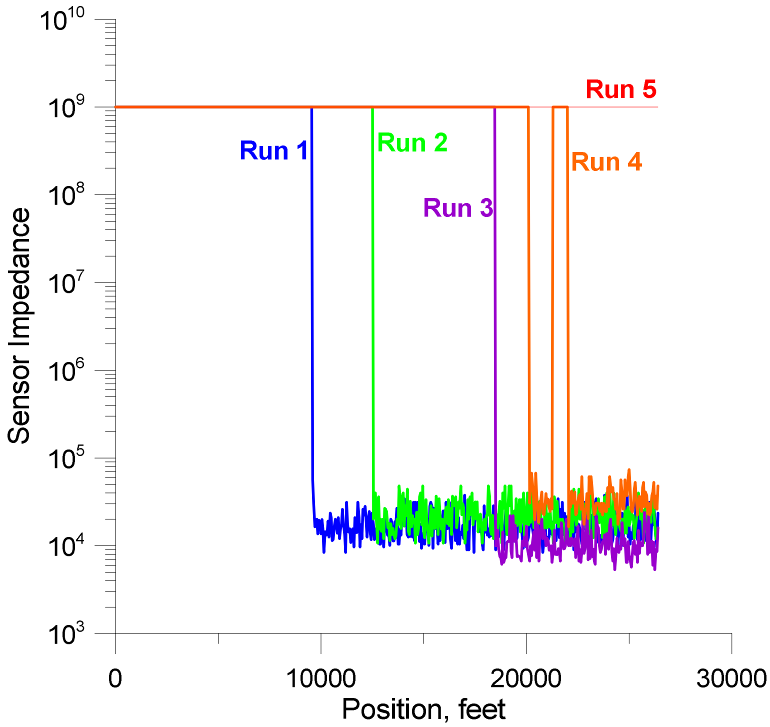

Figure 37. Sensor impedance measurements for an instrumented de-watering pig during subsequent pig runs.